Turfgrass and Landscape Irrigation Water Quality

Assessment and Management

Ronny R. Duncan • Robert N. Carrow • Michael T. Huck

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Dedication to

Dr. James R. Watson—a man of vision, character, and impact

As the authors of this book, we dedicate it to Dr. James Watson, an extraordinary individual who has devoted a lifetime to promoting water conservation and quality stewardship well before these topics were in the news or even on the minds of others. Water as a central theme in the life of Dr. James R. Watson started when he was the first Ph.D in an emerging science area—Turfgrass Science (Watson, J. R. 1950. Irrigation and compaction on established fairway turf. Ph.D. Thesis. Penn. State University. pp. 1–69). After graduation he was appointed assistant professor at Texas A&M in the Department of Agronomy. In 1952 he joined The Toro Company as Director of Agronomy and rose to the position of Vice President, Customer Relations and Agronomist. "Dr. Jim" has been widely honored within the science realm (Fellow and recipient of the Agronomic Service Award of the American Society of Agronomy; Fellow of Crop Science Society of America; President of the International Turfgrass Society) and the turfgrass industry (Harry Gill Award of the Sports Turf Managers Association; USGA Green Section Award; Old Tom Morris Award of the Golf Course Superintendents Association of America).

In the opinion of the authors, Dr. Watson has positively impacted water stewardship on a world-wide basis within the turfgrass industry more than any other individual. His influence has been multifaceted through: a) education via popular articles, science articles, and numerous presentations to science and professional turfgrass managers; b) equipment and concept development to enhance turfgrass irrigation equipment and practices; c) supporting and stimulation of research including a foundational role in the development of the USGA Turfgrass and Environmental Research Committee and a member of this committee since 1982 that has funded more turfgrass research than any other entity — with the initial and on-going focus being water; d) consulting on a world-wide basis including World Soccer venues and many other sports facilities and golf courses; and e) inspirational through the support, nurture, mentor, and model for many within all areas of the turfgrass industry—including the lives and careers of each of us.

Thank you Jim, a job and life well lived.

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Preface

Water—without it there is no life. Be it the life of humans, animals, or plants, we cannot do without it. Compared to other natural resources such as oil, and as valuable as oil may currently be, water is far more valuable as there are substitutes for oil, but no substitutes for water.

Currently, we best understand water quality as it pertains to potable drinking water for animals and humans. However, we are still learning many of the technical aspects about this critical resource when it is applied on soil and plants. With environmental extremes that range from persistent droughts to flooding, trying to grow turfgrass and landscape plants is a challenge. If salinity is added to water, you have significant interactions among the plant species and cultivars, the concentrations of salts and specific salt ions, the soil profile, and the site-specific climate that causes confusion when trying to manage turfgrasses and landscapes.

Although irrigation water quality is only now receiving significant attention in the golf course, turfgrass, and landscape industries, the problems related to salts contained in irrigation water resources have been recognized for many years. Decades ahead of his time, the golf course architect Dr. Alister MacKenzie wrote more than once on the subject in his manuscript "The Spirit of St. Andrews" (written in 1934, lost, then later discovered and published in 1995). Mackenzie described that the well water at Sharp Park, a new San Francisco Municipal Golf Course at the time, contained "as large a proportion as seven hundred parts per million of common salt." He went on to explain that "it was obvious few grasses would flourish under these conditions" so a decision was made to seed the course with *Agrostis maritima* brought in from Marshville, Oregon, because of the knowledge that it survived being flooded for two months each year with seawater.

Dr. McKenzie also mentions that at Cypress Point Golf Club "our water bill is enormous" and it would be possible to save that excessive expense by sinking wells on the property. But, he also questioned the risk of doing irreparable damage and asked "might it not be better to continue using the water known to suit the turf, not withstanding the great expense?" MacKenzie reported "searching the bulletins of the USGA and other sources" but he "could find very little written on the subject." He opined that: "If the Green Section were able by their experiments to solve our difficulties, they would save us thousands of dollars per year."

As it was then in 1934, it seems still to be the case that few turfgrass managers have received formal training in the intricacies of irrigation water. We hope this book will provide a foundational start to understanding the complexities of water quality, and will lead to science-based management decisions that are environmentally friendly and sustainable during this millennium.

The focus of this book is to provide comprehensive, science-based, in-depth information relative to (1) understanding irrigation water quality reports, (2) explaining specific irrigation water quality situations or challenges associated with various water sources from the initial source—onsite storage and delivery systems, turfgrass plants, the soil, and underlying hydrology spectrum, (3) development and implementation of best management practice options to address each specific type of problem that may affect turfgrass performance, and (4) addressing potential environmental concerns related to variable quality irrigation resource use on landscapes and recreational turfgrass uses from the landscape to the watershed levels. The diversity and nature of various water-quality-related challenges may initially seem to be somewhat overwhelming. However, our goal is to present field problems in a logical manner, with adequate scientific explanation, and with detailed practical information for resolving each specific problem.

The color photo insert pages provide a few representative graphic examples of water quality and water quantity challenges in the world. Water quality issues can be found throughout all countries and regions, varying in their specific degree or severity of expression in soils and plants and depending on geologic, hydrogeologic, and other site-specific environmental influences. Water quantity issues are directly dependent on precipitation shortfalls, excesses, and frequency-of-distribution patterns in conjunction with fluctuating climatic changes. Both water quality and water quantity are dynamic in nature, and constantly impact all turfgrass and landscape plant sustainability. (See color figures following page 106.)

Ron R. Duncan
Robert (Bob) N. Carrow
Mike Huck

The Authors

Ronny R. Duncan, Ph.D.

With degrees from Texas Tech University (B.S.) and Texas A&M University (M.S. & PhD.), Dr. Duncan spent from May 1, 1977 to June 30, 2003 at the University of Georgia-Griffin in grass research. His research program was initially focused on breeding/genetics/stress physiology of edaphic and abiotic environmental stresses on grain sorghum, then beginning in late 1993, on turfgrasses (tall fescue, seashore paspalum). His expertise ranged from drought and soil acidity stresses initially to eventually salt/salinity-related problems and turfgrass management involving water conservation strategies, water quality problems, and alternative water use on all turfgrasses. After retirement from the University of Georgia, he became vice president of Turfecosystems, LLC, to concentrate on teaching workshops for GCSAA/GIS on advanced turfgrass water quality, seashore paspalum management, salt-affected turfgrass sites, and turfgrass water conservation. He currently consults globally on all grasses and water challenges, continues to develop proprietary products for Turfecosystems, and will continue to write books dealing with management challenges on turfgrasses. He has developed and patented five seashore paspalum cultivars and developed five stress-tolerant tall fescue cultivars, which are currently on the market. He is a fellow in the Crop Science Society of America and the American Society of Agronomy. He has written over 200 refereed scientific publications and has published over 500 articles.

R. N. Carrow, Ph.D.

Dr. Robert Carrow is a professor of turfgrass science in the Department of Crop and Soil Sciences at the University of Georgia, located at the Georgia Experiment Station in Griffin. A native of Michigan, he obtained his B.S. (1968) and Ph.D. (1972) degrees in crop and soil sciences at Michigan State University. He was a faculty member in turfgrass science at the University of Massachusetts (1972–1976) and Kansas State University (1976–1984) before accepting a 100% turfgrass research position in 1985 from the University of Georgia.

Dr. Carrow has co-authored three books: *Salt-Affected Turfgrass Sites: Assessment and Management* (1998), *Seashore Paspalum: The Environmental Turfgrass* (2000), and *Turfgrass Soil Fertility and Chemical Problems* (2001). He is coeditor of *Turfgrass*, Agronomy Monograph No. 32 (American Society of Agronomy, 1992) and served in the Crop Science Society of America within the Turfgrass Science Division as chairman, board representative, and associate editor. From 1993–2004, he served as vice-president of the International Turfgrass Society for turfgrass scientists. Dr. Carrow is a fellow of the American Society of Agronomy.

He has written numerous scientific book chapters and journal articles (100) and trade journal articles (201). He is widely sought as a speaker and has made over

500 invited presentations on a worldwide basis to turfgrass professionals and 26 to scientific audiences in 38 states and several countries, including Australia, Canada, England, Singapore, Japan, and Guam. He has been a cooperator on the release of three bermudagrasses, four seashore paspalums, and three tall fescues. Dr. Carrow is currently working with coauthors' best management practices books related to turfgrass and landscape irrigation water quality issues; BMPs for salinity-affected turfgrass sites and BMPs for turfgrass water conservation/water use efficiency. For over 28 years, Dr. Carrow has conducted annual workshops in 2-day formats for the Golf Course Superintendents of America Association (GCSAA) in the areas of managing salt-affected sites, soil fertility and fertilization, soil physical problem assessment and management, and BMPs for water conservation on golf courses.

Dr. Carrow's current research is focused on monitoring spatial and temporal variability in soil properties, as well as turfgrass stress applications and protocols. The emphasis is on monitoring, mapping, and analyzing spatial/temporal variability in soil moisture, plant stress, soil compaction, and soil salinity for the purposes of (1) improving water-use efficiency and conservation by enhancing irrigation design and scheduling, and (2) development of new means to monitoring soil salinity by depth for enhancing leaching.

Dr. Carrow's research activities have included (1) climatic and soil stresses on turfgrasses, especially drought, saline/sodic, low soil oxygen, acid-soil complex, low light, and nutritional stress, (2) water conservation and irrigation water quality issues, (3) management of salt-affected sites and seashore paspalum, and (4) traffic stresses on recreational sites, both wear and soil compaction.

Michael T. Huck

Michael T. Huck is currently an independent turfgrass and irrigation management consultant with over 30 years experience in the golf course maintenance industry. He spent 6 years as an agronomist in the United States Golf Association's Green Section Southwest Region and 13 years as a golf course superintendent at three well-respected Southern California golf facilities. Those facilities each were irrigated with nonpotable recycled wastewater or saline groundwater.

After recognizing there was at the time little published information available regarding managing turf and landscapes irrigated with nonpotable water sources, he began studying articles and publications related to agricultural irrigation water quality. He then applied those principals to soil management and irrigating turf, trees, and other ornamental plants. His successes in overcoming the challenges of using nonpotable water were recognized in 1993 when invited to speak at a national conference on irrigating golf courses with wastewater. Each speaker at this conference was requested to submit a manuscript that later was assembled into the book *Wastewater Reuse for Golf Course Irrigation*. Years later, after joining the USGA Green Section, he authored and coauthored several articles on nonpotable and recycled water, water quality, and other irrigation related subjects.

Other areas of interest for Huck are irrigation distribution uniformity and scheduling efficiency. He is certified by the Irrigation Association as a Golf Course Auditor and integrates various analysis software and procedures normally used only in manufacturers testing laboratories to refine the field evaluation and scheduling process.

He finds these principles important for both conserving water and management of poor quality irrigation sources.

Mike obtained his Bachelor of Science Degree in ornamental horticulture with a turfgrass emphasis in 1982 from California State Polytechnic University, Pomona. He and Dr. Duncan currently copresent a full-day educational seminar for the GCSAA (Golf Course Superintendents Association of America) on the subject of turfgrass irrigation water quality assessment and management. Since 2003 he has provided independent consulting to the golf industry regarding turfgrass, soils, water quality, irrigation audits, and water management with his company, Irrigation & Turfgrass Services.

Part 1

Understanding Assessment of Irrigation Water

"Ode, On the General Subject of Water"

Water is far from a simple commodity,
Water's a sociological oddity,
Water's a pasture for science to forage in,
Water's a mark of our dubious origin,
Water's a link with a distant futurity,
Water's a symbol of ritual purity,
Water is politics, Water's religion,
Water is just about anyone's pigeon
Water is frightening, water's endearing,
Water's a lot more than mere engineering,
Water is tragical, water is comical,
Water is far from pure economical,
So studies of water, though free from aridity,
Are apt to produce a good deal of turbidity.

Kenneth Boulding, *Feather River Anthology*

1 Overview of Irrigation Water Quality Concerns

1.1 POTABLE WATER DILEMMA

Availability of adequate quantity of good-quality irrigation water is the number one issue confronting the turfgrass industry in the 21st century. Efficient water use requires that all water users adopt **best management practices (BMPs)** for water conservation, and one of the key strategies for water conservation on turfgrass sites is use of nonpotable or alternative irrigation water sources (Carrow et al., 2005a,b,c); thus, water quantity and quality are inextricably linked.

Human consumption and many industrial uses will unquestionably have higher priority for potable water than agricultural or turfgrass irrigation. The key difference between **potable** versus **nonpotable** or **alternative irrigation water sources** is water quality, where potable water is considered as drinking water quality. For turfgrass irrigation, nonpotable water resources are increasingly being mandated and regulated, especially on larger turfgrass sites. These trends bring the concept of **irrigation water quality** to the forefront within turf management programs; and addressing water quality issues has important multiple stakeholder implications in the political, sociological, emotional, recreational, and environmental arenas for the turfgrass industry (USEPA EMS, 2005).

The Environmental Literacy Council (2005) highlights multiple stakeholder impacts that result when addressing any environmental issue in its definition of the type of environmental knowledge and practice (literacy) needed in today's world to positively address environmental problems, whether in the turfgrass industry or in other segments of society, as:

> Environmental literacy requires a fundamental understanding of the systems of the natural world, the relationships and interactions between living and the nonliving environments and the ability to deal sensibly with problems that involve scientific evidence, uncertainty, and economic, aesthetic, and ethical considerations.

The key words and concepts in the preceding statement that are important for the turfgrass industry with respect to irrigation water quality are: *systems, interactions, deal sensibly with problems,* and the interplay between scientific, economic, aesthetic, and ethical considerations.

An overview of **global water reserves** is helpful to put into perspective the limited quantity of potable water compared to other available forms. Global water reserves are available in many different forms, with seawater (average 34,486 ppm total soluble salts) making up 96.5% of the total global water supply, whereas freshwater reserves total 2.5% (Gleick, 1993). Groundwater, which makes up 1.7% of the total global water supply, includes 55% saline and 45% freshwater. A total of 30.1% of the freshwater comes from groundwater. Lake water reserves (0.013% of total water resources) include 0.006% saline and 0.007% freshwater. Swamp water (0.0008%), river flows (0.0002%), glaciers and permanent snow cover (1.74%), and ground ice/permafrost (0.022%) account for the remaining global water reserves.

Global demand for fresh potable water (3.265% of total global water reserves) is doubling every 20 years (Gleick, 1993). Competition for this valuable resource will increase in the 21st century. To put this into perspective, during the past 30 years, the population in the United States has increased 52%, while total water use has increased 300%. Renewable water resources per person decreased 50% between 1960 and 1998 in the United States. Another 50% reduction is projected by 2025. By 2000, 20% of all U.S. communities experienced water shortages in the form of water rationing or short-term cutoffs.

With the limited quantity of potable water available combined with increasing demand, turfgrass managers will have no choice but to irrigate with recycled or other nonpotable water resources of reduced quality relative to potable sources. Use of alternative irrigation water sources, rather than potable water supplied by a municipal water treatment system, is not a new practice to many golf courses and other large turf areas. However, this is now becoming the normal practice in many areas as competition for potable water increases (Pettygrove and Asano, 1985; Snow 1994, 2003; Jury and Vaux, 2005; Oster, 1994; Shalhevet, 1994; Smart, 1999; Zupancic, 1999; Thomas et al., 1997; Huck et al., 2000; Carrow and Duncan, 2000; Marcum, 2006).

1.2 ALTERNATIVE IRRIGATION WATER SOURCES

As a starting point to understanding the challenges associated with the use of alternative irrigation water sources, it is important to understand how diverse these sources are. Alternative sources of irrigation water include the following:

- Larger streams, rivers, and flowing watercourses.
- Surface water in natural or constructed lakes, ponds or impoundments fed by streams, springs, or diversion channels from flowing water sources.
- Irrigation or drainage canals.
- High-flow (flood or storms) water diversion into storage ponds or lakes (type of water harvesting).
- Ponds or other catchment facilities fed by surface runoff from surrounding terrain during normal rainfall events (a type of water harvesting).
- Storm runoff from impervious surfaces captured in retention ponds, wetlands, or lakes (a type of water harvesting).
- Stormwater harvesting on a small, or micro, landscape scale using tanks or diversion to directly supply water to trees or landscape areas graded topographically to receive the waters (a type of water harvesting).
- Graywater harvesting for small landscape area uses.
- Groundwater from deep or shallow wells.

- Groundwater from aquifers not suitable for potable purposes owing to high salinity, but can be used on salt-tolerant grasses.
- Tertiary effluent from a sewage treatment plant, treated to allow for use on golf courses or public access sites. This source is likely to be the most prevalent alternative irrigation water source, and it is an example of water recycling.
- Recycled water collected from the drainage or stormwater lines of a golf course as well as associated housing development, treated by a private treatment facility for irrigation quality, and then reused for irrigation.
- Wastewater from a golf course and associated housing development or sewage treatment plant applied to a forested spray field, and then the use of wells to recover or recycle the filtered water for irrigation. In this instance, the soil serves as a filter and becomes the "water treatment."
- Stormwater from surrounding residential communities or from the golf course property diverted to grassed retention areas or percolation basins, and then the use of wells to recover the water for irrigation. In this instance, the soil and grass function as a filter and becomes the "water treatment."
- Wastewater or stormwater from a golf course, housing development, or sewage treatment plant collected and diverted through a series of artificial wetlands prior to reuse as an irrigation source. In this instance, the wetland basin serves as the filter and becomes the "water treatment."
- Seawater or seawater blends used on salt-tolerant (halophytic) grasses (Carrow and Duncan, 2000; Duncan et al., 2000b) in ecosystems conducive to managing the high level of salts that are deposited on the infrastructure.
- Desalination technologies to remove excess salts from seawater, brackish waters, or saline groundwater, and secondarily, the subsequent environmentally sustainable management of the concentrated brine.

Often, more than one irrigation water source may be available and used on a single turfgrass site. The availability of more than one water source can help buffer against possible shortages during drought periods; for example, constructed storage ponds could lessen the seasonal impact on existing water sources (such as streams or wells) during peak irrigation. As an example, consider the daily quantity of recycled water produced at a residential or municipal sewage treatment plant to remain relatively constant throughout the year. However, the end use of that water volume and level of salinity will fluctuate dramatically depending on local climate and season of the year. Therefore, "off-season" storage either at the treatment facility or on the golf course will become an increasingly important element of recycled water systems to achieve a consumption balance where total demand equals the available deliverable supply volume.

Different terms may be used relative to a particular water source, such as *recycled, reclaimed, water reuse, wastewater, effluent, stormwater, graywater,* and *water harvesting.* Some of these terms' definitions are narrower in scope, whereas others are broader; therefore, there is considerable overlap in these definitions. In this book, we will use the terms as defined in the following discussion. The term **wastewater** is often viewed as untreated water from homes, businesses, industries, and institutions, but it also can include untreated drainage or tailing water from agricultural, turfgrass, and mining enterprises. **Effluent water**, **reclaimed water, treated wastewater**, or **wastewater reuse** are often used interchangeably, normally with the meaning of partially or fully treated water from a water treatment facility that has been treated to a quality suitable to its intended eventual use, which could be any of the following: agricultural irrigation, landscape irrigation, industry use, nonpotable urban water uses (fire protection, air conditioning, toilet flushing, snow making, etc.), recharge of groundwater aquifers, replenishment of reservoirs or wetlands, and other nonpotable uses (Pettygrove and Asano, 1985; Bond, 1998; USEPA, 2004). We will use the term **reclaimed water**, rather than the alternative terms, in the context of water that has been treated in a treatment facility for irrigation use on landscape sites that allow safe human access and exposure. A very significant irrigation water source for golf courses now and in the future is reclaimed water (Snow, 1994; Huck et al., 2000; Mortram, 2003). It is estimated that over a thousand golf courses in the United States currently use tertiary treated effluent (Snow, 2003).

Recycled water is wastewater, urban stormwater, or harvested rainwater that has been treated, if necessary, to a quality level appropriate to its intended use; thus, recycled water is a broader term that encompasses all potential water reuse schemes. Recycled water often requires treatment in a water treatment facility to meet safety standards for irrigation use on sites where humans have access and exposure, but recycled water may not always require treatment, for example, harvested rainwater. Also, treatment may be by means other than a municipal treatment facility; for example, recycled water could include raw wastewater applied to a forested spray field and then recovered by deep wells after the applied wastewater has percolated through the soil into the underlying aquifer. In this case, the “treatment” is not by a wastewater plant but natural filtration by the soil. The collection of water from tile lines and its diversion into an irrigation pond on a golf course, followed by reapplication for irrigation, is another example of recycled water.

Stormwater reuse is when storm runoff water is collected and stored for future use. In urban areas, stormwater collection may be on a large scale from impervious and pervious surfaces where water is collected and diverted into community reservoirs (Thomas et al., 1997; WBM Oceanics Australia, 1999; Hall, 2005; Coffmann, 2000). Planned stormwater or drainage water collection from a large landscape site, especially if it includes any associated housing development, can result in substantial water for recycling back into landscape irrigation or other uses not requiring potable water quality. On some sites, the stormwater from impervious sites may be directed onto adjacent turfgrass areas and provide water without directed application through an irrigation system with proper contouring. In this case, the storage is not in a reservoir or lake, but within the soil.

Water harvesting in larger landscapes is usually thought of as treating or modifying watersheds to enhance or direct runoff that is collected in a lake or wetland for future use (FAO, 1994; Thomas et al., 1997; Todd and Vittori, 1997). The environment-friendly term *water harvesting* is not often used in relation to golf courses; yet it is a common localized practice. Many golf course irrigation lakes also serve as landscaping features and catch excess runoff, preventing the loss of substantial amounts of water from the site and retaining sediment that would otherwise be carried into streams or rivers. Catchment features are often part of an overall community stormwater control program mandated by governmental policies to control flooding. A recent survey of Georgia USA golf courses indicated that as much as 67 percent of irrigation water came from such nonpotable, surface sources (Florkowski and Landry, 2002). In the case of golf courses, the landscape is deliberately contoured to collect the excess runoff from rainfall, while allowing good infiltration of water into the soil under normal conditions.

Graywater is wastewater from kitchen, laundry, or bathroom sinks and outlets, but excluding human waste. Graywater is a type of water harvesting in which collection and use is tightly regulated. Graywater may have some use for small landscape irrigation.

Desalination is another potential water source in some cases (Agriculture, Fisheries, & Forestry–Australia, 2002a,b; Keene, 2003). The original water source may be seawater, brackish water, or saline groundwater. One significant issue with reverse osmosis (RO) or other forms of desalinization is the permissible and environmentally sustainable disposal of the concentrated brine (Andrews and Witt, 1993).

This brief review of alternative irrigation water sources reveals that all sources are not the same in terms of water quality concerns from the perspective of human health, environmental, or turfgrass management. In the next section, a brief overview of water quality concerns is presented.

1.3 OVERVIEW OF IRRIGATION WATER QUALITY CHALLENGES

Irrigation water quality concerns or considerations involve many stakeholders, because water easily moves within the hydrological cycle (Herbert, 1999) and often carries with it dissolved and suspended pollutants. Important examples of potential irrigation water quality impacts or concerns are the following:

- Human exposure and health for those using or working on irrigation turf sites
- Direct impact on the turfgrass and landscape plants
- Effects on soil, groundwater, and surface waters (Carr, 2005; Stevens et al., 2004; Thompson and Larsen, 2004; Harter, 2003)

Specific water quality concerns are often associated with particular irrigation water sources (Ayers and Westcot, 1994; Pettygrove and Asano, 1985; Snow, 1994; AWA, 2000). The umbrella terms of *nonpotable* and *alternative* irrigation water sources include a diversity of origins—for example, brackish or saline surface or groundwater, reclaimed, recycled, stormwater, graywater, or any other water source that is nonpotable. Each source may exhibit chemical, biological, or physical constituents that can challenge turfgrass performance and require site-specific cultural practices for environmentally safe use. The most prevalent constituents in many alternative water sources, which are often higher in concentration than those found within potable sources, are soluble salts and nutrients, but many **biological, physical, or chemical contaminants** are possible depending on the source, such as the following:

- **Biologicals**—human pathogens, plant pathogens, animal pathogens, algae, cyanobacteria, iron and sulfur bacteria, nematodes, weed seed.

- **Physical contaminants**—total suspended mineral or organic solids, turbidity, color, temperature, and odor.
- **Chemical constituents**—total soluble salts, specific salt ions, nutrient ions, potential root or foliage toxic/problem ions, total dissolved solids (sediment), alkalinity, trace elements, oxygen status, biodegradable organics, nonbiodegradable (refractory or resistant) organics, free chlorine residuals, hydrogen sulfide, or other gases.

A four-way interaction among water quality parameters and soil (physical, chemical, and biological properties), specific turfgrass species and cultivars, and the climate, especially extreme environmental conditions, will create site-specific challenges for all turf managers in the future. Understanding this four-way interaction is the key to successfully growing grass and to maximizing turf performance in the long term. Without a doubt, water quality is as good as it is going to be. From this point onward, decreasing quality and the subsequent application on recreational turf coupled with mandated water conservation programs will challenge even the best managers. Job security and turfgrass performance will parallel these water challenges.

Throughout this book, various water quality challenges will be addressed in detail, but a brief introduction of the most prevalent or encompassing ones will aid in understanding the depth and scope of challenges. Of all the potential irrigation water quality problems, some issues are more daunting than others. One challenge associated with many alternative irrigation water sources is **total soluble salt load,** because soluble salts have the potential for salinization of soils, aquifers, and surface waters, as well as adversely affecting turfgrass performance (Rhoades et al., 1992; Snow, 1994; Hanson, et al., 1999; Carrow and Duncan, 2006; Neilsen et al., 2003). As water quality decreases and salinity in that water source continues to increase, salts must be managed before, during, and after managing the turfgrass. With each application of water on areas covered by the irrigation system, some level of salts is deposited over the entire site (Table 1.1). Although some halophytic (salt-tolerant) turfgrasses can tolerate seawater irrigation or flooding for periods of time, the salt load in seawater is such that the practice is not recommended; and if practiced, only by blending the water and with considerable ecosystem infrastructure inputs to protect the environment can the grass be successfully managed (Duncan et al., 2000a) (Table 1.2). Loading of these salts into the soil profile over time is a concern unless these salts are properly leached down to drainage lines and removed from the root zone to minimize its negative impact to the turfgrass root system and to overall turf performance, as well as contamination of soil and possibly potable groundwater. Inattention to salt loading and disposal ultimately will lead to **salinization** of soils, groundwater, and surface waters. A whole systems approach must be adopted to deal with salinization, as noted by the FAO in their "integrated soil management for sustainable use of salt-affected soils" (FAO, 2005).

A second challenge with alternative irrigation water sources is **location of the water quality problem**: all problems encountered by a turf manager when using a particular water source may not be from direct application to the turfgrass or soil.

TABLE 1.1
Total soluble salt load applied in irrigation water at different salinity levels

Irrigation (ppm)	Water salinity (dS/m)	Salt (lb) applied per 1.0 in. of irrigation water[a]: Acre	Salt (lb) applied per 1.0 in. of irrigation water[a]: 1000 ft^2
500	0.78	113	2.6
1000	1.56	227	5.2
2000[b]	3.13	453	10.4
3000	4.69	680	15.6
5000	7.81	1133	26.0
7500	11.72	1700	39.0
10,000	15.63	2267	52.0
15,000	23.44	3400	78.1
20,000	31.25	4533	104.1
25,000	39.06	5667	130.1
34,500[c]	54.00	7820	179.5

[a] One inch applied irrigation water = 27,154 gal/acre = 623 gal per 1000 ft^2 = 245,000 L/ha.

[b] Irrigation water of salinity > 2000 ppm is considered "very high" in total salinity (Westcot and Ayers, 1985).

[c] Seawater is normally ~34,500 ppm salt.

TABLE 1.2
Properties of typical seawater

Ion	Ion concentration (ppm)	Ion concentration meq/L	Percentage total (%)	Percentage cations (%)	Quantity applied (lb) per 1000 ft^2 per 1.0 in. seawater
Cl^-	18,980	534.6	55.1	—	98.8
Na^+	10,556	458.8	30.7	83.8	54.9
SO_4^{-2}	2,690	56.0	7.8	—	14.0
Mg^{+2}	1,304	106.8	3.8	10.4	6.8
Ca^{+2}	420	21.0	1.2	3.3	2.2
K^+	310	9.9	0.9	2.5	1.6
HCO_3^-	146	2.4	0.4	—	0.8
CO_3	—	—	—	—	—
N	11.5	—	—	—	—
P	0.06	—	—	—	—
Mo	0.01	—	—	—	—
Fe	0.002	—	—	—	—
Mn	0.0002	—	—	—	—
Total	34,418	—	—	—	179

Depending on chemical, physical, and biological characteristics in the irrigation water, the problem that confronts the turfgrass manager may be at different points within the spectrum of water movement: from the initial source location, onsite storage, delivery system, turfgrass plant rhizosphere, soil profile, and underlying specific site hydrology. Thus, there may be multiple water quality challenges that can occur within the hydrological cycle on a particular site. For example:

- When irrigation water requires treatment for human exposure and health considerations prior to application on a turfgrass site with public access, insurance of proper treatment is important. In countries with well-regulated water treatment facilities, this is of less concern; but with on-site treatment schemes or in countries where water treatment is given less attention in dealing with health concerns, the end user must be assured that the water is safe for use. Carr (2005) reported that the percentage of wastewater treated by effective treatment facilities was 14% in Latin America, 35% in Asia, 66% in Europe, and 90% in North America.
- Another instance of water quality concern at the water treatment facility is when multiple golf courses are using a significant portion of the water from a public water treatment facility, and there are some quality concerns that could be addressed at the treatment facility (Stowell and Gelernter, 2001). For example, removal of phosphorous at the treatment plant would reduce the potential for eutrophication in irrigation lakes on the courses.
- Some groundwater sources can cause bore problems, pump impeller deterioration, line or nozzle clogging, or objectionable odors from gases such as hydrogen sulfides (Yiasoumi et al., 2005).
- Significant loads of suspended solids in a water sources should be addressed prior to pumping into the irrigation delivery lines.
- Irrigation ponds or lakes to hold an alternative irrigation water source may exhibit lake management problems owing to constituents (heavy metals, nitrogen, phosphorus) within the water (WOB, 2005).
- Some water sources may require acidification (such as water with highly alkaline or high bicarbonate concentrations) or addition of salts for various reasons prior to irrigation application (UltraPure water).
- Soluble salts, nutrients, and problem ions may have direct and indirect effects on the turfgrass plant when applied foliarly.
- Also, these same ions can have adverse accumulation effects on the soil physical properties.
- Soluble salt disposal via the drainage system requires a permitted disposal outlet. If excess soluble salts are not intercepted by drainage lines, they may percolate into the underlying aquifer. Even good-quality water applied on a site with existing salt accumulation below the root zone can cause future salinity problems if the percolated water causes the water table to rise and bring up soil salts.

Stacking together or pyramiding of several complex management regimes is another challenge that is becoming more commonplace, especially on sites with the combination of poor irrigation water quality, water restrictions/conservation, and more salt-tolerant turf and landscape species. One complex management regime is turfgrass management and irrigation practices for optimum water-use efficiency/conservation, which requires a whole systems or holistic BMPs approach with monitoring as well as frequent adjustments in practices influencing water use (Carrow et al., 2005a,b,c). A second complex management challenge is BMPs for salt-affected sites (where the irrigation source is a major contributor of salt load) to avoid salt accumulation and related stresses on the turfgrass. Monitoring of soil, water, and plants becomes more frequent in this dynamic system. Irrigation water sources rich in salts or nutrients will dramatically affect soil fertility conditions and plant nutrient status. Both become more dynamic in response to irrigation, soil and water amendments and additions, leaching events, and rainfall. Soil fertility and plant nutrition stresses are more common and less predictable. Poor irrigation water quality may necessitate a change in grass species or cultivar, which presents additional maintenance adjustment challenges for the turf manager. Thus, when water conservation pressures increase to the point where lower-quality irrigation waters are used, turfgrass management becomes more complex as individual BMPs for water conservation, salinity management, nutritional programs, and new grass use all interface; each such factor is complex in its own right, but when these are stacked together, the challenges markedly increase. Turf managers of the future must become whole-ecosystems (holistic) managers, able to understand and apply multiple BMPs for site-specific water use, water quality, new grasses, fertilization, and other management aspects (Carrow and Duncan, 2006).

As more turfgrass sites use poorer water quality, turfgrass managers and facility owners must address the foregoing challenges of salinization prevention, multiple water quality problems along the hydrological cycle on a specific site, and the stacking together of multiple complex BMPs. The authors anticipate that the integration of the potential environmental concerns arising from use of poor water quality for irrigation will require an **Environmental Management Systems (EMS) approach** on many sites (USEPA, 2005). The USEPA (2005) defines an environmental management system (EMS) as “a set of processes and practices that enable an organization to reduce its environmental impacts and increase its operating efficiency. An EMS is a continual cycle of planning, implementing, reviewing, and improving the processes and actions that an organization undertakes to meet its business and environmental goals.”

1.4 OUR FOCUS

With increased use of alternative irrigation water sources on turfgrass sites, the management of the sites is becoming more complex and systems oriented. The focus of this book is to provide comprehensive, science-based, in-depth information that will (1) make irrigation water quality reports understandable, (2) explain specific irrigation water quality situations or challenges associated with various water sources from the initial source–onsite storage–delivery system–turfgrass plant–soil–underlying hydrology spectrum, (3) aid development and implementation of best management practice options to address each specific type of problem that may affect turfgrass performance, and (4) address potential environmental concerns related to variable quality irrigation source use on landscapes and recreational turf uses from the landscape to the watershed levels. The diversity and nature of various water quality–related challenges may initially seem to be somewhat overwhelming. However, our goal is to focus on turf ecosystem problems in a logical manner, with adequate scientific explanation, and with detailed practical information for resolving each specific problem. Turf managers will naturally focus on those issues that are important for their site-specific situations.

When confronted with the term *water quality,* most individuals initially think in terms of protection for surface waters and groundwater from pesticides, nutrients, other pollutants, and sediment (Cohen et al., 1999). These constituents are of great interest and importance, but in this book we will focus on "irrigation water quality" and the associated environmental and management concerns that arise from the irrigation water source. The exceptions would be when pesticides, nutrients, or sediments are constituents of the irrigation water from a particular source.

2 Constituents of Concern in Irrigation Water

2.1 CONSTITUENTS IN IRRIGATION WATER

As noted in Chapter 1, irrigation water may arise from many diverse sources, including groundwater, lakes, ponds, streams, canals, lagoons, reclaimed water, ocean water, and blended combinations. Additionally, irrigation water is sometimes pretreated prior to use, such as acidification to remove excess bicarbonates; also, reclaimed water is sometimes used for irrigation purposes. Depending on the source of water and any treatment prior to irrigation, constituents may remain in the water that could (1) result in accumulation of undesirable chemicals in the soil that may adversely affect plant growth when absorbed by the plants or by hindering water uptake; (2) promote physical or chemical degradation of soil quality; (3) cause direct injury to plant foliage or roots when in contact with the water; (4) potentially cause health or environmental problems in lakes, ponds, or streams receiving the water; (5) result in deterioration of irrigation system components; (6) cause human health concerns on the site where irrigation water is applied; and (7) result in an unappealing water due to odor or color. Thus, assessment of irrigation water quality is an important step in determining potential problems (Rhoades et al., 1992; Ayers and Westcot, 1994; AWA, 2000). There are common or standardized methods to determine various parameters in water (Clesceri et al., 1998; USGS, 2005). Most laboratories that routinely evaluate water for irrigation purposes use highly accurate methods. Because there is no formal "chemical extractant" that is necessary for standard water sample analysis, results from laboratories should be consistent, assuming a good representative turf-exposure sample was collected.

Some of the constituents discussed in this chapter and in Chapter 3 can be classified as **pollutants,** if they are a health or environmental concern. A pollutant may be considered a **point source** or a **nonpoint source pollutant**. A point source pollutant would come from a single identifiable source where it would be discharged—such as discharge water from a factory or water runoff from an equipment wash-off area. Nonpoint pollutants come from widely dispersed sources such as runoff from paved urban areas, construction sites into an irrigation pond, or agricultural production irrigation (Bianchi and Harter, 2002).

Chapters 2 and 3 are designed to provide a good overview of irrigation water quality concerns, regardless of the source or location in the delivery system. The information in these chapters is foundational for management of various irrigation-related problems covered in the remainder of the book.

When the topic of irrigation water quality arises, constituents or concerns that come to mind often depend on the background of the individual. Turf managers focus primarily on parameters that influence turfgrass performance, soil conditions, and irrigation pond conditions. Irrigation water quality parameters that are most widely recognized as concerns by turfgrass managers are the constituents included in a **routine irrigation water quality analysis** (Table 2.1). The parameters listed in Table 2.1 are defined and discussed in Chapter 3, "Understanding Irrigation Water Quality Reports."

Others may view irrigation water quality from the standpoint of public health or environmental and agronomic concerns that are in addition to routine irrigation water quality parameters noted in Table 2.1. The focus in this chapter is to present various biological, chemical, and physical constituents that are not determined in a routine irrigation water quality test, but that may be present in irrigation water sources, with a brief discussion of each constituent. These are listed in Table 2.2. Individuals with

TABLE 2.1
Chemical constituents in typical routine irrigation water analyses for turfgrass situations (these parameters are defined and discussed in Chapter 3)

Water analysis	Typical units	Comments
	General water characteristics	
pH	pH units, 1–14	Very high or low pH is a warning of possible problems
Hardness	ppm, mg/L	Relates to Ca and Mg content and potential for scaling in pipes
Alkalinity	ppm, mg/L	Measure of acid-neutralizing capacity of water. Reflects bicarbonate, carbonate, and OH (hydroxide) content
Bicarbonate, HCO_3	ppm, mg/L, meq/L	Affects Ca and Mg precipitation from water
Carbonate, CO_3	ppm, mg/L, meq/L	Affects Ca and Mg precipitation from water
	Assessment of total soluble salts (salinity)	
Electrical conductivity, ECw	dS/m, mmhos/cm	Relates to potential for soluble salt stress on plant growth
Total dissolved salts, TDS	ppm, mg/L	Relates to potential for soluble salt stress on plant growth
	Impact on soil structure/water infiltration (Na permeability hazard)	
Sodium adsorption ratio, SAR, adj RNa	meq/L	Measure of potential for adverse effects of Na on soil structure
Residual sodium carbonate, RSC	meq/L	Measure of potential for Ca and Mg to precipitate from irrigation water by reaction with bicarbonates/carbonates
ECw and TDS	see above	These may also be listed in this section because they influence SAR

Water analysis	**Typical units**	**Comments**
	Specific ion impact on root injury or foliage uptake and injury	
Na	ppm, mg/L, meq/L	Na often injures plant roots
Cl	ppm, mg/L	Cl often accumulates in foliage
B	ppm, mg/L	Can cause root toxicity or shoot injury
	Specific ion impact on foliage from spray contact	
Na	ppm, mg/L, meq/L	Injury to sensitive plant foliage
Cl	ppm, mg/L	Injury to sensitive plant foliage
HCO_3	ppm, mg/L, meq/L	Does not cause injury but can be unsightly on foliage
	Nutrients and elements normally reported	
Nitrogen as total N, NO_3	ppm, mg/L	Nitrogen and the other nutrients contribute to plant nutritional needs. These should be considered part of the "fertilizer" requirements.
Phosphorus as total P, PO_4, P_2O_5	ppm, mg/L	
Potassium as total K, K_2O	ppm, mg/L	
Calcium as Ca	ppm, mg/L, meq/L	
Magnesium as Mg	ppm, mg/L, meq/L	
Sulfate as SO_4 or S	ppm, mg/L, meq/L	Sulfate value also used to assess black layer potential
Manganese as Mn	ppm, mg/L	
Iron as Fe	ppm, mg/L	
Copper as Cu	ppm, mg/L	
Zinc as Zn	ppm, mg/L	
Boron as B	ppm, mg/L	
Sodium as Na	ppm, mg/L, meq/L	
Chloride as Cl	ppm, mg/l	

Metal ions

Various metal ions are sometimes analyzed for in irrigation water if a problem is expected or for a new irrigation source. Ions are normally reported in ppm or mg/L and include Al, As, Be, Cd, Co, Cr, Cu, F, Li, Mo, Ni, Pb, Se, Sn, Ti, W, V, and Zn.

Miscellaneous

Residual Cl_2	ppm, mg/L	Excessive chlorine from water treatment
Total suspended solids, TSS[a]	ppm, mg/L	Suspended solids that are organic or inorganic in nature
pH_c	pH units	Indicates potential for lime precipitation
Nitrogen as ammonium NH4-N	ppm, mg/L	Seldom present except in wastewater. Ammonium testing is not typically included in water test package and must be requested.

[a] TSS is discussed in chapter text.

TABLE 2.2
Irrigation water constituents that are not typically determined in routine irrigation water analyses but are important for health, environmental, or agronomic reasons (these are defined and discussed in Chapter 2)

Water parameter	Comments
	Biological factors
Human pathogens	Important for wastewater that has been treated
Bacteria	In terms of total coliform or fecal coliform bacteria as "indicator organisms." Sometimes specific bacteria are determined such as *Escherichia coli.*
Protozoa	—
Viruses	—
Worms (helminths)	—
Plant pathogens	—
Algae	Problem in lakes
Cyanobacteria (blue-green algae)	Problem in lakes
Iron, manganese, and sulfur bacteria	Problem in lakes, borewells, pumps, and lines
Plant nematodes	—
	Physical Factors
Total suspended solids (TSS)	Suspended inorganic and organic materials that affect disinfection, contribute to clogging, and may adversely affect soil physical conditions
Turbidity	Measured in treated wastewater because it influences disinfection processes. High turbidity also indicates high TSS.
Color	Cosmetic appearance of water source
Odor	Decaying organic matter, algae, blue-green algae, and hydrogen sulfide can cause odor problems
Temperature	Stratification layers in water source; shallow lakes or ponds
	Chemical Factors
Dissolved oxygen (DO)	DO is especially important in lakes for aquatic and fish health
Biological oxygen demand (BOD)	Oxygen demand for bacteria to decompose the biodegradable organic matter in water
Chemical oxygen demand (COD)	Measure of oxygen use (demand) for oxidation of organic matter and inorganics that can be oxidized
Total organic carbon (TOC)	Includes dissolved and suspended organic matter in water
Free chlorine residual (Cl_2)	Residual Cl_2 gas in water after disinfection
Combined residual chlorine	Chloramines formed by reaction of free Cl_2 with ammonia
Trihalomethanes (THMs)	Formed by reaction of Cl_2 with naturally occurring organic and inorganic matter in water
Surfactants	Detergents
Hydrogen sulfide (H_2S)	Dissolved as a gas and smells like rotten eggs. Can occur in some wells and lakes.
Pesticides	—
Grease and oil	—

governmental agencies or wastewater treatment facilities often focus first and foremost on **public health concerns and related water quality constituents** rather than agronomic aspects. Health-related parameters are the same ones associated with use of reclaimed water for irrigation; and these are discussed in this chapter along with other parameters that are sometimes of interest. Common guidelines for reclaimed water that is to be employed for unrestricted urban use (i.e., for turfgrass sites with unrestricted public access) are noted in Table 2.3.

Irrigators logically ask the question relative to a particular parameter, "Is this a problem at the level found in my irrigation water?"; that is, they want guidance.

TABLE 2.3
Guidelines for unrestricted urban reuse of treated wastewater including turfgrass sites

Water Quality Parameter	2004 US EPA Suggested Guidelines[a]	2000 AWA Guidelines[b]	2004 State Range Values[c]	Georgia 2002[d]
BOD_5	< 10 mg/L	—	NS–30 mg/L	≤ 5 mg/L
TSS	< 30 mg/L	—	NS–30 mg/L	≤ 5 mg/L
Total suspended solids				
Turbidity				
Ave.	≤ 2 NTU	—	NS–2 NTU	≤ 3 NTU
Max.	≤ 5 NTU	—	NS–5 NTU	
Fecal coliform		Not stated except for restricted turf at < 10,000 cfu/100 ml		
Ave.	None		None–20/100 ml	< 23/100 ml
Max.	≤ 14/100 ml		23–75/100 ml	< 100/100 ml
Total coliform				
Ave.	—	—	2.2/100 ml	—
Max.	—	—	23/100 ml	—
Residual Cl_2	≤ 1 mg/L	—	—	Detectable at delivery point
Helminths (parasitic worms)	—	≤ 1 egg/L	—	—
Treatment	US EPA and most states indicate that specific wastewater treatments are required for reclaimed water to be used on unrestricted sites.			

[a] USEPA. 2004. Guidelines for Water Reuse. EPA/625/R-04/108. USEPA, Office of Water, Washington, DC.

[b] AWA (Australian Water Authority). 2000. Australian and New Zealand Guidelines for Fresh and Marine Water Quality. Paper No. 4, Chapter 9. Primary Industries. Australian Water Authority, Artarmon, NSW, Australia. See online at http://www.mincos.gov.au/publications/australian_and_new_zealand_guidelines_for_fresh_and_marine_water_quality/volume_3.

[c] From EPA (2004) for AZ, CA, FL, HI, NV, TX, WA.

[d] Georgia DNR, 2002. Guidelines for Water Reclamation and Urban Water Reuse. Dept. of Natural Resources, Environ. Protection Division, Atlanta, Georgia.

NS = Not specified by state.

Before discussing individual constituents, it is beneficial to understand what is meant by **guidelines,** how they may arise, and why they may differ by location. Some constituents affecting irrigation water quality have levels that are mandated by law, especially those associated with health or environmental aspects (Table 2.3). In these cases, the standard is not a guideline but a **mandatory regulation** that is very specific. However, the mandatory level often differs to some extent from one state or country to another. For many other constituents, especially those listed in a routine irrigation water quality report and discussed in Chapter 3, guidelines have developed to assist irrigators relative to possible problems that may arise from use of the particular irrigation source; however, the guidelines are not usually mandated by law and guidelines are relatively consistent across locations (Table 2.1). For some other water quality parameters, specific guidelines may not be documented, but general ones may simply list their constituents as being present or absent in water. In this book, the authors will use the term *guidelines* in the broadest definition to include both suggested and mandatory levels.

2.2 GUIDELINES

2.2.1 General Comments

As just noted, irrigation water quality test information is normally compared to guidelines that help to assess the suitability of the water relative to effects on plants, soils, other water sources, and health aspects. A routine irrigation water quality test is always a good idea for a turfgrass manager, even on sites where the water quality is thought to be very good; but there are situations when other parameters may need to be tested. It is important to understand potential sources of pollutants or materials in surface water and groundwater to determine whether irrigation water could possibly be polluted and, therefore, require additional assessment (i.e., testing) beyond the constituents measured in a routine irrigation water quality test.

Groundwater is subsurface water that has infiltrated into the soil and then percolated downward by the force of gravity. Due to longer contact with soil and minerals compared to surface water, groundwater normally has higher mineral content, but it is less likely to be contaminated by bacteria or other organisms. However, iron bacteria can occur in borewells used to access the groundwater. Some groundwater may contain appreciable salts if in contact with subsurface salt deposits or can contain high calcium and bicarbonate levels if passing through or exposed to limestone aquifers. Undesirable gases such as hydrogen sulfide can occur in some groundwater.

Surface water is water held on the surface of the earth. Pollutants that can occur in surface waters are more numerous and diverse than from most groundwater sources. Suspended sediments are common is surface waters because of runoff. Stormwater runoff may carry suspended or dissolved organic and inorganic materials, depending on the surface that the water has traversed. Ponds or lakes that receive excess phosphorous are prone to problems due to algae and aquatic plant growth. Types of surface waters are as follows:

- Artificial catchment ponds designed to collect runoff from rain or snowmelt
- Artificial containment ponds to hold waters to be used for irrigation, including recycled water
- Water features built into a golf course that also serves as an irrigation water source and for hydrological stabilization on the site
- Natural ponds or lakes
- Streams, rivers, irrigation ditches, or canals
- Shallow wells that receive appreciable surface water

For each constituent in irrigation water, we present **guidelines or mandatory regulatory levels** that typically represent those used within the United States, Australia/New Zealand, and internationally (USSL, 1954; Pettygrove and Asano, 1985; Ayers and Westcot, 1994; AWA, 2000; Carrow and Duncan, 2000; USEPA, 2004; WHO, 2005). However, within a particular country or state, there may be somewhat different guidelines, especially for mandated regulatory levels, such as constituents in reclaimed water. Also, guidelines may change to some extent over time. Thus, current mandatory regulations within a locality should be determined (AWA, 2000; USEPA, 2004; WHO, 2005). In many cases, country or state departments of natural resources or environmental protection agencies will be good places to obtain regulatory information as well as regulations from the local municipal government. Some potential pollutants do not have published guidelines pertaining to irrigation water, such as algae or iron and sulfur bacteria.

It is important to understand that water quality guidelines depend on the use of the water. For example, water quality guidelines and regulations differ depending on whether the water is considered for drinking, livestock, unrestricted urban/turfgrass use, or other uses. The publication by Provin and Pitts (2003) is a good example of guidelines given for drinking, irrigation, and livestock uses. In this book, the focus is on irrigation water quality for turfgrass situations characterized by unrestricted public access (sometimes called **unrestricted urban use**), which also brings in the dimension of human health exposure because people would come into contact with irrigation water in most situations. Health issues are especially important when reclaimed water is used for irrigation on turfgrass sites.

If a water source is to be used for irrigation of food crops, many of the same guidelines may apply, but there may also be some differences, especially concerning pathogens. Also, guidelines for potable (drinking) water for humans, aquaculture, groundwater recharge, argumentation of potable water sources, recreational use, or water for livestock will have unique parameters when used for those specific purposes (USEPA, 2004). Many of the same water quality parameters are important for each of these water uses, but guidelines become more stringent for potable drinking water, when human contact is allowed, or for food production, especially when using reclaimed water. As noted previously, irrigation water quality guidelines address potential problems in one or more of the areas of human health, environmental concerns, adverse soil effects, undesirable plant effects, irrigation system fouling/deterioration, or unwanted characteristics such as color, temperature, and odor.

2.2.2 GUIDELINE ASSUMPTIONS

Inorganic contaminants (such as salts or trace elements) may have a negative impact on turfgrasses through either (1) direct phytotoxicity to foliage during irrigation or (2) accumulation within the soil over time. Plants then may absorb the contaminant and exhibit shoot phytotoxic symptoms as they accumulate in the shoot tissues, or there may be direct injury to the root system. Ion toxicity guidelines for direct or indirect effects on plants have been developed for plants in general; that is, the guidelines used for turfgrasses are also used for agricultural and horticultural crops. Thus, turfgrass scientists use general plant and soil guidelines similar to scientists in other crops. Guidelines developed to address the problem of soil accumulation are based on the following internationally accepted assumptions (AWA, 2000):

- Annual application of irrigation water of 40 in. (1000 mm).
- Assumes that all contaminants remain in the surface 6 in. (150 mm) of soil.
- Irrigation will continue on an annual basis for a maximum of 100 years.
- The soil has a bulk density of 1.30 g cm^{-3}.

For inorganic contaminants (see Chapter 3, Section 3.8, "Trace Elements"), more that one **recommended value** may sometimes be given in this book. One is the normal maximum recommended value in mg L^{-1} that is used in the U.S. literature. Australia/New Zealand guidelines sometimes have two values: (1) a **long-term trigger value (LTV)** that is based on the foregoing assumptions, and (2) a **short-term trigger value (STV)** based on the maximum contaminant level that can be tolerated for a 20-year period with the same irrigation constituent loading rate. Both the LTV and STV are in mg L^{-1} of contaminant in the water. In some cases, a **cumulative contaminant loading limit (CCL)** is also presented, where this represents the maximum contaminant loading in soil defined in units of kg ha^{-1} within the surface 6 in. (150 mm) of soil.

Many factors influence contaminant behavior in the soil (soil texture, pH, organic matter content, leaching over time, salinity levels, climate interactions, and other factors), and plants vary in their tolerance to different contaminants. Accumulation of contaminants is less rapid on fine-textured than on sandy soils, assuming equal leaching for both soil types.

The constituents addressed in a routine irrigation water quality test (Table 2.1) are **chemical** in nature. However, categories of **water quality problems may be biological, chemical, or physical in nature,** such as the following:

- **Biological parameters**—human pathogens, plant pathogens, algae, cyanobacteria, iron and sulfur bacteria, nematodes, weed seed, and so on.
- **Physical contaminants**—total suspended mineral or organic solids, turbidity, color, temperature, and odor.
- **Chemical constituents**—total soluble salts, specific salt ions, nutrient ions, potential root or foliage toxic/problem ions, total dissolved solids or sediment (so-called fines), alkalinity, trace elements, oxygen status, biodegradable organics, nonbiodegradable (refractory or resistant) organics, free

chlorine residuals, hydrogen sulfide gas, hardness, free calcium carbonate, and others.

There are very few sources in the literature that deal with irrigation water quality issues in a systematic manner that cover a wide range of potential problems and not just salinity aspects. Excellent resources related to constituents that may be found in irrigation water, their description, a summary of preventative or corrective measures, and a listing of additional sources of information on specific issues can be found in (1) Chapters 4 and 9 of the Australian Water Authority guidelines for irrigation (AWA, 2000), (2) the Farm Water Quality and Treatment Web publication (Yiasoumi et al., 2003), and (3) the USEPA publication specific to use of reclaimed wastewater for urban reuse on turfgrass sites (USEPA, 2004). In our discussion of the various parameters, we have used these sources as well as others that are more limited in scope, but may be detailed on a specific problem.

2.2.3 COMMON SENSE AND GUIDELINES

The World Health Organization (WHO, 2005) has a focus on human health-developed or health-related guidelines related to use of wastewater (reclaimed water) for irrigated agriculture, especially food crops. These guidelines have been reviewed and were released in 2005 (WHO, 2005; Carr, 2005). The WHO guideline philosophy is worth noting:

> WHO Guidelines are based upon best available scientific evidence and broad participation. The Guidelines incorporate a risk-benefit approach and are developed around "good practices."... Overly strict standards may not be sustainable and, paradoxically, may lead to less health protection because they may be viewed as unachievable under local circumstances, and, thus, ignored. The Guidelines therefore strive to maximize overall public health benefits and the beneficial use of scarce resources. (Carr, 2005)

In the same paper, Carr (2005) notes that wastewater of domestic origin is much less likely to contain constituents related to health concerns than industrial wastewater sources. The best means to address exposure to toxic chemicals that may arise from industrial wastewater use for irrigation is to prevent addition of that source to the wastewater in the first place. Thus, whereas many potential chemical, biological, or physical materials could be listed as "concerns," treated wastewater (i.e., reclaimed water) used for irrigation purposes comes under rigid health standards and must be treated to comply with these standards. Additionally, the use of reclaimed water in turfgrass or landscape ecosystems is a major means of addressing shortages in potable water for the same uses. Wastewater treatment attempts to reduce nutrient loads to levels acceptable for direct release into surface waters, but subsequent removal (absorption or phytoaccumulation) by the turgrass and landscape plants after application efficiently utilizes those nutrients in an experimentally compatible manner (USEPA, 2004; Toze, 2006).

In the remainder of this chapter and in Chapter 3, various irrigation water parameters will be briefly discussed with respect to:

- Describing the constituent and where it may likely be a problem: irrigation well, lake, storage pond, catchment facility, on the turfgrass, in the soil, etc.
- Stating the nature of the potential problem.
- Presenting guidelines when they are known
- Providing a brief summary of corrective or preventive measures; however, a more detailed discussion of corrective and preventative measures will be found in chapters that deal with the particular situation where the constituent is most likely to be a limitation.

2.3 BIOLOGICAL WATER QUALITY FACTORS

Living organisms in water can significantly impact irrigation water. All living organisms are organic in nature. Some of the most common organisms that affect use of irrigation water are as follows:

- On sites with unrestricted human access, certain organisms can adversely affect human health. Microbiological examination of water that is to be used for irrigation on sites with human exposure or access is a routine practice.
- Presence of certain pathogenic organisms may indicate that treatment is necessary to bring the water to an acceptable health standard before it is permissible for turfgrass irrigation use.
- Some organisms can interfere with irrigation system operation, such as algae plugging filters or nozzles; or iron bacteria in borewells causing pitting of pump impellers.
- Certain organisms may cause problems in the ponds, streams, or lakes containing the water, as well as in borewells. Examples are eutrophication, toxins from blue-green algae, and enhancing turbidity by algae or bacteria in ponds.
- Plant pests are sometimes present in irrigation water, such as weed seeds, nematodes, pathogens or spores, or algae.

Most of the living organisms that affect irrigation water are microorganisms, but some are larger, such as nematode worms. Microbiological testing of irrigation water is common when the water is from a wastewater treatment facility (i.e., reclaimed water) or if there is any chance that the water has been contaminated by human or animal wastes. For irrigation water that is to be used on sites with unlimited human access, the microbiological testing requirements and microbiological quality standards are almost as stringent as for drinking water quality. The organisms that sometimes influence irrigation water are as follows:

- Human pathogens: bacteria, protozoa, viruses, worms (*Helminthes*)
- Plant pathogens
- Algae

- Cyanobacteria (blue-green algae, which are really bacteria)
- Iron, manganese, and sulfur bacteria
- Plant nematodes

In addition to these living organisms, **inert (nonliving) organic constituents** can cause problems in irrigation water. Inert organic constituents can be dead plant/animal tissues in various stages of decomposition or organic chemicals such as organic pesticides, grease, oil, and so on. In this section, living organisms are the focus, whereas inert organic compounds will be discussed in Section 2.5, "Chemical Water Quality Factors."

2.3.1 HUMAN PATHOGENS

Various biological organisms in water present health hazards for individuals in direct physical contact with contaminated water, including drinking contaminated water, or by exposure to aerosols or spray drift during irrigation. During wastewater treatment of water that will eventually be used for irrigation, the recycled water treatment provider would be responsible for the control of pathogenic organisms at levels suitable for the intended use of the discharge water. Wastewater treatment facilities, whether public or private, must meet governmental regulatory guidelines for water quality (WHO, 2005; USEPA, 2004). The turf manager should be concerned that water received for irrigation is properly treated for safe use on turfgrass sites, but would normally not be involved in the actual treatment process or managing the water to control these properties. In the United States, water treatment is traditionally maintained at a high standard, but this may not be true for all countries (Carr, 2005), so users of "reclaimed" water must be sure that it is safe for human contact. In Chapter 8, the use of reclaimed water for irrigation will be discussed in more detail. An excellent source of additional information is the EPA 2004 *Guidelines for Water Reuse* (USEPA, 2004).

Although properly treated and tested reclaimed water would be considered safe, sometimes an irrigation water source is contaminated from animal or human wastes during runoff into irrigation ponds, or in some areas, treatment of the water may be insufficient. If contamination is expected, it is very important to cease use of the water until testing can verify its suitability for safe use. Although many microorganisms are not harmful, some are pathogenic. Organisms discussed in the next sections (AWA, 2000; USEPA, 2004; WHO, 2005) are of particular concern from the health standpoint. The most prevalent microorganisms that may be a problem are listed, but many different types of bacteria or other organisms are possible with contaminated water.

Bacteria. These are single-celled, microscopic organisms with a rigid cell wall. Most bacteria are desirable and are important for microbial degradation of organic constituents in water and soil. Important undesirable pathogens are *Salmonella*, *Shigella*, *Escherichia coli (E. coli), Vibrio, Mycobacterium, Clostridium, Campylobacter coli,* and *Leptospira.* Pretreatment of irrigation water with disinfection methods is used to reduce these organisms to safe levels. Diseases that are caused by organisms with this group include typhoid fever, dysentery, cholera, and severe gastroenteritis (USEPA, 2004). Disease-producing bacteria are not easily identified in water without expensive and time-consuming tests (Ayers and Mara, 1996). The diversity and cost of testing for individual bacterial pathogens as well as the fact that low numbers of these organisms make testing more difficult preclude routine testing for each individual pathogen type. Testing is sometimes done if a specific health problem is expected.

Instead of testing for individual pathogens, routine microbiological examination of reclaimed water focuses on **indicator organisms.** The **total coliform group** *(Klebsiella, Citrobacter, Escherichia, Serratia,* and *Enterobacter)* of bacteria greatly outnumber the disease-causing bacteria in water; most of the coliform bacteria are not pathogenic; and they are easily measured. Because coliform bacteria are more persistent in water than most disease-causing bacteria, their concentration can indicate the concentrations or levels of pathogenic bacteria.

Fecal coliform bacteria, sometimes called **thermotolerant coliforms**, are a smaller subgroup within the total coliform bacteria that are specific to the intestinal tracts of warm-blooded animals and humans. Thus, presence of fecal coliform is a strong indicator of sewage or animal waste contamination (Swistock et al., 2000). Wastewater treatment facilities routinely test water that is to be discharged for total coliform, or fecal coliform, or both categories as the most important health indicator for discharged water. Water cannot be discharged unless it meets the total/fecal coliform requirements for the use of the discharged water—for stream allocation, for irrigation, for discharge into a lake, and so on. Common guidelines are presented in Table 2.3.

Protozoa. Protozoa are the simplest animal species and are single celled. Most are not pathogenic, but a few are, such as in the species *Entamoeba* (amoebic diseases), *Giardia* (diarrhea, gastrointestinal problems), Microsporida (diarrhea), and Cryptosporidium (diarrheal disease). Removal from water is often by sedimentation and filtering because they can form cysts that resist disinfection methods.

Viruses. Viruses are very small, and a number that are excreted by humans are capable of producing infections or diseases such as diarrhea, hepatitis A, polio, gastroenteritis, eye infections, and others. Some of the more common viruses are rotavirus and enteroviruses. Virus disease infections through waterborne means have been studied less than for other organisms.

Worms (helminths). Several parasitic helminths occur in wastewater, including roundworm (*Ascaris*), tapeworms, threadworms, and whipworms (*Trichuris*). These are all intestinal nematodes. The Tubifex worm is a common organism used as an indicator of potential helminth contamination. Disinfection, sedimentation, and filtration treatment greatly reduce these organisms, including the eggs and larvae. For unrestricted areas, helminth numbers should be <0.1 arithmetic mean number of egg/L for irrigation water (Scott et al., 2004).

For reclaimed water from a water treatment facility to be used for irrigation, concern is especially great for total coliform, fecal coliform, turbidity, BOD, total suspended solids, residual chlorine (Cl_2), and sometimes helminths (certain areas of the world) because these organisms all have human health implications. Turbidity, BOD (biological oxygen demand), and the other health-related parameters will be defined and discussed in later sections, but guidelines are presented in Table 2.3 along with total and fecal coliform guidelines. As previously noted, it is not feasible or necessary to test irrigation water for all of the potential waterborne microbial pathogens unless a specific problem in expected. The most common test is for total and/or fecal coliform bacteria as indicator organisms of potential pathogenic organisms (Ayers and Mara, 1996; USEPA, 2004). A high level of fecal coliforms would indicate that the water has had contact with human or animal wastes and that it has not received appropriate treatment to reduce health hazards.

The most stringent fecal coliform guidelines are for turfgrass/landscape irrigation with unrestricted public access such as a parks, playground areas, sports fields, or golf courses in a residential area, whereas an area (such as a sod farm) with restricted public access may be able to use water with less rigorous requirements. The typical guidelines reported in Table 2.3 are for turfgrass irrigation situations; however, individual states within a country as well as various countries may have guidelines that differ from those reported in Table 2.3 (USEPA, 2004).

In order to ensure compliance with health guidelines, specific water treatments may be mandated for the treatment facility, such as certain types of oxidation, coagulation, filtering, and disinfection. The EPA publications *Guidelines for Water Reuse* (USEPA, 2004) and *Onsite Wastewater Treatment Systems Manual* (USEPA MT, 2008) provide a good summary of treatment options for pathogens. For turfgrass facilities or developments considering a private water treatment facility, these publications would be very useful.

Although reclaimed water is mandated by law to be treated to conform to required levels of fecal coliform before it can be used for turfgrass irrigation, sewage contamination of irrigation water sometimes occurs and can result in excessive levels of pathogens. For example, during heavy rainfall, overflow sewage discharge from treatment facilities may contaminate surface waters that are later used for irrigation. If contamination is expected, the water should be tested.

In some areas of the world, public water treatment may be less available and an individual turfgrass facility may need to address treatment on a smaller scale (Carr, 2005). Yiasoumi et al. (2005) provide a good overview of irrigation water treatment at the farm level when contamination of the irrigation source occurs from livestock, wildlife, or human fecal matter. They summarize: (1) pretreatment options to remove sediments, organic matter, and fine clays; and (2) disinfection options by heat, UV radiation, filtration, ozone, and chemical treatments.

2.3.2 Plant Pathogens

It is possible to transmit fungi (*Pythium* spp., *Phytophthora* spp.), bacteria (*Pseudomonas* spp., *Xanthomonas* spp.), or viruses to plants through the irrigation water (Hong and Moorman, 2005). However, research is very limited in this area, and guidelines are not available. Infection of turfgrasses by this means would not be expected to be a common occurrence, but has occurred in greenhouses and even forages (AWA, 2000). The treatment procedures used for reclaimed water to prevent human pathogens would also prevent plant pathogens. Hong and Moorman (2005) reviewed management options for pathogen control, including slow sand filtration, UV light, chlorination, ozonation, heat, pressure, surfactants, antimicrobial compounds, suppressive potting mixes, and biological control agents.

2.3.3 ALGAE

Algae are microscopic plants that often form colonies (WOB, 2005). They contain chlorophyll and other pigments for carrying out photosynthesis, which requires carbon dioxide, light, and nutrients, especially nitrogen and phosphorous. Under favorable environmental conditions, algae can proliferate in irrigation ponds and result in several unfavorable conditions: (1) clogging of filters and nozzles, (2) they add organic matter to the water when the algae die that with decomposition depletes oxygen and may trigger fish kill in irrigation ponds, (3) unsightly algae scum may occur in water features, (4) turbidity is increased by algae in water, (5) algae in irrigation water may stimulate algae formation on turfgrass areas that have thin stands and where the surface remains moist, and (6) odors from algae-infested waters. Algae are not pathogenic nor do they produce toxins. No guideline levels have been set for algae in irrigation water.

Algae bloom is most likely to occur in irrigation ponds with excess phosphorous and nitrogen, high temperatures, high light conditions, shallow (depth) ponds, and stagnant water. The algae bloom process is called **eutrophication.** Algae suspended in the water are called phytoplankton. To help prevent eutrophication, phosphorus guideline levels for irrigation water are very low (see Phosphorus) and control of algae is primarily achieved by limiting phosphorus additions. For reclaimed water, treatment to remove phosphorus before delivery to the user is the best option. Within a pond, phosphorus can be precipitated and deactivated by addition of alum (AlOH), removal of nutrient-rich sediments, dredging shallow ponds to a greater depth, and diluting phosphorus-rich water with other low-nutrient water. Sometimes dark dyes help reduce light for algal growth. Pond aeration can aid in reducing algae bloom and in reducing oxygen depletion arising from algal decomposition.

If algae become too prevalent, filters as well as sprinkler nozzles may clog. Chlorination can be used to reduce the level of algae and other microorganisms within the system (Clark and Smajstria, 1999; Yiasoumi et al., 2007). Copper sulfate can control algae, but the rate must be carefully determined to avoid fish kill. Aquatic pond specialists or extension agricultural engineers should be consulted to ensure that proper procedures and regulations are followed for any chemical means of algae control. Mechanical removal of the algal scum may be necessary to reduce the organic matter load.

2.3.4 CYANOBACTERIA (BLUE-GREEN ALGAE)

Cyanobacteria, sometimes called blue-green algae, are bacteria that closely resemble algae because they are capable of photosynthesis, and they occur under the same conditions as algae. The genera that are most common are *Anabaena, Aphanizomenon, Cylindrospermopsis, Macrocystis*, and *Nodularia*. In addition to the same problems that algae cause in lakes and irrigation systems, cyanobacteria can produce toxins that are potentially harmful to humans, fish, and animals, and these toxins may persist in the environment (AWA, 2000; Yiasoumi et al., 2007). These photosynthetic bacteria can produce an iridescent green, vivid green, or pale blue color in ponds. Prevention is the best method for dealing with cyanobacteria, but if control is required, it should be done by professionals. Control measures would be the same as for algae (Gillett and Yiasoumi, 2004; NSW Algal Information, 2005; Zang et al., 2006). No specific guidelines are present for cyanobacteria in irrigation water.

2.3.5 Iron, Manganese, and Sulfur Bacteria

Certain iron, manganese, and sulfur bacteria can occur within irrigation pipes, fixtures, and well bores. These organisms use iron, manganese, and sulfur ions in the water under low-oxygen conditions to deposit bacterial slimes. The bacterial slimes can cause undesirable odors, water discoloration, clogged filters and nozzles, clogged pipes, pitted metal components, and mineral encrustation, thereby reducing pumping efficiency in bores (Carruthers, 1994; Smith, 2005; Wellowner, 2005). The term **iron biofouling** is used to describe the action of iron bacteria. Under anaerobic conditions, the reduced forms of iron and manganese are more soluble in water, whereas aeration causes precipitation as oxides and reduced concentration of these metals, as well as a less favorable environment for the organisms. These bacteria are not usually a problem within irrigation lakes or ponds unless the water is very stagnant, anaerobic, and high in these minerals. Although control of the slime bacteria in pipes is similar to measures used for algae, iron, manganese, and sulfur bacteria in boreholes may require specialized treatment.

Conditions that favor bacterial slime formation include the following (Wellowner, 2005):

- Dissolved oxygen of < 1.0 mg/L
- Soluble iron > 1.0 mg/L
- Soluble manganese > 0.02 mg/L
- Sulfide > 2.0 mg/L
- Bacteria > 10,000 CFU/ml (maximum number per ml)

2.3.6 Plant Nematodes (Plant Pests)

Hong and Moorman (2005) review research on nematodes in irrigation water. Nematodes that are plant pests are not normally considered to be present in sufficient numbers in irrigation water to present a problem for turfgrasses. Awl nematodes have been found in irrigation water, but this is rare. There are no published guidelines concerning nematode content in irrigation water.

2.4 PHYSICAL WATER QUALITY FACTORS

Physical constituents in irrigation water that may cause problems at times include the following:

- Total suspended solids
- Turbidity
- Color
- Odor
- Temperature

2.4.1 Total Suspended Solids

Inorganic particles (sand, silt, clay), organic matter (plant parts, algae, bacteria), and immiscible liquids (grease, oils) may be suspended in irrigation water. Suspended solids are objectionable in irrigation water because (1) clogging of screens, filters, or nozzles may occur; (2) inorganic particles can cause wear on pumps and equipment; (3) colloidal matter may decrease water infiltration into the turfgrass soil surface; (4) inorganic and organic colloids may protect microorganisms from the chemical action of chlorine or ultraviolet radiation (UV) disinfection (see Section 2.4.2, "Turbidity"); and (5) biodegradable organics can reduce oxygen status in the water (see Section 2.5.2, "BOD"). Relative to the first three problems, suspended solids are measured as **total suspended solids** in units of mg/L or ppm, and this measure is often designated by the initials **TSS**. However, this can lead to confusion because TSS is sometimes used to also represent "total soluble salts." Thus, the turf manager must be careful in reading a water quality report to understand which water quality parameter is represented by the TSS notation. We will use TSS to refer only to total suspended solids.

TSS in water can reduce the effectiveness of disinfection in wastewater treatment facilities. Prior to disinfection, many of the suspended solids are removed by sedimentation. To ensure effective disinfection, TSS is mandated by many states to be 5 to 30 mg/L, depending on the status in reclaimed water (Table 2.3) (EPA, 2004).

Suspended solids are common in surface water sources, most often owing to runoff of silt and clay or algal growth in stagnant waters. Reclaimed water is filtered to remove many of the TSS at the treatment facility because these materials would contribute to high turbidity levels, thereby reducing the effectiveness of disinfectant treatments. However, when reclaimed water is delivered to an irrigation pond and it contains ample nitrogen and phosphorous, algae bloom and eutrophication may result in increased levels of organic debris, contributing to higher TSS levels. Groundwater, because of filtering by the soil, normally will have less TSS than surface water sources or reclaimed water.

Suspended solids arising from organic materials, such as algae, should be reduced by controlling the source because filtering is difficult to achieve for these materials. Control measures for organics could include reducing phosphorous and nitrogen in the water, aeration, and possibly blending with other water sources with lower TSS concentrations. The larger inorganic suspended solids, such as fine sand and some silt, may require use of microfilters or settling ponds. Sand does not stay suspended in irrigation water unless the water is moving or agitated, so sand does not normally show up in laboratory TSS data. However, when sand is present in an irrigation source, it can cause severe wear on irrigation components. Norum (1999) provided a good discussion of sand problems and the use of sand separator systems to remove most sand contaminants.

Guidelines. TSS guidelines pertaining to plugging of an irrigation system, especially drip systems, are present by Ayers and Westcot (1994) as follows:

- None: <50 mg/L
- Slight to Moderate: 50 to 100 mg/L
- Severe: >100 mg/L[1]

There are no guidelines published pertaining to TSS potential to seal the surface of turfgrass sod, especially on a sandy soil. If the particulate matter is organic in nature, such as live/dead algae that could contribute to an algal layer at the surface, control measures noted by Clark and Smajstria (1999) and Yiasoumi et al. (2007) would be appropriate to maintain as low levels as possible. When abrasion is the problem from sand particles, a high degree of sand removal, usually by settling, would be desired. For silt and clay that may contribute to surface sealing of sand soils, an irrigation water with 50 mg/L (i.e., 50 ppm) TSS level would apply 3.1 lb of TSS/1000 ft^2 per acre-foot of irrigation applied (151 kg/ha per 30 cm of water applied). Wind deposition of silt and clay onto golf greens is often higher than this level. However, at 500 ppm TSS, accumulation would be at 30.1 lb TSS/1000 ft^2 per acre-foot of water, which over time may have a detrimental effect.

If a water quality report indicates a very high TSS value, such as 500 ppm, it is important to determine the following:

- Is the laboratory using the TSS notation to designate “total soluble salts” rather than total suspended solids? Total dissolved salts can be appreciably higher (up to several thousand ppm). If the water quality report reveals a value for electrical conductivity (EC in dS/m units) and multiplication of EC (in dS/m units) by 640 equals the TSS value in ppm or mg/L, then the TSS value reported is really total soluble salts and not total suspended solids.
- Did the laboratory determine the TSS value by evaporating off the water and weighing the residue? In this case, the residue would be the total of both suspended solids and dissolved salts, and the conversion of EC to TSS noted previously would not approximate the same value.
- Is the water source truly high in suspended solids, as noted by a high total suspended solids value that does not include dissolved salts? In such a case, the irrigation water should exhibit high turbidity, and settling of the solids should be apparent after a 24-hour period—sand particles settle in about 1 minute, but silt and clay fractions will require 24 hours. In cases where TSS is high, a combination of management approaches may be necessary such as settling ponds; flocculation and settling using alum; microfiltration; pH adjustment; or measures to control algae.

2.4.2 TURBIDITY

Turbidity, the cloudy nature or muddy appearance of water, is a measure of water clarity or clearness; from the standpoint of wastewater treatment, it is a measure of the transmission of light through water. It is one of the parameters that are mandated by law for water treatment facilities to monitor and obtain acceptable levels before the discharge water can be used for irrigation. A number of materials can influence turbidity, such as silt, colloidal clay, colloidal organic matter, dissolved organic acids, metal oxides suspended in the water, and plankton or other microscopic organisms; detergents; and other dissolved, emulsified, or suspended chemicals. High turbidity interferes with disinfection treatment at the treatment plant because the suspended solids make the disinfection treatments less effective. Wastewater treatment plants use settling, coagulation, and filtration to reduce turbidity to acceptable levels prior to disinfection.

Thus, water discharged from a treatment facility that is to be used for irrigation must have low turbidity with parameters conforming to **guidelines** noted in Table 2.3 (USEPA, 2004). Turbidity higher than these guidelines would indicate strong potential for disinfection treatments to be ineffective. Turbidity is measured in **NTU units**, or nephelometric turbidity units. A nephelometer is an instrument to measure the degree of light scattering caused by impurities in water. Typical requirement for recycled water to be used for irrigation of public access turfgrass areas is between 2 to 5 NTU of turbidity.

Another concept of turbidity is the visual perception of color and clarity of irrigation water from the turfgrass manager's view, or how that water would appear in an irrigation lake. In this case, an irrigation water source that is not from a treatment plant may exhibit turbidity, but without the health concerns of turbidity when present in a reclaimed water source. However, the presence of turbidity would indicate that a potential problem may exist, such as high levels of suspended clay colloidal particles or algae. The parameters that may influence visual clarity are covered in the specific sections such as "Color," "Total Suspended Solids," "Algae," and others.

2.4.3 COLOR

Color of irrigation water is less of a problem than when water is used for drinking or household uses. Nevertheless, normal water color is desirable. Discoloration of water can arise from many sources and may be an indicator of potential problems such as (1) suspended colloidal mineral—often brown, reddish, or somewhat white in color depending on the type of mineral material; (2) suspended decaying organic matter or dissolved organic matter—brown to black; (3) dissolved minerals such as Fe and Mn—reddish to brown; (4) aquatic organisms—greenish, iridescent green, vivid green, or pale blue; (5) iron and sulfur bacteria in pipes and boreholes often are black with a black slime; and (6) industrial waste materials of various colors. Identification of the cause of water discoloration will aid in determining any preventive or corrective treatment options. There are no color guidelines for irrigation water purposes.

2.4.4 ODOR

Odor is considered a physical property of water. Odors in irrigation water can arise from decaying organic matter in irrigation ponds, dissolved or suspended organic or inorganic materials, and dissolved gases (especially hydrogen sulfide, H_2S—see Section 2.5). Wastewater undergoing treatment often exhibits odor problems at the treatment facility that must be alleviated by containment, scrubbing, and controlling the various sedimentation processes. However, treatment normally solves the odor problem. Stagnant ponds with algal growth or decaying plant debris can result in undesirable odors associated with anaerobic conditions. Treatment for odors depend on the source, but may include aeration, chlorination, algae control measures, or flushing of pipelines.

2.4.5 Temperature

Irrigation water temperature has only a minor influence on soil temperature (Weirenga et al., 1971). However, water temperature in lakes and streams does influence aquatic plants, microorganisms, and fish (USEPA, 1986). Lakes typically demonstrate temperature stratification by depth over seasons, which in turn can affect aquatic life. Some examples of water temperature effects are the following:

- Different fish species exhibit temperature tolerances for survival of juveniles, adults, spawning, and embryo survival. The key temperatures are weekly maximum average temperature and short-term maximum temperature (USEPA, 1986). Fish used for aquatic plant control in lakes must be adapted to the expected water temperature regimes.
- Temperature affects the dissolution of chemicals and other pollutants in water, with increasing temperature enhancing dissolution rates.
- Temperature influences dissolved oxygen (DO), where DO increases with decreasing water temperature. DO in turn will affect fish and decomposition of organic matter in water.
- Increasing water temperature will increase organic matter decomposition rates, which can reduce DO.
- Indicator bacteria (total and fecal coliform) die more rapidly at higher temperatures, and presumably other enteric (bacteria that live in intestines) bacteria that may be present in water.
- Microorganisms in water may be influenced by temperature with green algae favored at 30 to 35°C (86 to 95°F) and blue-green algae at over 35°C.

There are no guidelines for water temperature relative to using any water source for irrigation purposes. However, because of the importance of water temperature, it is not unusual for a state's water quality standards to include temperature limits for various waters; and if total maximum daily loads (TMDLs) are developed for a specific water body, temperature may be included (see Section 2.6 for TMDLs). Shallow water depths should be avoided, if possible, owing to their tendency for rapid temperature increases during summer months.

2.5 CHEMICAL WATER QUALITY FACTORS

Although biological water quality parameters are very important for reclaimed water or any irrigation water source that may be contaminated by pathogenic organisms and affect human health, it is chemical constituents that are the most diverse in irrigation water, and cause the most agronomic problems. The primary areas of concern are the general water quality parameters, salinity and sodic aspects, specific toxic or problem ions, and nutrient ions that are listed in Table 2.1 as components of a routine irrigation water quality analysis and are the topic of Chapter 3. The chemical water quality factors discussed in this chapter are additional chemicals that may at times cause irrigation water quality problems, and include the following:

- Dissolved oxygen (DO)
- Biodegradable organic compounds, and the relationships of organic constituents to biological oxygen demand (BOD), total organic carbon (TOC), and chemical oxygen demand (COD)
- Free, residual, and combined chlorine
- Surfactants
- Hydrogen sulfide gas (H_2S) or other gases dissolved in water
- Pesticides
- Grease and oil
- Endocrine-disrupting chemicals
- Pharmaceutically active compounds

2.5.1 DISSOLVED OXYGEN (DO)

Oxygen in water can arise from natural aeration/diffusion from the atmosphere, mechanical aeration, and photosynthesis of aquatic plants, whereas loss of oxygen can be caused by decomposition processes of nonliving organic matter in water, plant respiration, and chemical oxidation processes in waters (WOB, 2005). Rapid addition of organic matter to a water body can occur when aquatic plants rapidly grow in response to high levels of nutrients, especially nitrogen and phosphorous. This process of eutrophication then depletes DO when the organisms die; biodegradable organic matter increases and enhances microbial degradation; which in turn uses DO. Prolonged ice cover of a lake may also cause depletion of DO due to the ice blocking diffusion of oxygen from the atmosphere. The most important impact of DO in terms of irrigation water is the influences that DO have in irrigation lakes or ponds. Low DO (anaerobic conditions) can result in fish kill. Low DO at the bottom of a lake may also lead to buildup of chemically reduced compounds, including ammonia and hydrogen sulfide gas (H_2S).

DO may be determined in irrigation water as an indicator of (1) the potential for fish kill or (2) as a pollution indicator. Low DO would indicate that a pollutant may be increasing biodegradable organic matter in the water body. In the latter situation, the organic matter may arise from direct addition, such as high suspended concentrations of organic matter in water entering an irrigation lake, or by buildup of biodegradable organic matter from aquatic plant growth in response to excess phosphorous or nitrogen. Thus, DO is a broad indicator of pollution or the health of a water body, but does not really indicate the source of the biodegradable organic matter or pollutant (phosphorous, nitrogen, suspended organic matter coming from an outside source, etc.).

The normal DO content of water is about 8 to 9 mg/L DO at 68°F (20°C), but DO can vary with water temperature, elevation, barometric pressure, and salinity. However, temperature has the greatest effect. Oxygen saturation is the percentage of actual DO concentration relative to that when complete saturation is at a given temperature. Healthy water should have at least 90% of the saturation level. As water temperature decreases, the DO concentration increases with oxygen saturation. For example, at sea level, DO is 8.6 mg/L O_2 at 77°F (25°C) and 14.6 mg/L O_2 at 32°F (0°C) (WOB, 2005). Note that colder water retains high oxygen levels. At below

5 mg/L, functioning of the biological communities in a water body is adversely affected, and at <2 mg/L, most fish will die (Chapman, 1996).

2.5.2 BIODEGRADABLE ORGANICS (BOD, COD, TOC)

Organic matter in water may be in living or nonliving forms. Many organic compounds are soluble in water, whereas other organics may exist in water as suspended solids. Organics come from human activity (synthetic compounds such as pesticides, detergents/surfactants, grease, etc.) or natural sources (decaying plant debris and dead microorganisms, as well as living organisms). Water entering waste treatment facilities often contains dissolved and suspended organics from stormwater runoff in the form of proteins, lipids, or fats (oils, greases, etc.), carbohydrates, and detergents, whereas lakes, ponds, and streams may receive organics from decaying algae and aquatic plants.

Additionally, organic matter in water may be categorized as follows:

Biodegradable material that can be used as a readily available food source by naturally occurring microorganisms. These constituents include carbohydrates, fats, proteins, acids, alcohols, esters, and aldehydes. When microorganisms decompose these materials, they consume dissolved oxygen from the water.

Nonbiodegradable compounds that resist microbial decomposition (also called **refractory** compounds), such as tannins, lignic acids, phenols, some complex polysaccharides, benzene, cellulose, chlorinated hydrocarbons, pesticides, and others. Refractory organic compounds may arise from natural sources, by-products of chlorine disinfection, and pollutants. Some of the nonbiodegradable chemicals can react with DO and contribute to DO depletion.

Organic matter can be troublesome in irrigation water for several reasons:

- In Section 2.3, “Biological Water Quality Factors,” living organisms that may adversely impact human or plant health were discussed.
- Organic matter contributes to TSS (Section 2.4.1) and turbidity (Section 2.4.2) issues that influence wastewater treatment effectiveness.
- Color (Section 2.4.3) and odor (Section 2.4.4) are affected by suspended and dissolved organic materials.
- Certain organic chemicals in water may react with chlorine or other disinfectants used to control microbial contamination of water to form trihalomethanes (see Section 2.5.3), which can pose some health problems in drinking water.
- Nonbiodegradable organic chemicals, such as pesticides, that may pose a residual hazard for human health, aquatic animal and plant life, or when the water is applied to plants.
- The focus of the current section is on interactions of organic chemicals with DO, as evidenced by BOD, COD, and TOC. Because high organics may deplete DO in water as microbial decomposition increases, water treatment

> facilities must monitor the potential for DO depletion from their discharge water; that is, if the discharged water has too much biodegradable or chemical reactive organic matter, these can deplete DO in the receiving water sources. Additionally, biodegradable and nonbiodegradable organics may increase in an irrigation stream or lake owing to additions of organic matter, such as by eutrophication from too high phosphorous in the incoming water that stimulates rapid aquatic plant growth.

Assessment of total organic compounds may be by **total organic carbon (TOC)** or **chemical oxygen demand (COD),** whereas biodegradable organic matter can be quantified in terms of **biological oxygen demand (BOD)** (Clesceri et al., 1998; USGS, 2005). Chapman (1996) provides a good discussion of these, as well as other, water quality parameters in the context of lakes or ponds.

Maintenance of sufficient concentrations of DO in steams and lakes is critical for aquatic plants, fish, and the aesthetic quality of the water. **Biochemical oxygen demand (BOD)** is the oxygen demand for bacteria to decompose the biodegradable organic matter in the water under standard conditions—normally 5 days at 20°C under aerobic conditions, which is noted as BOD_5. BOD determination is commonly used to determine the relative oxygen requirements for aerobic decomposition for biodegradable organic matter, whether discharging from a waste treatment facility or in any water source that may contain suspended or dissolved organic chemicals. For unrestricted urban reuse, the EPA suggests a BOD_5 of 10 mg/L, but this concentration ranges from 5 to 30 mg/L for different states (Table 2.3) (USEPA, 2004), whereas unpolluted waters often have BOD_5 of 2 mg/L (Chapman, 1996). A high BOD_5 would indicate an elevated level of organic substrate for subsequent microbial growth that could result in depletion of DO in the water and that may cause biofouling of distribution systems and rapid degradation of water quality. Because BOD_5 is a general indication of water quality, it is best used in conjunction with other factors such as total or fecal coliform levels, specific nutrient load, DO, and COD.

Chemical oxygen demand (COD) is a measure of the oxygen use (i.e., demand) for oxidation of the organic matter and inorganics that are susceptible to oxidation by a strong chemical oxidizing agent such as dichromate (Chapman, 1996). It differs from BOD in that it includes both biodegradable organic matter and also any other organic matter or inorganic materials that may be oxidized by a strong oxidizing agent (i.e., not just by bacteria); thus, COD values are higher than BOD values. It is a more complete and accurate measurement of the depletion of DO in water by organic and inorganic constituents; organics are normally the predominant materials affecting COD and DO. The goal for treated reclaimed water presented by the EPA (2004) is <20 to 90 mg/L, whereas Chapman (1996) notes values of <20 mg/L for unpolluted waters.

Total organic carbon (TOC) in waters consist of both dissolved and suspended organic compounds in various oxidation states—i.e., it is independent of the oxidation state. As with BOD and COD, TOC is an indicator of organic pollution of a water body; but it only provides a general indication of possible influence on DO. BOD and COD are better determinants of organic rather than DO interactions. Measurement of TOC upstream and downstream from a potential source of organic pollution can identify a pollutant source, and TOC is used to assess wastewater treatment effectiveness in removing organic constituents. For surface water, TOC is generally <10 mg C/L and for groundwater <2 mg C/L. Many states require a TOC of <1 to 5 mg C/L for reclaimed water when that water will be used to augment surface water sources. The USEPA (2004) states as a water treatment goal for water reuse that TOC range from <1 to 10 mg C/L.

2.5.3 FREE, RESIDUAL, AND COMBINED CHLORINE

When chlorine reacts with water, it forms hypochlorous acid, hyprochloric acid, or aqueous molecular chlorine. These forms are considered the **free chlorine** forms. During wastewater treatment using chlorine disinfection, free chlorine (Cl_2) may remain in the water and is called **free chlorine residual**. Chlorine treatment of water in a swimming pool can also contain residual chlorine and if this water is splashed on plants or used for irrigation; foliage damage can sometimes occur. Chlorine is highly reactive and unstable in water. Normally, the free chlorine residual rapidly dissipates when the water is discharged into an irrigation pond or aerated. Excessive chlorine can damage some sensitive plants. The recycling water guidelines for many states list a value of <1 mg Cl_2/L as desirable (EPA, 2004). Pettygrove and Asano (1985) note that most plants tolerate 1 mg Cl_2/L, but that at 5 mg Cl_2/L, severe foliage damage can occur. Because most irrigation water from a treatment facility is discharged into an irrigation lake prior to use for irrigation, levels of chlorine are normally sufficiently low to avoid damage.

The free forms of chlorine are highly reactive. Most of the free chlorine is reduced by reaction with organic matter. Some chlorine may react with ammonia to produce **chloramines,** which are called **combined residual chlorine** (Hudson, 2007). The total of free chorine residual (free forms of chlorine that have not been reduced by organic matter in the water) plus combined residual chlorine make up the **total residual chlorine**. Chloramines, combined residual chlorine, are of interest because they can be toxic to fish and aquatic organisms in low concentrations and may remain active in the water source for relatively long periods of time.

Trihalomethanes (THMs) are a group of chemicals formed by reaction of chlorine and other disinfectants with naturally occurring organic and inorganic matter in water (Pettygrove and Asano, 1985). The most common THM is chloroform. THMs are a public health concern in drinking water.

There are no irrigation guidelines for chloromines or THMs, but these residual chemicals are noted here because they are frequently mentioned in the context of wastewater treatment. There are drinking water standards for various THMs or total THMs.

2.5.4 SURFACTANTS

Surfactants can occur in surface waters from industrial and household wastewaters. Detergents are a common type of surfactant. Surfactants are not highly toxic to fish or aquatic plants. Their main influence on irrigation waters results from their reaction as foaming agents, which decrease the effectiveness of water aeration, may lower DO, and cause unsightly foam on water surfaces and around holding ponds.

Foam formation occurs at 0.1 to 0.5 mg/L surfactant (Chapman, 1996). Surfactants range from highly biodegradable to nondegradable.

2.5.5 HYDROGEN SULFIDE (GAS)

An odor problem (rotten egg smell) due to H_2S gas sometimes occurs in sulfur wells (Swistock et al., 2001). In this case, groundwater comes into contact with decaying organic matter high in sulfur under anaerobic conditions in which anaerobic sulfur bacteria produce the gas. The rotten egg smell is often detectable at less that 0.5 mg/L of H_2S. In addition to the odor, H_2S can cause metal corrosion and yellow-to-black grease-like stains in the irrigation pipes.

In lakes with a high growth activity of algae and other aquatic organisms (eutrophic lakes), the decaying organic matter may settle to the bottom, where the sulfur in the organic matter acts as a sulfur source. Especially in deeper lakes (> 20 feet) or lakes with little inflow mixing during the summer period, the bottom zone of an eutrophic lake can become anaerobic from low DO, which leads to accumulation of reduced compounds such as ammonium and hydrogen sulfide. If the irrigation intake is within this zone, the water may give off the rotten egg smell of H_2S gas (WOB, 2005). Also, the low DO content of this water may favor iron, manganese, and sulfur bacteria in the intake pipe and pump. Hydrogen sulfide may also collect in ice-covered lakes during winter months. If rapid turnover or mixing with the surface zones occurs in a lake with a strong hydrogen sulfide and ammonium layer, substantial fish kill can occur.

Hydrogen sulfide can also contribute to corrosion of metal. Additionally, in some environments, H_2S may convert to sulfuric acid and contribute to excessive water acidity, which also causes corrosion.

Potential treatment options are physical aeration, especially at the bottom of the lake, or chemical oxidation with an oxidizing agent such as chlorine dioxide, potassium permanganate, or ozone (Swistock et al., 2001). Water treatment specialists should be consulted for treatment options related to large-scale removal of H_2S from a groundwater source.

2.5.6 PESTICIDES

Pesticides are primarily organic or organic-metallic compounds that include fungicides, herbicides, algaecides, nematicides, and insecticides. Residues of pesticides may contaminate surface waters by runoff of the chemical in water, association with sediment movement, direct application, careless disposal of pesticides or their containers, and aerial drift. The presence of pesticides in surface waters used for irrigation could adversely harm the plants that are irrigated and cause damage to aquatic organisms within the water source or where the water drains.

There are no water quality guidelines for pesticides in irrigation water to be used for unrestricted turfgrass use areas; and few guidelines exist for irrigation water in general (AWA, 2000). In contrast, there are much more specific guidelines for pesticides that may be found in drinking water or waters used for aquaculture and livestock (AWA, 2000). In Chapter 4 of the AWA (2000) water quality document, a listing of "interim trigger value concentrations for a range of herbicides registered in Australia for use in or near waters" is provided. The crop threshold level in irrigation water is not specific to turfgrass, but applies to various food crops. WHO (2005) is currently developing standards for harmful chemicals in wastewater to be used for irrigation, including some pesticides. Generally, an irrigation water source will only be tested for one or more pesticides if the chemical is suspected to be present and if that chemical is causing a problem in an irrigation lake or on plants after application.

2.5.7 Grease and Oil

Petroleum hydrocarbons may contaminate irrigation water sources through runoff from impervious surfaces during water harvesting, discharges from industrial sources, or improper disposal of hydrocarbons on a site. Often, grease and oil that pollutes a water source will also contain metal contaminates. Hydrocarbon pollution is visually evident at low concentrations and can adversely affect fish and aquatic plants in irrigation waters. There are no guidelines for irrigation purposes, but for general guidelines in freshwater aquaculture, AWA (2005) noted <0.3 mg/L petroleum, <0.004 mg/L gas/oil, and <1.0 mg/L benzene.

2.5.8 Endocrine-Disrupting Chemicals

Endocrine-disrupting chemicals (EDCs) are compounds in the water or soil that can impact the structure and function of an organism's endocrine system in a way that affects the organism or its progeny. In addition to pesticides (Section 2.5.6), EDCs include compounds found in contraceptive pills, industrial chemicals (bisphenol A, nonylphenol, heavy metals, etc.), and phytoestrogens (Toze, 2006). Health impacts on humans are considered negligible because concentrations in treated reclaimed waters are very low, but some wildlife may be impacted when in constant or near-constant contact with waters receiving these materials.

2.5.9 Pharmaceutically Active Compounds

Some drugs used for humans or animals may be present in very low concentrations in treated reclaimed water, such as Ibuprofen, caffeine, cholesterol-reducing drugs, anti-epileptics, antibiotics, and antidepressants (Toze, 2006). Many pharmaceutically active compounds (PhACs) are removed during water treatment, whereas others are more persistent. Concentrations are much lower than found in drugs or personal care products, but there is some concern over development of antibiotic resistance in soil or water organisms.

2.6 TOTAL MAXIMUM DAILY LOADS

Within the United States, the EPA in the Clean Water Act requires all states to assess major water bodies to determine if various pollutants have caused the water to be degraded to the point that it cannot support its designated use, such as drinking water supply, recreation, and fishing (USEPA TMDLs, 2006). Impaired waters require **total maximum daily loads (TMDLs)** studies and for TMDLs standards to be developed. A TMDL is a calculation of the amount of a pollutant that a water body can receive and still meet water quality standards. The TMDL adds all of the allowable pollutant loads from all point and nonpoint sources:

$$\text{TMDL} = \text{WLA} + \text{LA} + \text{MOS}$$

where

WLA = sum of daily load of pollutants permitted as point source discharges.
LA = amount of pollution that nonpoint sources can discharge. LAs are calculated using computer models that predict pollution from various nonpoint sources.
MOS = margin of safety

TDMLs are not directly related to most irrigation water sources unless the turfgrass site is considered as a potential source of point or nonpoint pollution, in which case remedial action to reduce the pollutant of concern would be expected. States normally have Web sites within their Departments of Natural Resources or state EPA units that lead to the state's TMDLs information.

3 Understanding Irrigation Water Quality Tests

3.1 WATER QUALITY TESTING

3.1.1 Importance of Testing

In this chapter, the focus will be on the chemical constituents that are typically requested by turfgrass managers in a routine irrigation water analyses as well as some metals that are sometimes analyzed. In contrast, the emphasis in Chapter 2 was on various biological, physical, and chemical constituents in water that are not routinely included in a standard irrigation water quality analysis, but are sometimes determined to assess specific water problems, whether in a treatment facility, well, lake, irrigation lines, or after application on a site. One key point to remember is to collect a water sample from a sprinkler head on the front nine holes and again on the back nine holes of the golf course or two locations on a sports field. You need to know exactly what water quality is actually applied on the grass and you can contrast these two samples with the water source (lake, pond, river, canal, etc.) original sample.

In a routine irrigation quality test, the basic salt ions that are dissolved in water and their relative concentrations are especially important (Table 3.1), because they strongly influence potential salinity soil accumulation and turf response problems. When discussing various water constituents, problems associated with the particular parameter will be summarized, but preventive and corrective measures to address the problem will be dealt with in various chapters related to management of site-specific situations for that particular parameter.

Water quality assessment is one of the most confusing and complex problems facing turf managers, especially with saline or reclaimed irrigation waters. Variable

TABLE 3.1
Soluble salt ions common in irrigation water

Cations	Anions
Calcium (Ca^{+2})	Bicarbonate (HCO_3^-)
Magnesium (Mg^{+2})	Carbonate (CO_3^{-2})
Sodium (Na^+)	Chloride (Cl^-)
Potassium (K^+)	Sulfate (SO_4^{-2})
Hydrogen (H^+)	Nitrate (NO_3^-)
	Boron (BO_3^{-2})

levels of salts across the landscape, seasonally within some irrigation sources, and by soil depth coupled with extreme environmental conditions (high prolonged heat and humidity, severe drought, and traffic) magnify poor water quality problems. Water analysis reports often come back with data in confusing units or with no reference points. Also, some of the terms can be confusing, such as adj SAR, adj RNa, RSC, alkalinity, hardness, specific toxic ions, etc. However, knowledge of water quality parameters and the ability to understand information in a water quality report are essential for making maintenance adjustments, especially for turf managers using reclaimed irrigation water or salt-affected sources (Harivandi, 1999).

Understanding the types and quantities of chemicals that are applied to the turf system through irrigation water is critical because these have a dramatic influence on soil health, surface and subsurface waters, irrigation distribution system, and turf performance. Remember that the ecosystem will eventually equilibrate to the water quality components, that components in the water can foliarly feed directly into turfgrass shoots, and that many management and economic decisions will be based on water quality aspects. A few examples illustrate the implications of water quality:

- Water treatment equipment and amendments depend on the specific levels and balance of Na, Ca, Mg, HCO_3, and CO_3.
- Several soil amendment types and quantities are determined by water quality. Included would be decisions on equipment (such as injectors) to apply amendments.
- Fertilization becomes very challenging, especially on low cation exchange capacity (CEC) sites, and when large quantities of nutrients and competitive ions are added via irrigation (fertigation). Proactive and regularly scheduled water, soil, and tissue testing to monitor salinity accumulation impact, soil fertility, and plant nutrient status on a specific site should become more frequent.
- With saline irrigation water, leaching of excess salts is necessary. Leaching requires a well-designed irrigation system for uniform and dependable water distribution, and necessitates good irrigation scheduling and irrigation scheduling tools. Often, a good drainage system is necessary, and additional cultivation events will be required (thereby requiring acquisition of the appropriate cultivation equipment) for properly managing the salt load coming in with the water and loading in the soil.
- With ultrapure irrigation water, maintaining optimum soil nutrient levels (primary, secondary, and micronutrients) can be challenging, especially in the first few surface centimeters of the soil. The tendency of the low-salinity water is to strip cations from exchange sites even without excessive leaching-type irrigation applications. The stripping process can affect both plant-available nutrients and cations needed to preserve soil structure. Light and frequent nutrient or soil amendment applications either made topically or incorporated through irrigation injection (chemigation) may become necessary to manage ultrapure water and turf performance.
- Excessive rainfall deposition resulting from cyclones, typhoons, hurricanes, or slow-moving tropical storms can also challenge nutrient stabilization in the soil, because this ultrapure water source will strip all nutrients off the

exchange sites with these high-volume events. Immediately following these storms, the fertility profile needs to be rebuilt in the soil and foliar-uptake fertilizer sources will generally be required to spoon-feed the turfgrass during the granular source rebuilding process. Calcium sources such as gypsum, lime, or dolomite may be needed to ensure availability of this critical nutrient.

These examples demonstrate that costly infrastructural improvements are often required as irrigation water declines in quality. A lack of understanding of water quality test parameters can result in costly mistakes, both in management and infrastructure decisions and in achieving performance expectations for the turf.

The challenge is to know what key water quality components to look for when you receive laboratory analysis data, to utilize key data points of concern to make initial management decisions **based on science**, and to take a **holistic approach to management**, realizing that salinity challenges are dynamic and not static. Turfgrass managers must be flexible in making and implementing decision plans and not hesitate to ask questions. As water quality decreases, short-term management strategies will be reactive, adjusting to environmentally induced changes in turfgrass density, cosmetic appearance, playability, or pest infestation. Long-term management strategies based on water quality information, however, should be proactive, utilizing regularly scheduled activities such as cultivation (aeration), application of amendments (such as gypsum or acid), irrigation scheduling, and continuous monitoring (water, soil, and tissue) of the entire turf system.

3.1.2 UNITS AND CONVERSIONS

Water quality data are reported in various chemical units (Table 3.2). There is no "standard" requirement for laboratories to report water analyses data in particular

TABLE 3.2
Units of measure used in water quality testing (see Table 3.3 for conversion factors)

Unit	Comments
ppm	Parts per million
mg/L	Milligrams per liter
mmhos/cm	Millimhos per centimeter
Mmhos/cm	Micromhos per centimeter
dS/m	Decisiemens per meter
meq/L	Milliequivalents per liter. An **equivalent weight** of an element or radical is its atomic or formula weight in grams divided by the valance (charge) it assumes in compounds. Thus, for Ca^{+2} with an atomic weight of 40 g, the equivalent weight is 40/2 = 20 g. Equivalent weights are important when considering how much of one element or radical will react or displace another; i.e., how much Ca^{+2} is necessary to displace Na^{+1} (1 milliequivalent of Ca^{+2} = 1 milliequivalent of Na^{+}). Thus, it is a measure of chemical equivalency. See Table 3.3 for additional information on relationship of mg/L or ppm versus meq/L.

TABLE 3.3
Conversion factors important in water quality analysis

General

1 ppm = 1 mg/L

1 meq/L = 1 $mmol_c$/L

1 dS/m = 1 mmhos/cm = 1000 Mmhos/cm = 0.1 S/m

1 dS/m = mS/m divided by 100 = 1 mS/cm = 1F S/cm divided by 1000

1 dS/m = 640 ppm = 640 mg/L

1% concentration = 10,000 ppm = 10,000 mg/L = 15.6 dS/m

TDS (ppm) = ECw × 640; with ECw in dS/m

ECw (dS/m) = TDS (ppm) divided by 640 = TDS/640. Use 640 conversion when ECw is < 5.0 dS/m and 750 when ECw is > 5.0 dS/m.

Chemical conversions

Element or radical	Charge or valance	Equivalent weight	Atomic or formula weight
Ca^{+2}	2	20	40
Mg^{+2}	2	12.2	24.4
Na^{+1}	1	23	23
K^{+1}	1	39	39
Cl^{+1}	1	35.4	35.4
HCO_3^-	1	61	61
CO_3^{-2}	2	30	60
SO_4^{-2}	2	48	96
$CaCO_3$	—	—	100
$CaSO_4$	—	—	136
H_2SO_4	—	—	98
C	—	—	12
O	—	—	16
H^+	1	1	1
S	—	—	32

units, so it is important to understand common conversions, relationships, and terminology (Table 3.3).

3.1.3 ROUTINE IRRIGATION WATER QUALITY REPORT INFORMATION

Table 2.1 notes the chemical constituents that are typically found in a routine irrigation water quality report. Not all laboratories use the same format or categorization of constituents that are used in Table 2.1. The most important problems addressed in a water quality report and the constituents used to determine the magnitude of the problems are summarized in the following text (each of these will be discussed in more detail in later chapters):

- **General water quality characteristics**—Water pH, alkalinity, hardness, HCO_3, and CO_3.
- **Total soluble salts—**The potential for salinity stress on plants and salt accumulation in soils. ECw, TDS (ECw × 640). Some laboratories will occasionally use 700 or 750 as the conversion factor in waters approaching or exceeding ECw = 3.0 dS/m.
- **Sodium permeability hazard**—The assessment of whether Na level, in balance with Ca, Mg, HCO_3, and CO_3, will cause water infiltration and percolation problems. Sodium can cause deterioration of soil structure by aggregate slaking and colloidal dispersion of clays (dislodging of the calcium-stabilized clay platelets stacked in pancake fashion). No single water quality parameter can be used alone to determine the magnitude of this problem. Instead, a combination of parameters is used: SAR, adj SAR or adj RNa, RSC, concentrations of HCO_3, CO_3, Ca, Na, Mg, pHc, ECw, and TDS.
- **Potential surface soil sealing by calcite formation—**Irrigation waters very high in ions that form calcites may result in calcite formation near the surface over time. This is much less of a problem or concern than the effects of Na on soil physical problems. Parameters of concern are Ca, Mg, HCO_3, CO_3, RSC, and pHc.
- **Precipitation of calcite (lime) in irrigation lines—**pHc, saturation index.
- **Toxic ion concentrations relative to soil accumulation/root toxicity and excess uptake into foliage—**Na, Cl, B, metal ions.
- **Toxic ion concentrations relative to direct contact on foliage as irrigation spray—**Na and Cl.
- **Unsightly deposition on foliage, buildings, signage, irrigation controllers, course accessories, equipment, or cart paths—**HCO_3 and Fe
- **Nutrient content and influence—**The influence of irrigation water on soil fertility, plant nutrition, potential nutrient imbalance problems. Macronutrients (N, P, K, Ca, Mg, and S) (in wastewater: NO_3-N, NH_4-N), micronutrients (Fe, Mn, Cu, Zn, Mo, B, Ni, and Cl), Na, metals, and ratios of various nutrients or elements.
- **Eutrophication impact on lakes—**P and N.
- **Potential for black layer formation**—SO_4 and Na.
- **Total suspended solids (TSS)**—Potential to add “fines” to the soil surface and possibility of clogging irrigation system components.
- **Miscellaneous problems—**Residual Cl_2 or constituents noted in Table 2.2. These are not commonly included by most laboratories, but may be available by special request. For reclaimed water sources, the constituents in Table 2.2 may be determined at the treatment facility, negotiated with the treatment facility, or sometimes handled on-site.

Although all the foregoing points are potential irrigation water quality problem areas that can be assessed using water quality data, four problems areas are considered the **big four salinity stresses.** These will be discussed in greater detail later in the chapter, but at this point, it is essential to have a basic understanding of each. It is important on salt-affected turfgrass sites and where saline irrigation waters are used to understand that salinity stresses are the most prevalent; and to realize that salinity is not a single stress but a combination of four stresses, that is, salinities (Carrow and Duncan, 1998). Each of these four critical problem categories must be assessed using water analysis data. Each category is a "salt problem," but differs from the other three problem areas in activating unique chemical effects on soil parameters that will eventually impact turfgrass performance.

First, and most important, is **high total salinity (total soluble salts)** in irrigation water, which reflects the potential for a saline soil problem to develop, for salt contamination of ground and surface waters, and for affecting plant selection on a specific site. Saline conditions inhibit water uptake by turfgrasses and cause salt-induced drought, which is called **physiological drought stress**. This is the most common salt-related water issue that occurs on turfgrasses, and it is the primary one that must be managed on most golf courses or other recreational turfgrass areas. Total salinity problems are site specific and must be assessed on that basis, and the predominant management strategies involving grass selection, cultivation (aeration), and irrigation scheduling for leaching and avoiding drought stress must be developed accordingly.

The second salinity problem is **sodium permeability hazard**. High sodium concentrations, especially in conjunction with high bicarbonates and relatively low Ca^{+2} and Mg^{+2} levels in irrigation water, can cause a soil sodium permeability hazard. The term *permeability hazard* is used because the most important effect of excess Na on soil CEC sites is to reduce water infiltration and percolation. Sodium induces soil structural deterioration (slaking, aggregate destruction, clay and organic colloid dispersion, and deflocculation) leading to subsequent water infiltration/percolation problems, low oxygen diffusion into the soil profile, and poor turf rooting. Assessment and management strategies must (1) be based on site-specific soil and water conditions, and (2) be aggressively monitored and frequently adjusted to address specific constraints involving possible grass selection, amendments to the water or the soil, regular cultivation, and careful irrigation scheduling (leaching).

The third salinity problem is the presence of **specific toxic ions** that may (1) be direct root toxins as they accumulate or be absorbed at high levels within plants and cause leaf injury and foliage salt stress (Na, Cl, and B), or (2) be ions that can cause direct damage to foliage from spray contact (Na and Cl) or leave unsightly deposits (HCO_3 and Fe). Turfgrass and landscape plant selection is critical for addressing specific ion toxicity problems.

The fourth type of salinity stress is a combination of high-level **fertilizer additions and nutritional imbalances** induced by nutrients and elements in the irrigation water. Most of the imbalances are triggered by exceptionally high levels of one nutrient or element suppressing uptake of another (many of the micronutrients) or displacing a nutrient from the soil CEC sites (especially Na). The impact of chemicals from water that are added to the soil using good-quality irrigation water is often ignored, but with a poorer-quality source, chemical additions accumulate from the water application itself, from water treatments, and from soil amendment additions. Coupled with the need for active leaching programs and often variable water quality over the year, these factors result in highly dynamic changes over time in fertility and chemical stresses. Lack of attention and proactive monitoring for these changes can result in the rapid onset of nutritional stresses and usually create imbalances of these nutrients that significantly impact turfgrass performance and ecosystem sustainability.

3.2 GENERAL WATER QUALITY CHARACTERISTICS

3.2.1 Water pH

Water pH is a measure of water acidity or alkalinity, with typical irrigation water within the pH 6.5 to 8.4 for natural waters. The pH scale goes from 0 to 14, where water at pH of 7.0 is neutral and the H^+ equals the OH^- ion concentration; whereas at pH < 7.0, water is acidic and at pH >7.0, it is alkaline. Irrigation water pH is not usually a problem by itself, but abnormal pH can be an indicator of possible concerns (Ayers and Westcot, 1994; Yiasoumi et al., 2003). Irrigation water pH can influence soil pH over time, and directly impact irrigation equipment, concrete channels, and pesticide efficiency. Some possible problems are as follows:

- Low-salinity water (ECw < 0.2 dS/m) can sometimes exhibit pHs outside the normal range owing to very low buffering, but generally this is not really a problem.
- Irrigation water with pH > 8.0 often contains bicarbonates, whereas at pH > 9.0, carbonate ions and hydroxyl ions may be present.
- Because irrigation water that is alkaline often contains Ca, Mg, and $HCO_{3,}$ lime formation can occur, especially at high levels of these constituents within irrigation lines (scaling) or in the soil. Soils with free lime from irrigation water will usually exhibit a pH between 7.3 and 8.2. Thus, alkaline pH water applied to an acidic or neutral soil may cause shallow soil profile pH zones to increase within this range. Precipitation of Ca and Mg from irrigation water by HCO_3 and CO_3 is especially critical if appreciable Na remains to adversely affect soil structure.
- Water pH above 7.5 may adversely affect chlorine disinfection.
- The effectiveness of some pesticides is reduced at pHs outside the 6.0 to 8.5 range. Insecticide (organophosphate, carbamate, and synthetic pyrethroid) activity is significantly reduced when these chemicals are mixed in alkaline (pH > 7.0) water. A buffering solution should be added to the spray mixture. Fungicides are typically more stable within the foregoing range of pHs. Some products may already contain buffers; therefore, checking and adjusting the pH of the spray mixture is more important than the actual pH of the water itself (Harivandi, 1981).
- Increasing acidity below pH 6.5 can be corrosive on metal components as well as concrete irrigation canal linings.

Water pH can also impact nutrient availability because it can influence soil and thatch/mat pH over time, especially in the surface 1 in. (25 mm) (Carrow et al., 1998). Extremely acid (pH < 5.0) or highly alkaline (particularly pH > 8.5) irrigation water can affect microbe populations, microbial breakdown of granular fertilizers, and utilization of foliar-applied liquid sources when irrigation water is applied shortly after spraying. Occasionally, very highly alkaline water, such as pH 9.0, when applied during or after fertilizer applications, may tie up nutrients in microlayers near the soil surface where the turfgrass would have difficulty in initial uptake and subsequent utilization.

Sometimes, groundwater pH can be very acidic if affected by acid mine tailings or acid sulfate soil conditions. Acid mine drainage often has low pH (normally well below pH 5.0), high Fe, Mn, Al, other metals, and SO_4, whereas acid sulfate soil–affected waters will often exhibit low pH (often below pH 4.0), high Fe, Mn, Al, other metals, SO_4, and Na. In Australia, rising saline water tables have resulted in widespread acid sulfate soil formation in areas where the underlying minerals or sediments contain sulfide (Fitzpatrick, 1999). Thus, if these soil conditions have influenced the groundwater, caused acidic runoff, or come into contact with an irrigation lake through water harvesting, these constituents can be harmful to aquatic life as well as plants/soils that are irrigated with this water.

Water in lakes generally is sufficiently buffered to prevent major or rapid pH changes (see Section 3.2.2). However, small pH changes can occur daily, seasonally, and by depth in response to the balance of photosynthesis using dissolved CO_2 (which acts as carbonic acid, H_2CO_3) and respiration, which produces CO_2 (WOB, 2005). Groundwater sources containing carbonic acid may change pH, increasing by 1 to 2 points, after aeration in an open reservoir for a few hours. More dramatic pH changes can occur from pollution, as previously noted. Also, if acid rain reduces the soil-buffering capacity by removal of bicarbonates or carbonates, then more rapid pH changes can occur with only minor additions of more acidity. Acidity at $\text{pH} < 6.0$ can be toxic to fish and alter other aquatic relationships. One effect of more acid conditions is to enhance dissolution of phosphorous and heavy metals in lake sediments, triggering algal blooms or causing toxic reactions in both fish and plants.

3.2.2 ALKALINITY, BICARBONATE, AND CARBONATE

Alkalinity is a measure of the water's ability to absorb H ions without significantly altering pH (i.e., the ability of the water to neutralize acids). The major constituents in water that provide buffer capacity against pH change are HCO_3^-, CO_3^{-2}, and OH^- ions, where each constituent can react with excess H^+ ions (i.e., remove H^+ ions) to create CO_2 gas or water. High alkalinity is an indication of the presence of these ions. Laboratories will express alkalinity as calcium carbonate equivalent (mg/L or ppm $CaCO_3$) or meq/L $CaCO_3$, where 1.0 meq/L $CaCO_3$ = 50.04 mg/L $CaCO_3$. Normal irrigation waters range between 20 to 300 mg/L of $CaCO_3$ equivalent.

Alkalinity is often included in irrigation water analysis reports, but generally is not directly used, except by the greenhouse or nursery industries to determine the need to acidify water. Instead, most turfgrass managers use residual sodium carbonate (RSC; see Section 3.4.2) because it takes into account the balance of HCO_3 and CO_3 relative to Ca and Mg as a measure of the potential to precipitate out Ca and Mg from irrigation water either in irrigation lines or in the soil. Precipitation of Ca and Mg is important in terms of scale formation and potential sodic soil formation.

In lakes or ponds, bicarbonates and carbonates can be replenished in water from Ca, Mg, K, and Na carbonates in the sediments, unless these become depleted via acid rain or other long-term acid additions to the site. Thus, alkalinity may be used to determine buffering capacity of lakes or ponds where water with low alkalinity (“soft water” with < 30 mg/L $CaCO_3$ equivalent) contain few basic ions, have a low buffering capacity to resist pH fluctuations, and are more susceptible to acidification. “Hard waters” usually have high alkalinities (>100 mg/L), many basic ions, a high buffering capacity, and are less sensitive to acidification (Helfrich et al., 2001).

Concentrations of the individual ions HCO_3 and CO_3 are normally reported under the General Water Quality Characteristics section of reports, and this information is used for several types of problem assessments:

1. Sodic soil potential—Bicarbonate values can range widely, but as a general guideline, HCO_3 > 120 mg/L (1.97 meq/L) and CO_3 > 15 mg/L (0.50 meq/L) start to become a concern, especially when Na concentrations are > 100 mg/L (4.35 meq/L). The primary concern is that sufficient HCO_3 and CO_3 are present to react with Ca and Mg in the water, forming insoluble and unavailable complexes, and can eventually lead to a sodic condition owing to the loss of available Ca and Mg to counteract any Na levels in the water (comparisons must be made on a meq/L basis). These relationships are discussed in greater depth in Section 3.4.
2. Calcite formation in the soil—High concentrations of HCO_3 and CO_3 in combination with high Ca and Mg content can result in appreciable calcite or lime deposition in the soil (see Section 3.4.2).
3. Excess HCO_3 content may cause foliar deposition of lime on leaves impacted by irrigation water droplets (see Section 3.6).
4. Irrigation water with high HCO_3 content may contribute to iron chlorosis by fostering iron carbonate formation in the soil and removal of available Fe. There is no guideline for this problem, but values > 500 mg/L (8.2 meq/L) of HCO_3 may be a reasonable level to consider as a cause for concern.

3.2.3 HARDNESS

Hardness is often listed in irrigation water quality reports but, similar to alkalinity, is normally not used by turfgrass managers as much as RSC and absolute values of specific ions. Hardness usually refers primarily to dissolved Ca and Mg, but other cations such as Fe, Mn, Al, and Zn can also contribute to hardness. Hardness is expressed in terms of $CaCO_3$ equivalent in units of mg/L of $CaCO_3$, and sometimes as grains per gallon (17 mg/L of $CaCO_3$ = 1 grain $CaCO_3$ per gallon). Initially, hardness was used to determine the difficulty of producing soap suds and to form insoluble, greasy soap rings in wash basins. Also, it was used to assess the potential to leave scale deposits in irrigation pipes, especially when high phosphorous was present. For these purposes, as well as a general guide to lake water hardness and proneness to acidification, water hardness classes are summarized here (Yiasoumi et al., 2005):

- Soft: < 50 mg/L of $CaCO_3$ equivalent
- Moderately soft to slightly hard: 50–150 mg/L of $CaCO_3$
- Hard: 150–300 mg/L of $CaCO_3$
- Very hard: > 300 mg/L of $CaCO_3$

3.3 TOTAL SOLUBLE SALTS (TOTAL SALINITY)

The most common and important salt problem affecting turfgrass performance is accumulation of high total soluble salts leading to a **saline soil** condition. The most prevalent soluble salts are listed in Table 3.1, but the actual mix of salts can vary with the source. Total soluble salinity in water is determined by **electrical conductivity of the water (ECw)** and expressed in dS/m or mmhos/cm (Tables 3.2 and 3.3). Also, total soluble salts may be reported using the designation **total soluble salts (TSS)** or the term **total dissolved salts (TDS).** However, the notation of TSS is also used for "total suspended solids." It is important to know which meaning is intended in a water quality report because these factors are different; one measures dissolved salts and the other suspended inorganic and organic matter. The authors will use TDS for total soluble or dissolved salts and TSS for total suspended solids.

TDS is reported in units of ppm or mg/L. The conversion of ECw to TDS is usually by the formula:

$$\text{TDS (in ppm or mg/L)} = \text{ECw (in dS/m or mmhos/cm)} \times 640$$

For example, if a groundwater has a TDS of 10,000 ppm, the ECw would be 15.6 dS/m. The conversion factor of 640 should be used when ECw is < 5.0 dS/m, whereas at ECw > 5.0 dS/m the conversion should be 750.

Not all solutes have the same conductivity, and salt composition can differ from one source to another. Thus, some laboratories may use a different conversion factor, such as (1) 700 instead of 640, (2) 750 for waters with high sulfate or highly saline water (i.e., ECw > 5.0 dS/m), or (3) 744 for seawater-affected waters. To avoid confusion, we would suggest the following:

- Because it is ECw that is normally measured in the laboratory and then converted to TDS, the ECw value can be used instead of TDS. It is possible for a laboratory to determine TDS without measuring ECw by an evaporation method in which the residue remaining after evaporation of the water is used. However, this method can be misleading if any "suspended" solids are in the water because these would be reported as soluble salts rather than suspended solids.
- If a TDS value is desired, the laboratory or the turfgrass manager can use 640 as a conversion when ECw is < 5.0 dS/m; and when ECw is > 5.0 dS/m or the water source is a seawater-affected source or seawater blend, a conversion of 750 is appropriate.

Saline irrigation water can adversely affect plants in several ways (Carrow and Duncan, 1998). Seed germination, initial rooting, and vegetative propagule establishment are reduced by high total salt levels. The most important limitation is by the osmotic influence, whereby salts in water and soil solution attract water molecules, thereby reducing their availability for plant uptake. This effect is called salt-induced or **physiological drought**. Turfgrass symptoms to physiological drought include reduced growth rate, discoloration, wilting, leaf curling, and eventually, leaf firing or desiccation that can lead to total leaf death. Initially, the discoloration may be the blue-green color associated with drought stress, but soon the combination of salt and drought results in a general yellowing, followed by tissue desiccation, which can be yellow to dark brown depending on severity and the turfgrass species. Stand density and root volume gradually decrease over time.

Plant tolerance to the baseline salinity in irrigation water is very important for successful growth of turfgrasses and landscape plants under saline irrigation (Figure 3.1; Table 3.4). When irrigation water contains appreciable total soluble salts, ECw is a major factor considered in selecting appropriate turfgrasses and landscape plants that can tolerate the base level of salinity. Classification criteria of irrigation water salinity pertaining to plant salinity tolerance have evolved as more salt-tolerant turfgrass plants, especially halophytes such as seashore paspalum or alkaligrass, are used. Traditional water classification schemes have considered irrigation water

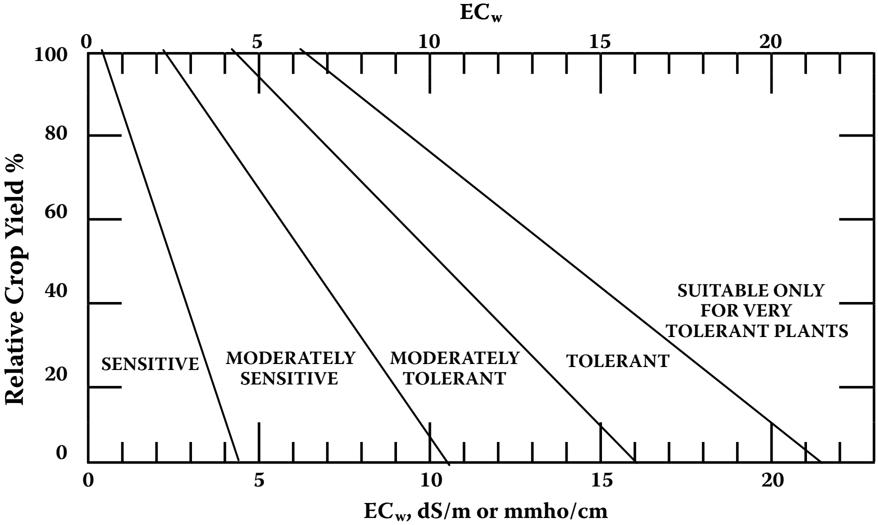


FIGURE 3.1 Irrigation water salinity (EC_w), relative salinity tolerance of plants, and relative plant growth under different salinity levels. Some very tolerant halophytes may exhibit 50% growth reduction at EC_w of >40 dS/m. (From Maas, E. V. 1984. Salt tolerance of plants. In B. R. Christie, (Ed.). *The Handbook of Plant Science in Agriculture*. CRC Press, Boca Raton, FL.)

TABLE 3.4
Irrigation water salinity classification (i.e., total soluble salts) relative to plant salinity tolerance, infrastructure, and management requirements

	Lauchli and Luttge (2002)		AWA (2000)		
Water salinity rating	**ECw dS/m**	**TDS mg/L**	**ECw dS/m**	**TDS mg/L**	**Description, plant tolerance**
Very low	<0.78	<500	<0.65	<416	Freshwater. Sensitive plants. Few detrimental effects.
Low	0.78–1.56	500–1,000	0.65–1.30	416–832	Slightly brackish. Moderately sensitive plants may show stress. Moderate leaching.
Medium	1.56–3.13	1,000–2,000	1.30–2.90	832–1856	Brackish. Moderately tolerant plants. Salinity will adversely affect most plants; requires selection for salt tolerance; careful irrigation; good drainage; leaching.
High	3.13–7.81	2,000–5,000	2.90–5.20	1,856–3,328	Moderately saline. Moderately tolerant to tolerant crops must be used along with excellent drainage, leaching program, careful irrigation, intensive cultivation, and proper management.
Very high	7.81–15.6	5,000–10,000	5.20–8.10	3,328–5,184	Saline. Tolerant crops must be used along with excellent drainage, leaching, irrigation, cultivation, fertility, and management programs.
Extremely high	15.6–50.0	10,000–32,000	>8.10	>5184	Highly saline. Very salt-tolerant halophytes. Excellent drainage, leaching, irrigation, cultivation, fertility, and management programs required.

salinities of ECw > 3.0 dS/m to be highly saline, that is, generally unacceptable except for very salt-tolerant plants, and requiring excellent drainage, frequent leaching, as well as intensive management (Westcot and Ayers, 1985; Ayers and Westcot, 1994). However, some commonly used turfgrass species can often tolerate salinity levels well above ECw = 3.0 dS/m if adequate leaching is practiced. Thus, the authors prefer the water quality guidelines and descriptions reported by Lauchli and Luttge (2002) (Table 3.4). In Australia and New Zealand, irrigation water guidelines also reflect a broader classification scheme (Table 3.4).

Species that are currently used as turfgrasses or are under development for turfgrass use on saline sites and that may exhibit threshold ECw (salinity at which plant growth starts to decline in response to salinity stress) values within the extremely tolerant range of ECw > 15.6 are the following: some *Paspalum vaginatum* (seashore paspalum) cultivars, *Sporobolus virginicus* (saltwater couch, seashore dropseed), *Zoysia macrantha*, some *Stenotaphrum secundatum* (St. Augustine grass) cultivars, some *Puccinellia* spp. cultivars (alkaligrass), some *Distichlis stricta* ecotypes (Brede, 2000; Carrow and Duncan, 1998; Barrett-Lennard, 2003). The cultivars or ecotypes of the aforementioned species that are most salt tolerant often exhibit ECw 50% growth values in the 30 to 50 dS/m range (Carrow and Duncan, 1998).

While salt-tolerant turfgrasses have allowed more saline irrigation water to be used in some situations, practical implications related to using highly saline irrigation waters must be considered. Most of the most salt-tolerant turfgrass species tolerate the salinity challenges, but do not remediate or adjust soil profile salt loading or water quality components. Therefore, the focus on growing these turfgrasses is devoted to continuous salinity management.

- As ECw increases above 3.0 dS/m, other salinity problems become "stacked" on top of total soluble salt stress because of the high concentrations and diversity of salts. These increased stresses include sodium permeability hazard, specific toxic ions, and nutrient challenges. Management becomes more demanding and costly.
- As noted under the "Description, Plant Tolerance" column heading in Table 3.4, as ECw increases, so does the need for infrastructure improvements and enhanced management involving adequate drainage systems, irrigation design/distribution uniformity and scheduling, leaching programs, cultivation equipment, and programs; also, water treatment and water/soil amendments and application equipment needs increase; fertility programs are much more dynamic in magnitude and frequency of changes; soil profile modifications/sand capping must be performed on the basis of infiltration/percolation rates; and the turfgrass must be carefully managed to avoid additional stresses as well as salt buildup in the soil. Duncan et al. (2000b) noted that many infrastructure and management decisions must be made prior to construction when using seawater, seawater blends, or other highly saline irrigation waters.
- Because of the foregoing challenges, it is best to use water with as low an ECw value as available. Even if higher-ECw water and a salt-tolerant grass are available, bear in mind that a decision to use high-ECw water is also a

decision involving costly infrastructure changes, additional types of salinity stresses, and a greater degree of management expertise (Duncan and Carrow, 2005).
- Based on the author's observations of sites using seashore paspalum, the highest ECw normally used for prolonged irrigation has been within the 15–20 dS/m range with excellent drainage, irrigation system and other infrastructure requirements, arid climate, and ample water quantity. At ECw 5–10 dS/m, long-term irrigation is not feasible on a salt-tolerant grass unless the salts can be effectively leached to avoid soil accumulation within the root system.

The salinity level of the irrigation water indicates the approximate soil salinity (expressed in terms of saturated paste extract electrical conductivity, or ECe) that can be achieved under "ideal" leaching conditions during periods when only irrigation water and not rainfall is applied. In reality, soil ECe is often higher than ECw unless the soil is very sandy with excellent leaching capabilities. Because ECw represents "the best" that the soil salinity will achieve without adding a better-quality irrigation water or receiving rainfall, this value is important for selection of turfgrasses that will tolerate this level of salinity.

Although there are turfgrasses that can tolerate very high salinities for periods of times, most of the species and cultivars used are within the 3 to 10 dS/m range. For example, many creeping bentgrasses exhibit a salinity tolerance of 3 to 6 dS/m, but there are some that can tolerate the 6 to 9 dS/m level; whereas all centipedegrass cultivars exhibit rapid growth reduction at 1.5 to 3.0 dS/m. Even for the very salt-tolerant species that can tolerate ECw well above 3.0 dS/m, irrigation water salinity as high as 3.0 dS/m can result in very rapid salt accumulation in soils that can stress even the salt-tolerant types unless a good aeration and leaching program is used. A more salt-tolerant grass allows more time to leach because of its tolerance capabilities, takes advantage of future rainfall, and avoids immediate salt stress; but salts cannot be allowed to continue to accumulate in soil profiles where pristine turfgrass is being managed at low mowing heights.

In addition to influencing plant selection, irrigation water salinity concentrations denote the level of management expertise and intensity that will be required on a site. This is indicated in Table 3.4 in the comments of water salinity ratings. In Part 3, management options for sites receiving saline irrigation water will be presented, but in general, as water quality declines, there must be increased emphasis on excellence in drainage systems, irrigation system water distribution uniformity, irrigation scheduling for proper water application and salt movement, leaching programs, cultivation programs, fertility programs, soil modification, and overall management. Proper salt disposal will become increasingly important to avoid salinization of soils, groundwater, or lakes. As irrigation water salinity increases, so does the potential for various toxic ion problems as well as nutrient/element imbalances.

With highly saline water, salts may impact irrigation system longevity and performance. Some irrigation companies have already made changes in system components (so-called salt water configuration) to withstand more corrosive waters.

Water salinity also has biotic effects on irrigation lakes and freshwater ecosystems (NIWQP, 1998; Neilsen et al., 2003). Aquatic plants, invertebrates, fish, and birds can all be affected by water salinity. Hart et al. (1990) provides a good review of salinity effects on various aquatic organisms.

3.4 SODIUM PERMEABILITY HAZARD

High Na content in irrigation water is a primary cause of sodic and saline-sodic soil conditions. The relative quantities of Ca, Mg, and Na in irrigation water are extremely important. Calcium is the primary ion that stabilizes soil structure. Magnesium offers secondary structural stability. When excess Na (>100 to 200 ppm) is applied through irrigation water, the Na content builds up in the soil over time, and through the high volume of Na^+ ions, will eventually displace the Ca^{+2} ions that are the building blocks that enhance the structural integrity of the clay fraction in the soil profile. This "counterion" relationship, which is dominated by a larger hydrated radius Na^+ ions (the nonhydrated Na ion is actually smaller than Ca^{+2}, but it has a larger hydrated radius owing to its inherent attraction for water films) with a weaker force or charge for holding clay particles together, eventually results in soil structural breakdown (deflocculation).

The result is a **sodic soil** (sometimes referred to as "black alkali" because the excess sodium solubilizes some of the organic matter fraction in the soil, which in turn rises to the soil surface and coats the soil. The deposit on the surface is black (with a slick oily or greasy appearance) or a **saline-sodic soil** (having both white salt and black decomposed organic matter deposit on the surface), in which excess Na^+ and high total salts are both present. Turfgrasses cannot thrive under these sodium permeability hazard conditions, because the soil structural breakdown results in a sealed soil with little or limited water permeability. Classic symptoms are heavily compacted depressed areas, areas with constant puddles or very slow infiltration/percolation, sparse turfgrass canopy density, and dead turf. Secondary symptoms can include surface algae and black layer formation because of the constantly moist conditions, an accumulation of sulfates, and the lack of oxygen getting to the turfgrass root system, because the soil structure has broken down with a sealed surface zone.

When Na predominates and is not countered by sufficient Ca and Mg, this salt ion will result in several adverse responses: (1) water infiltration into and percolation through the soil profile are greatly reduced by a decline in soil permeability (sealing) as soil aggregates degrade and colloidal particles are dispersed to form a more massive compacted soil structure; (2) poor soil physical conditions increase the potential for low-oxygen root stress during wet periods; (3) the quantity of water required to leach excessive Na and other salts increases; (4) irrigation scheduling to apply routine irrigation as well as extra irrigation water for leaching becomes much more challenging; (5) cultivation programs must be increased to maintain adequate downward water movement; (6) water treatment by Ca addition or acidification may be required depending on the balance of Na with Ca, Mg, HCO_3, CO_3, and ECw; and (7) soil amendment applications often are necessary and usually aggressive. Sodic conditions are time consuming and difficult to remediate.

The adverse effects of Na in irrigation water on water infiltration starts at the soil surface and then continues downward in the soil profile, so that eventually water percolation is reduced. Correction of sodic conditions requires the addition of Ca, displacement of Na from the soil CEC sites on clay particles, followed by leaching. Because the displaced Na has a tendency to go back onto CEC sites once it is displaced, the process of leaching is much slower than for leaching of soluble salts that more easily stay in the soil solution.

Although Na is the key ion in terms of adversely affecting soil structure, it is not the absolute concentration of Na that is important, but the balance and interactions of Na with Ca, Mg, HCO_3, and CO_3. Na activity is also strongly influenced by ECw, soil texture, and clay type. The parameters of concern are (1) SAR and adj RNa; (2) RSC; (3) absolute concentrations of HCO_3, $CO_{3,}$ Ca, Na, and Mg; (4) pH; (5) ECw or TDS; (6) soil texture; and (7) clay type.

3.4.1 SARw, adj SARw, AND adj RNa

Understanding SARw, adj SAR, and adj RNa. The **sodium adsorption ratio** of the water (**SARw, sometimes called RNa)** is the traditional means used to assess the sodium status and permeability hazard (Ayers and Westcot, 1994). Na, Ca, and Mg concentrations (in meq L^{-1}, or $mmol_c/L$) are used to compute SARw, where:

$$\text{SARw} = \text{RNa} = \frac{\text{Na}}{\sqrt{(\text{Ca} + \text{Mg})/2}}, \text{ in meq/L}$$

The traditional SARw is best used for irrigation waters that are low in HCO_3^- and CO_3^{-2} at concentrations of < 120 and 15 mg/L (2 and 0.5 meq/L), respectively. In the SARw equation, HCO_3^- and CO_3^{-2} concentrations are not included; therefore, it does not account for the effects of these ions. When HCO_3^- and CO_3^{-2} ions are present in moderate to high levels, these can react with the Ca and Mg to form lime by precipitation in the soil or sometimes in the irrigation lines. Thereby, soluble Ca and Mg forms are depleted that are essential to displace Na from the CEC sites on clay surfaces where the Na causes breakdown of aggregates and dispersal of clay platelets. Ca reacts very easily with the bicarbonate or carbonate forms, whereas Mg is somewhat less reactive, but high Mg can displace Ca from the CEC sites and then result in more precipitation of $CaCO_3$.

To account for the influence of HCO_3^- and CO_3^{-2} ions in the irrigation water, an **"adjusted" SARw (adj SARw)** was developed (Ayers and Westcot, 1976) using the formula:

$$\text{adj SARw} = \text{SARw } [1 + 8.4 - \text{pHc}]$$
$$= \text{SARw } [9.4 - \text{pHc}]$$

The **pHc value** is a theoretical, calculated pH value based on the irrigation water chemistry, which integrates the influence of Ca, Na, Mg, HCO_3, and CO_3 concentrations.

The tables to make these adjustments are presented by Ayers and Westcot (1976) and Carrow and Duncan (1998). By itself, the pHc value has been used to indicate the tendency to dissolve lime by the water as it moves through the soil with a pHc > 8.4 indicative of dissolution, whereas a pHc < 8.4 indicates a greater tendency to precipitate lime in the soil or in irrigation lines if the pHc is very low.

More recently, research has indicated that the adj SARw, as presented earlier, overestimated the sodium permeability hazard because it did not adequately account for changes in Ca after irrigation water addition due to the potential for dissolution or precipitation of Ca. The preferred adjustment in the SARw is now designated as **adj RNa** and uses a substitute **Cax value** in the SARw equation in place of Ca concentration.

$$\text{adj RNa} = \frac{\text{Na}}{\sqrt{(\text{Ca}_\text{x} + \text{Mg})/2}}\text{ , in meq/L units.}$$

The Ca_x factor comes from a table of HCO_3/Ca versus ECw where the table and example calculations are given by Hanson et al. (1999), Ayers and Westcot (1994), and Westcott and Ayers (1985). Use of adj RNa is best for irrigation waters that are high in HCO_3^- and CO_3^{-2}, such as concentrations of > 120 and 15 mg/L (2 and 0.5 meq/L), respectively. In the published literature where SARw or adj SARw has been used in tables or figures, adj RNa can be substituted for these values.

Using SARw and adj RNa. As previously noted, when HCO_3^- and CO_3^{-2} concentrations are low, SARw should be used, and when higher, adj RNa is best. The top of Table 3.5 gives the sodium permeability hazard classification if SARw or adj RNa are used alone. However, if either of these methods of determining sodium permeability hazard is used by itself, the results can be misleading. For example, ultrapure irrigation water can sometimes exhibit a very high SARw because Ca and Mg levels are very low, whereas Na is moderate. The authors have observed this on some coastal golf courses in the panhandle of Florida, where the high rainfall and sandy soils with low CEC have resulted in groundwater that is very low in Ca, Mg, and total soluble salts (i.e., ECw < 0.30 dS/m). In one situation, the irrigation water had the following parameters: 1 mg/L Ca, 0.5 mg/L Mg, and 140 mg/L Na. When the data are converted to meq/L, the SARw would be

$$\text{SARw} = \frac{6.09}{\sqrt{(0.091)/2}} = 28.6$$

On the basis of Table 3.5 (top), the SARw would suggest a high sodium permeability hazard, but in this unique situation, very little Na was present in the soil owing to high leaching from rainfall and irrigation.

Clay type is very important to consider when determining whether a particular irrigation water may present a sodium permeability hazard (Table 3.5, bottom). Clays can be classified as 2:1 and 1:1 types. Clays are crystalline in nature and are composed of layers such as tetrahedral or silica layers (Si-Al-O rich layer) or octahedral layers (Al-Mg-Fe-O/OH rich layer). The 1:1 clay types have 1 tetrahedral and 1 octahedral

TABLE 3.5
SAR_w and adj RNa guidelines to determine sodium permeability hazard

Sodium permeability hazard	SAR_w or adj RNa (meq/L)	Comments
	USSL (1954) classification	
Low	<10	Can be used to irrigate almost all soils without structure deterioration. Salt sensitive plants may be affected.
Medium	10–18	Appreciable Na permeability hazard on fine-textured soils with high CEC. Best used on coarse-textured soils with good drainage.
High	18–26	Harmful levels of Na accumulation on most soils. Will require intensive management, amendments, drainage, and leaching.
Very high	>26	Generally not suitable for irrigation at low to medium soil salinity levels.

Classification considering clay type and EC_w (Ayers and Westcot, 1976)

	Degree of problem		
	None	Increasing	Severe
EC_w (dS/m) (ultrapure water)	>0.50	0.50–0.20	<0.20
Adj RNa or SAR_w			
Montmorillonite (2:1)[a]	<6	6–9	>9
Illite, Vermicultite (2:1)[a]	<8	8–16	>16
Kaolinite, Fe/Al oxides (1:1)[a]	<16	16–24	>24

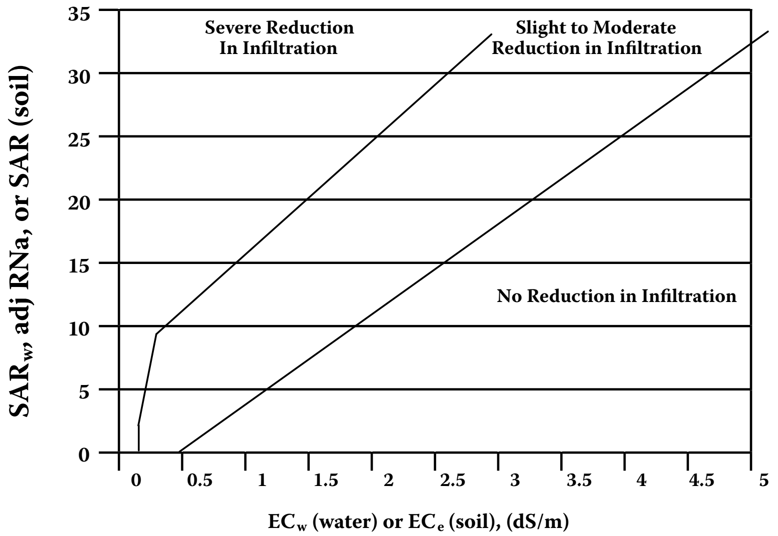
Note: Use adj RNa when HCO_3 (>2.0 meq/L, 120 mg/L) or CO_3 (>0.5 meq/L, 15 mg/L) are high; and SAR_w for lower values. Also, see Figure 3.2.

[a] 2:1 clays are shrink/swell types; 1:1 are nonshrink/swell types.

layer and are nonshrink/swell clay (i.e., nonexpanding/contracting); on wetting and drying, they do not shrink, swell, or exhibit crack formation when they dry. Common 1:1 clays are kaolinite, allophanes, or any other clays rich in Fe and Al oxides.

In contrast, the 2:1 clays have two Si tetrahedral layers and one Al-rich octahedral layer. These clays are by nature shrink/swell, will demonstrate cracking on drying, and include smectites (montmorillonite), illites, and vermiculites. By viewing whether cracking occurs on drying of the soil, such as a nonirrigated rough area, one can determine which clay type is present or is dominant.

As illustrated in Table 3.5 (bottom), 2:1 types, especially montmorillonites, are much more sensitive to structural deterioration by Na than are 1:1 clays. Even at an adj RNa of 6.0 on a montmorillitic clay, the irrigation water can start to cause surface degradation of the soil structure. It should be noted that these relationships



			Degree of Na Permeability Hazard		
			None	Slight to Moderate	Severe
Adj RNa or SAR$_w$ =	0	and EC$_w$ =	> 0.7	0.7-0.2	< 0.2
=	3	=	> 1.2	1.2-0.3	< 0.3
=	6	=	> 1.9	1.9-0.5	< 0.5
=	12	=	> 2.9	2.9-1.3	< 1.3
=	20	=	> 5.0	5.0-2.9	< 2.9

FIGURE 3.2 Sodium permeability hazard of irrigation water as influenced by EC$_w$ in graphic and table forms. As EC$_w$ increases, the adj RNa level at which water infiltration declines is greater. (From Oster, J. D. and F. W. Schroer. 1979. Infiltration as influenced by irrigation water quality. *Soil Sci. Soc. Am. J.* 43: 444–447.)

of adj RNa and clay type are even more pronounced as the percentage clay content increases. Thus, a soil with 30% clay content would exhibit fewer effects from an adj RNa of 6.0 than would one containing 60% clay of the same clay type.

Figure 3.2 and Table 3.5 (bottom) illustrate that ECw influences SARw or adj RNa relationships. Essentially, there are two major ECw situations that should be considered:

1. Ultrapure irrigation water (ECw < 0.50 and especially < 0.20 dS/m) can exhibit a slight to severe reduction in water infiltration even at low (<1.0) adj RNa. This problem is discussed in detail in Chapter 5.
2. At high ECw (> 3.0 dS/m), high salt concentrations can aid in maintaining adequate permeability even when adj RNa is high (15 to 30). Appreciable Ca and Mg ions are usually present in high-ECw water, counteracting the effects of Na.

3.4.2 RESIDUAL SODIUM CARBONATE

In Section 3.4.1, it was emphasized that determination of the sodium permeability hazard of irrigation water included consideration of SARw or adj RNa, ECw, clay type, and clay content. Another useful criterion is **residual sodium carbonate (RSC),** defined as:

$$RSC = (CO_3 + HCO_3) - (Ca + Mg)$$

The ion concentrations are expressed in meq/L.

The RSC determines whether excess Ca and Mg remain in the irrigation water after reaction with the carbonates, or whether all Ca and Mg are precipitated from the irrigation water (Table 3.6) (Eaton, 1950; Wilcox et al., 1954). A negative RSC indicates that more Ca and Mg are in the water than carbonates, where the excess Ca and Mg can act as counterions to displace Na. In contrast, a positive RSC means that all Ca and Mg have been precipitated and excess bicarbonate and carbonate remain that could react with any Ca added, such as by gypsum, dolomite, or lime application, once the Ca becomes soluble. The net effect is to reduce soluble Ca and Mg levels (complexed with bicarbonates or carbonates) while leaving soluble Na to create sodic conditions.

One obvious problem in using RSC to assess sodium permeability hazard is that the concentration of Na is not included. Thus, it is possible to have a very high RSC, but not to create sodic conditions if little Na is in the irrigation water source. The adj RNa is a much better indicator of sodium permeability hazard for the irrigation water, especially when ECw, clay type, and clay content are factored in the decision process. When Na is present along with a high (positive) RSC, sodium carbonate forms at the same time Na displaces Ca and Mg from soil CEC sites; and the soil

TABLE 3.6
Residual sodium carbonate (RSC) guides for irrigation water suitability when Na is present at a sufficient level to potentially create a sodic soil condition (Na > 100 ppm, 4.3 meq/L)

RSC value (meq L^{-1})	Na hazard
<0 (i.e., negative)	None. Ca and Mg will not be precipitated as carbonates from irrigation water; they remain active to prevent Na accumulation on CEC sites
0–1.25	Low. Some removal of Ca and Mg from irrigation water
1.25–2.50	Medium. Appreciable removal of Ca and Mg from irrigation water
>2.50	High. All or most of Ca and Mg removed as carbonate precipitates, leaving Na to accumulate. How rapidly Na buildup occurs depends on Na content of the water

Source: From Eaton, F. M. 1950. Significance of carbonates in irrigation water. *Soil Sci.* 69: 123–133; Wilcox, L. V. et al. 1954. Effect of bicarbonate on suitability of water for irrigation. *Soil Sci.* 77: 259–266.

becomes increasingly sodic. In order to ameliorate sodic soils, sufficient Ca must be added to displace Na in the sodium carbonate and on the CEC sites. Table 3.6 lists guidelines for RSC relative to suitability for irrigation water use when sufficient Na is present to potentially cause sodic conditions (Na > 100 ppm, 4.3 meq/L can be used as a "red flag" to assess Na problems more closely) (Eaton, 1950; Wilcox et al., 1954).

RSC is also useful is in defining irrigation water amendment and soil amendment needs. It is a valuable piece of information, along with Na content, to make informed decisions. First, RSC determines how much (if any) **unreacted Ca and Mg** remains available to counteract any Na present. The unreacted Ca and Mg become part of the Ca "amendment" needs to supply sufficient Ca and Mg to counteract the Na.

Second, when Na is present, no residual Ca and Mg remains, but residual carbonates are present; the RSC determines how much additional Ca amendment must be supplied to react with the excess or **unreacted carbonates**. Only after sufficient Ca and Mg are available from the irrigation water and added Ca to react with all the carbonates will there be the opportunity to add more Ca that will become soluble overtime and counteract the Na. Unless adequate Ca is added to react with the unreacted carbonates (or the carbonates are removed by acidification), sodium carbonate will accumulate.

Third, RSC is used to determine the **quantity of acid in water acidification** to reduce the residual bicarbonate and carbonate so that they will not react with Ca or Mg in the water or soil solution. Sufficient acid is added to evolve off the carbonate ions (both CO_3 + HCO_3) as CO_2 gas and water. The formula is

$$\text{RSC} \times 133 = \text{pounds of } 100\% \text{ } H_2SO_4 \text{ per acre-foot irrigation water}$$

In practice, sufficient acid is added to achieve 75 to 80% depletion of the residual carbonates, but to maintain pH > 6.0 and usually within the 6.5 to 6.8 range.

As noted, acidification of irrigation water is very important when it contains **both excessive Na and carbonates**, because an effective Ca amendment program cannot be achieved if most of the Ca reverts to lime or very insoluble forms. In Chapter 13, a stepwise procedure will be presented to illustrate how RSC information can be used to determine water acidification and amendment needs. For sites with irrigation waters containing appreciable Na and carbonates, amendment needs are best determined by starting with the irrigation water, and the RSC provides valuable information for these purposes (Carrow et al., 1999; Carrow and Duncan, 1998). Water quality values that raise a red flag to look at the potential need for acidification are as follows: RSC > 1.25 meq/L; Na content > 100 ppm or 4.3 meq/L; and HCO_3 > 122 mg/L or 2.0 meq/L. These values do not mean that acidification is needed, but they do indicate that a closer investigation is warranted by considering all other relevant information. In cases where the irrigation source has been used for some time, additional insight may be gained by also evaluating soil test results. Soil sodium accumulations measured by either exchangeable sodium percentage (ESP) or the sodium adsorption ratio (SARe) of the saturated paste extract (SPE) may help determine if acid treatment is necessary.

A fourth use of RSC is to determine the quantity of gypsum to add per acre-foot of irrigation water to supply **Ca to react with the remaining carbonates** to achieve a RSC = 0. The formulas used are

$$\text{RSC} \times 234 = \text{pounds of 100\% pure gypsum per acre-foot irrigation water}$$
$$\text{RSC} \times 86 = \text{kg of 100\% pure gypsum per 1000 m}^3 \text{ irrigation water}$$

Dihydrate gypsum injection could be used to deliver the required calcium amendment. Alternatively, the water could be acidified to remove excess carbonates and free up any complexed calcium.

Finally, when little or no Na is present but Ca, Mg, and carbonates are all very high, the RSC aids in assessing the potential for calcite precipitation. In arid situations, there is sometimes concern that lime deposition on the soil from the irrigation water may cause sealing overtime (Carrow et al., 1999). Concentrations of these constituents in irrigation water usually are as follows: 100–400 mg/L HCO_3; 0–5 mg/L CO_3; 25–200 mg/L Ca; and 20–40 mg/L Mg. Assume that an irrigation water source is very high in each of these components at: 811 mg/L HCO_3, 200 mg/L Ca, and 40 mg/L Mg. In this example, there is sufficient Ca (10 meq/L) and Mg (3.28 meq/L) to react with all the 13.3 meq/L of HCO_3. This water would result in a combined total of 2104 lb of $CaCO_3$ + $MgCO_3$ per acre-foot of applied irrigation water or 48 lb $CaCO_3$ + $MgCO_3$ per 1000 sq. ft. per 12 in. of irrigation water. As a comparison, a soil with 1% free lime in the surface 4.0 in. zone would contain about 230 lb per 1000 ft^2 of lime. In an arid climate in which rainfall would not assist in dissolving the precipitated calcite and the irrigation program was consistent, accumulation could occur, especially at the bottom-wetting front depth for routine irrigation water penetration. However, with use of acidifying fertilizers, periodic deeper leaching by irrigation or rains, and with normal deep cultivation practices, all of these management options would assist in preventing a distinct calcite zone that could inhibit infiltration or percolation in the soil profile.

3.5 SPECIFIC ION IMPACT (ROOT INJURY AND SHOOT ACCUMULATION INJURY)

Irrigation water may contain excessive levels of certain salt ions that can (1) adversely affect plant root tissues owing to soil accumulation or layering and (2) cause injury to shoot tissues owing to foliar uptake and accumulation in leaves. As total salinity increases in irrigation water, the potential for specific ion toxicity also increases. Germinating seed, young seedlings, and sprigs are especially vulnerable because of their juvenile developing root systems. The ions that most often cause toxicity problems include **Na, Cl, and B.** However, trace elements can also result in toxicity or ion competition deficiency problems over time in some situations (see Section 3.8). The same guidelines are used for soil accumulation (root injury) and shoot accumulation (shoot injury) (Table 3.7).

In terms of foliar uptake, accumulation, and injury, any of the soluble salts in soil solution can be taken up and potentially accumulate in leaf tissues. However, as irrigation water salinity increases, two of the most common salt ions likely to be present

TABLE 3.7
Specific ion toxicity (Na, Cl, and B) and miscellaneous chemical constituent problems in sprinkler irrigation water for sensitive plants

Potential toxicity problem	Units	Degree of restriction on use for sensitive plants[a]		
		None	**Slight to moderate**	**Severe**
		Soil accumulation and root/shoot accumulation injury		
Na	SAR (soil)	0–3	3–9	>9
	mg/L (ppm)	0–70	70–210	>210
	meq/L	0–3	3–9.1	>9.1
Cl	mg/L	0–70	70–355	>355
	meq/L	0–2	2–10	>10
Metal ions (trace elements)—see Table 3.11				
		Direct foliage injury (sprinkler irrigation)		
Na	mg/L	0–70	>70	
	meq/L	0–3	>3	
Cl	mg/L	0–100	>100	
	meq/L	0–3	>3	
		Miscellaneous		
HCO_3^-[b] (unsightly deposits)	mg/L	0–90	90–500	>500
	meq/L	0–1.5	1.5–8.5	>8.5
Residual Cl_2 (chlorine)	mg/L	0–1	1–5	>5
SO_4 (black layer)[c]	mg/L	0–90	90–180	>180

Boron toxicity potential

B (mg/L)	Comments
<0.5	Very sensitive. Some ornamentals affected (see Hanson et al., 1999)
0.5–1.0	Sensitive. Some trees, shrubs, ornamentals affected
1.0–2.0	Moderately sensitive
2.0–4.0	Moderately tolerant. Kentucky bluegrass
4.0–6.0	Tolerant. Only B-tolerant plants should be used
>6.0	Very tolerant plants should be used

[a] Guidelines in this table are for "sensitive" landscape plants. Turfgrasses are generally more tolerant than many ornamental trees, shrubs, and flowers.

[b] HCO_3 deposition is not a toxicity problem but is unsightly on foliage or ornamentals.

[c] SO_4 (black layer). High SO_4 in the soil often arises from irrigation water, especially acidified water and some reclaimed water. Under anaerobic conditions, SO_4 can be reduced to sulfide forms and stimulate black layer formation. A good leaching program will leach SO_4 ions to prevent accumulation. Also, high Ca ion content can precipitate SO_4 as gypsum.

Source: From Ayers, R. S. and D. W. Westcot. 1994. Water Quality for Agriculture. FAO Irrigation and Drainage Paper, 29, Rev. 1. Reprinted 1994. Food and Agric. Organiz., Rome, Italy. http://www.fao.org/DOCREP/003/T0234E/T0234E00.htm#TOC; Hanson, B. et al. 1999. *Agricultural Salinity and Drainage*. Div. of Agric. and Nat. Res. Pub. 3375. Univ. of Calif., Davis, CA; AWA (Australian Water Authority). 2000. Australian and New Zealand Guidelines for Fresh and Marine Water Quality. Paper No. 4, Chapter 9. Primary Industries. Australian Water Authority, Artarmon, NSW, Australia. See online at http://www.mincos.gov.au/publications/australian_and_new_zealand_guidelines_for_fresh_and_marine_water_quality/volume_3.

are Na and Cl. Chloride is a very common anion in irrigation water and can easily be absorbed by plants. As salts accumulate in leaf tips of grasses or outer margins of landscape plants in the topmost leaves, the salts can cause (1) osmotic stress by reducing water availability for cell uptake and inducing dehydration of cells, which can eventually lead to tissue desiccation and leaf firing; and (2) also induce direct toxic effects, depending on the salt ion.

Turfgrasses are generally less sensitive to Na and Cl uptake into leaves and foliar injury compared to other landscape plants, primarily because mowing removes accumulated ions in the shoot tissues. When trees and shrubs accumulate excessive salts, the initial symptoms are leaf wilting, followed by firing on leaf margins (yellow to tan color as tissue dies and desiccates), especially from excess Cl because that salt ion is rapidly translocated to growing points on the plant, and finally, leaves may fall from the plants. For tall trees, the upper leaves often exhibit leaf fall first.

Root cells preferentially bind Ca to exchange sites on cell walls (similar to soil CEC sites on clays or organic matter), which is beneficial because cell walls and cell plasma membranes require high Ca content to maintain viability or function. High Na ion concentration in the soil and subsequent absorption often results in Na competing with Ca ions on cell wall exchange sites, resulting in cell wall deterioration, especially near the root tips. The Na-induced Ca deficiency in root tissues is sometimes called Na toxicity. Highly salt-tolerant turfgrass and landscape plants possess tolerance to Na toxicity, but less salt-tolerant plants exhibit severe root injury from high soil Na accumulation and Na uptake.

Boron is often associated with saline hydrogeological conditions and is another element that can be a toxicity problem if concentrations are elevated in irrigation water. Surface water concentrations of B in natural ecosystems are normally <0.1 mg/L and rarely exceed 1.0 mg/L. Groundwater is usually <0.5 mg/L, but some groundwater can be as high as 5.0 mg/L, and agriculture drain water can be above this level if irrigation is from B-rich water (NIWQP, 1998).

Plant species vary in tolerance to B. Irrigation water quality relative tolerance guidelines are noted in Table 3.7 (bottom) (Ayers and Westcot, 1994; Hanson et al., 1999; AWA, 2000). The guidelines in Table 3.7 note the potential for B toxicity problems to occur over a relatively short term irrigation water use (i.e., <20 years) under conditions when soil B could accumulate (assuming no leaching losses or fixation losses). Kentucky bluegrass is the only turfgrass listed in these sources, and it is listed as moderately tolerant and able to tolerate 2.0 to 4.0 mg/L of B. Turner and Hummel (1992) report the B tolerance of grasses as follows: creeping bentgrass > perennial ryegrass > Alta tall fescue > Kentucky bluegrass > zoysiagrass > bermudagrass.

Boron phytotoxicity on plants may be exhibited by yellowing followed by a dark necrosis on the margins of older leaves. As soil pH increases from 6.3 to 7.0, B is more tightly adsorbed on clays and Fe/Al oxides. Thus, at pH < 7.0, leaching may prevent B accumulation, whereas at pH > 7.0, periodic lime applications to maintain high available Ca levels can help fix the B if it is found in less available forms. Leaching is more effective on coarser-textured soils than on fine-textured ones. Boron leaching also requires up to three times the amount of water needed to leach an equivalent amount of chloride salts.

The NIWQP (1998) reports the B toxicity threshold in lakes for an aquatic plant is 10 mg/L. However, aquatic invertebrates, fish, amphibians, and wildfowl could tolerate higher levels.

3.6 DIRECT FOLIAGE INJURY AND MISCELLANEOUS PROBLEMS

Plant leaves of trees and shrubs impacted by overhead sprinkler irrigation water may exhibit foliage injury from Na or Cl in the water (Table 3.7). Leaves that are in the pathway of the irrigation water stream may die. Foliar injury from either Na or Cl becomes more pronounced when irrigation is applied during daylight hours and with low humidity. Sodium initially tends to accumulate in the roots and lower trunks of trees and possibly woody shrubs. After 3, 4, or even more years as sapwood converts to heartwood, the accumulated Na is apparently released and transported to the leaves, causing burn. In some cases, this sudden Na release can result in death of the plant (Hall, 2004; Tanji, 1996).

HCO_3 concentrations in irrigation water are not phytotoxic to leaves at >8.0 meq L^{-1} or 488 ppm. However, HCO_3 can cause unsightly whitish deposits on leaves of ornamentals, trees, cart paths, and equipment (Table 3.7).

High iron concentrations can also cause unsightly reddish brown deposits on foliage, equipment, buildings, concrete cart paths, and other structures.

Residual chlorine (Cl_2) that is used to disinfect wastewater becomes toxic at >5 ppm for many plants (Table 3.7). Damage is expressed as leaf tip injury. However, chlorine is normally not a problem on turfgrass sites because most irrigation water is applied through overhead sprinkler systems and this gas dissipates rapidly when aerated. Storage of high chlorine water in lakes, ponds, or lagoons will accomplish the same dissipation phenomenon over time, especially if an aeration system is present in the storage area.

Total suspended solids (TSS) are discussed in Chapter 2 (Section 2.4.1) relative to the various influences TSS can have in irrigation. Reclaimed water used for irrigation with human access has stringent regulatory limits because TSS influences disinfection treatment effectiveness. Usually the limit is <30 mg/L (Table 2.3).

3.7 NUTRIENTS

All irrigation water will contain a certain level of nutrients in its composition, and reclaimed water may contain elevated levels of certain nutrients. Nutrients in irrigation water are a concern because of (1) soil accumulation and foliar contributions to the overall soil fertility and plant nutrition program for turfgrasses and other landscape plants (all macro- and micronutrients), (2) promotion of algae and aquatic plant growth in irrigation lakes (P, N), (3) human health hazard (NO_3), and (4) potential to contribute to black layer (SO_4). Because of the nutrient load in irrigation water, fertility programs must be adjusted to maximize turfgrass performance and to minimize environmental impact (King et al., 2000).

Huck et al. (2000) reported nutrient content guidelines for irrigation water, especially reclaimed water, with low to very high value ranges (Table 3.8). Table 3.9 lists conversion factors to convert ppm or mg/L of an ion to quantity of ion applied per

TABLE 3.8

Guidelines for nutrient content of irrigation water to be used for turfgrass situations; and quantities of nutrients applied per acre foot on irrigation water

Nutrient or element	Nutrient content in water in mg L^{-1} (or ppm)				Conversion to lb per 1000 ft^2 of nutrient added for every 12 in. of irrigation water applied[c]
	Low	Normal	High	Very high	
N	<1.1	1.1–11.3	11.3–22.6	>22.6	11.3 ppm N = 0.71 lb N per 1000 ft^2
NO_3^-	<5	5–50	50–100	>100	50 ppm NO_3^- = 0.71 lb N per 1000 ft^2
P	<0.1	0.1–0.4	0.4–0.8	>0.8	0.4 ppm P = 0.057 lb P_2O_5 per 1000 ft^2
PO_4^-	<0.30	0.30–1.21	1.21–2.42	>2.42	1.21 ppm PO_4^- = 0.057 lb P_2O_5 per 1000 ft^2
P_2O_5	<0.23	0.23–0.92	0.92–1.83	>1.83	0.92 ppm P_2O_5 = 0.057 lb P_2O_5 per 1000 ft^2
K	<5	5–20	20–30	>30	20 ppm K = 1.5 lb K_2O per 1000 ft^2
K_2O	<6	6–24	24–36	>36	24 ppm K_2O = 1.5 lb K_2O per 1000 ft^2
Ca^{+2}	<20	20–60	60–80	>80	60 ppm Ca = 3.75 lb Ca per 1000 ft^2
Mg^{+2}	<10	10–25	25–35	>35	25 ppm Mg = 1.56 lb Mg per 1000 ft^2
S	<10	10–30	30–60	>60	30 ppm S = 1.87 lb S per 1000 ft^2
SO_4^{-2}	<30	30–90	90–180	>180	90 ppm SO_4^- = 1.87 lb S per 1000 ft^2
Mn	—	—	>0.2[b]	—	
Fe	—	—	>5.0[a]	—	
Cu	—	—	>0.2[a]	—	
Zn	—	—	>2.0[a]	—	
Mo	—	—	>0.01[b]	—	
Ni	—	—	>0.2[a]	—	

[a] These values are based on potential toxicity problems that may arise over long-term use of the irrigation water, especially for salt-sensitive plants in the landscape; turfgrasses can often tolerate higher levels. For fertilization, higher rates than these can be applied as foliar treatment without problems.

[b] Based on Westcot, D. W. and R. S. Ayers. (1985). Irrigation water quality criteria. In G. S. Pettygrove and T. Asano (Eds.). *Irrigation with Reclaimed Municipal Wastewater—A Guidance Manual*. Lewis Publ., Chelsea, MI.

[c] See Table 3.9 for conversion factors.

Source: After Huck, M. et al. 2000. Effluent water: nightmare or dream come true? *USGA Green Section Record* 38(2): 15–29.

TABLE 3.9

Conversion factors for calculating pounds of nutrient per acre-foot of irrigation water from nutrient content in the water

Conversion factors that can be used are as follows:
1 mg/L = 1 ppm
1 mg/L NO_3^- = 0.226 mg /L N
1 mg/L N = 4.42 mg/L NO_3
lb of N per acre-foot of water = mg/L N in water × 2.72
lb of P per acre-foot of water = mg/L P in water × 2.72
lb of K per acre-foot of water = mg /L K in water × 2.72
lb of P_2O_5 per acre-foot of water = mg/L P in water × 6.24
lb of K_2O per acre-foot of water = mg /L K in water × 3.25
lb of Ca per acre-foot of water = mg /L Ca in water × 2.72
lb of Mg per acre-foot of water = mg/L Mg in water × 2.72
1 mg/L SO_4^- = 0.33 mg/L S
1 mg/L PO_4^- = 0.33 mg/L P

Example: Irrigation water has 15 mg/L NO_3.
15 mg/L NO_3 = (15)(0.226 mg/L N)
= 3.39 mg/L as N
lb N per acre-foot of water = (mg/L of N)(2.72)
= (3.39 mg/L of N)(2.72)
= 9.22 lb N per acre-foot water
Or, 9.22/43.56 = 0.21 lb N per 1000 sq. ft. per 12 in. irrigation water
1 acre = 43,560 sq. ft.

acre-foot of irrigation water. The ranges for all macronutrients except P are based on the possible effects on fertilization with continuous use of water. Phosphorous recommendation is based on limiting eutrophication, because P is often the primary limiting nutrient that affects aquatic plant and algal growth.

High concentrations of a particular nutrient could lead to overfertilization or nutrient imbalance with counterions, especially for the cations. Because N responses by turfgrasses and aquatic plants can be more pronounced than for other nutrients, high N levels must be taken into account in the overall N fertilization program. For example, reclaimed water high in N and applied on a cool season grass during hot periods can result in deterioration of the grass in response to excess N.

In the case of SO_4, higher concentrations could increase the potential for black layer formation if the SO_4 accumulates in the soil and anaerobic conditions occur. In Chapter 12, measures to limit this potential problem are discussed.

For assessing the potential to create a cation imbalance, ratios noted in Table 3.10 can be used as a general guide, where the key ratios are Ca:Mg, Ca:K, and Mg:K. Note that these ratios are based on nutrient concentrations in meq/L (chemically equivalent basis) rather than mg/L owing to ion equivalent weight differences. Although K is seldom high in irrigation water, high Ca content is common. Some

TABLE 3.10
General guidelines for cation ratios in irrigation water (ratios are based on cation content in meq/L basis)

Ratio	Preferred ratio limits[a]	Comments
Ca:Mg	Below 3:1	Ca deficiency may occur.
	Above 8:1	Mg deficiency may occur.
Mg:K	Below 2:1	Mg deficiency may occur.
	Above 10:1	K deficiency may occur.
Ca:K	Below 10:1	Ca deficiency may occur.
	Above 30:1	K deficiency may occur.

[a] Irrigation water with ratios outside these guidelines can still be used, but supplemental fertilization may be required to maintain soil nutrient balance.

irrigation waters, especially if influenced by seawater, are high in Mg. Another common situation is when excess Na in irrigation water inhibits K uptake and reduces K on soil CEC sites. High Na can also suppress Ca and Mg uptake and dominate CEC status. Cation ratios that are extreme often require supplemental fertilization to obtain balanced soil fertility status. Proactive and regularly scheduled soil testing can assist in determining fertilizer and amendment needs.

3.8 TRACE ELEMENTS

Ayers and Westcot (1994) note that trace elements are almost always present in all water supplies, but at low concentrations. Some reclaimed water may exhibit higher levels of trace elements, depending on manufacturing supplied wastewater sources. Also, irrigation water affected by acid mine drainage or acid sulfate soil conditions can have high trace element concentrations owing to the extreme acidity that can dissolve soil trace elements (Gray, 1997; Sundstrom et al., 2002). Another irrigation source that may contain trace elements is untreated stormwater runoff from impervious surfaces (USEPA, 2002). Although micronutrients may be included in a routine irrigation water quality analyses, other trace elements generally are not. However, if the irrigation water source is one of the aforementioned situations, it would be reasonable to obtain a full analysis.

The desired range for various micronutrients is at or less than listed for LTV levels in Table 3.11. The values recommended by Westcot and Ayers (1985) are also included in Table 3.8, where it is suggested not to exceed these levels for long-term use. The STV limits used by AWA (2000) and listed in Table 3.11 can be used as maximum levels for normal use.

TABLE 3.11
Recommended maximum concentrations of trace elements in irrigation water for long-term values (LTV) and short-term values (STV) based on AWA (2000) and Westcot and Ayers (1985)

	AWA (2000)		Westcot and Ayers (1985)	
Element	**LTV[a] (mg/L)**	**STV[b] (mg/L)**	**LTV (mg L^{-1})**	**Remarks**
Al (aluminum)	5.0	20	5.0	Can cause nonproductivity in acid soils (pH <5.5), but a pH >5.5 will precipitate the ion and eliminate any toxicity
As (arsenic)	0.10	2.0	0.10	Toxicity to plants varies widely, ranging from 12 mg/L for Sudangrass to less than 0.05 mg/L for rice
Be (beryllium)	0.10	0.50	0.10	Toxicity to plants varies widely, ranging from 5 mg/L for kale to 0.5 mg/L for bush beans
Cd (cadmium)	0.01	0.05	0.01	Toxic to beans, beets, and turnips at concentrations as low as 0.1 mg/L in nutrient solutions. Conservative limits recommended because of its potential for accumulation in plants and soils to concentrations that may be harmful to humans
Co (cobalt)	0.05	0.10	0.05	Toxic to tomato plants at 0.1 mg/L in nutrient solution. Tends to be inactivated by neutral and alkaline soils
Cr (chromium)	0.10	1.0	0.1	Not generally recognized as an essential growth element. Conservative limits recommended because of lack of knowledge on toxicity to plants
Cu (copper	0.20	5.0	0.2	Toxic to a number of plants at 0.1 to 1.0 mg/L in nutrient solutions
F (fluoride)	1.0	42	1.0	Inactivated by neutral and alkaline soils
Fe (iron)	0.20	10	5.0	Not toxic to plants in aerated soils, but can contribute to soil (iron) acidification and loss of reduced availability of essential phosphorus and molybdenum. Overhead sprinkling may result in unsightly deposits on plants, equipment, and buildings
Li (lithium)	2.5	2.5	2.5	Tolerated by most crops up to 5 mg/L; mobile in soil. Toxic to citrus at low levels (>0.975 mg/L). Acts similarly to boron

(continued)

TABLE 3.11
Recommended maximum concentrations of trace elements in irrigation water for long-term values (LTV) and short-term values (STV) based on AWA (2000) and Westcot and Ayers (1985) (continued)

	AWA (2000)		Westcot and Ayers (1985)	
Element	LTV[a] (mg/L)	STV[b] (mg/L)	LTV (mg L^{-1})	Remarks
Mn (manganese)	0.20	10.0	0.2	Toxic to a number of crops at a few tenths of milligrams to a few mg/L, but usually only in acid soils
Mo (molybdenum)	0.01	0.05	0.01	Not toxic to plants at normal concentrations in soil and water. Can be toxic to livestock if forage is grown in soils with high levels of available molybdenum
Ni (nickel)	0.20	2.0	0.2	Toxic to a number of plants at 0.5 to 1.0 mg/L; reduced toxicity at neutral or alkaline pH
Pb (lead)	2.0	5.0	5.0	Can inhibit plant cell growth at very high concentrations
Se (selenium)	0.02	0.05	0.02	Toxic to plants at concentrations as low as 0.025 mg/L and toxic to livestock if forage is grown in soils with relatively high levels of added selenium. For animals, an essential element but in very low concentrations
Sn (tin)	—	—	—	Effectively excluded by plants; specific tolerance unknown
V (vanadium)	0.10	0.50	0.1	Toxic to many plants at relatively low concentrations
Zn (zinc)	2.0	5.0	2.0	Toxic to many plants at widely varying concentrations; reduced toxicity at pH > 6.0 and in fine-textured or organic soils

[a] LTV—guideline for when irrigation water is used for a long time (>20 years) on a site.
[b] STV—guideline for when irrigation water is used for <20 years.

3.9 SUMMARY TABLE

Table 3.12 is a summary table with desired ranges of water parameters that may be in a routine irrigation quality report. Also, listed is the usual range found in irrigation waters, average domestic water (i.e., potable water), and average reclaimed water (Westcot and Ayers, 1985; Stowell and Gelernter, 2001).

TABLE 3.12
Summary of irrigation water quality guidelines

Water parameter	Units	Desired range	Usual range[a]	Average domestic[b]	Average reclaimed[b]
		General water characteristics			
pH	1–14	6.5–8.4	6.0–8.5	7.7	7.1
Hardness	mg/L	<150	—	—	—
Alkalinity	mg/L	<150	—	—	—
HCO_3	mg/L	<120	<610	174	194
CO_3	mg/L	<15	<3	3.0	0
		Total salinity (soluble salts)			
EC_w	dS/m	0.40–1.20	<3.0	0.8	1.1
TDS	mg/L	256–832	<2000	617	729
		Sodium permeability hazard			
SAR_w	meq/L	<6.0	<15	1.9	3.1
adj RNa	meq/L	<6.0	<15	1.9	3.1
RSC	meq/L	<1.25	—	−2.30	−1.88
EC_w	dS/m	>0.40	—	—	—
		Specific ion impact on root injury or foliage uptake injury			
Na	mg/L	<70	—	—	—
Cl	mg/L	<70	—	—	—
B	mg/L	<0.50	<2.0	0.17	0.44
		Specific ion impact on direct foliage injury from sprinkler irrigation			
Na	mg/L	<70	—	—	—
Cl	mg/L	<100	—	—	—
HCO_3 (unsightly on leaves)	mg/L	<90	—	—	—
		Miscellaneous			
Residual CL_2	mg/L	<1	—	—	—
Total suspended solids	mg/L	<30	—	—	—
pH_c	1–14	>8.4	—	—	—
		Selected nutrients/elements			
N	mg/L	<10	<2.2	—	—
P	mg/L	<0.1	<0.66	—	—
K	mg/L	<20	<2.0	4.0	26
Ca	mg/L	<100	<400	67	64
Mg	mg/L	<40	<60	24	23
SO_4 (black layer potential)	mg/L	<90	<960	171	196
Fe	mg/L	<1.00	—	0.16	0.20
Mn	mg/L	<0.20	—	0.01	0.03

(continued)

TABLE 3.12
Summary of irrigation water quality guidelines (continued)

Water parameter	Units	Desired range	Usual range[a]	Average domestic[b]	Average reclaimed[b]
Cu	mg/L	<0.20	—	0.04	0.03
Zn	mg/L	<1.0	—	0.12	0.08
Na	mg/L	<120	<920	70	114
Cl	mg/L	<70	<1062	82	130

[a] From Ayers, R. S. and D. W. Westcot. 1994. Water Quality for Agriculture. FAO Irrigation and Drainage Paper, 29, Rev. 1. Reprinted 1994. Food and Agric. Organiz., Rome, Italy.

[b] From Stowell, L. J. and W. Gelernter. 2001. Negotiating reclaimed water contracts: Agronomic considerations. *Pace Insights*. 7(3): 1–4. PACE Consulting, San Diego, CA.

4 Field Monitoring

Irrigation water quality has a profound effect on soil fertility and chemical properties, especially when ultrapure or poor-quality irrigation water is used. Frequent monitoring of water quality, soil fertility/chemical conditions, and tissue nutrient status becomes an important tool for gaining the scientific information required to make informed science-based management decisions. Because irrigation water quality and soil chemical properties are so closely linked, we will discuss both aspects in this chapter. Monitoring allows the turf manager to make educated decisions and implement management programs before the vigor and sustainability of turfgrass, trees, and ornamentals decline or soil structure is negatively affected.

Soil chemistry and irrigation water chemistry are closely related, and both must be monitored because all elements and chemicals contained in the water will eventually end up in the soil (Stowell and Gelernter, 1998). Several approaches should be considered when monitoring existing or developing problems related to the use of poor-quality irrigation water and subsequent problems that develop within the soil. Options include visual observations; use of portable hand-held field monitoring equipment; mobile monitoring approaches; in-place sensors; and regularly scheduled comprehensive analysis of water, soil, and plant tissue samples by an accredited agricultural water/soil/tissue-testing laboratory. Historical records of the monitoring and testing results on a site-specific basis must also be maintained to document changes in soil and water chemistry over time as well as changes resulting from amendment and management programs.

For anyone investigating the potential for salinity monitoring, an excellent information source is the FAO Irrigation and Drainage Paper 57 by Rhoades et al. (1999) (this can be obtained online at ftp://ftp.fao.org/agl/aglw/docs/idp57.pdf), as well as the article by Corwin and Lesch (2003).

4.1 FIELD ASSESSMENT BY VISUAL OBSERVATION

Visual observation often provides the turfgrass manager their first indication of potential or developing problems. A few examples include the following:

- White crusting at the soil surface when dry conditions indicate either high total salts or high bicarbonates (Hanson et al., 1999). Plants in the immediate area will appear drought-stressed even when soil moisture appears adequate (Carrow and Duncan, 1998).
- Localized areas of weakened, stressed turf or ornamental plants showing signs of early total salinity, sodium, or other specific "toxic" ion damage. Bermudagrass and ornamental plants show patchy stunted growth, often with a deep green to bluish discoloration (Waddington et al., 1992; Carrow

and Duncan, 1998). *Poa annua* putting greens often show an oily, mottled deep green sheen, eventually turning yellow and brown, as stress becomes more severe. Other symptoms include a general decline in growth rate, tip or margin burn of leaves, or drought stress-like symptoms when soil moisture otherwise appears adequate. Turf density decreases, and often weed encroachment increases. Salt-tolerant halophytic invasive species may also begin to encroach into the damaged turf areas (USSL, 1954).

- Foliar damage at and below the irrigation spray zone on ornamental plants and trees indicates high total salts, chlorides, boron, copper, bicarbonates, or other specific ions in the irrigation water.
- "Natural selection" of either native or introduced halophytic species with increased salinity tolerance often indicates isolated or localized problem areas related to poor drainage, high soil salinity, or shallow, saline water tables (USSL, 1954).
- Large cracks in dry soil indicate an expansive (expanding/contracting clay) soil type that will be more prone to structural damage when irrigated with water having a high SAR. Soils crack 1–2 cm wide when dry and swell closed when wet (Chhabra, 1996).
- Sodic soils are very slippery and soft when wet, but very hard when dry.
- Sodic soil color may turn black on the surface when wet because of a high humic acid fraction involving organic matter that migrates to the soil surface and dissolves when combined with sodium carbonate at a high pH. Algae can often be found on the black residue due to the constantly wet conditions at the surface.
- Hard surface crusts that puddle following rain or irrigation and inhibit seedling emergence are signs of high exchangeable sodium and low organic matter content (Westcot and Ayers, 1985; Oster et al., 1992).
- Surface soil flaking (resembling potato chip–like structures) indicates a developing surface structural problem related to low-EC irrigation water and infiltration/percolation/drainage reduction (Westcot and Ayers, 1985; Oster et al., 1992).
- White "cemented" layers indicate high soil carbonates (and possibly bicarbonates in irrigation water) associated with calcareous and caliche soils with high insoluble lime content and alkaline soil pH.
- Aerial photographs taken annually can help to monitor stressed turfgrass and landscape flora by identifying "hot spots" and the resulting decline associated with soil salinity accumulation (Stowell and Gelertner, 1998).
- Visually examining irrigation water cannot reveal chemical quality problems such as total salts, sodium, or toxic ions. However, the presence of suspended solids ("fines") that do not dissolve and can only be removed by filtration often are visibly identifiable by placing a water sample in a clear container and allowing it to set undisturbed for 24–48 hours. Suspended materials that require some amount of time to settle include inorganic materials including sand, silt, clay, and organic matter such as plant material, algae, and spores.

4.2 IN-FIELD MONITORING WITH HAND-HELD DEVICES

Portable, hand-held equipment is available to allow on-site monitoring of salts and sodium in both soil and irrigation water. Cost and sophistication vary from pocket-sized electrical conductivity meters to analyze salinity that cost approximately $60 to portable laboratories for analyzing various salts and sodium in soil and water that cost approximately $2000. When salts alone are the primary problem, the inexpensive meter will suffice; when sodium is a serious issue, then the more expensive and more sophisticated portable laboratory kit may be worth consideration, especially as salinity levels increase.

In-field soil salinity (ECe) measurement. Measurements obtained with inexpensive, pocket-sized, electrical conductivity meters can be accurately correlated to laboratory-conducted saturated soil paste extract (SPE) conductivity readings with an appropriate conversion formula (Stowell and Davis, 1993; Vermeulen, 1997). These measurements can then be used to determine when leaching events are needed to reduce accumulation of soil salinity. One meter that has been used extensively by many golf course superintendents in the Southwestern United States is the TDSTestr-4 manufactured by Oakton Instruments (1-888-462-5866 or http://www.4oakton.com/index.asp, part number WD-35661-40). These meters are also available from various sources, including catalogs and local turfgrass equipment, fertilizer, and chemical suppliers. The protocol for measuring soil ECe with the TDSTestr-4 is as follows (Stowell and Davis, 1993):

- Collect a representative soil sample of about 50 cc (2 oz) in a small cup.
- Add irrigation water (note: be sure to include a representative sample of irrigation water from your site) while stirring until the soil surface glistens, creating a saturated paste. (If water can be poured off, then too much water has been added and you will need to start over with fresh, dry soil.)
- Insert the TDSTestr-4 into the saturated paste. The probes should be completely immersed in the soil.
- Read the meter and convert the reading to an extract ECe equivalent with the formula: saturated soil extract EC (dS/m) = 0.8 + 2.7 [TDSTestr-4 EC (mS/cm)] (see Table 4.1).

In-field irrigation water salinity (ECw) measurement. When the TDSTestr-4 is immersed in liquid (irrigation water or leachate drainage), the meter will deliver an accurate reading in dS/m directly without requiring conversion. Sampling irrigation water on a regular basis is recommended to monitor seasonal changes in salt content.

Leachate/drainage water salinity (ECw) measurement. Collecting and monitoring leachate from drain lines, particularly at putting greens, will facilitate monitoring the effectiveness of leaching programs. Collect a sample following the completion of the leaching process at a collection port or end of the drainage line where the "out-fall" is brought to daylight. The sample should preferably be collected as close to the green cavity as possible so that it will not be diluted by drainage lines sharing the same out-fall, such as surrounding sand bunkers or open drain basins.

TABLE 4.1
Conversion table for determining the saturated soil extract EC (extract EC) from the direct TDSTestr-4 saturated soil readings (All values are in dS/m = mS/cm = mmhos/cm)

TDSTestr-4	Extract EC	TDSTestr-4	Extract EC	TDSTestr-4	Extract EC
0.1	1.1	1.1	3.8	2.1	6.5
0.2	1.3	1.2	4.0	2.2	6.7
0.3	1.6	1.3	4.3	2.3	7.0
0.4	1.9	1.4	4.6	2.4	7.3
0.5	2.2	1.5	4.9	2.5	7.6
0.6	2.4	1.6	5.1	2.6	7.8
0.7	2.7	1.7	5.4	2.7	8.1
0.8	3.0	1.8	5.7	2.8	8.4
0.9	3.2	1.9	5.9	2.9	8.6
1.0	3.5	2.0	6.2	3.0	8.9

Source: From Stowell, L. J. and S. Davis. 1993. Direct Measurement of Electrical Conductivity (EC) in Golf Course High Sand Content Soils. *Phytopathology* 83: 693.

When dilution from multiple drain lines is a concern, a port specifically included for leachate collection can be installed in the main drain line just outside the green cavity with a "T" fitting and riser that extends to the turf surface. A cap, plug, irrigation control valve box, or drainage grate can be used to cover the collection port. A small plastic cup or container attached to a wire or wooden handle can be fabricated to collect leachate samples from the drain line for testing with the TDSTestr-4. Adequate leaching has been accomplished once the ECw of the drainage sample is reduced to near the ECw of the irrigation source.

In-field irrigation water test for suspended solids. Suspended solids are inorganic and organic materials (inorganic matter such as sand, silt, clay, etc., and organic matter such as plant material, algae, spores, etc.) that do not dissolve in water and can only be removed by filtration. If the irrigation water is murky and suspended solids are a suspected problem, a rain gauge can be used for a rough estimate of the amount of solids applied throughout a full season of irrigation.

Fill the rain gauge with irrigation water collected from the sprinklers or quick coupler and allow the solid matter to settle for 24 to 48 hours. Then measure the depth of the particles and calculate the total amount of irrigation applied annually on the basis of annual ET replacement and depth of solids contained in the rain gauge. Example: If the rain gauge holds 6 in. of water and 30 in. of irrigation are applied, simply multiply the amount of sediment in the rain gauge by 5 to estimate the total applied each year (Moore, 1994).

In-field sodicity testing of soil and irrigation water. A portable laboratory system capable of testing both salinity and sodicity of soil and water has been developed in a cooperative effort between the United States Salinity Laboratory (USSL) at Riverside, California, and the Hach Company of Loveland, Colorado (Rhoades et al., 1989, 1997). The Hach SIW Salinity Appraisal kit and optional Platinum Series sodium electrode use electrochemical technology to measure conductance of a measured volume of saturated paste. These measurements are converted using mathematical factors programmed into the Hach SoilSYS personal computer software program to calculate salinity, sodicity, and estimated calcium and magnesium content in the saturated extracts. The results allow estimation of soil amendment and leaching requirements for the collected samples.

The cost of this portable laboratory begins at approximately $2200, not including the optional Hach Platinum Series sodium electrode that is required to conduct sodicity testing. However, long-term savings may be found in the lower cost of each individual on-site soil or water test. Costs are estimated to be approximately $5 per soil sample tested. Additional information regarding the Hach Soil and Irrigation Water (SIW) Salinity Appraisal Laboratory and the corresponding USSL Research can be obtained by contacting: The Hach Company, P.O. Box 389, Loveland, Colorado 80539-4224 USA, telephone: 1-800-227-4224, Fax 1-970-669-2932, www.hach.com, and the USSL Web site at http://www.ussl.ars.usda.gov/hachkit.htm.

In-field "tin can" sodicity/permeability soil test. An inexpensive and simple test to determine if soils have become impermeable because of excess sodium has been developed by Agricultural Extension Soil and Water Specialists of the University of California (Branson and Fireman, 1980). Their recommended procedure is as follows:

- Collect a soil sample (approximately 1 qt or 1.10 L) from an impermeable area in the field.
- Thoroughly dry the sample and pulverize the soil until the largest-size particles are about the size of coffee grounds.
- Add 1 heaping teaspoon of powdered gypsum to 1 pint (0.55 L) of the pulverized soil and mix thoroughly. Leave an equal amount of untreated soil.
- Prepare two cans as shown in Figure 4.1. Any can 4 to 6 in. (10–15 cm) tall is satisfactory.
- Put the treated soil in one can and the untreated in a separate can. Fill each can about three quarters full. Pack the soil by dropping each can from a height of about 1 in. (2.5 cm) on to a hard surface a total of ten times.
- Fill each can with irrigation water, disturbing the soil as little as possible.
- Collect the water that drains through the soil. When you have collected ½ pint (0.24 L) or more of water from the gypsum-treated sample, compare it to the volume collected from the untreated sample. If less than half the volume of water has passed through the untreated sample compared to the gypsum-treated soil in the same time, this indicates that your soil contains excess exchangeable sodium. It is likely that your soil would benefit from the addition of a chemical amendment such as gypsum to improve permeability.

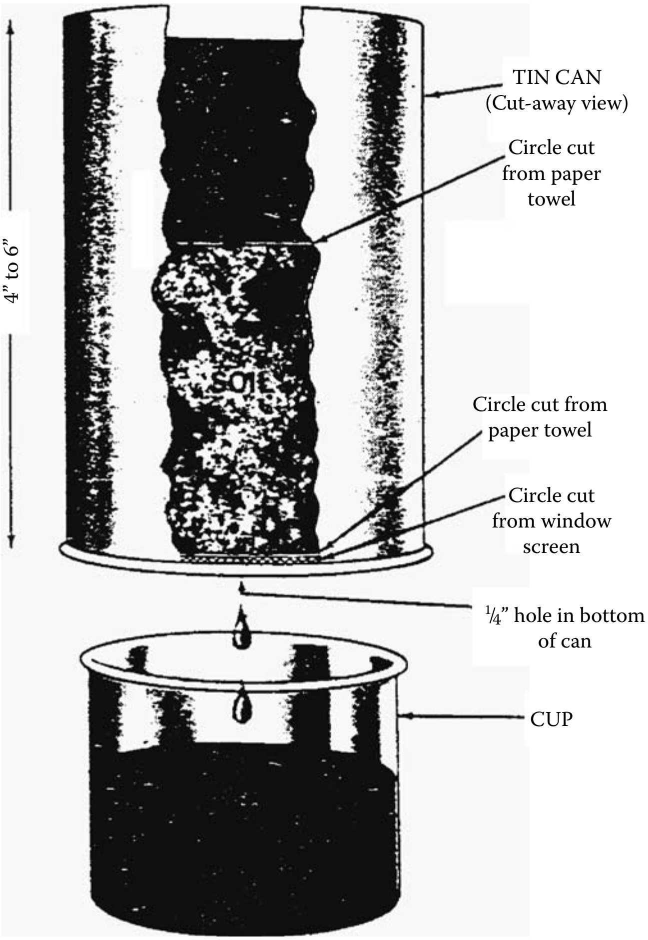


FIGURE 4.1 Tin can preparation for soil sodicity permeability test. (From Branson, R. L. and M. Fireman. 1980. Gypsum and Other Chemical Amendments for Soil Improvement. Cooperative Extension, University of California Leaflet #2149, Berkley, California.)

4.3 MOBILE FIELD MONITORING OF SALINITY

Soil salinity exhibits considerable **spatial variability** across the landscape because salts can accumulate at different levels depending on water application, water movement, and evapotranspiration (ET) patterns. For example, salts often accumulate in high, exposed sites, such as a hilltop, owing to high ET. In low areas, salts may accumulate due to runoff from the surrounds, and possibly from poor drainage or a high water table in the low area. Spatial variability also occurs by soil depth, where salts may accumulate at the surface under light, frequent irrigation; or they may accumulate within a zone deeper in the profile depending on the leaching depth. Seasonal variation in soil salinity levels is also typical in response to changes in irrigation regimes, natural precipitation, and sometimes variable irrigation water quality over a season.

To remove excess salts, a good irrigation program is required that applies sufficient water to leach the salts below the root zone (Carrow et al., 2000). However, knowledge of the actual soil salinity within the turfgrass root zone (especially around the crown region), just below the root system, and across the landscape is critical for development of effective leaching programs.

Rhoades (2005) and Rhoades et al. (1999) present an excellent discussion on in-place and mobile salinity sensing, particularly as related to agriculture. Mobile soil salinity monitoring is becoming much more of a effective tool for salt-affected sites so that turfgrass managers can make scientifically informed adjustments in irrigation scheduling, fertilization programs, and soil amendment applications (Carrow and Duncan, 2004). Use of sensor technology for monitoring soil salinity by soil depth and in a real-time mode is anticipated to become essential components of highly integrated irrigation systems of the future. Site-specific management of inputs is the foundation for the best management practices (BMPs) approach to turfgrass management, whether for fertilizers, pesticides, or water.

4.3.1 MOBILE FOUR-ELECTRODE SENSORS

Bulk soil electrical conductivity (ECa) can be measured by using a 4-electrode array (called 4-wenner array; Figure 4.2), which consists of four equally spaced electrodes,

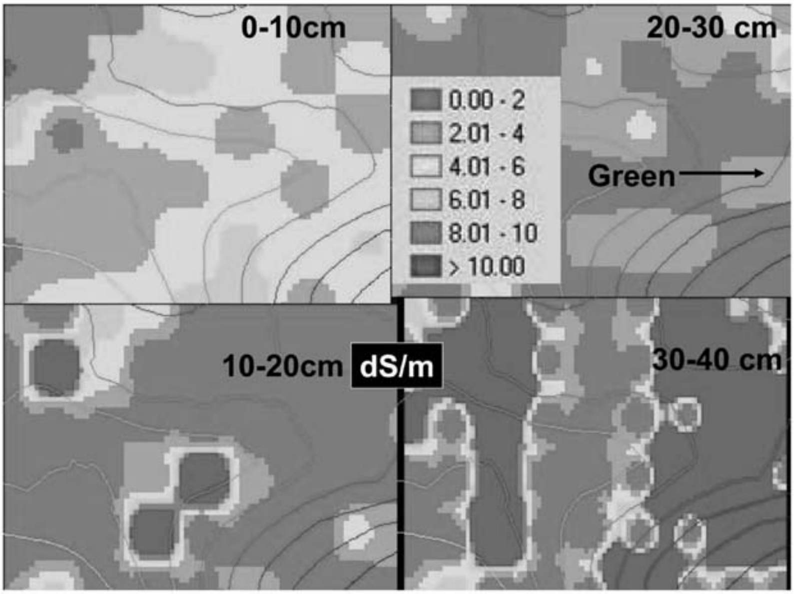


FIGURE 4.2 Salinity mapping by soil depth of a golf course fairway area (18.2 × 27.4 m; 60 × 90 ft) using the 4-wenner array approach at four soil depths (0–10 cm = 0–4 in.; 10–20 cm; 20–30 cm; 30–40 cm). The scale is in dS/m, where seawater is approximately 45 dS/m. (From Carrow, R. N. and R. R. Duncan. 2004. Soil salinity monitoring: Current and future. *Golf Course Manage.* 72(11): 89–92.)

a current generator, and a conductivity meter. When measurements are taken at field capacity, the ECa data can be converted to ECe basis with a calibration curve. Rhoades et al. (1999) provide instructions on how to make several versions of 4-electrode sensor probes, including in situ, hand-carried, and cart versions. One advantage of this approach is that salinity determination is averaged over a larger area, but still within the zone chosen rather than a small point within the soil. Commercial units are available, and all units appear to operate within the 0–20 dS/m range. However, evaluation under turfgrass situations is very limited. Units with potential include the following:

- Versis Technologies (www.versistech.com) has cart-mounted units that use coulters as the probes that monitor ECa at 0–1 ft (0–0.3048 m), 0–18 in. (0–45.72 cm), and 0–3 ft (0–0.9144 m) depths. The coulters cut into the soil surface. One unit can also monitor soil pH. Two problems with using these units on turfgrass applications are the following:
    1. The soil depths are not narrow enough for turfgrasses; 0–4 in. (0–10 cm) zones are much better for perennial turfgrass sites receiving poor-quality irrigation water that requires frequent monitoring.
    2. The coulters cut into the turfgrass sod.
- Landviser (www.landviser.com) has a hand-held mobile device (LandMapper ERM-01) that can determine ECa at various depths, depending on the probe configurations. The unit contains the power generator, meter, and probe arrays. In this case the small probes are only pushed into the surface 0.5 to 1.0 in. (1.25–2.5 cm) depth instead of using coulters. This device can be used to monitor soil salinity in field situations at different depths across landscapes (Rhodes et al., 1999). The authors have found that this method is very useful for monitoring salinity within 4 in. (10 cm) zones over time (Carrow and Duncan, 2004) (Table 4.2).
- Versis Technologies also has a cart-mounted “push probe” profiler where the 4-electrode array is on a sensor (0.63 in. or 15.75 mm diameter) that is pushed into the soil, and ECa as well as penetrometer readings can be determined every 1.25 cm (0.50 in.).
- Eijkelkamp (www.eijkelkamp.com) offers a hand-held mobile unit that uses a single sensor probe with four electrodes that can be pushed into the soil and will monitor at 6 in. (15 cm) zones.

4.3.2 Mobile Electromagnetic-Induction (EM) Sensors

EM units (www.geonics.com) have been widely used in general agriculture for field mapping of salinity (USSL, www.ussl.ars.usda.gov/index000.htm; Rhoades et al., 1999). EM is nonintrusive, and the device induces circular eddy-current loops, where the magnitude of the loops is directly proportional to the ECa of the soil within the region of the loops. An important disadvantage of this technology in turfgrass situations is the wide zone of measurements, where 12 in. (30 cm) is the narrowest zone. Because salinity is not normally uniformly distributed within the soil profile and

TABLE 4.2
Analytical results from two different laboratories for identical water samples

	Laboratory	
Constituent	**#1**	**#2**
pH	7.9	7.4
Conductivity	0.34 mmhos/cm	200 µmhos/cm
Calcium	41.6 ppm	33.6 ppm
Magnesium	5.4 ppm	6.4 ppm
Potassium	1.4 ppm	0.9 ppm
Sodium	25.8 ppm	36.0 ppm
Carbonate	0.2 meq/L	0.0 ppm
Bicarbonate	2.6 meq/L	183.0 ppm
Chloride	11 ppm	17.0 ppm
Sulfate	8.5 ppm	12.0 ppm

Source: Adapted from Petrie, S. E. 1998. How to Evaluate Water Sample Analyses. Solution Sheet, July. Unocal Agricultural Products, Brea, CA.

surface salinity conditions are important for turfgrasses, the EM approach is less useful compared to direct salinity monitoring by electrical conductivity. EM devices are hand-held or can be integrated into a mobile system (Rhoades et al., 1999).

4.4 IN SITU MONITORING AND SENSORS

Approaches to soil salinity determination for in-place installation may offer potential for turfgrass situations, but will require adequate evaluation. Installation sites should be key indicator spots that first exhibit salinity stress. In-place monitoring could aid in (1) indicating the initial onset of salinity stress due to salt accumulation or by capillary rise from below the root zone, and (2) determination of the appropriate leaching fraction and irrigation practices to best leach salts with minimal applied water.

Sentek's TriSCAN (www.Sentek.com.au) is a combination soil moisture and salinity sensor that has recently become available for in situ salinity monitoring and could be integrated into an irrigation control system. Sentek's technology is based on high-frequency electrical capacitance and can determine salinity and moisture within 4 in. (10 cm) zones in real time. The current version is for more sandy soils. Research is being conducted on Old Colliers Golf Course in Naples, Florida, using this unit.

Turf Guard from JHL Laboratory (www.turfguard.net) is a wireless sensor system that monitors volumetric soil moisture, soil conductivity, and soil temperature at two depths (approximately 5 in. or 12.5 cm apart) per sensor unit. Sensor information is sent on 5-minute intervals to the central controller that plots current readings, trends, and historical data graphically. Up to 500 wireless sensors can be supported on the system, and they can be relocated at any time by the golf course staff at the direction of the superintendent. The system is currently being evaluated at several Southern California golf courses.

Soil solution extractors (called imbibition-type sensors) and porous-matrix salinity sensors have both been available for a number of years for in situ use (Rhoades et al., 1999; Corwin and Lesch, 2003). Both devices require a much longer lag time before salinity changes are observed owing to their dependence on diffusion of ions. Also, these sensors have small sample volumes that often do not adequately represent spatial variability.

Others possibilities for in-place sensors include installation of small 4-wenner array sensors for real-time data, but the authors do not know of any commercial units. The ECH_2O-TE probes (www.decagon.com) are based on the 4-wenner array method and are suitable for in situ placement with a probe sensing length of 2.1 in. (5.3 cm). Also, time-domain reflectometry (TDR) is widely used for soil moisture measurements and can measure ECa. However, Corwin and Lesch (2003) report that "it is still not sufficiently simple, robust, or fast enough for general needs of field-scale assessment of soil salinity" for mobile or in-place use. Recently, the Stevens Water Hydra Probe II (http://www.stevenswater.com) and Turfguard (www.turfguard.net) sensor units have been marketed; both are based on TDR technology, but with modifications to allow for salinity determinations. Both units are limited to probe sensing lengths of about 2.2 in. (6.4 mm). Other salinity sensors are and will come onto the market, but should be carefully evaluated for turfgrass use, just as the ones noted previously should.

4.5 WATER SAMPLES AND TESTING IN THE LABORATORY

4.5.1 PROCEDURES AND FREQUENCY

Sampling procedures and frequency will vary depending on the quality of the water source, whether it is a well, stream, reservoir, or effluent. Irrigation wells under normal conditions present no particular problem unless the water is coming from saline strata or the location is near coastal areas. When natural replenishment of the aquifer equals water withdrawal, there will be very little change over time with regard to chemical constituents. However, when withdrawal of a water table exceeds replenishment, the chemical composition of the water can change and it is not possible to predict whether it will result in a deterioration or improvement of quality (Hagan et al., 1967). Consequently, at least annual water analysis should be conducted on the irrigation source to monitor any changes, and especially any deterioration in quality.

Sampling surface streams (such as canals) and rivers is more difficult because quality can change depending on the rate of flow/runoff, and whenever possible, sampling should be conducted at a gauging station. The frequency and timing of sampling can then be developed after studying the surface streams' flow characteristics. Controlled streams that are fed by reservoir discharge usually are more consistent in chemical composition (Hagan et al., 1967).

Sampling of large, deep reservoirs can be a complex process because the water may not be thoroughly mixed. It is not unusual for stratified layers of variable quality to exist under these conditions, and occasionally with rapid temperature changes (especially colder air temperatures); the lake or reservoir can "turn over," resulting in rapid fish kill because hydrogen sulfide or other low-oxygen zones are forced rapidly to the surface. In this case, it would be necessary to collect samples from various locations and depths, especially in the vicinity of the intake. Water in small reservoirs is usually more homogenous, and samples from the outlet or well intake position will normally be representative.

Effluent or reclaimed water supplies can vary seasonally, daily, or even hourly, depending on the individual situation. Reclamation plants processing large amounts of commercial and industrial wastes are more likely to show greater variations in water quality than plants processing primarily residential waste. Other areas will vary seasonally with influx/outflux of tourists in warmer climates during winter months or where sunshine prevails for increased golf play during winter months. Discussing the local sources of influent flows and seasonal effluent quality variations with the treatment plant operators can be beneficial in developing an effluent testing and monitoring program.

The frequency with which irrigation water should be sampled will depend on the origin of the water source, soil conditions, annual irrigation requirements, and local climatic conditions that affect seasonal variations in water quality. The minimum frequency for testing irrigation water should be once per year, prior to the beginning of the irrigation season, and whenever a problem is suspected. If a problem is identified, sampling every 1–2 months or more often may be necessary to accurately monitor the problem.

Effluent water sources may justify more frequent testing owing to the seasonal variability of water quality. Seasonal population shifts that occur in winter golf resorts ultimately affect the effluent quality. Equally, in agricultural or industrial regions, seasonal changes in manufacturing or food-processing demands may also change the quality of effluent supplies. Arid regions where various potable sources are imported and blended may find water quality changes as a particular source becomes more dominant in the blend. As an example, various locations in Southern California blend groundwater of varying salinity with higher-salinity Colorado River water or lower-salinity California Aqueduct water, depending on the availability of each source throughout the season. Snow accumulation in the Rocky Mountains that feeds the Colorado River will vary annually and impact not only the quantity of the water, but also the level of salinity in that water source. As municipalities fight over their particular allocation of water in the Colorado River, downstream constituents are faced with reduction in supply as well as escalated salinity levels. This example is one of countless numbers being orchestrated around the world daily and will only get worse as demands for potable water use increase. Recreational turf will continue to be relegated to alternative water resources for irrigation purposes.

Changes in groundwater quality are more dependent on withdrawal and recharge patterns tied to weather patterns (ET, drought, rainfall, and snowmelt). The greatest changes in groundwater quality will most likely occur in abnormally wet or dry seasons (prolonged extremes in environmental conditions on a local or regional basis), and sample collection should be based on the entire annual irrigation season taking into consideration recharge and withdrawal patterns. Coastal groundwater basins are also subject to increasing saltwater intrusion when withdrawal exceeds recharge rates. Saltwater intrusion becomes a more serious problem during prolonged drought. Geohydrologic assessments of recreational sites will become more and more important in these scenarios.

Surface water quality will be dependent on flow rates and the type of soils, minerals, and rock impacted in the course of surface and subterranean runoff. Rapid snowmelt or heavy rains upstream may affect water quality by increasing erosion and sediment loading in the water. Rivers and streams that lead into saltwater bodies fluctuate in quality depending on tidal currents pushing back upstream, especially during low outflow. Occasionally, a storage lake may be fed by urban runoff from streets, concrete or asphalt parking lots, and topography changes that funnel water to these lower areas for harvesting of this valuable alternative water resource. If located in a northern climate where road deicers are frequently used, total salts (magnesium and sodium, depending on the deicing salt used) can accumulate and concentrate to problematic levels in the water source that will eventually be applied to recreational turf and the soil profile underneath.

Potable irrigation sources are not immune to variations in quality, because they are often a combination or blend of surface and groundwater sources. Where two sources are blended, the quantity and quality of each source will determine the end quality of the potable source. Changes in potable water quality can occur throughout an irrigation season when the proportion of individual components/sources change. Therefore, understanding the origin of municipal water supplies and what circumstances may affect a change of quality is advantageous for long term turfgrass and salinity management.

Soil and climate conditions must also be taken into consideration when developing a water-monitoring program. If a site has expansive clays that are more sensitive to structural breakdown from sodium (expansion and contraction of the clays with drying and wetting cycles, which exposes the exchange sites to excess sodium buildup and eventual deflocculation or breakdown), more frequent testing may be justified. Climate as it relates to precipitation and irrigation requirements must also be considered. High evapotranspiration demand and low rainfall in arid regions are reasons to monitor water quality more closely because the consistent addition of poor-quality water to a soil can lead to negative turfgrass performance and loading of various salinity components that are difficult and expensive to reclaim.

4.5.2 SAMPLE COLLECTION

The water collected must be representative of the irrigation water applied. Poorly collected or contaminated samples result in misleading information. Because only a few ounces of a sample will represent millions of gallons eventually applied to a golf course, collecting a good sample is extremely important. There are no strict rules for sampling water. Equal attention should be given to the (1) sampling equipment, (2) timing, (3) location, and (4) handling the sample. Some laboratories will provide instructions on what type of containers (especially for recycled water) to use and the amount of water needed for analysis. Select a reputable laboratory, and if you are satisfied with their procedures and turnaround time, continue with that laboratory and build a historical data bank with them.

If no instructions are provided, use clean plastic bottles rather than glass because glass may become a source of boron (Harivandi, 1999). Plastic bottles also reduce the chance of breakage during transfer. Always use a clean bottle and wash (triple rinse) the bottle with the water that will be sampled prior to filling. Fill the container completely and seal. Avoid using soft drink, milk, or chemical containers, as residues are likely to remain in them. Label each bottle using permanent ink pens recording the date, time, and location of sampling. If it is not possible to submit samples to the laboratory the same day as they are collected, refrigerate or freeze them to reduce changes in EC and concentrations of Ca and HCO_3 due to lime precipitation (Oster et al., 1992).

To ensure the water represents the water used for irrigation on the property, either collect the water from (1) the sprinklers directly or (2) a quick coupling valve on the irrigation system. Collect the water at the end of a normal irrigation cycle after the pumps have been running for some time. Collect well water only after pumping for a minimum of 30 minutes; this should allow sufficient time for the well to flush and establish a representative water evaluation that exists during most of the pumping period (Oster et al., 1992). On golf courses, sample a sprinkler on the front nine holes and again on the back nine holes; then compare to a sample collected from your irrigation lake or water source.

4.5.3 Water Test Data to Request from Laboratory

Agricultural soil/water laboratories will offer a menu of available tests. This allows the customer to specify testing the sample's content of individual elements or a broad range of chemical constituents and properties. When working with salt-affected soils and poor water quality, the most comprehensive battery of tests should be conducted annually. The most important chemical constituents and their normal ranges found in water that need to be reported to determine irrigation suitability can be found in Chapter 3, Table 3.11.

4.5.4 Assessing Laboratory Water Test Results Accuracy

Two simple evaluations can be performed to verify the accuracy of a laboratory water analysis data (Petrie, 1998). These two tests are only valid for water sample analysis. There are no comparable methods for evaluating soil or plant tissue analysis. The first method is based on the fact that the overall electrical charge of a water sample must be approximately neutral; in other words, the total of the positively charged cations must approximately equal the negatively charged anions. It is unlikely that the cations will exactly equal the anions, and when their totals are exactly equal, it is usually because the laboratory measured the concentration of all the ions except the one that was estimated by the difference. If this is the case, the following technique will not work, and you may want to consider having your samples analyzed by another laboratory that actually measures all the constituents. Constituents reported in parts per million (ppm), milligrams per kilogram (mg/kg), or milligrams per liter (mg/L) must be converted to milliequivalents per liter (meq/L) (see Chapter 3, Table 3.2). Once converted to meq/L, the sum of the cations should be close to the sum of the anions.

The second test to determine the accuracy of the analysis is comparing the electrical conductivity of the sample expressed in dS/m (or mmhos/cm) to the sum of either the cations or anions. The conductivity should be approximately 1/10th the cation or anion concentration.

Table 4.2 represents the results reported by two different analytical laboratories for identical water samples simultaneously collected from the same well. Note the difference in reported units and individual values. These differences could have an impact on how the irrigation water should be managed or what type of treatment may potentially be selected.

Table 4.3 shows the reported results when converted to the same units of measurement. Using the first evaluation technique above, the total cations comes close to roughly equaling the total anions with laboratory #1 (3.3 versus 3.7). However, laboratory #2 shows a large difference between results (6.9 versus. 3.8). On the basis of these results, laboratory #1 appears to produce more accurate results than laboratory #2.

Using the second evaluation method, again the results of laboratory #1 are more accurate. Laboratory #1 results were close to the electrical conductivity, measured in mmhos/cm, equaling 1/10th the concentration of either the cations or anions.

TABLE 4.3
Evaluation of analytical results from two different laboratories for identical water samples to determine data accuracy

	Laboratory	
Constituent	**#1**	**#2**
pH	7.9	7.4
Conductivity	0.34 mmhos/cm	0.20 mmhos/cm
Calcium	2.1 meq/L	1.7 meq/L
Magnesium	0.45 meq/L	0.5 meq/L
Potassium	0.03 meq/L	0.02 meq/L
Sodium	1.1 meq/L	1.6 meq/L
Sum	3.7 meq/L	3.8 meq/L
Carbonate	0.2 meq/L	0.0 meq/L
Bicarbonate	2.6 meq/L	6.1 meq/L
Chloride	0.3 meq/L	0.5 meq/L
Sulfate	0.2 meq/L	0.3 meq/L
Sum	3.3 meq/L	6.9 meq/L

Source: Adapted from Petrie, S. E. 1998. How to Evaluate Water Sample Analyses. Solution Sheet, July. Unocal Agricultural Products, Brea, CA.

(ECw 0.34 mmhos/cm compared to cations totaling 3.7 meq/L or anions 3.3 meq/L). The results of laboratory #2 are quite different and open to question. (ECw 0.20 mmhos/cm compared to cations totaling 3.8 meq/L or anions 6.9 meq/L).

It is worth noting that both laboratories measured all the constituents, and neither laboratory estimated the concentration by calculating the difference. If the sum of the cations and anions had been exactly the same from either laboratory, the use of the sum of cations compared to anions to evaluate the results would become useless. Then the results could only be checked for accuracy using the relationship between the conductivity and concentration of either cations or anions.

If the laboratory analysis you receive contains an inconsistency similar to those noted in our example, then be sure to request a reanalysis of your sample. All laboratories make mistakes from time to time; however, if the results are consistently incorrect, then consider using another laboratory.

4.6 LABORATORY TESTING FROM SOIL SAMPLES

Laboratory soil samples should be collected annually at a minimum, and preferably quarterly, if local conditions and budgets warrant the expenditure. Avoid the temptation to change laboratories or compare results from different laboratories as different testing protocols and procedures will result in subtle differences of reported data, skewing historical results.

4.6.1 SOIL SAMPLE COLLECTION

The proper method of collecting and handling soil samples is determined by (1) the use to be made of the analyses, (2) the pattern and ease of recognition of the soil or crop variability seen in the field, and (3) previous known and proposed management practices. The results of soil testing will identify developing salt and sodium problems as related to the irrigation water quality, the current magnitude of existing soil problems, and a base of information usable to develop a comprehensive soil and water management plan (Carrow and Duncan, 1998). When a change of irrigation water source is planned, such as from potable to effluent, soil samples should be gathered from several greens, tees, fairways, and roughs well in advance of the conversion to track future changes in soil chemistry.

Soil conditions (drainage, texture, salinity, sodicity, etc.) can vary both across the surface (horizontally) and through the profile (vertically) across a property as well as over time (temporal changes). It is important that this variability be recognized, and if practical, measured in the sampling process because an average of results from highly variable areas may be of little use. An attempt should be made to identify similar soil conditions and sample them as a manageable unit. These units may be identified on the basis of appearance of the turf, soil surface, management history, texture, drainage, erosion, stress symptoms, etc. Aerial photography is one potential method of selecting sampling areas and identifying poorly performing turfgrass and flourishing turfgrass areas (Stowell and Gelernter, 1999). A composite sample of 10 to 20 subsamples can then be collected from each identified manageable unit. Areas with poor or abnormal growth can be sampled individually and compared with other areas of normal growth to diagnose localized problems.

The depth that samples are taken from will depend on the turfgrass species (i.e., rooting depth) and any other additional information that may already be known about the soil profile. Sample to the rooting depth to evaluate soluble salt levels and leachable nutrients and collect the soil in layers, preferably at 0–2 in. (0–5 cm) and 2–6 in. (5–15 cm) bulked samples to monitor salt flux across different zones in the soil. Taking one composite sample from 0–6 in. (0–15 cm) will provide only an average of the salt load in the sample and normally not be indicative of potential lethal salt concentrations near the turfgrass crown region (0–5 cm zone). Deeper subsurface samples may be of value to diagnose chemical and physical characteristics of subsoil layers and may explain unusual growth characteristics or internal drainage problems, especially if capillary rise of salts is suspected. Additionally, separate shallow and surface samples should be taken where sodium or salinity problems are suspected. Shallow samples (0–2 in. or 0–5 cm) can identify soil crusting problems and potential problems associated with germinating seed or rooting of vegetative propagules. Sampling stockpiles of sand, greens sand mixes, or gravel involves collecting approximately eight samples that are then composited, with half of the samples collected from the lower third of the stockpile and half from the top sections. Approximately 6 in. (15 cm) of the outer section should be removed and the sample collected inward from that point to minimize settling or rainfall/wind erosion problems that can lead to nonrepresentative samples in stockpiles.

The frequency of soil sampling will depend on the severity of problems and length of the growing season. Southern U.S. golf courses operating on a 12-month playing season and growing two turf crops (a warm season species and an overseeded cool season species) may find it necessary to conduct more frequent soil testing. This need may vary each season depending on annual changes in irrigation requirements, annual rainfall, soil and water quality, and grass species transitioning challenges. At a minimum, soil samples should be collected biannually.

The timing of sample collection should be based on climatic conditions, and soil and water quality. If a location has a predictable rainy season, samples collected after rains have subsided can determine (1) the amount of leaching that naturally occurred, and (2) how much leaching via the irrigation system will be required during the following dry season. If a prolonged drought is under way, or the site is located in an arid climate, sampling frequently throughout the growing season with a portable salinity meter to monitor salt flux to the surface and upper root zone accumulation is a beneficial strategy to monitor changing conditions. Annual soil tests for sodium accumulation should be performed prior to soil amendment (gypsum or other calcium products) application to determine both the need and rate. Applications made prior to the spring are generally most effective because warmer soil temperatures and more frequent irrigation applications will increase amendment breakdown activity and their subsequent nutrient availability.

Soil sample collection procedures should be based on the instructions of the individual laboratory selected for analysis. Accurate records of the areas sampled, fertilizers and amendments used, and general notes documenting turf performance in each area sampled should be kept for future reference. GPS mapping is an effective technique for monitoring "hot" spots on the site from one year to the next.

4.6.2 Laboratory Analysis of Soil Samples

Soil chemical and fertility status are greatly affected by irrigation water quality, especially with saline waters and many reclaimed sources. Soil testing can be used to determine current status of the soil with respect to salinity, sodium permeability hazard/status, specific ion content problems, and general fertility status. It is beyond the scope of this book to discuss in detail soil testing, but this topic is covered in detail by Carrow and Duncan (1998, 2000, 2004) and Carrow et al. (2002, 2003, 2004a,b).

Occasional laboratory soil tests should be conducted to monitor the progress of long-term salt/sodium management programs. Analytical procedures can vary slightly between laboratories, and the same laboratory should be used to accurately correlate results from one year to the next. Additionally, there are regional variations in test methods. In broad terms, two general methods are used to prepare soil samples for analysis that are related to salinity/sodic status: (1) the soil water suspension and (2) the saturated paste method (Carrow et al., 2003).

The soil water dilute suspension method is primarily used for nutrient testing. Equal parts of soil and water are measured by weight, mixed together, and nutrient extraction agents are added. The dilute suspension (commonly performed and reported as a 1:1 ratio and occasionally a 1:2 ratio in the United States; 1:5 ratios are used in Australia) is then analyzed. This technique is most commonly used when testing soil nutrient levels that are water soluble. Occasionally, salt and sodium levels will be reported using this method by laboratories outside the United States and in the temperate climate zones of the Eastern United States. The reliability of using water-soluble soil nutrient levels for making soil fertility or amendment recommendations is not scientifically sound, especially when compared to traditional chemical extractant methods (Carrow et al., 2004a,b). Levels of water-extractable Ca, Mg, and Na from dilute suspensions should not be used to determine soil SAR, because the SAR by definition is based on saturated paste extractable (SPE) levels of these elements (SARe). Also, soil EC determined by these methods will differ from saturated paste extract soil EC (i.e., ECe) values. When conductivity is measured from 1:1, 1:2, or 1:5 soil water suspensions, a multiplication factor as reported in Table 4.4 must be used to estimate an equivalent saturated soil paste value (Carrow and Duncan, 1998; Miller and Donahue, 1995; Westerman, 1990). Because the correct multiplication factor must be chosen (which is based on knowledge of soil texture), error can arise from the incorrect factor, as well as other errors (Carrow et al., 2003).

In the arid regions of the Western United States, the **saturated paste extract method** is most often used to analyze salt- and sodium-affected soils (Rhoades et al., 1989). The saturated paste soil test method is the preferred and more accurate analysis technique when working with saline and sodic soils. Soil reclamation and management formulas for calculating gypsum requirements, leaching requirements, as well as sodium and salinity hazard interpretation tables have been developed on the basis of saturated soil paste extract data. Additionally, most published plant salinity

TABLE 4.4
Estimation of saturated soil paste values (ECe) from measured values of 1:1, 1:2, or 1:5 soil water suspensions based on soil texture

	Soil water suspension multiplication factor		
Soil texture	**1:1**	**1:2**	**1:5**
Sand, loamy sand	3.5–4	6–8	25
Sandy loam, fine sandy loam, light sandy clay loam	—	—	20
Loam, fine sandy loam, silt loam, sandy clay loam	2.5–3	5–6	15
Clay loam texture, silty clay loam, fine sandy clay loam	2–2.5	4–5	12.5
Sandy clay, silty clay, light clay	—	—	10
Light medium clay	—	—	9
Medium clay	—	—	7.5
Heavy clay	—	—	6
Greenhouse growth media	—	3–3.5	5.5–6

Source: Adapted from Miller, R. W. and R. L. Donahue. 1995. *Soils in Our Environment*, 7th edition. Prentice–Hall, Englewood Cliffs, NJ; Carrow & Duncan, 1998; 2002; Westerman, R. L. 1990. *Soil Testing and Plant Analysis*—SSSA Book Series No. 3, Soil Science Society of America, Madison, WI.

tolerance data have been developed on the basis of the ECe (electrical conductivity) of the saturated soil paste extract.

As opposed to measuring out proportional parts of soil and water that is analyzed in the soil suspension method, irrigation water is mixed with a spatula into a specific measure of soil in the saturated paste method. The actual amount of soil varies depending on the specific test being conducted (USSL, 1954). Water is added to the soil and mixed until the soil is just saturated, reflects light, and the paste flows just slightly when the container is tipped. The liquid extract is then removed via a paper filter and vacuum pump after an equilibration period. This technique requires judgment on the part of the technician in determining when the proper level of saturation has been reached, but it is very repeatable. The complete method with specific instructions for various soil types is published by the United States Salinity Laboratory (USSL) in Agriculture Handbook No. 60, *Diagnosis and Improvement of Saline and Alkali Soils* (USSL, 1954).

The authors strongly suggest that the saturated paste extract procedure be used for determining ECe (assessing total soil salinity) and soil SAR (assess sodium permeability hazard), but not be used to make nutrient recommendations. It should be noted that in routine soil tests, the percentage Na saturation of the soil CEC sites provides a good estimate of the sodium permeability hazard/SAR (Carrow and Duncan, 1998).

4.7 HISTORICAL SOIL AND WATER QUALITY RECORDS

Maintaining records of visual observations, including photographs where practical, along with soil and water test data (both in-field and laboratory results), are critical to identifying immediate and long-term trends and evolving problems such as increasing B, Na (ESP or SARe in soil), Cl, ECe, TDS, or other limitations that would affect turfgrass performance. In cases where the irrigation water source has changed, noticeable changes in the soil chemistry may take 3 to 5 years to significantly change, depending on site-specific soil conditions, water quality, and annual amounts of natural rainfall.

Changes in water quality or soil chemistry can best be verified by historical records, preferably collected over time from the same analytical laboratory. Photographs of visual observations and historical records will help identify specific problems so that corrective actions such as leaching and amendment programs can be developed and implemented. Photographs and records can also be used to verify the improvements in soil conditions and plant health resulting from the reclamation or maintenance programs implemented by the turfgrass manager. Management of the salts is the key to developing a successful program to deal with reductions in water quality.

If a turfgrass site is to change irrigation water sources or treatment methods, it is sound practice to obtain water quality parameters and determine baseline soil and water quality status before making any changes. For example, if a new irrigation water source is used and a problem arises, the baseline information is very useful in determining whether the new irrigation water source was a contributor to the problem. Any radical shifts in water quality, especially any significant increases in salinity, can result in a rapid turf response in the form of yellowing and bleaching coupled with reduced growth rate (slow ball mark recovery in greens, slow divot recovery in tees and landing zones in the fairways, and increased wear susceptibility). If a shift in irrigation water quality use can be anticipated, the turf fertility program must be close to optimum and the transition from a better water quality to a poor water quality should be done gradually if at all possible. Otherwise, the turf will undergo a “multiple salinity transitioning shock,” the extent of which usually will be determined by total salt load plus specific Na, chloride, sulfate, calcium, and magnesium concentrations in the poorer-quality water. This transitioning shock can occur in both salt-tolerant and nontolerant turf species, but speed of recovery will usually parallel the level of salinity tolerance in the specific turf cultivar, with tolerant species recovering faster.

Part 2

Irrigation Water Quality Situations and Management

> Water is the most basic of all resources. Civilizations grew or withered depending on its availability.
>
> **Dr. Nathan W. Snyder, Ralph M. Parsons Engineering**

5 UltraPure/ Low-Electrolyte/ Low-Salinity Irrigation Water

5.1 INTRODUCTION

Ultrapure irrigation water (also referred to as **low-electrolyte** or **low-salinity water**) is extremely low in dissolved salt content. The United States Salinity Laboratory at Riverside, California, discovered in 1947 that water with extremely low salinity could cause reduced infiltration rates independent of the soil sodium content as measured by sodium adsorption ratio (SAR) (Christiansen, 1947). Other potential problems when irrigating with ultrapure water have since been identified such as corrosion of concrete and metal irrigation system components, rapid fluctuation of pH, and plant nutritional deficiencies. Additionally, salts added during the treatment of wastewater sources that originally were of ultrapure quality prior to reclamation can result in either deterioration or improvement of the water quality, depending on the types and quantities of salts and chemicals used in the treatment process.

Specific water treatment, nutrient, and soil management programs may, therefore, need to be developed to manage turfgrass sites successfully when irrigating with ultrapure irrigation sources. The management programs should be site specific, based on the results of a chemical irrigation suitability analysis that reports the amounts and types of salts contained within the water.

5.2 ULTRAPURE/LOW-SALINITY IRRIGATION WATER SOURCES

Rainwater, especially high-volume sources such as those generated by tropical storms/cyclones/hurricanes, monsoonal weather patterns, and snowmelt are the most common sources of ultrapure water and typically will have the lowest salt content of all irrigation sources. Generally, only a small amount of dissolved gases and salts originating from marine and terrestrial sources will be found in rain or snow, and the total amount will vary depending on the distance from the sea, proximity to air pollution (usually factories, ozone emissions, and vehicle exhausts) and areas of aeolic deflation (wind erosion) (Chhabra, 1996).

Surface water sources may also be low in salinity, depending on the types of rocks and soils present in the waterway as well as the total distance of flow before being captured for irrigation. Similarly, the dissolved salt content of a groundwater source can vary depending on the original source of water, the course and topography over which it flows, and whether or not it contacts salt-bearing strata during the recharge process. Ultrapure groundwater sources, within or at the base of mountain ranges where significant snowmelt or rainfall runoff normally occurs, are commonly found even in the arid western states and Hawaii.

5.3 IDENTIFYING ULTRAPURE/LOW-SALINITY IRRIGATION WATER

Identification of water purity in terms of salt concentration is based solely on water electrical conductivity, ECw. Published literature does not provide an exact salt concentration level (or actually, the lack of salt) where water infiltration is significantly reduced in soils. Generally, when ECw is equal to or below 0.50 dS/m (approximately 320 ppm TDS), slight to moderate infiltration problems can develop. As ECw drops below 0.20 dS/m (approximately 120 ppm TDS), problems can become severe (Oster and Schroer, 1979; Ayers and Westcot, 1994; Carrow et al., 1999).

5.4 PROBLEMS ASSOCIATED WITH LOW-SALINE IRRIGATION WATER

5.4.1 Fluctuation of pH

The pH of ultrapure water sources may rapidly fluctuate owing to their low buffering capacity due to low bicarbonate and carbonate concentration. Also, the pH of ultrapure groundwater sources in the western states is known to rise after pumping into an open reservoir. Groundwater exiting the well head often is one half to one full pH point lower that the same source after it has been stored for a short time in an open lake or reservoir. Occasionally, a change of as much as two full pH points may be witnessed. This is due to the evaporation of carbonic acid from the water; a somewhat similar phenomenon happens when opening a carbonated soft drink.

5.4.2 Infiltration and Percolation

Ayers and Westcot (1994) noted that "low-salinity water (<0.50 dS/m and especially <0.20 dS/m) is corrosive and tends to leach surface soils of soluble minerals and salts, especially calcium, reducing their strong stabilizing influence on soil aggregates and soil structure. Without salts and without calcium, the soil disperses and the dispersed, finer soil particles fill many of the smaller pore spaces, sealing the surface and greatly reducing the rate at which water infiltrates the soil surface. Soil crusting and crop emergence problems often result, in addition to a reduction in the amount of water that will enter the soil in a given amount of time and which may ultimately cause water stress between irrigations."

Once the minerals in the surface few centimeters have been leached from the soil particles, the colloidal particles' affinity for imbibing water increases, resulting in swelling and reduced stability of soil aggregates, which is followed by dispersion of the soil particles regardless of SAR (Hanson et al., 1999). A rule of thumb for California agricultural regions is that a minimum of 20 ppm calcium should be contained in an irrigation source regardless of ECw to avoid infiltration problems (California Fertilizer Association, 1985; Burt et al., 1998).

However, this infiltration problem is not universal. The varying infiltration rates of soils irrigated with ultrapure water are not completely understood, and additional research on this topic is needed. Severe infiltration problems that have been documented with ultrapure irrigation water sources on the eastern side of California's San Joaquin and Sacramento valleys are not always noted in other parts of the United States. Differing responses with regard to infiltration rates may be related to variations of soil parent material, organic content, cultivation practices, and environmental extremes. As an example, Burt et al. (1998) reported that high levels of mica in sandy loam soils cause these soils to be extremely sensitive to water permeability problems, and hence, they may react more adversely to irrigation with an ultrapure water source. In semiarid and arid regions, low organic matter content in soils is common, and these soils may be more susceptible to structural deterioration by low-saline waters (Grattan and Oster, 2003). Kaolinitic soils with low CEC and containing micas have been reported to be susceptible to surface sealing from rainfall (Chiang et al., 1993). In contrast, groundwater irrigation water applied to golf courses in the coastal areas of the Florida Panhandle, Alabama, Mississippi, and Louisiana often exhibit ECw values of less than 0.35 dS/m because of a combination of high, frequent rainfall and sandy soils with very low CEC, silt, or clay minerals. In these highly sandy soils with few fines to disperse and plug soil pores, water infiltration does not seem to be adversely affected as in the case of soils with somewhat higher clay and silt content.

When soil types have infiltration problems, the long-term visible and physical effects of irrigating with ultrapure water include surface crusting of bare soils, ponding of water after irrigation or rainfall, and saturated surface soils in conjunction with extremely dry soil 3 to 6 in. (75 to 150 mm) below the surface. The latter is a typical symptom found under complete turfgrass cover.

The sensitivity of bare soil to soil dispersion effects from ultrapure water are compounded by sprinkler irrigation droplet impact. Surface soil particles and aggregates disperse into smaller-sized soil particles and migrate into pore spaces, sealing the surface and reducing infiltration rates (Chiang et al., 1993; Grattan and Oster, 2003). The surface of bare soil will subsequently form a structural crust and interfere with seedling emergence or stolon pegging. These structural crusts may be less than 0.1 in. (2.5 mm) thick, and consist of sorted layers of clay that plug air porosity spaces between larger sand and silt particles, forming in as little as 90 minutes following irrigation. Additionally, once the surface is completely sealed, the reduced amount of water entering the soil in a given time frame may result in turfgrass water stress symptoms between irrigation applications (Ayers and Westcot, 1994).

On some sites, irrigation water that is high in total soluble salts and Na is used for substantial periods of the year, especially in dry seasons. However, during wet periods, the irrigation water in lakes may be diluted with rainwater to much lower ECw values, sometimes at ECw < 0.50 dS/m. Additionally, the soils are leached with rain water. In these situations, the soil surface may exhibit a saline-sodic condition in the dry seasons in which the high total soluble salts buffer against the Na effect on soil structure, resulting in a soil with good soil physical conditions, that is, good infiltration, percolation, and aeration. However, with rain and low-salinity irrigation water applications, soil physical conditions may actually deteriorate (Figure 3.2) (Bethune and Batey, 2002; Carrow and Duncan, 1998; Oster and Grattan, 2002). The rain and low-salinity irrigation waters can easily leach soluble salts out of the surface few inches and convert the soil from a saline-sodic to a sodic soil.

5.4.3 Corrosion Problems and Ultrapure Water

Ultrapure water can also be corrosive to metals and concrete. Low-salinity "soft" water (water with low carbonate hardness) tends to dissolve or leach the lime contained in concrete. Good-quality concrete does not suffer excessive damage; however, porous, poor-quality concrete damage can be significant. The rate of corrosion in dense concrete can be very slow or almost nonexistent while still being relatively rapid in softer, porous jointing materials (Ayers and Westcot, 1994).

One method of assessment that has been suggested to predict concrete corrosion is the **Langelier saturation index.**

$$\text{Saturation Index} = \text{pHa} - \text{pHc}$$

The saturation index predicts the tendency of water to either precipitate or dissolve lime. If the saturation index produces a negative number, then some concrete will be damaged, but the rate of attack will likely be very slow (Ayers and Westcot, 1994). A positive number indicates that lime precipitation is more likely. In order to calculate the saturation index, the actual water pH (pHa) and a theoretically calculated pH (pHc) must be known (also see Chapter 3, Section 3.4.1). To calculate pHc, Ca, Mg, Na, HCO_3, and CO_3 concentrations in meq/L from a water quality report are used (Table 5.1).

Concrete corrosion can affect the life of irrigation delivery canals, wet wells, concrete pipelines or culverts, and concrete-paved cart paths on golf courses. The most dramatic affects are noted when water is pumped through concrete pipelines, and it is assumed that the increased corrosion is related to friction, heat, and erosion created by the pressurized moving water.

Metal corrosion can be another concern with ultrapure water sources. Because metal corrosion is an electrolytic process, the rate at which the water attacks and dissolves metal surfaces will depend on a number of factors and chemical reactions. Physical factors such as velocity of flow, temperature, and pressure as well as the type of metal will also affect the corrosion process.

Corrosion problems with either metal or concrete can be complex, and no single indicator or test can predict the effect of low-electrolyte water on the potential life of equipment. However, several accelerated performance and chemical indicator tests have proved reasonably valuable in planning equipment needs and evaluating overall performance when corrosion concerns exist. More in-depth information on this subject has been published in *Corrosion and Encrustation in Water Wells: A Field Guide for Assessment, Prediction and Control,* FAO Irrigation and Drainage Paper 34 (Clarke, 1980).

TABLE 5.1
Information to calculate pHc values used in adj SARw and Langelier Saturation Index calculations

pHc = (pK2 – pKc) + pCa + p(Alk)

pK2 – pKc is obtained from the concentration of Ca + Mg in meq/L
pCa is obtained from the Ca in meq/L
p(Alk) is obtained from the concentrations of CO3 + HCO_3 in meq/L

			Obtained from water analysis
Concentration (meq/L)	**pK_2 – pKc**	**pCa**	**p(Alk)**
0.05	2.0	4.6	4.3
0.10	2.0	4.3	4.0
0.15	2.0	4.1	3.8
0.20	2.0	4.0	3.7
0.25	2.0	3.9	3.6
0.30	2.0	3.8	3.5
0.40	2.0	3.7	3.4
0.50	2.1	3.6	3.3
0.75	2.1	3.4	3.1
1.00	2.1	3.3	3.0
1.25	2.1	3.2	2.9
1.50	2.1	3.1	2.8
2.00	2.2	3.0	2.7
2.50	2.2	2.9	2.6
3.00	2.2	2.8	2.5
4.00	2.2	2.7	2.4
5.00	2.2	2.6	2.3
6.00	2.2	2.5	2.2
8.00	2.3	2.4	2.1
10.00	2.3	2.3	2.0
12.50	2.3	2.2	1.9
15.00	2.3	2.1	1.8
20.00	2.4	2.0	1.7
30.00	2.4	1.8	1.5
50.00	2.5	1.6	1.3
80.00	2.5	1.4	1.1

Source: From Ayers, R. S. and D. W. Westcot. 1994. Water Quality for Agriculture. FAO Irrigation and Drainage Paper, 29, Rev. 1. Reprinted 1994. Food and Agric. Organiz., Rome, Italy. http://www.fao.org/DOCREP/003/T0234E/T0234E00.htm#TOC.

5.4.4 NUTRITIONAL CONCERNS

Irrigation water can be a significant source of nutrients. Ultrapure irrigation sources often lack adequate amounts of minor and secondary nutrients essential for plant growth (Hagan et al., 1967). Boron (B) is one micronutrient commonly found lacking in ultrapure water sources as well as Mn and Fe. These nutrients may require occasional supplemental application as determined by soil testing, especially for B, because small amounts of B are essential for turfgrass growth. Other micronutrients may also be lacking, and regular soil testing is recommended.

Secondary nutrients such as Ca and Mg may also be lacking in ultrapure water sources, and supplemental applications may be necessary from both a nutritional standpoint and to improve infiltration and maintain adequate levels of these nutrients for uptake (Hagan et al., 1967). As previously noted, a rule of thumb in agriculture requires a minimum of 20 ppm calcium (1 meq/L) in an irrigation source, regardless of ECw, to avoid infiltration problems. This small amount would also likely be a recommended minimum from a nutritional standpoint in ultrapure waters and where less than 20 ppm calcium is contained in any irrigation water. Injection of a soluble calcium source would be an option in this case.

As ultrapure waters infiltrate into the soil, they are very effective in leaching salts from the soil because they can more easily dissolve minerals and deplete CEC sites of nutrients. General plant nutrition during grow-in and establishment is a concern, especially on sandy root zones and particularly those root zones lacking organic matter content, such as the California method of putting green construction. The combination of the capability for few nutrient additions from ultrapure water, greater leaching potential, and the low capacity of pure sand to retain nutrients until natural organic matter accumulation occurs in the rhizosphere will require regular monitoring of fertility and periodic supplemental applications.

Enhanced leaching of primary, secondary, and micronutrients throughout the grow-in irrigation regime could raise environmental concerns. Organic material or zeolite additions to raise the root zone CEC should be considered at the time of construction, and/or natural organic and slow-release fertilizers should be used until adequate organic matter has accumulated in the soil to provide higher CEC for nutrient retention.

Special concerns can arise when the source of a reclaimed or effluent irrigation water was originally ultrapure in quality. The effluent treatment process may add sodium, carbonate, and bicarbonate salts in amounts that become disproportionately high in relation to both calcium and magnesium. This potential problem, however, will depend on the types and quantities of treatment salts and chemicals used in the reclamation treatment or recycling process. The SARw, adj RNa, and RSC should be subjected to close scrutiny when using a recycled irrigation source derived from ultrapure potable waters. On the other hand, if adequate calcium is available in the original ultrapure water source, the reclamation process could potentially improve the water quality by the addition of salts other than sodium, carbonate, or bicarbonate. Each case with recycled water will be unique and require individual site-specific evaluation and proactive monitoring.

5.5 MANAGEMENT PRACTICES SPECIFIC TO ULTRAPURE/LOW-SALINITY IRRIGATION SOURCES

Blending. Options that can be considered to improve the overall quality of an ultrapure water source include blending with other water sources, frequent soil amendment applications, or injecting water-soluble amendments or fertilizers to increase the total salt content. Blending the ultrapure water source with another high-salt ion water source is one potential option. The final salt content of a blend will be proportional to the percentage of each water source used (see Chapter 7 for more information on blending). As an example, if water source A contains 1000 mg/L TDS (ECw = 1.56 dS/m) and the pure water source B contains 100 mg/L (i.e., ECw = 0.156 dS/m) and they are to be blended equally in a 25% to 75% ratio (source A/source B), the equation to use is

$$\begin{aligned}\text{ECw (final)} &= (\text{ECw source A})\ (0.25) + (\text{ECw source B})\ (0.75)\\ &= (1.56)\ (0.25) + (0.156)\ (0.75)\\ &= 0.390 + 0.117\\ &= 0.507\ \text{dS/m (or TDS} = 324\ \text{mg/L).}\end{aligned}$$

In Chapter 7, blending will be discussed in more detail in the context of estimating other water quality parameters such as SARw and specific elements such as sodium and calcium.

Amendments. Adding soil or water amendments is another consideration. In the case of ultrapure water sources, injection (via chemigation or fertigation) of the amendment directly into the water source prior to application on the turfgrass is the preferred method of treatment because treating the water source will continually treat the first few centimeters of soil surface with each irrigation application. Within this upper soil profile zone, the water permeability is first adversely affected by Na. Gypsum (dehydrate calcium sulfate) or other calcium (hydrated lime or calcium carbonate, calcium thiosulfate) sources can now be injected with specialized equipment to raise the ECw value to greater than 0.50 dSm and improve soil permeability. Oster and Grattan (2002) note that injection of gypsum directly into irrigation water at rates of 470 to 949 lb (526 to 1063 kg/ha)/acre-foot (325,851 gal or 1,231,717 L) will increase ECw by 0.15 to 0.30 dS/m, respectively, and corresponds to 2 to 4 meq/L (40–80 mg/l) of additional Ca. Gypsum injectors are available that feed dissolved gypsum and other soluble salts into irrigation lines. The same devices can also deliver finely ground gypsum as a suspension into irrigation lakes or ponds.

Soil application of gypsum, phosphogypsum, or a sulfur or acid source applied in combination with lime will supply additional calcium at the soil surface. Small trial areas treated with soil applied amendments can be used to determine if low infiltration is actually due to ultrapure water or another cause such as soil compaction. When ultrapure irrigation water is used as the sole irrigation source, application of soluble or suspended gypsum at the rates noted earlier via the irrigation system may be sufficient to produce positive results. If soil-applied treatments are chosen, then light and frequent applications need to be made to avoid ion leaching and resealing of the soil surface between amendment applications. Granular gypsum applied at rates of 15 to 30 lb per 1000 ft^2 (6.81–13.62 kg/92.9 m^2) per application applied 2 to 4 times per year may be sufficient to maximize infiltration.

Fertigation with cations can also be considered because the soluble fertilizers would raise total soluble salts within the surface. However, unless most of the salts are divalent cations, the effect on amelioration of soil structure may not be as effective as equivalent quantities of soluble or finely suspended Ca sources. The divalent Ca ion is more strongly associated with clay particles than are monovalent cations (such as Na or K) or even the divalent Mg.

On sites when irrigation water with high Na is periodically applied at least part of the year, more continuous applications of gypsum will likely be required, which may be a combination of irrigation water injection and soil granular applications. With onset of the rainy season, it may be necessary to apply gypsum, usually by granular treatment, at the beginning to ensure maintenance of adequate water infiltration. Total rates of gypsum will normally be much higher on a site with a saline-sodic or sodic condition induced by seasonal application of salt-laden irrigation waters followed by an excessively rainy season or use of ultrapure irrigation waters than when the primary soil permeability problem is solely from continuous use of ultrapure irrigation.

When low-salinity irrigation water contributes to reduced water infiltration by surface sealing, this condition will be most prevalent under the following conditions:

1. Soils prone to salt stripping at the surface.
2. When other factors that contribute to soil structure deterioration are present, such as surface compaction, limited ground cover (i.e., establishment period), low organic matter content, or periodic Na additions such as when irrigation water quality varies from saline to ultrapure over time.
3. When the cations, especially Ca, are not replenished at the surface.

On sites receiving only ultrapure irrigation and rain, appropriate treatment at establishment of a grass is very important. Once the grass is mature, gypsum application rates may be reduced to a level that maintains suitable infiltration for the specific site. This is usually determined by proactive testing on a trial area.

6 Irrigating with Saline Water Sources

6.1 SALINITY PROBLEMS: AN OVERVIEW

6.1.1 SALINITY: A DOMINANT ISSUE

Saline irrigation water sources include the following: saline groundwater (naturally saline, salt-affected by salt leaching, drainage water reuse, salt-affected by rising water tables, or seawater intrusion aquifers), brackish surface water, stormwater runoff, reclaimed water, and seawater or seawater blends. Recently, some states in the United States have mandated the use of reclaimed water or saline groundwater for larger turfgrass sites (Marcum, 2006). This is a trend that is expected to continue on a worldwide basis so that in the future, irrigation water applied on turfgrass will often be more saline than in the past (Miyamoto et al., 2005; Miyamoto and Chacon, 2006).

Several of the saline irrigation water sources involve some form of **water reuse (water recycling)** on a specific site. These reuse schemes will become more common in the future on turfgrass and landscape sites as water conservation becomes a greater issue. Examples of water reuse on a site-specific basis when salinity may become a part of the management concerns are the following:

1. **Site drainage water reuse** occurs when water has percolated through the soil into tile lines and then tile drainage water is collected from a containment site for direct reuse in irrigation water applied on parts of the property (see Section 6.4). This is a form of recycled water use, but without treatment except for what occurs during soil percolation before reapplication.
2. **On-site reclaimed water reuse** occurs when harvested water is collected from stormwater/sewage drain lines coming off a property, such as a golf course complex and surrounding or nearby housing development complex, treated at an on-site treatment facility, and then reused for irrigation and other suitable purposes on the site. In this instance, the drainage line water usually does not come from the soil drain lines where water percolated through the soil, but from the surface harvested stormwater and sewage/water drain lines (see Chapters 8 and 9).
3. **Site stormwater collection** harvested from surface runoff and/or stormwater drainage lines leading to the site go directly into a collection facility without the discharge intermingling with sewage water in the sewage lines.
4. Another unique saline irrigation water is **seawater and seawater blends** that are the focus of Chapter 7.

5. **Other water reuse schemes** involving water collected on or near the site and then used for irrigation. This could be as simple as using swimming pool water for irrigation, or more complex, such as using industrial water from cooling towers for landscape irrigation (Gerhart et al., 2006).

Among all the alternative types of irrigation water, saline irrigation sources present the most management challenges and the greatest potential for long-term adverse effects on the environment. Under moderate to highly saline (>2500 ppm total dissolved salts) irrigation water quality, it is very important to consider all the ramifications, not only on the specific site, but also on the entire environment. It is outside the scope of this book to discuss all the soil-plant-environmental aspects associated with saline irrigation water use. However, the focus of this chapter is on providing overview issues to consider when a saline irrigation source is used, especially when the water is moderate to highly saline, regardless of the source of salinity.

From this base of understanding, the reader will be able to better address salinity management challenges prior to site development with implementation of sound decisions pertaining to site selection, irrigation design, drainage installation, water treatment, plant selection, and other critical infrastructure decisions. It is essential to understand that salinity is a complex issue that must be correctly addressed at the planning, construction, and on-site management levels.

Key reference materials related to managing salt-affected sites for general agriculture include those authored by Ayers and Westcot (1994), Grattan and Oster (2003), Hanson et al. (1999), Padir and Oster (2004), and Rhoades et al. (1992). Carrow and Duncan (1998) concentrate on turfgrass sites. Sustainable turfgrass maintenance impacted by the many diverse issues associated with using any saline irrigation water requires a **holistic**, **comprehensive, sustainable management plan,** that is, **best management practices (BMPs)** for salt-affected turfgrass sites. In this chapter, we will present the components of a comprehensive BMPs approach that includes all potential issues, whether within the soil or the water features, as a template for science-based and sound management decisions when any saline water is used for irrigation (Table 6.1).

TABLE 6.1
BMP strategies for sites using saline irrigation water for environmental protection and turfgrass management

1. Site assessment. To identify factors that will influence salinity

a. Soil physical aspects

- Construction/renovation considerations. Impediments to infiltration, percolation, or drainage such as calcic, clay, or rock layers; deep-ripping or deep cultivation requirements prior to establishment; future cultivation equipment requirements; surface and subsurface drainage improvements; drainage outlets and salt disposal options; irrigation system requirements; presence of fluctuating or high water tables; sand-capping needs; preplant physical and chemical amendments to improve soil physical condition
- Identifying all salt additions. Irrigation water; water table; capillary rise from salt-rich subsurface horizon; mixing of salt-laden soil during construction or dredging; fertilizers; drainage onto the site
- Other. Soil texture; clay type; soil physical analyses of root zone media, including water-holding capacity

b. Soil chemical aspects

- Routine soil test information (normal soil fertility test; saturated paste extract salinity test)
- Additional soil test information—SAR, ESP, ECe, free calcium carbonate content

c. Irrigation water quality assessment

- Complete irrigation water quality analyses (Chapter 2, Table 2.1)
- Health aspects if needed (Chapter 2, Tables 2.2 and 2.3)
- Multiple irrigation water sources—Blending, drainage water reuse, reliability of each source, stability of each source in terms of constituents over time

2. Plant selection. Salinity tolerance is a primary consideration along with adaptation to climatic, pest, and site-use stresses (mowing height, traffic, etc.)

a. Turfgrass species and cultivars

b. Landscape plants

c. Buffer zone plantings

3. Irrigation system design. Uniformity of application; flexibility for water applications to minimize drought stress and salinity stresses (i.e., salinity leaching and management)

- Chemigation/fertigation flexibility

4. Irrigation scheduling. For normal irrigation needs and for efficient salt leaching

- Reclamation leaching programs and considerations
- Maintenance leaching programs and considerations

5. Identification of water and soil amendment needs for site-specific problems

- **Acidification**
- **Gypsum/hydrated lime injection**
- **Organic amendments**
- **Inorganic amendments**

6. Determination of proper amendment application protocols for site-specific problems. This includes equipment needs; rates, timing, and frequency aspects

7. Additional cultural programs

a. Surface and deep cultivation needs and equipment. Cultivation programs are very important on many salt-affected sites in order to effectively leach salts and to avoid layers that impede salt movement

b. Fertilization. Soil fertility and plant nutrition are very dynamic with the use of saline irrigation water owing to the combination of constituents added from the water, water treatment materials, and soil amendments, as well as leaching programs that differentially leach nutrients and elements. Of particular importance are soil and plant tissue concentrations of K, Ca, Mg, Fe, Mn, S, and Zn; and ratios/balances between/among competing ions

- Fertigation flexibility

c. Climatic and traffic stresses. Salinity enhances certain other stresses such as drought, high/low temperature, and wear/traffic. Thus, these must be carefully managed

- Rounds of golf/foot traffic
- Cart traffic

d. Cytokinin. Soil salinity suppresses cytokinin synthesis in the roots of plants, and grasses often respond (root system redevelopment; hormone stabilization) to application of this hormone (in seaweed or kelp extract products) on saline irrigated sites

e. Pest management

- **Preventive application program**
- **Curative application program**

8. Monitoring

a. Turfgrass root and shoot responses

b. Soil and plant fertility status

c. Soil salinity over time and by soil depth

d. Irrigation water quality over time

e. Salinity effects on surface and subsurface waters

6.1.2 LESSONS OF HISTORY

Salinization (salination) of irrigated land occurs when dissolved salts accumulate in the upper soil layers, whereas salinization of ground or surface waters occur when excessive salt loads come into contact with the waters. Primary salinization can occur from natural processes or secondarily as a result of human activities. **Natural** or **primary salinity** in soils and groundwater results from the following:

- Accumulation of salts in the soil over long periods of time from weathering of parent materials containing salts, especially in arid regions where natural leaching is limited by low precipitation.
- Oceanic salt carried by wind, rain, or flooding onto adjacent land areas.
- Salt movement into the root zone from a naturally high saline water table such as in coastal swamps or marshes. Sometimes the coastal soils are sandy in nature and can be easily reclaimed by leaching. However, it can be very difficult to remove excess soluble salts and high Na levels from coastal marine clays or more fine-textured soils, especially if the clay type is a 2:1 clay.
- Old ocean beds that have evaporated and left salt deposits at the surface or subsurface.
- Subsurface salt deposits can salinize the groundwater.

Secondary salinization results from the activity of humans, including irrigation and drainage practices. Understanding the causes of secondary salinization is especially important because preventive measures can often minimize adverse effects. Types of secondary salinization are the following:

- Irrigation with saline irrigation water where leaching or drainage is insufficient to prevent salt accumulation in the root zone. The percentage of irrigated lands affected by salinization includes 20–25% in the United States, 13% in Israel, 30–40% in Egypt, 15% in China, and 15–20% in Australia (Gleick, 1993).
- Irrigation with saline irrigation water where surface drainage does occur, but results in salinization of groundwater.
- Salt-laden leachate waters intercepted by tile drains may deposit salts into surface water.
- **Dryland salinity** is a type of secondary salinization and is a major problem in Western Australia (Rogers et al., 2005). Land clearing (native deep-rooted trees and shrubs) coupled with introduction of more shallow-rooted agricultural crops (nonirrigated or irrigated) can result in a rising water table that eventually leads to salinization and waterlogging of the surface. The vegetation changes result in more water draining past the root zone because the root systems are often more shallow for agricultural crops compared to native vegetation. The drainage water can result in a rising water table that in turn mobilizes soluble salts that are located below the root zone but above the normal water table. If the salt-laden water table rises to

> the root zone or the capillary fringe is within reach of the root zone, rapid and serious soil salinization can occur. Moreover, the groundwater also is salinized.

The relationship between irrigation and salinization of soil or groundwater is obvious from the previous examples. Pillsbury (1981) notes the historical importance of these interrelations:

> Many ancient civilizations rose by diverting rivers and irrigating arid lands to grow crops. For such projects to succeed, human beings had to learn to work cooperatively toward a common objective. The most fruitful of the ancient systems was created at the southeastern end of the Fertile Crescent, the broad valley formed by the Tigris and the Euphrates in what is now Iraq. From there civilization spread eastward through present-day Iran, Afghanistan, Pakistan, India and thence into China, wherever rivers disgorged through valleys of recently deposited alluvial soil. At its peak of productivity, each irrigated region probably supported well over a million people. All these civilizations ultimately collapsed, and for the same reason: the land became so salty that crops could no longer be grown on it. The salts that were washed out of the soil at higher elevations became concentrated in the irrigated fields as the water evaporated from the surface and transpired through the leaves of the growing crops. Although floods, plagues and wars took their toll, in the end the civilizations based on irrigation faded away because of salination.

Thus, history and current experience illustrate that use of highly saline irrigation water greatly enhances the potential to degrade soil and water resources unless specific infrastructure and management practices are implemented. Management must target both the plant and the soils on the site for environmental protection (Rhoades et al., 1992; Duncan et al., 2000b; Duncan and Carrow, 2005). Accumulation of excess total salts (salinization) and sodium (sodic soil formation) in the soil is more rapid as irrigation water quality declines, unless the salts are continuously managed. The influence of saline irrigation water will be greatest on the site to which it is regularly applied, but these practices can often impact the surrounding environment.

In most situations, the percentage of saline irrigated turfgrass land area compared to total community area is small. This localization aids in reducing the potential for adverse environmental impacts on community surface and subsurface waters as well as salinization of community landscapes and waters. However, in some locations with numerous golf courses or other large irrigated turfgrass sites, salinity impacts for turfgrass areas can be potentially significant if the salinity is not properly managed. Much of the attention for salinization of lands by irrigation practices has focused on agriculture lands in rural areas (Rhoades et al., 1992; Ayers and Westcot, 1994; Grattan and Oster, 2003), but with more saline waters used for landscapes in urban areas, urban salinization is receiving more attention (Wilson, 2003). Another trend has been the increased interest in potential effects of salinity on freshwater ecosystems (Hart et al., 1990; Neilsen et al., 2003).

6.2 SUSTAINABLE TURFGRASS MANAGEMENT AND BMPS

6.2.1 BMPs and Sustainable Management

As stated earlier, dealing with the many diverse issues associated with using saline irrigation water requires a comprehensive and sustainable management plan, that is, BMPs, for salt-affected turfgrass sites (Table 6.1). Before discussing individual BMPs components, a brief review of the BMPs approach to environmental issues is informative. Carrow et al. (2005b) and Carrow and Duncan (2006) noted that the BMPs approach initially evolved out of the 1977 Clean Water Act, but the overall philosophy can be successfully applied to all environmental issues because it (1) is science based, (2) is holistic or "whole-systems" in nature, (3) is applied on a site-specific basis, (4) incorporates consideration of all environmental (direct and indirect) impacts, (5) considers economic effects on the site and on society, (6) values educated long-term sustainable management, and (7) incorporates ongoing proactive monitoring and revisions.

The **sustainable agriculture** concept that arose after the BMPs concept incorporates these same features, but with the intention of addressing all aspects of the environment. Sustainable agriculture was addressed by Congress in the 1990 "Farm Bill" [Food, Agriculture, Conservation, and Trade Act of 1990 (FACTA), Public Law 101-624, Title XVI, Subtitle A, Section 1603 (Government Printing Office, Washington, DC, 1990) NAL Call # KF1692.A31 1990] (Gold, 1999). Under that law, "the term *sustainable agriculture* means an integrated system of plant and animal production practices having a site-specific application that will, over the long term:

Satisfy human food and fiber needs
Enhance environmental quality and the natural resource base on which the agricultural economy depends
Make the most efficient use of nonrenewable resources and on-farm resources and integrate, where appropriate, natural biological cycles and controls
Sustain the economic viability of farm operations
Enhance the quality of life for farmers and society as a whole."

It is essential for owners and managers of every turfgrass site using saline irrigation water to operate from a **sustainable environmental mindset** as embodied in the concept of sustainable agriculture. Because turfgrass is part of agriculture, our goal must be **sustainable turfgrass management**, which requires a BMPs approach in the management philosophy and actual implemented operations on the ecosystem.

6.2.2 Understanding the Primary Problems

Successful management of any problem starts with **understanding the problem**. Ramifications of salinity impacts on turfgrass management, soil quality, or water feature attributes are all associated with the constituents in the saline irrigation water. Salinity is not a single stress or problem, but there are four major salinity issues that are the primary problems individually requiring intensive site-specific attention. In review from Chapter 3, they are the following:

- **Total soluble salts**. These salts induce water deficits or physiological drought stress on the plant. Because the salts are soluble, if they do not react in the soil and precipitate as insoluble compounds or become attached to the CEC sites, they can readily move with the soil water. Thus, soluble salts can affect surface or groundwater. Management of total soluble salts, which involves aeration and leaching, is the most important primary problem when dealing with saline irrigation waters, whether from the grass management aspect or the environmental perspective.
- **Sodium as related to soil permeability hazard**. Excess Na causes soil degradation by creation of sodic or saline/sodic soils. Sodic soils exhibit reduced water permeability (infiltration, percolation, and drainage), decreased gas exchange (low oxygen or aeration), and a less favorable rooting media due to soil structural breakdown. Protection of soils from sodium degradation is another primary component of salinity management.
- **Ion toxicities** (Na, Cl, and B). Direct ion toxicities to roots or foliage affect plant selection, nutritional balances, vigor, performance, and sustainability.
- **Ion/nutrient imbalances** (Ca, Mg, K, P, N, SO_4, Mn, and others). Nutrient deficiencies can be easily induced in many saline irrigated sites owing to ion competition and imbalances. Soil fertility/plant nutrition challenges arise not only from the nutrient imbalances, but also from leaching programs to remove excess salts, water and soil amendments required to balance nutrients, and the dynamic nature of these management systems. Ion/nutrient imbalances can also occur in irrigation lakes and any surface waters influenced by the saline irrigation water.

BMPs for salt-affected sites consist of managing these constituents and their on-site and potential off-site impacts in a manner that is environmentally sound for the whole ecosystem (water–soil–wildlife–plant–climate system) as well as maintaining the economic, recreational, environmental, and aesthetic benefits of turfgrass sites to all stakeholders (Duncan et al., 2000a). BMPs for sites receiving saline irrigation waters must address two broad categories: (1) BMPs for turfgrass and landscape management, and (2) BMPs for environmental protection and long-term ecosystem sustainability. These BMPs will be presented in the following sections.

In addition to the materials in this chapter, other chapters that will offer further insight for saline situations are Chapters 7, 11, 12, 13, 14, and 15.

6.3 BMPS FOR TURFGRASS AND LANDSCAPE MANAGEMENT

Depending on the water source, salinity levels may vary from slightly saline to highly saline. In Chapter 3, it was noted that irrigation water salinity levels can vary greatly for site-specific turfgrass situations, especially with the availability of more salt-tolerant grasses, including true halophytes (Table 3.4). Even moderate or medium salinity levels (ECw = 1.56–3.13 dS/m or TDS = 998–2003 ppm) can adversely affect many turfgrass species and cultivars if the grass is not tolerant or the salts are not properly managed in the ecosystem. Management in these low-to-moderate salinity irrigation water situations is usually relatively easy. However, under highly saline irrigation water, a greater degree of management expertise, management inputs, infrastructure modifications, and environmental concerns are necessary. Successful management will require taking a holistic approach and managing each BMP component presented in Table 6.1. Components that particularly relate to management of irrigation water are discussed in the following sections.

6.3.1 TURFGRASS AND LANDSCAPE PLANT SELECTION

Species vary greatly in salinity tolerance as well as cultivars within a species (Table 6.2). Selection of salt-tolerant turfgrass species and cultivars becomes very important when using saline irrigation water in order (1) to prevent frequent salt-induced management problems, especially physiological (salt-induced) drought, nutritional disorders, greater wear injury, increased localized dry spots, increased disease problems (especially root-borne pathogens), and high-temperature/low-temperature stress, (2) to allow sufficient time to implement preventive and corrective management practices before rapid onset of plant injuries, (3) to allow a greater choice in

TABLE 6.2
Salinity tolerance ranking of turfgrass species

Common name	Scientific name	Highest salinity tolerance[a,b]	Grass type	Cultivars reported most tolerant within the species[b]
Seashore paspalum	*Paspalum vaginatum*	ST	Warm	SI Supreme, SI 2000, SeaIsle 1, SeaSpray (seeded type), Platinum TE
Alkaligrass	*Puccinellia* spp.	ST	Cool	Salty, Fults
Saltgrass	*Distichlis stricta*	VT	Warm	
Manilagrass	*Zoysia matrella*	VT	Warm	Diamond
Bermuda grass, common	*Cynodon dactylon* var. *dactylon*	VT	Warm	Sahara, Sunbird, Riviera
Bermuda grass, hybrids	*Cynodon* spp.	VT	Warm	Tifway (419)
St. Augustine-grass	*Stenotaphrum secundatum*	VT	Warm	Seville
Kikuyu	*Pennisetum clandestinum*	T	Warm	
Crested wheatgrass	*Agropyron cristatum*	T	Cool	
Western wheatgrass	*Elymus smithii*	T	Cool	
Tall fescue	*Festuca arundenacea*	MT-T	Cool	Alta, Apache II, Dynamic, Pure Gold, Tar Heel II, Tomahawk RT, Barlexas II

Common name	**Scientific name**	**Highest salinity tolerance**[a,b]	**Grass type**	**Cultivars reported most tolerant within the species**[b]
Perennial ryegrass	*Lolium perenne*	MT-T	Cool	Brightstar SLT, Citation II, Catalina, Catalina II, Charger II, Manhattan II, Quickstart, Quick-trans, Chaparral, Salinas, Manhattan 5GLR, Gray Star, $ilver Dollar, Citation Fore, Barlennium, Apple GR
Slender creeping red fescue	*Festuca rubra* spp. *Littoralis* (G.F.W. Meyer) Auquier	MT-T	Cool	Dawson, Oasis, Seabreeze GT, Barcrown II, Shoreline
Creeping bentgrass	*Agrostis stolonifera*	MT-T	Cool	Celebration, Cobra, Mariner, Penneagle Seaside, Seaside II, SR1020, Grand Prix
Strong creeping red fescue	*Festuca rubra* L. spp. *rubra*	MT-T	Cool	Flyer, Ensylva, ShademasterII, Inverness, SeaLink, Florentine GT
Buffalograss, American	*Buchloe dactyloides*	MT	Warm	
Blue grama	*Bouteloua gracilis*	MT	Warm	
Hard fescue, blue	*Festuca trachyphylla*	MT	Cool	Little Bighorn
Kentucky bluegrass	*Poa pratensis*	MS	Cool	Blacksburg, Glade, Livingston, Moonlight, Moonlight SLT, Northstar, Apollo, Moonbean, Bariris
Zoysiagrass	*Zoysia* spp.	MS	Warm	Companion (seeded), Diamond
Rough bluegrass	*Poa trivialis*	VS-MS	Cool	Laser, WinterLinks
Carpetgrass, common	*Axonopus fissifolius*	VS	Warm	
Centipede-grass	*Eremochloa ophiuroides*	VS	Warm	
Annual bluegrass	*Poa annua* var. *annua*	VS	Cool	
Colonial bentgrass	*Agrostis capillaris*	VS	Cool	

[a] Based on guidelines: VS (very sensitive) 0 to 1.5 d Sm^{-1} threshold ECe; MS (moderately sensitive) 1.6 to 3.0; MT (moderately tolerant); 3.1 to 6.0; T (tolerant) 6.1 to 10.0; VT (very tolerant) 10.1 to 18; and ST (superior tolerance) ECe > 18 dS/M.

[b] Highest salinity tolerance = the salinity tolerance of the best cultivars within the species; other cultivars will rank lower. Ratings are based on various sources and using the threshold ECe, which is the salinity where growth starts to decline at least 10% below the maximum growth. This value varies with cultivar within a species.

irrigation water sources on many sites, (4) to allow reuse of drainage water for irrigation in selected areas on a site, (5) to minimize salt leaching requirements, and (6) to aid in soil reclamation and protection on salt-affected sites. New halophytic grasses currently available (with more species likely to be introduced into the turfgrass industry in the future) will often have unique management requirements whether they are managed under saline or high-quality irrigation water; that is, management will differ from our "standard" non–salt-challenged cultivar strategies.

Tree, shrub, and other ornamental landscape plant selections are also a high priority when grown on saline sites. Tolerance of landscape plants to irrigation water contact on the foliage is one criterion. Careful location of sprinklers can help avoid plant injuries from spray drift, and the use of drip irrigation is another alternative. Additionally, tolerance to direct root contact with soil salts and uptake of salts into the foliage where leaf burn and physiological damage can occur are other landscape plant issues (Table 3.7). In many arid and semiarid locations, various groups may publish a list of local climate-adapted plants and their relative salinity tolerance (see Appendix section).

6.3.2 Selection of Irrigation Water

The focus in this chapter is on saline irrigation water sources, but some sites may have more than one alternative irrigation water source, with each source differing in quality. A feasibility study that analyzes water supply sources usually requires a qualified professional consultant to evaluate all potential sources with respect to supplying adequacy, economic viability, engineering considerations, and environmental impacts. Some general considerations that may apply to one or more of the sources that are particularly relevant to sites using saline irrigation water are the following:

- Blending options and associated costs. Blending of irrigation water sources may be an option to minimize the salt load. This may be as simple as dilution of a saline source in rain-fed lakes, or more complex, such as blending desalinized water with a saline source such as recycled water or brackish water. Volume of water for blending, storage capacity for each source, and flexibility in blending are all considerations.
- Quality variation over time is another consideration, and knowledge of spatial or temporal variations in water quality is essential to make appropriate management decisions. Some saline sources may vary in quality over time, and knowledge of this change is essential for proper flexibility in turfgrass and landscape management. In other instances, quality variations may be caused by harvested rainfall dilution within irrigation lakes that result in seasonal changes, but with multiple connected lakes, each lake may vary in overall salt load. Even within a lake receiving water from a saline stream, the quality near the inlet may be higher in salinity than across the lake. The lake may also vary by depth in quality. Size of the lake, depth of the water in the lake, need for possible aeration to minimize stratification, and location of pump intake are all considerations.

- Pond/lake construction to avoid seepage into the pond of any saline groundwater (from upconing) or saline harvested runoff. Lining or sealing the lake bottom are possible considerations.
- Pond/lake (whether an irrigation pond or a water feature) location, design, and inflow/outflow construction measures to avoid seepage into the soil and into fresh groundwater aquifers. This would be true of any water conveyance features such as canals or pipes. Drainage catchments and sump pumps would be considerations.
- On ponds or lakes where water withdrawal may exceed water recharge, especially in the summer, the influence that a drop in water level may have on fish, aquatic plants, and growth of undesirable plants along the exposed shoreline should be considered. When these water features are a part of a housing development, these issues concern individuals and other stakeholders.
- Determination of water rights, competition for a specific water source, permitting, regulatory negotiations at local, state and regional levels.
- Regulatory issues related to maintenance of in-stream flow for aquatic organisms, habitat sustainability, dilution requirements, or the recreational needs of other users.
- When considering surface water collection into ponds, appropriate buffer zones should be used for water quality protection.
- Well yield from aquifers and draw-down determinations/permitting.
- Stream flow during dry periods versus irrigation demand.
- Reliability and water volume both in the long term and over the seasons of a year for all water sources. The anticipated effects of any water use restrictions that may apply to a water source, and conservation regulations during prolonged drought periods should be included.
- Characterization of the underlying aquifer, which is the process of quantifying the physical and chemical features of an aquifer that may influence groundwater or the potential for contamination from an alternative saline irrigation water source. With increased use of saline irrigation water that requires a leaching program, the potential for contamination of the existing aquifer must be determined. If this potential exists, very careful contouring, subsoil profile sealing, and subsurface drainage with an appropriate outlet is necessary (Huck et al., 2000; Carrow and Duncan, 1998).
- A complete water quality test for any natural constituents in the water as well as any contaminants. Any permanent native grasses must be able to tolerate the salt levels in the water source especially when overseeded or reestablished.
- Potential to use an aquifer that is not used for potable purposes because of salinity, but may be available for irrigation.
- Potential for interaction of water or plant removal from a source on wetlands or streams, including sinkhole problems or other unforeseen ramifications.
- Energy costs to move water. This should be considered for well pumps and for transfer pumping costs, whether in pipelines or to pump from one pond to another.
- When more than one water source is used, consideration should be given to the potential loss of one or more of the sources due to prolonged drought or

infrastructure breakdown (such as dam failure), increased costs of maintenance due to corrosion or erosion, regulatory restrictions, or other reasons; and to the ramifications of losing a source.
- Costs associated with treatment of water prior to irrigation use. In recycling of storm/drainage waters for irrigation, treatment may encompass a typical water treatment facility. For use of desalinized water, the reverse osmosis (RO) or other treatment facility would be a significant cost. The most common water treatment is for irrigation water containing high sodium in conjunction with high bicarbonates that interfere with use of calcium amendments to prevent formation of a sodic soil (Carrow et al., 1999).
- Total area to be irrigated on schedule, including turfgrass and landscape areas.

6.3.3 IRRIGATION SYSTEM DESIGN AND DEVICES FOR EFFICIENT WATER USE

On salt-affected sites, controlled salt leaching is the most important management practice (Carrow et al., 2000), and effective leaching is very much a function of the irrigation system. Irrigation system design for uniformity of application and flexibility are essential. Any overirrigated sites will receive additional salt load, whereas any underirrigated sites will accumulate salts owing to lack of leaching and upward capillary movement of salts to the soil surface. Because excess salts induce physiological drought in plants, deficiencies in the irrigation distribution system/leaching program become readily apparent.

The Irrigation Association, in its extensive *Turfgrass and Landscape Irrigation Best Management Practices* document, notes that maximum water conservation on irrigated sites requires five BMPs related directly to the irrigation system (Irrigation Association, 2006). The five BMPs are the following:

- Ensure overall quality of the irrigation system.
- Design the irrigation system for the efficient and uniform distribution of water.
- Install the irrigation system to meet the design criteria.
- Maintain the irrigation system for optimum performance.
- Irrigation scheduling—Managing the irrigation system to respond to the changing requirements for water in the landscape (see Section 6.3.4).

Ensure overall quality of the irrigation system. Whether installing a new system or renovating an existing irrigation system, it will become increasingly important for all facility owners and managers to be proactive in obtaining the best-designed irrigation distribution system for uniform water application, excellence in zoning, and flexibility in control. Quality irrigation systems cost more money than inferior systems, but a good system can also save on water costs. A new or renovated irrigation system will be used by the turfgrass facility for a long time, and current and future regulations will bring increasing pressure for comprehensive and sustainable water conservation practices.

For saline irrigation water sources, distribution-efficient system quality also entails resistance to corrosive substances. Soluble salts in the water and soils surrounding buried components are a major concern. In the case of salt-laden reclaimed water, ammonia and chlorine can be other chemicals of concern that can impact survival of irrigation system components as well as turfgrass/landscape plants.

Irrigation system design for uniformity and efficient operation. Uniformity of water application is of prime importance, but quality design also requires effective zoning and flexibility in water applications (good controllers and sufficient water to allow good irrigation) to ensure that an adequate quantity of water can be applied at a rate that allows infiltration into the soil and with sufficient water volume to meet plant and salt leaching needs in a timely fashion. Pulse irrigation (irrigation applied in a series of pulses [application cycles] with sufficient time between events for infiltration and percolation by unsaturated flow) is especially important for efficient salt leaching and water use (Carrow et al., 2000). All three of these design criteria are necessary to achieve effective irrigation water application: applying water in a manner that avoids runoff and maximizes infiltration into the soil and unsaturated flow/percolation. General approaches or options for achieving these criteria in the initial system design or in modification of an existing system are covered in considerable detail in publications such as *Golf Course Irrigation Environmental Design and Management Practices* (Barrett et al., 2003); Irrigation Association Web site and bookstore contain several publications related to this topic (IA, 2005); and the Center for Irrigation Technology (2003) offers services and information pertaining to maximizing irrigation uniformity. Chapter 10 targets these concepts and concerns. Specific aspects that are important to consider in design for efficient and uniform distribution of water are noted in the following text and should be a part of the integrated BMPs program.

A. Sprinklers, Design, Zoning

- Careful evaluation of design criteria for selection of proper heads, nozzle sizes, rotation speed, head spacing, head configuration (equilateral triangular or square), pipe size and quality, and pressure. Errors in these aspects can adversely affect all uniformity components for water application on all zones. Wind speed and direction are critical factors influencing head spacing.
- Choosing sprinkler heads that do not exceed the infiltration rate of the soil is in theory the best approach, but is not always possible in practice. On sites where runoff occurs, nozzle adjustment may be necessary or the strategy may often require the use of sequenced pulse irrigation as a more practical solution; hence, the need for flexibility in control.
- Full and part circle rotary sprinklers should never be hardwired together on the same control station hydrozone unless they have matched precipitation rates and similar distribution patterns. Small-area lawn sprinklers (spray and stream rotors) offer these features. However, traditional large-area turf rotors used on golf courses are not typically available with matched precipitation features between full and part circle models.
- Low or adjustable trajectory nozzles can reduce the influence of wind, but may impact distribution profiles and, hence, distribution uniformity.
- Internal sprinkler pressure regulation or pressure regulation valves in distribution lines to ensure proper sprinkler operation with minimal misting.
- Adjustable arc heads for more site-specific targeting of water.

- Low-volume heads for sloped areas, sites with low water infiltration, and where wind drift is a problem.
- A flexible control system with ample quantity of water, and good pressure, low-volume heads can reduce evaporation losses and wind drift while allowing water to infiltrate into the soil.
- Use part circle sprinklers on interface edge areas to reduce water application on out-of play areas.
- Careful zoning into hydrozones that include areas with similar plants or similar water and environmental requirements. The primary factors generally considered are presence of different types of plants (trees, shrubs, turf, mixed plantings, etc.), slope, sun exposure, solar radiation (sun versus shade and duration), and primary wind direction. Soil type and soil variation—organic matter content, use of inorganic amendments, and subsoil variation—are also important. Individual head control of valve-in-head type sprinklers provides the ultimate control and is an optimum consideration.
- Zoning sprinklers on mounds to control irrigation times and using appropriate low-volume sprinklers, including low-volume spray heads for smaller mound areas.
- Manually placed low-volume hose-end microsprinklers, soaker hoses, etc. for treatment of localized high-moisture and salt-flux problem areas. All irrigation and salinity management strategies cannot be accomplished through use of only the automatic/in-ground system.
- Use of high-efficiency nozzles for better distribution and uniformity of coverage.
- Dual/opposing sprinklers to irrigate greens separately from surrounds. Part on Part and Part (surrounds) on Full (greens) configurations are used depending on preference of the superintendent)
- Dual distribution lines and sprinklers for delivering higher-quality water to greens compared to surrounds.
- Equilateral triangular spacing is more efficient than single row or square spacing of sprinklers.
- Use more sprinklers to achieve better coverage uniformity and allow closer spacing (actually a very effective water conservation tool because water use is determined by irrigated acreage and not the number of sprinklers per hectare or acre).
- In areas with strong prevailing winds at certain times of the year, consider an extra row of sprinklers located on the windward side zoned to be used during windy periods.
- Backflow devices and any necessary hardware required for a particular water source, such as recycled water with dual lines and safety measures to protect potable water.
- Variable-frequency drive-pumping system to apply water in the quantity required in an energy-efficient manner.
- Flow meters to accurately record actual water use (much more accurate than estimated flows by computer control systems).

- Future: (1) sprinklers with greater flexibility in water delivery; (2) heads that have two-way communication to controllers for changing sprinkler performance and to ensure correct operation; (3) wireless heads; (4) components of the irrigation system must be designed to allow for multiple means of electronic interfacing and a higher level of interfacing, especially with water-saving devices used as monitoring aids for irrigation scheduling; and (5) so-called smart sprinklers that monitor both salinity and moisture as well as plant use, with direct communication back to the irrigation controllers. These features could change zoning and irrigation concepts.

B. Control System

- Automatic central control systems should allow greater diversity in programming, including multiple start times; multiple independent programs; capability of short run times; pulse or cyclic irrigation scheduling; syringe and prewet cycles; interfacing with portable handheld controllers; interfacing with moisture and salinity sensors; and ability of the program to use weather data or soil data to schedule irrigation. Controllers vary in their capabilities; some have fixed irrigation intervals with fixed run times that can only be changed manually. Other controllers have fixed run times, and the user can rapidly change run times by a percentage adjustment. The next level is a controller that has user-programmed irrigation intervals, but can be automatically adjusted by historic or current evapotranspiration (ET) data. The most automated devices are controllers that automatically adjust the interval and run times within set limits. However, even the most sophisticated control system requires periodic human intervention.
- Future: Advanced control systems that can be highly automated using two-way communication and sensors to integrate real-time data will become the "norm" in many cases.

Maintenance of the irrigation system for optimum performance. Even the best-designed system must be maintained on a routine basis. On sites with highly automated irrigation systems with integrated real-time sensor inputs, it will be important to assign personnel who have the responsibility to routinely maintain a system and periodically conduct irrigation audits on parts of the system. The most common reasons for system malfunction are discussed in the following text. If the existing system does not exhibit these problems, this can be stated; if improvements are needed, then the strategy and plan to implement these improvements can be noted:

- Poorly adjusted sprinkler heads.
- Broken heads or sprinklers that are not rotating properly.
- Faulty or open control wiring (common where gophers or other burrowing animals are problems).
- Sprinklers that are not properly aligned, but are crooked or out of plumb. Use of 3-elbowed swing joints helps maintain alignment.
- Sunken heads.

- Heads where grass leaves or thatch interferes with operation.
- Clogged nozzles.
- Worn nozzles.
- Nozzles damaged during removal or replacement.
- Mismatched nozzles or heads within a zone for uniform precipitation rate.
- Mismatched nozzles or heads for the specific soil infiltration rate.
- Spray deflection by plants or other features.
- Malfunctioning valves.
- Water-saving devices not functioning, such as rain shutoff switches or soil moisture sensors.
- Improper irrigation scheduling problems—Run time per cycle or number of cycles are not adequate to apply sufficient irrigation water volume; overapplication of water due to incorrect scheduling; and schedules that are not adjusted for weather, season, or specific zones.

Subsurface irrigation and surface drip systems. Aboveground sprinklers distribute water through the air and leave the surface moist. These conditions can result in high evaporative losses of water and wind distortion of water distribution. Subsurface application of water to the plant root zone would reduce these problems. Subsurface irrigation can be achieved by several means:

- Using a fluctuating or adjustable water table. This approach has been successfully used on golf course greens and athletic fields. Good turf performance and water savings (conservation) can be achieved. With changes in grade, construction becomes more complicated but can be accomplished. If the irrigation water contains even modest levels of salts, salt accumulation can occur at the surface as salts are carried with water during capillary rise when the surface zones dry down due to ET (Allen, 1998).
- Using a stationary water table. This approach is not used on turfgrass sites, because grasses have seasonal root growth patterns, which influences the appropriate depth for the water table.
- Use of buried water emitters (SDI, subsurface drip irrigation).

Both the SDI and fluctuating water table systems will likely increase in use in arid regions, especially on golf greens and tees, berms, bunker surrounds, and other relatively flat areas. With saline irrigation water, a surface water application system may be needed to periodically leach salts, especially if they accumulate near the soil surface. Surface drip systems are very useful for site-specific irrigation on landscapes for trees, shrubs, and flower beds. With proper design and maintenance, these systems can effectively irrigate mixed plantings and single plants.

6.3.4 IRRIGATION SCHEDULING

Even with a well-designed, flexible irrigation system, efficient water use and salinity management depends on proper scheduling. In Chapters 4 and 11, considerable attention is given to salinity monitoring and proper irrigation scheduling for salt control, but within this section, some general comments will point to the integration of efficient water application to meet irrigation needs and leaching. Irrigation scheduling options include the following:

- *Experience* of the turf manager.
- *Climate-based approaches*, such as the use of weather stations, evaporation pans, or evaporometers that estimate climate ET or evaporation.
- *Soil-based methods* using soil sensors for soil moisture and salinity monitoring.
- *Plant-based methods*. The most common plant-based approach is to use indicator areas that exhibit drought stress (physiological and soil drought) first. Other approaches include the use of infrared thermometers or multispectral data.
- *Combinations of these approaches.*

Irrigation scheduling of the future must involve information from *within* an irrigation zone or on smaller microclimate areas to provide more site-specific guidance using an integrated irrigation system with linked controllers and moisture/salinity sensors (Buss, 1996; Neylan, 1997; Sudduth et al., 1999). Although many in the turf industry may be skeptical of adopting or developing new technologies and concepts that are necessary for site-specific irrigation, the demand for water conservation and salinity control measures will bring these changes. Site-specific or precision irrigation cannot be done without precise science-based data on the microclimate level, nor can it be accomplished without precise water application. One scenario that is becoming increasingly common, especially in arid regions, is for a golf course to be limited to an annual permitted quantity of water that is well below current use for many facilities. In such a situation, the facility must view all options to achieve the water volume limitation; and ideas that seemed impractical before may suddenly become very attractive. Highly automated controllers that can automatically adjust irrigation using daily climatic and soil sensor data will become more prevalent as the necessity for water conservation increases.

As the salinity level increases, a number of factors can impact the site or surrounding environment:

- Irrigation system design for uniformity and flexibility must be a reality.
- Potential need for water and soil amendments, particularly when the irrigation water may foster sodic soil conditions.
- Sand-capping in conjunction with subsurface drainage may become necessary on fine-textured soils with low infiltration and percolation rates.
- Drainage and environmentally sound salt disposal become essential, that is, protection of soil sustainability, surface/subsurface waters, and associated native flora and fauna become critical issues.
- Irrigation lake protection either from leaching into the groundwater or from saline groundwater moving into the irrigation lake.

- Management requirements are enhanced in cost, intensity (labor and otherwise), and complexity, especially irrigation, leaching, cultivation, fertilization, and pest control.
- **Irrigation water treatment** is often required when using saline irrigation water to address sodium permeability hazards due to an imbalance of sodium, bicarbonates, calcium, and magnesium. This is covered in detail in Chapter 12.
- Monitoring programs must be developed for plant, soil, and water aspects in order to deal with infrastructure, management, and environmental decisions.

In conclusion, use of moderate to highly saline irrigation water cannot be practiced without enhanced management skills, attention to potential environmental problems, and increased costs for management inputs and infrastructure improvements. Lack of attention to these matters in either the construction planning stages or ongoing management will be very costly.

6.3.5 DRAINAGE

Environmental impacts of saline irrigation water drainage can be diverse and serious, especially impacts on water resources (Dougherty and Hall, 1995; Mandramootoo et al., 1997; Tanji and Kielen, 2002). Environmental impacts of drainage may be beneath the site if the drainage water is not intercepted but allowed to drain into the underlying strata. When tile drains collect drainage water, problems may develop at the disposal site or downstream if disposal is in a stream. Potential impacts that are especially important include the following:

1. Pollution—Groundwater and surface water contamination from salts and other constituents in the drainage water.
2. Ecological—Negative impacts on native floral and fauna within water features, or peripheral wetland deterioration.
3. Hydrological—Influence on stream flows, flood regimes, and water table changes.
4. Soil degradation—Site where drainage water is disposed of on a soil or impacted by a rising water table.

Mandramootoo et al. (1997) and Tanji and Kielen (2002) provide excellent discussions on drainage water management and disposal alternatives on agricultural sites that can also be applied to turfgrass systems. In many situations, a combination of control measures may be required, such as the following:

- Water conservation practices—Good water conservation strategies not only conserve water but also minimize drainage.
- Irrigation water management—To control subsurface drainage, water table level, and capillary rise potential of salts.
- Drainage water treatment—Flow through wetlands, desalinization, trace element removal, and the numerous wastewater treatment processes that

can often be applied to drainage water for specific problems, whether chemical, physical, or biological.

- Drainage water disposal—This may be directly channeled into open surface waters (rivers, lakes, and the sea), deep aquifer injection, evaporation basins, solar evaporators/salt harvesting, or sequestering in the soil. Hauck (2004) and George and Nott (2004) provide excellent information on evaporation basin use and construction.
- Drainage water reuse (see Section 6.4).

6.4 DRAINAGE WATER REUSE

One strategy for water conservation and salt management is to reuse water that is collected from the drainage system for purposes that do not require special treatment; this practice is termed **drainage water reuse**. It is anticipated that drainage water reuse will become more common on large turfgrass sites, especially those able to use more salt-tolerant turfgrass species. Reuse conserves water while reducing the quantity of drainage water for disposal. Common reuse options for turfgrass sites include (1) reuse for irrigation of turfgrass and landscape plants and (2) reuse in wildlife habitats and wetland areas. There is considerable attention in California drainage water reuse for agricultural situations.

Reuse of drainage water can be accomplished in different schemes that depend on the quantity and quality of drainage water, time of availability, availability and quality of other water sources, precipitation patterns that influence drainage outflow and quality, and salinity tolerance of the turfgrass and landscape plants. Three means of using drainage water are the following:

- Direct use. In this case the water is collected and directly applied to the site without blending with another source. Proactive monitoring of salt concentrations with each use is a critical strategy.
- Blending. Mixing of drainage water with another irrigation water or higher-quality source can provide extra water while using salt concentrations that are within the turfgrass and landscape plant tolerances to the irrigation water, or for meeting water volume regulations on site.
- Cyclic use. Drainage water would be more available and more diluted following the rainy season. By storage in lakes, this source could be used during the months after the rainy season. Or, drainage water can be used as the irrigation source until soil salinity starts to increase to a level of concern, and then a higher-quality source could then be used for leaching and periodic irrigation.

On golf courses, salinity tolerance of grasses on roughs, fairways, tees, and greens may differ.

A dual irrigation system might be considered to allow drainage water reuse on the areas with the most salt-tolerant grasses. In sod production fields, as salinity in the drainage water starts to accumulate, its use may shift to fields with more salt-tolerant grasses.

Because drainage water is normally of somewhat lower quality than the initial irrigation water, it requires careful monitoring and management to prevent soil degradation or adverse effects on plants. Nutrients in drainage water should be considered part of the fertilization of the turfgrass and landscape site, just as is done with reclaimed water. Tanji and Kielen (2002) and Oster and Grattan (2002) provide detailed discussions of management of drainage water when reused for irrigation. Many of the problems and management schemes are the same as practiced on salt-affected sites (Carrow and Duncan, 1998).

Our intention in this chapter has been to highlight the issues related to use of saline irrigation water, because these are the most complex and challenging irrigation sources. When considering the use of a saline irrigation water source, the question of prime importance becomes, “is this sustainable and environmentally compatible?” This question can only be answered in the affirmative if wise decisions are made concerning site selection, assessment, and development; irrigation system design and scheduling; drainage; water treatment; soil infiltration/percolation; soil amendments; plant selection; and other infrastructure decisions. Shortcuts in these factors will not work for salinity; it is an unforgiving cumulative issue that can degrade water, soil, and plant resources if not properly addressed. Sustainable turfgrass management using the best science-based BMPs for salt-affected sites is essential.

7 Seawater and Seawater-Blended Irrigation Water

7.1 SEAWATER IRRIGATION

7.1.1 SEAWATER IRRIGATION: A POSSIBILITY?

A vast global storehouse of water is present in our seas and oceans; but, seawater irrigation—is this possible? Glenn et al. (1998) put forward the following thoughts about seawater irrigation on agronomic crops:

> The idea of using seawater for crop production along coastal deserts has been proposed over the past 30 years (e.g., Boyko, 1966; Epstein et al., 1980; Glenn et al., 1995; Iyengar and Ready, 1994), but is not yet a practical reality. The feasibility of seawater agriculture depends first on finding salt tolerant germplasm and second on developing suitable agronomic techniques for managing highly saline water sources.... Irrigation strategies for using highly saline water are not yet developed.

With the release of highly salt-tolerant seashore paspalum (*Paspalum vaginatum* Swartz) turfgrass cultivars, interest in seawater irrigation or seawater blends has risen in turfgrass culture (Duncan et al., 2000b; Duncan and Carrow, 2000).

Full-strength seawater irrigation may be possible in a very limited number of situations, but it is not very probable or environmentally sustainable and certainly would come with great cost, as is discussed later in this chapter. Other options involving seawater that may contribute to irrigation needs are (1) blending with another lower-saline source so that the seawater accounts for a percentage of the water requirement, but without an unmanageably high salt load, and (2) as the source for desalination. Seawater application onto turfgrass sites may occur for reasons beyond irrigation. Salt water intrusion into coastal aquifers that results in unintentional application of seawater onto well-established recreational turf, and coastal or lowland salt water inundation from storm surges/salt deposition can now be addressed with planting and site-specific management of the most salt-tolerant turfgrass (Carrow and Duncan, 1998). These extreme cases of the ultimate use of poor-water quality require serious science-based infrastructure development and diligent preconstruction, establishment, grow-in/postestablishment considerations for successful turfgrass management. The site-specific nature of salinity-challenged environments causes the most complex, and often, most confusing situations involved in turfgrass management. Mistakes or omissions become readily apparent in the form of reduced turfgrass density and off-color cosmetic grass appearance, and are amplified once the grass is planted and the turfgrass starts to respond to its salinity-challenged environment (root system development and maintenance).

The focus of this chapter is to emphasize those critical issues that arise when this worst-case water resource option (i.e., full-strength seawater) is selected for irrigation. The basic principles are applicable to sites using highly salt-laden effluent, brackish water, or blended sources.

One difference in seawater compared to other saline irrigation water sources discussed in Chapter 6 is that the composition is known and consistent. Table 1.2 (Chapter 1) and Table 7.1 presents the characteristics of typical seawater. Calcium and Mg levels may appear high, but when compared to the Na and Cl concentrations, these ion concentrations are much lower. Seawater will apply relatively limited Ca (in the context of what will be needed to counter the high Na), but the Mg content will be at a higher ratio with Ca compared to most irrigation waters, because ocean water is traditionally high in Mg. The balance between Ca and Mg is critical when grass color expression and nutritional stability factors are considered.

Salt is the ultimate growth regulator, acting to reduce gibberellin production, disrupt nutritional balances, and desiccate roots. The idea of using ocean water at 34,560 ppm or mg/L salinity (ECw = 46 dS/m, using a 750 conversion, or 54 using a 640 conversion; SARw = 57.4) should be treated with caution, because this water source contains 28.6 lb salt/100 gal water. A 500,000 or 950,000 gal irrigation cycle applied over an entire golf course, regardless of total irrigated acreage, would deposit 143,000 and 272,033 lb salt, respectively, spread out over that site with each irrigation cycle. The distribution of the salt will be dependent on the efficiency of the irrigation system. For a golf course with 70 acres of irrigated area and a 950,000 gal cycle, 3886 lb/A of salt or 89.2 lb/1000 ft^2 (43.7 kg/100 m^2) would be deposited each time the irrigation is turned on. Expressed another way, 2135 lb salt would be applied per 1000 ft^2 per acre-foot of water (i.e., 343 kg/100 m^2 per 10 cm irrigation water applied).

Use of ocean water would require 2378 lb/1000 ft^2 gypsum or 547 lb Ca/1000 ft^2 simply to counter the excess Na (10,556 ppm or 459 meq/L) in ocean water to remediate against soil deterioration from sodium (Table 1.2, Chapter 1 or Table 7.1). A total of 170 lb lime/1000 ft^2/acre-foot of ocean water would be needed to react with 168 lb sulfate (SO_4 = 2690 ppm or 56 meq/L in ocean water) to produce gypsum (approximately 230 lb gypsum formed per 1000 ft^2) and scrub out the excess sulfur in order to minimize black layer formation. The high chloride (18,980 ppm) concentration would suppress nitrate uptake and microbial conversion of granular-applied urea or ammonium-N fertilizers to nitrates. Ocean water contains 11.5 ppm of N; consequently, nitrate applications can be reduced by 2–3 lb/1000 ft^2/year on the turf.

A brief overview of the challenges that arise from these salt loads associated with seawater irrigation if applied to a turfgrass site helps develop a perspective for those considering use of full-strength seawater as an irrigation source. Turfgrass cannot be established with ocean water because of the growth inhibition effects and the direct impact on young juvenile roots. Ocean water could only be used on mature halophytic turf (such as seashore paspalum) with a properly designed infrastructure: sandy soil profiles with high percolation rates (>20 in. or 50 cm/hr); surface and subsurface drainage with sump pumps to move the excess salts off the property; proper disposal of removed salts; and the most efficient irrigation system in distribution uniformity and efficiency that can be purchased. Cultivation events would likely be weekly to promote infiltration, percolation, and drainage. Leaching events would be daily in a maintenance, rather than reclamation, schedule strategy and the water volume must exceed evapotranspiration at least >10% (humid climate) to 20% or more in an arid environment. Extra amendments (calcium, wetting agents, hormones such as cytokinins, micronutrients, etc.) would be needed weekly, and maintenance of all golf course equipment would increase exponentially, requiring washing with low-saline water and waxing each time the equipment comes off the site. Choices between granular and liquid fertilizers would become more critical. The challenges to maintain turf at a level of performance expectation and not create an enormous environmental disaster would be significant and never-ending. The absolute total management focus would be to effectively and efficiently manage salts; otherwise, salts will rapidly accumulate at levels that could sterilize the soil profile and overwhelm even the most salt-tolerant halophytic turfgrass. A majority of the salt-tolerant halophytic turfgrasses **tolerate salinity**, but they do not remediate or alter salt loads in soil profiles once they have accumulated.

7.1.2 THE DILEMMA

Water quality and availability of that water have a dramatic influence on site-specific turfgrass management strategies, regardless of whether salt-laden reclaimed water or ocean water or blends of the two sources are used as the source of water. Salt water intrusion is a major concern in coastal areas (Newport, 1997; Todd, 1997). Water withdrawal from coastal groundwater aquifers can contribute to degradation of water and soil quality due to intrusion by lower-quality water. Renewal time for fresh groundwater resources is estimated at 300 years (Gleick, 1993).

Salinization of soil and water resources is another problem associated with use of highly saline irrigation waters and was the subject of Chapter 6, which very much relates to sensible use of seawater for irrigation. Salinization of irrigated land occurs when dissolved salts accumulate in the upper soil layers on naturally saline lands, on lands with poor drainage, in arid/semiarid regions, or on lands utilizing salt-laden effluent (recycled water) over many years. Accumulation of excess total salts (salinization) and sodium (sodic soil formation) in the soil is more rapid as irrigation water quality declines, unless the salts are continuously managed. The dilemma confronting turfgrass managers is how to effectively use water of poor quality without causing excessive salt loading problems in soils that will result in substantial growth-regulated decline in turfgrass quality and performance. An additional concern is to not accumulate excess salts in the soil to a level where effective salinity and turf management become unfeasible. Yet, most recreational turf will be mandated to irrigate with alternative nonpotable resources, so more individuals will be considering the role of seawater irrigation (California Assembly Bill 174, October 1991) and especially blends of that water source.

7.2 BASIC PRINCIPLES

Glenn et al. (1998) presented basic guidelines for sites using seawater or seawater blends for irrigation on agronomic crops. The guidelines are presented as they would apply to turfgrass situations.

- Halophytic turfgrasses and landscape plants should be planted. Highly salt-tolerant grass species include seashore paspalum (*Paspalum vaginatum* Swartz), saltgrass (*Distichlis stricta*), and alkaligrass (*Puccinellia distans* (L) Parl).
- Golf courses and other recreational turf sites should be constructed on sandy, well-drained coastal areas with high initial infiltration and percolation rates for long-term sustainability.
- Irrigation volume should be available at sufficient levels to routinely leach salts, minimizing the concentration of salts in the root zone, and preventing dry-down of the surface due to high rates of evaporation and percolation. Constant leaching events, especially with lower-salinity water, are critical, and proper irrigation scheduling is essential for turf management success.
- Salts must be removed by adequate drainage on all irrigated areas and be properly disposed of to prevent contamination of any potable groundwater sources under the site and to prevent secondary soil salinization. In some arid sites with deep sands and deep water tables, sequestration in the soil may be acceptable with proper infrastructure design.
- Pumping cost of wells near the ocean is higher because of increasing irrigation demands (for proper leaching), but minimal water lifting is normally required due to shallow water tables, thereby offsetting some of those overhead costs.
- Coastal aquatic sites are impacted (especially salt water intrusion) and should be carefully monitored. Hydrogeological assessments are an essential pre- and postconstruction consideration for the site. Knowledge of the tidal influences and other water dynamics on the site before planting grass is important.
- Maintenance costs may be 50% higher than in non–salt-affected areas because of continuous application of amendments to minimize salt buildup, and because of increased corrosion that requires constant maintenance and regularly scheduled monitoring of irrigation components and other equipment for possible frequent replacement.
- Highly trained turf managers and support personnel are necessary because of the site-specific complexity of the salt-related problems when using ocean water for irrigation.
- Unnecessary traffic on turfgrass (fairways) should be eliminated to (1) offset wear recovery due to the normal growth reduction caused by salt stress (injury recovery, even for halophytic grasses, will be slower than for nonsaline water use) and (2) avoid compacting saturated soils frequently irrigated to field capacity in order to promote leaching.

- Salt management on the site will require more regularly scheduled surface and deep cultivation events to maintain sufficient macropore space for maintenance leaching.

7.3 CONSTRUCTION CONSIDERATIONS: INFRASTRUCTURE IMPROVEMENTS

As irrigation water salinity increases, and especially when blended ocean or brackish water is going to be used on turfgrasses, several preconstruction infrastructure improvements should be implemented before planting grass. Improvements at this stage will at least provide the site-specific microenvironments needed for long-term management of high-salinity water.

7.3.1 IRRIGATION SYSTEM CAPABILITIES

Chapter 10 contains additional information on this topic, but a review is appropriate in this section. Irrigation system design efficiency entails the following: sprinkler head spacing (i.e., closer spacing) for uniform water distribution and coverage; nozzle size tailored to soil texture (infiltration and percolation rates of fine-textured soils may require low application rates and timely pulse applications); and individual sprinkler head control (in volume and timing sequence, low flow heads on berms, mounds, bunker faces, surrounds, and slopes) to ensure flexible scheduling and application distribution efficiency. Pulse irrigation is essential on heavier-textured soils with low infiltration and percolation rates, or with poor or slow drainage characteristics, because it can become difficult to effectively manage irrigation water and to match precipitation rates (using large-volume applications or using widely spaced turf sprinklers) to the infiltration rates in these salt-challenged soils. Pulse irrigation provides water to the turf at a rate up to runoff; then stops to allow for infiltration/percolation, followed by repeated cycles during one day/night or multiple days/nights. On fine-textured soils, intermittent application of water throughout a daily irrigation cycle (or over 2–3 nights) via pulse irrigation provides for the following:

- Maximum leaching effectiveness of excess soluble salts by fostering unsaturated flow through all soil pores rather than saturated flow via the macropores.
- A more effective means of leaching excess Na that causes soil structural breakdown (sodic soil conditions).
- Minimal surface precipitation of Ca, Mg, and Na carbonates that may contribute to surface sealing, especially if a light (short-duration), frequent irrigation schedule is used.

Leaching is the number one management requirement for all salt-affected turfgrass sites. The purpose of leaching is to remove excess salts or prevent sodium and chloride accumulation, and this is especially applicable to seawater irrigation (see Chapter 11). The leaching requirement (LR) is the quantity of water required to maintain a moist soil profile with consistent net downward movement of salts below the turfgrass root zone that is over and above turf evapotranspiration (ET) replacement and any irrigation applied or rainfall deposited to account for nonuniformity of the irrigation system. Turfgrass ET can be high owing to a combination of coastal winds, topography changes, or high temperatures, especially during establishment when soil evaporation is excessive and turf density is minimal. As expected, total irrigation water needs to include ET replacement and irrigation to address irrigation design inefficiency and LR. Total irrigation water volume could average 20–50% higher when using ocean water or their blends compared to non–salt-affected situations just to accomplish the necessary leaching fraction with each irrigation event. Total control of irrigation distribution efficiency is a mandatory requirement for using ocean water and blends in order to apply ample water in a timely fashion. Because seawater irrigation should only be attempted on high sand sites with minimal clay or silt that could be dispersed by Na (i.e., sites with high infiltration and percolation rates), this greatly aids in reducing the LR. Finer-textured soils would have a very high LR, resulting in excessive waterlogging and irrigation scheduling difficulties.

The additional volumes of water needed to leach salts delivered by seawater or other poor-quality water blends can require special consideration when designing the hydraulic capacity of the irrigation system. Pipe sizes will need to be increased to avoid excessive flow velocities that cause subsequent "water hammer" and "fatiguing" damage to PVC components. Inadequate pipe sizing will result in a longer window for total operating time, resulting in sprinklers operating before dusk and after dawn, interfering with both maintenance operations and golf play. A general rule of thumb when designing the irrigation system is that no greater than an 8-hour window of operation should be needed to irrigate the golf course at maximum volume and ET while adjusting for the proper leaching fraction and any environmental challenges, such as high winds.

Because salt leaching is more effective with higher-quality irrigation water, considering the availability of a second irrigation water source for periodic use is important. One option as an alternative water resource, especially for blending, is **desalinization**, which is discussed in Chapter 12. Some general considerations are cost comparisons (equipment costs can average between $1–$1.5 million; constant energy use dependency; expensive maintenance) and volume of water produced (range varies from 100,000–600,000 gal/day depending on unit size, membrane efficiency usually 30–40%) (California Coastal Commission, 1999). Other aspects to consider include (1) permitted disposal of concentrated brine, (2) storage or direct blending options, (3) continuous or sequenced run time, (4) salt level of initial saline water source, and (5) target salinity of desalinized water for blending or direct use. The pros for reverse osmosis water to be used for turf irrigation include access to lower-salinity water and dependability of water quality. The cons for RO water include limited production volume that is time dependent, corrosion challenges on equipment, continuous high-energy requirements and high operational costs, added maintenance costs of equipment, disposal of concentrate, need for possible blending because of time-dependent low-volume output, need for possible storage, and initial startup costs.

When a better-quality water source is available in conjunction with seawater, consideration should be given to a **dual mainline system** to allow irrigation of salt-sensitive areas (overseeded cool season grass or primary grass putting greens, clubhouse landscape areas). Another alternative is a system of multiple storage lakes that allows blending or provides alternative lower-salinity water sources for leaching cycles. Under either of these scenarios, reverse osmosis could be incorporated into the system to supply water for occasional leaching, blending, or management of salt-sensitive areas. Any of these options should be included in the design phase on a cost-effective basis. The dual irrigation system would prove beneficial for the following:

- Irrigation of golf greens or environmentally and cosmetically sensitive areas with reduced salt-laden sources (such as reverse osmosis water or reclaimed water) and for effective leaching of salts downward below the turf root system, because better-quality water is more effective for leaching.
- Flexibility in use of alternative (hopefully lower-salinity) water resources during times requiring high-volume leaching events, especially after high-ET periods.
- Application of fertilizer or other amendments through the irrigation system.

Corrosion of irrigation hardware and other equipment exposed to ocean water and its blends is also a major concern and should be addressed within the design specifications and budget. Plastic pipe and sprinklers are naturally preferred where feasible. Where steel components are normally specified, epoxy coating, high-grade stainless steel (Austenitic), or ductile iron fittings on PVC mains should be investigated for improved longevity and economic feasibility. Custom manufacturing using "seawater-resistant" nonferrous metal blends, and marine or reclaimed water-grade equipment and paint may also be options for consideration. Components exposed to salty sprinkler spray (wetting and drying cycles) will deteriorate more rapidly than those that are always immersed or submerged. Items such as controller cabinets should be manufactured from stainless steel or plastic and be maintained in a relatively watertight condition to inhibit corrosion of internal electrical components and connections. All buried wiring splices should be made with the highest-quality waterproof-type connections. Another option would be to install a radio-operated control system that eliminates the need for hardwiring of a low-voltage signal loop between the central control computer and the satellites. This type of system would eliminate a number of additional and potentially troublesome electrical connections that are prone to failure under highly saline conditions.

7.3.2 SAND-CAPPING AND DRAINAGE

Highly sand soils are very desirable whenever using any moderate-to-high saline irrigation water, but when using seawater or seawater blends, it is essential. Salinity control by leaching is much easier on sands compared to fine-textured soils that have lower infiltration, percolation, and drainage rates. The leaching requirement is lower and salt removal is more rapid on sands. Additionally, sandy soils that drain more rapidly will return to playable conditions in less time following leaching and will resist compaction from maintenance equipment and other traffic when wet, unless sand sizes are predominately small in size (< 0.15 mm). Continuous paved cart paths and cart restrictions on the turfgrass areas are also recommended to minimize traffic damage from stresses due to (1) reduction of turfgrass growth rates caused by salt accumulation and recovery time required from high wear/traffic events, and (2) excess compaction when traffic occurs on saturated soils following regular leaching events. For sandy sites, compaction would be less of a concern.

Although use of a sand root zone seems logical when seawater or its blends are used for irrigation, many coastal sites contain marine clays or soils dredged from the ocean bay that contains considerable salt-laden "fines." These soils should be avoided if at all possible. For saline-sodic soils dredged from an ocean bay and capped as the top soil for growing the turfgrass, several practices are suggested to alleviate the high total salts and excess Na that will cause considerable soil structural deterioration:

- If these dredged soils are used, they should be deposited in nontraffic areas and on sites requiring limited irrigation (out-of-play areas).
- Deep tine (10–14 in./250–350 mm) aerate and apply 200–600 lb gypsum per 1000 ft^2 to the soil surface and rototill into the top 6 in./150 mm. Higher rates may be needed for heavier clay soils.
- Apply an additional 200 lb gypsum per 1000 ft to the surface and cap with 2+ in. (50+ mm) of coarse sand.
- Even in nontraffic areas, sand-capping should be used if possible. Cap with a minimum of an additional 6 in./150 mm of coarse sand. The more coarse the sand (especially 0.5 to 1.0 mm range and none exceeding 2.0 mm), the better the rate of infiltration and percolation and the faster the leaching with less volume of seawater or blended irrigation. Coarse sand in the 1.0 to 2.0 mm range should probably not exceed 10–20% by volume of the total coarse sand to minimize damage to golf clubs and maintenance equipment. Use of inorganic amendments such as zeolite will provide minimal water-holding capacity improvements and increased cation exchange capacity (CEC) for sequestration of critical nutrients such as K and micronutrients. Use of water-holding amendments, such as the porous ceramics or diatomaceous earth products should be minimized because most of the water-holding capacity is in micropores that are difficult to leach.

On any areas receiving traffic where the soil is fine-textured, high in silt and clay content with low infiltration and percolation rates, application of a 6–12 in./150–300 mm medium-to-coarse sand layer (cap) over the existing soil will enhance the leaching effectiveness of the root zone by (1) allowing a zone for water to be applied without runoff or waterlogging, (2) creating the ability to use pulse irrigation more effectively in a shorter time frame, and (3) reducing the surface soil compaction potential from traffic and sodic-induced soil structural deterioration that would reduce infiltration.

However, one precaution to consider is the initial salt load in the native soil under the sand cap. Those accumulated salts can move upward rapidly through the sand cap via capillary pores if water volume applied is surpassed by ET. The existing salt-laden soil should be aerated, if possible, and an application of granular gypsum or lime applied to the surface prior to sand capping. The volume of gypsum or lime to apply would be determined by the exchangeable sodium percentage (ESP) and base saturation percentage sodium values (Carrow and Duncan, 2000). If 4–5% by volume of zeolite is incorporated onto the coarse sand cap, this amendment would provide improved CEC, while enhancing cation nutrient-holding capacity.

One additional alternative—**a sand-based fairway system with full drainage**—could be considered. The concept involves creating the worlds largest USGA "green" by letting the subsoil seal with excess Na^+ and installation of a subsurface drainage system below the sand root zone layer. The drainage system would allow collection and disposal of the salt-laden drainage water, if engineered correctly, and would also protect any potable groundwater or aquifers in the immediate area. The root zone sand and any amendments (zeolite, for example, for improved nutrient management) should be evaluated by a reputed soil physical laboratory to determine performance characteristics and appropriate depth of the sand cap for effective salt management.

Construction costs would initially be higher, but savings in deep aeration, gypsum applications, and associated labor to perform these maintenance operations could conceivably pay for the drainage system over a 6-year period. For example, approximately 2378 lb gypsum (23% Ca) per 1000 ft^2 must be applied for every acre-foot of seawater irrigation to counter the high Na^+ concentration. In deep sands with less than 2–3% silt and clay, the gypsum rate can be reduced by 50–70%. However, these sand-capped sites will still require the high gypsum rates to maintain adequate Ca levels for plant growth and to maintain less sodic conditions in the subsoil so that fines do not rise as dispersed fines from the subsoil.

For practical purposes, assume the turfgrass area covers 100 acres and the gypsum costs $100 per ton, or about $2178 per month (at 100 lb per 1,000 ft^2 per month, or about $5180 per acre-foot of seawater). Assuming a 7000 yd turf area and $6.00 per linear foot for solid perforated pipe including main drains and occasional drain basins, a 30 ft lateral drain spacing would cost about $997,200 and 20 ft lateral spacing would cost about $1,432,800 initially for the fairway drainage. If the gypsum rates could be reduced to 50% for treating the sand cap (instead of keeping the subsoil draining) and utilizing subsurface drainage, the system could pay for itself relatively quickly. With heavy rains from monsoons, hurricanes, or tropical storms, this drainage system would be extremely beneficial for rapid removal of excess water and for minimizing puddling or slow infiltration on the fairways and costly downtime for a facility.

7.3.3 SALT DISPOSAL

The turf site design must include plans for *environmentally sound disposal of leached salts* (and/or brine/concentrate if reverse osmosis is used) when seawater or blends are to be used for irrigation. The primary considerations involve the following:

- Avoidance of salt accumulation below the turfgrass root zone in an increasingly concentrated form. Eventually, this zone of salt accumulation will rise to the soil surface and cause catastrophic injury to all plants and their root systems. Thus, a leaching program is essential. There may be some sites in arid regions where salt sequestration is acceptable in the subsoil; however, the leaching requirement must be such that the salt-laden horizon is well below the root zone, will not rise by capillary action into the root zone, and will not move laterally into lakes or other surface waters.

- Prevention of leachate or salt seepage into an aquifer that is used for drinking or other uses, or a freshwater off-site area, or contamination by salt water intrusion due to excessive removal from the potable or low-salinity water source.
- If water tables are near the surface, sump pumps might be needed to effectively move excess salts from the drainage lines to some permitted disposal site away from the turfgrass area.

These considerations involve proper land surface contouring, subsurface contouring, and adequate deep-tile drainage lines (3–5 ft/900–1500 mm) with outlets either directly into the ocean or into a carefully constructed and impervious well or holding pond. If the sand-capping system discussed in the previous section is used, tile lines would be constructed at a more shallow depth. The 34,486 ppm of total salts in seawater is equivalent to 2153 lb salt per 1000 ft^2 per foot of seawater applied. Deep coarse sands (>0.50 mm) with high percolation rates (>10 in./250 mm per hour) are strongly recommended when seawater and blends are used for irrigation.

Because drainage water will move to the drainage lines, any Na-dispersed fines may also move to the drain. Mixing coarse particle size gypsum in the drain trench backfill may help to avoid plugging. This practice is especially important if many fines are present in the root zone or in the subsoil that may migrate upward in the soil profile.

7.3.4 Site Assessment for Seawater Intrusion

Most of our discussion has focused on intentional use of seawater for irrigation, usually as a blend component, but as was noted earlier, unintentional seawater irrigation sometimes occurs. Thus, on coastal sites, site assessment for the potential contamination of irrigation water sources should be practiced. This entails monitoring water conditions by location and over time, especially if the source is brackish or the water is obtained from a well subjected to salt water intrusion where the salt water retreats during wet periods or encroaches during dry periods. Intrusion of salt water into a well head can occur abruptly, and consequently, regularly scheduled and proactive water quality testing will be necessary. If salt-laden effluent is used directly or blended with seawater, quality should be monitored over time. Relatively inexpensive electrical conductivity meters can be easily used by turfgrass managers for frequent on-site monitoring of total salinity.

Although seawater directly from the ocean has fairly consistent quality, seawater drawn from wells may be influenced by local soil and aquifer conditions, such as those exhibiting higher bicarbonates (HCO_3^-), or from excessive levels of other components, such as heavy metals or boron or extremely low pH (<5.0) conditions where Al or Mn levels might be exceptionally high. Knowledge of water constituents and their fluctuation over time is essential for making the correct and cost-effective management decisions.

7.4 ESTABLISHMENT, GROW-IN, AND MANAGEMENT OF TURF

7.4.1 GRASS SELECTION

As high-quality water becomes an increasingly scarce resource, continued development of salt-tolerant species (turfgrass, trees, ornamentals, and other landscape plants) will become significantly important for all recreational landscapes. The most evident example evolved out of research funded by the USGA that resulted in development of high-quality, environmentally friendly, salt-tolerant **seashore paspalum** (*Paspalum vaginatum* Swartz) turfgrass cultivars for use on greens, tees, fairways, and roughs with some cultivars, such as Sea Isle Supreme, able to tolerate ocean water quality for periods of time (Duncan and Carrow, 2000). This grass currently provides a unique opportunity in temperate and tropical climates to utilize alternative water resources for irrigation. Additional research and breeding efforts to improve salt tolerance of cool season species (some private companies have made this a priority) such as alkaligrass (*Puccinellia* spp.) will extend alternative water use to northern climates in the northern hemisphere and southern climates in the southern hemisphere.

Growth rates of all turfgrasses, including seashore paspalum, are reduced when exposed to increasing levels of salinity. Older hybrid bermudagrass (Tifway 419) and creeping bentgrass cultivars (Seaside, Seaside II, SR1020, and Celebration are better choices) will tolerate only about one third or less ocean level salt; and, therefore, may be suitable for use with some blended effluent and/or brackish sources depending on site infrastructure and water quality of seawater blends with less than 25% seawater component. However, selected ecotypes of seashore paspalum can tolerate straight ocean water (TDS = 34,486 ppm salt, $EC_w = 54\ dSm^{-1}$, SAR = 57.4 meq L^{-1}, Na = 10,556 ppm, Cl = 18,980 ppm, Mg = 1304 ppm, Ca = 420 ppm, K = 390 ppm, SO_4 = 2690 ppm, HCO_3 = 146 ppm) with sandy soil profiles, high percolation rates conducive to downward movement of salts, proper irrigation distribution uniformity, and site-specific fertility management. However, it has to be emphasized that long-term management of any turf with ocean water is not environmentally sensible and is not recommended. The grass may be able to tolerate the ocean water salinity, but the soils, unless the correct infrastructure components and grass management strategies are implemented, may not functionally survive the excessive salt loading with each irrigation cycle.

Landscape plants must also be able to tolerate high total salts, and the associated Cl and Na toxicity levels. Careful planning and proper management are the keys to success when using seawater blends for irrigation on turfgrass and landscape plants. Human and building exposure to spray drift of ocean water blends should also be considered.

Obviously, on sites that will be exposed to straight seawater (by short-term irrigation or flooding) or where seawater blends or similar brackish water will be used, selection of salt-tolerant grasses is essential. However, a word of caution: all cultivars of a particular species do not possess the same salt tolerance level. In the case of seashore paspalum, some are greatly stressed by exposure to 12,000 to 15,000 ppm salinity, and the more tolerant ones exhibit good growth at more that double these levels. The same situation is likely to be true for other halophytic plant species.

Additionally, the genetics controlling salinity tolerance in seed germination or juvenile seedling growth and the genetics controlling mature plant salinity tolerance are different, and management programs must be adjusted accordingly.

7.4.2 ESTABLISHMENT AND GROW-IN

Salinity tolerance during establishment is much lower than for mature turfgrasses, including very salt-tolerant halophytes. Thus, none of these grasses can be established from sprigs or seed using ocean water or high ocean water blends initially after planting and during early growth owing to the severe growth regulatory effects and root desiccation problems caused by the excess salts. Root system development would be severely or completely suppressed. Even sodding would be a problem because the root system would have difficulty in developing root hairs, in branching, and in developing stolons and rhizomes. Besides the high salt impact on the root system, turfgrass growth rates will be reduced, and the amount of reduction is determined by the level of salinity tolerance and microenvironmental interactions for each cultivar on each site. The result will be slow establishment and a prolonged grow-in period that will delay full turfgrass canopy coverage.

Wind, high temperatures, and exposed sandy surfaces during establishment and early grow-in can place very high evaporative demands on the overall turfgrass system. Under these conditions, salts can easily accumulate in the surface during establishment. It must be emphasized that during establishment and early juvenile growth, use of seawater or high seawater blends is not recommended. After the initial establishment phase, grow-in (achieving full coverage and transition to a mature stand with mature plants) may allow somewhat higher salinity levels, but more rapid coverage will occur with better-quality, low-salinity water. If highly saline irrigation water is to be used on a routine basis, then application of this water should be delayed until full grow-in and canopy coverage if possible, and seawater should definitely not be applied during the initial establishment phase.

Proper management techniques can minimize the need for an expensive replanting and aid in rapid establishment. Factors to consider during the initial establishment phase are the following:

- **Alleviation of Na-induced soil physical problems in the surface zone**. Aggressive deep and frequent shallow cultivation, monthly or more frequent gypsum or lime applications, medium-to-coarse sand topdressing, and frequent maintenance leaching are key management options during the critical establishment period. If the soil is already sodic from the influence of seawater or brackish water high sodium exposure, apply the quantity of gypsum or lime required to aid in reclaiming the soil prior to establishment because large quantities can be applied and deep tilled. This is especially important for soils containing even modest quantities of silt or clay. The quantity of gypsum or lime depends on the soil texture and how sodic the soil might be (i.e., percentage Na base saturation on the CEC, or exchangeable Na percentage, ESP) (Carrow and Duncan, 1998). Even if large quantities of gypsum or lime have been added, it is important to apply a surface application of 30 to 60 lb gypsum per 1000 ft^2 so that the soil surface does not seal from Na dispersion, which would make irrigation water infiltration and percolation difficult. As the grass matures and poorer-quality water is applied, gypsum or lime applications should be made periodically to maintain surface permeability and always be made to avoid creating Na-affected layers deeper in the soil profile from the frequent irrigation applications during establishment where water (wetting front) penetration tends to be in a uniform zone, often at 3 to 4 in. (75–100 mm). Applications to more mature turf stands is often done in conjunction with core aeration. The gypsum or lime is also an excellent continuous slow-release Ca source for plant nutritional needs, which is required in these situations. Acid sulfate sites may require not only gypsum but lime applications mixed into the root zone, and some product should be surface-applied during grow-in. Dolomite applications should be avoided because additional Mg is added with this product and ocean water and blends already have high Mg concentrations.

- **Reduction of total salts for establishment.** Seawater has a total salinity level of $EC_w = 46$ dS/m (using a 750 conversion, $EC_w = 54$ dS/m when a 640 conversion is used. The most appropriate conversion factor for seawater is 740). Total salts will only be reduced below 46 dSm^{-1} or 34,560 ppm TDS after a heavy rainfall (cyclone, typhoon, hurricane, etc.) or prolonged rainy period, by use of lower-salinity water resources (reclaimed, brackish, and reverse osmosis water or blends), or by blending with lower-salt-containing water resources. Thus, use of high-quality, low-salinity water is strongly recommended; and even with halophytic grasses, seed germination and establishment by vegetative means will be greatly reduced as salinity increases.

For seashore paspalum, the safe establishment limits seem to be irrigation water of TDS < 5,000 ppm regardless of means of planting to achieve a high percentage initial plant survival and reasonable rate of grow in and canopy coverage. Vegetative propagation by sprigging does not appear to offer any higher tolerance to salinity than by seeding (only one seeded type available at this time, SeaSpray) for seashore paspalum. Paspalum sprigs seem to be more sensitive to salinity of 4000 to 8000 ppm when temperatures are in the 75 to 90°F range, but above 90°F, salinity tolerance may be reduced by at least half. Although establishment may be possible at somewhat higher salinity levels, the process will be very slow and costly. For other halophytic species, the limits will likely be different. If the soil was saline, preestablishment irrigation must be applied to reduce the salinity levels to an acceptable level. Preestablishment leaching would be applied after adding gypsum or lime treatments. Leaching should be ample enough to leach salts to at least 8 in. (200 mm) deep in the soil profile, and then the site should not be allowed to dry or the salts will rise by capillary action to resalinize the surface. For highly saline sites, leaching beyond 8 in. (200 mm) would be preferable.

- **Maintenance of a uniformly moist soil profile**. Assuming no rain, soil salinity will be no lower than the irrigation water salinity used during establishment if an excellent leaching program is maintained. The drying process concentrates salts in the soil solution, thereby increasing the overall plant salinity stress. During the initial turfgrass establishment phase, irrigation should be frequent enough to avoid drying of the surface, but if the soil is more fine-textured, care should to be taken to avoid waterlogging. By maintaining a moist soil, salinity stress is reduced. As noted, on sites where the soil was highly saline, initial leaching is required to reduce surface soil salinity to acceptable levels to provide an manageable profile for root establishment and growth. Thereafter, irrigation should be frequent enough to prevent excessive drying of the surface and to prevent capillary rise of salts from lower in the soil profile—that is, the previously leached salts that are located deeper in the soil. In general, if water is moving upward and downward (fluxing) in the soil profile, salts will also be moving, resulting in a dynamic ecosystem with constant moisture and salt flux in the soil.
- **Adequate initial fertilization and careful monitoring of micronutrients**. A spoon-feeding approach (frequent applications, 1/10th to ½ X rates) is necessary on seawater blend irrigated sites, starting during the seed germination and/or sprig establishment phases. On mature turf stands, total annual fertilizer nutrients should be applied at 1.5–2.0 X for levels used on areas irrigated with non-salt-laden water; thus, a well-planned spoon-feeding or prescription fertilization program will be required. Spoon-feeding programs can be very diverse and include foliar, fertigation, water-soluble carriers, slow-release carriers (Carrow et al., 2000). During initial establishment, spoon-feeding should be practiced; but as the transition to poorer water quality is made, it becomes even more critical (although higher annual rates of fertilizer are required, the rate per application is similar to non-salt-affected sites, but with a frequency). Use of highly soluble fertilizers and fertigation through a well-designed irrigation system would be very beneficial during establishment, grow-in, and on the mature stand. Adequate phosphorus (2–3 lb P_2O_5 per 1000 ft^2) should be applied to the surface at planting to promote establishment. Soil test analysis will reveal the need for additional fertilizer nutrients in conjunction with nutrients supplied by the seawater. High leaching events can deplete micronutrient (Fe, Mn) levels, and careful monitoring is necessary on a continuous basis. Calcium and Mg are subject to leaching and should be monitored closely. Potassium should be applied frequently (often weekly owing to its high mobility) in a 1:2–3 ratio ($N:K_20$) with N. After initial establishment on sites using seawater blends or highly saline irrigation water, K nutrition may be even higher in some cases and still must be frequently applied. In summary, if salts are being effectively leached through the soil profile, you will also be leaching nutrients and your fertility program must be adjusted to account for the extra water volume needed to manage the excess salts.

7.5 MATURE TURF AND FERTILITY IMPLICATIONS

Use of seawater or seawater blend for turfgrass irrigation significantly impacts fertility management strategies on mature turfgrass stands as well as at establishment. Relative to more mature stands, some of the important impacts are the following:

- Seawater supplies additional elements and nutrients that require adjustment in fertilization protocols and chemical amendments (Table 1.2, Chapter 1; Table 7.1). All the salts contribute to total soluble salt load, with Cl and Na the most dominant followed by SO_4, Mg, Ca, and K, whereas micronutrients are low. Thus, seawater is not rich in most of the nutrients that plants need.
- The high soluble salt load requires aggressive leaching programs that leach valuable nutrients as well as the undesirable salts.
- Na is especially a problem because it replaces Ca, Mg, and K on the soil CEC sites, while inducing deterioration of soil structure and creating a less favorable rooting environment. Although this is an indirect effect of Na on root development and viability, it is significant in fine-textured soils.
- Na is a direct root toxin because it can displace Ca from root cells and cause direct root deterioration. Salt-tolerant plants are more forgiving of Na displacement of Ca in their root tissues owing to their root absorption regulatory mechanisms for that particular salt ion, but some injury will occur even on the most tolerant types when Na levels are excessively high.
- Additionally, Na suppresses K uptake and can easily displace K on soil CEC sites and make it susceptible to leaching.

TABLE 7.1
Quantity of nutrients and elements applied with typical seawater irrigation based on lb per 1000 ft^2 per acre-foot (325,851 gal) of applied seawater

Ion	lb/1000 ft^2/12 in. seawater	meq L	ppm	% of cations
Ca^{+2}	26.2	21.0	420	3.5
Mg^{+2}	81.4	106.8	1,304	17.9
K^+	24.3	9.9	310	0.8
Na^+	659	458.8	10,556	76.9
SO_4^{-2}	168	56.0	2,690	—
$C1^-$	1,185	534.6	18,980	—
HCO_3^-	9	2.4	146	—
CO^3	<1	—	—	—
N			11.5	—
P			0.06	—
Mo			0.01	—
Fe			0.002	—
Mn			0.0002	—

- Although seawater does not require water treatment by acidification (unless the other blended source is high in bicarbonates and results in conditions requiring acidification), it requires an aggressive lime or gypsum (Ca supplemental) program to provide available Ca to counteract excess Na on the soil CEC and to provide adequate Ca as a nutrient. On acid sulfate sites (with a combination of saline + sodic + acidic + Al/Mn toxicity), lime and calcium supplementation will also be required. High rates of soil amendments can induce deficiencies of K and some micronutrients.

The combination of the foregoing direct and indirect factors makes fertility management and management of saline and sodic conditions very dynamic and challenging (see Chapter 13 for more details on the following aspects). Each of the foregoing stresses must be addressed with appropriate management strategies. Thus, a holistic fertilization/chemical amendment program must address the following:

1. Proactive monitoring and maintaining adequate nutrient levels and balances, including macro- and micronutrients.
2. Adoption of a spoon-feeding approach for all nutrients.
3. Because seawater or seawater blends are most likely to be used on predominately sandy soils, enhancement of CEC by zeolite to achieve CEC levels above 3 meq per 100 g is a good science-based strategy, especially on greens and tees.
4. Removing (by leaching) undesirable soluble salts, especially Cl, Na, and SO_4. The Cl and SO_4 ions are readily leachable, and surface lime additions can help transform SO_4 to gypsum. Although some Na will readily leach, appreciable Na is retained in the soil root zone area on the CEC and precipitated as Na carbonate. It is only with displacement with Ca, together with the consistent addition of a suitable leaching water volume requirement, that the Na is transformed into more leachable forms (sodium sulfate).
5. Adding adequate gypsum and possibly lime to address sodic, acid sulfate conditions, and excessive SO_4 levels. Alleviation of sodic conditions and removal of excessive Na and Al (the latter when pH moves below 5.0) as possible root toxins can assist in creating a better root environment for nutrient uptake.

7.6 LONG-TERM MAINTENANCE COSTS

Seawater or seawater blended irrigation water requires **proactive management** to minimize the constant threat of creating saline-sodic soil conditions and their resulting impact on turfgrass performance. The soils will eventually equilibrate to the quality of irrigation water applied. Intensive management includes aggressive inputs of time, labor, and products, all at a high ongoing cost. The high salt loads inherent in seawater or seawater blends do not allow ignoring or putting off costs, because the salts will rapidly reduce turfgrass performance, deteriorate soil quality, and threaten surface and subsurface waters. Once a site has deteriorated, it is even more costly to remediate.

TABLE 7.2
Irrigation water blending options with variable salinity choices

% Blend = ocean water (34,500 ppm): effluent (1000 ppm) total dissolved salts (TDS)										
100:0	90:10	80:20	70:30	60:40	50:50	40:60	30:70	20:80	10:90	0:100
34,500	31,150	27,800	24,450	21,100	17,750	14,400	11,050	7,700	4,350	1,000
% Blend = ocean water (460 meq/L Na or 10,580 ppm): effluent (9 meq/L or 207 ppm) sodium concentration										
100:0	90:10	80:20	70:30	60:40	50:50	40:60	30:70	20:80	10:90	0:100
460	414.9	369.8	324.7	279.6	234.5	189.4	144.3	99.2	54.1	9 meq/L
10,580	9,543	8,505	7,468	6,431	5,394	4,356	3,319	2,282	1,244	207 ppm

Extra chemicals (lime, gypsum, micronutrient fertilizers, highly soluble fertilizers, seaweed extracts, and irrigation water for the leaching requirement) will be needed periodically at a higher rate than a comparable site with good water quality. Some of these added costs are offset by reduced needs for herbicides and other pesticides and by a less expensive water source. Do not base the fertility management program solely on granular or predominately on liquid amendments. Be flexible and supplement with economical sources as dictated by turfgrass response and science-based analytical data.

Cultivation equipment (both surface and subsurface types) to maintain constant water infiltration, percolation, and drainage for efficient leaching of salts through soils is another cost factor. Fine-textured soils will require much more aggressive cultivation programs than sandy soils. The longevity of a cultivation operation is typically reduced by one half on high-Na–impacted sites, and cultivation frequency must be increased. Both deep (10–12 in./250–300 mm) and shallow (3–5 in./75–125 mm) aeration practices are essential for proper and consistent salt leaching. Deep-tine cultivators include hydroject, Verti-drain, Soil Reliever, Aerway Slicer, and Deep-drill. Although not a cultivation device, the WaterWick drainage device can be used to inject high rates of gypsum into sodic sites or gypsum and lime into acid sulfate sites. The HydroJect units and solid tine (0.25 in. diameter by 3 in. long) cultivation can also be used as supplemental devices; periodically hollow-tine core aerate and needle tine to maintain adequate surface pore space and enhance water infiltration/percolation into the soil profile.

Extra irrigation equipment will be necessary. The corrosive nature of high salts in ocean water and its blends will require constant monitoring and more frequent replacement of certain components such as sprinkler heads and irrigation pump components. Irrigation systems designed to facilitate uniform application of water for salt leaching often require more heads because of closer spacing or dual irrigation lines. Additional lakes, pumps and piping for blending, dual irrigation systems, and desalinization/reverse osmosis equipment will increase ongoing long-term maintenance costs.

Injector systems can occasionally be used to treat seawater. Because seawater contains relatively low HCO_3 (146 ppm, 2.4 meq/L) and with Ca and Mg levels at 128 meq/L, acidification for bicarbonate removal is not necessary even in situations where blended water is pumped from ground wells near the ocean containing much higher levels of bicarbonates. However, acidification systems (H_2SO_4, N-phuric acid or urea sulfuric acid, N-control, pH airway, sulfurous dioxide generator) are sometimes used to aid in the formation of gypsum ($CaSO_4$) in the soil by acid reaction with routine, surface-applied lime ($CaCO_3$). This is one method of supplying considerable Ca to displace Na on soil cation exchange sites (CEC). The excess Na combines with the available SO_4 from the acids to form Na_2SO_4, which can then be leached. Another method of supplying high levels of Ca ions to counter high Na levels in seawater is a gypsum injector linked with the irrigation system. Finely ground dihydrate gypsum, and soluble $CaCl_2$, $Ca(NO_3)_2$, or other highly soluble liquid amendments can be added with units that mix the chemicals into water by agitation within a tank. In other units, such as the Diamond-K device, finely ground gypsum and other products can be injected by a simple water flow or shaking device directly into the irrigation line.

Accelerated replacement schedules for all equipment and course accessories are commonly required on sites irrigated with highly saline irrigation sources. Daily exposure to salt-laden irrigation spray, exudation water, and runoff can deteriorate metal components on mowing equipment, utility vehicles, and other accessories such as signs, benches, and ball-washers (much like the corrosion on automobiles in northern climates due to salting and deicing highways). Undercoating and rust proofing treatment/waxing of undercarriages on all equipment each time the equipment leaves the site are recommended. A potable water source should also be used when washing equipment after every use to slow the corrosion process. Wash pad disposal of the water from this facility must also be considered.

Turfgrass manager expertise is another cost. Turfgrass managers on sites with highly saline irrigation water must be well trained in order to maintain high-quality turfgrass at levels of expected performance in a very challenging situation in which the salt challenges are continuous. Salt-related problems are site specific and very complex because of multiple environment–turfgrass interactions. When seawater and its blends are used for irrigation, a thorough understanding of the implications of using this resource must be achieved, the proper infrastructure must be in place, and management decisions must be correctly made. Additionally, the halophytic grasses used on such sites are different from bermudagrass or other commonly used glycophytic grasses.

7.7 SUMMARY

To summarize the special concerns related to seawater or seawater blend irrigation, the following comments are appropriate:

1. **Straight seawater irrigation on turfgrass is feasible for short periods of time or in unintentional situations such as storm-induced flooding, but it is not recommended for long-term use.**
2. **Seawater can be blended with other water sources, but the following considerations are essential:**
   - Highly salt-tolerant turf species and cultivars must be grown.
   - Coarse sandy soil profiles with high infiltration, percolation, and drainage rates.
   - Irrigation strategies that keep salts moving with regular leaching events and keep the soil profile uniformly moist to minimize concentrated salts from rising into the root zone.
   - Good surface and subsurface drainage design.
   - Environmentally safe disposal of excess salts.
   - Careful nutrient management and continuous proactive monitoring.
3. **Pros of using seawater-blended irrigation water.**
   - Noninterruptible supply of irrigation water during drought shortages or rationing.
   - Reduced water costs when compared to “purchased” potable or reclaimed water.
   - Reduced pumping costs compared to similar quality brackish wells.

4. **Cons of using seawater irrigation.**
   - Higher ongoing maintenance costs: cultivation (labor, replacement tines, and equipment repairs), amendments, equipment replacement (undercoatings), salt/brine/drainage disposal.
   - Higher construction costs: sand capping, additional drainage, enhanced irrigation systems, reverse osmosis equipment, blending equipment, etc.
   - High level of management expertise required and the challenges are continuous.

8 Reclaimed Irrigation Water

8.1 RECLAIMED WATER USE ON TURFGRASS

8.1.1 Not a Trend but Mainstream

Use of reclaimed water (recycled, effluent, nonpotable, wastewater, etc.) for irrigation in agricultural and landscape situations has rapidly evolved from a rare practice to an emerging trend, and now to a mainstream practice. Recent publications presenting a global overview of the practice and issues related to using **reclaimed wastewater** (i.e., wastewater that is reclaimed and treated for safe use in agriculture or landscape irrigation) reflect this rapid evolution in the United States (USEPA, 2004), Australia (Stevens, 2006; Anderson, 2006), and internationally (Scott et al., 2004).

Some golf courses and other sites have used reclaimed water for a number of years (Harivandi, 1991; Snow et al., 1994; Borchardt, 1999; Zupanic, 1999; Huck et al., 2000); however, more recently many others have adopted this practice (Carrow, 2000). A survey conducted in 1978 reported 26 respondents then using recycled water (Snow, 1979). A 1999 survey conducted by the National Golf Foundation (NGF) reported approximately 13% of golf courses nationwide in the United States using reclaimed irrigation sources, and this figure increased to 34% in the southwestern arid region, where water availability is a constant challenge (NGF, 1999).

8.1.2 What Is Reclaimed Water?

Reclaimed water has been called by several other terms such as wastewater, effluent, urban water reuse, and recycled water, which can sometimes cause confusion. **Recycling** and **water reuse** are really broader terms that can denote any type of water recycling or reuse: wastewater, harvested urban stormwater, rainwater collected from roofs or other covered areas, drainage water reuse, and other water sources that are rechanneled for another cycle of use. The water may or may not be treated. Various recycling methods have evolved as a resource to conserve water by collection or harvesting and reuse. Some examples of recycling or water reuse that have application for turfgrass sites are the following:

- Urban wastewater specifically treated for reuse as irrigation on turfgrass and landscape sites. This source of water is often called **reclaimed water**. Reclaimed water is the focus of this chapter, which discusses the use of reclaimed water as one of the key strategies for water conservation purposes

(Carrow and Duncan, 2006). The treatment facility could be a centralized municipal system collecting domestic wastewater for treatment or a smaller municipal, decentralized satellite system to serve nearby areas with treated reclaimed water. In some cases, a private water treatment facility may obtain water from a municipal wastewater sewer line or lines coming from a development, treat the water for unrestricted urban irrigation use on a turfgrass site or development, and return the solids to the sewage line, where it would then go to the municipal treatment facility (Okum, 2000; Hamilton et al., 2004).

- **Drainage water reuse**, which was a topic discussed within Chapter 6.
- Collection or harvesting of **stormwater** from high-density areas for storage and later reuse. Stormwater could flow into sewage lines and be a component of the reclaimed treated water. Or, stormwater from surface runoff and/or channeled through stormwater drain lines or canals from a site could be deposited directly into a collection lake without the discharge intermingling with sewage water in the sewage lines. Stormwater issues are discussed in Chapter 9.

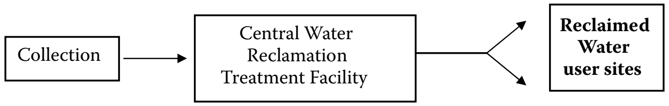
8.1.3 URBAN REUSE

Urban reuse is another term that is becoming more common and encompasses the various urban water reuse schemes. USEPA (2004) notes several uses of reclaimed water in urban areas that would be distributed via the nonpotable reuse system and are encompassed under **"urban reuse" applications**:

- Irrigation of public-owned facilities such as public parks, recreation centers, community sports fields, school yards and playing fields, highway medians and shoulders, public building and facilities landscapes.
- Irrigation of landscape areas surrounding single-family homes, multifamily residences, commercial, office, and industrial developments, as well as general wash down and other maintenance activities.
- Irrigation of golf courses, sports fields, or other recreational turf sites.
- Commercial uses such as vehicle-washing facilities, laundry facilities, window washing, and mixing water for pesticides and liquid fertilizers.
- Ornamental landscape uses and decorative water features, such as fountains, reflection pools, and waterfalls.
- Dust control and concrete production for construction.
- Fire protection through reclaimed water fire hydrants.
- Toilet and urinal flushing in commercial and industrial buildings.

In addition to the various urban reuse applications, many turfgrass facilities may benefit from other reuse applications such as (1) **industrial reuse**—cooling water for air conditioning systems, boiler make-up water, and (2) **environmental and recreational reuse**—natural and artificial wetlands, recreational and anesthetic impounds (i.e., artificial water body impoundments), groundwater recharge (surface water application contributes to groundwater recharge).

A. Central Treatment and Transport of irrigation water to Multiple Reuse Sites.



B. Reclamation of Portion of Wastewater Flow—some of the wastewater is removed from sewer lines for treatment in a satellite treatment facility with sludge returned to the sewage line.

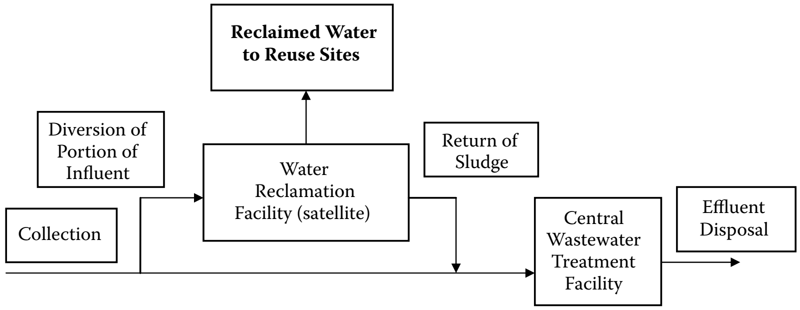


FIGURE 8.1 Common configuration for water reuse systems. (Adapted from USEPA 2004. Guidelines for Water Reuse. EPA/625/R-04/108. USEPA, Office of Water, Washington, DC.)

Initially, urban reuse of reclaimed water was primarily on golf courses and required dedicated reuse distribution lines to the courses from the central treatment facility as well as the normal potable water lines, that is, dual distribution lines. Retrofitting for dual lines from a centralized water treatment facility is very expensive. However, with increased emphasis on widespread adoption of reclaimed water use for urban, industrial, environmental, and recreational applications, municipalities are developing more expansive and widespread dual distribution systems for all users of reclaimed water. Costs associated with developing dual distribution lines for the municipalities may be offset by permitting delays in obtaining additional water supplies, reduced treatment costs associated with new water supplies, and reducing treatment to meet stricter surface water discharge requirements. Additionally, the use of decentralized or satellite treatment facilities closer to the end user has become more common as a means to reduce costs (Okum, 2000; Hamilton et al., 2004). These are especially cost-effective with new housing and golf course developments.

8.1.4 WATER CONSERVATION OR POLLUTION ABATEMENT

Use of reclaimed water as an alternative irrigation source for golf courses, sports turf, sod production, and large landscape or other recreational areas is a practice that should be readily embraced by turfgrass managers, site owners, government officials, and the public when the purpose is for **water conservation** but not when the primary purpose is **pollution abatement**. There are two primary reasons for the increasing use of reclaimed water on landscape sites (USEPA, 2004):

1. To conserve and extend available water supplies, where use of reclaimed water is one of the strategies for an overall water conservation program on turfgrass sites (Carrow and Duncan, 2006). In arid regions, this is often the driving force behind public water reuse programs.
2. Pollution abatement. Diverting effluent discharge from waste treatment facilities away from sensitive (and often potable) surface waters for use in irrigation is a form of pollution abatement. Removal of N and P by treatment to levels that are acceptable for discharge into surface waters is costly. Reclaimed water used for irrigation does not require N and P removal, because these nutrients are used by the plant or absorbed by the soil with application. However, storage of reclaimed water in an irrigation lake can be a problem for the site manager because eutrophication may be stimulated owing to the elevated N and P concentrations. Pollution abatement may be the primary reason to foster reclaimed water use for some municipalities.

Regulations for use of reclaimed water will differ depending on whether the water authority is focusing on pollution abatement or water conservation. For pollution abatement, large volumes of water are applied to a small land area and application rates will exceed ET demand, whereas for water conservation, application rates and water treatment are often designed more according to the needs of the end user. Applying reclaimed water above the site needs for ET replacement or at times of the year when the turf is dormant is environmentally unsound on a turfgrass or landscape site that is used for recreational purposes because of the potential for runoff into surface waters and excess leaching into the underlying aquifers. Additionally, excess water application causes wet, soggy conditions, excessive turfgrass clippings, and increased disease activity. Thus, pollution abatement regulations, if used to require excessive water applications on sites not adapted to receiving excess reclaimed water, actually enhances the potential for pollution problems.

8.1.5 BALANCE OF WATER CONSERVATION AND SALINITY

Although most reclaimed water use has been voluntary, it is now being mandated by municipalities in many regions. Such is the case in California, where Assembly Bill 174 was adopted in 1992, mandating the use of reclaimed water (where available) for all nonpotable applications such as irrigation and industrial use. Water-sensitive cities such as Tucson and Phoenix/Scottsdale, Arizona, and Las Vegas, Nevada, also impose their own unique mandated restrictions. They offer incentives for conservation, limit the amount of potable water available, or require nonpotable irrigation sources for new recreational turfgrass development projects. Often, no adjustments have been made in management programs to compensate for differences in water quality between the recycled water source and the previous irrigation source, and therein lay the challenge to long-term ecosystem sustainability.

In arid regions, water conservation is normally the impetus for promoting reclaimed water use. In their zeal to restrict overall water use for water conservation purposes (including restricting reclaimed water use on golf courses and for other urban reuse landscapes sites), some municipalities are fostering serious environmental and economic problems. In arid regions, the treated effluent or reuse water normally contains higher total soluble salts and Na compared to less arid regions because the influent into the treatment facilities is more saline rich. Recognition of this fact is essential for political and regulatory groups in order to develop realistic regulations that balance the environmental and economic aspects. In the USEPA (2004) guidelines, this important issue is addressed in Section 2.7.6, "Landscape Uses of Reclaimed Water with Elevated Salinity: El Paso, Texas." They note that cost-effective means of enhancing salt leaching are under evaluation. Leaching cannot be achieved unless an effective irrigation leaching fraction is applied during each cycle of water application in order to leach the salts, and this is not possible if regulations on total reclaimed water use are too restrictive to allow site managers to carry out a maintenance leaching program (see Chapters 6 and 11). This is an example of two environmental concerns, conservation and salinization, that must be balanced. Inattention to the salinization issue will have serious economic implications for the site and the community. The environmental challenge is to understand the management shifts required on a site-specific basis when using this water resource and adjust their management strategies for the water quality changes that reclaimed water use brings, especially in arid environments.

8.1.6 Challenges

Whether reclaimed water becomes a noninterruptible "dream come true" water supply for turf sites or a "nightmare" of agronomic problems depends on many factors, as implied by the previous sections. Ultimately, success depends on appropriate local regulations coupled with on-site agronomic management decisions based on the individual environment on-site, the soil profile, the turfgrass species and specific cultivars, the stability in water quantity, and management of water quality challenges. Water conservation (whether mandated or voluntary) and pollution abatement have become important interacting components with reclaimed water use an important aspect of these issues, and this conflict will globally impact all turfgrass managers. Turfgrass managers, politicians, regulatory personnel, and site owners will all be challenged to understand and manage the agronomic and environmental issues. These issues related to reclaimed water use for turfgrass irrigation will be a key topic in the remainder of this chapter.

8.2 REGULATORY ASPECTS

The primary concern of any reuse program is public health protection, especially on (1) unrestricted urban sites—irrigation on public areas where public access is not restricted, such as a public sports fields or parks; and (2) restricted urban reuse sites—irrigation of areas where public access can be controlled, such as golf courses, cemeteries, and highway medians. There are real health issues if reclaimed water is not properly treated before contact with humans (see Chapter 2, and Tables 2.2 and 2.3). Fortunately, there are very effective wastewater treatment methods and other measures that can be utilized to render the use of reclaimed water safe (USEPA, 2004). The USEPA noted that as of 2004, there had not been a confirmed case of infectious disease resulting from use of properly treated reclaimed water in the United States (USEPA, 2004).

Protection of public health is achieved by several levels of regulations. The specifics may differ from state to state and country to country, but the general approaches are similar (Scott et al., 2004; USEPA, 2004; Stevens, 2006). Approaches include the following:

- Water quality and treatment requirements. Reclaimed water must be treated for the intended end use. In the case of reclaimed water used for unrestricted or restricted urban reuse where human contact is likely, treatment must be at a high level to address health concerns (Tables 2.2 and 2.3). Treatments may include secondary treatment, filtration, disinfection suitable to meet the water quality guidelines such as in Table 2.3, and rigorous monitoring. These requirements are the responsibility of the provider/treatment facility and not the end user. Various states in the United States often require that treatment facilities not only meet specific levels for BOD, TSS, turbidity, and coliform, but that the water receive specific treatments, such as disinfection, filtration, and others (USEPA, 2004). Table 8.1 summarizes overall treatment levels. Unrestricted and restricted urban reuse would require at least secondary treatment with disinfection. It should be noted that in advanced treatment, specific constituents can be removed, such as N and P that may not be required by regulatory agencies for urban reuse but would be highly beneficial to specific end users. For example, reducing N, P, and Na at the treatment facility can assist end users concerned about eutrophication in irrigation lakes or potential formation of sodic soils. Sometimes, specific advanced treatment can be negotiated by water users at a cost lower than normal costs to deal with the problem at the site, especially if multiple users join in cost sharing for advanced treatments or the treatment facility deems a specific advanced treatment as desirable.
- Dual distribution lines from the treatment facility to the site.
- Requirements related to the end user site in terms of specific site characteristics, storage, distribution, use, and monitoring (DEC/NSW, 2003).

Our emphasis is on the latter aspect—the turfgrass or landscape site using reclaimed water. Regulations regarding reclaimed water vary considerably among agencies. The following discussions highlight many different regulations, but cannot be considered all-inclusive. It is important to contact the appropriate local agency monitoring recycled water use to determine what standards are required for each specific site.

TABLE 8.1
Commonly used wastewater treatment processes

Level of treatment	Contaminants and treatment processes
Preliminary	Focus: Large floating and suspended solids and grit Processes: Screening; shredding grit removal; removal of fats, oils, and grease
Primary	Focus: Suspended solids, some heavy metals Processes: Chemically assisted sedimentation by coagulation and flocculation to remove sludge from reclaimed water. Reclaimed water then goes to secondary treatment unless it is to be used for a purpose allowing only primary treatment, in which case it would require disinfection for pathogen removal (chlorine, UV)
Secondary	Focus: Suspended solids; biodegradable organics; volatile organics; some nutrients (N, P) Processes: Low-rate processes—stabilization ponds; aerated lagoons; anaerobic lagoons; wetlands; overland flow; soil-acquirer transfer. High-rate processes—trickle filter; biological aerated filter; rotating biological contactor; activated sludge; sequential batch reactors; secondary sedimentation. Reclaimed water undergoes disinfection for pathogen removal (chlorine, UV) if it is to be used at this stage of treatment without further treatment. If the specific use requires further treatment, the recycled water is then processed for advanced (tertiary) treatment prior to disinfection
Advanced	Focus: High level nutrient removal (N, P); suspended solids; heavy metals; organics removal; dissolved solids removal Processes: N removal—nitrification; denitrification; selective ion exchange; overland flow; biological nutrient removal; break point chlorination; activated sludge process. P removal—chemical precipitation using alum or iron salt; biological removal in activated sludge process Suspended solids removal—chemical coagulation; media/sand filtration; membrane filtration (microfiltration); reverse osmosis Organic and metal removal—carbon adsorption; chemical precipitation Dissolved solids removal—reverse osmosis; electrodialysis; distillation; ion exchange; nanofiltration. Disinfection for the intended use by chlorination, UV, ozone

Source: Adapted from Pettygrove, G. S. and T. Asano 1985. *Irrigation with Reclaimed Municipal Wastewater—A Guidance Manual*. Lewis Publications. Chelsea, MI; USEPA 2004. Guidelines for Water Reuse. EPA/625/R-04/108. USEPA, Office of Water, Washington, DC; Stevens 2006. Growing Crops with Reclaimed Wastewater. CSIRO Pub., Collingwood VIC, Australia.

8.2.1 CROSS CONNECTION

Human health concerns are the heart of reclaimed water regulation no matter what agency has developed them. The greatest concern on-site is cross-connection; in other words, the accidental contamination of a potable water supply with reclaimed water. This could lead to unsuspecting individuals consuming tainted water. There are two primary ways that this could take place.

First would be an accidental direct connection of a reclaimed water source pipe to a potable line. To avoid this possibility, most regulatory agencies require new recycled installations to clearly identify any and all lines with either purple colored pipe; burial tape marked "reclaimed, recycled, or effluent water"; or stenciling of pipe at specified distances with the same verbiage. The California–Nevada Section of the AWWA (American Water Works Association) first adopted purple to designate any nonpotable water sources. This has since become the recognized standard in most regions of the country. An annual cross-connection inspection of reclaimed water using sites is usually performed by the regulating agency. On a golf course, this can involve a 24-hour drain down of the clubhouse potable water systems to ensure they are not "directly connected" to the reclaimed irrigation system.

A second way that reclaimed water could contaminate a drinking source is through back siphoning into a potable irrigation system. A simultaneous chain of events would have to take place in order for this to ever occur, but nonetheless, it is possible. They include the following:

- A pump failure or line break causes a loss of pressure and subsequent drainage of the potable supply line, creating a negative pressure (vacuum) at the point of connection (POC) for the potable irrigation system.
- A remote control valve for the potable system is open, allowing effluent drainage to siphon backward into the sprinkler head past the POC and into the potable supply.
- When the potable system is again pressurized, contaminated water could then be delivered to drinking taps.

To avoid contamination problems, anti-backflow devices, such as RPPD (reduced pressure principle device), double check valves, or anti-siphon valves are installed at the point of connection between all potable sources and irrigation systems. The RPPD delivers the highest level of anti-siphon protection and is normally required at each potable POC for those sites using effluent water. Biannual testing of backflow devices by certified personnel are usually required to maintain effluent or reclaimed water irrigation permits.

Line separation regulations vary considerably regarding the separation distance required between potable and effluent delivery lines. Depending on local codes, between 12 in. (30 cm) and 10 ft (3.04 m) horizontal and a minimum of 12 in. (300 mm) vertical separation are normally required.

8.2.2 Public Notification

Signs, tags, and informational messages on irrigation equipment are often required to inform employees, golfers, and the general public that reclaimed water is used. In most cases, a minimum wording is requirement such as: "Caution—Effluent Irrigation Water, No Swimming—Do Not Drink." Most agencies allow additional wording that conveys a more positive message such as: "In the interest of water conservation, this facility irrigates with nonpotable effluent water. Please do not drink or swim in lakes." In addition to the minimum wording requirements, regulations often dictate a minimum letter size on such signs to ensure visibility from a reasonable distance. Areas and components where posting/notification is often required on golf courses include the following:

- Lakes
- Control satellites
- Scorecards
- Property perimeters
- Remote control valves
- Hose bibs
- Quick coupler valves. Also, regulations may require locking lids and/or specially threaded keys.
- Delivery pipe. Identification is by purple color, burial tape, or stenciled identification as specified by regulatory agency.

8.2.3 OPERATIONAL GUIDELINES

Most agencies impose strict operational guidelines regarding how and when automatic irrigation may operate; examples include the following:

- Unattended automatic irrigation may only operate between 9:00 PM and 6:00 AM.
- Runoff or puddling is not allowed.
- Compliance failures with operational guidelines will result in the termination of service.
- System shutdown required when wind exceeds 15 mph.

Such restrictions can cause operational problems when the need to apply water during the day arises. Additional supplemental irrigation, watering in of chemical or fertilizer applications, and establishment of seed or sprigs require an employee with appropriate protective gear present to observe operating sprinklers and protect unsuspecting individuals from accidentally coming into contact with reclaimed water. This requires additional labor; in the past, an unattended syringe cycle performed the job. Where winter overseeding of Bermuda grass is practiced and multiple daytime irrigations are needed, golf course or facility closure throughout the germination period becomes necessary to promote good seedling establishment and avoid violations.

8.2.4 OTHER REGULATIONS

Employee training. The turfgrass manager is normally responsible for maintaining required records and abiding by all local regulations. All maintenance staff who come in contact with or work in and around reclaimed water must also be trained to understand the (1) proper procedures used, (2) rules and regulations, (3) proper protective clothing to wear in case of exposure, and (4) basic cross-connection and backflow principles and procedures applying to reclaimed water use.

Inspections. Part circle perimeter sprinkler heads tend to fall out of adjustment over time and a monthly self-inspection of perimeter sprinklers is required in some jurisdictions to make certain reclaimed water is not leaving the permitted property. The turf manager must submit a monthly report to the regulatory agency. Annual or semiannual walkthrough site inspections with health department officials and/or water department inspectors are also generally required.

Plan submission. Copies of blueprints are also requested by some regulatory agencies for their files. This allows the agencies to have a permanent record of any reclaimed water distribution/irrigation lines should public utilities crossing the golf course or landscape area require repair.

Miscellaneous requirements. Other miscellaneous restrictions and monitoring programs may be required to protect adjoining properties, groundwater, and buildings. Examples include the following:

- Minimum lake lining thickness of 40 mil.
- Verification of ET (evapotranspiration) versus irrigation water volume applied.
- Setbacks or a buffer zone between reclaimed water use and housing/property lines, edible crops, potable wellheads, freshwater lakes, streams, and rivers. Distances ranging from 50 to 1000 ft (15.2–304 m) have been reported.
- Protection of drinking water dispensers (coolers, fountains) on the golf course from overspray or spray drift.
- Minimum daily use requirements.
- Monitoring systems to observe pH, nitrates, orthophosphates, ammonia, coliform bacteria, biological oxygen demand (BOD), turbidity, chlorine residual, other changes in groundwater, freshwater streams, lakes, and monitoring wells.

8.2.5 NEGOTIATIONS

Especially in arid regions, water quality may significantly vary over time, and volume available for a specific user may vary. Thus, a trend has been established for individual users (a single golf course), or more commonly a group of users (i.e., several golf courses in an area), to **negotiate contracts** with the supplier to reduce potential problems (Stowell and Gelernter, 2001). Although this is more common in arid regions, this trend is likely to become a normal operational guideline over time regardless of location. Recommended maximum contractual limits can be used to prevent the water quality from exceeding reasonable limits for specific parameters, especially Na, because it has so many potentially negative aspects, readily accumulates in ecosystems, and is difficult to remove and manage compared to other salt ions. Other potential problems are N and P from the standpoint of promoting eutrophication in the irrigation water lakes. Treatment facilities may reduce treatment costs for reclaimed water relative to treatment requirements if the reclaimed water from the treatment facility was to be discharged into a water body. One area for cost saving is to allow higher N and P levels in the reclaimed water at the treatment plant for subsequent use on recreational turfgrass sites. This is a cost benefit to the treatment facility, but may increase the user costs for lake treatments and storage.

Although there are definite regulations that are not negotiable, there are several areas that are negotiable with the reclaimed water supplier or water authorities. **Common areas of negotiation** are the following:

- Cost.
- Water quality. When a group of water users have similar needs, it is possible to negotiate with the water supplier concerning treatment options that could be performed at the treatment facility with less cost than each user to deal with the issue on site. The participants of the group cost share to pay for the treatment or a portion of the treatment. Examples would be to limit Na content, reduce treatment chemicals that contain sodium, reduce bicarbonate content with acidification, or reduce P levels with alum application during the settling phase at the treatment plant.
- Water availability. Issues include maximum and minimum use requirements, interruptions, what to do if the delivered water does not meet health or contract specifications, seasonal availability, and other end use items.
- Monitoring and reporting. The water authorities may impose different monitoring and reporting requirements depending on the site-specific hydrogeology and water quality of the reclaimed water. Costs are associated with monitoring wells, water tests, and reporting. Although some items may be more rigid owing to regulations, there often is flexibility.

Stowell and Gelernter (2001) note that the contract should especially include (1) definitions on the maximum acceptable water quality limits, (2) on-demand delivery guarantees with access to potable water during pump or delivery line repair periods, and (3) stipulations to avoid the required use of reclaimed water when irrigation is not needed (i.e., end user takes water "on demand" only), such as during rainy or dormancy periods. A turfgrass facility could unreasonably be required to accept a certain volume of reclaimed water when it is not needed. This "must-take" scenario transfers the need for extra water storage and disposal requirements from a government unit to a private user. These issues ultimately become economic costs if they are not negotiated in the contract.

8.3 OVERALL WATER QUALITY

Use of reclaimed water requires consideration of several agronomic and environmental issues (Pettygrove and Asano, 1985; Pescod, 1992; Ayers and Westcot, 1994; Snow et al., 1994; Bond, 1998; DEC/NSW, 2003; Scott et al., 2004; Stevens, 2006). These issues are similar for agronomic, horticulture, or turfgrass plants. Marcum (2006) and Pepper and Mancino (1994) have reviewed the research related to effects of reclaimed water use on turfgrass systems, and Wu et al. (1995) reviewed research noting the effects on landscape plants.

The quality of reclaimed water or effluent, such as the amounts and types of dissolved salts and nutrients, will vary at every location and can change throughout the year. All effluent will have some level of salt and variable nutrient concentrations. Many water reclamation treatment plants offer customers periodic laboratory test results at no charge; however, these data are often incomplete for assessing irrigation quality because they are oriented to the "human impact factor" and have nothing to do with disposal on soils or turfgrass performance. Therefore, soil and water samples should be analyzed on a regularly scheduled basis by a reputable agricultural soil and water laboratory to determine baseline information necessary to develop short- and long-term comprehensive management plans that address specific needs of the individual site. It must be emphasized that **no single management program will be appropriate across the board for any two reclaimed water users because of varying soil and water chemistry and microclimatic differences and interactions.**

Irrigation water quality guidelines to assess potential for turfgrass or agronomic problems are the same as for all other irrigation water sources. These are presented in Chapter 3 and include the following:

- Table 3.4. Total soluble salts.
- Table 3.5. SARw and adjRNa for sodium permeability hazard.
- Table 3.6. Residual sodium carbonate (RSC) for sodium permeability hazard.
- Table 3.7. Specific toxicities (Na, Cl, B) and potential problem ions (HCO_3, Cl_2, SO_4).
- Table 3.8. Nutrient levels.
- Table 3.11. Trace elements.
- Table 3.12. Summary table with average water quality values and nutrient contents of reclaimed sources in California as examples of typical reclaimed water.

8.4 TOTAL SOLUBLE SALTS

The first concern when examining reclaimed water quality is to evaluate the salinity hazard. High total soluble salts in reclaimed water is most likely to occur in arid regions where saline soils and groundwater are common and influence the quality of water going into a treatment plant. In contrast, high total soluble salts is often low in humid-region reclaimed water. Total soluble salts will normally be reported as EC_w (electrical conductivity of water) or TDS (total dissolved salts). EC_w is reported in decisiemens per meter (dSm^{-1}), and TDS is reported in parts per million (ppm) or milligrams per liter (mg/L). A guide for evaluating the salinity hazard of an irrigation water source is found in Chapter 3, Table 3.4. In Chapter 6, a more extensive discussion of saline irrigation water sources is given; so for managers with saline reclaimed water, Chapter 6 is applicable. However, a summary of important salinity aspects is presented here. Buildup of total soluble salts (Na, Cl, HCO_3, CO_3, Ca, Mg, K, SO_4, others) in the root zone:

- Inhibits turfgrass water uptake, thereby, contributing to moisture stress. In severe cases, turfgrasses can exhibit drought stress symptoms while the soil still appears moist (at or near field capacity), and this phenomenon is termed **physiological drought stress**.

- Cause turfgrasses to lose color and to not respond to nutrient applications (i.e., yellowing, browning, or purpling-varies with species).
- Increases the opportunity for direct salt toxicity that is caustic to root tissues due to excess levels of Na, Cl, or B.
- Enhances the potential for excessive uptake of salts into shoot tissues where leaf firing, water redistribution, and tissue injury can occur. These stress symptoms are especially prevalent on saline-sensitive (glycophytes) trees/shrubs/flowers in the landscape and on salt-sensitive grasses.

Juvenile plants are more sensitive to salt injury than mature grasses, and a high-salt-content reclaimed water or effluent can reduce initial rooting establishment and survival rates of seedlings or sprigs. As an example, in regions where winter overseeding is practiced, cool season grass-planting rates should be increased by 10–20% to produce an acceptable quality turfgrass playing surface when irrigating with salt-laden reclaimed water. Extra irrigation water is normally applied for leaching of surface root zone salts prior to and after seeding or sprig planting. All newly rooting turfgrass plants can be negatively impacted, because the increased salinity can shut down or slow down the rooting from seeds or sprigs. Consequently, increasing the seeding or sprigging rates and staggering the planting schedule over 2–3 weeks provides some insurance that an acceptable cool or warm season turfgrass density can be achieved in spite of the reclaimed water quality.

Practical experience has shown that established creeping bentgrass/*Poa annua* mixture greens can become difficult to manage when water EC_w approaches 1.5 to 2.0 dSm^{-1} (soil ECe > 3.0 dSm^{-1}), and hybrid Bermuda grass greens begin showing reduction in quality at higher salt contents, closer to the range of ECw 4 to 15 (ECe 6 to 20) dS/m, depending on specific cultivar. A pure stand of creeping bentgrass falls somewhere between these ranges, with an exception being *Seaside* and some other more salt-tolerant cultivars (Chapter 6, Table 6.2) that have been reported to tolerate an EC_w of 6.0 dSm^{-1} while being maintained at 3/16 in. (4.7 mm) mowing height. The actual point where turfgrass decline begins is dependent on many factors such as degree of leaching, soil physical properties, surface and subsurface drainage, air and soil temperatures, humidity, irrigation system distribution efficiency, specific management programs, turfgrass genetic tolerance, and the skills of the turfgrass manager. Cool-season grasses are most susceptible to salinity stress in mid to late summer as they become weakened by high-temperature stresses and high evapotranspiration, especially when maintained at close mowing heights. Application of sufficient leaching water volume to prevent accumulation of soluble salts in the root zone can allow grasses to grow well up to their threshold ECe levels or even somewhat above; but, without leaching, soil EC (ECe) soon increases to above the reclaimed ECw level and salinity stress escalates. A delay in exercising this management strategy can result in salinity-induced root and shoot desiccation with a rapid deterioration of turfgrass root volume, quality, and density.

8.5 SODIUM PERMEABILITY HAZARD

The next significant concern of reclaimed or recycled water quality is the influence of Na on soil structure, especially if the soil has >3% clay or silt that allows colloidal dispersal or fines to move in the profile. Many reclaimed water sources are not high in Na, but this ion may be excessive in some cases (especially in areas using sodium-based water softeners). When excessive Na is present in reclaimed water, the cost to the end user can be appreciable for soil amendments, cultivation, possible on-site water treatment, and other management costs.

The most common situations for high-Na reclaimed water are in arid regions and/or in communities that have hard water and **water softeners** are widely used. Residential water softeners use rock salt (often sodium chloride), whereas public water treatment facilities often use soda ash (sodium carbonate) to reduce calcium and magnesium scaling problems. Regardless of the site of treatment, Na becomes concentrated in the influent coming into treatment plants, and this is reflected with higher Na content in the reclaimed water used for recreational turfgrass irrigation. Both sodium treatment chemicals and sodium-based water softeners add extra sodium along with carbonates, bicarbonates, or chloride to the reclaimed water that cannot be removed in the reclamation process. A water softener removes primarily Ca and displaces it with Na, which is just the opposite of what must be done for sodic soils and managing perennial turfgrasses. High Na is one of the major causes of degradation of soil structure as a natural resource by creation of sodic conditions; and it adds more cost to the end user to prevent sodic soil formation (FAO, 2006).

Replacement of NaCl with potassium chloride (KCl) for water hardness treatment is one strategy for reducing the Na load in reclaimed water (Wu et al., 1995; Weber et al., 1996; Andorka, 2003). Because of this, many water districts in the southwestern United States that use reclaimed water for irrigation have banned residential water softener use; however, the effort is somewhat futile when water softener salts can be purchased in local grocery stores. More stringent regulations are needed along with research to evaluate different salts that are less harmful to soil structure deterioration and plant growth.

On fine-textured soils, excess Na in reclaimed water causes structural deterioration, which reduces water infiltration/percolation/drainage and often causes low soil O_2 problems. Although sandy soils do not have "structural aggregates" to be broken down by the dispersive action of excess Na, any colloidal-sized particles (colloidal clay or organic matter) in the sand profile are more likely to migrate downward and form a layer. In arid regions during prolonged dry periods, routine irrigation applications often cause particles to move to the depth of irrigation water penetration (wetting front) in sand mixes because excess accumulated Na disperses colloidal particles, which are more prone to migrate and eventually accumulate as a layer usually somewhere in the upper soil profile. Over time, this layering can lead to a less permeable zone and reduced water percolation; enhance the potential for a perched water table above this zone; and can eventually lead to black layer formation (if sulfates accumulate and concentrate) in response to low soil aeration. Poor soil water permeability that is induced by excess Na is especially serious if the reclaimed water also contains appreciable total salts, because salt leaching is often restricted owing to water conservation programs. The primary management strategies for high total salt accumulation in soils are aeration and leaching.

Irrigation water is assessed for its potential to cause Na-induced water permeability problems by determining: (1) SARw—sodium adsorption ratio of water; (2) adj RNa—the SAR is adjusted for the influence of HCO_3 (bicarbonate) and CO_3 (carbonate) on precipitation of Ca and Mg from the irrigation water and soil solution, thereby allowing Na to dominate the CEC; and/or (3) the RSC (residual sodium carbonate) value, which compares HCO_3 and CO_3 concentrations to levels of Ca and Mg (meq/L basis) and reflects how much insoluble precipitate is formed in the soil. Carrow et al. (1999) or Carrow and Duncan (1998) have more detailed explanations for these parameters, but basic guidelines are presented in Tables 3.5 and 3.6.

SAR_w is preferred for assessing the Na-induced permeability hazard when HCO_3^- is <120 mg L^{-1} and CO_3^{-2} is <15 mg L^{-1}. Above these levels, adj RNa and RSC values should be used because these include the actual interactive chemical influence of HCO_3, CO_3, Ca, and Mg or Na activity. There are currently two methods used by laboratories to adjust the SARw for the influence of these ions. The first method was originally presented in the 1976 edition of *Water Quality for Agriculture* by Ayers and Westcot and used the formula:

$$\text{Adjusted SAR} = \text{SAR}\ (9.4 - \text{pHc})$$

This formula, according to the 1985 edition of the same publication, is no longer preferred as it tends to overpredict the sodium hazard. The currently recommended method of determining adjusted SAR (designated as **adj RNa**) uses the SARw formula with a substituted value for calcium derived from a table where the ratios of calcium, carbonates and bicarbonates are compared to the water ECw. For more in-depth information regarding current methods for calculating adjusted SAR, refer to Hanson et al. (1999).

Sodium permeability hazard of effluent water is affected not only by the SARw (or adj RNa), but also by the following:

1. ECw or total salt content of the water. High ECw or total salt concentration in the water inhibits the dispersing influence of Na. Thus, SARw and ECw should be assessed together (Chapter 3, Table 3.5 and Figure 3.2).
2. Soil type. Expanding clays (2:1 clays, which exhibit cracking on drying), such as montmorillonite and illite, are much more susceptible to structural breakdown (at adj RNa as low as 4) than are 1:1 clays (kaolinite, Fe/Al oxides, which do not crack when drying), which can tolerate adj RNa < 16 (Table 8.1). Particle migration by Na-induced action can occur in sands at adj RNa of near 4 when the reclaimed water ECw is <1.5 dSm^{-1}. However, if the reclaimed water contains appreciable salts (ECw > 1.5 dSm^{-1}), migration may not occur until adj RNa nears 16. Particle migration on sands affected by Na is most likely to occur during grow-in when both water infiltration/percolation and water application rates are high.

Infiltration and permeability problems can develop if the SAR or adj RNa is high. Gypsum, acid, or other soil/water treatments may be appropriate. For a more in-depth discussion of this subject, refer to a previously published Green Section Record article titled "Treating the Cause, Not the Symptoms" by Carrow et al. (1999) and Chapter 12 of this book.

8.6 SPECIFIC ION PROBLEMS

Several specific salt ions contained in reclaimed irrigation water may cause problems such as direct toxicities to root or shoot tissues or nutrient imbalances. These are briefly discussed in the next sections.

8.6.1 BICARBONATES AND CARBONATES

High bicarbonates are relatively common in reclaimed water. Although HCO_3 >500 ppm (8.2 meq/L) can cause unsightly, but not harmful, deposits on foliage of plants, HCO_3 or CO_3 levels that result in turfgrass nutritional problems are not specific. Instead, the imbalance of HCO_3 and CO_3 with Na, Ca, and Mg is the most important consideration. When $HCO_3 + CO_3$ levels exceed Ca + Mg levels (in meq L^{-1}), the Ca and Mg are precipitated as insoluble lime in the soil and as scale in irrigation lines. Two problems can arise from excess lime precipitation (Carrow et al., 1999).

First, if Na is moderately high (>150 ppm or 6.5 meq/L), removal of soluble Ca and Mg by precipitation into the relatively insoluble carbonate forms will leave Na^+ free to start to dominate the soil CEC sites and potentially create a sodic (soil structural deterioration) condition. As a general guideline, HCO_3 at >120 mg L^{-1} (1.97 meq/L) or CO_3 >15 mg L^{-1} (0.50 meq/L) in conjunction with at least moderate Na levels are a potential cause for concern. The degree of Na permeability hazard can be determined by adj RNa and RSC values along with consideration of soil type and ECw. Exchangeable sodium percentage (ESP) and base saturation %Na are indicators of how much sodium has loaded into soil profiles from use of the high-sodium irrigation water. High Na on the CEC sites will also depress plant availability of Mg, K, and Ca. Acidification of irrigation water is the normal management option for alleviating these excess bicarbonates/carbonates, because it breaks up the complexes and releases Ca and Mg back into the ecosystem to counter the excess Na.

Second, on sandy soils, the precipitated calcite (lime) may start to seal some of the macropores and reduce water infiltration. With light, frequent irrigation, the site of sealing may be near the surface, whereas under heavier, less frequent irrigation, a calcite layer may form deeper in the profile at the normal depth of irrigation water penetration (wetting front). This problem is only somewhat serious under the combination of high HCO_3/CO_3 + high Ca and Mg + arid climate + sandy soil profile (Carrow et al., 1999). The sealing layer can be broken up by a combination of cultivation (aeration) and use of acidic fertilizers or elemental S. Because it is confined primarily to highly sandy areas such as greens, acidifying the reclaimed or effluent water for an entire golf course would be an expensive option. In contrast, when high Na is present and is a problem on soil types across all grassed or landscaped areas, irrigation water acidification is more feasible and beneficial. The RSC (residual sodium carbonate) value is used to determine the potential management decision for this problem, where RSC = $(HCO_3 + CO_3) - (Ca + Mg)$, in meq L^{-1} (Table 3.6) in combination with the adj SARw.

8.6.2 TOXICITIES FROM EXCESS NA, CL, AND B

Although the guidelines for root toxicities or soil accumulation of these ions in Table 3.7 (Chapter 3) are most appropriate for sensitive trees and shrubs, excessive levels can cause turfgrass root deterioration, but usually at higher levels than noted in the table. **Excess Na** can displace Ca in the cell walls and cell membranes of root tissues and cause root deterioration and nutritional imbalances. As excess Na displaces Ca in root cell walls and membranes (for example, the plasma membrane), these cells often start to leak their contents. Potassium can be lost by root cell leakage. Turfgrasses with low-to-moderate total salinity tolerance often are susceptible to this type of root injury, which then results in roots that are less efficient for overall nutrient and water uptake/osmoregulation. Calcium in a relatively soluble form (not lime) in the root zone corrects this type of Na toxicity (i.e., in reality, a Ca deficiency in the root tissues), especially when leaching removes the excess Na. Foliar application of Ca is not effective for Na-induced root toxicities, because Ca is the least mobile nutrient and is not translocated from shoot to root tissues. However, grasses irrigated with reclaimed water containing high Na (>200 mg L^{-1}) but low Ca (<20 mg L^{-1}) may benefit from foliar Ca to limit Na replacement for Ca in shoot cell wall surfaces. The foliar Ca source should be a soluble one that allows foliar uptake—for example, finely ground lime or gypsum suspensions can be applied foliarly, but foliar uptake will not occur. Soluble Ca sources that are actually absorbed foliarly include calcium nitrate, calcium chloride, calcium acetate, calcium chelated with amino acids or alcohols, and calcium glucoheptonate or gluconate. The symptoms of Ca deficiency in the leaf tissues will be chlorosis of the leaf tissue, usually in a mottled appearance, that progresses to a light yellow discoloration where leaf Ca content would be below the sufficiency range for the species (Carrow et al., 2000). This foliar Ca application should be conducted on a limited trial basis to determine whether any visible response occurs. Normally allow 4 to 7 days for a greening response to occur in the turfgrass plant when calcium is absorbed through the shoots owing to its relative immobility internally in the plant. If the normal green color does not return, additional nutrient tissue testing may be needed.

High chloride does not cause direct turfgrass root tissue injury except at very high levels (i.e., >500 ppm) that are well above the guidelines in Table 3.7 for more sensitive plants. Instead, on turfgrasses, Cl inhibits water uptake as a salt and, thereby, nutrient uptake. Nitrates are especially vulnerable to excess Cl levels. Excess highly mobile chloride is normally translocated to and sequestered in the growing points of plants, which for turfgrass plants is the end of growing leaves. Mowing of turfgrasses normally limits shoot injury from Cl accumulation by removal of the leaf tips.

Treatment of reclaimed water may leave excess **residual free chlorine** (which is Cl_2, a highly reactive form). At greater than 1 mg L^{-1} residual chlorine, foliage damage can occur. After a few hours in a holding pond, when aerated, or when run through a sprinkler system, Cl_2 dissipates into the air. Residual chlorine is normally listed as a separate item on a reclaimed water quality test because it is not the same as Cl ions.

Boron toxicities can be a problem on turfgrasses, especially in arid regions. Injury is expressed as a leaf tip and margin chlorosis. Mowing of turfgrasses aids in reducing B accumulation in shoot tissues when clippings are removed, but at B soil levels > 6.0 mg kg^{-1} (saturated soil paste extract), injury may occur. Kentucky bluegrass is most sensitive at > 2.0 mg kg^{-1}. Irrigation water containing >3.0 mg L^{-1} of B may result in soil accumulation. Except on acid sands, leaching of B is difficult and requires approximately three times the amount of water to leach this element than would be needed to remove an equivalent quantity of Cl or total salts (Ayers and Westcot, 1985).

8.6.3 EXCESS SULFATE

Reclaimed water is often relatively high in SO_4. The primary problem of high SO_4 additions onto turfgrass sites is that when anaerobic conditions occur (usually occurring when aeration events have been reduced and surface sealing occurs), the SO_4 is transformed into reduced S. Reduced S can react with reduced forms of Fe and Mn to create FeS and MnS compounds in the soil. These compounds are potential contributors to black layer when accompanied by sealing of soil pores, which leads to additional anaerobic conditions. Thus, a high S level is normally not the initial cause of an anaerobic condition, but it will greatly amplify the condition and require a more aggressive cultivation program when leaching programs do not move the S compound below the turfgrass root system.

Normally, 2 or 3 lb S per 1000 ft^2 per year is sufficient for turfgrass nutritional needs, and this amount is often provided by SO_4 content in water or with sulfate-based fertilizers. SO_4 content in reclaimed water often ranges from 100 to 200 ppm. Irrigation water at 200 ppm SO_4^{-2} would supply 4.2 lb S per 1000 ft^2 per acre-foot of reclaimed water.

When SO_4 content is above desirable levels in irrigation water (>180 mg/L), the best means of reducing high levels is by leaching. The SO4 ion is readily leachable. Another method is by application of lime to the soil at low rates, which can help "scrub" SO_4 from the system. As SO_4 in the irrigation water reacts with Ca from the lime, gypsum ($CaSO_4$) is created. In this form, S is much less soluble and is protected from becoming reduced (more stable). Application of 10 lb $CaCO_3$ per 1000 ft^2 provides about 3.8 lb Ca that can react with 9.1 lb SO_4, which is equivalent to 3 lb S per 1000 ft^2. Thus, for every 3 lb elemental S (or the equivalent rate of 9.1 lb SO_4) added with irrigation water, 3.8 lb Ca will remove the S through the process of gypsum formation. The Ca can come from the irrigation water itself, but if this is not sufficient, lime can be added to the soil surface to remove the remaining SO_4 in conjunction with aeration and irrigation.

8.7 NUTRIENT CONSIDERATIONS

A number of nutrients may be present in reclaimed water that can affect turfgrasses and landscape plants (Huck et al., 2000; King et al., 2000) (Table 3.8). The quantities of these nutrients have a major influence on environmental concerns and on turfgrass fertilization programs. Important considerations with respect to the **macronutrients** (N, P, K, Ca, Mg, and S) and **micronutrients** (Fe, Mn, Ca, Zn, Mo, Ni, and B) are found in Table 3.8. Heavy metals and organic/inorganic compounds could also be found in this water resource, depending on factories in the area that may be providing nutrients to the total reclaimed or effluent water (Table 3.11).

Nitrogen, P, K, and various micronutrients are often contained in reclaimed water. Similar to total salt content, the types and quantities of these nutrients will vary depending on the prior use of the water and the level of reclamation treatment. Seasonal variations must be monitored and tracked through regularly scheduled soil and water analyses, and fertility program adjustments should be made accordingly. Specific nutrients are addressed in the following text.

Water pH. In Chapter 3 (Section 3.2.1), irrigation water pH was discussed, and this discussion would apply to reclaimed water. The water pH can alter soil surface pH and thatch pH (in particular, acidic thatch, especially with acid injection, which decreases microbial populations) over time. Soil nutrients are most "plant available" at soil pH 6.0 to 7.5. However, the chemical constituents that cause irrigation water to exhibit a pH outside of this range is more important than pH by itself. The influence of reclaimed water pH on irrigation lake conditions is noted in Chapter 14.

Nitrogen. The quantity of N added over time in the irrigation source will directly contribute to the nutritional needs of turfgrass and other landscape plants receiving irrigation. Thus, seasonal and annual N-fertilization must be adjusted accordingly, and turfgrasses should be used that can tolerate the N level applied. Some turfgrasses deteriorate rapidly when overfertilized with N, especially those with low N requirements such as red fescues, centipedegrass, and seashore paspalum. On golf greens, high N in the water may produce more growth than desired, (expressed as excess clippings, scalping, slower putting speeds, thatch accumulation, greater succulence, enhanced disease susceptibility, and reduced hardiness), especially if the total annual N exceeds 4 to 6 lb N per 1000 ft^2 (*Poa annua* or creeping bentgrass) or 8 to 12 lb N per 1000 ft^2 (Bermuda grass) within most U.S. locations. Cool-season grasses receiving excess N during hot, dry summers are especially prone to deterioration from overfertilization.

Reclaimed water can pose a unique situation regarding N because the N is readily plant available. Total N loading in the soil is a possibility, especially with heavier-textured soils and when irrigation applications containing high amounts of organic and/or ammonium nitrogen are made during cool soil temperatures. A flush of growth can result after a rapid increase in soil temperature, such as after a warm spring rain. The conversion of ammonium and organic N to nitrate at various soil temperatures and time periods is shown in Table 8.2. Additionally, because N content in reclaimed water cannot be controlled, the possibility of developing excessive growth and possible disease problems can increase during weather conditions in which the turf manager would normally withhold fertilizer. The severity of this problem will depend on the seasonal quantity of N contained within the water and the turfgrass species.

If reclaimed water is stored on-site in an irrigation pond, eutrophication may occur. Water containing even 1.1 ppm N can result in flourishing algae and aquatic

TABLE 8.2
Nitrification at various soil temperatures

Soil temperature (°F)	Time (weeks)	Percentage nitrification[a]
75	2	100
52	12	100
47	12	77
42	12	35
37	12	5

[a] Nitrification. Conversion of ammonium-N to NO_3–N (nitrate) by nitrifying soil bacteria.

Source: Adapted from California Fertilizer Association. 1985. *Western Fertilizer Handbook*. 7th edition. Interstate Printers and Publishers, Danville, IL.

plant growth. Barley straw is an effective management option to tie up excess NO_3 in these water features and to reduce algal growth (Gaussoin, 1999).

Reclaimed water may contain relatively high total N, and when combined with storage conditions in an irrigation lake favoring transformation to the nonionized ammonia ion (NH_3), it is possible that ammonia toxicity could occur when the water is applied to the turfgrass. Ammonia toxicity has been reported in marine sediments in euthrophic settings (Burgess et al., 2003). Ammonia toxicity has been reported on turfgrasses from compost applications, but not from reclaimed water. However, the authors have observed a couple of situations in which this problem was expected because of site conditions that favored ammonia presence, reported ammonia odor, and turfgrass injury to seedlings. Conditions that would enhance the potential for ammonia accumulation are high pH (>9.5), low oxygen, high temperatures, and relatively high N in the reclaimed water that could convert to ammonia. These conditions could occur within strata of a lake, especially if the lake bottom was rich in organic deposits (Burgess et al., 2003; Arauzo and Valladolid, 2003). Lake aeration with bottom diffusers, as well as any method of controlling N and P levels to reduce eutrophication potential, would inhibit ammonia formation.

Phosphorus. Limits on P in irrigation water are lower than other macronutrients because P is a primary promotion factor for algal and aquatic plant growth. Excessive P that reaches ponds, lakes, or streams can markedly increase growth of these problem plants. Turfgrasses can easily tolerate annual P additions up to 2.0 lb P_2O_5 per 1000 ft^2 from irrigation water, but aquatic plants would be greatly stimulated if this P-ladened water reached streams or ponds. The combination of high N plus P would also be most detrimental in causing eutrophication (lack of dissolved O_2 in water). If steps are taken to prevent lake or stream water contamination by P from reclaimed irrigation sources, higher P levels can be tolerated. However, if soil levels of P build up over time, P may reach waterways through leaching or high-rainfall runoff events. Buffer strips may be needed for transitioning into environmentally sensitive areas.

Treatment facilities providing reclaimed water to a user for irrigation purposes may not need to reduce P concentration in the water to the same level as necessary if they were discharging the effluent into surface water bodies. This would result in financial savings to the treatment facility. However, if the water is stored in an irrigation lake prior to application, the P buildup could cause eutrophication with algal blooms, proliferation of aquatic plants, low-oxygen conditions, and odor problems for the end user. Essentially, costs of P control in the water are passed from the treatment facility to the end user. Additionally, it is not unusual for overflow of reclaimed water to surface waters to be considered an unpermitted discharge, even when the pond is specifically constructed to allow only reclaimed water and direct water falling on the surface to enter the pond. Potential options for reclaimed water users are to (1) negotiate with the treatment facility to reduce P to a level that is less of a problem or to provide a monetary consideration for the costs that the end user must bear related to the higher P level, and (2) negotiate with the water authorities to allow overflow of water during unusual rain storms from the irrigation lake to not be considered an unpermitted discharge.

Potassium. Recreational sites require ample K owing to high traffic/wear challenges, so any K in irrigation water is often viewed as beneficial. If K is high in reclaimed water, adequate Ca and Mg are normally available to prevent any nutrient imbalances, but excess K will contribute to overall total salinity. Reclaimed water high in total salts or Na require more leaching of the turfgrass root zone profile, which can easily leach K from the soil because this nutrient is quite soluble, is highly mobile, and turfgrasses normally require frequent supplemental K fertilization.

Calcium. Potential problems from high Ca were addressed in Section 8.6.1. Turfgrass managers should be aware of the total Ca added by the water source, because reclaimed water, and even rainwater (1 to 8 ppm Ca), contains Ca. As noted in Table 3.8, reclaimed or effluent water with 60 ppm Ca would add 3.75 lb Ca per 1000 ft^2 per 12 in. irrigation water (equivalent to 16 lb $CaCO_3$). Thus, rainwater at 8 ppm Ca would add 0.50 lb Ca per 1000 ft^2 (2.2 lb $CaCO_3$ equivalent) per 12 in. rain. Ca nutritional needs are often easily met from Ca in irrigation water. Some consultants have recommended foliar or granular Ca applications (for example, calcium silicate) to turfgrass sites in recent years. This is a questionable practice unless:

- Very high soil Na (sodic soil) or soil Al (excessively acid (pH < 4.8)) conditions exist. In both cases, these ions can displace Ca from root tissues and soil CEC sites to the point where Ca deficiency in the *root* tissues causes root deterioration. Under these conditions, soil application of Ca is required to provide available calcium for root uptake, and not a foliar Ca treatment, because Ca does not translocate from the shoots to the roots.
- As noted in Chapter 6 on saline irrigation water, reclaimed water with high Na (>200 mg L^{-1}) and low Ca (<20 mg L^{-1}) could potentially reduce Ca in shoot tissues. This is normally not observed with reclaimed water, but has been determined for some more highly saline irrigation water sources. Foliar Ca additions may be beneficial in this instance, coupled with normal irrigation scheduling to move the calcium to the root system for uptake.
- Unusually high Mg additions (either fertilizers high in Mg or ocean-influenced sites) may require Ca fertilization if a Ca source is not already required to control excess Na problems. The primary response for adding

Ca is to improve soil physical properties because Ca is a better soil colloid aggregating agent than Mg. Brackish or seawater exposure can result in soils that could be high in Mg.

Lower pH (<5.5) soils benefit from lime amendments to adjust pH to within pH 6.0–7.5 for better availability of nutrients in general, but Ca levels are still adequate for turfgrass nutrient needs even at very low pHs until the point of Al toxicity to roots (<pH 4.8). Plants do not require more than 2 to 6 lb of Ca per 1,000 ft^2 to meet all nutritional needs. However, on acidic soils with pH < 5.5, a rapid greening response after lime or gypsum application is not unusual. This response is because more favorable conditions for *Nitrosomonas* and *Nitrobacter* stimulation are created, which transform NH_4^+ into NO_3^-. Many grasses prefer NO_3^- and respond to enhanced NO_3^- availability (i.e., greening response). These soil bacteria activities are limited at low pH, primarily because of low Ca and not because of low pH or H^+ toxicity.

Problems that may occur from applying Ca when not required include the following:

1. Magnesium or K deficiencies (two nutrients that can be deficient in turfgrasses) may be enhanced.
2. Confusion may be caused by emphasizing a problem that does not exist except in special cases.
3. Calcium applications (within 1–2 in. or 25–50 mm of the soil surface) that raise pH above 7.0 in the upper 1–2 in. of the soil surface when not required (for example, excess calcium silicate applications with minimal aeration and movement into the soil profile) can enhance conditions that are conducive to take-all development.
4. Ethical and economical issues may arise when recommending a nutrient amendment that is often added normally by irrigation sources in abundant quantity.

Water originating from snowmelt may contain <20 ppm Ca, and additional amendments would be needed to provide levels above 20 ppm or 1 meq/L Ca for infiltration and percolation into soil profiles (see Chapter 5).

Magnesium. Most often, Mg is present in reclaimed water at lower levels than Ca. Sometimes, however, Mg content will be relatively high, which can reduce Ca on CEC sites and restrict K availability. In these cases (and when using seawater or brackish water), supplemental Ca may be needed to maintain adequate Ca (3 meq/L Ca: 1 meq/L Mg ratio) to promote good soil physical conditions, to counter Na^+ toxicities, and for turfgrass nutritional balances. Also, supplemental K will be necessary to maintain ample balanced K nutrition.

More often than excess Mg, low Mg content in irrigation water is a problem, or low Mg availability may be caused by the addition of high Ca applications when using irrigation water that has too much Na. Another problem of increasing frequency is Mg deficiency induced by excessive applications of unneeded Ca (i.e., calcium silicate) on sandy sites. Similar to Ca, knowledge about Mg content and rates applied in the irrigation water are very useful in avoiding deficiencies or excessive Mg problems (Table 3.8). Excessive Mg can mimic excess Na; consequently, maintaining a balance with Ca is critical for long-term turf maintenance.

Sulfur. Reclaimed water is often higher in SO_4 content than other sources. Normally 2 or 4 lb S per 1000 ft^2 per year is sufficient to meet turfgrass nutritional needs and this amount is often provided in irrigation water or with N, K, or Ca and sulfate-based fertilizers. The issue of excessive SO_4 content in reclaimed water is discussed in Section 8.6.3.

Iron (Fe). The 5.0 mg L^{-1} guideline in Table 3.11 for Fe in irrigation water is not related to any potential "toxic level," but to continuous use that could cause (1) precipitation of P and Mo and contribute to deficiency problems for turfgrasses (P) or landscape plants (P or Mo); (2) staining on turfgrass shoots, sidewalks, buildings, and equipment; (3) potential plugging of irrigation pipes by anaerobic Fe sludge deposits, which can be a problem at >1.5 mg L^{-1} Fe; (4) high, continuous rates of Fe that may induce Mn deficiency or much less likely, Zn and Cu deficiencies; and (5) high deposition of iron products on turf surfaces coupled with high rainfall events or high irrigation applications that causes surface and subsurface movement into lakes or ponds. On heavily leached sands, where Mn content is often low, this may become a problem.

At 5.0 mg L^{-1} Fe, 12 in. (300 mm) of irrigation water would add 0.31 lb Fe per 1000 ft^2, whereas a typical foliar application is 0.025 lb Fe per 1000 ft^2, but in only 3 to 4 gal water per 1000 ft^2. In most reclaimed or effluent water sources, Fe concentrations are low, and turfgrasses will respond to foliar Fe. When total salinity is high, Fe plus a cytokinin (from seaweed or kelp extracts) as a foliar treatment is often beneficial, because salt-stressed plants exhibit low cytokinin activity and reduced Fe availability, especially if $pH > 8.0$. Increased cytokinin concentration in the turf can enhance root production or redevelopment in salt-stressed plants with low-to-moderate levels of salt tolerance.

In those rare cases where Fe is high enough in combination with sulfides to cause plugging of irrigation pipes and anaerobic sludge/iron bacterial slime deposits, iron should be oxidized to an insoluble form, precipitated, and filtered before entering the irrigation system. Chlorination to a residual of 1 mg/L chlorine or mechanical aeration in an open pond to cause precipitation prior to filtration are management options (Ayers and Westcot, 1994) (see Chapter 12).

Manganese (Mn). Manganese can become toxic to roots of many plants. So, use of reclaimed water high in Mn (>0.20 mg L^{-1}) can contribute to this problem, especially on poorly drained acidic soils. Acidic anaerobic conditions transform soil Mn into more soluble (i.e., toxic) forms. If reclaimed or effluent water is high in Mn, liming soil to pH 6.0 to 7.5 and providing good drainage greatly reduces the potential for Mn toxicities. At >1.5 mg L^{-1} Mn in irrigation water, Mn can contribute to sludge formation within irrigation lines. Also, high Mn may inhibit Fe uptake and promote Fe deficiency. Supplemental foliar Fe would prevent this problem. Most of the time, reclaimed water sources are low in Mn content and supplemental Mn would be needed for sustaining turfgrass performance with salinity challenges.

Copper (Cu), Zinc (Zn), Nickel (Ni). The irrigation water levels in Table 3.11 are based on potential to develop toxicities on sensitive landscape plants over time. Turfgrasses can tolerate relatively high rates due to mowing of leaf tips, where these elements tend to accumulate. Unusually high Cu and Zn could inhibit Fe or Mn uptake and, thereby induce deficiencies of these nutrients, even on grasses. In those cases, supplementation with specific low-concentration nutrients would be warranted on turf.

Molybdenum (Mo). Molybdenum toxicity would be very unlikely in turf plants, but livestock feeding on grasses high in Mo can be affected. Mo deficiency can occasionally occur on low-pH sites because it acquires hydrogen ions, becomes less ionic, and forms polyanions that render it less readily available for uptake by turf roots. In addition, Mo and salinity will interact; specifically, Mo will directly compete for exchange sites with divalent oxyanions (SO_4^{-2} and HPO_4^{-2}).

Other Trace Elements. Reclaimed water may contain excessive levels of some elements. These are reported by Ayers and Westcot (1994) and Snow (1994). These elements would not directly influence turfgrass nutrition, but would be of concern for toxicities on some landscape plants. Little is known regarding heavy metal effects on turfgrasses; however, because of the risk to human health, vegetable or herb gardens used by club restaurants should be protected from receiving any reclaimed water spray or irrigation. Local regulations may require a minimum setback or buffer area irrigated by potable water in these cases.

8.8 TOTAL SUSPENDED SOLIDS (TSS)

Reclaimed water is filtered to remove many of the TSS at the treatment facility because these materials would contribute to high turbidity levels, thereby reducing the effectiveness of disinfectant treatments. However, when reclaimed water is delivered to an irrigation pond and it contains ample N and P, algal bloom and eutrophication may result in increased levels of organic debris contributing to higher TSS levels. Suspended solids arising from organic materials such as algae should be reduced by controlling the source because filtering is difficult to achieve for these materials in irrigation lakes. Control measures for organics could include reducing P and N in the water and aeration.

If the reclaimed water is not of high quality and has not received filtration treatment, suspended solids (colloidal clay or organic particles) and dissolved organic matter can be present. Some of these organic materials are humic substances such as fulvic acids and humic acids that have been observed to show both soil aggregating and antiaggregating qualities. In addition to humic substances, dissolved organic matter may also contain hydrophilic substances such as proteins, polysaccharides, and other compounds (Levy et al., 1999). Irrigation with low-quality reclaimed waters that are high in organic matter load often results in a significant decrease of infiltration (saturated hydraulic conductivity) by blocking water-conducting pores. The total effect on hydraulic conductivity is controlled by the quantity of organic matter and particle sizes of the suspended inorganic or organic solids. Unfortunately, no specific guidelines have been published for predicting the TSS hazard when managing turfgrasses.

8.9 MANAGEMENT ASPECTS

Use of reclaimed water will alter management protocols and occasionally elevate budgets in a number of areas. Important aspects are discussed in the following sections. If the reclaimed water contains significant total soluble salts or Na, management expertise and expenses will be significantly higher compared to better-quality irrigation water sources.

8.9.1 MONITORING

Use of reclaimed irrigation water may entail increased proactive monitoring for protection of groundwater. This may be a case-by-case situation determined during the permitting process, depending on the site hydrogeology and reclaimed water quality (USEPA, 2004). However, reclaimed water that is more saline will often require frequent monitoring. Depending on the number of monitoring wells, frequency of reporting, and data required, groundwater protection monitoring can be expensive and the turfgrass facility should negotiate for minimal monitoring and reporting costs (USEPA, 2004).

More saline reclaimed water sources will also result in increased soil, water, and tissue testing to monitor salinity aspects and salinity/nutritional interactions. In addition to the effects of salinity, reclaimed water is often more nutrient rich than other sources, and therefore requires more careful soil-testing and tissue-testing programs. Owing to the dynamic fluctuations in salinity and nutritional parameters coupled with the complexity of salt-affected sites, specialized consultant costs are likely to increase with the use of saline reclaimed water.

8.9.2 DRAINAGE AND LEACHING

When using saline reclaimed water, adequate drainage is critical. Ample water is needed to leach soluble salts. Positive surface and subsurface drainage are the keys to avoiding puddling and, hence, development of anaerobic conditions, algae, or black layer problems. Even a properly constructed USGA green will be plagued with these algae-induced, black, leather-like surface layers if there are “birdbaths” on the surface that collects and holds water. Inclusion of any water-holding inorganic amendments in any greens mixes should be carefully done and be strictly based on science-based comprehensive physical characteristics in that mix. Surface, internal (soil), and subsurface drainage are critical and necessary infrastructure additions, especially on recreational turfgrass sites to provide adequate water infiltration and percolation movement of reclaimed water so it can reach the drains. French drains may be needed in certain areas such as in the lowest edges that transition to the first-cut areas, approaches, or aprons around greens in order to avoid the “dam” influence of surface and subsurface reclaimed water movement with slopes and inundations on those greens. Additional drainage may be required on tees and throughout low-lying areas of fairways, depending on the turfgrass species salt tolerance and internal soil profile drainage characteristics.

8.9.3 CULTIVATION PROGRAMS AND LEACHING

Poor-quality reclaimed water in conjunction with poor internal water percolation and drainage and/or heavily thatched turfgrass may require intensive cultivation programs to keep salts moving downward. As clay and silt content increases, so will cultivation and leaching challenges. Cultivation frequency should be increased particularly in spring and early summer prior to stress periods. Early season coring of greens with hollow tines followed by back filling with topdressing sand performs a dual function of:

- Creating additional channels for water to infiltrate when leaching during the summer stress periods.
- Initiating deep root development prior to the onset of summer heat and salt stress or in the fall prior to normally dry, winter high golf play periods.

Spring/early summer is also the time of the season when deep aeration treatments would be preferred for similar reasoning. Mid to late summer frequent cultivation events, using less aggressive techniques such as high-pressure water injection, slicing, spiking, small star, or quad-tine use may also be required, especially in daily or prolonged rainy conditions when air porosity is normally reduced in soils. These activities will keep the surface layers open to gas exchange and will promote acceptance of adequate volumes of water when applied for leaching. If salts are allowed to accumulate in the surface 1 or 2 in. (25–50 mm) by mid to late summer from light, frequent irrigation, leaching before cultivation may be necessary or the water will flow through the cultivation holes without removing salts between holes. Nondisruptive cultivation also helps manage and avoid black layer development by improving oxygen movement into the soil profile. Light topdressing after cultivation is acceptable provided the turfgrass is not under heat or salt stress, but is often avoided if the greens show any amount of abiotic stress; or topdressing can be applied at a light rate a few days before or after cultivation during stress periods.

8.9.4 SUPPLEMENTARY/DUAL SPRINKLER SYSTEMS

If the reclaimed water is saline, leaching programs on sensitive areas such as golf greens may benefit from creative irrigation systems and programs. Development of a "maintenance leaching" philosophy and practice are highly recommended in contrast to a "reclamation" philosophy (see Chapter 11). Leaching with stationary in-ground pop-up systems can be performed provided irrigation system distribution uniformity is good enough to promote uniform leaching, and multiple start times (pulsing) can be scheduled to avoid runoff. Performing a catch-can test to visually examine application uniformity will show coverage deficiencies. Performing the pulse leaching process over 2–3 evenings can also be more successful than saturating the turfgrass area with possible runoff in one night. A targeted 3/4 to 1 in. (18–25 mm) of water can be appropriately applied each night, depending on the efficiency of the irrigation system and the tendency for runoff.

Avoiding excessively wet surrounds and boggy greenside bunkers may prove difficult when leaching with stationary full circle sprinklers. This problem is more severe in coastal areas with low ET (evapotranspiration) rates. Under conditions of poor irrigation distribution, poor internal soil drainage, and/or low ET rates, turf managers can substitute portable landscape or orchard sprinklers having low precipitation rates and soaker hoses for leaching instead of in-ground systems (Gross, 1999). This allows precise placement of water on the greens surface to avoid saturating surrounds and bunkers. The low-flow sprinklers or soaker hoses are simply turned on after dark and allowed to run until sunrise with a low application rate and minimal runoff.

In the most severe cases of poor-quality reclaimed water, dual irrigation systems are installed utilizing two mainlines: one supplying potable water exclusively to the greens and another providing reclaimed or effluent water to the remainder of the course. This strategy can greatly reduce leaching requirements and putting green salt stress. Finally, it is important to avoid leaching (1) immediately following fertilizer application to avoid exorbitant nutrient/nitrate leaching, and (2) when heat and humidity are ideal for disease development. The loss of turfgrass density from salt stress is slower to occur than from disease activity; however, salt-stressed turfgrass is more susceptible to disease damage and will often take longer to recover owing to the saline-induced growth rate reduction.

8.9.5 SPECIES SELECTION

Reclaimed water can affect turfgrass selection in two primary situations. First, as noted in Section 8.7, the turfgrass species and cultivar must be able to tolerate the nutrient load applied with the reclaimed water. This can be a problem, especially for N load on a seasonal and annual basis for grasses requiring low N and for cool season grasses during summer months when excess N can contribute to grass decline. Second, when the reclaimed water contains significant total soluble salts, the trees, shrubs, and turfgrass species must be sufficiently salt tolerant to tolerate any salinity stress from irrigation with the reclaimed water. Certain cultivars within a species often perform better than others (Table 6.2). Additionally, remember that salt tolerance levels on mature turfgrass are genetically different from salt tolerance levels of germinating seeds or initially rooting vegetative stock (sprigs). Additional information on salinity and plant selection is found in Chapter 6.

On an established property (retrofit project), these issues can present problems. Sensitive trees, turfgrasses, shrubs, and flowers may require replacement. An interseeding program for turfgrass areas may be needed to increase tolerant cultivars in the turfgrass sward. Raising cutting heights slightly, although often unpopular with golfers, can also increase salinity tolerance of greens; the old saying “slow grass is better than fast dirt” applies when irrigating low-salinity-tolerant greens cultivars with reclaimed water.

8.9.6 MANAGEMENT COSTS

Monitoring of expenses associated with reclaimed water use was discussed in Section 8.9.1, but additional domestic-water-related costs may occur. These costs are as follows:

Amendment programs. Reclaimed water with an imbalance of sodium, bicarbonates, and Ca may require water treatment and/or soil amendments.

Increased sodium concentration in the water may require adding calcium (gypsum, calcium chloride) to the soil or water. If carbonates and/or bicarbonates are high, water acidification could be required (see Chapter 12). These situations add expenses to maintaining the golf course and could be negotiating points with the water authority when bargaining for reclaimed water.

Equipment deterioration. Very similar to how road salt deteriorates automobiles in northern climates, reclaimed or effluent water high in salts accelerates the corrosion of many metals. The use of plastics, corrosion-resistant galvanized steel, and stainless steel are recommended along with providing potable water at the equipment wash rack area. The life expectancy of mowing equipment, utility vehicles, metal fencing, irrigation controller cabinets, and course accessories (metal benches, ball washers, trash cans, etc.) all will be reduced from the daily exposure to more saline runoff and guttation water. Maintenance and repair of equipment, especially corrosion-prone electrical safety switches, normally increase. If wash-pad water is recycled for multiple use on equipment, close monitoring of salinity increases will be needed.

Retrofit costs. Costs of retrofitting hardware when preparing to accept reclaimed water may include upgrading backflow prevention devices, informational signage, tags to properly identify hose bibs and remote control valves, and replacement of quick couplers (Feil et al., 1997; DEC/NSW, 2003).

Overseeding costs. Courses that overseed dormant Bermuda grass will be forced to close so that daytime irrigation can be performed during establishment, causing a loss of revenue. Additional cool-season grass seed (10–20%) can be required to provide acceptable turfgrass density, depending on salinity of the water and the specific turf cultivar.

Water savings. Reclaimed water costs are often reduced (15% or more compared to that of potable), but can offset by some other costs; however, leaching requirements may raise the annual quantity of water used if the reclaimed water is saline. This reduced cost trend may also reverse as demands for all water continues to increase and additional uses and demands are created for reclaimed water in the new millennium.

Fertilizer savings. Some fertilizer savings can be expected with the nutrients added by the reclaimed water. The actual amount will vary seasonally at each site. Monitoring nutrient additions from the recycled water source through frequent soil and water analysis is essential. Although routine fertilization costs may be reduced, soil and water amendment requirements as noted earlier may increase.

Other costs. Often, the requirement for backflow device testing increases from one to two times per year. Additional laboratory testing of soil, water, and tissue should be included in the budget as well as monitoring replacement equipment costs. Reclaimed water costs are usually 85% or less than potable sources, and agreements on long-term prices should be determined to ensure a consistent cost saving concerning basic water budgets. The cost saving in the purchase price will aid in offsetting additional management/equipment expenses that arise from reclaimed water use.

8.9.7 OTHER MANAGEMENT CONSIDERATIONS

8.9.7.1 Fertilizer Selection

Fertilizer selection must be considered when developing programs to manage salinity, especially where sensitive species are grown, and if reclaimed water contains appreciable nutrients. Soluble, quick-release products have much higher salt indexes (burn potential) than slow-release or organic fertilizers (Table 8.3). Selecting

TABLE 8.3
Salt index (relative effect of fertilizer materials on the soil solution)

Material	Salt index	Partial salt index per unit of plant nutrient
Ammonium nitrate	104.7	2.99
Ammonium phosphate (11-48-0)	26.9	2.442
Ammonium sulfate	69.0	3.253
Calcium carbonate	4.7	0.083
Calcium nitrate	52.5	4.409
Calcium sulfate	8.1	0.247
Diammonium phosphate	29.9	1.614 (N)
Dolomite (calcium/magnesium carbonate)	0.8	0.042
IBDU[a]	5.0	0.161
Methylene urea (40% N)	24.6	0.61
Milorganite[c]	0.042	0.007
Monoammonium phosphate	34.2	2.453 (N)
Polymer/polymer-coated urea	24.5	0.647
Potassium chloride (50%)	109.4	2.189
Potassium chloride (60%)	116.3	1.936
Potassium chloride (63%)	114.3	1.812
Potassium nitrate	73.6	5.336 (N)/1.580 (K_2O)
Potassium sulfate	46.1	0.853 (K_2O)
Sodium chloride (water softener salts)	153.8	2.899 (Na)
Sulfur-coated urea (38%N)	24.5	0.647
Sulfate of potash—magnesia (Sulpomag)	43.2	1.971 (K_2O)
Superphosphate 16%	7.8	0.487
Superphosphate 20%	7.8	0.39
Superphosphate 45%	10.1	0.224
Superphosphate 48%	10.1	0.21
Urea	75.4	1.618
Ureaform (40% N)	6.1	0.163

Note: Higher salt index values indicate a greater potential for fertilizer burn or increasing salt load. Adapted from *Western Fertilizer Handbook*, 7th edition.

[a] Data provided by the Scotts Company.

[b] Data provided by ParEx.

[c] Data provided by the Milwaukee Metropolitan Sewerage Company.

products with a lower salt index during the summer months can help reduce the overall salt load placed on turfgrasses and soils at a time when ET rates are high. Using a "spoon-feeding" approach of low fertilizer rates on a more frequent basis is another approach. If the recycled water contains ample levels of a nutrient, supplemental fertilization may be omitted for the particular nutrient. As salinity level in the recycled water increases, the potential for nutrient imbalances also increase.

8.9.7.2 Ornamental Lakes and Irrigation Reservoirs

Reclaimed water presents many lake management challenges as aquatic weeds and algae proliferate in nutrient-rich water. Small ornamental ponds are particularly problematic when water temperatures rise. They become stagnant, with strong odors developing as aquatic plants die and consume dissolved oxygen. Aeration in lakes or ponds will reduce odors and increase dissolved oxygen, but can also cause foaming, thus causing an aesthetic problem. Antifoaming agents are usually effective but short-lived, and therefore can be an expensive measure.

Chemical controls for algae and aquatic weeds are available, but become an ongoing expense (see Chapter 14). Another potential problem can arise with the continuous application of copper-based products. Over several years, the repeated cycle of aquatic weed and algal blooms followed by copper-based chemical control can result in an organic sludge developing on the lake bottom; the sludge may accumulate a high copper content, thus becoming a hazardous waste. Straw bales are an effective biological control of filamentous algae, but appear ineffective in managing planktonic varieties (Gaussoin, 1999).

Irrigation reservoirs usually present less of a management problem because of the regular turnover of water. A direct connection of the irrigation system to the reclaimed water supply can eliminate the irrigation reservoir requirement and problems associated with managing lakes; however, a backup system should be in place to supply water in the event that the reclamation plant is shut down for emergency service. Limiting the total number of lakes in a new design to only the irrigation reservoir will limit management problems. A well-designed lake system can minimize problems. Points to consider include the following:

- Size lakes to promote rapid turnover of water; the fresher the water, the less serious the problem.
- Line lakes to allow easy maintenance and cleaning following drain down.
- Inclusion of electrical service and equipment to aerate and circulate water.
- Provide adequate lake depths (at least >5 ft; >1.5 m) to maintain cooler water temperatures.
- Position supply inlets and pump intakes at opposite ends of the lake or pond to promote circulation and dilution, and avoid development of stagnant areas. Avoid positioning the pump intake on the lake bottom, if possible, to minimize sediment uptake and lower-quality water due to salt stratification in layers with lake depth.

8.9.7.3 Climate

The local climate has a large influence on management. Areas of the country that receive high rainfall may not require regular leaching with the irrigation system unless a drought occurs. Arid regions will require diligent management and scheduled leaching events to manage high sodium and total salt accumulations if the reclaimed water is salt rich.

8.10 SUMMARY

Reclaimed water has both advantages and disadvantages related to regulatory, agronomic, economic, emotional, availability, and operational issues. The greatest advantage of reclaimed or effluent irrigation water is that the supply volume will likely not be interrupted by a drought. The disadvantages vary depending on expenses, water quality, and regional/state/local operational restrictions that may be imposed. Summary points to remember include the following:

- Consider water quality for irrigation suitability and long-term environmental impact (total salinity, Na permeability hazard, specific ion toxicities, etc.).
- Consider nutrient content effects on the fertilization program.
- Consider the climate and annual rainfall, especially the potential for prolonged extreme events, and shifts in water quality.
- Provide positive surface drainage.
- Provide good internal drainage.
- Provide subsurface drainage.
- Regularly monitor soil and water chemistry (in-house and with laboratories.)
- Select salt-tolerant species of turfgrasses, trees, and ornamentals when the water quality is saline.
- Adjust cultural programs as necessary (mowing heights/frequency, cultivation, fertilization, etc.).
- Avoid storing excess quantities of reclaimed water in lakes.
- Budget appropriately.
- Comply with local regulations.

The thought of using reclaimed water is definitely nothing to lose sleep over. Whether reclaimed water becomes an agronomic nightmare or not will be like many other things in life—what you make of it! It must be emphasized that the problems are manageable if prudent decisions are made during construction, when negotiating with water authorities, and when developing turfgrass maintenance programs. Success cannot be guaranteed, but with a well-thought-out management plan, you can have high quality and sustainable turfgrass using reclaimed water.

9 Stormwater Reuse and Irrigation

9.1 TRANSITIONS IN STORMWATER MANAGEMENT

9.1.1 STORMWATER REUSE

The integration of harvested stormwater, floodwater, saline groundwater, reclaimed water, agriculture recycled water, and coastal water resources will be the future of irrigation on recreational turf (Beltrao et al., 2003). Of these sources, stormwater reuse for irrigation will be a significant and important component of turfgrass and landscape irrigation in the future. **Stormwater** is generated by precipitation and runoff from land, pavements, building rooftops, and other surfaces. Stormwater runoff accumulates pollutants that may be present, such as sediments, oil and grease, chemicals, nutrients, metals, and bacteria as it moves across land and other surfaces. Heavy precipitation or snowmelt can also cause sewer overflows, which in turn may lead to contamination of water sources with untreated human and industrial waste, toxic materials, and other debris.

Is stormwater a flood problem, a water quality problem requiring treatment before depositing into a body of water, or a valuable resource for water reuse? Hatt et al. (2004) provide a good summary of what is becoming the current attitude relative to stormwater: "The current drought in much of Australia has highlighted the need for improved management of the urban water cycle. In particular, there is now recognition that stormwater provides a potential resource that could help to reduce demand for potable water supplies. Clearly, utilization of stormwater for water supply purposes depends on the quality of that stormwater, and the integration of treatment and utilization systems is therefore critical" (ISWR website; TWDB, 2005).

For many years, stormwater was an issue of efficient drainage design for the almost exclusive purpose of **flood control** by capture of the total rainwater and disposal in storm sewers (CSQA, 2003a; Bowser, 2004). Within the past 30 years, with the U.S. Clean Water Act, emphasis shifted to "stormwater management"; but the management emphasis was almost exclusively focused on **protecting water quality** by reducing pollutants contained in stormwater from discharging into waterways. Even considerable attention to infiltration and aquifer recharge measures, which appear to be water conservation measures, were undertaken for water quality protection purposes and protection of the hydrological cycle, but not for direct **stormwater reuse or recycling**. Thomas et al. (1997) noted the transition of stormwater management to a more holistic, integrated model in their comments: "More attention is being given to water issues in urban planning, landscape management, and environmental management, so as to naturalize urban water courses and water bodies, and to harvest and store treated wastewater and stormwater, including the artificial recharge of aquifers near towns and cities. Stormwater management objectives are thus being widened so that reuse, pollution control, environmental amenity, and ecological integrity are being set alongside traditional flood control objectives for drainage systems."

Until recently, the practice of stormwater harvesting for supplemental irrigation has been for food production in less developed countries (FAO WH, 2006). It is worthwhile for readers considering stormwater as a potential irrigation source to review the practices for stormwater capture noted in FAO WH (2006). Although some degree of stormwater reuse has been practiced in more developed countries, especially at an on-site basis, it has only been in the past few years that significant attention has been directed to stormwater as a valuable water resource to help address water supply shortages. Australia has taken a lead in formulating a national approach (Thomas et al., 1997; WBM, 1999). Dillon and Ellis (2004) stated the potential for more vigorous stormwater reuse in Australia as follows: "Security of Australian city mains water supplies is diminishing due to population growth, capped catchments, and aquifers, increasing climate variability, lowering of dam spillways, and environmental flow requirements. Yet all capital cities discharge more stormwater and treated water sewage than they import from catchments. If irrigation farms had water use efficiencies as low as cities, they would be closed."

Consequentially with water competition and recognition of the large quantities of stormwater available for reuse, the definition of "stormwater management" is shifting to include water reuse as a conservation measure. In a worldwide survey, WBM (1999) reported that in the United States, most governmental stormwater activities were related to water quality improvement, but that Florida was focusing increasing attention on stormwater recycling. Related to this shift in redefining stormwater management to include reuse is the realization by local to national governmental entities that an integrated approach to urban water management is essential. An integrated approach entails supporting, enhancing, and utilizing the natural neighborhood or urban water cycle to achieve a sustainable urban environment by managing urban water: supply, wastewater, and stormwater.

Currently, the primary means of achieving integrated urban water management is by national, state, and local governments encouraging implementation of holistic water-cycle management within new local developments (i.e., neighborhood level) in North America, Australia, and Europe (van Roon, 2007). Various systems/names and examples will be discussed in the next section.

9.1.2 SCALE OF STORMWATER CAPTURE

Capture of stormwater for irrigation and other reuse purposes (discussed later) can be at several aerial scales: a home site, a business building, complex of buildings, single landscape site with associated buildings, development, neighborhood or cluster of developments, municipality, or a regional watershed basis (WBM, 1999; Kinkade-Levario, 2004; UWinfo, 2006; USGBC, 2006; WSUD, 2006). Stormwater management and reuse complexities increase as the aerial scale increases with such issues arising as:

- Facilities to capture and store the stormwater.
- Treatment schemes and facilities to treat the water to acceptable standards.
- Distribution infrastructure, such as pumps and pipelines, to move water to storage and to transfer water to the intended use.
- Receptor sites that are willing to purchase and can use the water.
- On large-scale neighborhood developments or clusters of developments, reclamation of wastewater may also be incorporated in water treatment and reuse schemes along with stormwater.

Individual home, business landscape site. Details of schemes for stormwater harvesting at the individual landscape site for reuse on the site are presented by Waterfall (1998), Diaper (2004), and TWDB (2008). Water harvesting from individual home or business sites has been most often practiced in arid or semiarid regions. However, with the "green building" emphasis of the United States Green Building Council (USGBC) for developing sustainable buildings, stormwater management and reuse is becoming more widespread (Langston, 2006; USGBC, 2006). The USGBC has a Leadership in Energy and Environmental Design (LEEDS) Green Rating System that establishes a national standard for development of sustainable buildings and their landscape. Stormwater management strategies to address water quality and quantity aspects include using garden roofs, pervious pavements, constructed wetlands, retention ponds, and reuse of stormwater for nonpotable uses such as landscape irrigation and toilet flushing. Green roof stormwater retention is another example of stormwater management and reuse on a single building (VanWoert et al., 2005).

Stormwater has been harvested and used on individual turfgrass sites more often than most realize. On-site collection of stormwater and reuse for irrigation are common practices for many golf courses. A recent survey of golf courses in Georgia revealed that 67% of irrigation water was obtained from on-site surface water capture into lakes (Florkowski and Landry, 2002). One reason that golf courses have taken a lead in stormwater reuse is because the surface and subsurface drainage collection feature could be incorporated during construction; that is, the infrastructure to allow proper transport, treatment (via swales, wetlands, etc.), and collection in retention ponds or lakes was developed for reuse (WWE, 1996; Dodson, 2005). Thus, the infrastructure to deal with excessive stormwater control, on-site treatment of stormwater for protection of water quality, and retentions for reuse can be fully developed to allow integrated water management. Also, the water quality is generally high owing to collection from turfgrass and other landscape areas with good ground cover to minimize sediments and associated constituents. Many times, the water is captured as runoff from vegetative sites within the confines of the course and does not include stormwater capture of runoff from impervious roads or parking lots associated with the clubhouse or maintenance facility that may contain potential pollutants.

Development, neighborhood, or cluster areas. Low-impact urban design and development (LIUDD) focuses on supporting, enhancing, and utilizing the natural water cycle within a neighborhood, development, or cluster of these areas in order to achieve a sustainable environment within these units and, ultimately, on an urban or watershed scale (van Roon, 2007). Neighborhood stormwater systems using the LIUDD principles are promoted under different names, such as Low-Impact Development (LID) in North America (USEPA, 2000), Sustainable Urban Drainage Systems (SUDS) in the United Kingdom (Chatfeld, 2005), and Water Sensitive Urban Design (WSUD) in Australia (WSUD, 2006). More recently, the LEEDs concept has been expanded into a LEED for Neighborhood Developments (LEED-ND) program to apply the concepts of sustainable development to neighborhood design (USGBC, 2006). In each of these systems, turfgrass is an important component of the landscape for multiple purposes, including an irrigation site for stormwater reuse. Additionally, many developments or neighborhood communities include golf courses or parklands that are a part of the collection and treatment system.

Municipality and regional watershed areas. Because extensive infrastructure changes necessary to effectively capture and treat stormwater are much easier to incorporate before an area is developed, implementation of municipal and watershed stormwater capture is most likely to be primarily achieved within new developments in these areas. However, in locations where there are shortages of potable water, aggressive large-scale recycling is being practiced. Usually, larger-scale stormwater programs include the following techniques, with many of these issues involving not just stormwater but also integration of reclaimed water into sustainable water management (WBM, 1999; Antich et al., 2002; Hall, 2005):

- Fostering by government guidelines and regulations, widespread use of individual property, neighborhood, or cluster water-sensitive design schemes.
- Aquifer storage and recovery. When a suitable aquifer is present, this approach to stormwater management offers large storage capacity and aids in the reliability of stormwater supply during dry periods.
- Use of urban wetlands, reservoirs, and lakes for large-scale water treatment and storage for nonpotable uses.
- Provision of adequate water treatment and delivery systems for use of the water.
- Maintaining stream flow and water quality within the various water features.
- Stormwater treatment schemes and treatment facilities. Stormwater treatment can be more complex and diverse than for reclaimed water and is discussed later in this chapter.
- Dual reticulation systems. Communities with reclaimed water reticulation systems would benefit from this infrastructure improvement to be used for both reclaimed and stormwater reuse.

Compared to the municipal or large watershed scales, infrastructure (collection, treatment, and distribution), educational, and use questions can more easily be addressed during new construction of smaller entities such as the home or business landscape site, individual turfgrass sites (golf course, parkland), or development complex of homes, businesses, and golf courses. And, as previously noted, it is at these aerial levels that stormwater reuse is increasingly become a reality.

One argument against stormwater capture that is sometimes given is that the runoff is necessary for maintaining stream flow. It is important to realize that stormwater capture and treatment features normally result in greater water infiltration into the soil to recharge aquifers and increase underground flow to rivers, streams, and lakes. Hall (2005) notes that "all stormwater runoff eventually reaches some larger body of water... and it carries all of the trash and contaminants with it. 'Atlanta, the nation's most rapidly sprawling metropolitan area, documented that recent sprawl development sends an additional 57 billion to 133 billion gallons of polluted runoff into streams and rivers each year.' This water would have otherwise filtered through the soil to recharge aquifers and provide underground flows to rivers, streams, and lakes." The point is that good recapture schemes will aid in recharging these water areas without the pollutants carried by direct runoff, thereby maintaining water flow and quality.

9.2 USES OF STORMWATER

Specific use of captured stormwater or harvested water depends on the aerial scale and whether the quality of water is suitable to a particular use. If treatment is built into the stormwater capture, then more uses are possible.

- Landscape irrigation. The primary use of stormwater in many locations in the future will likely be for irrigation of urban landscapes, which is the focus of this chapter. Irrigation may be on large landscape areas, such as golf courses and parklands, or individual home sites, depending on the infrastructure developed to capture the water.
- Aquifer recharge is one use for stormwater collection and refers to "the collection and treatment of stormwater before it is discharged or injected into suitable available unconfined or confined aquifers" (WBM, 1999; Hall, 2005). The stored water may then be available for future reuse as well as for other purposes such as to reduce groundwater salinity or inhibit salt water intrusion into an aquifer.
- Aquifer replenishment. One means of stormwater capture on sites is to foster infiltration into the soil that aids in replenishment of the underlying aquifer, which in turn may be used for potable water uses in the future.
- Urban lake and wetland development. Lakes and water features constructed specifically for stormwater collection that is to be reused for irrigation also add to the community wetland habitats and aesthetics. Stormwater in lake and wetland areas may be used for stream flow augmentation if it is of suitable quality.
- Industrial uses such as evaporative cooling, car washing, or other suitable uses.
- Lake and wetland creation on an individual site or part of a development. A retention pond or lake that continuously contains water after the water has been transported though an appropriate treatment sequence to enhance quality by removal of pollutants will be a high-quality pond or lake feature as evidenced by the fish and wildlife activity associated with golf course water features (Dodson, 2005). These water features can also become a component

of the development's fire control plans and site aesthetics. Also, water that is appropriately treated on a site may be used for stream flow augmentation.

- On a home or building site where stormwater or harvested water is retained in rain barrels, cisterns, or bioretention areas, reuses may be for landscape irrigation, garden irrigation, fire control, toilet flushing, or car washing. Green roof landscaping using captured and retained stormwater is another use that incorporates treatment in the plan.

9.3 CHARACTERISTICS OF STORMWATER

Water quality characteristics of the two major urban reuse water sources (reclaimed water and stormwater) vary considerably from each other as do treatment options for the specific pollutants within these sources; thus, we have discussed these sources in separate chapters (see Chapter 8 for reclaimed water issues). Quality of stormwater is markedly influenced by the nature of the surface that the water has contact with, particularly whether an impervious or pervious surface. **Impervious surfaces** are defined as natural or human-made surfaces that water cannot penetrate and include cement and asphalt areas of roads, parking lots, sidewalks, and other transport areas; rooftops of buildings; and recreational facilities such as tennis courts, basketball courts, and decks (USEPA, 2005). **Pervious surfaces** are those that allow infiltration of water and include forests and wetlands; lawns and other turfgrass areas in private and public areas; intensively landscaped areas; vacant lands; and runoff treatment areas. Bare soil may be pervious to a certain precipitation load but once saturated, runoff occurs accompanied by sediments, including any constituents attached to the sediments. Grassed buffer zones that transition into environmentally sensitive areas are now being required to intercept these uncontrolled runoff problems.

Polluted stormwater runoff is considered **nonpoint source pollution**, which is defined as pollution that does not come from a point source but originates from aerial (spatial) diffuse sources that are mostly related to land use. USEPA NPS (2006) provides a good summary of sources of nonpoint pollution (runoff from agriculture, urban areas, forestry, boating and marinas, others) as well as an overview of management from various sources. **Point source** pollutants come from a stationary location or fixed facility from which pollutants are discharged. Any single identifiable source of pollution, for example, a pipe, ditch, ship, ore pit, or factory smokestack, is a point source.

Pollutants within stormwater are often presented in the context of urban stormwater, where water contacts large areas of impervious surfaces or eroded soil. In contrast, stormwater runoff from a grassed area such as a golf course fairway and rough area will not have many of the sediments or other types of pollutants found in stormwater from these sites. Common pollutants in stormwater are presented in the following text (USEPA, 2005).

Sediment and debris are diverse types of solids found in stormwater runoff and are usually the first category of pollutants thought of when stormwater is discussed (Kayhanian et al., 2005). The initial categorization of solids is divided into **litter** (>6.35 mm in size) and **nonlitter** (<6.35 mm) components. Litter can be further classified as dry, wet, and gross. Dry litter fractions can float or be nonfloatable with nonbiodegradable or biodegradable characteristics. Sediment pollution includes eroded soil from construction sites, agriculture, deforestation, overgrazing, urban runoff, and mining (USEPA, 2004).

Gross pollutants is a term often used to denote trash, debris, and floatables. Common examples are grass clippings, leaves, and street litter (CSQA, 2003a). These may carry heavy metals, pesticides, and bacterial or any materials associated with the litter. Biodegradability of organic materials, whether suspended or dissolved, is associated with depletion of dissolved oxygen in the stormwater and water bodies receiving the stormwater (USEPA, 2004). The implications for deposition of these solid fractions on golf courses long term, especially on USGA specification greens with low height of cuts and using poor-quality irrigation water, are mostly negative and can lead to more frequent and costly renovations than expected.

Four particle fractions (or "fines") have been described in stormwater runoff solids (Kayhanian et al., 2005):

- Dissolved fraction: "Any constituent that lacks an internal environment and whose fate is not affected by coagulation-breakup mechanisms or gravitational settling."
- Colloidal fraction: "Any constituent that provides a molecular milieu into and onto which chemicals can escape from the aqueous solution and whose environmental fate is predominantly affected by coagulation-breakup mechanisms, as opposed to removal by settling." (Gustafsson and Gschwend, 1997)
- Gravitoidal fraction: "Any constituent that can bind chemical contaminants and rapidly settles through water by gravitational sedimentation."
- Sediment fraction: "All particulates associated with sediment deposited on highway surfaces, or in the storm sewer system."

Sediments as the suspended solid fractions (**termed total suspended solids, TSS; or suspended sediment concentration, SSC**) are a primary pollutant due to their impact on water bodies and their aquatic life, water clarity, provision of additional exchange sites for subsequent salt loading, layering capability in upper soil profiles that can lead to reduced water infiltration and oxygen flux, especially in golf course greens or other sandy profiles. Excess upper soil zone moisture retention can increase surface pathogen problems on the turf; reduced oxygen levels can promote root-colonized pathogens such as take-all [*Gaeumannomyces graminis* (Sacc.) Arx & Oliv. var. *avenae* (E.M. Turner) Dennis] and summer patch (*Magnaporthe poae* Landschoot & Jackson) that can lead to loss of shoot density and are difficult to control.

Sediment is detrimental both in the suspended and deposited forms. In suspension, sediment impairs aquatic life by enhancing turbidity and interfering with photosynthesis (turbid waters) and oxygen status. Nutrients, metals, and hydrocarbons are often association with the sediments, which can influence aquatic life and sites receiving irrigation water from these water bodies. Sediment also causes wear on irrigation pumps and equipment, while causing sedimentation of lakes and streams.

For determination of sediments, TSS test methods are based on EPA Method 160.2 and the American Public Health Association (APHA) method (*Standard Methods for the Examination of Water and Wastewater).* TSS concentration is measured by withdrawing a "representative mixed" 100 mm aliquot from the stormwater sample and passing the aliquot through a tared glass-fiber filter. The retained sediments are dried and weighed for calculation of TSS.

The SSC method (Kayhanian et al., 2005) utilizes the entire stormwater collected sample and is modeled after ASTM D3977-97. The evaporation method involves placing the sample in a tared evaporating dish until all water has evaporated and weighing the dish for SSC calculation. Sample sizes are limited to 0.2–20 L in volume, 5–550,000 ppm sediment concentration, and <35,000 ppm dissolved solids concentration. High total dissolved solid samples require a correction factor.

The filtration method involves filtering the entire sample through a tared glass-fiber filter disk. The filter and retained sediment are dried and weighed for SSC calculation. Sand concentrations need to be <10,000 ppm and clay concentrations <200 ppm. The wet-sieving filtration method involves pouring the entire sample onto a 62- or 63-micromillimeter sieve and weighing the retained material. A 300–500 mL portion of the sample passing the sieve is analyzed by the evaporation or filtration method. The entire coarse fraction is analyzed, but only a small aliquot of the fine fraction is included in the analysis.

In addition to sediments and debris, other pollutants of concern in stormwater are as follows:

- **Nutrients.** Stormwater runoff containing N and P are especially of concern because these nutrients greatly influence aquatic plant growth and often cause excessive growth of aquatic plant and algae. Eutrophication impairs the water bodies and reduces dissolved oxygen levels. Nutrients in stormwater may arise from fertilizer applied to impervious surfaces such as sidewalks and driveways; it is not unusual for agencies to attribute this source to "lawns," which implies runoff from grassed areas. Educational efforts for homeowners and landscapers applying fertilizers greatly reduce this source. Actual runoff from grassed areas is much less, especially if the fertilizer is lightly irrigated after fertilizer application to wash it into the soil and soil thatch/mat area. Other sources of nutrients include nutrients associated with sediment or debris, pet wastes, failing septic systems, and atmospheric deposition of industrial or automobile emissions.
- **Heavy metals**. Heavy metals may arise from automobile emissions or industrial sources. Metals can accumulate in sediments and be toxic to aquatic life. Most prevalent metals include Cu, Zn, and Pb.
- **Bacteria and viruses.** Water contacting animal or human excrement or sanitary sewer overflow are sources of bacteria and viruses that are human health hazards.
- **Oil and grease hydrocarbons.** Sources of these hydrocarbons are oil and grease from leaks, spills, and washing of equipment and vehicles; hydraulic fluids; restaurants; and waste oil disposal. Oil and grease hydrocarbons are toxic to aquatic organisms in low concentrations. Other hydrocarbons are industrial sources and road leachate (asphalt) and runoff containing tire wear materials, deposition from exhaust, and oils.
- **Other organics**. Stormwater may contain compounds such as solvents, cleaners, sealants, and others chemicals because of improper disposal or spills.

- **Pesticides.** Stormwater may contain pesticides either as dissolved in the water or associated with sediments.
- **Salts.** Deicing salts (sodium and calcium chlorides) on roads and bridges can result in dissolved salts in stormwater. In areas with saline soils, stormwater moving over the soil can dissolve some of the salts and result in increased salinity within the stormwater.

9.4 REGULATORY OVERVIEW

Stormwater management, especially for pollution control, has received considerable regulatory attention. Prior to discussing stormwater management approaches on a site-specific basis, a brief overview of the regulatory areas impacting stormwater will be useful. The principal legislation establishing requirements for control of stormwater pollutants is the **Federal Clean Water Act (CWA)** and subsequent amendments. The major CWA programs are (USEPA CWA, 2006; USEPA WST, 2006):

1. Establish water quality standards (WQS) for water bodies based on specific designated uses.
2. Antidegradation policy for the purposes of protecting waters.
3. Water body monitoring and assessment,
4. Reports on condition of the nation's waters. If monitoring and assessment indicate that for some uses and/or parameters, a water body or segment is not meeting WQS, then that water is considered "impaired" and goes on a special list called the **303(d) list,** named after the section of the CWA that calls on states, approved tribes, and territories to create such lists.
5. **Total maximum daily load (TMDL)**. For impaired water bodies, a TMDL is established to specify the maximum amount of the specific pollutant that a water body can receive and still meet the state water quality standards (Tice, 2005; USEPA TMDLs, 2006). At least one TMDL must be done for every water body or segment impaired by one or more pollutants. TMDLs are done for each pollutant, but if a water body or segment was impaired by two or more pollutants, the TMDLs for each pollutant could be done simultaneously. The first element of a TMDL is "the allowable load," also referred to as the pollutant "cap." It is basically a budget for a particular pollutant in a particular body of water, or an expression of the "carrying capacity." This is the loading rate that would be consistent with meeting the WQC for the pollutant in question. The cap is usually derived through use of computer models.

In addition to identifying impaired waters and establishing pollution standards, the Federal CWA contains a number of regulatory and voluntary tools for achieving needed reductions. The most important regulatory and voluntary means of achieving pollution standards is the **National Pollutant Discharge Elimination System (NPDES) permit program**, established in **Section 402** of the Clean Water Act, which initially regulated a wide array of discharges falling under the CWA's definition of "point" sources from municipal, industrial, and construction discharges.

In the 1987 amendment, nonpoint sources were included that would allow a more comprehensive approach to abate and control water pollution. Phase I established application requirements for stormwater permits for **municipal separate storm sewer systems (MS4s)** serving populations over 100,000 and construction sites over 5 acres (USEPA, 2005). Phase II, initiated in 1999, set regulations for small MS4s in communities under 100,000 and construction sites between 1 to 5 acres, and sometimes under 1 acre (USEPA, 2005). For small MS4s permits, a set of six minimum assessment, evaluation, and control measures are required along with establishing measurable goals and implementing appropriate BMPs for each of the six areas. The areas are the following:

- Public education and outreach on stormwater impacts
- Public involvement and participation
- Illicit discharge detection and elimination
- Construction site runoff control
- Postconstruction stormwater management in new development and redevelopment
- Pollution prevention and good housekeeping for municipal operations

Detailed information related to BMPs for the foregoing areas have been published (CSQA, 2003a,b; USEPA, 2005). To obtain a NPDES stormwater permit, a **stormwater management plan** (SWMP) must be developed and implemented by municipalities. **Do I need an NPDES permit (USEPA NPDES, 2006)?** "It depends on where you discharge pollutants. If you discharge from a point source into the waters of the United States, you need an NPDES permit. If you discharge pollutants into a municipal sanitary sewer system, you do not need an NPDES permit, but you should ask the municipality about their permit requirements. If you discharge pollutants into a municipal storm sewer system, you may need a permit depending on what you discharge. You should ask the NPDES permitting authority. NPDES permits are issued by states that have obtained EPA approval to issue permits or by EPA regions in states without such approval."

In addition to the federal NPDES program, other programs target reduction of water pollutants. Each state and local government will have regulations in response to the federal programs. Additional federal programs related to certain issues are as follows:

1. **CWA Section 404**. The permit program established by Section 404 of the CWA deals with the placement "of dredged or fill materials into wetlands and other waters of the United States."
2. **CWA Section 401** of the CWA is a state water quality certification. It requires that before a federal agency can issue a license or permit for construction or other activity; it must have received from the state in which the affected activity would take place a written certification that the activity will not cause or contribute to a violation of relevant state water quality standards. Downstream states or entities whose individual WQS might be exceeded as a result of federal approval of the upstream activity can also play a role in the 401 process.

3. **CWA Section 319** created a federal program that provides money to states, tribes, and territories for the development and implementation of programs aimed at reducing pollution from "nonpoint" sources of pollution. The CWA provides no federal regulatory authority over nonpoint sources, in contrast to point sources.
4. **CWA Section 106** authorizes federal grants to states, tribes, and territories to support the development and operation of state programs implementing the CWA.

9.5 STORMWATER MANAGEMENT

9.5.1 Treatment Trains

In the regulatory section (Section 9.4), all the stormwater regulations targeted protection of water quality and not reuse. As noted at the beginning of this chapter, the nature of stormwater management changes when stormwater reuse for water conservation purposes becomes a part of the emphasis. However, the extent of change caused by inclusion of stormwater harvesting for reuse depends on the particular situation. For example, on a golf course with a well-designed nonstructural and structural (discussed later in this section) plan for stormwater control during excess precipitation and a good set of treatment structures to remove pollutants to deal with water quality issues, the only change may be discharge of the treated water into a suitable retention pond or lake (i.e., irrigation lake). In fact, this is already the practice on many golf courses (Florkowski and Landry, 2002). This practice illustrates that when integrated stormwater management includes reuse as one of the goals, of primary importance is management of excess stormwater for flood control and treatments to ensure protection of water quality; then the water will be suitable for irrigation or other uses. In contrast, new buildings, landscapes, developments, or development clusters may need to include significant structural modifications to ensure flood control, treatment for the intended uses, and collection for reuse, but these modifications are much easier to include during planning and construction at these levels than for municipalities and large watersheds as a whole.

When stormwater reuse is included as a priority, then water must be retained for this purpose (Hall, 2005). On a municipal or watershed basis, stormwater harvesting may include means of enhancing water infiltration into the soil for recharge of the local aquifer and subsurface flow to rivers, streams, and lakes. Reuse in this case would be after transport though the soil. However, on the basis of an individual building site, development, or cluster of developments, stormwater reuse would include retention of water at the end of any water quality treatment methods for reuse in irrigation or other suitable uses.

It is beyond the scope of this book to detail all the types of stormwater treatment methods, but a review will be useful in understanding the concepts. Because stormwater collection, treatment, and reuse will increasingly become incorporated into new developments or cluster of developments and a common reuse for the stormwater will be irrigation of landscape sites, it is important for turfgrass managers to understand potential problems and treatment options. The term **treatment train** is often used to indicate the concept of multiple treatment methods using a systems approach. Minton (2006) noted that there are two variants of this concept: concept 1, a set of source control best management practices (BMPs), possibly followed by a treatment device, or concept 2, a series of separate treatment structures or "boxes." This second concept of treatment train focuses on structural devices or practices and relates to using a series of multiple structural practices that treats the stormwater to improve water quality prior to discharging the water into a lake, pond, or cistern for irrigation reuse (or into a water body if the stormwater is not to be captured for reuse) (Minton, 2006). Minton (2006) stated that common treatment trains include: wet pond + wetland; swale + prairie wetland + marsh wetland; oil/grit separator + sand filter + wet pond. Each unit of the treatment train should have a specific and unique function.

The first concept of treatment trains noted by Minton (2006) is the most comprehensive and is based on a series BMPs that can be grouped into two basic categories (Table 9.1) (Thomas et al., 1997; CSQA, 2003a,b; USEPA, 2005):

1. **Nonstructural practices** that prevent or minimize runoff problems by reducing potential pollutants or managing runoff at the source. Both regulatory controls (codes, ordinances, regulations, etc.) and voluntary pollution prevention measures are included. A further division of nonstructural pollution controls is as follows:
    - **Land use practices**, where land use is controlled in sensitive areas of the watershed.
    - **Source control measures** are targeted at prevention or reduction of potential pollutants at their source before they come into contact with runoff or aquifers. Educational efforts to prevent pollutants are within this area.
2. **Structural practices** are engineered means to manage or alter flow, velocity, duration, and other characteristics of runoff by physical means.

TABLE 9.1

Structural and nonstructural stormwater management approaches for flood control, protection/improvement of water quality, and stormwater reuse

Structural (physical devices and means)	Nonstructural (regulations, guidelines, strategies)
Source controls	**Source controls**
On-site detention	Zoning
Permeable surfaces—sandy soils, cultivated	Subdivision regulations
Contouring to spread water and reduce flow	Low-impact development design strategies
Infiltration trenches	Restrictive covenants
Infiltration basins	Required buffers and setbacks
Grassed swales	Source pollution prevention regulations
Sand filters	Spill control programs

Structural (physical devices and means)

Source controls

- Peat or charcoal filters
- Mixed media filters
- Vegetative filter strips
- Extended detention ponds
- Vegetative buffer areas
- Wet ponds
- Biological control wetlands
- Shallow wetland biofilter areas
- Retention pond or lake[a]
- Multiple pond systems
- Wetland retrofits
- Illicit connection controls
- Water quality inlets
- Dry wells for infiltration
- Porous or pervious pavement for infiltration
- Retention vaults
- Hydrodynamic boxes
- Baffle boxes
- Catch basin inserts
- Alum
- Aquifer recharge for reuse[a]
- Cistern, vaults, rain barrel retention[a]

In-line controls

- Inlet design
- In-line storages
- Overflow/bypass design
- Radar/real-time control
- Litter booms
- Gross pollutant traps
- Geotextile filters
- Hydrodynamic separators
- Oil/grit separators
- Chlorination/dechlorination
- Coagulation
- Lamellar decantation

Nonstructural (regulations, guidelines, strategies)

Source controls

- Road maintenance programs
- Fertilizer and pesticide BMPs for application
- BMPs for water quality and conservation
- EMS adoption for site management[b]
- Public and facility management education
- Voluntary environmental stewardship programs
- Pet and animal control
- Drain labeling
- Permitting regulations
- Water circulation planning models
- Inundation models
- Design storm models
- Adaptive management

[a] Storage methods for stormwater reuse. Infiltration methods that contribute to aquifer recharge and subsurface flow to rivers, streams, and other water bodies are also indirect means of stormwater reuse.

[b] Environmental Management Systems. See www.usepa.gov and search EMS.

Source: After Thomas, J. R. et al. 1997. Wastewater Re-use, Stormwater Management, and National Water Reform Agenda. CSIRO Land and Water Research Position Paper 1, Canberra, Australia; USEPA 2005. *National Management Measures to Control Nonpoint Source Pollution from Urban Areas.* EPA 841-B-05-004. USEPA, Office of Water, Washington, DC; Dodson, R. G. 2005. *Sustainable Golf Courses: A Guide to Environmental Stewardship*. John Wiley, Hoboken, NJ.

Concept 1, consisting of a BMPs train or set of BMPs, can be applied to all aerial scales from a municipality or watershed (USEPA, 2005), a new development (USEPA, 2000; CSQA, 2003a), construction phase (CSQA, 2003b), golf course (Dodson, 2005), or to a single building site (USGBC, 2006). Figure 9.1 illustrates a BMP treatment train for a development or cluster of developments (the actual components are based on site-specific conditions). In this example, the initial phase encompasses practices to reduce runoff and potential pollutants by means of erosion control measures, pollution source control measures, public education to assist in reducing runoff and pollutants at the source, capture of roof runoff, and applying low-impact development concepts (USEPA, 2000).

In the second phase, stormwater is conveyed through a series of constructed features designed for specific treatment purposes, such as removal of sediment, gross pollutants, and other specific pollutants (often with some form of filters). The choice of treatment features depends on the specific pollutants on a site, with care being taken not to duplicate unnecessary treatments (Minton, 2006). An excellent discussion of primary structural features for stormwater treatment is provided by Minton (2004, 2005a,b,c) for basins (wet ponds, extended detention dry ponds), fine-media filters, and flow-through treatment swales and strips. Additionally, Minton (2006) provides insight into combining various constructed features into successful treatment trains for specific purposes. Comprehensive presentations on structural practices are found in EPA publications (USEPA, 2000, 2003, 2005) and the California Stormwater Quality Association (CSQA, 2003a,b) publications. Dodson (2005) applies holistic treatment trains to golf course situations and discusses their relative effectiveness.

The third phase is the inclusion of any additional treatments to improve stormwater quality for the intended use on the site. The fourth and final phase is to provide final treatment, control peak discharge rate to the desired storm (e.g., 2, 10, 25 year) by detention ponds or vaults, and retain stormwater for reuse when retention may be in retention ponds or lakes on a facility.

In reviewing the example shown in Figure 9.1, it becomes apparent that two overall goals are achieved with respect to water: protection of water quality and protection of water quantity. The first objective of an effective treatment train is to protect water

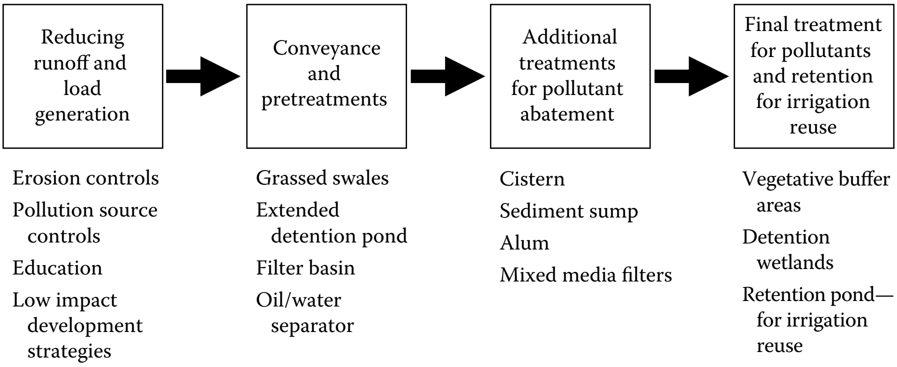


FIGURE 9.1 BMP stormwater treatment train.

quality by using a mixture of artificial and natural biofiltration practices, such as grassed/vegetated swales, fine-media filters, filter strips, bioremediation cells, sand filters, and constructed retention basins with wetland zones (extended detention dry ponds, wet ponds or wet basins with extended detention layers, extended detention basins with wet pools or micropools, constructed wetlands) (Minton 2004, 2005a).

The second objective was to protect water quantity within the hydrologic cycle using a mixture of artificial and natural infiltration practices such as subsurface infiltration systems, infiltration strips or trenches, infiltration basins, and prolonged contact (extended detention) between water and soil using canals or basins having wetland bottoms with or without native adapted flora. The combination of filtration and infiltration practices contributes to flood prevention by reducing surface quantity runoff and postconstruction peak flows, while allowing recharge of the underlying aquifer of a municipal or large watershed (USEPA, 2005). Hall (2005) notes that stream flow augmentation is not just by surface flow of water that may contain pollutants but by subsurface flow from groundwater that is of higher quality. When stormwater is retained on a single site, such as a golf course, for future irrigation, infiltration and contributions to aquifer recharge often occur during movement of water to and through treatment trains, during storage, and after the irrigation is applied. Thus, aquifer recharge and, ultimately, contributions to stream flow are part of the hydrological cycle on these areas as well as surface contributions during excessive rainfall events, because total stormwater capture is not normally possible. In addition to the various structural practices noted, nonstructural administrative practices are often used to protect water quality and quantity, such as elimination of directly connected impervious surfaces (concrete or normal asphalt), riparian setbacks, green space or conservation development zones, and open space development.

9.5.2 ADDITIONAL COMMENTS ON POLLUTANT TREATMENTS

As the list in Table 9.1 and listings in USEPA (2005) illustrate, there are a number of nonstructural and structural choices for developing an integrated stormwater management plan. Improvements in constructed structural approach will continue to be made but most likely not major changes in this area. However, in the area of in-line control devices, there is a consistent introduction of new designs or devices normally targeted toward specific pollutants or categories of pollutants. In the remainder of this section, a few example approaches or tools are discussed for illustration of some applications that have been made on turfgrass sites without the intention of being a complete listing.

Pollutant loads are calculated based on water quality parameters related to land use and soil type. An example of a case study for a landscape site is given by Simpson et al. (2004). They used the following to determine pollutant loading:

$$L = P \times Pj \times Rv/12 \times (EMC \times A \times 2.72)$$

where

L = pollutant load (lb/yr)
P = annual average precipitation (in./yr)
Pj = rainfall correction factor

Rv = runoff coefficient
EMC = pollutant event mean concentration (mg/L)
A = watershed area (acres)

where 12 and 2.72 are conversion factors, where 12 in. = 1 ft and 2.72 lb/yr = ((ft/yr)(mg/L)(ac)) × ((43,560 sq ft/ac)(lb/453,593 mg)(28.317 L/cu ft)) (Source: *EPS's Guidance Manual for Preparation of Part 2 of the NPDES Permit Application for Discharges from Municipal Separate Storm Sewer Systems;* Simpson et al., 2004).

Reduction of pollutant load from environmental loading of nutrients such as nitrogen and phosphorus, suspended solids, hydrocarbons, and heavy metals such as lead, copper, and zinc can be reduced using differential settling and biological uptake. Particulate pollutant settling efficiency and biological uptake/transformation are dependent on runoff detention time duration and presence of appropriate wetland and aquatic vegetation. Oxide-coated sand and calcite in various forms (including crushed seashells) removes dissolved phosphorus (Minton, 2005c). Dissolved metals can be removed with organic media (peat, leaf compost, and soybean hulls) and different types of zeolites as general-purpose removers (Cinar and Beler-Baykal, 2005; Inan and Beler-Baykal, 2005). Organic media and sand will remove petroleum hydrocarbon pollutants because of their hydrophobic nature. Activated carbon sources, including organic media, will remove pesticides.

Polyacrylamides (PAMs) can be used for erosion control and for sediment control via coagulation and flocculation (Baxter, 2005). These polymers target particles down to 20 microns by attaching to soil particles of opposite charge and agglomerating into heavier particles that normally settle out and improve turbidity. Anionic polymers are less toxic to aquatic organisms and are recommended over the cationic products, but they are safe for humans when used properly. Polymer coagulant and flocculant blends involving Chitosan, DADMAC, PAC, and tannins have been used effectively when considered part of a systemswide control strategy.

Golf courses are being mandated to maintain water hazards on the site to conform to the National Pollutant Discharge Elimination System (NPDES) by installing a stormwater system to proactively remove particulates from its water features. This system is much more than simply directing watershed-harvested water into drainage lines for disposal. A "Capture Flow" system (Carson Industries, La Verne, California) uses a three-stage system. In the first stage, stainless steel basket traps floating debris and trash up to 1/8th-inch in diameter. Oil-absorbent booms on side walls reduce the hydrocarbon load entering the storm drain system. As water level rises, stormwater flows through the third-stage polypropylene filter and is discharged through an outlet pipe. Sediments settle in the sump area of the catch basin floor. The system maintains the aesthetic value of the golf course, reduces lake maintenance costs, and increases the efficiency of water-pumping equipment on the course. Such a system is installed on Eagle Glen Golf Course in Corona, California.

Additionally, installation of porous or permeable pavements can provide infiltration for adjacent impervious areas (Baxter, 2005; Traver et al., 2005). The porous design has good total suspended solids, oil/hydrocarbon, and metal pollutant-removal properties. The asphalt composition and costs are identical to regular pavements except that aggregate fines have been removed, providing larger pore spaces for water infiltration into the underlying stone bed. The stones are uniform in size to permit continuing water infiltration to the geotextile layer (prevents upward migration of soil particles that could plug the pores) and, eventually, to the soil layer.

Sand or mixtures with a second media are the most commonly used filter mediums to remove dissolved pollutants in stormwater or harvested recycled water. Secondary medias include peat and soybean hulls, iron/manganese/aluminum oxide coatings on sand (for sequestration of metals), activated carbon (for organic compounds), calcite, dolomite, and iron filings (for phosphorus) (Minton, 2005a).

9.6 STORMWATER REUSE ON GOLF COURSES

When reclaimed water use or stormwater reuse are discussed, golf courses are often the first sites identified for these practices. As previously stated, stormwater has been collected from on-site landscape areas, moved through appropriate treatment trains, and discharged into retention lakes and ponds on golf courses and then reused for irrigation purposes for many years (WWE, 1996). In most past situations, the stormwater from impervious surfaces was not used so that many pollutants were avoided. By taking care to allow buffer areas, avoiding fertilization and pesticide application near water features, and using other good IPM and nutrient management practices, only minimal nutrient and pesticides loads are going into the lakes from storm events (Dodson, 2005). Thus, stormwater collection lakes on these golf courses were not impaired by these pollutants. The collected water is normally diluted by natural reuse for irrigation back onto the same grass and other landscape areas.

When golf courses are compared on a landscape area to other landscape areas within municipalities and larger watersheds, it is difficult to find other sites within these entities that contain as many structural and nonstructural controls for successfully dealing with stormwater—whether from the perspective of stormwater control, stormwater quality treatment, or stormwater reuse. Dodson (2005) expands beyond stormwater issues into other areas of "environmental sustainability" and notes that "Golf courses can also be built and managed to treat wastewater and act as part of the stormwater management systems for entire communities.... Golf courses, if properly sited, appropriately designed, and effectively managed, may provide many of the same attributes of a nature reserve."

FLORIDA CASE STUDY: STORMWATER POLLUTION PREVENTION PLAN—OPERATION AND MAINTENANCE—ENCOMPASSING GOLF COURSES

Golf courses will be designed, constructed, and managed in accordance with the Signature Program of Audubon International. The Principles for Resource Management required by the Signature Program will be incorporated into the design and operation procedures of the golf course. Those principles include site-specific assessment, habitat sensitivity, native and naturalized plants and natural landscaping, water conservation, waste management, energy conservation and renewable energy sources, transportation, green space and corridors, agriculture, and building design. Best management practices will utilize an integrated turf management system on the golf course that minimizes the quantity of fertilizer, pesticides, and herbicides through careful monitoring of turf health, and application of chemicals only where and when needed. Guidelines for the practices were integrated from the 1995 Florida Department of Environmental Protection Best Management Practices for Golf Course Maintenance Department and from the Environmental Principles for Golf Courses in the United States. Categories for common areas include general principles, plant protection and nutrition, water usage, waste management, and facility operations. Residential categories include general principles, landscaping and yard maintenance, water usage, waste management, and yard drainage. Solid waste management categories include management and handling of urban refuse, litter and leaves/clippings, sanitary facilities for temporary storage, and refuse collection requirements.

Stormwater management and treatment is designed to maximize the attenuation of stormwater-generated pollutants prior to discharge off-site or for eventual use as a blended irrigation source on golf courses. System components include wet detention lakes and lake interconnect pipes; storm water inlets, pipes and culverts; swales and grassed water storage areas; ditches or canals; outfall or discharge control or weir structures; earthen embankments (dikes and berms); and sediment trap structures (baffle boxes and proprietary devices). Pollution control guidelines were developed for nutrient and pesticide management, street sweeping, solid waste management, operation and maintenance of stormwater management and treatment systems, routine water quality testing, animal/livestock waste storage and disposal, and construction activities. Site design source controls and best management practices involving watersheds discharging to impaired or sensitive water bodies were developed for reduced turf coverage, low-water-use native landscape plantings, water-conserving irrigation systems, stormwater reuse, rooftop runoff, pervious pavement installation, and animal/livestock waste storage and disposal.

Stormwater conveyance and pretreatment BMPs for watersheds discharging to impaired or sensitive water bodies were developed with filter strips/vegetated stormwater inlets, vegetated/grassed swales, sediment trap structures, dry detention/retention pretreatment, additional stormwater treatment volume management, wetlands, littoral berms/settling basins/phytozones with detention areas, planted filter marshes, planted littoral zones, increased flow paths, and chemical treatment. The following formula can be used to document the effectiveness of the monitoring program:

$$\text{Treatment efficiency} = \frac{\text{Mass of pollutant (inflow)} - \text{Mass of pollutant (outflow)}}{\text{Mass of pollutant (inflow)}} \times 100\%$$

where

high = >75% load reduction or sequestration
medium = 30–75% load reduction or sequestration
incremental = <30% load reduction or sequestration

Adapted from: Florida DEP NPDES Guidance for Stormwater Pollution Prevention (http://www.dep.state.fl.us/water/stormwater/npdes/swppp.htm) and Best Management Practices for Enhancement of Environmental Quality on Florida Golf Courses. 2007.

9.7 SUMMARY

Stormwater management is currently, and will continue to be, a critical strategy to provide acceptable quantity and quality water for blending with other alternative sources to be used for turf irrigation. Proper infrastructure implementation and subsequent monitoring of water quality will be essential components to successful use of this strategy during this century. Integrated stormwater management at small (buildings, single home site) to large aerial scales (municipalities) will increasingly consider the retention and reuse of stormwater as a water conservation measure. Often, the primary reuse will be for landscape irrigation purposes. Individuals involved in all facets of the turfgrass industry should become more familiar with this potential alternative irrigation water source.

Part 3

Management Options for Site-Specific Problems

10 Irrigation System Design for Poor-Quality Water

10.1 IRRIGATION OPERATION AND POOR WATER QUALITY

Irrigation system design and operation/scheduling program are profoundly affected when poor irrigation water quality is being applied to recreational turfgrass. In this chapter, we will provide an overview of the issues that must be considered with respect to the irrigation system and scheduling. The irrigation system is an essential tool for managing poor-quality water, especially in climates where evapotranspiration exceeds rainfall, or rainfall events are relatively infrequent or seasonal in distribution. Precisely controlled, uniformly applied irrigation applications are critical when leaching to manage salt and/or Na accumulations (Carrow et al., 2000; Duncan and Carrow, 2000; Tanji, 1996). Without excellent distribution uniformity, overwatered, saturated wet areas can develop where excess irrigation is applied that exceeds soil infiltration and permeability rates (Duncan and Carrow, 2000; Zoldoske, 2003). Conversely, in the process of managing those wet areas and trimming back irrigation, drier areas can become salinized if a sufficient leaching fraction is not being applied. Therefore, where salt and/or Na management is required, investing in a more sophisticated irrigation distribution system is justified.

Effectively leaching salts without developing excessive wet areas requires an irrigation design that optimizes both distribution uniformity and control (Tanji, 1996). Distribution uniformity impacts salt distribution, leaching fractions, runoff, and total water consumption. Control capabilities allow matching water applications/precipitation rates to soil conditions (infiltration, percolation, and drainage rates). Additionally, sites with multiple turf cultivars, especially those cultivating both warm- and cool-season turfgrasses, often require sophisticated sprinkler controls that allow precise management of leaching, such as tees, greens, and fairways on golf course areas. The capacity of the hydraulic design (main and lateral line sizes) must account for increased water volumes needed for leaching fractions based on the irrigation water quality and threshold salinity values of specific turfgrass cultivars.

Successfully managing sites irrigated with poor-quality water may necessitate designing the irrigation system with capabilities and features not required with good-quality water. Depending on a site's individual water chemistry, specialized hardware to add amendments or remove odors may be needed. Higher salt concentrations and resulting corrosion with recycled and brackish waters may require alternative hardware components and/or other design considerations. Disinfectant chemicals used occasionally in effluent water have been known to degrade rubber gaskets and soft plastic components, resulting in a problem that occasionally surfaces after retrofitting older irrigation systems to deliver recycled water.

Soil conditions must also be considered in the programming and management of the irrigation control system (Carrow et al., 2000). Evapotranspiration and leaching fractions will determine the total amount of water/number of cycles applied during each irrigation event. Sprinkler precipitation and soil infiltration rates together will determine the maximum duration of individual irrigation cycles (Oster et al., 1992; Tanji, 1996). Water-holding capacity of soils will dictate the length of time (frequency) between irrigation events. Management practices will determine the turf manager's overall success in leaching undesirable salts and, ultimately, the development of a deep and vigorous turfgrass root system.

As the use of halophytic turfgrass species such as seashore paspalum *(Paspalum vaginatum)* and inland saltgrass *(Distichlis spicata)* become more common, it is inevitable that use of water sources with increasing salinity will become more common (Duncan and Carrow, 2000; Vermeulen, 1997). Because highly saline waters are generally more corrosive, irrigation system components will require increased corrosion resistance in conjunction with other special design considerations.

10.1.1 Salt Distribution and Leaching

As saline water is applied by overhead sprinkler irrigation, vertical water flow results in salt movement down into the soil profile with the infiltrating and percolating water (Hanson et al., 1999). Application of a small amount of water in addition to the evapotranspiration replacement requirement is required to move the salts deep into the profile and avoid toxic accumulations within the plant root zone and upper soil profile. The excess water is commonly referred to as the **leaching requirement (LR)** or **leaching fraction (LF).** Wherever evapotranspiration plus the leaching fraction has not been met in the field, saline soils will develop (Pira, 1989; Tanji, 1996). Therefore, a relationship exists between deep water percolation and salt migration because at lower depths, salt distribution and accumulation will depend on how uniformly water is applied (Hanson et al., 1999; Pira, 1989). Sprinkler distribution patterns and irrigation scheduling programs, therefore, have a primary influence on salt distribution within the soil profile.

10.1.2 Distribution Uniformity Effects on Leaching and Salt Distribution

Sprinkler distribution uniformity refers to how evenly water is applied. If the amount of water applied is the same throughout the field, uniformity would be 100% and the same amount of water would be applied at every location in the field—assuming that all water infiltrated into the soil at the point of application. Unfortunately, no irrigation system is capable of delivering 100% uniformity, and different parts of the field will receive different amounts of water (Hanson et al., 1999). However, a good irrigation system design can greatly enhance uniformity of water application.

TABLE 10.1
Average leaching fractions needed to maintain a minimum 5% leaching fraction throughout the field

Distribution uniformity (DU%)	Average leaching fraction (LF%)
55 = poor	90
65	62
70	49
75	37
80	31
85	23
95 = good	14

Source: From Hanson, B. et al. 1999. *Agricultural Salinity and Drainage*. Division of Agriculture and Natural Resources Publication 3375. University of California, Davis, CA.

Distribution uniformity (DU) is a measure of how uniformly irrigation water is applied by the system and will be discussed in greater detail later in this chapter. Where DU of applied water is poor, there can be significant differences in amounts of water applied to the wettest compared to those applied to the driest locations; therefore, the poorer the DU, the more total water required to meet the leaching requirement within the driest area while applying excess water to the wettest sites (Hanson et al., 1999; Skaggs and van Schilfgaarde, 1999). This is illustrated in Table 10.1, which shows the average leaching fraction required at different distribution uniformities to maintain a 5% leaching fraction in the area receiving the least total amount of water (Hanson et al., 1999). These differences in application rates result in salts being displaced lower in the profile where more water is applied and shallower where less water is applied, thereby creating inconsistent turf quality and playing conditions. Hence, salt movement and resulting turfgrass quality can be made more uniform by more uniform water application (Hanson et al., 1999; Skaggs and van Schilfgaarde, 1999).

In addition to moving salts uniformly into the soil profile, uniform sprinkler distribution can reduce the total watering requirement when leaching, limit development of wet and dry areas, and potentially save water (Hanson et al., 1999; Skaggs and van Schilfgaarde, 1999; Zoldoske et al., 1994). The more uniform the irrigation application by the sprinklers, the less the need for excess irrigation to adequately irrigate dry or saline areas (Tanji, 1996). Supplemental drainage lines then become less important as less deep percolation and surface runoff will occur. Manual labor for spot irrigation with hand-directed hoses or portable sprinklers is also reduced.

10.1.3 WATER QUALITY, SALINITY THRESHOLDS, AND LEACHING FRACTIONS

Different turfgrass and ornamental species require different amounts of water under the same environmental conditions to replace their daily ET and leaching requirements. Research has shown that as much as 20% more water is required by cool-season turfgrass species compared to warm-season turfgrass species under the same environmental conditions (Brown and Kopec, 2000; Ritchie et al., 1997). Annual water requirements of warm-season turfgrasses overseeded with cool-season cultivars typically fall somewhere in between a solid stand of warm- or cool-season turfgrass (Brown and Kopec, 2000).

Additionally, the leaching fraction for each turfgrass species and cultivar is dependent on its threshold salinity tolerance (Carrow and Duncan, 1998; Carrow et al., 2000). Depending on water quality, these leaching fractions can add significant irrigation amounts in addition to ET replacement to maintain salt movement through the soil. This additional percentage of applied water must be factored into the hydraulic capacity of the irrigation system and what impact it will have on the duration of the watering window (Carrow et al., 2000).

10.1.4 LEACHING FRACTIONS AND IRRIGATION SYSTEMS HYDRAULIC DESIGN

The leaching fraction must be accounted for when designing the irrigation system because additional water volume must be considered when sizing pipe. If these flow requirements are not considered, either maximum flow velocities will be exceeded or the watering window will need to be extended. Excessive flow velocities result in severe surge pressures and water hammer that lead to premature pipe and fitting failures, thereby shortening the useful life of the irrigation system. Extended water windows will interfere with players accessing the golf course, maintenance operations, and/or local regulations requiring all automatic irrigation to be completed within specific nighttime hours. These regulations are often mandated by municipalities when irrigating with reclaimed, recycled, or effluent water (Feil et al., 1997; Huck et al., 2000; Snow, 1994).

10.1.5 SOIL TYPES AND WATER QUALITY EFFECT ON CONTROL SYSTEMS AND DESIGNS

Soil infiltration, permeability, and internal drainage characteristics can vary considerably among fairways on native soils or greens and tees that may have been constructed with sand-based root zones. Ideally, the precipitation rate of the sprinkler system will not exceed the infiltration rate of the soils (Oster et al., 1992). However, in the real world, this is not always possible because sprinkler precipitation rates very often exceed soil infiltration rates. Computerized control systems must often be used to deliver multiple irrigation cycles—that is, pulse irrigation. This strategy provides time between each application cycle, allowing water to infiltrate into the grass canopy and upper soil profile while avoiding surface runoff (Carrow et al., 2000). This control feature to allow pulse irrigation is commonly referred to by manufacturers as “cycle and soak.”

In addition to computerized cycle-and-soak control capabilities, there is a need for each area of control to be as small in size as possible. This allows maximum flexibility for variable site conditions (soil types, slope, sun, wind exposure, etc.) that warrant special management when irrigating with poor-quality irrigation water. The ultimate and ideal arrangement is one "valve in head" sprinkler per control station, commonly referred to as either "individual or single head control."

10.2 IRRIGATION SYSTEM DESIGN CONSIDERATIONS FOR MANAGING POOR-QUALITY WATER

The overall performance of an irrigation system is often limited by the performance of an individual component or subsystem. To manage poor-quality water containing high salts and/or sodium, optimizing distribution uniformity must be the first priority of the irrigation design. Uniform distribution will significantly reduce the challenges of salinity management. However, when using poor-quality irrigation water, there are a number of items that may need to be addressed, including regulatory and/or operational perspectives, and these are discussed in this section.

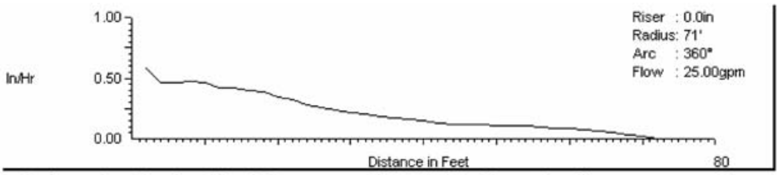
Sprinkler and nozzle selection and spacing evaluation. The sprinkler is the most important part of the irrigation system because it distributes the water over the land. How uniformly it accomplishes this task determines the effectiveness and efficiency of the irrigation system (Pair et al., 1983). Selection of the best-performing sprinkler, nozzle, and spacing combination is therefore critical to the success in managing poor water quality with the specific site irrigation system, and avoiding any salt accumulation in the soil profile along with excessive wet or dry areas.

Sprinkler and nozzle performance have been evaluated since the early 1940s with statistical calculations. The two most common measures of sprinkler uniformity are **CU (Christensen's coefficient of uniformity)** and **$\mathrm{DU}_{\mathrm{LQ}}$ (low quarter distribution uniformity)**, where each is expressed as percentages. The higher the reported percentage, the more uniform the water application with 100% uniformity representing perfectly uniform coverage. However, this is unattainable because even rainfall distribution does not fall with 100% uniformity.

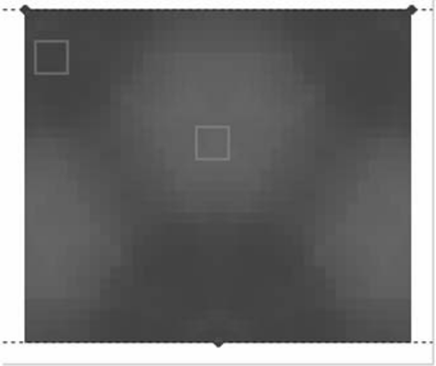
A shortcoming of both CU and $\mathrm{DU}_{\mathrm{LQ}}$ is that neither takes into account the location of the wetter and/or dryer application areas, such as whether drier or wetter values are concentrated in a localized area, or dispersed throughout the entire pattern, where a surrounding high value may benefit an adjacent low value. Therefore, two different sprinklers that produce the same CU and $\mathrm{DU}_{\mathrm{LQ}}$ results may deliver noticeably different performance in the field if the driest and/or wettest values are concentrated rather than dispersed (Pair et al., 1983). Golf course irrigation designers have long recognized this problem with CU and $\mathrm{DU}_{\mathrm{LQ}}$ and would, therefore, often rely on past field experience when selecting sprinklers, nozzles, spacing distances, and geometric configurations.

Personal computers changed this in the 1980s when the Center for Irrigation Technology (CIT) located at the California State University (Fresno, California) developed their **Sprinkler Profile and Coverage Evaluation (SPACE)** software (SPACE, 2007). Sprinklers can now be objectively evaluated before they are installed in the field, through indoor testing and analysis of that data with the SPACE software (Barret et al., 2003; Solomon, 1988; Tanji, 1996).

For a small fee, the CIT staff tests a sprinkler and nozzle combination inside their laboratory to develop a profile (Figures 10.1 to 10.3). The profile data collected from a sprinkler can then be input into the SPACE software for further analysis. Overlaps of profiles at spacing distances and configurations (square, rectangular, triangular, etc.) set by the operator will synthesize densograms. The densograms (Figures 10.1 to 10.3) graphically express the uniformity of the overlap with light and dark areas



a. Triangular Head to Head Coverage using Wedge Shape Profile



b. Square Head to Head Coverage of Wedge Shape Profile

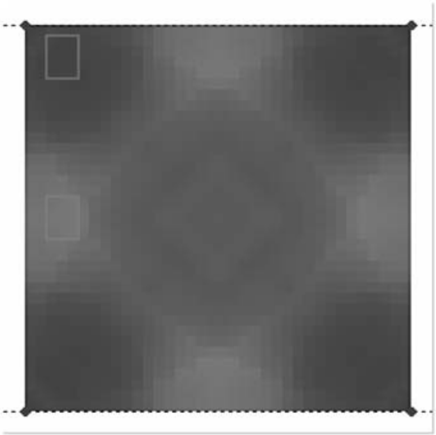
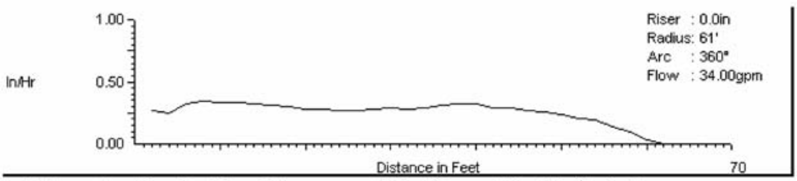


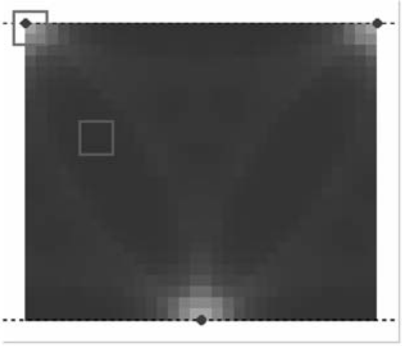
FIGURE 10.1 Wedge-shaped sprinkler profile and head-to-head coverage densograms: (a) triangular head-to-head coverage using wedge-shaped profile; (b) square head-to-head coverage of wedge-shaped profile.

(representing dry and wet areas, respectively). Densograms allow a visual preview of projected sprinkler coverage and performance before installing the equipment in the field. Several other reports of statistical, numerical, and graphic information that report other performance measures, including the old standards of CU and DU_{LQ} can also be printed from the SPACE program.

Unfortunately, indoor evaluation has shortcomings. It cannot predict the influences of wind, elevation above sea level (air density), operating pressure changes



a. Triangular Head to Head Coverage of Flat Shaped Profile Sprinkler.



b. Square Head to Head Coverage of Flat Shaped Profile Sprinkler.

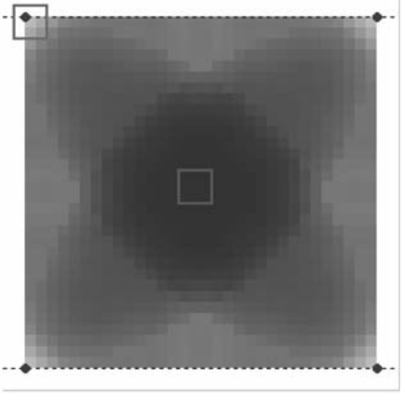
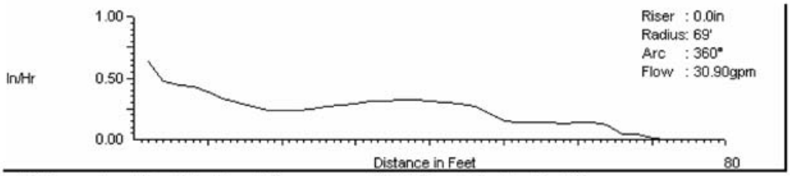
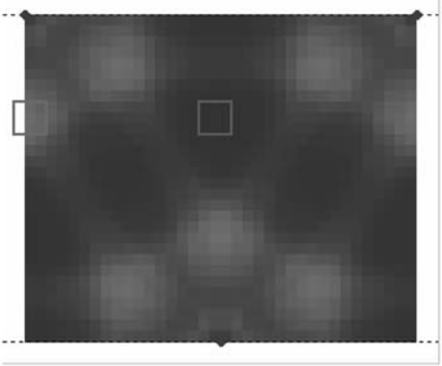


FIGURE 10.2 Flat-shaped profile and triangular head-to-head coverage densograms: (a) triangular head-to-head coverage of flat-shaped profile sprinkler; (b) Square head-to-head coverage of flat-shaped profile sprinkler.



a. Triangular Head to Head Coverage of "Valley" in the Profile



b. Square Head to Head Coverage of "Valley" in the Profile

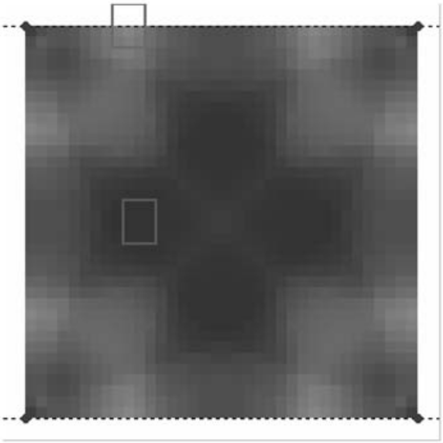


FIGURE 10.3 Sprinkler profile containing a "valley" and head-to-head coverage densograms: (a) triangular head-to-head coverage of "valley" in the profile; (b) square head-to-head coverage of "valley" in the profile.

due to land elevation changes, air or water temperature, humidity, or other factors that may affect how water is distributed after leaving the nozzle. However, it can prevent certain failure, as evidenced by the examples found in Figures 10.1b, 10.2b, and 10.3b. Laboratory evaluation of sprinklers is the best method of sprinkler selection currently available, and is better than simply installing sprinklers in the ground and waiting for problems to develop on the soil surface later. If nothing else, indoor testing and computer modeling can allow for a better understanding of any given irrigation design limitations (Barret et al., 2003).

Pressure-regulated valve in head sprinklers and remote control valves. Irrigation system design in which poor irrigation water is present should specify that all valve-in-head sprinklers and remote control valves have internal pressure regulation devices. Pressure regulation devices may be optional, depending on the manufacturer. Pressure regulation maintains more consistent nozzle flow and precipitation rates. Both factors contribute to delivering the highest distribution uniformity possible.

Geometric configurations (square versus triangular). Irrigation texts stress the critical importance of placing sprinklers on consistent geometric configurations to maximize distribution uniformity (Barret et al., 2003; Pair et al., 1983; Pira, 1989). In-ground agricultural systems are most often established on square and rectangular spacing at least partially as a result of the need to move laterals with sprinklers on fixed spacing down the field from set to set (Pair et al., 1983). Turfgrass sprinkler systems are usually established on an equilateral triangular spacing (Pair et al., 1983). Field sprinkler research from the early 1940s statistically demonstrated that equilateral triangular spacing had the potential to deliver high uniformity without the need to overlap coverage beyond 50 to 60% of the diameter (Pair et al., 1983). Field experience at golf courses throughout the arid southwestern United States and the three examples from the SPACE software (Figures 10.1 to 10.3) tend to support equilateral triangular spacing as preferable over square spacing to optimize distribution uniformity.

Combating wind effects on distribution uniformity. Wind of any speed distorts distribution profiles, and the amount of distortion depends on the water droplet sizes created by the nozzle design (Barret et al., 2003; Pair et al., 1983). As a rule of thumb, when wind speed exceeds 5 to 6 mph, coverage uniformity can begin to suffer (Barret et al., 2003; Pair et al., 1983). Reducing the impact of wind on distribution has been attempted in a number of ways, such as reducing upwind or overall spacing and/or reducing operating pressures. Reducing operating pressure at the nozzle, while staying within manufacturer-recommended ranges, will produce larger droplets that travel less distance in wind than fine droplets produced at higher pressure (Barret et al., 2003; Pair et al., 1983). Improving performance in wind with spacing adjustments, especially where heads are offset to the upwind side, is risky. Unless wind speed and direction are very constant, especially during the nighttime hours when most irrigation is done, offsetting heads is not recommended (Barret et al., 2003).

Hydraulic systems (pump station, mainline and lateral piping network). The pumping and piping systems need to deliver water throughout the site at an adequate, relatively uniform pressure to allow the sprinklers to operate efficiently. There is a direct correlation between sprinkler operating pressures and nozzle flow rates; thus, pressure variations will affect the uniformity of in-field precipitation rates (Skaggs and van Schilfgaarde, 1999). Additionally, pressure will affect distribution uniformity if it is outside the sprinkler manufacturer's recommended range. Pressure that is too low will result in large droplets and poor droplet distribution, whereas pressure that is too high creates excessive atomization and wind drift that affects droplet distribution (Zoldoske et al., 1987). Pressure-regulating or pressure-boosting devices may be needed on sites with severe terrain to maintain uniform pressure.

The pumps and piping networks must also be sized to handle additional flow volumes for leaching requirements. The system should be able to complete a full irrigation cycle at maximum ET replacement plus the required leaching fraction within the time frame of any mandated watering window. For example, many recycled/effluent regulations state that all unattended automatic irrigation operations must be completed within a specific time frame such as between the hours of 9 PM and 6 AM, a nine hour window (Huck et al., 2000; Snow, 1994).

There may be additional reasons to shorten the watering window to less than regulations may require. Special off-peak "time of use" energy rates are often available that can save considerably on electric costs. Another potential reason for a shortened window of operation would be time for the irrigation application and leaching fraction to infiltrate the turfgrass canopy and soil surface, and provide a firmer playing surface for early morning golfers.

Parallel/dual mainline distribution systems. Recycled water use has become mandated for landscape irrigation in parts of the United States (California Assembly, 1991). However, many water providers/regulators will allow maintaining golf putting greens during nondrought conditions with potable quality water while using a nonpotable source to irrigate the remainder of the golf course. They recognize that putting greens comprise a relatively small area of high-value, salt-sensitive turf.

It is becoming more common for golf course irrigation systems to utilize parallel/dual (two) mainline loops to distribute the recycled/alternative water to the tees, fairways, and rough areas and potable water to the putting greens. Local regulations may also mandate dual systems for setbacks from surrounding residences, environmentally sensitive areas, and/or potable quality surface and groundwater sources (Barret et al., 2003). Dual systems require special equipment, including items such as air gaps and/or RPPD (reduced pressure principal devices) backflow devices to protect the potable source from cross-connection contamination with the alternative/recycled water source. Minimum separation distances between the two mainline systems along with colored pipe (typically purple to signify nonpotable and either blue or white to signify potable) are also normally required. Local regulatory agencies should be consulted regarding specific design requirements for a parallel/dual delivery system. Also, equipment must be included that is required to safely blend or deliver the alternative water to the greens in case of a drought, when mandatory potable water use restrictions may be imposed.

Single/individual sprinkler control. Maximizing sprinkler control down to the smallest manageable area is critical when working with poor-quality water. Computer central controllers combined with single/individual head control (one station/one wire/one sprinkler) provide the ultimate control system that allows leaching of specific areas along with micromanagement of wet and dry spots. Single individual head control requires additional satellite controllers that are well worth the investment on sites with poor water quality and/or where water-use efficiency is a necessity.

If the construction budget will not allow single head control, then the following alternative can be used to cost-effectively plan for future upgrading to this feature. Size the 110 V.A.C. power system to accommodate enough satellite controllers to eventually provide single/individual head control. Individual 24 V.A.C. wires can be brought from each sprinkler back to the satellite controllers. The individual wires can be bundled as multiple sprinkler stations in the controller cabinet or in an underground valve box next to the satellite. This allows the option of adding satellites and splitting stations into single/individual head control in the future as the budget permits. It also allows reassigning individual sprinklers to different stations without trenching in additional wire if management problems occur later. The cost of the additional wire is minimal when installing a new system and is worth any additional investment.

Dual green sprinklers/leaching sprinklers. It is becoming increasingly popular to install two sprinklers at the putting surface. The configuration between opposing part circle sprinklers or one full and one part circle can vary depending on the turfgrass manager's personal preference. Opposing part circle sprinklers allow irrigating or leaching the putting surface with minimal effect on the surrounds. However, maintaining the arc adjustment and managing the areas where the overlap is insufficient or excessive can be challenging. Combining a full circle (for regular irrigation applications) and opposing part circle sprinkler for supplemental applications to surrounds or occasional leaching of the greens reduces the problems associated with exactly matching the overlap of opposing part circle sprinklers.

Weather and soil moisture monitoring equipment. Weather and soil moisture monitoring equipment can provide useful information to irrigation managers working with poor-quality water. A leaching fraction can be added to evapotranspiration (ET) estimated by weather monitoring to allow scheduling irrigation events that meet both the ET replacement and leaching requirements. Soil moisture sensors can also be installed to monitor how deeply each irrigation application penetrates. By installing soil moisture monitoring sensors at various depths, the irrigator can determine when the entire root zone has been adequately wetted.

Equipment used to predict ET can range from simple evaporative gauges costing a few hundred dollars to sophisticated weather stations costing several thousands of dollars. The simplest of evaporative gauges use an exposed porous ceramic surface that evaporates water from a container to simulate ET. Manual readings are taken by the irrigator each day of how much water has been lost from the calibrated container. The more sophisticated weather station systems monitor multiple parameters such as wind, relative humidity, temperature, and solar radiation, and calculate ET with formulas that consider the influence of each parameter on evaporation and transpiration (crop water use).

The modified Penman–Monteith equation published in the FAO Irrigation and Drainage Paper #56 (Allen, 1998; Campbell Scientific, 2004) is becoming the industry-accepted standard of the turfgrass scientific community and many state-operated weather system networks. However, recognize when purchasing a weather station that not all suppliers choose to adhere to this standard ET formula. Some weather stations, including those operated in conjunction with computerized irrigation control systems, use their own proprietary ET formulas (Irrigation Association, 2007; Campbell Scientific, 2004). This can cause great confusion when comparing data between weather stations operating under identical climatic conditions and requires the crop coefficients to be adjusted for each different formula (Brown, 1999).

Setbacks and buffer zones. Recycled, brackish, and other saline irrigation waters can require setbacks or buffer zones from surrounding residences/property lines, environmentally sensitive areas, wetlands, potable surface water sources, and potable groundwater wellheads (Barret et al., 2003). Distances have been reported as varying between 50 to 1000 ft depending on local regulations (Barret et al., 2003). Concerns addressed by setbacks and buffer zones range from overspray and wind drift of recycled water into designated areas, to concerns of leaching or runoff into potable surface and groundwater sources. Wellheads are particularly susceptible to leaching immediately surrounding the area where soil has been disturbed when drilling the well. The concern is not always directly related to irrigation leaching, such as if a pipe were to break and flood the area immediately surrounding the wellhead. If irrigation application is desired in the areas designated for setbacks, a dual system delivering potable water as previously described is typically required.

Corrosion-resistant components. Salts in irrigation sources can range from under 100 ppm to amounts approaching that of seawater (in excess of 34,000 ppm). As salt content of the water increases, so does the need for the corrosion resistance of irrigation system components (pumps, mainline fittings, control cabinets, internal sprinkler components, wire splices, etc.). Exposure to both high-salinity water and salinized soils can cause corrosion of metal components (Clarke, 1980). Sprinkler manufacturers have responded with the increased use of plastics for control cabinets, sprinklers, and other components. High-quality, corrosion-resistant marine/naval grade paints, epoxy coatings, hardware, and metals commonly used in salt water and various industrial applications (corrosive reverse osmosis water and acid) are options for refurbishing existing equipment (Micro Surface Corporation, 2007; Wink Fasteners, 2007). Plastic pumps, as used in industrial handling of salt water, corrosive acids, and deionized/reverse osmosis ultrapure water have not yet entered the irrigation industry, but the potential exists as waters of lesser quality continue to be used for irrigation (Vanton Pump, 2007).

Chlorine and chloramine component degradation resistance. Potable and wastewater facilities have used disinfectants, typically chlorine, for the past 100 years to kill bacteria prior to distribution (Hudson, 2007). Though effective against waterborne microbes and pathogens, chlorine generates disinfection byproducts (DBPs) that with long-term exposure may cause cancer and, therefore, the EPA has now set DBP limits (Hudson, 2007; Skipton and Dvorak, 2002).

Consequently, many potable water treatment facilities have switched from using free chlorine to chloramine (a chlorine–ammonia mixture termed "combined chlorine" in water and wastewater reports) or a mixture of chlorine and chloramine (termed "total chlorine" in water and wastewater reports) (Hudson, 2007; Skipton and Dvorak, 2002). Chloramine has several advantages over free chlorine; it produces less DBPs, and has less effect on the taste and odor of potable water. Chloramines react more slowly with the pathogens than chlorine, but because they do not evaporate rapidly from open water bodies such as chlorine, they remain active longer, performing the disinfection process and increasing the total contact time with the pathogen (Hudson, 2007; Skipton and Dvorak, 2002). Typical chloramine compounds used for disinfection are monochloramine (NH_2Cl), dichloramine ($NHCl_2$), or trichloramine (NCl_3) (Hudson, 2007; Skipton and Dvorak, 2002).

Chloramines are toxic to fish (both freshwater and saltwater), reptiles, and amphibians. Also, chloramines cannot be present in water used for kidney dialysis because they interfere with oxygen absorption if taken directly into a living organism's bloodstream. They are safe for consumption in drinking water by humans and animals because normal digestion neutralizes the ammonia before entering the bloodstream (Hudson, 2007; Skipton and Dvorak, 2002).

Although chlorine can, and is, still used in both recycled and wastewater disinfection, it has been theorized that chloramines could be formed in wastewater as free chlorine reacts with organic nitrogen compounds. The significance of this is chloramines have also been identified as potential problems with regard to the corrosion of metals and degradation of rubber and some specific plastics ingredients. Early recycled water users and irrigation equipment manufacturers often attributed premature plastic and rubber parts failures of sprinklers, pump seals, and gaskets contained in repair couplings and/or bell joint pipe to high residual chlorine resulting from the disinfection process. It now appears that the problem may actually be related to free chlorine that preferentially reacts with ammonia and organic amino acids contained in recycled water and results in the formation of N-chloramine compounds. Research conducted at the University of Jordan supports this theory (Fayyad and al-Sheikh, 2001).

A study conducted by the American Water Works Association (AWWA) Research Foundation in 1993 determined that corrosion and degradation of certain metals and elastomers common to distribution plumbing parts and accessories were related to their exposure to chloramine compounds (Reiber, 1993). The study tested seven metal surfaces, seven common elastomers, and three thermoplastics. The results are reported in Table 10.2. Most irrigation components are now manufactured with components resistant to chloramine degradation, but occasionally an older system at a site retrofitted with recycled water may demonstrate problems. Fortunately, PVC (polyvinyl chloride) and CPVC (chlorinated polyvinyl chloride) compounds typically used to manufacture irrigation pipe, fittings, and lake liners appear to be resistant to chloramine degradation (Harvel Plastics, 2007; Vinidex Systems, 2007; Callery, 2003).

Water treatment systems. Evaluating water quality prior to designing a new irrigation system allows advance planning for water treatment systems that might be needed to improve infiltration or displace sodium (Carrow et al., 1999). If treatment equipment is included in the system, it is necessary to provide an area large enough to house and power equipment such as sulfur burners, sulfuric acid injection, gypsum injection, or fertigation equipment near the pump station or irrigation reservoir. Also, provide an adequate storage area for the on-site supply of amendments.

Miscellaneous items. Sites using effluent and other nonpotable irrigation sources often are required to provide warning signs and/or tags at property lines, storage lakes, tags on remote control valves, etc., stating the water is not suitable for human consumption. Purple pipe or burial tape signifying nonpotable water lines is also commonly mandated (Feil et al., 1997). Occasionally, devices to automatically cease irrigation operations at a particular wind speed are required (Snow, 1994). On-site weather stations for ET replacement verification and minimum lake lining thickness requirements (recycled effluent) have also been reported (Snow, 1994). These requirements can vary between states and local agencies; it is recommended to consult with local regulators regarding specific codes in your area.

TABLE 10.2
Corrosion and degradation reactions of common distribution plumbing and appurtenance materials to free chlorine and chloramines

Material type	Specific product	Free chlorine	Chloramine (combined chlorine)
Metals	Mild steel	Not specifically reported	Not specifically reported
	Copper	Moderately accelerated corrosion	Slightly accelerated corrosion
	Brass	Moderately accelerated corrosion	Slightly accelerated corrosion
	Bronze	Moderately accelerated corrosion	Slightly accelerated corrosion
	Pb-Sn solder	Slight pitting/corrosion	Slight pitting/corrosion
	Sn-Sb solder	No pitting or corrosion	No pitting or corrosion
	Sn-Ag solder	No pitting or corrosion	No pitting or corrosion
Elastomers	Natural rubber	Hypochlorous acid disinfectants are significantly less damaging to elastomers as compared to chloramines	Both monochloramine and dichloramine solutions with few exceptions produced greater swelling, deeper and more dense surface cracking, a more rapid loss of elasticity, greater loss of tensile strength as compared to equivalent concentrations of free chlorine. Chloramines are uniquely injurious to elastomers and produced conclusive results when compared to other forms of chlorine disinfectants. Natural isoprenes (rubber) and synthetic isoprenes most susceptible to attack. Synthetic polymers developed for chemical resistance performed well in chloramine exposure.
	Acrylonitrile butadiene		
	Styrene-butadiene		
	Chloroprene		
	Silicone		
	Ethylene-propylene		
	Fluorocarbon		
Thermoplastics	Celcon®	Susceptible to chlorine attack	Susceptible to chloramine attack
	Delrin®	Susceptible to chlorine attack	Susceptible to chloramine attack
	Udel®	Impervious to chlorine attack	Impervious to chloramine attack

Source: From Walker, R. et al. 1995b. Landscape Water Management Auditing. Irrigation and Training Research Center, Cal Poly San Luis Obispo, CA.

Recycled water/effluent disposal. Occasionally, effluent water delivery contracts require that a site use a set amount of water daily whether the turfgrass requires irrigation or not. Under such circumstances, it may become necessary to irrigate out-of-play areas for the sole purpose of effluent disposal to avoid playing areas from becoming excessively wet. This process may be referred to as slow rate land applied groundwater recharge. If out-of-play areas are not available for surface/sprinkler applications during the nonirrigation season, subsurface drip irrigation systems may be a viable alternative. These systems can apply small amounts of water 24 hours per day at rates matching soil percolation rates. The low application rate spread across a 24-hour period disposes of the effluent while maintaining the playing surface in a dry playable condition. Subsurface disposal may not be feasible in layered or extremely heavy clay soils where water may wick to the surface through capillary action.

Potable water recycling equipment wash rack. It is a common practice to wash mowing equipment in the rough at quick coupler locations connected directly to the irrigation system. However, when irrigating with higher-salinity water sources, this can accelerate corrosion and the ultimate deterioration of turfgrass maintenance equipment (Huck et al., 2000). Therefore, when irrigating with saline water sources, provisions should be made for equipment wash areas using water with lower salinity (potable) to prolong equipment life and recycling wash rack drainage water that will conserve potable water resources.

10.3 IRRIGATION SYSTEM MAINTENANCE TO MAINTAIN OPTIMUM DISTRIBUTION UNIFORMITY

Not all sites converting to poorer-quality water will have the opportunity to replace their irrigation system. Those sites that are fortunate enough to install state-of-the art systems will also need to maintain their performance over time. Therefore, regular maintenance and occasional minor upgrades to optimize the irrigation system's performance and distribution uniformity are important for both new and old irrigation systems. The following items should be considered as part of an ongoing maintenance program.

10.3.1 EVALUATING AND "TUNING UP" IRRIGATION SYSTEMS

Without even considering the effects of wind and land slopes, distribution uniformity is often the weakest component of many irrigation systems new and old alike. An irrigation audit and catch-can test is a good method to evaluate and document water application efficiency. However, before performing the actual catch-can tests, a number of influencing factors should be inspected and their current condition documented. Developing an irrigation system "tune-up checklist" of the following items is suggested.

Spacing and geometric configuration. The distance between sprinklers as well as geometric configuration (squares or equilateral triangles) should be uniform because both affect distribution and precipitation rates. Sprinkler spacing of a well-installed design will be within plus or minus three feet of the design specification.

This provides for a reasonable margin of error and the accuracy that can be maintained in the field. Spacing within this range should be uniform throughout the primary playing areas. Spacing adjustments to make the system "fit" the property should be made near perimeters in out-of-play rough areas (Barret et al., 2003). It is not practical to try and move hundreds of sprinklers to correct poor spacing; however, checking spacing in a few areas of questionable coverage and documenting problems can explain factors contributing to poor distribution uniformity and poor turfgrass performance conditions.

Lifting and leveling low sprinklers. Low-positioned sprinklers must occasionally be lifted to compensate for thatch accumulation and soil settling to avoid surrounding turfgrass from disrupting spray patterns. Heads that are tilted to the turfgrass surface must be leveled so the trajectory of the nozzles will not be changed. Just a few degrees from level will change the radius wetted by the sprinkler. Lifting and leveling sprinklers manually with nothing more than a shovel is very labor-intensive difficult work. Each sprinkler raised and leveled can require 45 minutes or more time. A device sold as the ***Levelift*** mechanizes the process and greatly improves the efficiency of lifting and leveling low sprinklers (Levelift, 2007). This device uses the irrigation system's hydraulic pressure to place a safe amount of lifting force on the sprinkler canister. At the same time, water is bypassed to a probe (similar to devices used to deep water and feed tree roots) that is inserted into the ground to wet the soil surrounding the swing joint.

The injected water liquefies the soil surrounding the swing joint into a "soup-like consistency, and the sprinkler is then automatically pulled to the proper grade. A small amount of dry soil or sand is then hand-packed around the sprinkler body flange to fill the void created. A few irrigation flags are placed surrounding the head to discourage traffic from entering the area of softened soil. Within 24 hours, the liquefied soil will drain and become firm enough to support normal golf car and maintenance equipment traffic. The time from start to finish to lift a sprinkler with this device is typically between 5 to 15 minutes depending on soil conditions (Levelift, 2007).

Sprinkler brand, model, and nozzle sizes. Assuming that spacing is relatively uniform, sprinkler brands, models, and nozzle sizes should be uniform within the same area of coverage and control. Different brands, models, and nozzles have differing flow rates and distribution profiles. Therefore, mixing sprinklers and nozzle sizes will affect precipitation rates and distribution uniformity. Replacing worn-out nozzles or nozzles of varying sizes with new nozzles of the same size can cost effectively provide a reasonable improvement in distribution uniformity.

Nozzle replacement can become necessary after 7–10 years of normal use. The time frame may be less if water contaminated with sand or suspended solids that can accelerate wear is used. Visual checks for damage can sometimes identify problems; however, the shank end of drill bits can be used as a gauge to more accurately assess wear between new and older, worn-out nozzles. If nozzles have to be replaced, compare high-efficiency, after-market nozzles with the OEM (original equipment manufacturer) replacements (Full Coverage Irrigation, 2007). The after-market nozzles have been reported to significantly improve distribution uniformity of older systems and systems with low-pressure problems.

Operating pressure (line pressure and sprinkler nozzle pressure). Uniform coverage is compromised when operating pressures are not consistent and within manufacturer-specified ranges (Harvel Plastics, 2007; Barret et al., 2003; Huck et al., 2000; Tanji, 1996; Oster et al., 1992). Pressure regulation valves in mainlines and at pumping stations should be regularly serviced and adjusted to deliver line pressures as specified in the original irrigation design and specifications. Depending on the severity of elevation changes throughout the site, pressure reduction, regulation, or boosting devices may be a part of the system and will need occasional maintenance and adjustment.

To accommodate minor variations in line pressures across a golf course, valve-in-head sprinklers and remote control valves are available (sometimes an optional feature) with internal pressure regulation devices. These devices also require periodic maintenance and repair. To test their performance, measure the operating pressure at the sprinkler nozzle with a pitot tube and pressure gauge. If nozzle pressures of valve-in-head sprinklers' internal pressure regulators vary by more than 5% of manufacturer-specified ratings readjustment, repair or replacement of the regulator spring and/or regulator assembly may be needed. If the system is a block design, regulators at the remote control valve (if equipped) will require adjustment.

Operating pressure should be tested at various locations throughout the golf course during a normal watering cycle if high- or low-pressure problems are suspected. Portable pressure-recording devices are the preferred method to collect data over a 24-hour period; however, a simple pressure gauge mounted on a quick coupler can be used to spot check problem areas in an emergency. Operating pressure data can help identify various problems, including too many sprinklers or satellite controllers operating simultaneously, improperly operating pressure boosting and/or regulating devices, and/or areas where pipe was not adequately sized.

Sprinkler rotation speed. Rotation speed should be checked and recorded as another diagnostic tool. Rotation speed will vary slightly depending on sprinkler brand, model, nozzle size, stator size, operating pressure, and condition of the gear drive or impact mechanism. Rotation speed should be reasonably consistent between similar brand/model sprinklers for uniform water distribution. Impact rotors should complete one revolution in approximately 2 minutes (plus or minus 15 seconds), whereas gear drive rotors normally complete one revolution between 2.5 to 3.0 minutes.

The stream from a sprinkler rotating too rapidly will break into smaller droplets and be affected more so by wind (Barret et al., 2003; Zoldoske et al., 1987). Additionally, rapid rotation causes the main nozzle stream to curve owing to a whiplike action resulting in a smaller wetted radius that affects distribution patterns. Sprinklers rotating too slowly may pause, stop rotating, rotate erratically, or not complete a full rotation during short irrigation cycles. This can create isolated puddles or localized wet areas. Contact the manufacturer for exact specifications regarding proper rotational speeds for each model sprinkler.

When rotation speeds are found to be outside of the suggested ranges, they can often be corrected. Possible causes for improper rotation speed for impact sprinklers include improperly adjusted arm spring tension, worn-out or damaged nozzles, worn-out bearings and bushings, or misadjusted or bent drive spoons. The cause of improper rotation speed with gear drive sprinklers is typically related to mismatched nozzle and stator combinations (or stator settings with adjustable-type stators) or debris partially plugging the stator passageways or bottom screen.

Control systems. Upgrading to computer-driven solid-state control systems with flow management capabilities can help to maintain proper operating line pressures by not allowing too many sprinklers or controllers to operate simultaneously (Barret et al., 2003). Flow management options also compress the watering window by optimizing sprinkler and satellite controller operating sequences. Reducing the water window, while maintaining a proper operating pressure range and flow rate, improves both distribution coverage and energy use efficiency.

Wind. Wind speed should be less than 8 miles per hour to collect meaningful catch can data, but 5 miles per hour might actually be a more reasonable cutoff (Barret et al., 2003; Irrigation Association, 2003; Walker et al., 1995a,b). The real question that must be asked is, what range of wind speed is typical during the normal irrigation time? If a wind speed gauge (anemometer) is not available, the safe range of wind speed can be estimated with the "upwind/downwind" ratio test. Measure the throw of water upwind and then downwind. Calculate the ratio (upwind divided by downwind), which should be less than 0.6 to proceed with the catch-can test (Walker et al., 1995b).

Other. When preparing to conduct an audit, record specific data from the areas selected to be tested for future reference. Items such as the hole number, location (fairway, tee, green, etc.) satellite and station identification numbers, general conditions of the turfgrass, whether sprinklers are at proper grade, land slopes, tree interference, etc. (Barret et al., 2003; Irrigation Association, 2003; Walker et al., 1995a).

10.3.2 CATCH-CAN UNIFORMITY EVALUATIONS

As mentioned previously, poor irrigation water distribution uniformity results in salt distribution problems, excessive water use when leaching, and the need for additional hand-watering labor to avoid both poor turfgrass and poor playing conditions. Catch-can distribution uniformity testing is a necessary but frequently overlooked maintenance test for irrigation systems. Many turfgrass managers assume their systems operate at peak performance, but very few actually take the time to perform catch-can tests to measure actual performance. During the mid-1980s, the Irrigation Training and Research Center (ITRC) at Cal-Poly, San Luis Obispo, California, developed an irrigation system assessment and landscape water management program for the California Department of Water Resources. Several golf course irrigation systems were audited to determine their low quarter distribution uniformity (DU_{LQ}) during the project. The golf courses' DU_{LQ} results ranged from 50 to 90%; most fell between 70 and 85% (Kah and Willig, 1993).

A similar study conducted in 2002 at five Florida golf courses, all with irrigation systems less than 5 years of age, produced average DU_{LQ} of 50% for fairways, 57% for tees, and 60% on greens (Miller et al., 2003). The variation of results between the California and Florida examples are assumed to be related to their specific irrigation system designs. Factors such as larger versus smaller spacing distances and square as opposed to triangular configurations could all come into play. However, this cannot be confirmed because the articles summarizing the studies did not report these particular data.

The process of conducting catch-can tests is not difficult and with some training should be within the skill sets of most assistant superintendents or irrigation technicians. Catchments are placed between at least two sprinkler rows; some auditors use symmetrical patterns whereas others will use random arrangements. For landscapes where sprinklers spaced less than 50 ft apart, catch-cans are typically placed near each sprinkler head in the area being tested and half way in between each sprinkler (commonly referred to as "at the head and in-between") (Walker et al., 1995b). When data that are more precise is desired, additional catch-cans can be placed on 5 to 15 ft centers.

The Irrigation Association's (IA) Certified Golf Irrigation Auditor (CGIA) Program currently recommends a minimum of 24 catch-cans be used in each area being audited. Spacing on greens and tees is suggested to be 15 ft on center. The minimum catchment spacing on fairways is suggested to be one catchment near each sprinkler and two catchments spaced uniformly between each sprinkler (Irrigation Association, 2003). Care is necessary so that the catchments placed nearest each sprinkler do not interfere with the spray pattern and trajectory and thereby deliver erroneous data. Sprinklers should operate long enough to collect a minimum of 25 mL in each catchment. A rule of thumb is five revolutions of each rotor or 15 minutes of operation will typically deliver this minimum volume. Cylindrical containers with straight walls allow direct measurement with a thin ruler; noncylindrical catchments require using a graduated cylinder and conversion of the data based on the throat opening area of the catchment. Graduated calibrated containers are available that allow measurements to be directly read.

The amount of time the sprinklers operated and the volume of water collected in each individual catchment for analysis are recorded. The measured run time (as opposed to the programmed run time) is needed to calculate the field precipitation rate and to evaluate the accuracy of the control system. Normally, catch-can tests are conducted after completing repairs and adjustments identified in the "tune-up" process; however, to document the effects of the repairs and adjustments, performing "before" and after tests can be worthwhile.

10.3.3 EVALUATION OF CATCH-CAN TEST DATA

Results of catch-can tests are used to calculate distribution uniformity. The ***low quarter distribution uniformity*** (**DU_{LQ}**) formula is most commonly used for turfgrass applications whereas the previously mentioned Christensen's coefficient of uniformity (CU) is more often used in agriculture. DU_{LQ} is determined by sorting all catch-can data from the lowest to highest values. The average of the lowest 25% of values is divided by the average of all the values (Barret et al., 2003; Irrigation Association, 2003; Walker et al., 1995a,b).

$$DU_{LQ} = (\text{Minimum}/\text{Average}) \times 100$$

where

DU_{LQ} = low quarter distribution uniformity
Minimum = average of lower 25% of catchments
Average = average of all catchments

Based on results of audits conducted in California by the Cal Poly ITRC while developing their water management program, guidelines were developed for ranking irrigation system performance by sprinkler type (Table 10.3). The Irrigation Association's *Certified Golf Course Auditor Handbook* offers a similar table that has been modified to reflect a nationwide influence and climate zones that regularly receive rainfall (Irrigation Association, 2003) (Table 10.4). Note that Tables 10.3 and 10.4 distinguish how performance varies between the various sprinkler types. Also, sprinkler performance may also vary depending on brands, models, nozzles, and the age of the equipment (Zoldoske, 2003).

Fixed spray heads that are typically used in clubhouse and residential lawns, as well as small landscapes and flowerbeds that are spaced 10 to 18 ft apart are least efficient. On the golf course, fixed spray heads are occasionally found in specially landscaped areas surrounding tees, snack bars, restrooms, etc. Matched precipitation rate multistream rotor-type nozzle retrofits are now available that can be installed in major manufacturer's spray head bodies (Walla-Walla Sprinkler Company, 2007).

TABLE 10.3
Estimated distribution uniformity (DULQ) by sprinkler type and system quality

Sprinkler type and application	Excellent (achievable)	Very good	Good (expected)	Fair	Poor (needs improvement)
Multiple stream gear and impact rotors	85	80	75	65	60
Single stream gear rotors	80	75	70	65	55
Single stream impact rotors	75	70	65	60	50
Fixed spray heads	75	70	65	55	50

Source: From Miller, G. et al. 2003. How uniform is coverage from your irrigation system. *Golf Course Manage.* 71(8): 100–102; Oster, J. D. et al. 1992. Water Penetration Problems in California Soils—Diagnosis and Solutions. Kearney Foundation of Soil Science, Division of Agricultural and Natural Resources, University of California, Riverside, CA. 165 p.

TABLE 10.4
Estimated distribution uniformity (DULQ) by sprinkler type and system quality

Sprinkler type	Excellent (achievable)	Good (expected)	Poor (needs improvement)
Rotary sprinklers	80	70	55
Fixed spray heads	75	65	50

Source: From Ritchie, W. E. et al. 1997. Using ET_O (reference evapotranspiration) for turfgrass irrigation efficiency, *California Turfgrass Culture* 47(3 & 4): 9–15.

The multistream rotor nozzles can improve DU_{LQ} significantly (often into the mid-70% to low 80% range) on systems spaced in the 10 to 30 ft spacing range.

Single stream impact and gear rotors that are used in medium-sized areas are generally spaced from 20 to 50 ft apart. They are most commonly used for irrigated slopes, athletic fields, larger landscape beds, medium-sized lawn areas, and agricultural use. Single stream rotors produce moderately good to high uniformity.

Multiple stream impact and gear rotors also come in various sizes and can be used at various spacing distances (typically 50 to 100 ft), depending on the make and model of the sprinkler and the irrigation system design. They are typically used for turfgrass irrigation of larger sites such as golf courses or athletic field complexes. Multiple stream (multiple nozzle) style sprinklers typically produce the highest uniformity when properly matched to their application. Golf course and large area turfgrass rotors are typically classified as multiple stream impact and gear-driven rotors. Uniformity of 80% is achievable and is a realistic expectation with a properly designed, installed, and maintained multirow golf course irrigation system. Systems performing at less than the good ranking (70%) should be evaluated for areas of potential improvement such as nozzle replacement, head lifting, pressure adjustments, etc. Results below the "poor" ranking (55–60%) following a system "tune-up" indicate that major repairs, upgrades, or complete system replacement may be warranted. Under these circumstances, a more extensive system evaluation by a qualified golf course irrigation designer is suggested.

10.3.4 Future Potential for Enhancing Irrigation System Design and Scheduling

The primary problem confronting agriculture and turfgrass/landscape irrigators in terms of achieving higher water use efficiency/conservation is **site-specific variability**, both (1) spatial across the landscape and within the soil profile and (2) temporal, over time. Site-specific management, including irrigation management, requires site-specific information in order to determine when to irrigate, how much to apply, and where to apply irrigation only on the specific sites needed.

Sensor technology has been used in precision agriculture to move toward higher efficiency by dealing with site variability (Corwin and Lesch, 2005a,b; Yan et al., 2007). Mobile spatial mapping of site conditions has potential for precision turfgrass management, especially with respect to water use efficiency/conservation and salinity management on complex sites with a high degree of spatial and temporal variability. Carrow et al. (2007a,b) have developed mobile devices compatible with GPS/GIS technology that are capable of rapid measurement of surface zone volumetric water content (VWC, where VWC data was used to map spatial evapotranspiration/ET patterns), turfgrass stress (NDVI, normalized differential vegetative index to map plant stress), penetrometer resistance (PR to map soil compaction), and electrical conductivity of bulk soil conductivity (ECa) by soil depth to map soil salinity. Measurement flexibility allows daily mapping during dry-down periods following irrigation or rainfall events. Six field applications and protocols involving a holistic approach to improved water use efficiency/conservation and salinity management are currently under development. The six applications are as follows:

1. Initial mapping information to identify relatively easy alterations in irrigation design and/or scheduling for uniformity
2. Evaluation of system design for degree of uniformity to determine if the system is efficient or requires replacement
3. Audit of a newly installed system with respect to adequate design for uniformity and as a tool to help turf managers maximize the use of their new system
4. Defining **site-specific management units (SSMU)** on saline and nonsaline sites
5. Determination of the best location for placement of in-situ sensor arrays to truly represent SSMU areas
6. For salt-affected sites, the use of these technologies for monitoring salinity spatial and temporal changes for salt management: where to leach, how much water to apply, is leaching effective.

Combining systematic protocols for each of these applications can provide a more precise and robust water-auditing approach and a holistic approach to water-use efficiency on complex turfgrass sites.

10.3.5 Developing Base Irrigation Schedules

The Irrigation Association's Certified Golf Course Auditing process suggests developing "base irrigation schedules" for programming the system (Irrigation Association, 2003). Although most turfgrass managers know best how to irrigate their particular site, calculating the base schedules can offer insight into developing a successful irrigation and leaching protocol intended to drive turfgrass root systems to a greater depth. Base schedules are developed on the basis of site-specific data collected during the audit. Items such as peak daily ET, replacement, soil infiltration rates, soil moisture retention, sprinkler precipitation rates, and run time multipliers based on distribution uniformity are all considered when calculating the base schedule (Irrigation Association, 2003). For additional information regarding the Certified Golf Course Irrigation Auditors Educational Class conducted jointly by the Irrigation Association and Golf Course Superintendents Association of America, visit www.irrigation.org or www.gcsaa.org.

10.3.6 Other Miscellaneous Irrigation System Maintenance

Maintaining pump efficiency by optimum pump pressures and flow rates is critical to maintaining good distribution uniformity. Regular pump testing allows comparing past and present performance to determine if operating conditions, energy use, and/or output of pressure or flow have changed owing to wear and tear of bowls, impellers, motors, etc. Pump tests measure various operating aspects and estimate overall efficiency and power costs while operating under the conditions of the test (Center for Irrigation Technology, 2005). Water flow rate, pump lift pressure, discharge pressure, and energy input are each measured. Both well pumps and booster pumps should be tested every 1 to 3 years depending on annual usage and operating conditions. For example, a well that pumps water contaminated with sand or suspended solids might be tested annually, whereas a booster pumping clean water might only be tested every 2 to 3 years. Public utilities, pump dealers, and independent pump repair/testing companies typically perform this service (Center for Irrigation Technology, 2007). In some cases, testing and repair costs may be shared between the pump owner and the utility company because there is a mutual benefit to reducing energy use (Center for Irrigation Technology, 2007).

Maintaining air-release valves in proper operating condition can reduce ruptured pipe and damage from water hammer. Annually or semiannually lubricating and "exercising" mainline and lateral valves by closing and opening them can clean corrosion that forms on the threads of the actuator mechanism. Fabricating a long-stemmed oilcan that reaches the valve stem is suggested to treat frozen and stiff operating valves with a penetrating lubricant a few days prior to the exercising process. A qualified pump technician/electrician should annually tighten all the high-voltage (480 V.A.C.) electrical connections, change oil in electric pump motors, and replace or repack pump shaft seals.

10.3.7 MANAGING A POOR SYSTEM USING POOR WATER QUALITY

There will be cases where a new irrigation system is out of the question, or will require considerable time to develop and budget. Assuming that all reasonable measures possible have been taken to improve the distribution uniformity (DU_{LQ}) and undesirable leaching and management capabilities still result, spot leaching with portable sprinkler equipment may be required (Kah and Willig, 1993). Low-precipitation-rate portable sprinklers (small nozzle, impact or multistream rotor lawn models) mounted on portable bases can be used to leach areas of poor coverage and/or native soils areas with low infiltration rates. In the most severe cases, agricultural (orchard) microspinner-type sprinklers with ultralow precipitation rates between 4.5 to 30.0 gal per hour (approximately 0.08 to 0.50 gal per minute) can be interconnected on lengths of flexible polyethylene tubing. These techniques are commonly used on pushup constructed putting greens with poor internal and subsurface drainage to avoid saturating surrounds and greenside bunkers with excess irrigation from full circle greenside sprinklers (Carrow et al., 2000; Gross, 1999).

Supplemental sprinkler systems, sometimes referred to as "cheater systems," comprise a few small lawn sprinklers can be permanently installed to leach or supplement irrigation to areas chronically lacking coverage. Installing these systems with their own manual or remote control valve can increase the flexibility of their use.

Porous pipe, also sold as "Leaky Pipe," and conventional "soaker" hoses are excellent tools to spot leach/irrigate small problem areas without disrupting golfers. Soaker hoses and porous pipe typically have low precipitation rates that are well matched for use on native soils. Recognize that low-precipitation-rate equipment (lawn sprinklers, microsprinklers, and soaker hoses) will require pressure and flow regulation if directly attached to the golf course irrigation system via quick couplers (Gross, 1999).

10.3.8 ECONOMIC IMPLICATIONS OF POOR IRRIGATION SYSTEM DESIGNS

There is an old cliché that states: "There never seems to be enough time and money to do things right the first time, but there is always enough time and money to do things over." Too often, cutting corners to generate cost savings is applied to large-capital golf course construction projects, such as irrigation systems (Zoldoske et al., 1987). The original thinking was that a 5 to 10% savings on a one to two million dollar expenditure is a significant amount. The decision makers often feel that stretching sprinkler spacing distances or reducing pipe sizes to save a few percentage points on material costs cannot have a great impact on course conditions. Unfortunately, cutting corners on the irrigation system will be one of the greatest factors affecting the turfgrass manager's ability to succeed, especially when using poor water quality or attempting to achieve good water use efficiency. It is impossible to justify a million dollar plus irrigation system on labor and cost savings alone, even when evaluated over the life of a new system. However, the long-term implication of cutting corners to save a few percentage points of the initial construction budget often results in additional maintenance costs that reach beyond initial savings. Consider the following example.

A $1.5 million irrigation system is expected to deliver a 30-year useful life. A 10% savings ($150,000) can be realized if smaller-diameter mainline and lateral pipes are used and sprinkler spacing is expanded from 65 to 70 ft. However, additional hand-watering labor will be needed to manage dry areas and manually leach salinized areas lacking proper coverage while trying to maintain course conditions to the customer's expectation levels.

Compare those savings of $150,000 to hiring one additional $7.00 per hour laborer for 12 months. Over the 30-year useful life of the system, nearly three times those initial savings will be spent on hourly wages to compensate for system inefficiencies through hand watering and other maintenance strategies. This estimate does not include cost of living wage increases, taxes, benefits or additional materials, water, energy, and equipment associated with the hand-watering position, not to mention that any resulting decline in golf course conditions will affect revenues and harm the course's reputation among patrons.

Recognize that there is a close correlation between the number of sprinklers in the design, amounts of and costs of materials needed, and number of labor hours needed to complete the installation. Typically, irrigation systems can be broken into three categories, with each comprising approximately one third of the total project cost:

- Labor for design, staking, trenching, pipe fitting, wire burial, wiring connections, etc.
- Pumps, pipe (mainline and laterals), fittings, swing joints, conduit and wire (24 V.A.C. direct burial and 110 V.A.C.).
- Sprinklers and control systems (central computer, software, satellites controllers, and weather station)

Once installed, approximately two thirds of the total system's material costs and installation labor are both literally and figuratively buried. If undersized pipe is installed, the costs of both the pipe and installation labor have been wasted and cannot be recovered. A similar scenario occurs when sprinklers are spaced too far apart to be efficient. The sprinkler can be recovered, but the wiring and pipe are often not worth the cost of labor involved to salvage them. This is partially why it can be less expensive to replace an entire irrigation system as opposed to salvaging portions, especially where sprinkler spacing and pipe sizing are the main problems. Experience teaches that it is more expensive to repair design flaws and problems after the fact than to install the system correctly in the first place. Or, as the cliché previously mentioned states, eventually enough time and money are found to do it over!

In this chapter, we have outlined a number of irrigation system design, scheduling, and maintenance aspects that are affected by irrigation water quality. As more low-quality irrigation water is used on turfgrass sites, these considerations will become even more important, especially if the irrigation water is saline in nature.

11 Effective Leaching of Saline/Sodic Sites with Irrigation Water

11.1 SALINITY MANAGEMENT

Ineffective irrigation practices that fail to control salts contribute to a loss of 10 million hectares (25 million acres) of arable land annually, resulting in soil salinization or sodification in the world (Essington, 2004; Umali, 1993; Talsma and Philip, 1971). Currently, 5% of global arable land and 23% of cultivated lands are saline, and 8% of arable and 39% of cultivated sites are already sodic (Essington, 2004). Unquestionably, poor irrigation water management has directly caused and will continue to cause salt accumulation and the subsequent escalation of soil secondary salinization sites on a global basis (Umali, 1993). Because recreational turfgrass has been relegated to use of alternative water resources with varying levels of salinity, the threat of increasing salinization and sodification on these sites will continue unless ongoing and proactive salt management is implemented.

Salinity stresses from additions of excess soluble salts and sodium in the irrigation water to the soil are such dominant stresses that unless these are controlled, all other management practices (1) cannot compensate for these stresses and (2) will not result in the degree of response that would occur on a non-salt-affected site. Salinity management is essential, and the core of salinity management is leaching; that is, salinity management is synonymous with leaching of salts. Leaching is the single most important management practice for alleviating or preventing salt stresses on turfgrass sites.

The additional irrigation water to prevent accumulation of excessive soluble salts to a level injurious to the grass is called the **leaching requirement (LR).** The LR is in addition to the irrigation water required to meet the evapotranspiration (ET) needs and any irrigation water required to compensate for nonuniformity of the irrigation system. The original definition of LR was the fraction of infiltrated water that must pass through the root zone to keep soil salinity from exceeding a level that would significantly reduce crop yield (USSL, 1954). This was modified by Rhoades (1974) into the form now considered as the traditional LR (Table 11.1). The LR concept will be discussed in greater detail later in Section 11.5, but for now, it is sufficient to note that irrigation water quality (salinity level) and turfgrass salinity tolerance are the two major factors in determining LR. The traditional LR refers to a **maintenance leaching** program to maintain salt levels below a critical level with each irrigation

TABLE 11.1
Determination of the maintenance leaching requirement (LR)

Concept:

Once the soil salinity level in the turfgrass root zone is at an acceptable or desirable level, the leaching requirement (LR) approach is used to maintain this level. The "*leaching requirement*" (LR) is the minimum amount of water that passes through the root zone to control salts within an acceptable level. A traditional formula to determine LR is (Rhoades, 1974):

$$LR = EC_w/5EC_e - EC_w$$

where

EC_w = irrigation water salinity (dSm^{-1})

EC_e = threshold soil salinity at which growth starts to decline for the turfgrass on the site. See Carrow and Duncan (1998) for an extensive listing.

Example:

For a turfgrass with a threshold EC_e of 6 dSm^{-1} and irrigation water has an $EC_w = 2$ dSm^{-1}, which means that the LR is 7.1% more irrigation water volume than to meet ET needs. Thus, if irrigation of 1.00 in. of irrigation water is required to replace soil moisture lost by ET, an additional 7.1% or (1.00 × 0.07) = 0.07 in. of water would be required for a total of 1.07 in. to maintain salinity conditions. An additional quantity of water would be required to compensate for nonuniformity of the irrigation water. It should be noted that a more saline irrigation water with higher EC_w or a less salt-tolerant grass would both increase the LR.

Source: After Rhoades, J. D. 1974. Drainage for salinity control. In J. van Schilfgaarde (Ed.). *Drainage for Agriculture*. Agronomy Monograph No. 17. Soil Sci. Soc. of American, Madison, WI, pp. 433–461.

cycle and not to a **reclamation leaching** program to aggressively leach salts from an already salt-laden soil down to an acceptable level for turfgrasses. These two situations are also discussed later in the chapter.

When the irrigation water contains appreciable salts, turfgrass managers must develop a mind-set to "keep the salts moving downward," and management decisions must be made in the context of how soil salt levels or their movement into and through the soil profile are affected. For example, switching to a light, more frequent irrigation regime is a common practice on creeping bentgrass or annual bluegrass putting greens in the summer months, but this practice results in salt accumulation at the surface and the increased potential for capillary rise of salts from lower in the soil horizon. Or, during winter dormancy periods of warm-season grasses, managers may not realize that a dry winter can cause appreciable capillary rise of salts from salt-laden zones deeper in the soil, resulting in poor spring turfgrass performance. Thus, the salt management strategy should be one of managing salts before, during, and after managing the turfgrass. Short-term decisions based on convenience or speed can lead to future long-term headaches and poor turfgrass performance. This is one area of turfgrass management where cutting corners or expecting miracle cures to solve the problems are not going to work. Stay with the basics, and base your management decisions on science and not testimonials, magic potions, or silver bullet products/equipment.

Although the salinity management/leaching principle is simple, achieving an effective leaching program that keeps salts moving past the root zone is complex. Prior to discussing development of leaching programs, we discuss the various factors influencing the decision-making process that must be understood. Salinity management is influenced by a number of factors, especially those noted in the following text (Carrow and Duncan, 1998; Hanson et al., 1999; Yenny, 1994):

- Type of salt problems present
- Soil (edaphic) factors, such as texture, structure, pore-size distribution, cation exchange capacity, clay type, and other factors
- Turfgrass species and cultivars, and other landscape or native plants on the site
- Irrigation water quality/quantity/application uniformity and efficiency
- Environment (rainfall quantity and patterns, temperature, relative humidity, and wind speed) and time of year

11.2 SALT TYPE AND SALINITY MANAGEMENT

Development of an effective salinity management program starts with understanding which salt problems are present that may require leaching: presence of high total soluble salt levels, high soil Na, potential for B accumulation, high chloride levels, high sulfur accumulation, high bicarbonate/carbonate concentrations, or a combination of any of these. Irrigation water quality tests will aid in determining the potential for developing each of these growth-limiting issues, and soil tests will show the current soil status with respect to each salinity problem. More detailed information on these specific salinity problems is presented in Chapter 6.

High Soluble Salts. High total soluble salts is the most common and injurious salt problem (i.e., saline or saline-sodic soil) affecting turfgrass. In this case, the salts causing injury are soluble, resulting in high salt concentrations in the soil solution. When the soils dry down, some of the salts precipitate out of solution, but when the soil is rewet, they dissolve back into the soil solution. Indicator points are measured as electrical conductivity (EC) of irrigation water (EC_w) or within soils (EC_e, from a saturated soil paste extract) (Carrow and Duncan, 1998; Duncan et al., 2000; Hanson et al., 1999). When total soluble salt reaches excessive levels in the root zone, turfgrass water uptake is reduced (osmotic potential inside the turfgrass root is greater than the osmotic potential outside the root), resulting in osmotic desiccation, or what is sometimes called **physiological drought** or salt-induced drought. This salt-induced drought stress causes typical grass drought symptoms of wilting and reduced growth rate even though soil moisture may appear to be adequate (at or near field capacity). The water is present, but the plant cannot take up sufficient moisture to prevent drought symptoms because the solution salts attract water molecules and reduce plant availability of the water. As the stress continues, grasses often start to exhibit chlorosis, leaf tip necrosis, desiccation of lower leaves or individual tillers, and a decline in canopy density and quality (Carrow and Duncan, 1998; Yenny, 1994). Advanced stress damage can include discoloration, such as yellowing, purpling, or browning, depending on the individual turfgrass species and specific cultivar. These symptoms are often mistaken for disease problems, which may be false, or in some cases disease attack may be stimulated by weakened turfgrass and favorable weather conditions for the pathogen (Yenny, 1994). In other words, the primary problem is high total salinity, and the secondary problem is the emergence of a visible disease challenge on the turf.

Because these salts are soluble, the majority of the salt ions are in solution under well-irrigated soil moisture conditions, and removal of these salts only necessitates a sufficient volume of water and time to effectively promote downward movement and leaching to an acceptable level. Soil amendments to compensate for excessive Na (gypsum) or irrigation water treatment (acidification, gypsum) are not required. Only sufficient irrigation or rain water to meet ET needs plus irrigation to compensate for nonuniformity of the irrigation system and the LR is necessary to leach root zone total soluble salts to an acceptable level for the grass on the site. Thus, only sufficient water (quantity) applications are needed during this management stage, whereas soil or water amendments that are necessary for sodic situations will not improve total salt movement. However, a wetting agent that fosters a more uniform wetting front movement is an example of an amendment that could promote more effective leaching.

With sufficient water moving through the soil, leaching may require <1 to 4 weeks for reclamation purposes, depending on the soil texture, clay type, irrigation water quality, climatic conditions, and other factors. In the case of maintenance leaching, the LR is to maintain adequate salt levels on a continuous basis. However, accumulation of excessive soluble salts can also rapidly reappear owing to high salt additions from irrigation water without ample leaching as well as from soluble salts moving by capillary rise from below the root zone upward into the root and crown area near the surface. Short-duration, frequent irrigation with saline water contributes to this phenomenon. Salt load can double with each cycle using this irrigation application strategy.

High soluble salt stress arising from irrigation water applications will be accompanied by soil fertility and plant nutrient availability challenges (see Chapter 13). The diverse chemical constituents in the irrigation water can easily create nutrient imbalances. When coupled with leaching programs that can leach desirable nutrients in combination with variable water quality over the year (arising from changes in irrigation water quality or simply a wet and dry season where rain influences/does not influence leaching and irrigation lake quality), soil fertility and plant nutrition programs become much more dynamic: changes occur more frequently and with a greater magnitude compared to similar situations with good irrigation water quality.

In summary, as far as high soluble salts are concerned, this is the most serious global salinity problem because of the following reasons:

1. The most common source of salts are the irrigation water, so the salt stress is across the whole irrigated landscape.
2. Soluble salts restrict water uptake and induce drought/desiccation stress on the plant.
3. It is the most easily controlled and rapidly controlled of the salinity problems.
4. Soluble salts can accumulate or rapidly reappear under the right conditions.
5. Dynamic nutritional challenges will be associated with this salinity stress.

With these characteristics, it is easy to understand why total soluble salt stress is considered the dominant stress on sites where it is present and why it is a dominant stress—because both water and nutrient uptake are adversely affected.

Excessive Na in the soil (sodic). Excessive soil Na levels can lead to soil structural deterioration (i.e., sodic or saline-sodic soil) and to specific ion toxicity in shoot and root tissues (Carrow and Duncan, 1998). The sodicity (sodium-rich) component, also termed **Na permeability hazard,** is measured by the soil SARe (sodium adsorption ratio of the saturated paste extract), the SAR_w (SAR or adj SARe of irrigation water), and RSC (residual sodium carbonate) value of irrigation water (Duncan et al., 2000a).

It is not unusual for high total soluble salts and excessive Na to both be present on a site, especially if the irrigation water contains Na as one of the dominant soluble salts. However, it is also possible for a sodic problem to arise from irrigation water with an unusually high ratio of Na to other salts even when the total soluble salinity is modest. Or, more commonly when excessive bicarbonates cause precipitation of soluble Ca and Mg from the irrigation water as lime, thereby leaving Na as the dominant cation without a counterion to displace it from the soil CEC sites.

Repeated application of irrigation water containing excessive Na can result in increased Na on the CEC sites and formation of Na carbonate precipitates in the soil. Sodium can then cause structural breakdown by slaking, dispersion, and deflocculation processes (Carrow and Duncan, 1998). As clay content increases and/or the clay type is a 2:1 clay, these processes become more pronounced. Soil structure deterioration from excess Na^+ on the soil colloid (clays, colloidal organic matter) exchange sites causes the following: a decline in water infiltration/percolation/drainage (i.e., the reason for the term **Na permeability hazard**) as microporosity increases at the expense of macropores; low soil O_2, which further limits rooting; waterlogged and poorly drained soils; sometimes, accumulation of excess sulfur under anaerobic conditions, leading to black layer symptoms; negative nutritional availability problems; and sometimes, surface moss or algae accumulation problems.

Leaching of Na requires addition of a relatively soluble Ca source to displace the Na from the soil cation exchange sites so that the Na comes into solution (usually as sodium sulfate) and can be leached with an adequate quantity of water (Carrow and Duncan, 1998). A soluble Ca source should be added whenever leaching with Na-laden irrigation water is performed. If not, the Na problem can be compounded by the leaching of all remaining Ca, allowing replacement with Na supplied by Na-laden leaching water, and thereby causing a complete sealing at or near the soil surface.

Compared to removal of high levels of total soluble salts, a much longer time period will be required and more water must move across the soil profile to leach Na. The Na on CEC sites and in Na carbonate must exchange or dissolve into solution over time and can re-form if insufficient Ca and/or leaching is practiced. Generally, for the reclamation of a Na-affected site, one or more years may be required to alleviate the Na-induced soil structural breakdown problems. The long time period is due to these chemical processes as well as poor physical conditions for leaching on an already Na-affected site. Additionally, the high Ca amendment rate and necessity of the Ca to be in contact with the Na-affected CEC sites and sodium carbonate throughout the root zone contribute to the slow process of altering already sodic or presodic sites. If an acre-foot of soil is considered to weigh 4 million pounds, 3400 lb/A (3808 kg/ha) of gypsum would be needed for each meq/L exchangeable Na to reclaim 1 ft (30 cm) of that soil. Obviously, proactive prevention of a sodic condition from forming is more important and less expensive than reclaiming a sodic soil, especially if grass is already planted on the site. Sodic soils, especially on fine-textured soils, will not support a proper surface turfgrass canopy, even with halophytic turfgrass species.

When irrigation water is a contributor to potential sodic soil formation, the key issues pertaining to a leaching and management program are the following: sodic soil stresses do not form as rapidly as high soluble salts; when formed, they require a considerably longer time frame for correction; leaching alone is not sufficient, but a relatively soluble Ca source must be regularly applied to provide a displacement ion for Na; acidification of irrigation is often necessary if high water bicarbonates result in appreciable Ca and Mg precipitation as lime that leaves Na as the dominant cation; nutritional challenges are even more dramatic and dynamic than for high total soluble salts because soil amendments, water treatments, and more limited root production influence soil fertility and plant nutrition along with the inherent irrigation water constituents and leaching programs.

Boron. Toxic soil levels of the salt B is another salt-related problem that requires leaching. The B often arises from the irrigation water source. Because B is absorbed to soil particles, two to three times the leaching water volume is necessary compared to the quantity needed for removal of total soluble salts. In conjunction with leaching, collection and off-site disposal of clippings can assist in reducing B concentrations in soils because it accumulates in turfgrass leaf tips. This strategy can also be used with total salt and sodium problems as a supplemental method of salt reduction.

High chlorides, sulfates, and bicarbonates. Chlorides are highly mobile when applied to soils and will often move with the wetting front during infiltration and percolation. An easy monitoring strategy for leaching involves sampling 0–3 in. (0–75 mm) and 3–6 in. (75–150 mm) soil profiles, submitting for saturated paste extract analysis, and documenting the levels of chlorides in the two zones. The presence of higher chloride levels in the bottom zone compared to the top zone is a good indication of the effectiveness of a leaching program.

Sulfate leaching can also be monitored using a similar sampling strategy and analysis, because sulfates generally have good mobility in soil solution. Bicarbonate and carbonate complexes with Ca and Mg are not as mobile, and you may often find higher concentrations in the upper profile compared to a lower zone. Acidification is normally the strategy to break up these bicarbonate and carbonate complexes, releasing Ca and Mg, while the bicarbonates and carbonates are chemically eliminated or diminished as carbon dioxide and water.

Regardless of leaching strategy, movement of excess salt ions down through a soil profile will generally be through macropores (air porosity, >0.12 mm in size). Maintenance of those soil macropores for leaching will involve regularly scheduled aeration events in the cultivation strategy to keep those salts moving downward, hopefully to the drainage lines.

11.3 SOIL FACTORS AND SALINITY MANAGEMENT

Major differences in soil properties are especially apparent when comparing *sandy soils* (i.e., sands, sandy loams, and loamy sands) to *fine-textured types* (i.e., soils containing appreciable silt and clay). On golf courses, sandy soils are typical of high-sand greens, whereas fine-textured types are representative of pushup greens (native soil greens), fairways, roughs, and many tees. Athletic fields may be either sand media or native soils. A number of soil characteristics that differ between coarse versus fine-textured soils profoundly influence salt and water movement and retention, and therefore, leaching practices.

Cation exchange capacity. **Cation exchange capacity (CEC),** the ability of a soil to retain cations, is much higher for fine-textured soils compared to sands because CEC sites reside on clay particles and organic matter. As a result, fewer total soluble salts, Na, or B are required before CEC sites of sands are adversely affected compared to fine-textured soil CEC sites, and these salts start to accumulate in the soil solution, where they are more active. Although salts accumulate more rapidly to adverse levels in sands, removal by leaching is also generally more rapid owing to normally high infiltration/percolation rates.

Soil pore-size distribution. Pore-size distribution within a soil is affected by texture, structure, and organic matter content and has a major influence on water movement, water retention, salt movement, salt retention, and soil aeration. **Macropores** (aeration porosity), soil pores with a diameter >0.10 mm, are much more prevalent in sands than fine-textured soils, whereas in sands, **micropores** (capillary pores, moisture retention porosity) are more dominant. Macropores are critical for rapid water movement into the soil surface (**infiltration**), through the root zone (**percolation**), and beyond it (**drainage**). Effective leaching cannot be accomplished without macropores, and macropores must be present across the entire soil profile depth.

Sandy soils with >85% sand content exhibit sand particle-to-particle contact that opens up macropores between particles, and this arrangement resists compaction. Thus, salt leaching is much easier in sandy soils. If excessive “fines” are added to the soil or excessive organic matter, infiltration rates can decline and salinity leaching becomes more difficult. Sometimes, “sand substitutes” (calcined clay, diatomaceous earth materials, or zeolites) are added to sands, usually for moisture retention purposes (porous ceramics or calcined clay products; diatomaceous earth products) or sometimes for enhancing CEC (zeolites). These materials normally contain a preponderance of micropores that are very fine and thus retain water with most of the water not plant-available. Also, the total pore volume is increased (see “Total pore space” in the following text). If saline irrigation water is used, these additional micropores will be filled with saline water, which will not easily leach. The authors have seen several situations where >15% sand substitute (volume basis) was added and the irrigation water was saline. Salt leaching of these soil medias was much slower and more challenging than with unamended sands profiles.

In terms of salt leaching, as microporosity increases (regardless of sources such as clay, sand substitutes with considerable microporosity, soil-compaction-destroying structure, excessive organic matter, etc.), salinity leaching becomes more difficult and requires a greater volume of water. Salts leach relatively easy and rapid in macropores, but in micropores, most saturated flow (when water is added in sufficient volume to create rapid, saturated flow conditions) bypasses the micropores and flows through the macropores. Under nonsaturated flow conditions, such as pulse irrigation or slow and prolonged rains, water can move through the micropores, but this is a much slower process (and requires a longer period) to achieve sufficient flow to leach the salts.

Even a thin zone or layer within a soil profile that has few macropores will not only limit water movement, but result in salt accumulation above this layer. Any soil layer or horizon that inhibits water movement will be a major hindrance to effective leaching, whether it is at the surface (surface compaction) or subsurface (i.e., B horizon, cultivation pan, buried layer from flood deposition of fines, etc.). Cultivation operations to enhance infiltration and percolation (deep cultivation techniques) are essentially done to create temporary macropores. If the cultivation holes are filled with a sand (>0.25 mm), the macropores remain open for a longer period of time. Thus, turfgrass managers must be familiar with their complete vertical soil profile and should "visualize" (view speed of water infiltration) whether sufficient macropores exist for effective leaching downward into the deep subsoil, or hopefully to the drain lines.

Clay type. Clay type has a pronounced influence on water movement. Nonshrink/swell clays (kaolinite, allophanes, and Fe/Al oxides) are called *1:1 clay types*, and these do not crack when drying or seal by swelling when wet. Cultivation operations generally last longer on 1:1 clays than the *2:1 types* discussed in the following text. Also, a higher level of Na^+ is required on 1:1 CEC sites before soil structure deterioration, usually at >24% Na saturation compared to > 4 to 6% Na for many 2:1 types (montmorillonite, illite). Generally, 1:1 clays are more resistant to soil compaction than 2:1 clays. Because 1:1 clays evolve in humid, high-rainfall areas, they often exhibit a B horizon where clay content is higher owing to movement/migration downward over many years. For example, many southeastern U.S. Piedmont red clay soils (1:1 types) contain 40 to 50% clay in the B horizon compared to 15 to 25% in the surface A horizon, and water movement is slower across the B horizon. Pulsing the water applications or use of low-flow sprinklers and soaker hoses are methods for effectively leaching these B horizon or higher clay composition soils.

Most clay types in the United States, including arid/semiarid regions and many marine (coastal) clays, are 2:1 clays—these can be present in most climatic zones. When drying, 2:1 types are "self-cultivating" because cracks form. Unfortunately, under well-watered to saturated moisture situations, these clays swell and most macropores are lost. When total salinity problems develop on these soils, deep cultivation followed by filling the cultivation hole with sand or sand plus gypsum (sodic sites) is necessary to maintain a sufficient volume of macropores in order to reach at least the depth of cultivation. In contrast, deep cultivation operations are effective for longer time periods on 1:1 clays even without filling holes with sand.

Soil structure. **Soil structure** refers to the arrangement of sand, silt, clay particles, and organic matter into structural units or aggregates. For example, a soil with appreciable silt and clay may have aggregates composed on sand, silt, and clay held together by organic-matter-aggregating agents arising from soil microbial activity. These aggregates are normally sand-sized or much larger and act as units that increase macoporosity for enhanced water movement and aeration. As aggregates are formed, macropores are developed between aggregates or structural units. Structure is very important as silt and clay-content increases on fine-textured soils.

Soil compaction from recreational traffic destroys much of the structure and macropores in the surface 3 in. (75 mm) zone, but a well-structured soil will usually have some macropores deeper in the profile. The 2:1 clays are much more prone to soil compaction and structural deterioration than are 1:1 types. As noted previously, high Na causes structural deterioration of fine-textured soils. This is especially serious on 2:1 clays because they often have poor drainage even under low Na owing to their swelling/sealing nature.

Although high Na content does not cause "structural breakdown" of single grain sand particles, it does cause any colloidal particles (clay or organic matter in nature) present to be dispersed and become susceptible to particle migration. Pond, lake, or river water with high turbidity can contribute to these "fines" during irrigation. Often, these fines accumulate at the normal depth of irrigation water penetration and can cause a layer that sequesters and concentrates excess salts such as sulfates, which could eventually induce black layer formation. This sequence of events would then inhibit salt leaching and damage turfgrass roots.

Capillary rise. Soluble salts move with the soil water. If there is net downward movement of water due to rain or irrigation to achieve an adequate leaching fraction, salt movement is downward away from the root system. However, these salts may accumulate below the root zone in an area that can be very salt laden. If water moves upward via evaporation, the salts also move upward. The most common upward movement is by **capillary rise** in the micropores, which can result in major redistribution of salts within the soil profile. Capillary rise of salts will be more rapid on fine-textured soils than on sands because fine-textured soils contain more micropores.

Factors that enhance capillary rise of salts are low leaching rates, high ET conditions, and a high water table. Some water conservation regulations limit ET replacement to 70–85% potential ET (ETo) on turfgrasses in arid regions and do not take into account the need for an LR to prevent soil structural deterioration from Na accumulation and concentration. Under high evapotranspiration (ET) conditions, salts may start to rise upward by capillary action driven by surface drying from ET losses (Table 11.2). If the replacement irrigation applications provide "no leaching fraction" and are equal to or less than ET, the net movement of salts will be upward into the root zone and eventually may result in surface accumulation (Figure 11.1).

Water table. Water table location is another soil factor influencing salinity control. Sometimes, the natural water table level is near the surface. The **capillary fringe** of semisaturated water conditions above a free water table is usually 2 to 8 in. (50–200 mm) for sands and 8 to 12 in. (200–300 mm) for fine-textured soils. However, high ET conditions and limited leaching can cause salts to rise well above these distances over time by long-term capillary action. Capillary rise on fine-textured soils is still strongly controlled by climatic conditions (i.e., ET) at a depth of 2.5 to 3.0 ft and possibly down to about 5.0 ft. An example of long-term capillary rise is upward salt movement of a dormant turfgrass during dry, winter months from a salt-laden zone that may be well below the root system in the normal growing season when irrigation and rainfall keeps the salts from rising.

TABLE 11.2
Evapotranspiration averages by environment for turfgrasses under well-irrigated conditions for different climate conditions

	Average evapotranspiration[a]	
Climate situations	**in. per day**	**mm per day**
Cool humid	0.10–0.15	2.50–3.75
Cool dry	0.15– 0.25	3.75–6.25
Warm humid	0.15– 0.20	3.75–5.00
Warm dry	0.20– 0.25	5.00–6.25
Hot humid	0.20– 0.25	5.00–6.25
Hot dry	0.25–0.35	6.25–8.75

[a] The actual ET varies with grass species/cultivar, wind speed, management level, etc., but these values provide "ballpark" estimates. Also, as soil moisture level declines, ET decreases dramatically.

A rising water table can bring salts that have accumulated above the water table into the root zone area. In Western Australia, large areas of the landscape have become salinized by a slowly rising water table caused by removal of deep-rooted trees and shrubs that prevented deep penetration of water and dissipated it as ET. This is a type of secondary salinization and is called **dryland salinity** (Barrett-Lennard, 2003).

Another water table issue is when the water table is near the surface and poor irrigation water quality requires a high LR. Over time, the water table may rise even higher and cause massive salinization of the root zone. On sites where shallow water tables may rise, the turfgrass manager should investigate means of lowering the water table when possible, such as utilizing additional drainage lines with possible sump pumps to deposit the excess rising water into drainage canals or wetland areas.

Turfgrass soils often contain layers in the soil that inhibit water percolation or drainage. This can create a temporary **perched water table** as water flow is slowed or stopped when the wetting front reaches this layer. Salts will then accumulate above the layer and can rise to the surface whenever low leaching rates or high ET occurs. A good concept to remember is, "if a layer impedes water movement, it also impedes salt movement, and therefore enhances salt accumulation."

Subsurface layers that are 1 to 3 ft below the surface are often overlooked in arid or semiarid regions where heavy rainfall events (that are sufficient to pond water up to the soil surface) are rare. But, these "hidden layers" can contribute to major salt accumulation and layering so that when conditions favor capillary rise, the resulting water has very high salinity.

Another "perched water table" is found in many constructed profiles with high sand content, such as the USGA green construction method where the interface between the root zone media and a coarse sand layer creates a perched water table (USGA Green Section Staff, 2007). In this case, ample macropores are present, but

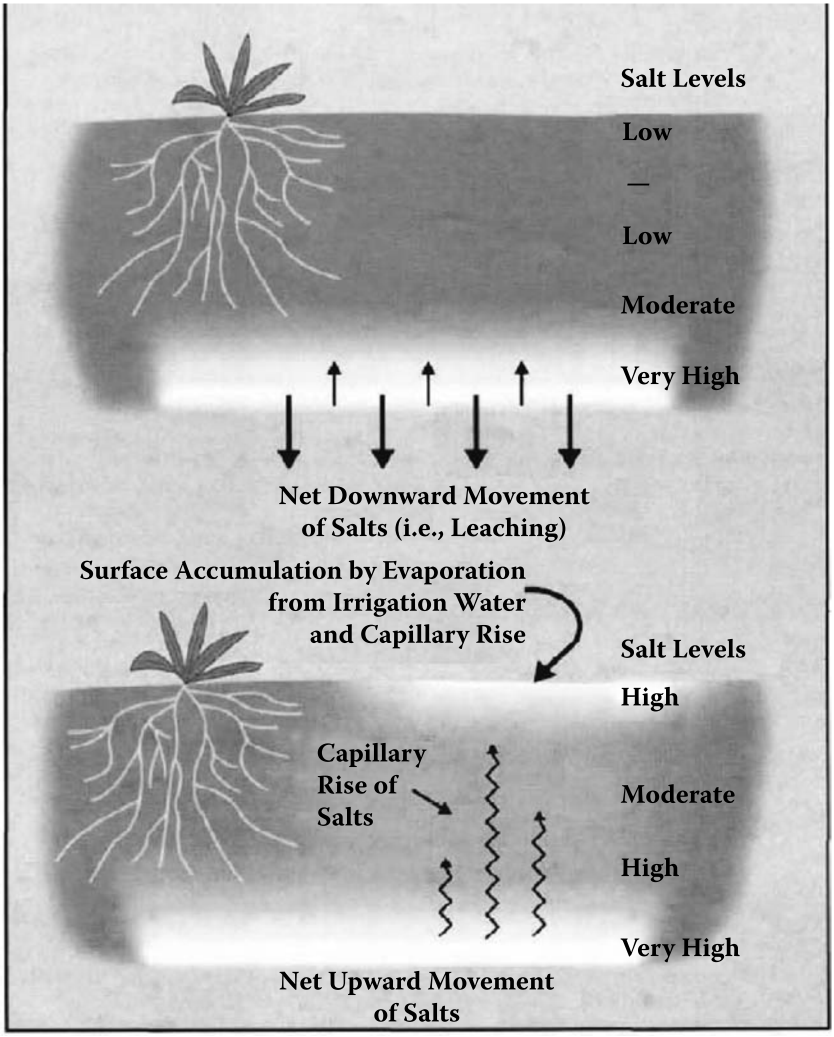


FIGURE 11.1 Examples of salt levels throughout the soil profile. Top: Represents good leaching conditions with adequate leaching requirement (LR) applied. Bottom: Represents what happens when insufficient water is applied in midsummer under high evapotranspiration (ET) conditions. (From Carrow, R. N. et al. 2000. Leaching for salinity management on turfgrass sites. *USGA Green Section Record* 38(6): 15–34.)

sufficient water is required to break the perched water tension and to initiate rapid drainage or "flushing" of the root zone. During summer months when ET is high and saline irrigation water is used, salts above the perched water table zone may start to rise toward the roots and soil surface if extra leaching is not applied periodically. Prolonged drought, high temperatures, and dry, windy conditions can escalate or enhance the concentration of these salts and their capillary rise to the soil surface, especially if a lighter and more frequent irrigation regime is imposed.

With the exception of the layer within the USGA greens, layers found in turfgrass soils that limit water percolation/drainage and enhance salt accumulation have few macropores due to excessive fines or compaction. Cultivation practices to break up these layers are important in salinity management. The cultivation depth must penetrate completely through the layer to promote water flow when excess water application by irrigation or rainfall occurs and to prevent a zone of salt accumulation, or for a normal LR in a maintenance leaching program to result in net downward movement of the salts.

Total pore space (pore volume, PV). The total pore space or pore volume of a soil also influences salt leaching (Rhoades and Loveday, 1990). Soils with higher PV require more water to leach the same quantity of salts, especially if the micropores are more prevalent. The PV range of sands, loams, and clays is about 35 to 40%, 40 to 50%, and 45 to 55%, respectively. For a soil depth of 12 in. (30.5 cm), 1 PV of applied water would represent 4.2 to 4.8 in. (sands), 4.8 to 6.0 in. (loams), and 5.4 to 6.6 in. (clays) (10.7–12.2, 12.2–15.2, 13.7–16.8 cm, respectively) of irrigation water. Thus, more water is required to leach fine-textured soils than sands. When micropores are predominant, the leaching must be much slower in order to allow time for the water to move by nonsaturated flow through these small pores.

11.4 GRASS TYPE AND SALINITY MANAGEMENT

Level of salinity tolerance of the turfgrass species/cultivars on the site as well as any other introduced or native landscape plants are especially important criteria in determining the appropriate salt leaching programs.

Salinity tolerance. As demonstrated in the example in Table 11.1, the LR is influenced by what salinity level the grass can tolerate; thus, salinity tolerance of the grass is one the most important factors affecting overall salinity management practices. The turfgrass **threshold EC_e** is used as a guide to acceptable soil salinity levels, where threshold EC_e is defined as the soil salinity at which turfgrass growth starts to decline compared to a nonsaline condition (Carrow and Duncan, 1998). Grasses with higher threshold EC_e have a lower LR compared to grasses with a lower threshold EC_e, because soil salinity can be maintained at a higher background level. Grasses with moderate to very high salinity tolerance may be irrigated to maintain the soil salinity at greater than the threshold EC_e, perhaps at EC_e of 25 or 50% growth reduction, as long as the grass has acceptable quality and is able to tolerate any stresses that are present. The grass vigor and ability to withstand wear from traffic are especially important on recreational sites when considering the appropriate maintenance EC_e.

One common misconception about highly salt-tolerant grasses (halophytes such as seashore paspalums), is that a high salinity tolerance, as exhibited by a high threshold EC_e, indicates that a grass should be maintained at that level. As salinity in the irrigation water increases, so does the potential adverse impacts on the environment, on management costs, and on ecosystem sustainability challenges (Carrow and Duncan, 1998; Beltran, 1999). The most important management benefit associated with using a more salt-tolerant grass compared to a less tolerant one when irrigation water is saline is that the grass response to salinity does not occur as rapidly, which allows time for the manager to implement corrective practices without significant visible turfgrass stress.

Turfgrass rooting and salinity. When assessing salinity tolerance of turfgrasses, it is important to determine tolerance of the root system because salinity tolerance can vary with tissue type (Lee et al., 2005). Grasses exposed to high-salinity environments must be able to develop and maintain a viable and extensive root system to exhibit adequate shoot salinity tolerance. For reclamation leaching, rooting depth determines the "root zone" that must be leached. Thus, a deeper-rooted plant will require more water for leaching during reclamation of soil salts on a site.

Turfgrass rooting depth also impacts salinity management for routine maintenance leaching. Provided that adequate soil moisture is present in the lower one third of the root system to avoid salt concentration (i.e., soil moisture is about field capacity in this zone), turfgrass growth is related to average root zone EC_e regardless of the salt distribution within the root zone. Thus, when monitoring soil EC_e by depth within the root zone, the average EC_e is the value used to compare with the turfgrass salinity tolerance level selected, such as EC_e for 25% growth reduction. Especially with high-saline irrigation water, irrigation events should be scheduled to avoid depletion of soil moisture within the lower one third of the root zone, which would result in increased soil EC within this zone, with serious salt stress occurring. Irrigation events are, therefore, scheduled more often than on a similar nonsaline site in order to maintain a higher average soil moisture content and to avoid excessively high soil EC. Also, a deep-rooted turfgrass will allow for more days between irrigation events than a shallow-rooted grass as long as the specific cultivar has adequate salinity tolerance to the water quality used for irrigation. Although irrigation events may be scheduled more often on sites irrigated with saline irrigation water, the quantity of water should still be based on ET replacement, compensation for nonuniformity of the irrigation system, and the actual LR for the grass cultivar.

11.5 WATER QUALITY AND SALINITY MANAGEMENT

While many soil, climatic, and plant characteristics influence salinity management, the single most important component aspect is the quality of the irrigation water. Irrigation water not only is often the source of the salts that must be managed, but also its quality has an essential influence on the quantity of water to achieve salinity control in both reclamation and maintenance leaching programs.

11.5.1 Maintenance Leaching, Leaching Requirement, and Irrigation Water Quality

Irrigation water quality strongly influences the quantity of water necessary to leach salts, with more water required as salinity level in the water increases. As noted previously, the leaching requirement (LR) is the minimum amount of water that must pass through the root zone to control salts (i.e., keep salts moving) in the root zone within an acceptable level. The traditional LR approach is used for "maintenance leaching," in which sufficient water is applied to maintain soil salinity at a currently acceptable level (Rhoades, 1974).

It must be emphasized that the LR is intended to be applied with every irrigation event for maximum effectiveness and to obtain salt leaching with the minimal quantity of water. Comments often made are that applying additional water for salt leaching will result in wet, soggy conditions; or there just is not sufficient time to apply all the extra water. If a true maintenance LR program is used, however, these are not valid comments; but they are valid when salt accumulation reaches a level in the soil profile requiring reclamation leaching. To illustrate, as a general rule for the total quantity of irrigation water required for a specific irrigation event, replacement of ET losses would account for 60–85%; 10–30% would be for nonuniformity of the irrigation system; and 5–15% for the LR. For example, if ET replacement was 1.0 in. (25 mm), the quantity for nonuniformity of the system would be 0.20 in. (5 mm), and the LR of 7% or 0.08 in. (2 mm), then the total quantity of irrigation water would be 1.00 + 0.20 + 0.08 = 1.28 in. (25 + 5 + 2 = 32 mm). The 0.08 in. LR is not the cause of undue wet conditions or too little scheduling time; inaccurate estimates of replacement ET and nonuniformity of the irrigation system are the primary causes.

Turfgrass managers sometimes state that they would prefer to apply the LR only once a week or once a month. This is no longer a maintenance leaching program, but a reclamation leaching program, which is discussed in the next section. Whenever salts are allowed to accumulate before leaching, the quantity of water required will be substantially greater than if a true maintenance LR program was followed at every irrigation event.

Several methods have been or could be used to determine the LR (Corwin et al., 2007; Carrow and Duncan, 1998). Corwin et al. (2007) recently reviewed and compared various steady-state models and more complex transient models that could be used for determination of LR. However, the traditional method of Rhoades (1974) provides a good approximation and considers irrigation water salinity level (EC_w, dSm^{-1}) and grass salinity tolerance using the **threshold EC_e** (the soil salinity, EC_e, at which growth declines compared to growth under nonsaline conditions), where (see Table 11.1)

$$LR = EC_w/5EC_e - EC_w$$

where

EC_w = electrical conductivity of irrigation water

EC_e = threshold EC = electrical conductivity of saturated soil paste at which turf growth starts to decline by at least 10%.

An example will illustrate the influence on LR of irrigation water quality. For a turfgrass with a threshold EC_e of 10 dS/m and using irrigation water quality of 2.0 dS/m, the LR by the preceding formula would be

$$LR = 2.0/5(10) - 2.0 = 0.042, \text{ or } 4.2\%$$

This LR would require 4.2% more irrigation water volume to be applied above the replacement ET plus any for correction of nonuniformity of the irrigation system application. However, if the irrigation water quality has an EC_w of 4.0 dS/m, the LR then becomes 8.7%.

Some of the models proposed to estimate the LR that are discussed by Corwin et al. (2007) include factors beyond what are in the traditional LR, such as composition of irrigation water, salt precipitation processes, ET reduction under salinity, soil water content by rooting depth, preferential flow, and unsaturated flow affects. Some may ask, which LR model should I use? In turfgrass situations with saline irrigation water and a perennial ground cover, salinity management by leaching is an ongoing process that must be constantly monitored and adjusted. The "system" is not static or steady state, but common changes over a season are as follows:

Irrigation water quality may change over the year.
High rainfall periods alter soil salinity and salinity level within irrigation lakes.
Turfgrass growth changes with dormancy periods.
Environmental stresses and traffic stresses may change with impact of salinity tolerance.
Other dynamic factors.

What the steady state–based LR of Rhoades (1974) does is to estimate a reasonable LR by accounting for two of the most important factors, namely, irrigation water quality and plant tolerance to salinity. It is a "ballpark estimate" that provides a good starting place for determining an effective LR. From this starting point, a successful salinity leaching program will require adjustment over time, the following points being some of the most important management considerations:

- Ongoing monitoring of changing irrigation water quality and soil salinity conditions by water quality and soil tests with adjustments made based under actual field conditions. If field monitoring demonstrates that leaching is not sufficient, then the LR should be increased, or conversely, decreased if leaching is adequate until an appropriate LR is defined.
- The actual LR does not change unless irrigation water quality changes or the grass salinity tolerance changes. The latter could occur when a cool-season grass is used to overseed a more salt-tolerant warm-season grass; or when during renovation, more juvenile seedlings or vegetative plant parts are present, which have lower salinity tolerance levels than a mature plant.
- Sometimes the quality of the irrigation water source changes over time. This would necessitate a change in the LR based on changes in the EC_w.
- Although the LR does not often change, the quantity of water to replace ET does change with weather. Thus, an underestimation of ET will result in salt accumulation, not because of an insufficient LR but because of insufficient ET, which accounts for the majority of the irrigation water replacement requirement.

- Lack of attention to irrigation system uniformity with respect to irrigation water application will result in nonuniformity of irrigation water application and, thereby, a parallel response in effective salt leaching.

Assuming the initial root zone salinity level is acceptable, when the LR is not sufficient to maintain salt leaching, two adverse salt responses occur: (1) salts applied in the irrigation water start to accumulate within the surface 2–3 in. (50–75 mm), and (2) capillary rise of salts from deeper in the soil and beyond the root zone will bring concentrated salts back into the root zone (Figure 11.1). Often, this zone of accumulated salts has a very high EC_e, and when it reaches the lower root zone can induce a rapid salinity stress (desiccation). To alleviate the salinity stress (physiological drought with reduced water uptake that is critical for plant transpirational cooling) now requires much more applied water than the LR amount because it is a reclamation problem.

This scenario is most often observed on high sand creeping bentgrass/*Poa annua* golf greens irrigated with water of medium-to-high salinity where there has been a change to lower-volume/shorter-duration irrigation events that may be applied more often. If conditions require shifting to a light, more frequent irrigation regime and, therefore, away from a true LR program for a period of time, then it is important to understand the implications. Even turfgrass managers with relatively low total salt concentrations in irrigation water (500 to 600 ppm) may experience this situation under extreme environmental conditions such as prolonged drought or in arid climates, persistent windy conditions, temperatures >32°C, and ET rates consistently exceeding irrigation volume applications. The turfgrass manager may be achieving adequate leaching in the spring and early summer using ample irrigation volume or with well-distributed rainfall. However, by midsummer, three events can impede leaching: (1) with hot, dry weather, the ET increases the quantity of irrigation water needed simply to maintain soil moisture (Table 11.2); (2) turfgrass roots start to die back; and (3) turfgrass managers shift to light, more frequent irrigation (especially on cool-season grasses and with sandy profiles for temporary temperature reduction during the heat of the day), which does not supply sufficient water to leach and will concentrate salts near the soil surface owing to inadequate percolation of the irrigation water deeper into the soil profile. The concentrated salts at the surface then reduces water uptake through increased osmotic pressure, potential salt damage to plant crowns and rhizomes, and desiccation of shallow roots and root hairs near the soil surface. If water conservation programs are mandated, salinity levels can increase rapidly in a short time period (in a matter of 1–2 weeks) with short-duration, frequent irrigation events. The situation depicted in Figure 11.1 (bottom) then occurs.

Light, frequent irrigation increases salt accumulation in the surface, where most of the crown-region regenerated roots are located. And, salts rise by capillary action into the root zone from (1) a high-salt zone common for pushup greens or (2) the perched water table of a USGA green that is not adequately "flushed." Injury normally appears on the most elevated, open, and exposed greens or slopes where high ET conditions prevail because of angle of the sun, high solar radiation, and wind movement. Mounds, "berms," and slopes are normally among the first areas to show stress. Because the creeping bentgrass/*Poa annua* is now under high temperature stress, salt-induced drought is a serious additional stress symptom and disease outbreaks are commonly observed.

In this sequence of events, the basic problem is that the overall irrigation quantity is not sufficient to maintain effective salt leaching, and a shift has been made from a maintenance leaching program to one that will require regular reclamation leaching. The turfgrass manager must now apply an extra leaching irrigation every 1 to 4 weeks (depending on water quality, soil and environmental conditions) to avoid upper soil profile salt accumulation and attempt to reestablish an irrigation program that applies sufficient water to allow for adequate leaching until a maintenance leaching program can be reestablished. The frequency between leaching events will vary depending on climatic conditions (solar radiation, wind, temperature, humidity, and resulting ET demand), water quality, root zone depth and the threshold ECe of individual turfgrass cultivars, and the depth of subsequent leaching and irrigation events. The leaching frequency and threshold ECe can be accurately determined by use of an inexpensive portable EC meter (Vermeulen, 1997). Soil ECe at the soil surface and throughout the profile can be monitored regularly (daily if necessary), and as the threshold ECe is reached, leaching can be initiated to purge the perched water table.

A practical method to ensure that the perched water table on a USGA green has been completely purged of salts is to locate the outflow drain line exiting the green cavity and install an inspection port. Drainage flow can be observed and water samples collected and tested with the portable (ECw) meter. Once the ECw of the drainage water is at, near, or exceeds the ECw of the irrigation water, then acceptable initial leaching has been accomplished in that green's profile. Drainage line ports exiting tees or low topography zones in fairways can also be monitored for leachate salinity to determine effectiveness of the leaching program on those sites.

Although native soils may require 1 to 4 weeks to reclaim, well-drained sand-constructed putting green root zones with perched water tables can often be reclaimed in 1 to 3 days when high total salts are the primary salinity limitation. Between leaching events, additional irrigation may be needed on a light, frequent basis until turfgrass roots regenerate, which may not occur on creeping bentgrass/*Poa annua* greens until cooler weather occurs. If the irrigation water contains high levels of sodium and the sodium loads on the soil cation exchange sites, a calcium amendment such as gypsum must be used in conjunction with a proper leaching program to effectively move the excess sodium deeper into the soil profile.

11.5.2 RECLAMATION LEACHING AND IRRIGATION WATER QUALITY

In the previous section, emphasis was on maintenance leaching and the LR concept for maintaining salinity levels at an existing acceptable level. In contrast, **reclamation leaching** is when soil salt accumulation is above the acceptable level for the plant and salts must be leached to achieve an appropriate soil EC_e level. Because soil salinity levels are already excessive, reclamation leaching compared to maintenance leaching requires a higher quantity of water to decrease salinity within the root zone to acceptable levels. Once this acceptable level is achieved, the LR irrigation approach (maintenance leaching) using less "extra" water can be used.

The reclamation approach is necessary for two primary situations in turfgrass management: (1) when a seriously salt-affected soil (e.g., highly saline and/or sodic condition) must be leached of excess salts before the grass can be established; and (2) when a turfgrass manager has not maintained an adequate LR, and therefore, the grass root zone has increased in salinity to severe stress levels. As noted in the previous section, this latter situation is most likely to occur during hot, dry summers when ET rates have increased, but the total water applied for ET plus quantity of water to account for nonuniformity of the irrigation system plus LR has not been adjusted to keep up with actual ET. Cool-season turfgrasses subjected to this sudden and intense salinity shock (a combination of drought, high temperature, and greater wear stresses from slower growth, all induced by salts) often do not survive. The "take-home lesson" for this situational stress is "proactive prevention" by adequate, continual application of sufficient LR water to keep salts moving downward and away from the turfgrass root system.

Reclamation leaching requirements can be estimated by the Rhoades and Loveday (1990) procedure (Table 11.3). This procedure takes into consideration intended

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TABLE 11.3
Determining reclamation leaching needs[a]

$D_w = k \times D_s \times EC_{eo} - EC_w / EC_e - ECw$

D_w = depth of water to apply for leaching (feet)

D_s = depth of soil to be reclaimed or leached (feet)

EC_e = final soil salinity desired in dS/m. This value is usually the threshold ECe for the turfgrass being used or somewhat less than the threshold ECe

EC_{eo} = initial or original soil salinity in dS/m

EC_w = salinity of irrigation water used for leaching in dS/m

k = factor that varies with soil type and water application method (efficiency of irrigation system)

For sprinkler irrigation applied by pulse irrigation that results in unsaturated flow conditions by allowing drainage for 1 to 2 hours (sands) to 2 to 8 hours (fine-textured soils) between a pulse irrigation event with repeated pulse events until the total quantity of water necessary for leaching is applied, use:

k = 0.05 for high sand content each with >95% sand content (i.e., <5% silt + clay content)

k = 0.10 for all other soils

For continuous ponding or continuous sprinkler irrigation that results in saturated flow conditions with water applied to keep the soils saturated during leaching use:

k = 0.45 for organic soils

k = 0.30 for fine-textured soils

k = 0.10 for sandy soils

[a] Adjustments in the "k"value for high-sand-content greens are based on experience of Carrow, Huck, and Duncan.

Source: Adapted after Rhoades, J. D. and J. Loveday. 1990. Salinity in irrigated agriculture. In B. A. Stewart and D. R. Nielson (Eds.). *Irrigation of Agricultural Crops*. Agronomy No. 30. Amer. Soc. of Agron., Madison, WI.

depth of salt leaching, desired final soil EC_e, current or initial soil EC_e , leaching water quality (EC_w), and soil type/irrigation method. The reclamation equation by Rhoades and Loveday (1990) is

$$D_w = k \times D_s \times EC_{eo} - EC_w/EC_e - EC_w$$

where

D_w = depth of water to apply (in feet)
D_s = depth of soil to be reclaimed in feet
EC_e = final soil salinity desired in dS/m
EC_{eo} = original or initial soil salinity in dS/m
EC_w = irrigation water salinity in dS/m
k = factor for soil type and irrigation method, where the "k" factor for pulse sprinkler application is: 0.05 for 95% sands; 0.10 for all other soils; and the "k" factor for continuous ponding/flooding is 0.45 for organic soils, 0.30 for fine-textured soils, and 0.10 for sandy soils.

As an example of the use of this method to estimate the quantity of irrigation water to apply for reclamation leaching (i.e., D_w) assume: (1) a high sand content golf green with an initial soil EC = 12.0 dSm^{-1} (i.e., EC_{eo}); (2) the turfgrass being used has a salinity tolerance threshold EC_e of 5.0 dS/m, which is therefore the final desired soil EC_e; (3) the irrigation water used for leaching will be applied in pulses and has an EC_w of 2.5 dS/m; and (4) the desired leaching depth (D_s) is 16 in. (40 cm) to reach the drain tile, where 16 in. = 1.33 ft (0.40 m). Based on these conditions, the quantity of irrigation water to apply would be **D_w = 0.253 ft = 3.0 in. (7.62 cm) of water.**

To illustrate how the quantity of water for leaching can change dramatically with various situations, if we assume that all other factors remain the same except for the following:

- The leaching water quality is better and EC_w = 1.0 dS/m rather than 2.5 dS/m. Then, D_w = 0.183 ft = **2.2 in. (5.59 cm) water.**
- The leaching water quality is of lower quality at EC_w = 4.0 dS/m rather than 2.5 dS/m. Then, D_w = 0.532 ft = **6.4 in. (16.26 cm) water**.
- The soil is not a high concentration of sand, but a push-up native soil green of about 85% sand with a "k" factor of 0.10. Then, D_w = 5.06 ft = **6.1 in. (15.49 cm) water.**
- The grass has a threshold salinity tolerance of 3.0 dS/m rather than a threshold EC_e of 5.0 dS/m. Then, D_w = 1.26 ft = **15.2 in. (38.6 cm) of irrigation water.**
- The grass has a threshold salinity tolerance of 3.0 dS/m rather than a threshold EC_e of 5.0 dS/m and the soil is 85% sand with a "k" factor of 0.10 instead of 0.05. Then, the D_w = 2.53 ft = **30.3 in. (76.96 cm) of water**.
- The grass is a silt loam fairway (k = 0.10) with a threshold EC_e of 3.0 dS/m and a leaching depth of Ds = 2.5 ft. Then, the D_w = 4.75 ft = **57 in. (144.78 cm) of irrigation water.**

In each of these examples, the least quantity of water necessary for a reclamation leaching was 2.2 in. (5.59 cm) of irrigation water and the most was 57 in. (144.78 cm). If the site is one with an existing turfgrass, the 2.2 in. would be in addition to ET replacement and any irrigation to compensate for nonuniformity of the irrigation system. It is instructive to note that the LR for maintenance leaching are most often in the 0.50 to 0.15 range, which for a 1.0 in. (2.5 cm) irrigation event to replace ET and apply sufficient water for nonuniformity of the irrigation system, the quantity water is 0.05 to 0.15 in. (1.27–3.81 mm) water. This illustrates why turfgrass managers with saline irrigation water should strive to achieve and maintain a maintenance leaching program and not to get into a situation where reclamation leaching is necessary. To program 2.2 in. of extra water, in addition to ET replacement and to adjust for nonuniformity of the irrigation system, would be a substantial challenge on most sites, especially considering that the foregoing calculations were all based on a pulse irrigation sequence; that is, 0.15 in. of extra water does not create a soggy, waterlogged site or create a difficult scheduling problem; but 2.2+ in. of additional water could create a problem. If a flood or high-volume irrigation regime was used to create saturated flow, the quantities of applied irrigation water would double or triple.

The **estimated influence of rainfall** can be determined by substituting a low EC value for the "irrigation water" when the other factors are known. For example, in the initial example situation, the quantity of water indicated was 3.0 in. (76 mm) irrigation water required with an EC_w of 2.5 dS/m. Assuming all other conditions are the same, we could use an EC_w of 0.10 dS/m for rainfall and estimate the quantity of rainfall to accomplish the desired leaching to the depth selected. In this case, the D_w (as rain) = 0.16 ft or 1.9 in. (4.83 cm) of rain. This quantity would be a good estimate if the rain came as a light continuous one that would maintain unsaturated flow. However, if the rainfall was heavier, then the "k" factor from Table 11.3 would become 0.10 rather than 0.05 and the quantity of effective rain would be double, or become 3.8 in. (9.65 cm), with the assumption that all the water will infiltrate into the soil at the site of impact.

Assuming all other factors remain the same in the initial example and then compare the leaching needs using irrigation water with EC_w = 1.0, 2.5, and 4.0 dS/m would result in D_w values of 2.2, 3.0, and 6.4 in., respectively. This illustrates that water quality has a very important influence on reclamation leaching and on maintenance LR. A second implication is that turfgrass managers should use their rainfall periods to maximize leaching, especially when reclamation leaching is necessary. For example, irrigating just prior to the forecasted rain event to wet the soil profile to near field capacity will maximize the leaching potential of whatever level of rain may fall on the site. Additionally, following a good rainfall period during which substantial salt leaching has occurred, salts will be at an acceptable level and the leached salts will be below the root zone; the rule should be to immediately initiate a maintenance LR program. Sometimes, turfgrass managers do not initiate a maintenance leaching program in order to "conserve water," with the result that salts again begin to accumulate. Rather, the LR fraction should be implemented to prevent salts from rising back into the root zone via capillary upward movement. If resalinization of the root zone is allowed to occur, a reclamation leaching strategy will necessitate substantially more water being applied than the maintenance strategy in order to reduce the salt load in the soil profile.

11.6 CLIMATIC CONDITIONS AND SALINITY MANAGEMENT

Climatic conditions impact salinity management in several ways. Of prime importance is the climatic influence on ET and, therefore, the frequency and quantity of water to replace ET lost from the soil since the last irrigation or rainfall event. High-ET conditions (high temperatures, low humidity, high solar radiation, and persistent wind) requires more frequent irrigation or higher quantities of water to replenish a deeper soil profile (i.e., from deeper water penetration, and less frequent irrigation). In arid climates or dry seasons, there is less rainfall to recharge the soil profile across a landscape, so irrigation water is applied not just to replenish the ET losses but also to compensate for nonuniformity of the irrigation system in order to prevent dry areas. The net result of these factors is more water applied on a site.

When saline irrigation water necessitates a maintenance leaching program with an LR, this furthers contributes to the total water needs; that is, as pointed out previously, the LR is normally only 5–15% additional water per irrigation. With high-ET conditions, the site manager is challenged to apply sufficient water within the irrigation time frame to meet the total irrigation water requirement. Insufficient irrigation application to meet all needs results not because the LR is so high, but because the ET or quantity of water to compensate for nonuniformity is not estimated correctly or that water was not applied because of time or system constraints. The net result is that salts are deposited into the root zone without adequate leaching to remove them, and soil EC_e will increase. **Salinity accumulation in the surface** couple inches occurs where much of the crown, rhizome, root, and stolon tissues are located.

The second major influence on salinity management in a high-ET climate is the impact on **capillary rise of salts** from below the root system. Without net downward movement of water or at least sufficient water to maintain equilibrium, salts will start to move upward by capillary action. If the zone of high salt concentration is dry, capillary action is minimal. However, this zone may contain sufficient moisture from past irrigation events or rainfall to allow for capillary rise. When the salt-laden zone is near the bottom of the existing root system, then it does not require much time for the lower root zone to be subjected to very high saline conditions in a short time frame. The double response of salt accumulation at the surface and salt increase within the lower root zone can cause rapid and dramatic salinity stress on the plant.

Other influences of climate on salinity management are seasonal changes in rainfall distribution; effects of rainfall on water quality in irrigation lakes (for example, dilution of salinity in a irrigation lake that predominantly receives a saline water source); effect of prolonged high-ET conditions on concentrating salts within an irrigation lake; and winter dormancy periods. Each of these climatic influences illustrate the necessity for the turfgrass manager to (1) always consider how conditions are affecting salt accumulation in soil or lakes, and (2) monitor soil and irrigation water quality as needed to track salt accumulation changes before they become problems.

11.7 ENHANCING EFFECTIVENESS OF SALT LEACHING

Whether the leaching program is for maintenance or reclamation leaching, there are certain practices that will enhance the effectiveness of salt leaching with the least quantity of irrigation water application. As the salinity level increases in irrigation water, the importance of these practices also increase. The most important considerations are as follows:

- Irrigation system design
- Irrigation water application method
- Cultivation and drainage
- Sand-capping
- Soil and water amendments
- Accurate estimation of total irrigation needs
- Salinity monitoring

11.7.1 IRRIGATION SYSTEM DESIGN

Huck (1997) presents an excellent discussion on **irrigation system efficiency and design** considerations related to saline irrigation water, as does Chapter 10. The key points will be reiterated here for emphasis. Nonuniformity of water application may result from several factors, including (1) improper sprinkler head spacing for wind and water pressure conditions, including hydraulic losses from friction and elevation differences; (2) incorrect sprinkler or nozzle size for the site; and (3) poor system maintenance such as leakage, sprinkler/nozzle wear, and mixing of nozzles. Adjustments in these factors during design and, if necessary, after installation can improve delivery efficiency and, therefore, enhance leaching of salts. The effectiveness of any leaching program and development of repeated localized saturated or salinized areas within the sprinkler patterns is directly related to the distribution efficiency of the irrigation system.

Where irrigation uniformity is lacking and cannot be improved because of a poor irrigation system, the use of portable hose end sprinklers or soaker hoses can be effective methods to distribute additional water onto areas lacking adequate coverage. Ultralow precipitation rate or variable adjustable flow models are most effective. They are normally placed in the problem area and allowed to operate from dusk until dawn.

Site-specific water management is important for salinity management and to avoid waterlogged areas. Some examples are the following:

1. Dual irrigation systems for greens and the surrounds. The ideal system would include the ability to irrigate greens with a different higher-quality (lower-salinity) water source, but dual systems, even with the same water source, allow for better scheduling and distribution efficiency.
2. Mounds, “berms,” steep slopes, and bunker tongues present a problem, because these are high-moisture flux areas. West- and south-facing exposures in the Northern Hemisphere are especially vulnerable to high ET losses and salt accumulation. On facilities with highly saline irrigation

water, irrigation designers should consider how to provide adequate water on these peripheral areas.

3. On fairways, south-facing slopes (Northern Hemisphere), where ET is normally greater, should be zoned to allow such areas to be irrigated adequately.

Ideally, individual sprinkler control where one station operates one sprinkler should be considered when highly saline irrigation water is used. Portable sprinklers can also be used effectively to specifically leach putting green surfaces and avoid flooding bunkers or saturating green surrounds and aprons during the leaching process (Gross, 1999).

11.7.2 IRRIGATION WATER APPLICATION METHOD

A highly efficient irrigation system design with good zoning is a priority for effective leaching of salts. However, the method of water application, even with a well-designed system, strongly influences the quantity of water for effective leaching (Hanson et al., 1999; Rhoades and Loveday, 1990). A review of the “k” factor (determined by irrigation method and soil type) in the reclamation leaching formula illustrates the importance of the water application regime (Table 11.3). Potential means to apply water for reclamation or maintenance LR needs are (1) heavier applications that favor saturated flow of water into and through the soil profile, or (2) by lighter-volume applications, especially in repeated cycles or pulses, that result in unsaturated flow and minimize runoff.

Heavy, continuous water application by sprinklers where the soil is essentially saturated or near saturation throughout the leaching period would be similar to soil conditions that may occur from **heavy rainfall or continuous ponding/flooding** of water above the soil surface. Water application by any of these methods requires the most water to achieve leaching, especially on fine-textured soils. Under **saturated flow** or near saturated soil conditions, water flow is primarily through the larger macropores and water does not effectively leach between the macropores, that is, within soil aggregates or micropore areas. On high-sand-content soils, which do not form aggregates but have more single grain sands in the structure, saturated flow works better than on fine-textured soils for salt leaching. However, if the high-sand-content soils have a high organic content in the surface zone or contain an appreciable volume of sand substitutes (calcined clays, diatomaceous materials, zeolites, etc.) to significantly increase the total and micropore space (porosity) volumes, these soils will also require higher quantities of water for leaching.

Heavier applications of irrigation water that result in saturated surface soil moisture conditions will foster greater runoff and uneven distribution of water over the landscape with more excessively wet and dry spots. Also, saturated flow favors development of “finger flow” or “preferential flow” conditions within areas with more macropore channels. Both runoff and preferential flow within a soil would obviously adversely affect salinity leaching across the landscape, but also results in very inefficient use of water from a water use efficiency or conservation standpoint.

Under conditions of saturated flow, it is likely that wetting agents would not have much effect in creating a more uniform wetting profile.

In **pulse irrigation** (also called **cycle and soak**), water is applied in increments generally in the range of 0.20 to 0.33 in. (5.1–8.4 mm) with a time interval before the next pulse, and this cycle is repeated until the desired total quantity of water is applied. Each cycle limits the quantity of water to avoid runoff and saturated surface conditions. Instead, the surface soil moisture conditions result in unsaturated infiltration and percolation of the applied water, where water moves as a more uniform wetting front across both macropores and micropores. Runoff from the soil surface is minimized, and uniformity of application is maximized. The pulse irrigation method simulates a light, continuous rainfall that applies water at less than the soil's saturated infiltration rate. Such rainfall events are very effective in salt leaching. Pulse regimes of applying water are very effective and efficient in leaching salts. Normally only one quarter to one half the water is required for pulse irrigation compared to heavy continuous irrigation; that is, it takes 2–4 times as much water to leach to the same degree using heavy application than would be used with the pulse method.

Pulse irrigation is also a very water-use-efficient means of water conservation even on sites without salt deposition and soil accumulation issues. A deeper, less frequent irrigation regime by pulse irrigation for enhancing water use efficiency and salt leaching can:

- Allow the maintenance of viable roots deeper in the profile to take advantage of any water that moves deeper into the soil from precipitation, whereas a shallower zone of irrigation water penetration by lighter applications can result in root pruning. Root pruning may appear to allow salts to be leached rapidly below the lower root zone, but these salts would accumulate in a relatively shallow zone that could quickly rise back into the root zone.
- Result in salt movement deeper into the soil compared to either light, frequent irrigation or heavy events that result in primarily saturated flow.
- Allow for more opportunities to take advantage of precipitation events, and thus allow canceling or delaying irrigation events.
- Reduce runoff and eliminate many excessively wet and dry areas.

Thus, pulse irrigation is both a good water use efficiency/conservation strategy and a good salt-leaching protocol. A question that often arises in arid regions is, how deep and how infrequent? As an example, assume that the full root zone is recharged to field capacity on a Bermuda grass fairway with a 2.0 ft (0.61 m) deep root system and a fine-textured soil. During dry down, the water is extracted from the surface zone first and then progressively moves downward. By the time that water is extracted to <50% field capacity in the surface 1.0 ft (0.30 m) of soil, the turfgrass may be exhibiting a growth rate that is too slow for recovery from wear or may even be showing some drought stress symptoms; yet the lower root zone may be at 75–95% field capacity. Thus, the controlling factor for irrigation is when the surface soil and turfgrass conditions require irrigation for the use of the grass on the site. In this case, sufficient water would be applied by the pulse regime to recharge the surface 1.0 ft (0.30 m). During the next one or two dry-down cycles, the deeper 1.0 ft of soil would gradually dry to a point that it would require recharging. This particular irrigation cycle would require more water and perhaps two nights of pulse irrigation to achieve the quantity of water needed for effective leaching of salts on the site. With the foregoing example, if the irrigation water was saline, the LR fraction would cause a net downward flow of water; and the lower soil profile should not be allowed to dry too much—perhaps to about 75% field capacity before recharging. The point of this discussion is to emphasize that **neither efficient water conservation nor salt leaching can be accomplished without a significantly wider adaptation of pulse irrigation regimes.**

Generally, the time interval between pulses is 0.5 to 1 hour (sands), 1 to 2 hours (loamy sands, sandy loams), 2 to 4 hours (loams), and 3 to 6 hours (clays). Sometimes, when the soil has a low surface infiltration rate and the quantity of total water is relatively high, the pulsing strategy can be accomplished over several nights—it does not have to be limited to a single night application. In reclamation leaching situations in which pulsing may be conducted over several consecutive nights, temporary traffic control may become necessary to minimize potential rutting and compaction of saturated native soils, particularly in fairways and roughs and when golf carts are not restricted to cart paths. A good surface cultivation program to maintain adequate water infiltration without runoff will reduce the time between irrigation pulses and may allow a higher quantity of water per pulse application.

As noted for pulse irrigation, water flow within the soil is primarily as unsaturated flow, which moves as a more uniform wetting front downward through the soil profile. Water movement occurs more in the micropores than in the macropores; therefore, leaching is more effective because soluble salts in the micropores will move with the water. Wetting agents often aid in maintaining a more uniform wetting front for leaching under a pulse irrigation regime.

11.7.3 CULTIVATION AND DRAINAGE

Infiltration, percolation, and drainage of applied water are essential for salt leaching. The site-specific soil profiles on a golf course or other recreational turfgrass areas should be assessed in terms of any barriers to water movement, starting with infiltration. Carrow and Duncan (1998) present the most common soil physical problems on sandy and fine-textured soils that impede water movement downward though the whole profile. Appropriate cultivation, soil modification, and drainage operations should be conducted to ensure that water and salts are moveable. Drainage and salt disposal options should also be considered as part of an overall water management plan (Carrow and Duncan, 1998).

A good cultivation program is a necessity on sites with saline irrigation water in order to maximize infiltration, percolation, and drainage. All cultivation devices perform at least one task, which is to create temporary macropores—some are small macropores whereas others are very large, depending on the device. Adequate macropores are especially important at the surface in order to allow adequate infiltration of water. Even with pulse irrigation, it is important to allow as large a "pulse" quantity as possible before the surface starts to saturate. Also, an adequate number of macropores throughout the root zone soil profile allows more efficient capture and movement of natural precipitation. Essentially, cultivation is used to allow for better irrigation programs both from the water use efficiency and salt management standpoints.

On high-sand-content greens, the surface 1 to 2 in. (25–50 mm) zone is where water movement rate is generally the least. If a good maintenance LR program is followed so that salts have not been allowed to accumulate in the surface, periodic surface cultivation to maintain vertical "macropores" or holes across this zone is beneficial to allow rapid water infiltration during heavier rains. Green et al. (2001) demonstrated the effectiveness of cultivation to enhance infiltration rates on golf greens even in very arid climates in terms of salinity leaching. However, if salts are allowed to accumulate at the surface to the point where a reclamation leaching program is necessary and leaching is attempted by heavy irrigation volume application, cultivation may result in poor salinity leaching between the cultivation holes at the surface. Areas immediately surrounding open aeration holes become damaged and are subject to brown discoloration from irrigation water salt desiccation. Cultivation will not hinder salt leaching if a pulse irrigation regime is followed, because the whole surface area is subjected to slow water infiltration and percolation and not just in the aeration holes.

On fine-textured soils, when salts accumulate in the surface zone or deeper in the root zone to a point where reclamation leaching is required:

1. A good surface cultivation program is necessary to allow rapid infiltration and is effective in breaking surface tension that may result from high total salt accumulation at the surface, which usually occurs with capillary rise of salts from below the surface.
2. Deep cultivation is needed to allow water percolation; also, this strategy will allow water penetration during heavy rains.
3. Additional drainage, such as through tile lines, may be needed to keep the salts moving away from the root zone. Additionally, this cultivation program strategy will help promote some evaporation from the soil/turfgrass canopy and hopefully minimize problems with surface pathogen and algae/moss buildup.

11.7.4 SAND-CAPPING

Sometimes, regardless of a good cultivation program, soil conditions are such that even a pulse irrigation regime is not effective. Some very fine-textured soils have very low infiltration and percolation rates; and if these soils are 2:1 clays and have become sodic, infiltration rates are even lower, such as on marine clays. At other times, the soil may be very shallow, such as a shallow layer of decomposed granite over an impervious caliche layer. In these cases, sand-capping may be necessary to a depth of 3–8 in. (7.6–20.3 cm), depending on the severity of the problem and quality of the irrigation water. Sand-capping may be accomplished during construction, by renovation, or by topdressing over several years, where it normally requires at least 3 years of topdressing to achieve a 1–2 in. (25–50 mm) sand layer to see some positive grass performance results. With a sand layer, there is a sufficient soil zone to infiltrate and hold water until it can percolate to allow a pulse irrigation regime. This high-sand zone is resistant to compacting forces and sodic-induced breakdown of soil structure, while being relatively easy to leach within the added sand zone.

At the interface of the sand-cap and underlying soil, it is essential to develop a cultivation program that will penetrate through this interface. Also, high levels of gypsum may be applied on the top of the fine-textured soil prior to sand-capping in order to help alleviate sodic conditions at this interface and minimize the capillary movement of salts from the lower zone into the sand-capped zone. For areas with decomposed granite that have been crushed for a "topsoil" that may be over a hard zone of uncrushed decomposed granite or caliche, shattering this hard layer would be beneficial in order to create some channels for deeper water penetration. The authors understand that some turfgrass managers have used the Blec Groundbreaker® with sand injection capabilities to both break up hard layers and inject sand to enhance leaching capabilities.

11.7.5 Soil and Water Amendments

Water and soil amendments to ensure good water infiltration and on sodic sites to facilitate alleviation of sodic conditions are another consideration. The various situations requiring irrigation water treatment have been discussed by Carrow et al. (1999) and Carrow and Duncan (1998) (also see Chapter 12). Proper amendment selection (for water and soil), application method, and rates are all very important, especially when sodic conditions may occur or are already present. Aggressive gypsum treatments with surface treatments of primary importance are required if the irrigation water can cause sodic soil conditions. As noted when discussing maintenance and reclamation leaching, wetting agents can often help with salt leaching if they enhance infiltration of water and a more uniform wetting front under unsaturated flow conditions. However, treatment of irrigation water or the soil with amendments will be ineffective for alleviating salt problems unless a good leaching program is followed. You must adopt a whole systems approach when dealing with salts and their management.

11.7.6 Accurate Determination of Total Irrigation Requirement

As noted previously, accurate determination of the **total irrigation water quantity (total irrigation quantity, TIQ)** is important to ensure sufficient irrigation is applied to meet ET replacement across the landscape and allow salinity leaching. In Chapter 10, the concept of distribution uniformity (DU) was presented as well as the DU_{LQ} (see Chapter 10, Section 10.3.3) concept. Distribution uniformity of the lower quarter was shown to vary from 50 to 90% in golf courses in California in a study by Kah and Willig (1993). The DU_{LQ} is often used to adjust irrigation quantity for the effects of nonuniformity of an irrigation system. The run time multiplier (RTM) is used to adjust the number of minutes that a system will run to achieve the TIQ, where the RTM is related to the DU_{LQ} by (Irrigation Association, 2005):

$$RTM = 100/DU_{LQ}$$

where

RTM = run time multiplier (dimensionless)

DU_{LQ} = distribution uniformity based on the lower quarter and is a measure of the distribution uniformity of the system.

For DU_{LQ} of 50 and 90%, the RTM would be 2.00 and 1.11, respectively. Thus, if the soil moisture replacement lost by evapotranspiration (ET) is 0.80 in. (20.3 mm) and the leaching requirement (LR) is determined to be 0.12 in. (3.0 mm) of irrigation water, then the RTM can be used to determine a TIQ that would account for nonuniformity of the irrigation system by:

$$TIQ = RTM\ (ET + LR)$$

In the example given, the TIQ would be 1.84 in. (46.7 mm) or 1.02 in. (25.9 mm) of water for the RTMs of 50 and 90%, respectively. Most often, in irrigation system controllers, the number of minutes of run time to apply ET + LR is determined and then multiplied by the RTM to achieve the same results as those obtained earlier. Turfgrass managers are strongly encouraged, however, to think in terms of "quantity of water applied" rather than "minutes of irrigation time." Salt leaching requires an adequate quantity of water based on salinity load in the irrigation water, and only by monitoring the quantity of applied water can there be sufficient confidence and science-based decision making for achieving long-term effective maintenance leaching.

Leskys et al. (1999) noted that low LFs could be used for salinity control if the irrigation distribution was optimized. The foregoing example illustrates this point, that is, that irrigation distribution uniformity has a major influence on the total irrigation quantity required for maintenance leaching. The majority of the TIQ comes from ET and RTM, and not LR. Note that for the two examples where RTM values were dramatically different, LR does not change. This is also the case with ET, whether during a high-ET demand period or a weather period with lower daily ET demands, the LR does not change—but daily or weekly ET can significantly change. The **take home lesson** is that for both high water use efficiency/conservation (regardless of good or poor water quality) and effective salinity management using a maintenance leaching program:

- ET replacement requirement must be accurately determined on a site-specific basis, that is, within small microclimate zones and ideally at the single irrigation head basis.
- Irrigation uniformity is critical to reduce total water use.

11.7.7 SALINITY MONITORING

For maintenance and reclamation leaching, the emphasis is on total soluble salts and their removal, and over a longer time period, a reduction in Na on CEC sites and as sodium carbonate in the soil. Normally, a site contains an array of soluble salts. If a leaching program is effective and no rain occurs, the soil salinity (expressed as EC_e) will be similar or slightly higher than the irrigation water salinity (EC_w). If rainfall has occurred prior to soil sampling, the soil salinity may be lower than the irrigation water quality. If the only irrigation water is going on a site, then the soil salinity level at the surface will not be better or have a lower EC_e than the irrigation water. This is the basis for using threshold EC_e for the grass on the site as the target level to maintain soil salinity by leaching. Thus, monitoring total soluble salts in the soil surface and by soil depth is the best means of monitoring the success of a salinity management program. Additional information on salinity monitoring can be found in Chapter 4.

Although total soluble salts within the soil, as indicated by soil EC_e, is the best means of assessing leaching effectiveness, good **indicator ions for the effectiveness of leaching programs** are Cl and SO_4. If the water quality test and soil tests indicate that Cl or SO_4 are the dominant salt ions, the water required for leaching these ions is somewhat less than for other soluble salts owing to their high mobility. If these two ions are consistently in the soil solution at levels above the base levels in the irrigation water, this is a good indication that the leaching program is not very effective. Assuming no rainfall, these two ions in the soil should be similar to those in the irrigation water levels. These ions may be reported in a routine soil test.

Sometimes, a turfgrass manager who is acidifying irrigation water to remove bicarbonates so that a Ca amendment can be added to displace Na, which then must be leached, may express concern over the accumulation of SO_4 from the acidification treatment, that is, because this ion could contribute to black layer formation under anaerobic conditions. If the SO_4 is accumulating in the soil above the base level in the treated irrigation water, then the leaching program is not adequate, nor will the expected benefits of acidifying and Ca amendment programs be achieved. Leaching is the most important component of salinity management, and if it is not accomplished, regardless of predominant salt ions in the irrigation water, the other management practices will not make up for inadequacies in this area.

11.8 SUMMARY

Development of a salinity management leaching program requires a holistic approach with consideration of a number of soil, water, and grass factors. It must be emphasized that leaching of salts is the most important component of any salinity management program. Unless salts are consistently leached from the root zone, resalinization will occur from continued irrigation water salt additions and from upward capillary movement from below the root zone. The "peak time of year" for massive resalinization and the accompanying decline of turfgrass performance is often mid to late summer. This is the least favorable time for salinity stress and the most difficult time to institute reclamation leaching. The best option for managing salinity is a continuous, routine maintenance leaching program using an adequate LR. The most common reason for not applying sufficient irrigation water volume for leaching of salts is to underestimate the daily ET requirement for replacement of soil moisture lost by ET as well as to not account for nonuniformity in the irrigation system in terms of quantity of irrigation water to apply, rather than to underestimate the LR fraction of total irrigation water needed to move salts.

Also, it is important to understand that many of the scientific principles outlined in this chapter were initially developed for annual agricultural crop production situations in which daily equipment and pedestrian traffic, maintenance of a perennial grass playing surface, and continuous need for low mowing heights are not an area of concern. Therefore, the situation may occur where the outlined procedures cannot be implemented without compromising playing conditions or where implementation of other management programs (deep cultivation, traffic restrictions and control, course closure) might be limited, required, or not be completely effective.

12 Water Treatment for Specific Problems

12.1 OVERVIEW OF WATER TREATMENT

Water treatment is a complex subject. In this chapter, the focus will be on irrigation water issues and treatment approaches to common problems except those related to irrigation lake or pond storage, which are covered in Chapter 14. Irrigation water problems may confront the turfgrass manager at different points within the spectrum of water transfer, that is, at the initial source location; at the onsite storage; in the delivery system; during application onto the turfgrass plant and into the soil profile; and following application interacting with the surface or subsurface hydrology. Many of these problems can be addressed with various water treatment options. Resources specifically dealing with farm or landscape irrigation water quality and possible treatments are provided by Ayers and Westcot (1994), AWA (2000), Provin and Pitt (2003), Luke and Calder (2005), and Yiasoumi et al. (2005).

Because large turfgrass sites may require considerable irrigation water to be treated when a quality problem occurs, water treatment information targeted to drinking water users of smaller systems or water treatment in general may be of interest when exploring an issue. Crittenden et al. (2005) provide an extensive discussion of water treatment in general. The National Drinking Water Clearinghouse Fact Sheet series (NDWC, 2008) has online Tech Brief fact sheets on a number of water-treatment-related topics (Table 12.1). These are not specific to irrigation, but are targeted to small water treatment operators, and much of the information is applicable to irrigation situations. The USEPA Municipal Technologies for Wastewater Treatment Web site (USEPA MT, 2008) also has considerable information and fact sheets on various treatment technologies (Table 12.2).

System clogging is one of the primary problems that may require treatment. Clogging of pumps, irrigation lines, or nozzles can result from chemical precipitates, physical materials, and biological materials (Luke and Calder, 2005). As clogging issues are rather diverse, each specific problem will be discussed in the section related to it. However, as an overview, potential clogging problems are as follows:

- Chemical precipitation clogging problems—$CaCO_3$ or $MgCO_3$ or bicarbonate complex compound equivalents, $CaSO_4$ or gypsum, heavy metal hydroxides/oxides /carbonates/silicates/sulfides, or fertilizers (phosphate and its complexes, aqueous ammonia, iron/zinc/copper/manganese compounds).

- Biological clogging problems—Filaments, leaves, slimes, algae, microbial deposition from excess iron/sulfur/manganese, bacteria, or small aquatic organisms (freshwater clams, snail eggs, larva, mollusks).
- Minerals—Sand, silt, or clay in the water supply.

TABLE 12.1
The National Drinking Water Clearinghouse Fact Sheet series on water treatments

- Basic water and wastewater formulas
- Chlorination
- Corrosion control
- Disinfection
- Filter backwashing
- Filtration
- How to operate and maintain manganese greensand treatment units
- Ion exchange and demineralization—Natural organic materials and synthetic organic chemicals might be present in water supplies, especially from surface water sources, causing taste, odor, or color problems in a community's drinking water
- Iron and manganese removal
- Lime softening
- Membrane filtration—A semipermeable membrane is a thin layer of material capable of separating substances when a driving force is applied across the membrane. Once considered a viable technology only for desalination, membrane processes are increasingly employed for removal of bacteria and other microorganisms, particulates, and natural organic material, which can impart color, taste, and odors to water and can react with disinfectants to form disinfection by-products
- Organic removal
- Ozone
- Package plants
- Slow sand filtration
- Taste and odor control turbidity control
- Ultraviolet disinfection valves
- Water treatment plant residuals management

Source: NDWC. 2008. National Drinking Water Clearinghouse. Tech Brief Fact Sheet Series on various water treatments. Hosted on the National Environmental Service Center Web site. http://www.nesc.wvu.edu/techbrief.cfm.

TABLE 12.2
The USEPA Municipal Technologies for wastewater treatment site

- Conventional wastewater treatment and collection systems
- Combined sewer overflow treatment and control
- Storm water treatment and management
- Biological treatment processes
- Physical/chemical treatment processes
- Advanced treatment processes
- Conventional biosolids treatment and reuse procedures
- Biosolids technologies
- Disinfection and odor control
- Alternative collection systems
- Decentralized treatment systems, including on-site systems
- Application of effluent and biosolids
- Constructed wetlands
- Wastewater reuse

Source: USEPA MT (2008) fact sheets on various treatment technologies. http://www.epa.gov/owm/mtb/index.htm.

12.2 WATER ACIDIFICATION

Acidification of irrigation water is an area of confusion for many turfgrass managers, and a number of questions arise: What are the reasons for acidifying water? When should water be acidified? What methods of acidification should be used? What acidifying products should be used? These important questions have pros and cons for consideration. When considering acidification, the specific issue requiring acidification of the water or soil (with water acidification as a method to reduce soil pH) must be identified, and then options can be considered in terms of cost of equipment, chemicals, timing (frequency of irrigation lake turnover), and labor.

12.2.1 Moderate-to-High Na and High HCO_3/CO_3

One situation that actually requires acidification as a primary management practice is the combination of moderate-to-high sodium (Na) plus high bicarbonate (HCO_3) or carbonate (CO_3) content in irrigation water, where the bicarbonate and carbonate react with Ca and Mg to precipitate insoluble lime ($CaCO_3$, $MgCO_3$). Under these conditions, even moderate levels of Na can cause sodic soil formation with structural deterioration and, therefore, eventually reduce the water infiltration rate. Even in cases where the irrigation water contains little Ca or Mg, high levels of HCO_3/CO_3 in the irrigation water will react with any soluble Ca/Mg in the soil to precipitate lime. This reaction greatly reduces the effectiveness of applied gypsum or S-source plus lime (to create gypsum) by reacting with soluble Ca/Mg released from these amendments to form less soluble compounds, and which are often microlayered in the upper soil profile. This chemical action will leave excess soluble Na to increase the ESP (exchangeable sodium percentage) on the soil CEC sites without soluble Ca or Mg available to inhibit or counter this Na accumulation process.

Red flag values indicating that acidification may be needed are irrigation waters with >2 meq/L (122 ppm) bicarbonates in combination with (1) > 2 meq/L (40 ppm) calcium and/or >2 meq/L (25 ppm) magnesium; (2) > 4.35 meq/L (100 ppm) Na; and (3) a RSC >1.25 meq/L. These red flag levels are just indicators that the irrigation water source and specific site conditions (soil type, type of clay, uniformity of soil profile, rainfall patterns, topography, etc.) should be carefully assessed as to potential long-term problems that may arise from continuous and excess Na accumulation. Irrigation water would then normally be characterized by a high adjusted SAR_w ($adjSAR_w$) that would be considerably greater than the unadjusted SAR_w value. The $adjSAR_w$ takes into consideration the presence of HCO_3/CO_3, and when these compounds are high, the $adjSAR_w$ increases relative to the unadjusted SAR_w value.

When the combination of factors noted in the previous paragraph occurs, acidification of irrigation water that evolves the HCO_3 and CO_3 off as CO_2 gas would be highly desirable because (1) the Ca and Mg ions in irrigation water remain soluble because there are fewer HCO_3 and CO_3 ions to react with; (2) the Ca and Mg ions can then help to displace Na from the soil CEC sites; and (3) fewer HCO_3 and CO_3 ions are added to the soil, which allows soil-applied Ca amendments to be more effective in producing relatively soluble Ca that is potentially available for turfgrass root absorption, rather than precipitating as lime and remaining unavailable and insoluble. More soluble Ca and Mg can also contribute to the plant nutritional requirements for these nutrients, and in the case of Na root toxicity, higher available Ca levels counteract the Na stress. Because the RSC value is a measure of the balance between bicarbonate plus carbonate and Ca plus Mg levels, these data are useful in assessing the potential for lime formation, and readers are encouraged to review Section 3.4.2 (Chapter 3) to understand how RSC values can be used to determine the quantity of acid to remove most of the bicarbonate and carbonate ions.

12.2.2 MODERATE-TO-HIGH NA PLUS CALCAREOUS SOILS

When managing sodic soils or attempting to prevent formation of sodic conditions, gypsum is often applied to provide a relatively available form of Ca: gypsum acts as a slow-release form of Ca and is more soluble than lime. However, gypsum can be formed in the soil by using a S source plus a lime source, where these two sources slowly react to form gypsum in the soil. If a soil is already moderately to highly calcareous (>5% free calcium carbonate content), the free lime can act as the Ca source, but it must be acidified by a S source to form gypsum. Some of the S could come from granular applications of elemental S, which would undergo microbial transformation to H_2SO_4, which then reacts with the lime. Ammonium sulfate fertilizer is another potential S source for this reaction. However, S applied through the irrigation water, normally in the SO_4 form, is also another means of generating gypsum if lime is present. If fact, when acidifying irrigation water, one means of "scrubbing out" excess SO_4 from the irrigation water (so that high levels of SO_4 do not occur in the soil) is to apply light applications of lime at the soil surface to react with the SO_4 from the water to form gypsum (see Section 12.2.7). In this case, the lime is periodically applied to the surface so that a constant supply of gypsum would form in the soil to reduce the potential for black layer problems.

In the case of natural calcareous soils, the free lime can also react with SO_4 to create gypsum. However, in this situation, the soil surface supply of free lime may eventually be depleted, thereby resulting in Na dominating in the surface zone without the counterion of Ca from gypsum dissolution because the gypsum would form only where the lime is located. Sometimes in arid regions, a calcitic layer is present several inches below the soil surface. Acidification of irrigation water may contribute to slow dissolution and softening of the calcitic layer over a long period of time, but little of the Ca would be at the soil surface for alleviation of sodic conditions (countering excess accumulated Na).

12.2.3 HIGH CA/MG; HIGH HCO_3/CO_3; LOW NA

Sometimes irrigation water contains unusually high Ca/Mg and HCO_3/CO_3 concentrations, but Na is absent or at low levels. As the HCO_3/CO_3 react with Ca/Mg, insoluble lime ($CaCO_3$, $MgCO_3$) precipitates, often at the surface 1 cm of a bare soil or at the depth of irrigation water penetration on irrigated sites with a turfgrass cover. In arid environments, there is sometimes concern that lime deposition in the soil profile from the irrigation water may cause sealing over time (Carrow et al., 1999). Calcite-induced sealing would differ from Na-induced deterioration of soil physical conditions. The question can arise as to whether irrigation water acidification is necessary in the case of high Ca/Mg and HCO_3/CO_3 concentrations, but low Na.

As an example of the quantity of calcite deposition, we assume high concentrations of all components and that all materials react to form $CaCO_3$ or $MgCO_3$, such as:

- 200 mg/L Ca = 200/20 = 10.0 meq/L Ca
- 40 mg/L Mg = 40/12.2= 3.3 meq/L Mg
- 811 mg/L HCO_3=811/61 = 13.3 meq/L HCO_3

To calculate the quantity of Ca and Mg in an acre-foot (325,851 gal) of irrigation water, the quantity of each element in mg L^{-1} (ppm) is multiplied by 2.72 (Table 5.8; Carrow and Duncan, 1998).

- 200 mg/L Ca × 2.72 = 544 lb Ca/acre-foot of irrigation water
- 40 mg/L Mg × 2.72 = 109 lb Mg/acre-foot of irrigation water

These values are equivalent to formations of 1700 lb per acre-foot $CaCO_3$ (32% Ca) and 404 lb per acre-foot $MgCO_3$ (27% Mg). Combined, the total would be 2104 lb $CaCO_3$ + $MgCO_3$ per acre-foot of water; or 48 lb per 1000 ft^2 per 325,851 gal irrigation water applied.

If we assume an arid climate in which most water is by sprinkler irrigation at 1.0 in. (25 mm) per week and a 12-month growing season:

1.0 in. × 52 weeks = 52 in. (1300 mm) water = 4.3 acre-feet (~1.4 million gal).

Thus, (4.3 acre-feet) (48 lb calcite per 1000 ft^2 per 12 in. irrigation) = 206 lb calcite/1000 ft^2 deposited per year.

For a "worst-case situation" we will assume that all calcite is deposited in the surface 0.25 in. (6.25 mm); but actually much of the calcite would be more likely to precipitate at the depth of routine irrigation water movement (depth of the wetting front).

Because an 8 in. (200 mm) acre-furrow slice of soil weighs 2,000,000 lb, a 0.25 in. "slice" weighs 1435 lb per 1000 ft^2. The 206 lb calcite would represent about 14% by weight of the total, assuming all calcite was within the surface 0.25 in. zone, but only 0.01037% of the 2,000,000 lb acre-feet furrow slice. Thus, this quantity of calcite is sufficient to cause at least some sealing of the surface profile if all calcite was localized at or near the surface, but with any dispersion throughout the entire soil profile, it would be much less likely to cause pore-sealing problems. To observe any significant calcite accumulation in a zone that might cause some reduced infiltration or percolation, the following set of conditions would have to be satisfied:

- Sand soils with limited particle size surface area would be more susceptible than fine-textured soil.
- Irrigation water with unusually high HCO_3 and high Ca/Mg concentrations.
- An arid climate in which high irrigation water use would result in considerable annual additions of calcite.
- Reliance on light, more frequent irrigation events rather than less frequent and deeper (higher-volume) applications. Light, frequent irrigation applications would favor deposition of the calcite at the soil surface under high-ET conditions, whereas deeper but less frequent irrigation applications would favor calcite deposition near the depth of the wetting zone (normal irrigation water penetration).
- A long growing season, including a winter cool-season grass overseeding period, which would result in high total water use and calcite deposition over an entire year.

In semiarid or humid regions, calcite accumulation at the soil surface would be less likely because the rainfall (i.e., low ECw, HCO_3, Ca, Mg, often acidic pH) would tend to dissolve the calcite or at least move it deeper and increase its dispersal throughout the soil profile. Also, annual additions of calcite would be reduced because irrigation would be less frequent.

When the foregoing combination of conditions favors calcite accumulation within the soil surface zone, would acidification of irrigation water be a solution?

The answer is yes, but it is not necessarily the best solution, especially when considering that acidification would need to be carried out 24/7 in order to continually remove the HCO_3/CO_3. Also, on a golf course, only the sand-based greens may show a decrease in infiltration, whereas more fine-textured soil areas might display a much slower or only minimal reduction in infiltration rates. Treating the irrigation water for the entire golf course would not be necessary, but water treatment for the greens would be a definite consideration, especially if the greens are zoned separately from surrounding areas in the irrigation cycle. In contrast, the problem of high HCO_3 with high Na causes sodic conditions that adversely affect all soils; therefore, acidification of the water for all areas of the golf course throughout the growing season would be important for minimizing this problem. Additionally, a calcite layer is essentially a physical barrier to water infiltration; it could be broken by periodic regularly scheduled cultivation. Or, the use of acidifying fertilizers such as $(NH_4)_2SO_4$, or judicious application (<3 lb/1000 ft^2) of elemental S to the turfgrass surface would aid in dissolving any distinct calcite layer by changing it into more soluble and mobile forms such as gypsum ($CaSO_4$) and $MgSO_4$.

As it is not unusual to add 25 to 50 lb of $CaCO_3$ (lime) per 1000 ft^2 to turfgrasses growing on acid soils, the question could arise as to how lime additions may differ from lime precipitation from the irrigation water. When limestone is applied, discrete particles rather than a sheet-like layer is deposited at the soil surface, which is similar to what occurs with irrigation water source applications. Calcite coatings can form on particles (especially sands with their small surface area and low CEC) and start to bridge between particles under conditions of high calcite formation, resulting in filled pores (reduced pore space). This could create problematic air and moisture flux conditions under which the soil surface would seal and cause reduced water infiltration/percolation. Natural caliche soils certainly exhibit calcite layers where water movement is decreased, so a similar situation could occur on a "micro" scale within the surface 1 or 2 cm if all calcite remained in this zone. However, just as added limestone slowly dissolves and moves in soils, calcite initially deposited at the soil surface will exhibit some dissolution and will generally reprecipitate deeper in the soil.

12.2.4 Moderate-to-High Na and Low HCO_3/CO_3

Another potential irrigation water quality situation is when Na is moderate to high but the HCO_3/CO_3 concentrations are low with an RSC of <0 meq/L. In this situation, the HCO_3 and CO_3 ions are not sufficient to precipitate Ca or Mg and are not contributing to high soil levels of HCO_3 or CO_3. Thus, acidification to remove HCO_3/CO_3 would not be warranted.

12.2.5 Water Acidification for the Purpose of Acidifying the Soil

Normally, when soil acidification is considered, turfgrass managers think of using elemental S or an acidifying N-carrier such as ammonium sulfate. However, acidification of irrigation water is also a means of delivering excess H ions to the soil for the purpose of reducing pH.

Essentially any reason to acidify soil or irrigation lines could be used as a justification for irrigation water acidification. These include the following:

- Soil pH reduction to improve nutrient availability. For example, pH >8.5, and especially above 9.0, can impact uptake of micronutrients and also affect microbial breakdown of some fertilizer compounds. Reducing soil pH below 8.0 can improve availability of nutrients for turfgrass uptake. Note that pH <5.0 can also negatively affect microbial populations and lead to nutrient toxicity (Al and/or Mn) and eventually result in soil and turfgrass nutritional imbalances.
- Reduce pathogen populations, for example, reducing soil pH to below 6.5 to suppress take-all (decline) disease problems. The effectiveness of this strategy depends on whether the soil has sufficient Mn that becomes more soluble under acidic conditions to assist in suppressing the organisms.
- Improve leaching of boron in the soil.

As there are other options for acidifying the soil, the turfgrass manager should consider the cost-effectiveness of these treatments. One factor to consider is that for soils without free calcium carbonate, soil pH will decrease with relatively low inputs of elemental S, acidifying fertilizer, or acidic irrigation water. Once the target soil pH is reached, further acidification is not desirable, so for the water, acidification equipment may not be required after this point. If the soil is buffered with >1–2% free calcium carbonate, it requires considerable acidification before any permanent pH change is observed; that is, the free calcium carbonate must be dissolved before actual soil pH declines on a permanent basis. In such cases, it is not cost-effective to attempt pH reduction, because the benefits do not warrant the cost, and there are alternatives to balancing any nutrient problems that may be present at the higher pH (Carrow et al., 2001).

As noted in Section 12.2.3, when the irrigation water is contributing to free calcium carbonate formation in the soil due to high Ca/Mg and HCO_3/CO_3 concentrations in the water even though the Na is low, water acidification is an option (1) to reduce calcite formation by evolving off the HCO_3/CO_3 and (2) aid in dissolving any calcite as it transforms the Ca to the more soluble and mobile gypsum form. In this situation, soil pH should be monitored to prevent excessively acid conditions in the surface inch if the calcite is completely removed and more acid is being added than is needed.

12.2.6 Acidifying Products

Water can be acidified by injection of liquid acids or reaction with sulfurous gas. Sulfuric acid is no longer allowed for use in some locations owing to its dangerous and corrosive nature, but many other liquid acid products are available for injection purposes. When phosphoric or urea sulfuric acids are selected, the fertilizer value of the product must be considered. Zia et al. (2006) provide a very good review of research on sulfur acid generators and alternative acidification methods in agriculture, and Kidder and Hanlon (1998) discuss some of the agriculture issues. O’Brien

(1996), Carrow and Duncan (1998), Amrhein (2000), and Gross (2003) discuss acidification in turfgrass situations. In his article, Gross (2003) presents some cost estimates on various water treatments, including acidification.

Acidifying products for water treatment include the following:

1. Sulfuric acid addition at 133 lb 100% sulfuric acid/acre-feet water will offset 1 meq/L bicarbonate. The target is pH 6.5–7.0 and not the complete removal of all bicarbonates, because water pH would drop dramatically without any buffering from the bicarbonate and carbonates. Sulfuric acid is directly injected into the irrigation mainline similar to other acids, which allows for uniform mixing into the water stream as it moves into the irrigation system for application on the turfgrass site. However, there are safety concerns about handling concentrated sulfuric acid.
2. N-pHuric fertilizer (100 gal 15/49 contain 189 lb N; urea sulfuric acid). This product mixes urea with sulfuric acid. When mixed with urea, there is less concern about safety in handling the sulfuric acid product.
3. pHairway is also a urea sulfate acid material, but listed as a monocarbamide dihydrogen sulfate. It is injected into the irrigation line for water acidification and contains urea.
4. Sulfurous acid generation (caution when acidifying calcareous sands and oxygen scavenging resulting from water chemistry changes) (target pH 6.5–7.0). With sulfurous generators, the acidified water is normally mixed into the irrigation lake and is generally aerated to reoxygenate prior to application on turfgrass sites.
5. Phosphoric acid infusion (30–45% P_2O_5). This product is not used for long-term purposes owing to caution concerning phosphorus loading in soils.

Acid reactions in water are as follows:

$H_2SO_4 + 2HCO_3 \rightarrow 2\ CO_2 + 2H_2O + SO_4$, where the CO_2 is evolved off as gas.

$H_2SO_4 + CO_3 \rightarrow CO_2 + H_2O + SO_4$

Acid reactions in calcareous soil:

$H_2SO_4 + CaCO_3 \rightarrow CaSO_4 + H_2O + CO_2$

$CaSO_4 + \text{Na soil} \rightarrow \text{Ca soil} + Na_2SO_4$ (leachable compound)

Acid reactions in a sulfurous gas generator:

$S + O_2 + \text{Heat} \rightarrow SO_2 + H_2O \rightarrow H_2SO_3 + \tfrac{1}{2}\ O_2 \rightarrow H_2SO_4$

Some cautions to consider for acidified irrigation water use:

1. Use on calcareous sands can eventually change particle size, because these sands are softer and highly reactive to acidification. Percolation rates may

decline slowly, and some sealing of pores may occur. Compaction from high traffic can be a persistent problem.

2. If water acidification results in acidic conditions in the thatch layer (acidic thatch), reduced microbial activity may cause increased thatch accumulation.
3. Buildup of excess sulfur/sulfates that can eventually lead to black layer problems (see Section 12.2.7).

Essentially, any acid can reduce water pH and cause HCO_3/CO_3 to evolve off as CO_2 gas. With the increase in acidification of irrigation water for turfgrass sites using Na-containing water, alternative acidification products have appeared in the past few years. Noncorrosive synthetic acids have been used in the past for industrial cleaning and are now being touted for use in alkaline irrigation water treatment for golf courses. Most of these products do not reveal on the label the exact composition of the product, and to date, only testimonials are available on the use of these products. Most of these products contain a suspected nitrogen component, and the turfgrass manager does not know if the response on the turfgrass was due to the N residual or some other factor. In general, if the full contents of the product are not revealed on the label, the turfgrass manager should be cautious about using the product over the entire golf course until unbiased scientifically researched and peer-reviewed published studies have proven its utility. The long-term turfgrass use of these products is currently unknown. As has been demonstrated with other acidification products, alleviating one problem, such as excess bicarbonates, can also lead to other management problems (such as excess sulfates, nutrient imbalance responses, low pH thatch and decreased microbial populations) that require an adjusted maintenance strategy to compensate for the newly created problem.

12.2.7 EXCESSIVE SO_4 IN IRRIGATION WATER

Sometimes, irrigation water is naturally high in SO_4 ions, and reclaimed water often exhibits high levels. Also, irrigation water acidified with a SO_4-based acid or SO_3 generator will be high in SO_4 ions. One concern is that under anaerobic (low soil oxygen) conditions, high levels of SO_4 could become reduced to H_2S, FeS, or MnS compounds, which could contribute to **black layer** development. The FeS and MnS precipitates are gel-like and seal the soil, which interferes with water infiltration and percolation and further contributes to anaerobic conditions (Carrow et al., 2001). However, if the acidification is not conducted on sites with moderate-to-high Na and sufficiently high HCO_3/CO_3 levels in the irrigation water to react with Ca and Mg, then the soils will become increasingly sodic with poor soil physical conditions: low water infiltration and low aeration. Thus, removal of excessive levels of SO_4 is important to minimize black layer problems while utilizing acidification treatment of irrigation water. The normal range of SO_4 is 30–90 ppm, where 90 ppm = 1.88 lb S per 1000 ft^2 for every 12 in. irrigation water (325,851 gal).

Because an effective leaching program is important on salt-affected sites, one method of controlling SO_4 is by leaching, as it is one of the most easily leached soluble salts. However, on some sites with difficult-to-leach soils (2:1 expanding clays, caliche layers, volcanic pumice, etc.), the levels can remain high. Regardless of whether a sodic soil is easy or difficult to leach, it is beneficial to effectively utilize the SO_4 by reacting it with lime to form gypsum. This reaction can be achieved by adding lime to the soil surface periodically to react with the acidified irrigation water. Calcareous soils have free $CaCO_3$ that can serve as the lime source. However, over time, the free $CaCO_3$ at the surface may become depleted, resulting in a reduction in water infiltration rate. If this happens, lime should be applied to the surface to maintain a Ca source at the soil surface to react with the S source.

Reaction of the SO_4 plus lime creates gypsum ($CaSO_4$), which is beneficial for alleviating sodic conditions provided that leaching is sufficient to remove the Na in the form of Na_2SO_4. Approximately, 100 lb (45 kg) of lime is needed to react with every 98 lb of H_2SO_4 applied in the irrigation water. Thus, if 100 lb of H_2SO_4 were applied per acre-foot of irrigation water, 104 lb (116 kg) of $CaCO_3$ per acre would be required to react with the H_2SO_4 to form about 136 lbs/acre (152 kg/ha) gypsum. The same rates can be used for SO_4 as are used for H_2SO_4 because they are almost equal. In the case of 90 ppm SO_4 in irrigation water, this is equivalent to 245 lb of SO_4 per acre-foot of irrigation water. Thus, approximately 255 lb of lime should be applied to the surface for every acre-foot of irrigation water applied. Because the lime should convert to gypsum, the pH should remain relatively stable. This process makes positive use of any SO_4 used to treat the irrigation water by contributing to the overall gypsum requirement to remediate the sodic conditions while decreasing the quantity of free SO_4 in the soil. However, insufficient leaching could layer the Na_2SO_4 near the bottom of the wetting zone, so a regularly scheduled deep aeration program combined with a good irrigation water-leaching program should be followed as much as possible in the turfgrass management program.

12.3 CALCIUM WATER TREATMENTS

Sometimes, irrigation water is amended with Ca products. It is important to understand the situations in which this practice may be useful. Calcium may be injected in the irrigation water for three primary reasons:

- To improve water infiltration when using ultrapure irrigation water is covered in Section 12.4. Normally, >20 ppm (>1 meq/L) Ca is required for initial water infiltration in most soils.
- To add Ca for improving the available soil Ca concentrations, such as in soils with high Mg/Ca ratios, with high Na:Ca ratios, or unusually low Ca levels.
- As a means of adding Ca to alleviate or prevent sodic soils and improve water penetration. When the water has ECw 0.5–1.9 (TDS 320–1216 ppm) combined with high SAR (generally >9.0), calcium addition can improve poor infiltration problems. Calcium treatment can also be effective when soil ESP (exchangeable sodium percentage) has accumulated at 15% or greater in the soil.

For these latter two situations, Ca additions to the irrigation water are only feasible if HCO_3/CO_3 concentrations are low and, thus, their influence in complexing Ca/Mg in the water source is minimal. The added Ca to the irrigation water will then remain soluble and available to exchange or counter for excess Na and/or balance with Mg on the CEC sites.

Calcium water treatments can include soluble Ca forms such as calcium nitrate and calcium chloride dehydrate ($CaCl_2 \cdot 2H_2O$). However, the total quantity of calcium nitrate is limited to avoid excessive N application, and for $CaCl_2$, it must be diluted with sufficient water to prevent foliar burn and the rate controlled to avoid accumulation of excessive soluble salts. When $CaCl_2$ is mixed with water, considerable heat is generated, so plastic components must be protected.

Calcium materials that may be applied through the irrigation system are gypsum dihydrate (calcium sulfate, $CaSO_4 \cdot 2H_2O$), anhydrite gypsum ($CaSO_4$), and calcium polysulfide (lime-sulfur). The dihydrate gypsum dissolves more rapidly compared to the anhydrite form. Regardless of the form, the particle size must be fine, such as 98% passage through a 200 mesh screen and 100% through a 100 mesh screen. Gypsum is normally injected downstream from filtration equipment to prevent any clogging.

Examples of gypsum injectors used in turfgrass situations include the Diamond K injector (low-tech; utilizes wobble sprinkler and venture siphon with no power source needed), Ag Solution Master from Soil Solutions, and Turbo Mix from Montague/Fisher Inc. (mechanical agitation via 110 or 220 VAC, diaphragm pump). With the exception of the unique design for the Diamond K device, gypsum injectors either (1) use agitation to dissolve gypsum in a tank before injection into the irrigation line or (2) force water through a tank of gypsum to dissolve the gypsum.

Gypsum should not be injected at a rate that exceeds its solubility rate or it will remain in suspension. Although it can continue to dissolve as it moves through the pipes, suspended gypsum can cause wear on irrigation components, so it is ideal to allow dissolution before injection. In field situations, a very high rate is 14.7 meq/L of Ca, where 14.7 meq/L = 1265 ppm dihydrate = 3440 lb of pure dihydrate per acre-foot irrigation water = 791 lb Ca per acre-foot of irrigation water. However, more realistic and typical rates are in the 2.0 to 5.0 meq/L Ca range, which would be 5.0 meq/L Ca = 1170 lb of pure $CaSO_4 \cdot 2H_2O$ per acre-foot of irrigation water = 27 lb of pure $CaSO_4 \cdot 2H_2O$ per 1000 ft^2 per 12 in. of irrigation water. As a general rule, if more than 5.0 meq/L Ca is required by the soil–plant system to correct sodic-induced water infiltration/penetration problems, additional calcium sulfate is surface-applied in granular form. To alleviate or prevent sodic conditions that seal the soil surface, it is important to apply gypsum on a continuous basis so that it maintains good surface physical conditions and pulse-releases with each irrigation or rainfall.

12.4 CALCIUM INJECTION AND ULTRAPURE WATER

Ultrapure irrigation water usually occurs from snowmelt sources or from continuous high-volume rains during monsoon/hurricane/typhoon seasons or slow-moving tropical systems, but some groundwater sources may also have low EC_w. Very pure irrigation water will have a low electrical conductivity ($EC_w < 0.50$ dS/m or TDS < 320 ppm). Prolonged use of very pure water can "strip" cations and salts from the CEC sites, usually in a zone of less than 1 cm in depth from the soil surface. Regardless of SARw, this reaction results in sealing or crusting at the soil surface with subsequent reduced irrigation water infiltration as clay particles (that are normally stabilized by

Ca) become dispersed after drying. These soil structural and reduced water infiltration problems become accentuated when electrical conductivity is extremely low ($EC_w < 0.20$ dS/m or TDS < 128 ppm).

Reduced infiltration is especially noticeable on a site with limited turfgrass density or coverage, such as during germination and early seedling establishment or on areas thinned by foot/cart/equipment traffic because direct raindrop or irrigation water impact enhances crusting at the soil surface. However, this phenomenon can occasionally occur under a full turfgrass cover with excessive traffic and compaction or surface sealing. The symptoms would be exhibited by greater runoff on sloped areas than would normally be expected, slower infiltration on level sites, and slower drainage of low topography areas than normal.

The management choices for this problem include (1) increase the salt concentrations at the soil surface with periodic soil application of gypsum, phosphogypsum, or a S-source lime product. Soil-applied treatments can be used on a trial area to determine if low water infiltration is due to ultrapure water or from another cause such as soil compaction; or (2) increase the salt concentration in the irrigation water to above 0.50 dS/m or TDS > 320 ppm. Increasing dissolved Ca in low-salinity water by 1 meq/L of Ca (i.e., 234 lb of pure $CaSO_4{\bullet}2H_2O$ per acre-foot of irrigation water) will increase ECw by 0.075 dS/m. Thus, 5.0 meq/L dihydrate gypsum would increase ECw to 0.38 dS/m. If $CaCl_2{\bullet}2H_2O$ is used as the salt source, 1.0 meq/L Ca = 201 lb of $CaCl_2{\bullet}2H_2O$ per acre-foot of water would increase the EC_w by 0.075 dS/m.

TABLE 12.3

Equivalent rates of calcium salts, acids, and acid-forming amendments for irrigation water treatment (ac-ft = acre-foot of irrigation water)

Chemical name	Trade name	Pounds per ac-ft H_2O to provide 1.0 meq/L of Ca or HCO_3	Pounds per ac-ft H_2O to provide 2.5 meq/L of Ca or HCO_3	Pounds per ac-ft H_2O to provide 5.0 meq/L of Ca or HCO_3
Sulfur	Sulfur	43.6	109	218
Calcium sulfate dihydrate	Gypsum 100% pure	234	585	1170
Calcium chloride dihydrate	Calcium chloride 27% Ca	201	503	1005
Calcium polysulfide	Lime-sulfur 9% Ca, 24% S	183	458	915
Ammonium polysulfide	Nitro-Sul®	69–136	172–340	345–680
Potassium thiosulfate	KTS 25% K2O, 17% S	256–513	640–1283	1280–2566
Ammonium thiosulfate	THIO-SUL® 12% N, 26% S	110–336	275–840	550–1680
Urea sulfuric acid	US-10 N-Phuric 10/55	148–242	370–605	740–1210
Sulfuric acid	100% sulfuric acid	133	333	665

Source: From Carrow, R. N. et al. 2001. *Turfgrass Soil Fertility and Chemical Problems: Assessment and Management*. John Wiley & Sons, Hoboken, NJ, p. 153.

In situations where infiltration has been limited due to surface sealing, water infiltration can increase substantially. Some aeration events (spiking, slicing, needle tining, and hydrojecting) may be needed to break the surface tension and open the crusted surface zone so that irrigation water will infiltrate into the soil profile.

12.5 WASTEWATER TREATMENT ISSUES FOR IRRIGATION

Wastewater treatment is a vast subject with many potential treatment options (WHO, 2005; Whitlark, 2002. Normally, the turfgrass manager is not concerned about treatment on-site, but is concerned that the water is treated by the wastewater treatment facility in an acceptable manner for both short-term and long-term irrigation use. However, some types of on-site treatment may be needed at times. One area where on-site wasterwater treatment may become more common is in large developments where wastewater and/or stormwater lines are tapped as they leave the site, the water is treated for reuse for irrigation and fire protection on the site, and the by-products are returned to the sewage lines (Sydney Water, 2008). This is termed **sewer mining**.

In Chapter 8, reclaimed irrigation water was discussed in detail; in this section, some issues related to treatment strategies and the eventual irrigation end-user are emphasized. Effluent or reclaimed sewage water may undergo several levels of treatment, depending on regional, state, province, or country guidelines (USEPA, 2004). **Primary treatment** usually involves sedimentation or the removal of solids by flocculation and settling in open ponds exposed to evaporation and subsequent concentration of some water quality components, such as total salts (Crittenden et al., 2005). **Secondary treatment** is normally biological, where oxidation or ozonation is used in conjunction with additional sedimentation of primary treated water. **Tertiary treatment** can include coagulation, flocculation, clarification, filtration, and disinfection (chlorination, bromination) of secondarily treated water. **Advanced treatment** of tertiary treated water utilizes granulated carbon to remove organics and membrane filtration of microorganisms, pathogens, and spores as well as occasionally, physical barriers to remove certain salts (such as phosphorus-based compounds), and ionic decontaminants can be provided if it is economically beneficial. Denitrification may also be required for outfall disposal to a body of water (creeks, rivers, lakes, or oceans) in environmentally sensitive locations or where subsurface groundwater recharge is to be performed. Ultrasound, ultrafiltration, and ultraviolet radiation can be used in the advanced treatment process. The next level of treatment beyond the advanced level is reverse osmosis or desalinization.

A growing trend in the southwestern United States is to provide various qualities of recycled water in order to attract a customer base outside of turfgrass and landscape irrigation. This has been referred to as providing **designer water or quality-on-demand water.** An example is the West Basin Municipal Water District (WBMWD, 2008) in Southern California, which offers five different levels of treatment to industries requiring and willing to pay for the advanced recycled water treatment. The five water source grades that WBMWD offers include the following:

- **Tertiary water:** Secondary treated water that has been filtered and disinfected for a wide variety of industrial and irrigation uses.

- **Nitrified water:** Tertiary water that has been nitrified to remove ammonia for industrial cooling towers.
- **Softened reverse osmosis water**: Secondary treated wastewater pretreated by either lime clarification or microfiltration, followed by reverse osmosis and disinfection for groundwater recharge, which exceeds, most of the time, state and federal drinking water standards.
- **Pure reverse osmosis water:** Secondary treated wastewater that has undergone microfiltration, reverse osmosis and disinfection for the nearby company's or refinery's low-pressure boiler feed water.
- **Ultrapure reverse osmosis water:** Secondary treated water that has undergone microfiltration, reverse osmosis, disinfection, and second pass reverse osmosis for high-pressure boiler feed water.

Most of these treatments (an exception is reverse osmosis) do not remove excess sodium, bicarbonates, or total dissolved salts. The major reason for total soluble salt increases and Na loading into treatment facilities is Na-based water softeners from both commercial and residential properties, most notably in arid and semiarid regions of the world (Allies et al., 2005; MRWPCA, 2008). Regeneration of ion exchange water softeners produces an effluent brine solution of sodium chloride that also contains large amounts of calcium and magnesium (Wachiniski, 2005).

The usual disposal is through discharge into the sanitary sewer system, where that brine ultimately ends up diluted within the recycled water. The brine usually varies from 1.5 to 7% of the amount of water softened, and TDS usually ranges between 35,000 and 45,000 ppm. The Metropolitan Water District of Southern California estimates as much as a 30% market penetration due to water softeners throughout their service area. The MWD service area extends north from San Diego to Oxnard and east from the Pacific Ocean to Riverside to include complete and portions of six Southern California counties.

The regenerated brine can have a significant impact on recycled water quality; let us assume the following points, from local knowledge and the data already presented:

- MWD potable source waters typically range in TDS from 300 ppm (California State Water Project) to 500 (Colorado River) ppm.
- 30% of all water returned to the sewer system was treated by water softeners.
- 4.25% of softened water is brine returned to the sewer system.
- Average TDS of brine is 40,000 ppm.
- Estimated incremental increase due to salt additions via human diet, previous uses, sewerage plant treatment, etc., is estimated to be 70 ppm TDS.

The 30% portion of softened water will carry 2198 ppm TDS to the sewer system, of which 659 ppm will contribute to the final effluent:

- 4.25% × 40,000 ppm = 1700 ppm
- 95.75% × 470 ppm = 450 ppm
- Total 2150 ppm
- 30% × 2198 = 645 ppm

The 70% portion of unsoftened wastewater carries 470 ppm, and will contribute 329 ppm to the final blend (70% × 470 ppm = 329 ppm). The final recycled water product will therefore be in the range of 974 ppm. This is consistent with a study presented at the 2005 American Water Works Association (AWWA) Membrane Treatment Conference that reported recycled water TDS produced in Scottsdale, Arizona, increased in the range of 400 ppm. The source was determined to be almost exclusively (40%) sodium chloride from customer additions via water softeners. Those additions reportedly brought that final effluent to between 900 and 1100 ppm TDS and the sodium load in the recycled water being discharged onto golf courses in the 220–260 ppm range. Bicarbonates and other ions can be increased slightly above the level normally found in the initial incoming (influent) water source owing to treatment chemicals such as soda ash. Table 12.1 list several treatment chemicals that also include sodium or other salts.

Influent concentrations of total soluble salts and Na going into the treatment facility and then passed on to the reclaimed customer then becomes a primary cause for salt accumulation, soil deterioration, plant damage, and management costs to alleviate the problem at the end-user site. Thus, reclaimed water customers should consider (1) negotiating limits on the Na and total soluble salts that are passed on to them; (2) possible development of a cost-share for additional water treatment to achieve quality goals; (3) supporting additional treatment capacity to allow sufficient water for leaching of salts if total water for leaching is limited; (4) support legislation that promotes the use of potassium-based water softeners (MRWPCA, 2008); and (5) ensuring that the reclaimed water is treated sufficiently to avoid excessive N and P being passed on to the end user. If treatment facilities are depositing the effluent into public waters, they must treat that water to remove much of the P and N, but if the effluent is sold for irrigation use, the treatment facility may not be required to treat to the same degree. However, this passes the potential water quality problems of excess N and P to the irrigator. All of these issues are essentially ones to be dealt with in contracts with the treatment facility doing the actual water treatment. A number of irrigation users can come together and negotiate as a group; this is the most efficient and effective means for all concerned end users. The critical salt ions for negotiation should include sodium (<125 ppm or 5.4 meq/L), bicarbonates (<122 ppm or 2.0 meq/L), chlorides (<355 ppm or ~10.0 meq/L), and sulfates (<180 ppm or 3.75 meq/L). Calcium concentrations will need to at least equal the Na, bicarbonate, and sulfate meq/L levels to counter their potential to accumulate in the soil profile and foliar feeding directly (Na) into turfgrass shoots. Otherwise, salt loading into the ecosystem will become the primary limitation to sustainable management of the turfgrass on the site. If those four primary salt ions are reduced in the recycled water, the total dissolved salts will also normally be reduced either through the treatment process or through blending.

12.6 IRON AND MANGANESE

12.6.1 Problems

Manganese occurs in some groundwater, but is much less of a problem for irrigation than Fe. However, for drinking water, Mn is undesirable because it causes a gray/black appearance, can stain fixtures, and results in an unpleasant taste. High levels of Mn can contribute to deposits on plants, accumulation of Mn in soils to levels toxic to many roots, and clogging of irrigation equipment by MnO_2. Levels <0.2 mg/L of Mn are best for long-term irrigation use. Forms of Mn include (1) **manganous**—Mn^{+2} is the soluble form found under low aeration and acid ($pH < 5.5$) conditions; and (2) **manganic**—Mn^{+4}, which is the oxidized state and precipitates as MnO_2. Treatment of Mn problems is by oxidizing (aeration), precipitation, and filtering in a manner similar to the oxidizing treatment for Fe, which is discussed later in this section.

Iron occurs naturally in groundwaters and is a more serious problem than Mn for irrigation. Forms of Fe include (1) **ferrous iron**—Fe^{+2}, soluble iron, ferrous bicarbonate, ferrous hydroxide, develops in anaerobic/reducing environments such as boreholes (Carruthers, 1994) or pipes and occasionally in deep lakes/ponds that do not turnover rapidly. Water may be initially clear, but becomes cloudy when exposed to air, then oxidizes and turns into reddish ferric iron, which then can cause Fe precipitates; (2) **ferric iron**—Fe^{+3}, nonsoluble, cause of reddish color, ferric hydroxide, oxidized form; and (3) **organic Fe**—organically bound Fe, complexed with decomposed vegetation, called tannins or lignins, and that have a weak tea or coffee color. Each Fe form can exist alone or in combination with the others. Certain Fe-fixing bacteria react with the soluble Fe^{+2} (ferrous) iron as an energy source and oxidizes it to Fe^{+3} (ferric state) and deposits it into slimy gelatinous materials that surround them. These bacteria grow in stringy clumps and are found in most iron-bearing waters.

Relative to irrigation water and irrigation, Fe problems include (Yiasoumi et al., 2005; Zinati and Shuai, 2005) the following:

- Red staining of sidewalks, cart paths, and equipment.
- Brownish stains on leaves of ornamentals and reduction of photosynthetic capability.
- Clogging of pipes, boreholes, pumps, and fittings from the iron bacteria. These slimes are sticky and can attach themselves to the irrigation pipes, causing blockages.
- Piping and sprinklers may become clogged from Fe oxide or hydroxide precipitates.

For irrigation water, soluble Fe levels may be high in anaerobic environments such as boreholes, deep dams, or pipes, which can stimulate Fe bacteria at 0.2 mg/L; cause reddish deposits at 0.3 mg/L; and at >5.0 mg/L may be toxic to some plants and cause nutritional imbalances with other micronutrients. Ayers and Westcot (1994) listed the degree of clogging potential on drip irrigation systems from Fe or Mn as <0.1 (none); 0.1 to 1.5 (slight-to-moderate); and >1.5 mg/L (severe).

12.6.2 MECHANICAL OXIDATION AND SEDIMENTATION

Soluble (reduced forms) ferrous Fe and Mn occurs in some groundwaters or deep ponds where the water intake is in the anaerobic layer that favors formation of soluble forms—raising the intake to near the surface would be suggested in the latter situation. If the soluble Fe and Mn are not removed before going into the irrigation lines, there is the chance of iron oxide or hydroxide precipitates clogging irrigation lines, plugging microirrigation system emitters, or plugging screens with flakes of oxides. Removal of soluble Fe and Mn prior to going into irrigation lines can be achieved by the processes of oxidation to form insoluble precipitates and precipitation or sedimentation out of the water (Yiasoumi et al., 2005; NDWC—Iron and Manganese Removal, 2008). Organically bound Fe or Mn are not effectively removed by mechanical oxidation. Filtration may be required for microirrigation systems or any irrigation system if precipitated particles are carried in the water into irrigation lines.

To increase Fe precipitation, increasing water pH to at least 7.2 is recommended by using hydrated lime (calcium hydroxide) at about 0.25 lb per 1000 gal (30 gm per 1000 L) or trickling water over a crushed limestone bed. Iron is more soluble at acid pH, and precipitation will not be very effective. Oxidation is best accomplished by mechanical aeration of the water followed by settling. Aeration can be enhanced by:

- Spraying the water into the air
- Diffusion of air through the water such as air diffusers at the bottom of irrigation ponds
- Bleeding air into the intake side of a pump
- Agitating the water with propellers or paddles
- Cascading water over baffles into a settling tank or utilizing gravity flow over rocks

The iron then **settles** out of the aerated water. If the aeration is in a pond, the precipitated materials settle to the bottom, where it could become soluble again if this zone is anaerobic. Using a bottom diffuser and maintaining the intake near the surface will help prevent further problems. If a sedimentation tank is used, the precipitated sludge material would require periodic drainage. Whether filtration is required depends on the degree of suspended iron oxide particles, but mechanical aeration and settling is normally sufficient for turfgrass irrigation purposes.

12.6.3 CHEMICAL OXIDATION, SEDIMENTATION, AND FILTERING

Mechanical oxidation and settling in an irrigation pond is normally sufficient for turfgrass situations, but for other landscape plants or nursery irrigation, chemical oxidation may be required. Also, when Fe or Mn bacteria are present and cause bacterial slime to plug irrigation components, chemical oxidation may be needed. The most common chemical oxidation processes for irrigation water treatment are chlorination and potassium permanganate. Chlorination is further discussed in Section 12.7 for other uses beyond control of Fe and Mn bacteria.

Chlorination. Yiasoumi et al. (2005) noted that if further control following aeration and settling is needed, chlorination can be used to control iron deposits if pH is below 6.5 and the iron concentration is less than 3.5 mg/L (3.5 ppm). If pH is above 6.5, the iron concentration must be below 1.5 mg/L (1.5 ppm) to use chlorination effectively. Chlorine also kills iron bacteria on contact (Smith, 2005).

Potassium permanganate. Potassium permanganate oxidizes Fe into the insoluble oxide form. Potassium permanganate is often used with **manganese greensand**, which acts as a filter, trapping the oxide. The manganese greensand process has been used effectively for removing iron, manganese, and hydrogen sulfide. Manganese greensand is glauconite, an iron, potassium, aluminosilicate zeolite material of marine origin that is stabilized, and then coated with manganese oxide in various valence states. This coating provides glauconite with its special chemical oxidation-reduction properties for the removal of iron and manganese as well as small quantities of hydrogen sulfide. As an oxidizing agent, the main advantage of potassium permanganate oxidation is the high rate of reaction, which is many times faster than that of chlorine. The reaction is not sensitive to pH within the range of 5 to 9.

12.7 CHLORINATION

Chlorination is used to **disinfect**, decrease **biofouling**, **deodorize,** and as a **chemical oxidation agent** for treated water (Ayers and Westcot, 1994; Granberry et al., 2005; Yiasoumi et al., 2005; Clark and Smajstria, 1999; NDWC—Disinfection, 2008; NDWC—Chlorination, 2008). Thus, the equipment, treatment procedures, and rates may differ depending on the particular problem. It is important to determine the specific problem and whether there are other options.

Chlorine gas (Cl_2) is a strong oxidizing agent. It is corrosive, difficult to handle, and requires special injection equipment. Because it is poisonous, it must be handled with great care. Liquid sodium hypochlorite (NaOCl) is the easiest form to use and is readily available as household bleach (5.25% chlorine) or from swimming pool companies as 10% formulations. Powdered calcium hypochlorite is a dry powder, but is not recommended for irrigation injection owing to the problem of Ca potentially forming precipitates. On-site chlorine gas generators are available where chlorine gas is generated by adding NaCl to water and applying a DC current, which generates chlorine gas, some ozone, and NaOH. The chlorine gas is vacuumed into the water supply.

Disinfection is focused on ensuring water is safe for drinking or irrigation use, but waterborne organisms are also targeted when they are involved in biofouling. For most turfgrass and landscape sites, disinfection is not common; however, Yiasoumi et al. (2005) discusses irrigation water disinfection for farm irrigation.

Biological fouling is almost inevitable whenever untreated water is pumped from a lake, pond, or rivers. Chlorination treatment of drip irrigation systems is relatively common to correct or prevent clogging of drip emitters by algae and bacteria, as described by Benham and Ross (2002), Granberry et al. (2005), and Clark and

Smajstria (1999). Iron and Mn bacteria biofouling of irrigation lines and equipment requires chlorination. Algae will be discussed in Chapter 14. Chlorine treatment is often an option for other biofouling agents such as fungi, bacteria, algae, bryozoans, and mollusks (zebra mussels, shipworms, etc.). Baxter (2006) and Schmiede (2006) discuss chemical treatment of boreholes relative to controlling Fe bacteria and disinfection. Ayers and Westcot (1994) reported the following chlorine doses for control of various biological fouling problems:

- Algae: 0.5 to 1.0 mg/L continuous or 20 mg/L for 20 minutes
- Iron bacteria: 1.0 mg/L, but varies with bacterial count
- Hydrogen sulfide: 3.5 to 9.0 times the H_2S content (mg/L)
- Slimes: 0.5 mg/L continuous.

Luke and Calder (2005) make the following recommendations relative to treatment of trickle irrigation lines, but some of these can apply to regular irrigation lines. They suggest chlorinating the water supplies if there is organic matter such as algae in the water supply, or more than 0.1 mg/L of iron. Some chemical costs may be avoided if water with more than 1 mg/L of iron is pretreated to precipitate the Fe:

1. Continuous injection of 1 to 3 mg/L (ppm) of chlorine into the mainline before the filter is a very effective means of combating algal growth and bacterial deposition of red iron sludge in laterals and emitters.
2. Maintain a residual level of 0.5 to 1 mg free chlorine/L at the furthermost emitter to ensure saturation of the entire system and leave chlorinated water in the system at shutdown.
3. Run the system with chlorinated water for a short time weekly during the "off" season to stop algal and bacterial development.
4. Deliver a slug of 50 to 100 mg/L chlorine into the irrigation system on a monthly basis, and before the start of an irrigation season. They suggest doing this at the end of an irrigation cycle so that the slug is left in the lines as long as possible (at least 24 hours). Then open the lateral ends and flush the system thoroughly with the nominal concentration of chlorine before starting the next irrigation cycle. Some growers inject 20 to 30 mg/L chlorine into the system for the last 30 to 60 minutes of irrigation, rather than applying 1 to 3 mg/L continuously. This can be an advantage when injecting fertilizer because some products may react unfavorably with chlorine. However, this method usually is only practical when using a fully automated irrigation controller.

Because some biofouling agents are invasive species, good initial sources of information are the National Invasive Species Information Center (NISIC, 2008) and the USGS Nonindigenous Aquatic Species (USGS, 2008). Species that have been an increasing problem for turfgrass and landscape irrigation systems are bryozoans and hydroids. Bryozoans (moss animals) (*Plumatella* or *Fredericella* species) and hydroids (*Cordylophora*) are colonial invertebrate animals that prefer dark places (Wood and Marsh, 1999; Folino-Rorem and Indelicato, 2005; Wood, 2005).

Bryozoans have free branches that become tangled and intertwined, filling the pipeline interior with a dense meshwork that impedes or blocks water flow. Pieces of these colonies may break away and clog sprinkler heads and other end-use devices. Special in-line filters may help prevent this problem, but in most cases, a regularly scheduled maintenance program can avoid it altogether. Wood and Marsh (1999) reported control by 5 hour exposure to 1 mg/L of sodium hypochlorite and prevention at 7 mg/L of residual chlorine. Folino-Rorem and Indelicato (2005) noted that chlorine treatment of up to 5.0 mg/L did not kill the hydroid colonies, but that concentration did curtail growth.

Wood (2005) reported for a golf course in Indiana irrigating from a small retention pond that in the spring and fall, sprinklers were often seriously clogged with fragments of bryozoan colonies dislodged from inside the irrigation lines. The lake itself had a large population of bryozoans (*Plumatella casmiana*) growing on rocky rubble that lined the lakeshore. Masses of buoyant statoblasts (tough capsules of buds) formed what appeared to be a brown scum nearly a meter wide along the windward shore. The solution was (1) to treat the water to remove the rubble; with no substrate on which to grow, bryozoans disappeared from the lake; and (2) the irrigation system was treated once with hypochlorite, after which the fouling problem was resolved.

When water is treated with chlorine, whether in a wastewater treatment facility or on-site, the total chlorine in the water is that chlorine that is present in free plus bound forms. **Free or residual chlorine** is chlorine that is present in the form of hypochlorous acid, hypochlorite ions or as dissolved elemental chlorine. **Bound chlorine** is that fraction of the total chlorine that is present in the form of chloramines or organic chloramines. For drinking water safety, some level of free chlorine is desirable to ensure that the water was adequately treated for human safety exposure to biologicals. However, excessive free or residual chlorine concentrations in water treated for irrigation can sometimes cause plant injury on sensitive species. It has been reported that with Cl_2 concentrations that exceed 5 ppm and that are delivered directly from the treatment plants or through on-site treatment to the irrigation system, some foliar burning can occur on landscape plants and turfgrass shoots. However, if the high-chlorine water is delivered to storage reservoirs or ponds, the chemical normally dissipates rapidly (especially with aeration) before application on the recreational turf. Normal application through sprinklers on golf courses or residential sites where the water source is aerated causes rapid dissipation of chlorine as a gas prior to application on turfgrass or landscape areas.

12.8 CARBONATE SCALE AND SALT ENCRUSTATION PROBLEMS

With the use of more saline irrigation water on many turfgrass sites, **salt encrustation** can occur. Salt encrustation is not an issue in irrigation piping, because the salts are primarily soluble, but salts can deposit as grayish crusts on irrigation system components. If insoluble carbonate scale is intermixed with salt encrustations, water will dissolve the soluble components but not the carbonate. Encrustations present a cosmetic issue, but the primary concern over salts on irrigation components or any equipment in contact with the saline irrigation water is corrosion (see Section 12.10).

Carbonate scale inside pipelines is caused by calcium and magnesium carbonate, gypsum, and calcium phosphate precipitation on the lines, and it is sometimes mixed with other material such as iron, sand, or gypsum. Because these carbonate scales have low water solubility, water moving through the lines does not remove the deposits. Water that is high in dissolved Ca or Mg or both is called **hard**. The terms **hard water** or **water hardness** are usually thought of in relation to home water sources and the effects that it has on laundry soap not lathering and soap scum deposits. Water hardness is defined in terms of calcium carbonate ($CaCO_3$, also known as "lime") concentration. Provin and Pitt (2003) note that HCO_3 and CO_3 levels of 180 to 600 mg/L may result in lime deposits in irrigation systems.

Carbonate scale formation is normally a gradual process that is enhanced by a combination of high temperatures, high pH, and excess calcium or magnesium carbonates and sulfates. The tendency for calcium precipitation in water can be predicted, but there is no proven practical method to evaluate how serious the problem will be because it depends on many factors. A first approximation of the calcium precipitation can be made using the calcium carbonate saturation index (Langelier's index), which gives the relationship between pH, salinity, alkalinity, and hardness. Langelier's saturation index simply says that when reaching the calcium saturation point in the presence of bicarbonate, lime (CaCO3) will precipitate from the solution. The saturation index is defined as the actual pH of the water (pHw) minus the theoretical pH (pHc) that the water could have if in equilibrium with CaCO3, where:

$$\text{Saturation Index} = \text{pHw} - \text{pHc}$$

Positive values of the index (pHw > pHc) indicate a tendency for $CaCO_3$ to precipitate from the water, whereas negative values indicate that the water will dissolve $CaCO_3$. The value of pHw is obtained from laboratory data, whereas pHc is estimated using the procedures described by Ayers and Westcot (1994) and reported by Carrow and Duncan (1998). All water having positive values should be considered potential problem water for use through drip irrigation systems, and the need for preventative measures should be considered in the site design. Also, a pHc value of <8.4 is indicative of a tendency for lime precipitation.

The best goal of pH adjustment is to acidify the water to keep scale-forming calcium and magnesium ions in solution and not allow them to precipitate. Injecting the acid continuously downstream of the filter is the preventive option in situations where scale formation is very likely (see Section 12.2.6). In situations where scale formation has already occurred, injecting sufficient acid to lower the pH to 2 to 4 for 30 to 50 minutes before the end of the irrigation cycle is the common strategy. Leave the acid in the lines for at least 24 hours, and flush the system thoroughly before starting the next irrigation cycle. Acid corrosion is not a problem on PVC pipe, but it can cause corrosion on metal pipes. Flush the system thoroughly before starting the next irrigation cycle.

12.9 CORROSION

Chemical corrosion is not a major problem on most turfgrass and landscape sites, because PVC pipe is so widely used. PVC pipes do not scale, rust, pit, or react chemically with irrigation water constituents. However, if suspended solids, such as sand, silt, clay, or metal oxides, are present on a routine basis, physical corrosion or wear can occur, and that wear problem is usually most evident on nozzles.

External corrosion of metal irrigation pipes is due to the groundwater characteristics (low resistance, high salinity, and low pH) causing metal oxidation or if the water is unusually acidic, such as in acid sulfate soils, resulting in metal dissolution (MRWA, 2008). Corrosion is an electrolytic process in which the groundwater interacts with the metal piping and dissolves away the surface or oxides in the metal. Options for protecting pipes from external corrosion include wrapping, cathodic protection, and pipe replacement.

Internal corrosion is affected by water characteristics (dissolved oxygen, chlorine, acidity), velocity, temperature, and pressure (USEPA, 1984; Yiasoumi et al., 2005; NDWC, 2008; MRWA, 2008). Treatment options include pH adjustment, using chemical inhibitors (zinc orthophosphate, polyphosphates, orthopolyphosphate blends, and silicate materials), avoiding excessive oxygen levels in the pipelines, cathodic protection, and pipe coatings.

12.10 SULFUR BACTERIA AND SULFIDES

Sulfur can be present in irrigation water in the oxidized sulfate form (SO_4) or in the reduced form as the gas hydrogen sulfide, H_2S. Sulfur-reducing bacteria are present in nature and consume sulfate by-products of organic acids and H_2S in the water. These are anaerobic bacteria, so they are found in low-oxygen environments such as pipes, deep wells, some groundwaters, and at the bottom of lakes if the lower zone is anaerobic. Problems associated with H_2S are (Swistock et al., 2001; Scherer, 2005) as follows:

- The “rotten egg” smell, with <1 mg/L giving a musty odor and 1 to 2 mg/L sufficient to give the rotten egg odor.
- Similar to Fe and Mn bacteria, sulfate-reducing bacteria create slimes that are biofouling agents.
- H_2S is corrosive to metal.
- It causes yellow to black stains on materials.
- Along with FeS and MnS, H_2S contributes to black layer formation (Carrow et al., 2001).

There are several treatment options for smaller volumes of water such as drip irrigation or home wells. These include activated charcoal, shock chlorination, oxidation or aeration, and oxidizing filters (Swistock et al., 2001; Scherer, 2005). If an irrigation source is high in H_2S, treatment is likely to be cost prohibitive. A couple of situations in which corrective action may be implemented are now described. H_2S coming from the bottom lake layer that is anaerobic due to the irrigation intake being located in this zone is one such situation. A floating intake system that obtains water above this zone could be used (Smart, 1999). If the well has sulfur-reducing bacteria that are contributing to biofouling or if there is biofouling in the existing irrigation lines, then shock or continuous chlorination may be attempted. Sulfur bacteria can be located behind scale and is more difficult to control than Fe or Mn bacteria. Swistock et al. (2007) and Scherer (2005) report on well and spring chlorination, and other reference sources related to chlorination are Ayers and Westcot (1994), Granberry et al. (2005), Yiasoumi et al. (2005), Clark and Smajstria (2006), NDWC—Disinfection (2008), and NDWC—Chlorination (2008).

12.11 ODORS

Odors can arise from several sources such as decaying vegetation, mold, Fe/Mn/S bacteria, iron, chlorine, petroleum, and salts (Yiasoumi et al., 2005; Satterfield, 2006). Treatment should be targeted for the cause, but includes chlorination, aeration, removal of Fe, clarification with flocculants, removal of algae, and activated carbon filters.

12.12 FILTRATION

Suspended inorganic or organic materials can cause clogging problems as well as wear on irrigation system components. Microirrigation systems definitely require a filtration system to avoid clogging the small emitters and lines. However, large landscape irrigation systems are also affected by various suspended materials, such as the following:

- Sand, silt, and clay. Norum (1999) discusses sand problems and possible solutions for irrigation systems.
- Organic matter such as algae, Fe/Mn/ S bacteria, and bryozoans.
- Ferric hydroxide or oxide precipitates, Mn precipitates, and suspended carbonates.

Because clogging materials can arise from many sources, it is important to identify the specific problem before purchasing filtration equipment. Yiasoumi et al. (2005) suggests that a water analysis should include at least the following:

- Suspended solids. Quantity in mg/L and the nature of the particulates.
- Iron in mg/L
- Hardness ($CaCO_3$)
- pH
- Mn in mg/L

From this information, irrigation specialists can determine the best approach and whether filtration is needed. Irrigation filtration types include screen filters, centrifugal separators, disc filters, and sand-media filters. There are also prefilters such as settling basins, trash racks or screens, sediment traps, and floating debris traps (Norum, 1999; Shuster, 1999; Yiasoumi et al., 2005). Because some filters work best on inorganic material and others on organic contaminants, the nature of the particles is important.

Screen filters are most widely used for sand, sediment, and other inorganic solids, but biosolids can clog the screens. Screen filters can be manually or automatically cleaned, but for large irrigated landscapes, automatic cleaning screens are usually necessary owing to the water volume and frequency of applications. The orifice sizes of the irrigation nozzles determine the screen-size or mesh. Generally, the filter screen is one-fifth the size of the smallest sprinkler orifice (Shuster, 1999). Screen filters are used for primary filtration, but also sometimes in conjunction with media screens as secondary filters.

Centrifugal sand separators do not really filter directly, but use spinning action to force heavier particles to the outside, where they settle in a collection chamber that is purged periodically. These devices can handle large quantities of sand and are usually installed on the suction side of the pump to remove sand before it causes wear on the pump and valves. Sometimes they are used as prefilters for other filtration devices. Centrifugal sand separators are effective for sand removal, but are ineffective for organic contaminants; however, not all sand may be removed, so additional screen filters may be required downline. The flow rate must be suitable for the specific centrifugal sand separator, which may cause a problem with variable rate systems.

Disc filters use a series of grooved discs stacked on top of one another, with the degree of fineness depending on the space between discs to remove organic and inorganic debris. The molded grooves determine the mesh rating for the filter. Manual and automatic wash features are options.

Media filters are also known as sand and gravel filters. The media or combinations of media are layered in pressurized vertical tanks. Water exits the bottom through small holes that retain the media. Media filters are very good at removal of suspended inorganic and organic fines. Normally, there are several media tanks, and only one is backwashed at a time to remove the debris. Manual and automatic backwashing systems are available. A secondary screen or disc filter is often used after the media filter to prevent suspended solids from the media filter getting into the irrigation system.

Shuster (1999) noted that the following information would be necessary to determine filtration options:

- Maximum flow rate in gpm of the system
- Mesh or micron level needed, based on the smallest orifice size of the sprinkler nozzles
- Maximum system pressure in psi
- Current filters or filter system used, and their filter size and type
- Source of water
- Water tests, as previously noted by Yiasoumi et al. (2005)

12.13 DESALINATION

An extreme irrigation treatment option is desalination, in which most of the salinity and nutritional components can be removed from the water with sophisticated membrane technology. Cutright (2007) stated that there are over 12,000 desalination plants worldwide, with 60% in the Middle East, with a total daily output of 5 to 7 billion gallons. Unit equipment costs can vary from a few hundred thousand to $1.5 million, depending on desired R.O. water output. Agriculture, Fisheries, and Forestry—Australia (2005a,b) and TWDB (2008) provide an in-depth review of desalination technologies, costs, and challenges. Cutright (2007) presented the primary considerations related to desalination as initial costs; maintenance costs; incidental killing of sea life at the intake; brine disposal; energy requirements; need for a consistent water source to be used in desalination; and compliance with state and federal regulatory agencies governing water pretreatment, drinking water processing (if the water is to be used for drinking purposes) and disposal. Powell (2007) and Aylward (2005) reported on recent desalination activities for turfgrass irrigation purposes and the issues are the same as those noted by Cutright (2007). The pros and cons of the conventional RO unit are summarized as follows:

Cons

- High initial capital outlay for equipment
- Constant energy demands to run the unit
- Need for blending with other alternative water resources
- Low-to-moderate output per day
- Permit requiring disposal of reject concentrated brine and its corrosive nature problems
- Regular membrane maintenance and high operational expenses required
- Possible need for storage
- If total salts and specific salt ion concentrations are reduced, other nutrient (Ca, Mg, and micronutrients) concentrations are reduced

Pros

- Dependable water quality
- Flexibility in generating different salinity levels in the process tailored to specific site and grass requirements
- Ability to remove a requested amount of total salinity and specific toxic salt ion (Na, Cl) concentrations out of the initial brine water source
- Known quantity of water output

Brine disposal is generally into the ocean for coastal plants or into porous strata such as limestone or sandstone for land-locked desalinization plants. The output of the RO units can range from 100,000 to 600,000 gal/day of desalinized water, depending on unit size and membrane capacity; initial source water TDS, and output efficiency varies depending on initial source water TDS, but is normally between 25 and 50%. Consequently, concentrated brine disposal is a serious consideration and requires governmental permitting for disposal. The RO water can either be deposited directly

TABLE 12.4
Chemical removal processes used in desalination

Chemical removed	Process	Comments
Boron	Nanofiltration, reverse osmosis (RO)	pH dependent (alkaline close to 11). Membrane type critical. *Desalinization* 185(1): 131–137
	Electrodialytic (ED)	Membrane dependent (9–10 pH) *Desalinization* 185(1-3): 139–145
	B-selective sorbents + RO/ED	*Desalinization* 185(1-3): 147–157
	Hydrothermal treatment with Calcium hydroxide to form Ca borate	*Water Research 3*9(2): 2543–2548
Micropollutants	Flat Membrane Cassette (FLAMEC) Ultrafiltration and microfiltration	*Desalinization* 185(1-3): 167–183
Heavy metals	Colloidal-based micellar-enhanced ultrafiltration (MEUF)	*Desalinization* 185(1-3): 185–202
Oily wastewater + phosphate and sulfate ions	Ultrafiltration (UF) + RO	*Desalinization* 185(1-3): 203–212
	Hydrophobized vermiculite at pH 9	*Water Research* 39(2): 2643–2653
Fluoride	Chemical adsorption/precipitation	*Desalinization* 185(1-3): 241–244
	Ion exchange, RO/ED	Photopolymeric selenium anionic
Zinc	Nanofiltration	*Desalinization* 185(1-3): 245–253
Sulfides	Nanofiltration	*Desalinization* 185(1-3): 269–274
Nitrates	Nanofiltration	*Desalinization* 185(1-3): 281–287 Membrane dependent; alkaline pH
Chromium	Purification/concentration	*Desalinization* 185(1-3): 335–340
	Acidified potassium dichromate	*Desalinization* 185(1-3): 307–316
Ammonium and phosphorous	Sand filtration + polyether-sulfone (PES) in UF	*Desalinization* 185(1-3): 317–326
Organic matter	Coagulation/UF process alum (Al_2 $(SO4)_3$) + PAC(polyaluminum chloride) at pH 6–8	*Desalinization* 185(1-3): 327–333
Oleate (lipid wastewater)	Anode conversion to methane using RuO DSA electrode under potentiostatic control	*Desalinization* 185(1-3): 351–355
Textile effluent	MF/UF/NF	*Desalinization* 185(1-3): 399–409
Tannery effluent	Pillared clay	*Desalinization* 185(1-3): 419–426
Copper	Sawdust adsorbent	*Desalinization* 185(1-3): 483–490
Nitrates	Synthetic resin Amberlite	*Desalinization* 185(1-3): 509–515
Perchlorate (ClO_4^-) and Nitro-organics (RDX, HMX)	Activated carbon preloaded with cetyltrimethyammonium chloride (CTAC)	*Water Research* 39(19): 4683–4692
Phenols	Ozonation and carbon biofiltration	*Desalinization* 182(1-3): 151–157
Sulfates, bicarbonates, nitrates	Donnan dialysis	*Desalinization* 182(1-3): 339–346
Fe, Mn	Flow filtration technology	*Water Research* 39(18): 4463–4475
	Activated charcoal	*Desalinization* 182(1-3): 347–353
Cr, Cd	Resin Amberlite	*Desalinization* 180(1-3): 151–159
	Calcined hydrocalcite	*Water Research* 39(12): 2535–2542
Silicon, B	Electrodeionization (EDI)	*Desalinization* 181(1-3): 153–159

into the wet well for subsequent irrigation or blended into a holding pond for eventual irrigation of lower-salinity water.

Under ocean floor seawater intake and discharge is a recent development in which the intake and discharge pipes are installed under the ocean floor with a permeable layer above it. This greatly reduces inadvertent killing of marine life (such as coral reefs) and serves as an additional filter for brine disposal (Cutright, 2007). Also, the use of brackish water of approximately 3,000 mg/L salt compared to over 30,000 mg/L for seawater greatly reduces brine disposal issues, energy costs, and ongoing membrane replacement costs (Hildebrandt, 2007). The brackish water usually comes from aquifers too saline for drinking water that may range from 300 to 1000 ft deep. Membrane technology also continues to rapidly improve throughput efficiency with reduced treatment costs. Nanofiltration is one example (Cutright, 2007).

This technology is energy dependent, with frequency of use dependent on water volume demands. Hawaii has been a leader in development of the ocean thermal energy conversion (OTEC) process that utilizes the heat energy stored in the tropical ocean to produce energy for desalination (Zapka, 2007; RET, 2008). Because the ocean is a huge heat energy sink, OTEC plants utilize the temperature differential between warm surface seawater (76–82°F/24.5–27.5°C at 50 ft depth) and deep seawater (43–46°F/6–8°C at 2000–3000 ft depth) to produce electricity, desalinized freshwater (5 L for every 1000 L of cold seawater), and provide energy-efficient, nonpolluting air conditioning or industrial cooling. The temperature difference must be about 36°F (or 20°C) for the system to work efficiently. When this cold seawater flows through a separate atmospheric heat exchanger, it condenses freshwater from the always-humid tropical air (Gersid and Worzel, 1967). Large production plants have the capability of producing up to 5 million gallons of desalinized water per day (Bender, 2001), with smaller units producing 25,000–50,000 gal per day (Craven and Sullivan, 1998). This technology is being considered for blended water use on golf courses in some Caribbean countries in conjunction with freshwater generation for conventional human population use. OTEC technology also eliminates both the concentrated brine problem and the high energy demand problem.

Pros for use of desalinized water for turfgrass irrigation include options for using or blending lower-salinity water and the dependability of the water quality that is generated. More sophisticated units can reduce ocean water at 34,500 mg/L salts down to 500–1500 mg/L of salinity. Cons include limitation on production output per day versus irrigation demands, corrosive nature of the reject concentrate, high energy requirements and high operational costs, high maintenance costs for the equipment and for membrane replacement, need for permitted disposal of the reject concentrate, need for blending to extend water volume to meet peak irrigation demands, need for storage, and the high initial startup costs.

Beyond removal of many of the soluble salts, sometimes there are specific constituents in the water that are necessary to remove for irrigation use. Several additional treatment processes are summarized in Table 12.2 for various constituents that could be found in alternative water sources.

12.14 "IN-LINE" WATER-CONDITIONING DEVICES

Several nonchemical water treatment products are on the market with strong claims regarding water conditioning (West, 2002). In general, some of this equipment uses directional flow, electrostatic or alternating electrical fields, permanent magnetic fields, or catalytic redox media with heavy metals "to change the properties of water." General treatment categories for these conditioners include electromagnetic, electrolytic, light-related or far-infrared, depressurizing, oscillations and vibrations, and redox. Equipment that have entered the turfgrass industry include the following:

- ESP (electrostatic precipitator)—Designed to alter the molecular structure of water through the use of multiple radio frequencies
- CARE-FREE® water conditioner—Catalytic water treatment device that uses ionic conversion over multiple venturies and dissimilar precious and semiprecious metals to neutralize calcium and other agents into stable molecules.
- Perm-Core or Magnetizer—Water conditioner uses magnetic lines of force to reduce surface tension, making the water more "soluble" and altering fluid flow in order to eliminate scale or $CaCO_3$ formation.
- Magnawet water conditioner—It reduces the surface tension of water, making it more mobile, by passing water through a cobalt magnetic field. The water retains its magnetic properties for 36 hours,
- FRE-FLO—Catalytic device that lowers surface tension and turbulent flow, causing dissolved CO_2 to precipitate micron-sized $CaCO_3$ crystals that are suspended in water for removal.
- Ozonators (Oxion)—This produces ozone (O_3) and other negatively charged oxides of nitrogen to form hydrogen peroxide (H_2O_2) and nitric acid (HNO_3) by injecting the ionized air into water through a submicron injector, creating extremely small bubbles that increase solubility and dispersion.
- Ecosmarte—It utilizes ionization and oxygenation to place an ionic copper residual in water, effectively "making the water wetter" by reducing surface tension.
- Seair diffusion system—It uses oxygenation, ozonation, and pH control to increase dissolved oxygen levels up to 500% above supersaturation, to oxidize and sterilize water, and to dissolve CO_2, thereby lowering pH levels.
- Other devices can be found on the Web site by Lower (2008).

To this point, very little unbiased scientific data support the agronomic use of these devices on turfgrass or agriculture (Shepard et al., 1995; Robillard et al., 2001; Martin and Gazaway, 2003; Leinauer et al., 2007). Baker and Judd (1996) reviewed the use of magnetic devices for amelioration of scale formation and found many cases of no effect and a few instances of some positive but minor effects in terms of magnitude in resolving salinity challenges. The inhibition of scale formation that did occur appeared to result from effects on size and crystal nature of the lime. Most often, testimonials and on-site "observations" are emphasized in promotional venues, but these claims normally lack controls or replicated science. Recently, Keister (2008) discussed the lack of performance of nonchemical devices (NCDs) in the water treatment arena. To quote Jim Oster, Department of Soil and Environmental Sciences, University of California–Riverside:

> My position on these products is that unless they add something to the water or remove something from the water, they do nothing to the water!

12.15 CONCLUDING STATEMENTS

In this chapter a number of physical, chemical, and biological problems and their treatment options were discussed that can influence irrigation water quality or delivery. Additional issues are discussed in Chapters 13 (nutritional) and 14 (lakes, ponds, and streams). It is apparent that proper identification of the problem or problems present in the water is a critical first step before considering any treatment options. There is no one "silver bullet" treatment for irrigation water that will work on all of these diverse salinity-in-irrigation-water issues. Because effective treatments usually involve costs for equipment, materials, and maintenance, mistakes can be costly with little to no resolution of problems associated with regular use of those saline water resources. Salinity is the most complex abiotic stress that can be imposed on perennial turfgrass ecosystems. Management programs must be oriented toward basic agronomic principles and proactive monitoring with scientifically verified strategies for sustaining turfgrass performance on each specific site. Understanding the irrigation water treatment options and implementing the correct options that suit specific situations is essential for making the proper management decisions, regardless of turfgrass species or cultivar being grown or the soil profile and infrastructure challenges that are inherent to the site.

13 Nutritional Considerations with Variable Water Quality

13.1 WATER QUALITY AND NUTRITION

Irrigation water constituents are part of the overall fertility program on a turfgrass or landscape site. When irrigation quality is of normal drinking water quality and is consistent, this is often overlooked because soil fertility and plant nutrition is affected primarily by what is applied by fertilization, liming, and any nutrients contained in management products applied to the turfgrass. Changes in fertility status are rather slow and predictable. However, certain irrigation water quality situations complicate nutritional programs either because of excessive additions of one or more nutrients or elements, imbalances between nutrients or elements, or lack of nutrient or elements (Alam, 1999). The most common situations include the following:

- Saline irrigation water sources—see Chapter 6
- Reclaimed water—see Chapter 8
- Ultrapure irrigation water—see Chapter 5
- Resources with unusual levels or balances of chemical constituents, such as higher than normal metals, B, or S

In arid regions, it is common for reclaimed water to become more concentrated in salts over time, so reclaimed water issues and salinity issues become combined. In previous chapters, various issues related to each of these situations were presented, but in this chapter, the focus is on how soil fertility and turfgrass and landscape plant nutrition programs are affected. Among these four general situations, the most challenging is saline irrigation water.

Discussion of plant nutrition across all plant types as affected by salinity are given by Naidu and Rengasamy (1993), Ayers and Westcot (1994), Marschner (1995), Grattan and Grieve (1999), Alam (1999), and Barker and Pilbeam (2007). Kelly et al. (2006) discusses crop nutrition when using reclaimed water for irrigation. Carrow et al. (2001) and Carrow and Duncan (1998) focus on turfgrass nutritional issues under salinity conditions.

13.2 IRRIGATION WATER QUALITY TESTS, SOIL TESTS, AND TISSUE TESTS

As the concentrations and diversity of constituents in irrigation water increases, so does the need for more frequent proactive measures, such as the following:

- Irrigation water quality testing (see Chapter 3)
- Soil testing, including field monitoring of soil salinity and moisture
- Tissue testing, as well as field monitoring of soil salinity (see Chapter 4)

Irrigation water quality testing is essential and must be conducted more frequently when a new irrigation water source is used until the levels of constituents and the consistency of values are determined over time. It is very common for irrigation water quality to be variable. Irrigation water tests have a major influence on whether water treatments are necessary, which soil amendments should be used, and the actual soil chemical status. Additionally, nutrient additions from the irrigation water source must be accounted for within the overall plant nutrition and soil fertility program. This is especially important when using reclaimed water. Table 13.1 contains normal levels of nutrients in reclaimed irrigation water and includes conversions that can be used to determine nutrients added per 1000 ft^2 per 12 in. for each irrigation water application. This table was presented in Chapter 3 as Table 3.8, but is repeated in this chapter for reader convenience. Because irrigation water quality testing is covered in detail in Chapter 3, readers are referred to that chapter for additional comprehensive information.

Soil testing is also required on a more frequent basis, including field monitoring of soil salinity as discussed in Chapter 4. Soil tests are of two general categories: (1) routine soil fertility testing and (2) specially requested analyses that relate to salt-affected soils (saturated paste extract salinity test). A complete physical analysis of soils, especially sands for greens mixes and for fairway/rough capping, provides additional science-based data that can be used to improve ecosystem infrastructures that favor salinity management decisions. Because a detailed discussion of soil testing and interpretation is beyond the scope of this book, turfgrass managers are encouraged to study the articles by Carrow et al. (2003, 2004a,b) and Skorulski (2003), which are published series on practical soil testing that include the specific types of soil tests and their interpretation.

Tissue testing is also commonly used to identify problems. When saline irrigation water is applied over turfgrass shoots and moves into the soil profile, there are ample opportunities for deficiencies to occur, especially micronutrients, Ca, and K. A good resource for understanding tissue testing on turfgrasses and their interpretation is provided by Plank and Carrow (2008). Tissue analyzed in a wet chemistry laboratory and subjected to spectrophotometric digital readouts is favored over near infrared reflectance (NIR) analyzed data when dealing with salinity-challenged nutritional problems.

TABLE 13.1
Guidelines for nutrients contained in irrigation water and quantities that may be applied per foot of irrigation water. Also, average effluent water quality reported by Stowell (1999) and Asano et al. (1985).

Nutrient	Nutrient content in water in mg L^{-1} (or ppm)				Conversion to lb per 1000 ft^2 of nutrient added	Average Effluent	
or element	Low	Normal	High	Very high	for every 1 in. of irrigation water applied	Stowell[c]	Asano et al.[d]
N	<1.1	1.1–11.3	11.3–22.6	>22.6	11.3 ppm N = 0.71 lb N per 1,000 ft^2	—	1.4
NO_3^-	<5	5–50	50–100	>100	50 ppm NO_3^- = 0.71 lb N per 1,000 ft^2	—	6
P	<0.1	0.1–0.4	0.4–0.8	>0.8	0.4 ppm P = 0.057 lb P_2O_5 per 1,000 ft^2	—	8
PO_4^-	<0.30	0.30–1.21	1.21–2.42	>2.42	1.21 ppm PO_4^- = 0.057 lb P_2O_5 per 1,000 ft^2	—	24
P_2O_5	<0.23	0.23–0.92	0.92–1.83	>1.83	0.92 ppm P_2O_5 = 0.057 lb P_2O_5 per 1,000 ft^2	—	18
K^4	<5	5–20	20–30	>30	20 ppm K = 1.5 lb K_2O per 1,000 ft^2	26	15
K_2O	<6	6–24	24–36	>36	24 ppm K_2O = 1.5 lb K_2O per 1,000 ft^2	31	18
Ca^{+2}	<20	20–60	60–80	>80	60 ppm Ca = 3.75 lb Ca per 1,000 ft^2	64	59
Mg^{+2}	<10	10–25	25–35	>35	25 ppm Mg = 1.56 lb Mg per 1,000 ft^2	23	16
S	<10	10–30	30–60	>60	30 ppm S = 1.87 lb S per 1,000 ft^2	65	59
SO_4^{-2}	<30	30–90	90–180	>180	90 ppm SO_4^- = 1.87 lb S per 1,000 ft^2	196	180
Mn	—	—	>0.2[b]	—		0.03	—
Fe	—	—	>5.0[a]	—		0.20	—
Cu	—	—	>0.2[a]	—		0.03	—
Zn	—	—	>2.0[a]	—		0.08	—
Mo	—	—	>0.01[b]	—		—	—
Ni	—	—	>0.2[a]	—		—	—

[a] These values are based on potential toxicity problems that may arise over long-term use of the irrigation water, especially for sensitive plants in the landscape — turfgrasses can often tolerate higher levels. For fertilization, higher rates than these can be applied as foliar treatment without problems.

[b] Based on Westcot and Ayers (1985) and Harvandi (1994).

[c] Stowell (1999). Average of effluent water used on six golf courses in Southern California.

[d] Asano et al. (1985). Average of water quality from six water treatment plants (advanced treatment) in California.

13.3 SALINE AND RECLAIMED IRRIGATION WATER AND NUTRITIONAL CHALLENGES

13.3.1 FACTORS CONTRIBUTING TO NUTRITIONAL CHALLENGES

In many locations, reclaimed irrigation water has only slightly more nutrients than other irrigation water sources such as groundwater or stormwater runoff in lakes. However, as noted in arid regions, saline reclaimed irrigation waters are being applied more frequently on turfgrass. Thus, we will deal with these two irrigation sources together. Excluding any excessive soluble salts in reclaimed water, the usual nutritional issues associated with reclaimed water are (1) N, P, or S, if they are high, and (2) possible micronutrient levels and potential imbalances.

In contrast, saline irrigation water (including saline reclaimed water) has a number of additional issues of concern for managing turfgrass. Attempting to give a short description of fertility programs under saline irrigation water is challenging. Each irrigation water source is unique as are the soil profiles and other infrastructure site conditions, but soil fertility and plant nutrition with saline irrigation water are characterized by (1) high additions of certain nutrients or salt ions, (2) imbalances where one nutrient or element may suppress uptake or availability of another, (3) root toxic or shoot toxic ions (Na, Cl, B), and (4) micronutrients, as well as macronutrients, interacting with salinity and therefore directly affected by water quality. The net result is that soil fertility and plant nutrition become very variable, much more complex, and sometimes more confusing, impacting the making of management decisions. Factors contributing to a much more dynamic and challenging fertility program are the following:

- The *irrigation water* can easily become the primary input that adds the most chemical constituents to the soil–plant ecosystem—higher in total accumulative ion quantity over a complete growing season than all other inorganic or organic amendment or product additions.
- *Irrigation water treatments.* In addition to the natural constituents in the irrigation water, any added chemicals contribute to the total accumulation (often highest in the upper 2 in. or 50 mm soil profile zone), such as SO_4 from acidification.
- *Soil amendments.* When Na is present, it is common for gypsum to be added to the soil directly as a granular application or injected via the irrigation system. Organic and inorganic amendments must be carefully added to the soil infrastructure based on scientifically based research; excessive additions can escalate the salt-related problems.
- *Salt-leaching programs* oriented for downward movement of excess salts through the soil profile are implemented to primarily leach undesirable soluble salts, but if salts are leached, soil nutrients (potassium is quite vulnerable because it can be normally found in soil solution) will also be leached.
- *Changes in soil nutrient and salt ion* accumulation status become more dynamic because of (1) spatial distribution within the soil profile, because nutrients and salt ions are applied to the surface; (2) spatially across the

landscape and differential soil profiles, since irrigation system design and scheduling (water volume and duration of the irrigation cycle) result in differing quantities of water and constituents in the water applied over an area; and (3) temporally, across a growing season or year as water quality may change with time, such as the normal transition from rainy to dry seasons.
- *Irrigation water quality* often exhibits spatial and temporal variability. When irrigation water quality is poor, there can be more substantial differences across irrigation lakes from the influent side to the outflow outlet as well as stratification by depth. Seasonal variability in water quality may be due to weather patterns, such as dry and rainy seasons, or a single source may vary over time in quality, such as outflow from treatment plants with seasonal tourist occupation changes in resorts.

The specific reasons or goals for fertilizing turfgrasses are more complex compared to sites with good consistent irrigation water quality. When dealing with salinity, there are several primary reasons for developing a flexible nutritional program with fine-tuning of the fertilizer compositions and associated amendment applications based on proactive soil profile, water, and tissue sampling. For example, fertilization must be targeted to achieving the following goals:

- To meet basic plant nutrient needs for the specific glycophytic (with variable salt tolerance levels) or halophytic (salt-loving) turfgrass species and cultivar(s) planted on specific sites. When salinity additions are gradual and high, the grass species may change to a more salt tolerant one (actual salt-tolerance mechanisms are fully activated for a specific cultivar interacting with the salinity challenges on that specific site, or a true halophytic grass cultivar is planted), which requires turfgrass managers to modify their whole ecosystems management programs to accommodate grass adjustments to salinity or to facilitate the management of the new species or cultivar in some cases.
- To correct nutrient deficiencies, toxicities, and imbalances induced by saline irrigation water, irrigation water treatments (acidification, salt additions), soil treatments (gypsum, lime), and other amendments (wetting agents, zeolite, cytokinins, or other hormones) required to correct or adjust for irrigation water-induced problems. With variable and poor water quality, nutrient deficiencies, toxicities, and imbalances all become more frequent occurrences and may be ongoing problems that must be continuously addressed due to the frequency of saline irrigation water applications.
- To correct for leaching of soluble salts and the interactive solubility/mobility of specific nutrients. The key strategy is to ensure a consistent availability of essential nutrients to meet the sufficiency requirements for each turfgrass species/cultivars grown on a specific site.
- To maximize plant stress tolerance responses, especially salinity, drought, wear, heat and cold, and pests. Many plant stress tolerance mechanisms are affected by particular nutrients, such as K that is directly and essentially

involved in drought, cold, heat, and wear tolerances, and indirectly in salinity stress tolerance via turgor pressure maintenance as salinity increases.

- To alleviate soil chemical problems involving low or high pH, sodic soil conditions, acid sulfate soils, bicarbonates and/or carbonate complexation and unavailability/insolubility of key nutrients (Ca, Mg, Fe, and P), excess sulfates, excess chlorides, etc.
- To regulate or control plant growth rates for adequate wear tolerance and minimize excessive organic matter accumulation that can develop with excessive N and irrigation applications.
- To sustain turfgrass root volume and enhance root system redevelopment under salinity challenged conditions, especially related to Na root toxicities, Al/Mn toxicities (acid sulfate soils), and Na deterioration of the soil profile and pore space integrity
- To compensate for inherently low CEC soil profiles and soils with either very low or very high organic matter concentration that may occur in sandy soils installed to promote leaching of high total soluble salts.
- To maintain soil microbial populations as salt accumulation increases, especially in soil profile zones where thatch accumulation problems normally exit. When considering all the factors that influence plant nutrition and soil fertility when using saline irrigation water, it is important to view each nutrient individually, but also consider the whole ecosystem—i.e., a holistic or whole systems approach. Fertilizers also contribute to the salt load and total soluble salts because many are salt-inducing products (Table 13.2). Management adjustments must be made in several areas on an on-going basis. A whole systems approach when dealing with saline irrigation water that encompasses (1) water quality and specific nutrient load/imbalance, (2) accumulation of specific salt ions and of total salinity in the soil profile, (3) dominance/imbalance of toxic ions on the CEC sites, and (4) actual uptake of nutrients by the turfgrass plant, actual availability of each nutrient for root or foliar absorption, and fertilizer form (liquid, granular), method of product application, carriers or chelation chemistry in the actual fertilizer product, and timing of application.

13.3.2 IMPORTANT NUTRIENT RELATIONSHIPS AND INTERACTIONS

For guidelines related to assessing specific ion toxicity or problem salt ions in irrigation water, Table 3.7 of Chapter 3 provides a summary. For irrigation water quality guidelines, Table 3.12 of Chapter 3 contains this information, whereas Table 13.1 lists nutrient concentrations that are common in reclaimed water sources.

Water pH. The water pH can alter soil surface pH and thatch pH over time. Soil nutrients are most readily available in the soil pH range from 6.0 to 7.5. However, the chemical constituents that cause irrigation water to exhibit a pH outside of this range are more important than pH by itself. Another secondary effect of low pH irrigation water used in conjunction with acid-forming fertilizers that can be found on turfgrass sites is acidic thatch or a thin, highly acidic micro-zone at the surface that

TABLE 13.2
Salt indices of selected fertilizers

	Salt index	
Fertilizer source	Based on equal amounts of material	Based on equal amounts of plant nutrients
Sodium chloride	153	
Potassium chloride	116	1.94 K_2O
Ammonium nitrate	105	2.99 N
Sodium nitrate	100	6.06 N
Calcium chloride	82	
Urea	75	1.62 N
Potassium nitrate	74	5.34 N/1.58 K_2O
Ammonium sulfate	69	3.25 N
Calcium nitrate	65	
Ammonia	47	0.57 N
Potassium sulfate	46	0.85 K_2O
Magnesium sulfate (Epsom salts)	44	
Sulfate of potash–magnesia (potassium magnesium sulfate)	43	1.97 K_2O
Diammonium phosphate (DAP)	34	0.64 P_2O_5/1.61 N
Monoammonium phosphate (MAP)	30	0.49 P_2O_5/2.45 N
Triple (concentrated) superphosphate	10	0.22 P_2O_5
Slow release carriers	<10	
Gypsum	8	
Normal (ordinary) superphosphate	8	0.39 P_2O_5
Potassium monophosphate	8	0.16 P_2O_5/ 0.24 K_2O
Limestone	5	
Natural organic (5% N)	3.5	0.70 N
Dolomitic lime	1	

Source: From Carrow, R. N. et al. 2001. *Turfgrass Soil Fertility and Chemical Problems: Assessment and Management.* John Wiley & Sons, Hoboken, NJ.

affects microbial breakdown of granular fertilizers. Acidification of irrigation water can also cause similar problems.

High chloride does not cause direct turfgrass root tissue injury except at very high levels (generally >355 mg/L) that are well above the guidelines in Table 3.7 for more sensitive plants. Instead, Cl inhibits water uptake and, thereby, nutrient uptake. More importantly, high Cl^- may reduce NO_3^- uptake. If the irrigation source has consistently high Cl^- content (such as found in water sources involving seawater, brackish, or salt-water inundation as well as some recycled or effluent sources) (Duncan et al., 2000), then N rates may need to be increased by 10 to 25% using primarily NO_3^- forms applied foliarly using a "spoon-feeding" strategy. High accumulated chlorides in the upper soil profile can affect *Nitrosomonas* conversion of urea-N or ammonium-N fertilizer products to nitrates, and the fertility program must be adjusted according to the needs and absorption capability of each specific turfgrass cultivar.

High total salinity and sodium permeability hazard. The presence in the irrigation water of excess total salts or high Na that may induce a sodic soil condition will necessitate extra water be applied for leaching. This will result in leaching of all nutrients to a greater degree and require somewhat higher supplemental nutrient levels, especially on sandy soils. Fertilizers are not applied at higher rates than normal per application. However, fertilization should be more frequent using a spoon-feeding approach (larger amounts of slow-release fertilizers applied less frequently or smaller amounts of fast release fertilizers applied frequently or direct sprays or fertigation of liquid products) so that annual rates are 10 to 50% higher. Slow-release nutrient forms can be incorporated using a prescription philosophy to aid in maintaining adequate sufficiency levels in a specific turfgrass cultivar. Fertigation through the irrigation system is another excellent prescription fertilization strategy that allows easy concentration adjustments based on nutrient contents in the water and the specific soluble product.

When high Na content in irrigation water requires appreciable Ca to be supplied to dislodge Na from the CEC sites, extra Mg and K will be needed to maintain adequate soil test levels and nutrient balances for these nutrients. Light, more frequent applications are better than heavier but infrequent treatments. Potassium is exceptionally mobile, readily being displaced from the CEC sites by Na, and moving in soil solution down through the soil profile with irrigation water wetting fronts. Weekly applications may be warranted in extreme cases where saline water is used for irrigation and with sandy soil profiles.

Nitrogen. The quantity of N added over time in the irrigation source will directly contribute to the needs of turfgrass and other landscape plants receiving irrigation, and this is especially an issue with some reclaimed waters. Thus, supplemental N-fertilization must be adjusted accordingly and turfgrasses should be used that can tolerate the levels applied. Some turfgrasses deteriorate rapidly when overfertilized with N, such as red fescues and centipedegrass. On golf greens, high N in the water may produce more growth than desired, especially if the total annual application of N exceeds 4 to 6 lb N per 1000 ft^2 (*Poa annua* or bentgrass) or 8 to 12 lb N per 1000 ft^2 (bermudagrass), and consequently contributing to thatch buildup. If irrigation water containing even 1.1 ppm N is stored in ponds, algae and aquatic plant growth may flourish. High chloride levels can suppress uptakes of nitrates. With increasing salinity >2500 mg/L, *Nitrosomonas* bacterial conversions from urea or ammonium–N fertilizer sources may be reduced and nitrate might not be available for turfgrass uptake.

Phosphorus. The limits on P in irrigation water are lower than other macronutrients because low P is a limiting factor for enhanced algae production and proliferation of aquatic plants in lakes or ponds. The authors are aware of instances where water treatment authorities have reduced treatments to remove excessive P and N in reclaimed water when it is sold to turfgrass sites for irrigation. This reduction in treatment level is relative to what is required by law if they had discharged the effluent into a public water body. However, if there is not discharge into a public water body, the treatment facility may be able to lawfully reduce treatments. This does transfer any problems associated with excessive levels of these nutrients to the end user. Because reclaimed water is often stored in a lake or pond and is generally not fully used directly from the incoming pipeline, there can be appreciable eutrophication (direct oxygen depletion). Contract negotiations with the treatment plant or resource provider should specifically address these issues—really one of public responsibility to reduce N and P pollutants being transferred to end users.

Excessive P that reaches and accumulates in ponds, lakes, or streams can markedly increase growth of these problematic aquatic plants. Thus, turfgrasses can easily tolerate annual P additions up to 2.0 lb P_2O_5 per 1000 ft^2 from irrigation water, but aquatic plants would be greatly stimulated if this water accumulated in streams or ponds. The combination of high N plus P would also be most detrimental in causing eutrophication (lack of dissolved O_2 in water), and turf growth could be affected. If steps are taken to prevent lake or stream water contamination by accumulated excess P from the irrigation source, higher P levels can be tolerated by the turfgrass. But, if soil levels of P build up overtime, P may reach waterways through subsurface leaching or surface cascading and runoff.

An additional consideration is level of bicarbonates/carbonates that might be concentrated in irrigation water. Phosphates can bind with these compounds to form insoluble Ca-P compounds that are not available for turfgrass uptake. In high leaching areas, phosphorus applications may need to be increased 25–50% above nonsaline situations, with granular applications being made 3–6 times annually in order to meet specific turfgrass sufficiency levels.

Potassium. Because recreational turfgrass sites require ample K, any K in irrigation water is often viewed as beneficial. If K is high in reclaimed water, there is normally adequate Ca and Mg to prevent any nutrient imbalances, but K will contribute to total salinity. The key to turfgrass K fertility adjustments is to supply sufficient available levels of this critical nutrient on a continuing basis for root uptake, taking in consideration water infiltration/percolation rates (because K is highly mobile) and Na levels in the irrigation water, which can dislodge K from CEC sites and force it into soil solution. Potassium is then quite susceptible to leaching because of its mobility and can rapidly become deficient. Key ratios within the irrigation water to consider include K:Na (2–4:1 on meq/L basis), Ca:K (10–30:1), $N:P_2O_5:K_2O$ basis (2–3:1:4-8); and Mg:K (2–10:1). Potassium needs to be 3–8% base saturation on the CEC. As salinity increases, 1.5–3 times K rates may be required to maintain K sufficiency levels in turfgrass plants due the combination of the following: Na suppressing K uptake, Na enhancing K displacement from the CEC sites, and Na enhancing potential for K leaching. Na often requires high Ca additions that also compete with K at the CEC sites and for root uptake; greater leaching occurs on saline sites where K is one of the easiest to leach, and high K is needed to maximize salinity and other stress tolerance mechanisms. Potassium is an essential nutrient for root system maintenance plus all other abiotic (drought, heat, cold, traffic/wear) stress tolerances. For salinity, K is a very important ion governing osmotic adjustment, and for seashore paspalum it is essential for full osmotic adjustment and cannot be substituted by another inorganic or organic osmolytes (Lee et al., 2007, 2008).

Calcium. When saline irrigation waters are used, Ca is one of the most important stabilizing nutrients and the one element that causes the most confusion. Turfgrass managers should be aware of the total Ca added by the irrigation water source since groundwater, surface water, reclaimed water, and even rainwater (1 to 8 ppm Ca) all provide some concentration of Ca. As noted in Table 3.8, 60 ppm Ca would add 3.75 lb Ca per 1000 ft^2 per 12 in. of irrigation water (equivalent to 16 lb of $CaCO_3$). Thus, rainwater at 8 ppm Ca would add 0.50 lb Ca per 1000 ft^2 (2.2 lb Ca CO_3 equivalent) per 12 in. rain. Key considerations include Ca:Mg (3:1 meq/L basis), Ca:K (10–30:1), and Ca:Na+Mg (2–3:1) ratios as indicators of potential nutrient imbalances with increasing salinity. Calcium is a critical nutrient to keep balanced in salt-challenged systems because of its soil stabilization function (dislodging excess Na from CEC sites and its flocculation of colloids), importance for root cell membrane integrity, and turfgrass nutritional requirements. The key consideration is the actual availability of calcium for uptake by the turf with fluctuating soil chemistry and salinity interactions. The need for a multipronged product application approach is a critical strategy to ensure this essential nutrient is available for turfgrass root uptake. Granular sources such as gypsum or lime (with a sulfur source to create gypsum in the soil) should be applied to the soil to counter excess Na on the soil CEC, to reduce Na root toxicity, and to provide consistently available Ca for turfgrass root absorption.

From the authors' experience, it appears that frequent application of a high Na content irrigation water over the turfgrass shoot tissues may actually strip Ca from leaf tissues and reduce actual Ca tissue content. Thus, foliar applications of Ca are often needed under these conditions for nutritional balance in the turfgrass shoots. Also, Ca amendments are commonly applied to soils at high rates to alleviate sodic conditions and prevent Na toxicities to root tissues (Na displacement of Ca in root cell membranes, causing deterioration of the root tissues). Thus, as the use of saline irrigation water has increased, so has the number of Ca products that can be applied. Unfortunately, the fertilizer formulations and rates recommended by some of the manufacturers of the products are not agronomically sound. One example is *foliar fertilization*, which is an excellent spoon-feeding approach to enhance nutrient-use efficiency of Ca and other nutrients under saline irrigation, but a distinction should be made between foliar feeding nutrients through fertigation and direct foliar sprays; this distinction is particularly critical for Ca:

- *Fertigation.* Applies nutrient via the irrigation system and almost all of the nutrients are washed off of the leaves and those nutrients enter the plant through the roots system.
- *Direct foliar spray application.* Uses 1–2 gal of water per 1000 ft^2 to apply a nutrient and a high percent (>90%) of the nutrient usually stays on the leaf tissues if the grass has a reasonable shoot density and no rain or irrigation water is applied for a certain time period, depending on the nutrient and the product chemistry.
- *Foliar applied versus foliar uptake.* A suspension can be foliar applied, but the suspended particles will not be foliarly absorbed because they are not soluble. A liquid nonsuspension material can be foliarly absorbed directly

> through the leaf system. Thus, not all products that are foliarly applied are actually absorbed through the foliage.

Several nutrients are mobile (N, P, K, Mg, Cl, and Na) and can be translocated downward in the plant after foliar application and absorption. Other nutrients are somewhat mobile (S, Cu, Mo, Zn, and B), whereas a few (Ca, Fe, Mn, and Si) are relatively immobile. The immobility of Ca and its slow internal movement within the turfgrass plant can be attributed to its primary functions: cell membrane stabilization, constituent of cell walls, carbohydrate translocation, protein synthesis, activation of enzyme systems, and enhancement of nutrient uptake in roots and movement of those nutrients into cells.

It is not unusual for finely ground gypsum, lime, or other insoluble Ca forms to be put into a suspended formulation and then sold at a high price for "foliar feeding." Normally, the product literature points out how Ca foliar feeding can prevent Ca deficiency of tissues and how Ca can displace Na in the soil and alleviate sodic conditions. The question is whether such a product can really perform either of these claims. Table 13.3 summarizes the solubility and suitability for foliar applications of various Ca fertilizers. Effective Ca foliar feeding under salt-challenged conditions involves at least 10% Ca in the product that is applied to the foliage or leaves at a rate of 0.10 to 0.25 lb Ca per 1000 ft^2 using 1 to 2 gal water per 1000 ft^2, and the nutrients are water soluble and not in suspension. Uptake is rapid through the leaf ectodesmata pores, cuticle cracks, and stomata pores. Once inside the leaves, the nutrients pass

TABLE 13.3
Calcium fertilizer materials, relative solubility, and suitability for foliar application

Fast-release and high-solubility (foliar application for foliar uptake) liquid products
Calcium nitrate
Calcium chloride
Calcium gluconate/glucoheptonate
Calcium complexed with sugar alcohols or amino acids
Calcium acetate

Intermediate-release and intermediate-solubility (suspension or granular products; root uptake or clipping removal)
Calcium sulfate (gypsum) (regardless of sieve particle size)
Calcium thiosulfate

Slow-release and low-solubility (suspension or granular products; root uptake or clipping removal)
Calcium hydroxide/oxide
Calcium carbonate (lime) or powdered coral
Dolomite (calcium/magnesium carbonate)
Calcium silicate

directly into cells through the cell wall and plasma membrane, or enter the apoplasm (space between cells) and then are possibly transported in the xylem (upward). More mobile nutrients can enter the phloem (for upward or downward translocation) and be transported to the root tissue, but immobile Ca will not be translocated downward from the turfgrass shoots after foliar absorption.

Not only is fertilizer product form important, but the rate and timing or frequency of applications are also critical for achieving Ca sufficiency levels in turfgrass plants. If the target is to apply foliar Ca to alleviate Ca deficiency in shoot tissues, the rates given above are appropriate as long as they are foliarly absorbed. However, a critical salinity question must be considered: Does the Ca that is not foliarly absorbed help to alleviate sodic soil conditions by displacing Na from soil colloids? For remediation of sodic conditions, the Ca application rates are normally at 10 to 20 or more pounds per 1000 ft^2. Thus, the claim that Ca at 0.10 to 0.25 lb Ca per 1000 ft^2 will assist in sodic soil conditions is misleading.

Application of granular sources such as gypsum or lime that involve root uptake will entail a lag period of 3–4 weeks before actual stabilization in the turfgrass shoots, whereas liquid sources that involve actual foliar uptake can take 4 to 7 days before visual results (decrease in yellow discoloration in the shoots) are observed. With high salinity challenges, and depending on level of salinity tolerance in the specific turfgrass cultivar, those visual results could take up to a week. Hot, dry environmental conditions will limit nutrient uptake. Mowing of leaves or excessive irrigation/rainfall before uptake will wash the nutrients into the soil for possible eventual root absorption. If clippings are returned to the soil, the nutrients can become available for uptake after microbial breakdown; if clippings are removed after uptake, the nutrient will not be recycled. When collecting clippings for tissue analysis, allow 1 to 2 weeks after liquid product application to the leaves before sampling. Otherwise, elevated and misleading nutrient concentrations could be revealed with the tissue analysis, and unnecessary fertilizer product applications could result.

Magnesium. Most often, Mg is present in irrigation water at lower levels than Ca. Sometimes Mg content will be relatively high (infusion from ocean water, brackish water, or salt-water intrusion into wells), which can reduce Ca on CEC sites and restrict K availability (Duncan et al., 2000). Exceptionally high levels of Mg will mimic excess Na in the soil and internally in turfgrass plants, affecting nutritional balance. In these cases, supplemental Ca may be needed to maintain adequate Ca for maintenance of good soil physical conditions and to counter Na toxicities. Seawater has a high Mg content, so salt water intrusion sites may exhibit this problem. Also, supplemental K will be necessary to maintain ample K nutrition. Normally, a 3 to 8 Ca:1 Mg ratio (meq/L) is suitable.

More often, low Mg, rather than excess Mg, content in irrigation water is a more dominate problem. Low Mg caused by the addition of high Ca amendments for irrigation water that contains too much Na is another common situation. Another problem of increasing frequency is Mg deficiency induced by application of unneeded Ca on sandy sites, especially with calcareous sands. As with Ca, knowledge about Mg content and rates applied in the irrigation water are very useful in avoiding deficiencies or excessive Mg problems. Some turfgrasses such as seashore paspalum actually require high levels of magnesium and will thrive in environments where higher than normal concentrations are found in irrigation water or in the soil profile. But balancing these high levels with Ca supplements is still required in the fertility maintenance program, especially where turfgrass color expression (Mg is the core molecule in chlorophyll) is important.

Sulfur. It is not unusual for SO_4 content in reclaimed water to be 100 to 200 mg/L, and groundwater influenced by seawater intrusion may be even higher (seawater contains about 2600 mg/L SO_4). Sulfur deficiencies may occur on high rainfall, sandy soils that do not receive SO_4 from rainfall due to their location relative to industrial activity. Normally 2 or 3 lb S per 1000 ft^2 per year is sufficient for turfgrasses, and this concentration is often provided by SO_4 containing N, K, Mg, or Ca fertilizers. Irrigation water at 200 mg/L SO_4 would supply 4.2 lb S per 1000 ft^2 per 12 in. water.

Iron (Fe). In addition to macronutrients in irrigation water, **micronutrients** (Fe, Mn, Cu, Zn, Mo, Ni, and B) can affect turfgrass fertilization. Table 3.11 has recommended maximum concentrations of trace elements in irrigation water for long-term values (LTV) and short term values (STV) based on AWA (2000) and Westcot and Ayers (1985). The 5.0 mg/L guideline in Table 3.11 for Fe in irrigation water is not related to any potential "toxic level," but continued use could cause (1) precipitation of P and Mo, and deficiency problems for turfgrasses (P) or landscape plants (P or Mo); (2) staining on plants, sidewalks, buildings, and equipment; and (3) potential plugging of irrigation pipes by anaerobic Fe bacteria sludge deposits, or potential accumulation in lakes and ponds. This accumulation can be a problem at >1.5 mg/L Fe, and high, continuous rates of Fe may induce Mn deficiency or much less likely, Zn and Cu deficiencies. On heavily leached sands, where Mn is often low, this Fe-induced deficiency may become a problem. At 5.0 mg/L Fe, 12 in. of irrigation water would add 0.31 lb Fe per 1000 ft^2, whereas a typical foliar application to turfgrasses is 0.025 lb Fe per 1000 ft^2, but in only 3 to 4 gal water per 1000 ft^2. In most instances, Fe concentrations are low, and turfgrasses will respond to foliar Fe. When total salinity is high, Fe plus a cytokinin as a foliar treatment is often beneficial, since salt-stressed plants exhibit low root cytokinin activity. Critical **indicator ratios** include Fe:Mn:Mg (1:1:1 with pH <8.0 and 3:1:1 when pH > 8.0).

Manganese (Mn). Manganese can become toxic to roots of many plants, so use of irrigation water high in Mn (0.20 mg/L) can contribute to this problem, especially on poorly drained, acidic (pH < 5.5) soils. Acidic, anaerobic conditions transforms soil Mn into more soluble (and toxic) forms. If water is high in Mn, liming to pH 6.0 to 7.5 and good drainage greatly reduces the potential for Mn toxicities. At >1.5 mg/L Mn in irrigation water, Mn can contribute to sludge formation within irrigation lines. Also, high Mn may inhibit Fe uptake and promote Fe deficiency in turfgrasses. Supplemental foliar-applied Fe would prevent this problem. With most turfgrass situations, Mn is very low in irrigation water and supplementation over and above a regularly scheduled micronutrient application may be needed as salinity increases. Mn:Zn ratios should be 1:1, because both are essential nutrients for activating salinity tolerance in turfgrasses, and both micronutrients have other critical functions (disease suppression for root-borne pathogens, enzyme activation for growth and development).

Copper (Cu), Zinc (Zn), Nickel (Ni). The irrigation water levels in Table 3.11 are based on potential to develop toxicities on sensitive landscape plants over time.

Turfgrasses can tolerate relatively high rates due to mowing of leaf tips. Unusually high Cu and Zn could inhibit Fe or Mn uptake and, thereby, induce deficiencies of these nutrients, even on grasses. In this case, these nutrients would need to be supplemented in the overall fertility program for maximum turfgrass performance, especially with increasing salinity challenges.

Molybdenum (Mo). Molybdenum toxicity would be very unlikely in plants, but livestock feeding on grasses high in Mo can be detrimental. In turfgrasses, as salinity increases, Mo is exposed to direct competition with divalent oxyanions (sulfates and phosphates) for exchange sites. Excess applications of gypsum or lime, single superphosphates, and sulfur acidification can affect Mo availability for grass uptake. Mo acquires hydrogen ions and becomes less ionic as soil acidity increases, hence Mo is less readily absorbed by turfgrass roots or forms Mo polyanions that are completely unavailable for uptake.

Boron (B). Boron is often associated with saline hydrogeological conditions and is another element that elevate to a toxicity problem if concentrations are too high in irrigation water. Toxicity can occur from irrigation water, wastewater, composted sewage sludge, or native arid soils. Leaching is easiest in acidic sodic soils that are sandy. As soil pH increases from 6.3 to 7.0, B is more tightly adsorbed on clays and can be complexed with Fe/Al oxides. Thus, at $\text{pH} < 7.0$, leaching may prevent B accumulation in soils, whereas at $\text{pH} > 7.0$, light lime applications to maintain high Ca levels can help fix the B in less available forms. Leaching is more effective on coarser-textured soils than on fine-textured ones, and acidification may be needed to enhance the B movement through the soil profile.

Other trace elements. Reclaimed water may contain excessive levels of some elements such as heavy metals. These elements as reported by Westcot and Ayers (1985) and Snow (1994) are presented in Table 3.11. These elements would not directly influence turfgrass nutrition (because some grasses are effective phytoaccumulators of heavy metals), but would be a concern for toxicity responses on some landscape plants.

Bicarbonates and carbonates. High bicarbonates are relatively common in reclaimed water and some groundwater sources (Eaton, 1950). While $HCO_3 > 500$ mg/L can cause unsightly, but not harmful, deposits on foliage of plants, there are no specific HCO_3 or CO_3 levels that result in grass nutritional problems. Instead, it is the imbalance of HCO_3 and CO_3 in conjunction with Na, Ca, and Mg sequestration that is most important. When $HCO_3 + CO_3$ levels exceed Ca + Mg levels (in meq/L), both Ca and Mg can be precipitated as insoluble and unavailable lime deposits in the soil profile and/or as scale in irrigation lines. Two problems can arise from excess lime precipitation:

- If Na is moderately high (>100 to 150 mg/L), removal of soluble Ca and Mg by precipitation into the relatively insoluble carbonate forms will leave Na to dominate the soil CEC sites and create a potential sodic soil condition. High Na concentrations on the CEC sites will depress availability of Mg, K, and Ca. Acidification of irrigation water is the normal management strategy for this situation; the acid breaks up the insoluble lime precipitate as carbon dioxide and water, freeing up the Ca and Mg for potential root uptake. The extra calcium is also then available to compete with Na for positioning on the CEC sites.

- On sandy soils, the calcite (lime) may start to seal some of the pores and reduce irrigation water infiltration/percolation.

Root toxicities from Na, Cl, and B (see Table 13.3.) Specific ion toxicity (Na, Cl, and B) and miscellaneous chemical constituent problems occur for sensitive plants when using sprinkler irrigation water (after Ayers and Westcot, 1994; Hanson et al., 1999; AWA, 2000). Although the guidelines for root toxicities or soil accumulation of these ions in Table 3.7 are most appropriate for sensitive trees, shrubs, and other landscape plants, excessive levels of Na^+ can cause turfgrass root deterioration at higher levels than are indicated in the table, especially for glycophytic grasses. Many of the halophytic grasses very strictly regulate the uptake of Na to a certain concentration in the plant, then exclude additional uptake, leaving the Na ion in the soil and competing for CEC sites with other fertilizer nutrients. Chlorides are often readily absorbed and moved very quickly to the ends of the growing points in both landscape plants and turfgrasses, resulting in leaf tip burn symptoms. Landscape plants will continue to load the excess chlorides into the growing points until the leaves and stems die. For turfgrasses, excess chlorides are normally recycled by normal mowing practices or can be removed by collecting and proper disposal of clippings.

13.4 ULTRAPURE IRRIGATION WATER AND NUTRITIONAL CHALLENGES

Readers are encouraged to read Chapter 5 for a more comprehensive treatment of causes and management of sites with ultrapure irrigation water; but in this section, we will note the most important issues related to soil fertility and plant nutrition. Ultrapure irrigation sources often lack adequate amounts of minor and secondary nutrients essential for plant growth and since nutrient additions from the water is limited, regular soil testing is recommended (Hagan et al., 1967). As ultrapure waters infiltrate into the soil, they are very effective in leaching salts from the soil since they can more easily dissolve minerals and deplete or strip CEC sites of nutrients. General plant nutrition on sandy rootzones and particularly those rootzones lacking organic matter content, which accounts for much of the CEC on these sites, is a special concern. The combination of few nutrient additions from ultrapure water capability, greater leaching potential, and low CEC sands (that are unable to retain nutrients) requires close monitoring of fertility. Under these conditions, even spoon-feeding on a frequent basis may not provide sufficient nutrients, and the duration of availability and grass root uptake response can be very short. The authors and Carrow et al. (2001) have recommended the application of the inorganic amendment zeolite in such situations to increase permanent CEC capability to at least a 2.5 to 3.0 cmol/kg range. For a zeolite with a CEC of 150 cmol/kg, an application of about 225 lb per 1000 ft^2 would be required to alter the average CEC of the surface 4.0-inch soil profile zone by 1.0 cmol/kg. This zeolite application is slightly less than a 1%-by-volume weight amendment to the 4.0-inch (10 cm) zone and should be done in conjunction with a cultivation event (core or solid tine aeration) to integrate the product into the soil profile.

13.5 PRODUCTS AND LABEL PROBLEMS

In the Ca section, the challenge of products was noted that actually would not work for the problems described on the product label due to: (1) a chemical form that could not be taken up foliarly, even though the product was sold as a foliar-applied product, and (2) the rate used being between 1000th to 10,000th of the concentration that is actually required for the stated problem (in this case alleviation of sodic soils). Another commonly observed and increasing problem that seems to be stimulated by saline irrigation water sources is the "proprietary product" where the manufacturer does not completely list the active ingredients; patents were actually developed to allow protection plus disclosure, but this "protection" seems to be insufficient for some manufacturers. Fertilizer and pesticide manufacturers have operated under patent laws with full disclosure of product materials and constituents in terms of chemical nature and quantity and have been able to compete in the market place. So the "proprietary product" nonlabel used for so many products is just not valid.

In the case of poor irrigation water quality, the turfgrass manager must make many adjustments and use a multitude of products, but each product should be used for a specific reason, in the correct formulation and at the correct rate. The authors strongly recommend (based on experience) to not apply products when the material is not fully documented on the label, especially because developing good fertilization and salinity management programs are already complex enough, and introducing unknowns into the equation is not a good maintenance practice due to the potential for unexpected interactions with salinity chemistry. One reason some manufacturers do not wish to list the active ingredient in their products is because it is a common material available from much less expensive sources.

Another version of not listing an active ingredient is to include an ingredient that will give a fertility response, such as soluble N or foliar Fe, but those rapid response nutrients are generally not listed on the label. If a product is not sold as a fertilizer, it does not require a product label for disclosure on quantity and composition. The only reason for this practice is to ensure a turfgrass response, which is often attributed by the grass manager to be due to the "inactive active ingredient" in that particular product.

A tremendous amount of chemistry is deposited in the top 2–3 in. in a turfgrass soil profile, ranging from normal fertilizers to wetting agents to hormones to pesticides (insecticides, fungicides, herbicides) and other chemical enhancement products. When saline irrigation water and that complex chemistry is added to the ecosystem, unexpected interactions can occur that can result in quite rapid deterioration of closely mowed turfgrasses both cosmetically and in overall sustainable performance. Full disclosure of all product constituents is essential for long-term management of turfgrasses, especially with any level of salinity challenges on both the soil and the turfgrass.

13.6 SUMMARY

In summary, when the irrigation water is nutrient rich and/or salt laden, it becomes the greatest source of desirable and undesirable nutrients and elements of all management inputs. In contrast, when irrigation water is ultrapure, it becomes the greatest means to reduce soil nutrients. Either way, the irrigation water cannot be ignored in terms of fertility and plant nutrition programs.

Irrigation water sources with high concentrations of chemicals will cause the most problems and fertility programs must be adjusted accordingly. It is instructive to note that for water quality testing, two of the four "salinity problem" areas are directly related to nutrients; namely; nutritional status of the water and status of toxic or problem salt ions. Most fertilizer products have a salt index. Although total soluble salts are the number one salinity problem that accounts for turfgrass manager success or failure on a salt-affected site, just behind this in importance is their ability to maintain soil fertility and plant nutrition in a ever-changing dynamic stress-impacted environment. Most turfgrass managers learned about developing fertility programs under much more stable and tranquil conditions using a good low salinity irrigation water supply.

For maintenance of a sustainable soil/plant nutritional program, the most important aspects include these essential points:

1. Soil chemical properties are primary (CEC level, nutrient balances and imbalances, nutrient concentrations and interactions, pH, salt control and management) considerations.
2. Soil physical problems are also equally important (especially excessive organic matter and other amendments, frequency of cultivation programs, or any factor that limits water movement).
3. Soil biological activity or biostimulants are least important as good turfgrass growth usually equates to good conditions for microbial activity.
4. The ecosystem is dynamic and constantly changing (salinity persistently magnifies those challenges with each irrigation application).
5. The diversity of products should be considered: whether granular or liquid, and their specific solubility, whether they are actually foliarly absorbed, whether they are biostimulants with fully disclosed composition, or whether they are fully researched under unbiased actual turfgrass management conditions.
6. Implementing a common sense basic fertility program (there are no magic bullets or miracle products) and keeping management decisions as simple as possible under the very complex salinity umbrella.

14 Lake, Pond, and Stream Management

14.1 OVERVIEW OF SURFACE WATER QUALITY AND STORAGE

14.1.1 WATER QUALITY PARAMETERS OR STRESSORS

In this chapter the focus is on irrigation water quality problems and treatments in irrigation lakes, ponds, or streams. This is a companion chapter with (1) Chapter 12, which dealt with problems other than within the irrigation lake, pond, or stream, such as in pipes, wells, acidification, calcium treatments, and other issues, and (2) Chapter 13, which detailed the nutritional challenges arising from application of saline irrigation water. Chapters on specific irrigation resources (Chapters 5 through 9) also contain important information on problems specific to various water resources and their suggested management options. One such issue is salinity in irrigation water, whether in the initial source or in the irrigation lake, which was the focus of Chapters 6 and 7 and will not be discussed in this chapter.

The 21st century has brought about a change in turfgrass water management because of rapid population increases, "megacity" development and escalated urbanization, growing freshwater scarcity and reduced application on recreational turfgrass sites, increasing competition among all water users, depletion of fresh fossil water reserves, and significant concerns for environmental protection (Lazarova and Asano, 2005). Recreational turfgrass and landscape irrigation water applications are being relegated (and often mandated) to using nonpotable, alternative water resources that characteristically contain some salt and nutritional loads with both short- and long-duration use implications on environmental sustainability. Turfgrass management equates to environmental management when these water resources are used over time, and an important component of environmental water management is entrenched within the surface waters of irrigation lakes, ponds, and streams and their maintenance as primary water sources. Water reuse and conservation principles are often superimposed on these management strategies. In short, turfgrass and landscape managers must manage the **water quality** of their lakes, ponds, and streams for both **environmental quality** and **irrigation quality**, while often considering water conservation best management practices (BMPs) (Carrow, 2006).

When the term *water quality* is used, it implies the quality of the aquatic environment, but it is not a simple parameter because water bodies and streams possess diverse physical, chemical, and biological properties, which in combination, influence water quality. Physical, chemical, and biological factors that impair water quality are called **environmental stressors,** are defined as physical, chemical, or biological agents that potentially impact human health and welfare, environmental resources, or global systems. The focus in this chapter is on irrigation water quality in storage facilities—the quality traits of the water that affect continuous irrigation use on turfgrass and landscape sites, and these traits are listed in Table 14.1. However, there is considerable overlap between irrigation water quality and environmental water quality impairments or environmental stressors of concern in the Clean Water Act (USEPA CWA, 2006).

As noted, important characteristics of lakes and ponds and the water contained in them as related to irrigation use are summarized in Table 14.1. Many of the treatment options for these issues are discussed in this chapter with respect to treatments (often preventative treatments) within water storage facilities and primarily in lakes, ponds, and streams. Background information on many of the irrigation water problems is found in Chapters 2 and 3. Good references for lake, pond, and stream characteristics that influence turfgrass and landscape irrigation are Chapman (1996), Holdren et al. (2001), Beard (2002), Trounce (2004), Yiasormi et al. (2005, 2007), USEPA CL (2008), USEPA RS (2008), Water on the Web (2008), Ennis and Bilausa (2000), Franks et al. (2004), Hopko (2006), Shaw et al. (2008), Schultz et al. (1997), and USEPA (1986).

14.1.2 SOURCES OF STRESSORS

In the United States, lakes and reservoirs are a major water resource and comprise 40.6 million acres. Inland lakes and reservoirs provide 70% of the drinking water as well as water for irrigation, industry, and hydropower. The quality and protection of these lakes are monitored by the Environmental Protection Agency (EPA) as required by Section 305(b) and 314 of the Clean Water Act. Each state is required to identify pollutants or stressors causing impairment of designated uses for streams, lakes, and estuaries; to periodically report on the sources of these stressors (such as disposal from wastewater treatment plants or mine reclamation runoff); plus groundwater withdrawal, contamination, and subsequent physical, chemical, and biological impacts on the surrounding environment.

For golf courses and other turfgrass sites, irrigation lakes or ponds often serve as a retention facility for flood control and pollution abatement where the watershed includes considerable area outside of, and usually surrounding, the turfgrass facility. Also, streams often enter a landscape area from an upstream watershed. Thus, the quality of surface waters on a facility is often a reflection of any problems that may arise in the upstream, or water flow, watershed (Lee and Jones-Lee, 2005). When surface-water problems affecting irrigation does occur on a turfgrass site, the first response is to assess the cause. Because pollution may occur upstream or on the site, it is important to consider both. Common sources of stressors impairing surface-water quality that may arise either on site or from upstream sources are listed in Table 14.2 and include

- Hydrologic modifications causing sediments either upstream or on site (flow alterations/regulation, dredging, dam construction)
- Channelization (amplified variations in runoff and stream flow)
- Agricultural discharges (animal feedlots, irrigated/nonirrigated crop production, riparian pasture grazing/pastureland)
- Industrial discharges

TABLE 14.1
Physical, chemical, and biological characteristics of a lake and its water quality

Physical characteristics

Lake types
Depth, nature of littoral zone/littoral shelf
Water source
Temperature, mixing and stratification
Retention time
Drainage basin/lake area ratio
Lake water levels
Water clarity/turbidity
Temperature
Trophic state/eutrophication
Sediment—depth
Odor

Chemical characteristics

Dissolved gasses—dissolved oxygen, carbon dioxide, ammonia, H_2S, others
Phosphorus
Nitrogen
Sulfate
Soluble salts/salinity/electrical conductivity
Sodium
pH—acidification, alkalinity/hardness, buffering capacity
Ionic balance—bicarbonates, carbonates, Ca, Mg, K, H
Metals and micronutrients—dissolved Fe
Organics
Chemical nature of bottom sludges
Biological oxygen demand (BOD), total organic carbon (TOC), and chemical oxygen demand (COD)
Fecal coliform
Pesticides

Biological characteristics

Oxygen-depleting materials (dead algae, dead aquatic plants)
Algae
Cyanobacteria—blue-green algae, photosynthetic bacteria
Aquatic plants—macrophytes (aquatic weeds)
Bacteria—pathogenic from duck/geese waste
Zooplankton—beneficial microscopic animals feed on algae
Animal nuisances—zebra mussels, bryozoans
Pathogens

Sources: Chapman, D. 1996. *Water Quality Assessments: A Guide to the Use of Biota, Sediments and Water in Environmental Monitoring*. 2nd edition. E&FN Spon. London; Holden, C. et al., 2001. *Managing Lakes and Reservoirs*. N. Am. Lake Manage. Soc. and Terrene Inst. in coop. with Off. Water Assess. Watershed Prot. Div. U.S. Environ. Prot. Agency, Madison, WI; Yiasoumi, B. et al., 2005. *Farm Water Quality and Treatment. Agfact AC.2*, 9th edition; Yiasorumi, B. et al., 2007. Managing Blue-Green Algae in Farm Dams. PrimeFact 414. NSW Dept. of Primary Industries, Orange, NSW, Australia; Water on the Web, 2008. Understanding: Lark Ecology Primer. Water On The Web, Minneapolis, MN.

- Land disposal of wastes (trash dumps, recycling plants)
- Municipal discharges
- Reclaimed water used for irrigation—may contain higher than normal N, P, or other compounds compared to water being discharged into a public water body instead of a irrigation lake
- Urban runoff/storm sewers (sticks, leaves, grass clippings, motor oil and coolant residue, litter, or other debris)
- Runoff of sediment, pesticides, nutrients, and salts for on-site and/or upstream residential or commercial lawns, landscapes, construction sediments, etc.
- Natural sources (e.g., salt deposits)
- Silviculture
- Streambank modification (stabilization, buffer zones)
- Surface mining (resource extraction, mine tailings)
- Atmospheric deposition
- Highway maintenance and runoff
- Drainage and filling of wetlands
- Forestry activity (clear-cutting, habitat modifications)
- Recreational turfgrass/landscape site development over fresh-water aquifer recharge (infusion) zones

TABLE 14.2
Common sources of stressors impairing surface quality of irrigation lakes and ponds

Hydrologic modifications causing sediments either upstream or on site (flow alterations/regulation, dredging, dam construction)
Channelization (amplified variations in runoff and streamflow)
Agricultural discharges (feedlots, irrigated/nonirrigated crop production, riparian pasture grazing/pastureland)
Industrial discharges
Land disposal of wastes (trash dumps)
Municipal discharges
Reclaimed water used for irrigation—may contain higher than normal N, P, or other compounds relative to if the water was discharged into a public water body instead of a irrigation lake
Urban runoff/storm sewers (sticks, leaves, grass clippings, motor oil and coolant residue, litter)
Runoff of sediment, pesticides, nutrients, and salts for on-site
Natural sources (e.g., salt deposits)
Silviculture
Streambank modification (stabilization, buffer zones)
Surface mining (resource extraction, mine tailings)
Atmospheric deposition
Highway maintenance and runoff
Drainage and filling of wetlands
Forestry activity (clearcutting, habitat modifications)

Source: After Lee, F. and A. Jones-Lee. *Stormwater* 6(5): 62–67.

A comprehensive assessment for environmental or health-related water quality can be complicated and include aspects not listed in Table 14.1 (Chapman, 1996; Holdren et al., 2001; Artiola, 2004). For example, the description of the quality of the aquatic environment can be assessed by quantitative measurements, such as physicochemical determinations (in the water, particulate material, or biological tissues); biochemical or biological tests (BOD measurement, toxicity tests, N–P–Cl concentrations); or semiquantitative and qualitative descriptions such as biotic indices, visual aspects, species inventories, odors, etc. These determinations are conducted in the field and laboratory and produce various types of data, which are adapted to different interpretative techniques. Such an assessment is targeted to overall water quality and identification of any stressors. For a minimum assessment related to irrigation use, Beard (2002) suggested the following:

- Full irrigation water quality analyses
- BOD
- COD
- Total P and N
- Source of nutrient loading
- Turbidity
- Dissolved oxygen
- pH
- Nature of any biological stressors—type of aquatic weeds, algae type, pathogenic spores, etc.

14.1.3 WATER STORAGE CONSIDERATIONS

Most alternative water resources will need to be stored in catchment facilities for later use, usually either in lakes, ponds, or reservoirs. The source of that water can come directly or indirectly from sewage treatment plants (Chapter 8), stormwater harvested from surrounding areas (Chapter 9), saline aquifers (Chapter 6), brackish or seawater blends (Chapter 7), snow or ice melt (Chapter 5), reverse osmosis (Chapter 12), or secondary storage reservoirs, canals, or rivers.

Problem irrigation ponds or lakes often are a result of several factors that combine to cause algal blooms, excessive aquatic plant growth, turbidity, poor water quality, odor, or other problems. Common contributing factors to these problems include nutrient loading, shallow depths, suspended solids, sediments, and biological imbalances. Several factors must be considered to prevent these problems when storing these water resources:

1. Salinity load: Total dissolved salts, sodium concentration, bicarbonates and carbonates, sulfates, specific type of salts (i.e., magnesium chloride, calcium chloride, and sodium chloride from desalting ice or runoff from snow-covered roads). Salinity additions into the stored water should be minimized from the surrounding soil or groundwater. For example, in arid regions where the soils may contain a zone of high salt accumulation at 1 to 4 ft below the surface, care must be taken during construction not to mix this

salt-laden soil into the surface of areas to be planted in turfgrasses or landscape plants and to keep them separate (with an impervious liner/bentonite layer) or block the high-salinity layers from seepage into the pond or lake.

2. Nutrient supply rate: Especially nitrates and phosphates, but all other nutrients, including calcium, magnesium, heavy metals, and micronutrients. Additions should be reduced where feasible. Treatment plants are usually focused on chlorides because of local, state, federal, and/or national guidelines.
3. Hydrology: Depth of water table, proximity to coastal sites and salt water inundation, storm surges, flooding, salt spray, proximity to freshwater reserves or aquifer recharge sites.
4. Shape, size, and depth (>10 ft or 3.1 m) of the catchment facility: Watershed area, surface area, total volume of water, sealed (lined) or unsealed containment, evaporation, dependability of replenishment.
5. Sedimentation: Deposition of fines (silt, clay, organic matter, or sand sizes <0.15 mm) and ease of cleaning (especially critical for water stored from rivers or canals). Sediment inflow should be minimized and/or isolated from pumping equipment if possible, and undue sedimentation from decaying organic matter within the water body should be reduced.
6. Connection to and hydrology of multiple lakes or ponds on site; pump intake positioning (floating or on bottom); pumping costs for water movement or use of balance pipes and/or gravity-operated transfer systems; aeration potential when moving water from one feature to another through fountains or via open streams with gravity flow rock-style rapids and/or waterfalls.
7. Proximity to and potential impact on freshwater resources (recharge zones) where groundwater contamination by deep percolation may be an issue, may require lining with synthetic barriers or sealing with clay in conjunction with catchment facilities and recycling, and/or surface water contamination may occur when rapid or high storm rainfall events result in uncontrollable overflows reaching a stream, lake, canal, or river and may require minimum freeboard levels.
8. Electrical outlets for aeration and circulation equipment, on-site water treatment, blending options.
9. Buffering components in water to minimize rapid pH swings when stored.
10. Miscellaneous skimmer basket/filtration systems to manage debris accumulation such as sticks, leaves, grass clippings, litter, and other trash.

These bodies of stored water can typically contain various levels of nutrients. Microbes (algae, phytoplankton, and zooplankton) will use and recycle/redistribute nutrients during their life cycles. Eutrophication can result when nutrient loads increase enough in concentration to supply water-based plants. Examples include nitrates and phosphorus contained in recycled or effluent water, harvested stormwater or spring snowmelt runoff (salt products for melting ice and snow), or seasonal air temperature–induced turnover of lakes and ponds (that do not have aeration systems and the salts stratify in layers based on depth and ion concentrations) used for turfgrass irrigation (Keating, 2005). Nutrient accumulation can occur with the breakdown of organic debris, such as leaves, sticks, and grass clippings, or from nutrient-laden soil particles (sediment or “fines”) being deposited into catchment facilities from runoff. The resulting elevated nitrogen and phosphorus concentrations can create hypoxia or low oxygen-laden water.

Many of the ponds used for water storage and subsequent use on turfgrass are retention ponds, or facilities that maintain a permanent pool of water. However, in more arid regions with low or sporadic rainfall distribution, some of these ponds may actually be detention ponds, or dry facilities that contain water only as a result of rainfall or other runoff events (Jones et al., 2006). Regardless, safety design issues in the construction of these storage facilities include safety racks on outlet pipes, nonhazardous embankment slopes including a safety shelf conducive to maintenance by personnel and equipment, elimination of nonstagnant or standing water areas that are prone to mosquito-breeding habitats and the West Nile virus risk, adequate-sized spillways for extreme rainfall events and subsequent overflow, and separated inflow and outflow pipes (by distance and direction) to promote good circulation and minimize the creation of a continuous flow stream and/or use as an energy dissipater at the outlet where it discharges into the water storage facility (Jones et al., 2006).

14.2 LAKE AND POND ECOLOGY

A basic understanding of lake and pond fluctuation and dynamics over a year, the potential for stratification, and problems that may result from these responses is a good starting place for enhancing lake and pond management (Smart, 1999; Ennis and Bilawa, 2000; Holdren et al., 2001; Otterbine, 2003; Hopko, 2006; Shaw et al., 2008; Water on the Web, 2008). The most important factors are light, temperature, nutrients, and oxygen.

14.2.1 Lake Ecological Characteristics

Light and temperature. Sunlight is the major energy source for aquatic ecosystems, and affects activities directly through photosynthesis and temperature regimes. Absorption of light results in heat that must be dissipated, which influences the thermal layers or stratification and circulation patterns in the water body. Photosynthesis occurs only in the upper layer of the pond or catchment facility because this is the area in the water column that sunlight is able to penetrate, and this area is called the **euphotic zone**. Shallow bodies of water less than 9 ft (3 m) in depth more commonly experience problems such as bottom-rooted weeds or benthic algae.

During the summer, temperature differences between the upper (**warmer, epilimnion**) and lower (**cooler, hypolimnion**) waters can become great enough for the zones to become thermally separated due to water density with little mixing between layers—a process called **thermal stratification**. The area created between the warm and cold layers, called the **thermocline** or **metalimnion**, can act as a physical barrier preventing any vertical mixing in the lake, and encouraging algae growth throughout the warm surface waters. Thermal stratification impacts the water quality in a lake primarily because of its effect on dissolved oxygen levels. Compared to cooler water, warm water has a reduced capacity to hold oxygen, that is, water at 52°F can hold over 40% more oxygen than water at 80°F. As water temperature increases, the water's capacity to hold oxygen decreases. Thermal stratification occurs in a seasonal cycle with the thermocline becoming more severe in late summer and late winter. Lakes and ponds in warmer weather regions experience a shorter annual cycle, especially in late summer and early fall.

Dissolved oxygen in a lake comes primarily from photosynthesis and wave and wind action. During stratification, the colder bottom waters are separated from both of these oxygen sources, and an anoxic or oxygen-poor area occurs. Aquatic organisms require oxygen to survive; in its absence, organisms must move from the anoxic area or die. Anoxic bottom waters lose most, if not all, of the zooplankton and aerobic bacteria necessary for efficient and effective digestion, and less-effective, more pollutant-tolerant forms of anaerobic bacteria will develop.

The lack of dissolved oxygen sets in motion a series of anaerobic chemical reactions within the water in this zone and bottom sludge materials that further reduce water quality: sulfide is converted to hydrogen sulfide, insoluble iron is converted to soluble forms, N forms can convert to ammonia, suspended solids increase, and a severe decrease in the decomposition of waste materials on the pond bottom (**benthic zone**) will result. These conditions are most likely to occur within the strata of a lake, especially if the lake bottom was rich in organic deposits and there are the right combination of pH, low oxygen, and temperature (Zinder and Brock, 1978; Burgess et al., 2003; Arauzo and Valladoilid, 2003; Hargreaves and Tucker, 2004; Holmer and Starkholm, 2001).

Shallow lakes are even more challenging where ponds less than 6 ft (1.8 m) in depth tend to be very warm, allowing for the entire water column to be productive with weed and algae growth. These types of lakes need extra maintenance consideration when determining the correct water-management solution.

Nutrients. Another essential factor in lake ecology is the impact of nutrients on the aquatic ecosystem. There is a direct correlation in the level of available nutrients, especially P and N, and the populations of algae and aquatic weeds. Knowledge of the sources of nutrients and their reactions in lake ecology aids in designing management programs. Phosphorus has been identified as the single greatest contributor to aquatic plant growth; 1 g of phosphorous will produce 100 g of algal biomass. As P and other nutrient levels in the water increase, so do algae, aquatic plant, and weed growth, leading to severe problems from an environmental and aesthetic viewpoint. Accumulation of partially decomposed organic debris (dying aquatic plants, algae, grass clippings, leaves, etc.) in the lake bottom further competes for oxygen in this zone and acts as a reservoir for P, N, and S compounds. In addition to the dead vegetation, other sources of nutrients in waters entering the lake (such as wastewater, which is unusually rich in nutrients such as N, P, and S concentrations that have not been reduced by treatment) are sediments and runoff from adjacent areas (Cummings, 2002; Lembi, 2003; Rafter, 2006).

Bottom silt and vegetation in the lake. Vegetative life in the lake and sediment at the lake bottom are the primary sources of nutrients. When P and N do not limit algae growth, an algal bloom can occur because algae can proliferate rapidly with the right environment. Unfortunately, these plants die and begin to sink to the lake's bottom, adding to the biomass, or total amount of biological material in the pond (Kim et al., 2002). Die-off may increase in cloudy weather and cold periods. This adds to the "aquatic compost pile" at the bottom, or **benthic zone**. The layer of dead plant material acts as a nutrient source for future algae and aquatic weed blooms, a phenomenon called **nutrient cycling**. Nutrient cycling creates additional demands on the available oxygen in the bottom waters and creates a low oxygen stress situation.

Dissolved oxygen. The third essential factor in lake and pond ecology is the role dissolved oxygen plays. As previously stated, dissolved oxygen arises primarily from photosynthesis, wind and wave motion, mechanical mixing, and as the rain passes through the atmosphere where it picks up free oxygen and deposits it in a dissolved state into the surface waters of the lake. Depletion of oxygen is stimulated by

- At night and just before dawn—as photosynthesis does not occur at night but respiration continues, there is a net oxygen loss during this period.
- Cloudy and still (windless) days—photosynthesis may decline, but decomposition continues.
- Hot and humid days.
- When the nutrient content of the lake or pond is high.
- After a chemical application inhibiting photosynthesis (plant growth regulator) or stimulating aquatic plant death (aquatic herbicide).

Natural decomposition processes in the aquatic ecosystem are oxygen dependent. Aerobic digestion is a fast and efficient way of breaking down nutrients. Moreover, an abundant supply of dissolved oxygen supports the oxidation and other chemical processes that help keep the lake in ecological balance. Dissolved oxygen in a healthy lake ecosystem is normally between about 8 and 14.6 mg/L, depending on temperature and atmospheric pressure. Whenever oxygen levels fall below three to four parts per million (mg/L), an oxygen stress will occur.

Oxygen is important to all forms of life in the lake and supports the food chain. A healthy ecosystem in a lake contains a wide variety of plants and animals, including a healthy biological system to biodegrade organic compounds. The bottom of the food chain consists of microscopic algae that are consumed by slightly larger zooplankton. Each level of consumer transfers a small fraction of the energy the lake receives up the food chain to the next level. This means that a few sport fish depend on a much larger supply of smaller fish, and in turn the smaller fish depend on a large base of plants and algae, and the large mass of plants and algae require an even larger amount of nutrient to grow. Thus, a healthy food chain can remove a tremendous amount of nutrient out of the water, but oxygen supports the entire ecological system.

The most immediate reactions to oxygen depletion would be fish kills or odors. Long-term issues include nutrient buildup, sludge accumulation, and a chemical imbalance in the lake. Two types of bacteria (aerobic and anaerobic) are naturally present in all lakes and ponds. Bacteria are the primary decomposers in the water, and break down or decompose the nutrient load by feeding on the organic nutrients and digesting them into nonorganic compounds that algae and aquatic plants cannot readily use for food. **Aerobic bacteria** are the most effective of these bacteria, and only live in the presence of oxygen where they metabolize or break down nutrients while respiring or consuming oxygen in the process. They are very efficient, breaking down organic nutrients, carbon dioxide, and other materials, and are roughly seven times faster in organic digestion than anaerobic bacteria.

Anaerobic bacteria also exist in pond water that is oxygen deficient and break down organic nutrients. They are not as effective as aerobic bacteria in the digestion of organic wastes and in recycling soluble organic nutrients into the water column. Noxious by-products, such as methane, ammonia, and hydrogen sulfide, are created by anaerobic decomposition. These potential toxic by-products are especially prevalent in the bottom of lakes or ponds with anaerobic conditions or sediments. In general, any foul-smelling waters can be assumed to be anoxic or oxygen-deficient. Irrigation intakes should be positioned above these bottom stratification zones to minimize damage to turfgrasses or landscape plants.

A balanced or healthy aquatic ecosystem contains a fairly low population of algae and aquatic weeds as well as other forms of bound or free nutrients. Anaerobic bacteria feed on the organic nutrients and digest them into nonorganic compounds that algae and aquatic plants cannot use as readily for food.

Hopko (2006) described the type of interactions that occur over time in lakes and that affect their balance. He noted that, as a lake ages, the levels of nutrient rise due to an increase in runoff and organic bottom sediment or fertilizer used in the surrounding area, and subsequently in the amount of algae and aquatic weed growth. As aquatic plants (desirable ones plus other weeds) and algae grow and die, the organic matter sinks to the bottom of the pond to decompose, resulting in a sudden increase in the activity and population of aerobic bacteria due to the large food supply. Lake depth will decrease as the biomass at the lake bottom accumulates. Aerobic bacteria will use a large amount of oxygen as they digest organic waste, with the primary source of oxygen in the pond coming through surface contact, rainfall, and plant photosynthesis. With thermal stratification, the top and bottom layers of the pond will not mix, and oxygen recharge to the lake bottom is insufficient to support aerobic digestion. Serious oxygen depletion in the lower layers of the lake may result in nutrient cycling, fish kills, and foul odors caused by anaerobic digestion. The problem is caused by poor water quality that has excessive nutrient levels, poor circulation, and low oxygen levels.

With so many interacting processes, balance is critical to the aquatic ecosystem; without it the pond or lake will deteriorate. There are many steps that can prevent an imbalance from occurring, and knowing the causes will assist in determining the best solution for each application. Some methods include proper pond construction, including the placement of aquatic plants on the shores of a pond to assist with the filtering of excessive nutrients, chemical applications, and the addition of oxygen through aeration systems and devices (Skorulski, 2000).

14.2.2 IRRIGATION POND OR LAKE DESIGN

Irrigation lake or pond construction is an important factor contributing to a balanced ecosystem. An important **preventative measure** for many potential irrigation lake or pond problems is **good design and construction**. Irrigation ponds may involve two basic types: (1) urban stormwater runoff ponds that also serve as an irrigation storage lake or pond, and (2) ponds built specifically for irrigation water storage and not for stormwater runoff/catchment (Thayer et al., 2003). Urban stormwater ponds technically are called *wet detention areas* and have the primary purpose of flood control, but also can serve as a protection facility for localizing polluted waters, and then secondarily provide water storage as an irrigation lake or pond. Stormwater ponds are often constructed with shallow sloping areas called **littoral shelves** to provide a habitat zone for rooted plant life that supports a rich biological community. A **littoral zone** should be constructed with a littoral shelf, which is a shallow water shoreline of 1 to 2 ft depth with a base slope of 3 to 1 or less (Beard, 2002). The root plants may be emerged, floating, and submerged as the water depth increases. This zone is constructed to the depth of normal sunlight penetration for photosynthesis with light penetration >1%. The actual depth varies with water clarity, but about 6 to 9 ft is a good estimate. Beyond the littoral zone is the **limentic zone**, where the light does not normally penetrate to the lake bottom to promote survival of bottom-rooted plants. Beyond the littoral shelf, a relatively steep slope of 6 to 1 is often used with common lake or pond depths of 10 ft minimum (minimum at normal drawdown) to 25 ft. Stormwater ponds often have local permits associated with them that require sustainable management of aquatic plants in the pond, including maintaining a certain amount and type of plants. Before attempting any weed control measures in stormwater detention ponds, the water management district in which you are located should be contacted. It is advisable to contract a professional licensed pond management company to manage weed problems in stormwater ponds.

If the pond is strictly for irrigation and not receiving runoff, then construction of pond banks should be as steep as possible along the edges to a depth of several feet to avoid shoreline vegetation from becoming established. They should often gradually slope to a depth of at least 8 to 10 ft to the pond center, but greater depths would be better, especially in warm climates. The construction of a small bank (or berm) around the entire pond can divert rainwater runoff that may be rich in nutrients and suspended solids (leaf litter, trash, etc.). The water that percolates through the berm into the pond will be filtered rather than flowing directly into the pond itself. Brush and trees are often removed along the edge to increase berm stability and reduce leaf and branch litter. Grass species should be encouraged to grow along the banks to prevent erosion and washouts, and these areas are often sod-planted to minimize establishment problems.

Shallow lakes are even more challenging to manage, especially because ponds less that 6 to 8 ft deep tend to concentrate warm-temperature water, allowing the entire water column to be productive with weed and algae growth. Deeper ponds (10 to 20 ft deep) have fewer aquatic weed problems than shallower ponds.

Construction of lake and ponds to harvest and channel incoming water provides improved circulation, aids in preventing temperature increases (such as easily occurs in stagnant ponds), and contributes to a healthy storage facility. Construction of waterfalls or features that aid in water aeration and movement is also useful.

14.3 TURBIDITY

14.3.1 Causes and Problems

Turbidity refers to the clarity or murkiness of the water and is an indicator of the quantity of suspended solids in it. Turbidity measures the scattering effect that suspended solids have on light—the higher the intensity of scattered light, the higher the turbidity. Contributors to water turbidity include suspended clay, silt, fine organic matter, and microscopic organisms, predominantly living algae. The clay and silt end up in rivers, channels, and dams from eroded catchment material washed into irrigation lakes or ponds after storm events. Fine organic matter can result from catchment vegetation washed into the storage or stream, or it may be dead organic material produced in the water body itself, such as algae, bacteria, and fungi as they die and settle. Even after inorganic or organic suspended solids settle out of the water, bottom sediments can be resuspended by pump operation, wind mixing, activities of aquatic life such as carp, and thermal inversion (where bottom layers of water rise to become the top layers).

Particles that remain suspended for long periods of time are particularly a problem. Both clay and very fine organic particles contribute to the colloidal fraction that tends to stay suspended for long periods. For a calm water column of 2 ft, sands can settle out within 1 min and silt in about 10–12 h, but colloidal matter can remain suspended for much longer periods. The colloidal particles reduce photosynthesis because light penetration is limited, which can reduce daytime oxygen concentrations. Particles can stain objects and plumbing fixtures, clog irrigation sprinkler base screens, spray nozzles and drip emitters, contribute to a buildup of biological growth and sludge in drippers and pipes, and reduce the efficiency of water-softening units. Suspended decaying organic material adds to biological oxygen demand and can reduce dissolved oxygen levels while combining with other chemical (calcium or magnesium carbonate, calcium sulfate, heavy metals, hydroxides, oxides, carbonates, silicates, sulfides, and fertilizers such as iron, phosphate, ammonia, zinc, copper or manganese), physical (sand, silt, clay), and biological contaminants (filaments, slimes, microbial depositions, bacteria, and small aquatic organisms). A buildup of slime in pipes and drip emitters is usually the result.

Heavy sediment loads in the water can lead to filling of irrigation lakes and future dredging costs as well as surface sealing of turfgrass soils. For modified high-sand root zone mixes, this addition of "fines" can lead to reduced water infiltration and oxygen diffusion into the soil profile. Clay and silt deposits on recreational turfgrass soils would make the soil much more prone to soil compaction by traffic. Deposition of sediment on leaves of landscape plants is unsightly and reduces photosynthesis. Sediment can also act as a carrier of phosphorus, other nutrients, and pesticides. Turbid water influences the effectiveness of disinfection techniques, including ultraviolet light and chlorination.

14.3.2 TURBIDITY CLARIFICATION AND OTHER TREATMENTS

The type, source, and load of suspended solids should be determined as a first step (Hargreaves, 1999). Because suspended organic and inorganic solids may arise for incoming water from the upstream or runoff watershed, it is important to determine the source. Initial management steps to reduce turbidity should be preventative measures to reduce soil sediments and plant debris from entering the lake. Shorelines should be stabilized to prevent collapse of soils into the water. Reducing the organic load through control of aquatic weeds and algae are discussed in a later section of this chapter.

Turbid water may be treated by **clarification,** which is the chemical removal of clay, silt, and other suspended matter. For turfgrass situations, this would normally not be an ongoing process because filtration is more likely to be used, but there may be cases of lake remediation where rapid, one-time clarification is desired. Many of the same flocculants used to remove suspended solids are also used for P removal. Clarification is achieved by adding a flocculant, which causes the suspended particles to settle to the bottom, and the flocculating products used in irrigation lakes or ponds are the same ones often used in wastewater treatment plants. Hargreaves (1999), Wurts and Masser (2004), and Yiasoumi et al. (2005) provide an overview of turbidity treatments in farm ponds (Table 14.3) and recommend the following flocculating agents:

- Alum (aluminum sulfate) is the most common clarifying agent and is available in liquid or solid form (Mason et al., 2005; Steinman and Ogdahl, 2008). Alum is most effective at pH 6.8 to 7.5. Mason et al. (2005) indicated that alum was nontoxic within the pH 5.5–9.0 range with Al concentrations that are not expected to exceed 50 μg/L. Use below pH 5.5 is not recommended due to greater Al solubility. Alum is also very effective in P removal. Flocculating action is faster in the alkaline pH range. Typical rate is 0.40 to 0.65 lb per 1000 gal treated water.
- Ferric alum is also widely used where a small amount of iron increases the effectiveness of alum over a wider pH range with a pH range of 5.5–8.5. Rates normally range from 0.40 to 0.65 lb per 1000 gal treated water. Blocks of ferric alum can be placed in channels feeding into the pond or catchment facility.
- Ferric chloride is a good alternative to alum. This product works best with a pH >5.0. Up to 2.4 lb per 1000 gal treated water can be applied to the pond.
- Ferric sulfate should be used with a pH >5.0. Rates up to 2.1 lb per 1000 gal treated water are recommended.
- Gypsum does not change the pH of water, and once applied, requires 2–3 days for settling. Rates up to 2.5 lb per 1000 gal treated water can be applied to the pond.
- Lime (calcium hydroxide form) will increase water pH. Rate up to 2.5 lb per 1000 gal treated water are recommended. Wurts and Masser (2004) discusses liming of ponds for pH adjustment and not turbidity control, but many of the same practical suggestions are applicable to both situations.

It is preferable to treat the water in tanks rather than in a pond, especially for ongoing treatment. However, for a one-time clarification treatment, pond application can be used. Tanks should have drain outlets for removing sludge material. In the case of treatment, especially with alum or ferric alum, any regulations affecting release of treated water into watercourses should be determined. If particulate matter enters from runoff or stream flow into an irrigation lake, then turbidity may again occur, especially after rains. After clarification, filtration may still be required, particularly if micro or drip systems are being used for irrigation.

TABLE 14.3
Clarification or flocculating agents for irrigation lakes and ponds to improve clarity by reducing turbidity

Alum (aluminum sulfate) is the most common clarifying agent and is available in liquid or solid form (Mason et al., 2005; Steinman and Ogdahl, 2008). It is most effective at pH 6.8 to 7.5. Mason et al. (2005) indicated that alum was nontoxic within the pH 5.5 to 9.0 range with Al concentrations not expected to exceed 50 µg/L. Use below pH 5.5 is not recommended due to greater Al solubility. Alum is also very effective in P removal. Flocculating action is faster in alkaline pH range. Typical rate is 0.40 to 0.65 lb per 1000 gal treated water.

Ferric alum is also widely used where a small amount iron increases the effectiveness of alum over a wider pH range with a pH range of 5.5 to 8.5. Rate 0.40 to 0.65 lb per 1000 gal treated water. Blocks of ferric alum can be placed in channels feeding the pond.

Ferric chloride is a good alternative to alum. pH > 5.0. Rate up to 2.4 lb per 1000 gal treated water.

Ferric sulfate. pH > 5.0. Rate up to 2.1 lb per 1000 gal treated water.

Gypsum. Does not change pH of water. Requires 2–3 days for settling. Rate up to 2.5 lb per 1000 gal treated water.

Lime (calcium hydroxide form). Increases water pH. Rate up to 2.5 lb per 1000 gal treated water. Wurts and Masser (2004) discusses liming of ponds for pH adjustment and not turbidity control, but many of the same practical suggestions are applicable to both situations.

Sources: Hargreaves, J. A. 1999. Control of Clay Turbidity in Ponds. Southern Reg. Aquaculture Center, Publ. No. 460. Miss. State University, Stonesville, MS; Wurts, W. A. and M. P. Masser. 2004. Liming Ponds for Aquaculture. Southern Regional Aquaculture Center, Miss. State University, Stoneville, MS; Yiasoumi, B. et al., 2005. Farm Water Quality and Treatment. Agfact AC.2, 9th edition.

14.4 ALGAE AND CYANOBACTERIA (BLUE-GREEN ALGAE)

14.4.1 Descriptions and Problems

Algae are small plant forms that are important for the ecology and health of ponds and lakes. They lack roots, stems, and leaves, but, like other plants, have **chlorophyll** as their primary photosynthetic pigment. However, **algal blooms** are excessive growth of a particular algae species that cause a number of problems to arise (Cummings, 2002; Yiasoumi et al., 2005, 2007; Neylan, 2008; Benson and Raikow, 2008):

- Depletion of dissolved oxygen as the algae die and decompose
- Increased rate of decaying organic matter deposited in the lake bottom
- Algae scum at the surface
- Clogging of filters, meters, and valves
- Odors
- The algae increase suspended organic matter and treatment processes
- Toxins may occur

A considerable variety of algae is found in freshwater that range in size from microscopic to large masses. Common algae include the following:

- **Green algae** are the most diverse and may be microscopic or present as large clumps or mats of tangled filaments. The long green ribbons often seen in rivers, channels, or low-lying swampy areas are green algae. These can easily clog irrigation filters, meters, and valves.
- **Diatoms** are microscopic and unicellular but also form filament clumps and colonies. Some types are planktonic and are suspended in the water. Some can discolor the water with a brown hue.
- **Dinoflagellates** and **cryptomonads** are generally only visible under a microscope and have flagella that allow them to move. Flagellates can also give water a brown hue and are major contributors to odors. Cryptomonads make the water appear red and can photosynthesize under low light conditions.

Cyanobacteria are **photosynthetic bacteria** that are also called **blue-green algae** even though they are not algae. Because these organisms respond to the same factors that stimulate algal bloom, they resemble algae, and treatments are similar. They are often grouped with algae as a lake or pond problem. Blue-green algae are microscopic, but large colonies and aggregated filaments easily form and become visible in water. Blue-green algae are capable of very rapid blooms and produce thick surface scum that tend to accumulate on the downwind side of a water body. The scum appear to be a curdled green, gelatinous mass. Water discoloration has a distinct green acrylic appearance that may range from pale green, bluish green, or dark green to brown in color. Blooms are often accompanied by strong musty, earthy, and putrid odors.

Toxins are a major concern with blue-green algae when they die. Some cyanobacteria are capable of producing toxins that cause wildlife and livestock to become ill. Yiasoumi et al. (2007) note that, if blue-green algae are expected to be the problem, the water should not be touched or used in any manner until it is confirmed by testing. Care should be taken regarding using such water for irrigation because toxins are slow to break down. Uses such as cooking, bathing, laundry, and recreational activities such as swimming are all affected by blue-green algae. Skin contact through showering or swimming may result in skin irritations, swollen lips, sore throats, eye and ear irritations, rashes, and hay fever symptoms. Drinking affected water may result in diarrhea, nausea, vomiting, and muscle weakness. Boiling the water will not reduce the effect of blue-green algae toxins. See your local doctor immediately if you experience symptoms you think result from blue-green algae in your water resource.

Yiasoumi et al. (2005) report that, in Australia, genera of blue-green algae that are toxic include *Anabaena, Microcystis, Cylindrospermopsis,* and *Nodularia.* In New South Wales, *Anabaena* and *Microcystis* are the most common types of freshwater blue-green algae causing blooms. *Anabaena* generally grows in rivers and lakes, and *Microcystis* is often found in lakes and reservoirs. Toxic blue-green algae can produce three different forms of toxins:

- Hepatotoxins attack the liver and other internal organs. They can cause gastroenteritis, nausea, vomiting, muscle weakness, and visual disturbances.
- Neurotoxins affect neuromuscular performance and can lead to paralysis and respiratory arrest.
- Lipopolysaccharides are skin irritants that can cause dermatitis and conjunctivitis. They may also cause stomach cramps, nausea, and fever if consumed.

Both algal and cyanobacterial growth are affected primarily by (1) aeration because they are aerobic plants, (2) available nutrients, especially N and P, where as little as 0.01 mg/L of phosphate can stimulate growth, (3) temperature, with higher growth as temperatures increase, which is particularly a problem with shallow ponds in the summer months, and (4) light, because they are photosynthetic; so low light and blocked light (dyes) decrease viability and may cause die-off. Thus, algal blooms are most likely to occur under the following conditions:

- Nutrient-rich waters, especially P and N.
- Calm water with no or limited flow.
- Warm water temperatures at or above 65°F.
- Low-turbidity water that allows light penetration for photosynthesis.
- Slightly alkaline pH.
- Conditions favoring stratification with the warm surface waters stimulating growth, whereas the cooler, anaerobic bottom conditions allow P to be released from sediments.
- Low levels of zooplankton, which are microscopic animals that feed on algae but vary in population and type on a seasonal basis.
- Algal blooms may occur even when the foregoing conditions are not present.

Algae management options are diverse and include (1) P and nutrient control/removal, (2) pond aeration methods, (3) shading chemicals (dyes), (4) barley straw, (5) ultrasonic waves, (6) chemical control such as peroxide compounds, copper sulfate, or potassium permanganate, (7) carbon, and (8) biological compounds (such as some aerobic bacterial products in conjunction with aeration). For algae control, phosphorus management and mechanical aeration are the treatments most often used, but an integrated approach is often best that includes several methods.

14.4.2 PHOSPHORUS/NUTRIENT CONTROL

The most important treatment option is to deal with nutrient loads, preventing P and N additions being the first primary consideration. Most turfgrass managers will have already implemented the common measures on their site to prevent nutrient loading of their surface waters, such as elimination of erosion that may carry sediments and associated nutrients; buffer areas between ponds and fertilized sites; careful placement of fertilizers; and minimal rates on areas adjacent to ponds or lakes. During storm runoff periods, waters with sediments or plant debris from outside the facility, such as urban runoff, may enter streams and lakes and carry nutrients. A series of lakes with the primary catchment lake receiving the most sediments, plant debris, and nutrients with vegetative filtering may assist in the protection of an irrigation lake further down the chain of ponds or lakes. Control of geese, coots, and other waterfowl, if they contribute to nutrient load, can be considered.

Treated wastewater may contain higher P and N than other irrigation sources. Users should negotiate contracts with water treatment facilities for treatment to the levels that would be required if the water was discharged into public surface waters. This issue is an increasing reason for irrigation lake problems on golf courses using reclaimed water. If treatment by the public treatment facility is reduced from the levels required for discharge into public waters for the purpose of financial savings, the net result is to pass a major environmental issue on to the end users who must then pay for the public-created problem. In some cases, the treatment facility requires an on-site secondary biological treatment (often chlorine) of the treated water prior to disposal into the storage lake or pond as a backup in case of periodic failure of equipment at the primary treatment facility. This secondary treatment requirement is often included in the contract agreement with the facility receiving the treated water.

Another option for sites that receive reclaimed water with sufficient P and N to cause algae and aquatic weed problems is to have the water delivered under pressure directly into the mainline piping system rather than an irrigation lake (Gross, 2008). Others have stored reclaimed water in tanks or covered reservoirs. However, direct delivery of recycled wastewater containing high amounts of NH_4-N and NO_3-N may result in excessive nitrogen applications during high evapotranspiration (ET) conditions and can be harmful to sensitive plants. Storage of high N recycled water in an open reservoir allows for nitrification of NH_4- to NO_3 and denitrification, reducing total N load in that water naturally through aeration (mechanical and/or natural wave action) and through uptake and respiration by aquatic organisms (algae and other aquatic plants). The amount of denitrification possible will depend on the residence time of the recycled water in the reservoir, temperature, and amount of aeration and biological activity that is occurring.

Phosphorus removal by alum or other flocculating agents is sometimes used on lakes that have limited inputs, but require P levels to be reduced because it is not usually an ongoing treatment; see Section 14.3.2 for chemicals and rates (Mason et al., 2005; Steinman and Ogdahl, 2008). Alum and gypsum are the most often used materials to remove P from water. Gypsum appears to be less effective if pH values in the water are below 10. Application is best carried out before summer, and before a bloom has developed. Because of variations in water quality and algae, it is advisable to conduct a preliminary trial in a large drum to establish the correct dosage. Precipitation into less soluble P forms (Al-P, Fe-P, Ca-P compounds) that settle to the lake bottom, thereby reducing P in the water, can suppress algal and aquatic weed growth. However, it is important to minimize disturbing the sediments and to maintain good oxygen conditions so that more soluble P forms do not occur under anaerobic conditions. Aeration, discussed later, will assist in avoiding the anaerobic benthic layer.

In addition to reducing P inputs and precipitation/inactivation of P, removal of nutrient-rich sediments may be necessary for lakes that have received long-term P additions. Another option is to dilute the nutrient-rich lake water with freshwater and flush the lake of nutrients and suspended organic matter.

14.4.3 AERATION

As lakes and ponds tend to exhibit stratification during warm months, which results in low oxygen status in the bottom stratification zone, aeration is a means to provide better water circulation and oxygen status for improving natural pond and lake ecosystem health (Skorulski, 2000; Beard, 2002; Otterbine, 2003; Rafter, 2006; Neylan, 2008). Construction features such as waterfalls for natural aeration is beneficial. Mechanical aeration is often required, and the benefits include

- Improved oxygen status in the bottom zone suppresses P release from sediments. Release of P is much greater under anaerobic conditions, which in turn stimulates algal growth. Thus, aeration effects on reducing P solubility from sediments can suppress all types of algae and blue-green algae.
- Improved oxygen status in the bottom or benthic zone also helps to prevent formation of toxic sulfides and ammonia compounds that form under anaerobic conditions.
- Aeration combats the development of filamentous algae because they do not reproduce well in moving water. Unicellular algae are not affected by this process.
- Mixing of algae deeper into the pond to below the level of light penetration can suppress algae because photosynthesis is limited.
- Aeration effects cooling by mixing the cooler bottom waters with the surface warmer water. However, if the lake is shallow (<10 ft), and the whole water body increases in temperature, cooling effects will be minimal; but on deeper lakes, cooling does occur. Reduction in surface water temperatures will slow aquatic and algae growth to some extent.
- If the lake has appreciable dissolved (soluble) Fe due to anaerobic conditions, then improved oxygen status can result in precipitation of the Fe as insoluble Fe oxide forms.
- Aeration assists in the denitrification of recycled wastewater.

Aeration by **mechanical aeration systems** is often used, and it is effective as a preventative practice to maintain adequate oxygen and water circulation rather than as a treatment after algae formation. Mechanical aeration systems are generally three types: surface sprays or fountains; horizontal aspirators; and bottom diffusers or pond bubblers (Skorulski, 2000; Otterbine, 2003; Rafter, 2006).

Fountain aerators spray water into the air with a number of patterns possible. These devices float on the water and provide an aesthetic quality. Surface spray–type aerators provide the best vertical circulation in lakes of less than 15 ft. The intake should be low enough to circulate water from the cooler, hypolimnion zone, where the dissolved oxygen is lowest, into the surface. As the water is sprayed into the air, it becomes oxygenated, and the water movement aids in breaking up filamentous algae or algae clumps.

Horizontal aspirators are sometimes used for shallow lakes of 3–12 ft depth. These devices create water circulation and pull air from the atmosphere down a supply tube. For filamentous algae or aquatic weeds, such as duckweed that do not do reproduce well in moving waters, these aerators are effective. They do not result in very much vertical circulation but cause horizontal water movement.

Air diffusion or bubble systems are unobtrusive because they are below the water surface. They work well on deeper ponds of >12 ft. Because water aeration occurs as the air bubbles rise to the surface, greater aeration results from deeper systems, which allow for greater air contact. These devices oxygenate the lower zones and help circulate water from the lower to the surface layer.

Care should be taken to ensure the correct size, type, and placement of these devices. General guidelines for surface and horizontal aspirators is usually 12 hours per day during the spring, summer, and fall, with units removed in the winter in cold climates. Bottom diffusion systems can operate 24 hours per day, year round.

14.4.4 SHADING CHEMICALS

Dyes can be used to inhibit photosynthesis by blocking light penetration. Lake dyes are available in liquid or powder forms, and the dye should be government approved. Improved lake appearance comes from masking turbidity or color problems and by the added color.

14.4.5 OZONE GENERATORS

Ozone (O_3) is a powerful oxidizing agent and is often used as a disinfectant in treatment facilities. It is created with UV light and then pumped into a mechanical circulation or aeration system (Beard, 2002; Otterbine, 2003). There must be an adequate circulation or aeration system to mix the ozone throughout the water body for it to be effective. Within an hour, the ozone reverts to oxygen. Ozone can kill bacterial cells by causing lysing (bursting) while adding oxygen to the water for algae control and water clarity. Systems should be sized for the lake volume and characteristics. Ozone gas is corrosive, and the systems must not allow escape into the control boxes, which has been reported to require high maintenance, at least in earlier devices.

14.4.6 BARLEY STRAW FOR ALGAE CONTROL

An excellent initial source of information on barley straw and algae control is the publication by Lembi (2002), but other reference materials are by Everall and Lees (1996), Otterbine (2003), and Ferrier et al. (2005). The success of barley straw for algae control has been mixed. Its activity is algistatic (prevents new growth of algae) and not as an algicide (which kills existing algae). Thus, barley straw is best as a preventative measure with attention to (Lembi, 2002):

- Aerobic decomposition of the barley by fungi is what results in the compound or compounds that suppress algae. It is not clear what the compound is and whether it comes from the straw or fungi. To allow aerobic conditions, the straw should be loosely packed in netting and placed relatively shallow at a depth of 4–6 ft.
- Time is required for the decomposition process, so application must be before an expected algal bloom period. Activity appears to last about 6 months, so reapplication would be necessary.
- Decomposition is temperature dependent and below 50°F; it may take 6–8 weeks for adequate decomposition but only 1–2 weeks at higher temperatures. Once activity occurs, suppression normally continues for 4–6 months.

- A general rate for lakes with a history of algae problems is 225 lb of straw per acre-area of the lake, with turbid lakes requiring higher rates.
- Straw should be placed at several places around the lake rather than one location. Liquid and flake decomposition product sources also are now being marketed.

14.4.7 ULTRASONIC DEVICES

In recent years, devices that float on or just beneath the water and emit ultrasonic waves have been marketed for algae control (Lee et al., 2002; Rafter, 2006; Zhang et al., 2006; Morris, 2007). Only algae are targeted. Control appears to be by collapsing the gas vesicles in the algae that control their floating, fracturing the cells and inhibiting cell division (Zhang et al., 2006). Most research has been on blue-algae, but other forms may be killed as well. The time for treatment effectiveness is related to turbidity, sunlight, and nutrients, with 30–90 days estimated for effectiveness (Morris, 2007). These devices are usually run continuously from just after ice melt to just before freezing and are combined with other algae control tactics.

14.4.8 SULFUROUS ACID GENERATOR

Sulfur burners that generate sulfurous acid, which is injected into water body, can reduce pH and bicarbonate/carbonate levels. Normally, acidification devices used to evolve bicarbonate and carbonate ions so that they will not chemically react with Ca and Mg in water will treat to about pH 6.5, which leaves some bicarbonate and carbonate to act as a buffering compound against rapid pH changes, as happens in acidic lakes that do not have sufficient carbonates for buffering. Treatment can be at a higher rate and can reduce pH further, causing the water to become more acidic. Lakes treated with sulfurous acid have been reported to exhibit greatly reduced algae growth, but the reasons are not stated. One possibility is that sulfurous acids can react in waters to possibly form sulfites (hydrogen sulfite, sodium bisulfite), which have disinfection action and are known to kill microbes.

14.4.9 OTHER POSSIBLE ALGAE CONTROL MEASURES

Chemical treatments. Chemical control is considered as a last or short-term resort and does not deal with the primary causes of algal bloom (Neylan, 2008). They are fairly quick and can control stubborn problems but can also result in large quantities of dead plant material (both algae and other aquatic plants) that rot and sink to the bottom, which can rapidly reduce dissolved oxygen levels, resulting in possible fish kill and odors. When large quantities of blue-green algae die, they can release toxins.

The algaecide dose depends on water alkalinity. Liquids can treat the whole water body column, whereas granular materials affect primarily the bottom zone. Only government-approved chemicals should be used, with treatment by a licensed applicator. Only static water bodies should be treated, and not ones with outflow.

Activated carbon. Yiasoumi et al. (2005) discussed the role of activated carbon related to toxin removal. Activated carbon filters have long been used to improve the taste of domestic water supplies and reduce odors, but they can also be used to remove many types of blue-green algae toxins. Activated carbon is a processed form of charcoal and comes in two types—granular activated carbon (GAC) and powdered activated carbon (PAC). GAC offers the better method of treatment, particularly when algal blooms are a regular occurrence. The level of toxin removal is dependent on contact time, flow rate, and the extent the filter has previously been used.

In-line GAC filters are commercially available for use at a domestic level. Filter the water through a conventional sediment filter before passing it through the carbon filter. This will remove larger particles and increase the life of the carbon filter.

Biological control (bioaugmentation). Otterbine (2003) notes that the addition of bacterial compounds has been used for many years for wastewater treatment and fish ponds. Bacteria can compete with the algal for nutrients and suppress algal growth by reducing the nutrient load. Also, these aerobic bacteria (which consume oxygen) increase breakdown of organic sludge components in the bottom sediments while improving clarity and reducing odors. Thus, aeration is essential for results from bacterial additions. It is recommended that algal blooms be harvested or chemically treated before using bioaugmentation. Results are best with pH between 6 to 9 and temperatures between 55 and 100°F.

Slow-release oxygen compounds. Calcium perioxide or other perioxide compounds that are coated to result in slow release over time are marketed as a slow-release oxygen material to apply to lake bottoms. At treatment rates of approximately 25 lb per acre, the quantity of oxygen release would be very small, especially when metered out over time and compared to the level of oxygenation by a bottom diffuser device.

14.5 ANAEROBIC BOTTOM ZONE

It was noted previously that the lake bottom is a critical area, especially if it becomes enriched with nutrient-rich sediments (organic or inorganic in nature) and anaerobic conditions prevail. Four nutrient-related issues that are prevalent under anaerobic conditions in the sediment layer are phosphorus, nitrogen (ammonia), sulfur, and iron. Smart (1999) noted the importance of a floating intake structure in irrigation lakes to avoid intake of water from the anaerobic zone as a simple preventative measure. Regardless of the potentially problem nutrient, care should be taken to minimize additions; use aeration to maintain aerobic conditions; avoid disturbing the sediment and mixing with the water; adding aerobic bacterial compounds to stimulate decomposition if organic matter is a major contributor to the bottom debris; and control excessive algae and aquatic plant debris from settling out by harvesting if necessary.

Phosphorus. Phosphorus, which is reacted to form low-solubility Fe-P, Al-P, and Ca-P compounds under aerobic conditions and settle in the pond bottom, will remain low in P release if the pond bottom remains aerobic. However, under low dissolved conditions, P may start to become more soluble and stimulate algae and aquatic plant growth (Kim et al., 2002). Phosphorus bound in inorganic compounds is less soluble than P contained in organic rich sediments.

Ammonia. Total ammonia is the combination of unionized ammonia (NH_3) and the ammonium ion (NH_4^+) (Hargreaves and Tucker, 2004). The NH_3 form is highly toxic, and injuries can occur to root and shoots of irrigated plants in less than an hour of exposure. This form can rapidly predominate with a combination of high total ammonia, water pH > 9.0, and high water temperatures. Reclaimed water may contain relatively high total N, and when combined with storage situations that allow anaerobic conditions, transformation to the unionized ammonia ion (NH_3) is favored; and it is possible that ammonia toxicity could occur when the water is applied to turfgrass. Anaerobic storage conditions could result when recycled water is (1) not aerated and irrigation is by direct connection; (2) in the lower strata of nonaerated holding ponds or lakes from which irrigation water is withdrawn, especially if the intake is in the lower or bottom, low-oxygen zone (S-rich water resource that converts to sulfides under anaerobic conditions, or acidified urea–N product deposition into the lake); and (3) water is held in pipelines under high temperatures and anaerobic conditions for long periods, especially when fertigating some N or S products.

Ammonia toxicity has been reported in marine sediments in euthrophic settings (Burgess et al., 2003). It has also been reported on turfgrasses from compost applications, but not from reclaimed water. However, the authors have observed a couple of isolated situations where this problem was expected based on site conditions that favored ammonia presence, reported ammonia odor, and turfgrass injury to seedlings. Conditions that would enhance the potential for ammonia accumulation are pH > 9.5, low oxygen, high temperatures, and relatively high N in the reclaimed water or fertigated products that were not completely flushed out of the irrigation lines and that acidified N-product converted to ammonia between irrigation cycles. These conditions could occur within the strata of a lake, especially if the lake bottom was rich in organic deposits (Burgess et al., 2003; Arauzo and Valladoilid, 2003). Lake aeration with bottom diffusers as well as any means to control N and P levels to reduce eutrophication potential would inhibit ammonia formation. Direct connections of reclaimed water should be carefully evaluated to ensure that anaerobic, high-pH, and high-temperature conditions do not result in ammonia toxicity.

Sulfur. In Chapter 12, Section 12.11, the issues of anaerobic conditions on S and sulfur-reducing bacteria were discussed; but in this section the emphasis is on anaerobic lake bottoms. Problems associated with H_2S are noted in Section 12.11 as reported by Swistock et al. (2001) and Scherer (2005). Specific to lake sediments, Zinder and Brock (1978) and the review by Holmer and Storkholm (2001) provide extensive information on formation of anaerobic S compounds, especially the gas hydrogen sulfide (H_2S). There are several treatment options for smaller volumes of water such as drip irrigation or homewells, and include activated charcoal, shock chlorination, oxidation or aeration, and oxidizing filters (Swistock et al., 2001; Scherer, 2005). However, for large water bodies such as a lake or pond, the best treatment options are lake aeration and limiting S additions to prevent sulfide formation. Once sulfides form, lake aeration, sediment removal, and restricting S additions will help to alleviate the problem, but odors may be evident during the process.

Iron. Soluble ferrous Fe and Mn (reduced forms) are favored by anaerobic conditions at lake bottoms. If the soluble Fe and Mn are not removed before going into the irrigation lines, there is the chance of Fe or Mn oxide or hydroxide precipitates clogging irrigation lines, plugging micro-irrigation system emitters, plugging screens with flakes of oxides, or causing red or blackish deposits on leaves and other objects. Removal of soluble Fe and Mn prior to going into irrigation lines can be achieved by the processes of oxidation to form insoluble precipitates, and precipitation or sedimentation out of the water (Yiasoumi et al., 2005; NDWC—Iron and Manganese Removal, 2008). Organic bound Fe or Mn are not effectively removed by mechanical oxidation. Filtration may be required for microirrigation systems or any irrigation system if precipitated particles are carried in the water into irrigation lines. To increase Fe precipitation within a lake, increasing water pH to at least pH 7.2 is recommended by using hydrated lime (calcium hydroxide) at about 0.25 lb per 1000 gal (30 gm per 1000 L) or trickling water over a crushed limestone bed. Iron is more soluble at acid pH, and precipitation will not be very effective.

14.6 AQUATIC PLANTS

Nutrient-rich waters that promote algal growth will also stimulate aquatic plant growth. Two potential problems associated with aquatic plants in irrigation lakes are excessive growth and aquatic weeds (undesirable plants) (Kay, 1998; Beard, 2002; Lembi, 2003; Thayer et al., 2003; Trounce, 2004). Due to the extensive nature of this topic and specialized treatments, readers are referred to local aquatic plant specialists familiar with lake and pond aquatic plant control. General control measures are as follows:

- Proper pond construction to limit rooting plants
- Identification of the specific problem, which for aquatic weeds means identification of the plant species
- Mechanical control—skimming, dragging, raking, underwater cutting
- Environmental control—limiting N, P, and other nutrients; light attenuation (dyes, covers); dredging sediments; draining the lake or pond in serious situations to dry out the bed and remove plants; artificial water circulation
- Biological control—vegetation-eating fish such as grass carp, common carp, tilapia; natural predator insects and plant pathogens
- Chemical control—aquatic herbicides
- Integrated control measures using two or more of the foregoing approaches

14.7 ODOR AND COLOR

In Chapter 12, Section 12.11, odors were discussed. Odor problem that could arise from several sources, such as decaying vegetation, mold, Fe/Mn/S bacteria, iron, chlorine, petroleum residues, and salt accumulation (Yiasoumi et al., 2005; Satterfield, 2006). Treatment options depend on the situation (well, pipelines, irrigation lake, etc.) and include chlorination, aeration, removal of Fe, clarification with flocculants, removal of algae, and activated carbon filters. Odor problems in lakes are caused by decaying organic matter in stagnant water, dissolved or suspended organic or inorganic materials, and dissolved gases in conjunction with increasing anaerobic conditions. For irrigation and lake situations, prevention of S additions, limiting N and P that stimulate excessive algal and aquatic plant growth, and mechanical aeration are key factors in odor prevention.

14.8 POND AND LAKE COLOR INDICATORS

Black with black slime normally indicates iron and sulfur bacteria are present. Brown to black color might indicate suspended decaying organic matter or dissolved organic matter. Brown, reddish, or somewhat white color could indicate suspended colloidal material. Reddish to brown color usually indicates dissolved minerals such as iron or manganese. Greenish, iridescent green, vivid green, or pale blue color is indicative of aquatic organisms.

14.9 STREAMS

Streams are often a vital part of turfgrass or landscape water ecosystem that provide aesthetic benefits, and aquatic and other wildlife enhancement, and may serve as irrigation sources. Sediments (inorganic and organic), debris, and nutrient loads are the major concerns related to irrigation. Maintaining the integrity of stream banks (stabilization) and adjacent buffer strips are two key issues (Schultz et al., 1997; Beard, 2002; Franks et al., 2004). Stream banks should (1) have good stability in the short and long term, (2) provide for lateral flow or seepage from adjacent areas into the stream, (3) be visually acceptable, and (4) enhance the quality of wildlife and aquatic flora and fauna. The document by Franks et al. (2004) provides comprehensive information on different stream stabilization options.

14.10 UNSTABLE WATER pH (LAKE LIMING)

In Section 14.4.8, avoiding excessive acidification of irrigation lakes and ponds to the point where bicarbonates and carbonates are essentially all evolved from the water was mentioned. In such situations, the buffering capacity of the lake water is lost, and water pH may exhibit wild swings with very little addition of acids or alkaline materials. This is not a favorable situation for aquatic life and lake health. In nature, this can occur owing to prolonged acid rains that slowly evolve the bicarbonates and carbonate from the water and lake sediments, and where the calcium carbonate in the lake sediments could replenish the lost bicarbonates and carbonates. The same condition could occur with excessive or long-term water acidification when the lake bottoms have limited lime loads. Helfrich et al. (2001) and Wurts and Masser (2004) discuss lime applications and methods to replenish lime in the lake bottoms and stabilize water pH.

14.11 NATURAL TREATMENT (LEACH FIELDS)

Irrigation water treatment options, such as discussed in Chapters 12, 13, and 14, are implemented either prior to receiving the irrigation water (reclaimed water) or on site. One on-site treatment option that deals with a host of environmental and irrigation water quality parameters is leach fields. Some sites may capture stormwater or wastewater from their surroundings and use a leach field rather than an on-site treatment plant for water treatment, with the naturally filtered water recaptured by deep wells for reuse in irrigation, pond augmentation, and fire control. With increasing regulatory control over withdrawal (overdraft) of underground water reserves out of aquifers, recreational turfgrass must rely more and more on surface water (lakes, ponds, streams, rivers, canals) for irrigation. (However in some regions, particularly California and other southwestern states that are accessing the Colorado River system, surface water is regulated as much or perhaps even more than groundwater, with strict limits on river withdrawals. As an example during the spring of 2008, California's Sacramento Delta, a snowmelt runoff source that supplies potable water to over 25 million Californians and irrigation water to tens of thousands of farmland acres, entered into what has been described as a "court-induced regulatory drought" in order to protect fish and the environment. Pumping from the delta was expected to be reduced by between 14 and 37% of normal capacity, amounting to a reduction of between 800,000 and 2,000,000 acre-feet of irrigation water per year.)

Most recycled or effluent water is deposited into ponds or lakes on the golf course or nearby facility (hopefully with tertiary or advanced treatment) for withdrawal and reuse on turfgrass and landscape plants. In some locations with less than tertiary water treatment, natural land application treatment systems (spray irrigation for surface and subsurface filtering, rapid infiltration in a flooded basin with high soil permeability, and overland flow on vegetated slopes involving surface chemical, physical, and biological processes) and leached drainage water collection, plus subsequent storage, can be utilized for turf irrigation (Roth, 2005). Benefits include minimal operation and maintenance, simplicity, cost-effectiveness, efficiency, and reliability in a natural ecosystem. Leach-field success is dependent on soil permeability, groundwater depth, site terrain, and presence of low-permeability soil layers or subsurface rocks (Roth, 2005).

In summary, lake, pond, stream, or any kind of water catchment facility, as a primary or secondary source of water for irrigation of turfgrasses and landscape plants, must be carefully maintained in the whole ecosystems management strategy for long-term environmental sustainability. Once a source of water for irrigation, they will become more and more rare, and use of multiple nonpotable sources will be the common best management practice. Storage of those water resources will be a key component for turfgrass management over the next decade and understanding the maintenance of these storage facilities will be essential to growing grass within climatic extremes.

Part 4

Environmental Concerns Related to Irrigation Water Sources on the Watershed/Landscape Level

15 Integration of Irrigation Water Sources to Minimize Environmental Concerns

An Increasing Challenge to Turfgrass Performance

> Grass is the forgiveness of nature—her constant benediction. Forests decay, harvests decay, flowers perish, but grass is immortal.
>
> **Brian Ingallis**

15.1 INTRODUCTION: WATER SOURCES AND SALINITY LOAD INTEGRATION

Regardless of the source of irrigation water used on golf courses—recycled, effluent, reclaimed, reuse, brackish, gray, stormwater, well water, rivers, reservoirs, ponds, lakes, creeks, streams—all of these sources will contain some level of salinity and possibly nutrients (Huck et al., 2000). Alternative irrigation water quality applied to recreational turfgrass is as good as it will ever be and over the next few decades will continue to get worse, that is, more saline. Reuse of irrigation water, blending of various sources, harvesting water from watersheds (refer to Chapter 9 for additional information)—these will be normal, rather than novel, practices for irrigating grass in this century. As salt is the ultimate growth regulator, maintaining turfgrass growth and development, achieving acceptable putting standards on greens, tolerating the wear and traffic challenges that will be imposed on the turfgrass, and sustaining grass survivability long term without loading excess salts into the soil profile will be ultimate goals (Carrow and Duncan, 1998; Duncan et al., 2000). The strategy should be one focused on applying the lowest saline irrigation water that is available, and adjusting the site-specific management program to the salt load in the water.

15.2 THE HOLISTIC MANAGEMENT STRATEGY

You cannot manage turfgrass with salinity challenges and changing environmental conditions unless you take a comprehensive **whole ecosystems approach** to management. If you are one-dimensional in your grass management with increasing salinity, turfgrass performance will eventually suffer. Salts are unforgiving and will slowly and silently accumulate in the soil profile at various depths over years to eventually cause significant problems in turfgrass canopy density, cosmetic appearance, and playability. Proactive monitoring of water, soil, and turfgrass tissues provides science-based information on critical areas of the whole or entire ecosystem—encompassing the turfgrass plant; site-specific soil chemical, physical, and biological properties; irrigation water quality; drainage system effectiveness; irrigation system distribution efficiency; influence of the "peripheral surrounds"; environmental interactions; and decision-making capabilities of the turfgrass manager.

15.3 MULTIPLE INTERACTIONS

As irrigation water quality decreases and salinity increases, interactions among the *water, soil type and profile, turfgrass species and cultivar, and the environment* also increase. This four-way interaction is what makes salinity so confusing and complex and the impact on turfgrass performance becomes increasingly **site specific** where management must be focused on specific "microsites" (Carrow and Duncan, 1998). In the past, such microsites were referred to as "indicator spots." But, with salt and nutrient-laden irrigation water, almost every grass performance area on a golf course can differ from surrounding areas and from nearby courses; so instead of considering only a few indicator spots, the entire turfgrass and landscape area on the site has a greater chance of exhibiting considerable site-specific differences. As salinity increases, turfgrass management will subsequently need to increase. If it does not parallel the increase in salinity, the grass performance will eventually decrease, and grass death is usually the result. Management of salts before, during, and after managing the grass should be the top priority; otherwise, salt loading in the soil will result, and grass performance could eventually become unacceptable.

15.4 CRITICAL MANAGEMENT CONSIDERATIONS

15.4.1 Proactive Monitoring

Proactive monitoring of *soil* nutritional and salt ion accumulation status, *water* quality parameters and their fluctuations over time, and *tissue* nutritional status provide critical science-based information for making management decisions as salinity increases (Carrow and Duncan, 1998; Duncan et al., 2000). Standard soil fertility tests can provide basic data on potential quantity of nutrients for absorption from the soil. Additionally, you may need to ask for other laboratory tests—such as the **saturated soil paste extract (SPE)** test—to get proper information on the salinity status of your specific soils for the site. The SPE provides data on sodium adsorption ratio (SAR), exchangeable sodium percentage (ESP), total dissolved salts (TDS) of the soil extract and/or electrical conductivity of the extract (ECe), and other salt ions or compounds such as sodium, sulfates, chlorides, boron, and bicarbonates that are sometimes not routinely analyzed in normal soil fertility tests. The proactive strategy can often minimize many of the potential salinity-imposed problems and be more cost effective with little or no turfgrass performance "downtime" on the golf course or recreational grass site. Utilizing the science-based soil, water, and tissue data is the critical strategy for long-term grass sustainability when using saline water resources for irrigation. Proactive monitoring can encompass regularly scheduled and budgeted water, soil, and tissue sampling, with subsequent holistic ecosystem management decisions predicated on historical and recent changes in the analytical data.

15.4.2 REACTIVE MONITORING

Salinity monitoring can also be reactive. Reactive monitoring can normally occur when salts have already impacted turfgrass performance, causing root pruning, thinning of canopy density, nutritional imbalance problems, decreased cosmetic appeal, and/or predisposition to insect, disease, and weed encroachment challenges. The reactive strategy can result in quite costly and time-consuming soil, water, and grass reclamation programs that are needed to remedy salt buildup–related problems in soil profiles that result in negative turfgrass interactions. Salinity problems can take time to eventually cause turfgrass-related problems (usually determined by irrigation water quality), and the remedy to reverse the salt challenge can be quite complex, expensive, and difficult to rectify.

15.4.3 SAMPLING STRATEGIES

Sampling of soil profiles at the 0–3 in. (0–7.5 cm), and 3–6 in. (7.5–15 cm) zone in the soil profile, then bulking samples from good grass performance areas and more challenging sites can provide essential contrasting information that can be used to make management decisions that provide information on the following:

1. Movement of salts (and also fertilizer nutrients) through the upper soil profile zones.
2. Leaching effectiveness (moving salts down below the root system, especially chlorides and sulfates because both salt compounds move either with the wetting front or just behind the wetting front during irrigation cycles). Ideally, sampling soils periodically from the bottom of the root system or just below this area in the rhizosphere can provide critical indicator information on potential salt accumulation layers and their potential for return salt capillary movement into the upper root zone. You can also ask the analytical laboratories for a salinity analysis of your irrigation or drainage water, not only the water coming out of the wells, rivers, ponds, or lakes, but also the water actually coming out of the sprinkler heads or drain lines on the golf course or sports field. Finally, you need to collect clippings from good and bad turfgrass areas on the course and submit the tissue for a wet chemistry/spectrophotometric analysis to provide proper information on nutritional balances and imbalances caused by increasing salinity. *Data from the normal soil fertility, water, and tissue analyses* can then be used to *adjust the fertility program,* based on the water salinity impact in the soil plus the nutrient concentrations that the turfgrass can potentially or

actually absorb and utilize. Micronutrients are especially sensitive to salinity increases in the ecosystem and should be closely and regularly monitored both in the soil and in the grass tissue (Carrow and Duncan, 1998). It must be emphasized that one should not base fertility program adjustments on the saturated paste extract salinity test.

15.4.4 Understanding the Salinity Impact

Education starts with each grass manager becoming familiar with terms such as total dissolved salts (TDS), electrical conductivity of soil extracts and water (ECe and ECw, respectively), sodium absorption ratio (SARe and SARw), adjusted sodium absorption ratio (adjSARe and adjSARw), residual sodium carbonates (RSC), impact on general plant salinity tolerance threshold growth (ECw, TDS), impact from root contact or uptake (Na, Cl, B), impact from foliage contact (Na, Cl), and impact on soil structure (SARw and adjSARw, ECw, TDS) (Carrow and Duncan, 1998). Critical salinity impact nutrients that are often at near-toxic or toxic levels include Na, Cl, B, bicarbonates and carbonates, and sulfates. Nutrients that are often imbalanced in turfgrasses include many of the micronutrients such as Ca, Mg, N, Mn, Zn, Cu, and Fe, as well as the macronutrients P and K. Saline soils have high total dissolved salts; sodic soils are dominated by excess Na, and saline–sodic soils contain a combination of both high total salts and excess Na (Carrow and Duncan, 1998). In addition to irrigation water adding significant levels of nutrients, the leaching program to manage excess soluble salts can also change the availability of soluble nutrients. Simply stated, if you are leaching salt ions, then you are also leaching fertilizer nutrients and your fertility program must be adjusted accordingly. All components of salinity significantly affect turfgrass rooting and long-term performance, lending credence to adoption of the whole systems or holistic approach to management, with proactive monitoring as an essential strategy for managing salts, minimizing accumulation in the soil profile, and maximizing grass performance. However, there is a reality check involved.

15.4.5 Additional Limitations

When excess sodium, chlorides, sulfates, boron, and bicarbonates/carbonates accumulate in the soil, they impact soil and turfgrass nutritional stability/availability. When high levels of sodium (concern levels >125 ppm or >5% base saturation) buildup in the soil to the point of displacing calcium between the colloids, soil structural breakdown can occur, leading eventually to sodic soils (Carrow and Duncan, 1998). Sodium can dominate the cation exchange sites and granular fertilizer utilization efficiency can be decreased. Excess chlorides >355 ppm can affect nitrogen nutrition. Excess sulfate levels >180 ppm can accumulate and layer in the soil profile, leading to potential black layer problems in conjunction with anaerobic conditions. Excess boron levels >3 ppm can lead to additional nutritional imbalances. Bicarbonate levels >120 ppm and carbonate levels >15 ppm have a propensity to complex with calcium, magnesium, and phosphates to form insoluble precipitates, layer in the soil, reduce water percolation rates, and reduce the availability of these key nutritional elements

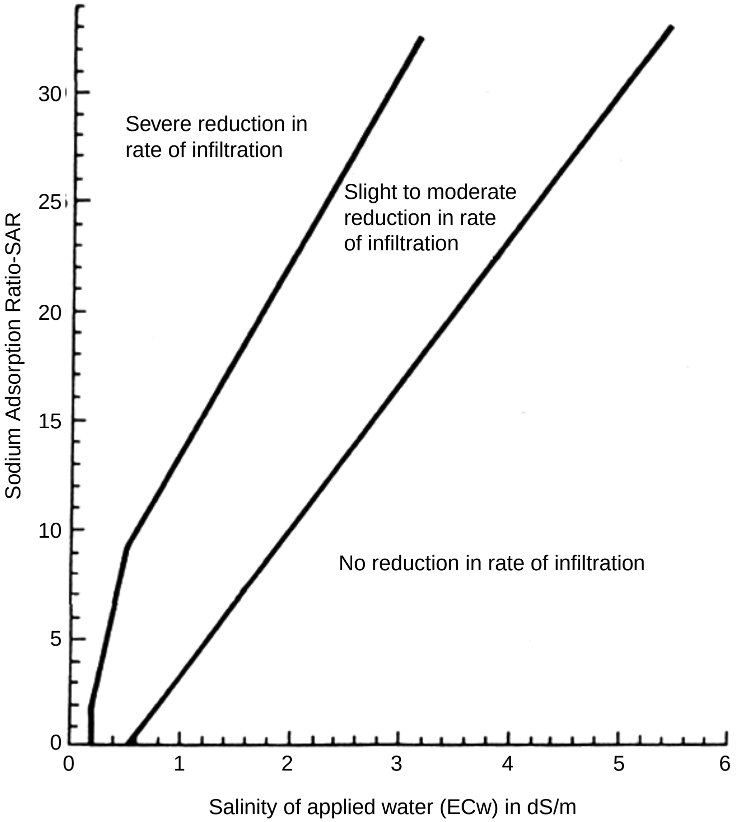

FIGURE 15.1

for turf uptake. Actual levels of Ca and Mg are key concentrations that must be balanced in the soil and the plant to maintain turf health.

15.4.6 THE REALITY CHECK: SALT LOADING FROM THE IRRIGATION WATER SOURCE OR SOURCES

A primary concern is what impact the increasingly saline irrigation water can have on accumulation of total salts in the soil and its potential for foliar feeding directly into the turfgrass shoots to disrupt nutrition with each irrigation cycle.

Data in Table 15.1 provide the realistic expectations when applying saline irrigation water to turfgrasses. If excess total salts accumulate and layer in the soil rhizosphere, a turfgrass salinity threshold level can be surpassed that will eventually overwhelm the inherent capability of the grass cultivar to withstand and persist with salinity (Carrow and Duncan, 1998). The soil-related salt impact will be on root system development, redevelopment, and maintenance. Secondarily, carbohydrate allocation to shoot maintenance will be decreased, the turfgrass becomes less

TABLE 15.1
Salt load in irrigation water based on different application rates over a typical 90-acre (36.4 ha) golf course

	lb (kg) of salt per application		
Salinity level total dissolved salts (ppm)	**500,000 gal (1.8925 million L)**	**750,000 gal (2.83875 million L)**	**900,000 gal (3.4065 million L)**
500	2075 (941)	3113 (1412)	3735 (1694)
1000	4150 (1882)	6225 (2824)	7470 (3388)
1500	6225 (2824)	9338 (4236)	11,205 (5083)
2000	8300 (3765)	12,450 (5647)	14,940 (6777)
3000	12,450 (5647)	18,675 (8471)	22,410 (10,165)
4000	16,600 (7530)	24,900 (11,295)	29,880 (13,554)
5000	20,750 (9412)	31,125 (14,118)	37,350 (16,942)
10,000	41,500 (18,824)	62,250 (28,237)	70,008 (31,756)
15,000	62,250 (28,237)	93,375 (42,355)	112,050 (50,826)
20,000	83,000 (37,649)	124,500 (56,473)	149,400 (67,768)
34,500[a]	143,175 (64,944)	214,763 (97,416)	257,715 (116,900)

Note: 1 acre-inch irrigation over 90 acres=2,443,860 gal or 9,250,010 L.

[a] Ocean water.

aggressive, and the grass is predisposed to secondary stresses, especially greater disease infestation, and occasionally insect problems. Normally, the first symptoms recognized by turfgrass managers are cosmetic color changes, reduced aggressiveness in turfgrass growth rates (slow recoverability of ball marks in greens, and divots in tees and landing zones in fairways) and slow response to fertilization, and disease infestation. However, salt loading in the soil profile, and especially in the upper 2–4 in. (5–10 cm) near the grass crown region, can be an initial primary limitation that decreases growth rate, depending on turfgrass species plus specific cultivar salinity tolerance and the overall salt concentration. Water uptake and nutrient absorption (especially granular fertilizer nutrients) are usually decreased because of the desiccation of root hairs, branch roots, rhizomes, and surface stolons. Excess salts that are foliarly absorbed in the shoot system with each irrigation water cycle can suppress stolon growth and tillering, because of its growth regulator effect on gibberellin, auxin, and cytokinin hormonal production in the grass shoots. The turfgrass plant reverts to the injury repair mode using carbohydrate reserves, and becomes more vulnerable to pathogen and insect attack. Reduced turfgrass canopy density and dead turfgrass can be the end result. Turfgrass management shifts to a reactive strategy (fungicide, insecticide, and fertilizer applications), and because high salinity is being applied to the turfgrass ecosystem with each irrigation cycle, the battle to manage turfgrasses for survivability and performance becomes an increasing challenge.

Even low levels of salts can accumulate in soils because salt is added with each irrigation application, that is, 500 ppm irrigation water dispersing one ton of salt with one 500,000 gal application (Table 15.1) (Munshaw et al., 2004). Low-level salinity might not initially cause problems, but if the salts are not managed properly to minimize accumulation and layering in the soil over years, turf quality traits will eventually deteriorate because of accumulation and layering in the soil (Munshaw et al., 2004). Ocean water irrigation (at 34,500 ppm TDS) is not recommended in any situation because of the massive salt loading potential (Duncan et al., 2000). Development of certain seashore paspalum ecotypes that can tolerate ocean water salinity is important not because you might want ocean water for irrigation, but because the salinity tolerance is beneficial (1) to allow the turf manager time to make management adjustments under normal high saline irrigation practices with saline water at lower salt levels than ocean water, and (2) on sites susceptible to ocean flooding, storm surge, or persistent salt spray, which would allow survival and recovery from these periodic catastrophic events. Irrigation system distribution efficiency and leaching program effectiveness are keys to proper long term soil salinity management strategies (Carrow et al., 2000).

15.5 THE TURFGRASSES

Current development of grass cultivars with improved levels of salinity tolerance is providing previously unavailable options for managing grasses using variable quality recycled and increasingly saline irrigation water (Munshaw et al., 2004; Marcum and Murdoch, 1994; Meyer et al., 1989; Qian et al., 2000). The development of seashore paspalum (*Paspalum vaginatum* Swartz), the most salt-tolerant warm season grass species, for golf course use has provided flexibility in managing a turfgrass that is more forgiving as salinity increases in the turfgrass environment (Duncan and Carrow, 2000). The added advantage of this grass is the tournament-quality attributes and the cosmetic appearance resembling Kentucky bluegrass that occurs with proper management. Private companies are developing cool season grasses that have higher salinity tolerance than in the past. The availability of these salt tolerant cultivars is and should continue to improve turfgrass performance on golf courses. Realize also that germination of seeded warm and cool season grasses in saline water and the maintenance of more mature turfgrass plants after germination are controlled by different genes governing salinity tolerance. Combining the dual germination and maintenance salinity tolerance mechanisms into one package is ongoing, but will take time to properly develop. Additionally, just because you have a highly salinity tolerant turf cultivar does not mean that ocean or highly brackish saline water should be used long term on the golf course.

The central benefit of a salt-tolerant grass is that it provides more flexibility for the turfgrass manager to manage salts without immediate turfgrass injury when environmental extremes occur. But salts must be managed or the salt-tolerant grass can be overcome because its tolerance threshold level has been surpassed due to salt loading in the soil profile. A common misconception in using a highly salt-tolerant grass is that the grass is “the answer” if poor quality saline water is used for irrigation. But the grass is only one component of the whole ecosystem. A salt-tolerant grass must be used in conjunction with adoption of management options such as salt leaching, possible need for water and/or soil treatments, drainage improvements, fertilization adjustments, and scheduled aeration events, to name a few, for long-term turfgrass sustainability and performance. Do not create an environment to grow grass that is worse than the one you inherited when growing salt-tolerant grasses. Mismanagement of salts in the soil can result in problems that are time consuming, expensive, and difficult to remediate.

15.5.1 BLENDING OPTIONS FOR SPECIFIC TURFGRASSES

Regardless of water source or level of salinity, many turfgrass managers will be faced with blending multiple sources to supply the quantity of water needed for turfgrass requirements plus leaching (refer to Chapter 11 for additional information) of excess salts (salinity management) plus the salinity tolerance threshold of the grass cultivar. Blending formulas utilize salt calculations as those concentrations are directly proportional.

Option 1. Total dissolved salts (TDS) in irrigation water sources

TDS	% Blend	ppm contribution	Final blend TDS
1000	20	200	
640	80	512	712 ppm
1000	80	800	
640	20	128	928 ppm
5000	25	1250	
800	75	600	1850 ppm
5000	50	2500	
800	50	400	2900 ppm
5000	75	3750	
800	25	200	3950 ppm
34,500	25	8625	
1500	75	1125	9750 ppm
34,500	50	17,250	
1500	50	750	18,000 ppm

Note: 34,500 ppm water = ocean water.

Option 2. SAR and adjSAR component calculations

Nutrient	Source 1	80% blend	Source 2	20% blend	Total blend
Na	16 meq/L	12.8 meq/L	25 meq/L	5 meq/L	17.8 meq/L
Ca	4	3.2	12	2.4	5.6
Mg	4	3.2	8	1.6	4.8
HCO	6	4.8	10	2	6.8
CO	4	3.2	2	0.4	3.6
TDS	2500 ppm	2000 ppm	800 ppm	160 ppm	2160 ppm

An additional consideration is how to use highly saline and lower saline irrigation sources. Should you blend the two sources to create as low salt concentrations as possible? Or should you use the higher salinity water and then flush once or twice weekly with the lower salinity water source? The answer to those questions will be dictated by the salt load in each water source, the soil profiles in the greens and other grassed areas, the ability to sustain acceptable infiltration/percolation rates, the quantity of water available from each source, the distribution efficiency of the irrigation system, the leaching potential on the site, the environmental extremes, and whether management is reactive or proactive in managing the salts.

15.5.2 WATER QUALITY EFFECTS ON HERBICIDES

Some herbicides may be adversely affected by quality factors in water used in the spray tanks. If the irrigation water source is used to fill the spray tank, such factors as pH, turbidity, dissolved minerals, and general water chemistry (particularly alkalinity or carbonate/bicarbonate concentrations) can occasionally affect herbicide efficacy (Morris, 2006; Harivandi, 1981).

Turbidity (caused by suspended or dissolved solids such as silt or organic matter) can reduce the effectiveness of glyphosate (Roundup®, Rodeo®, Razor®, Prosecutor®, Eagre®, AquaNeat®), paraquat (Gramoxone®), diquat (Reward®), and 2,4-D amine. These herbicides can also be sensitive to dirt or blown dust on plant surfaces. Dicamba (Banvel®, Vanquish®) are relatively unaffected by suspended solids in spray water.

Water pH above 7 can affect weak acid, postemergence herbicide efficacy and buffering adjuvants (such as the acidifier LI 700® or the water conditioners/buffering agents Choice®, Quest®, or Request®, Latron®, Aero Dyne-Amic®, Blendex®, Optima®, Penetrator Plus®, and Setre-FA-1®) are often added to lower pH to the slightly acidic to neutral range. Increasing water pH can increase the solubility of sulfonylurea herbicides (Manage®, or halosulfuron), and theoretically increase their activity.

Electrical conductivity <0.50 dS/m (500 uS/cm) or total dissolved salts (TDS) of 320 ppm are unlikely to affect efficacy of most herbicides (Morris, 2006). Higher salinity waters can affect efficacy at times.

Hardness or calcium carbonate equivalent can reduce the effectiveness of glyphosate and 2,4-D amine. Hardness in the range of 350–700 ppm (20–40 grains/U.S. gal) can affect glyphosate at the lower and upper ranges of the labeled application rates, respectively. With 2,4-D amine, 600 ppm (35 grains/U.S. gal) is the threshold hardness (Morris, 2006), and 500 ppm $CaCO_3$ is the threshold alkalinity. Water bicarbonate concentrations in the 500 ppm to 1000 ppm (8.2–16.4 meq/L) range can affect the efficacy of glyphosate, 2,4-D amine, sethoxydim (Poast®, Vantage®), and clethodim (Envoy®). For glyphosate, approximately 10–15% of the product can be complexed with calcium and magnesium, thereby rendering that portion ineffective for herbicidal activity. The maximum allowable labeled rate can be used or ammonium sulfate fertilizer can be added if recommended on the label to overcome the antagonistic effects of hard water. However, for 2,4-D amine, the ammonium sulfate fertilizer addition is not possible and these options are available: switch to a more volatile ester formulation, use a nonionic surfactant, or reduce the water volume to the minimum required for proper application coverage (Morris, 2006). Timing the herbicide application at the optimum growth stage of the target weed can also be critical for effective control under these conditions.

TABLE 15.2
Water hardness chart

Very soft	8–50 ppm	(0.5–3 grains/U.S. gal)
Soft	50–120 ppm	(3–7 grains/gal)
Moderately hard	120–600 ppm	(7–35 grains/gal)
Hard	600–1200 ppm	(35–70 grains/gal)
Very hard	1200–3000 ppm	(70–175 grains/U.S. gal)

High iron concentrations in water can also reduce the activity of glyphosate, as well as plug screens and nozzles on spray equipment with an oxidized precipitate. Waters with high Fe levels should be avoided when mixing pesticides.

With high sodium concentrations in water at pH >7.0, herbicide efficacy can be reduced. Prior to pesticide mixing, measure the concentrations of Ca, Mg, Na, and Fe in the water to be used for mixing. If the sum of the cations exceeds 400 ppm, some corrective action may be necessary to maximize efficacy. If bicarbonate levels are >300 ppm, corrective action in the spray tank may be warranted.

Additional information can be obtained from the following Web sites: http://www.agr.gov.sk.ca/docs/crops/integratedpestmanagement/weedcontrol/waterquality and http://www.oregonstate.edu/dept/nurseryweeds/feature_articles/spray_tank/spray_tank.htm.

15.6 SUMMARY

Growing grass with any concentration of salinity in the irrigation water is not a simple or single dimensional management consideration. Multiple challenges and site-specific interactions among the grass cultivar and its genetic salinity tolerance, the quality of the irrigation water, the soil profile, and uncontrollable changing environmental conditions combine to create the most confusing and stressful challenges to growing grass for any manager. With the dynamic and ever-changing grass ecosystem, changes in soil chemistry and physical conditions can and will occur as salinity in the irrigation water increases. Salt accumulation in soil profiles and foliar feeding of salt ions directly into grass shoots can rapidly alter nutrient availability and nutritional balances. Constant proactive monitoring and recognition of salt-related grass symptoms are essential for successfully managing the turfgrass long-term. The challenges are complex, but the grass management program should be based on science-based information and should be kept as simple and as basic as possible.

The increasing use of poorer quality irrigation water dramatically affects the soil chemical and physical properties, which in turn can adversely affect turfgrass performance—and these challenges will be persistent, ongoing problems. The level of turfgrass management skills to deal with the diverse direct and indirect effects of poor water quality will be substantially greater than for the same site with good (lower salinity) irrigation water. The whole plant–soil–water–climatic system becomes much more dynamic and the changes must be systematically monitored;

site-specific management must be the norm; turf managers must resist the temptation to look for the "one magic bullet" solution—such as a salt-tolerant grass, irrigation water acidification, sand-capping, and other management options. All of these infrastructure improvement options are potential tools that require strategically planned implementation in conjunction with grass management adjustments made across the whole ecosystem for long-term success.

16 Case Studies

Water Data Analysis and Interpretation

When assessing any soil or water quality data, you will need to convert ppm or mg/L to meq/L by dividing by the equivalent or molecular weight of each nutrient or salt ion:

Ca: divide by 20
Mg: divide by 12.2
Na: divide by 23
Sulfates: divide by 48
Chlorides: divide by 35.4
Carbonates: divide by 30
Bicarbonates: divide by 61
K: divide by 39

CASE STUDY 1: IRRIGATION LAKE (HAWAII)

pH	9.17		
Hardness (ppm)	75.67		
Conductivity (dS/m or mmhos/cm)	0.53		
SAR	3.59		
Adjusted SAR	2.47		
pHc	8.71		
RSC	–0.44		
Calcium	12.53 ppm	0.63 meq/L	2.84 lb/ac in.
Magnesium	9.93	0.82	2.25
Potassium	4.34	0.11	0.98
Sodium	70.13	3.05	15.91
Iron	1.96	0.44	
Total alkalinity ($CaCO_3$)	50.28	11.40	
Carbonate	21.70	0.72	4.92
Bicarbonate	17.24	0.28	3.91
Chloride	105.53	2.98	23.93
Sulfur as SO_4	30.72	0.64	6.97
Salt concentration (TDS)	338.56	76.79	
Boron	0.10	0.02	
Cation/anion ratio	0.99		

Points of concern:

1. pH > 8.0 coupled with rapid pH elevation
2. Conductivity too low at 0.53 dS/m
3. Ca < 1 meq/L or 20 ppm
4. Mg > Ca (meq/L)
5. Na + Mg > Ca (meq/L)
6. Not enough Ca to counter the Na concentration
7. Has algae in the lake

Optional management decisions:

1. Not enough buffering or calcium for soil infiltration/counter to Na load: add hydrated lime or gypsum.
2. Purchase a gypsum or lime injector.
3. Blend with reclaimed water that is higher in salinity.
4. Purchase an aeration system.
5. Add alum to settle out phosphorus.
6. Do not acidify the water.

CASE STUDY 2: THREE WATER SOURCES (HAWAII)

Source	Reject concentrate	Well	Irrigation lake
pH	7.6	7.4	8.0
ECw mmhos/cm	3.50	1.46	2.45
TD salts ppm	2240	934	1568
TD solids ppm	2885	1004	1824
SAR	4.76	6.09	5.87
adjSARw	5.29	6.23	6.36
Ca meq/L	6.09	0.95	2.94
Mg meq/L	20.15	4.85	10.61
Na meq/L	17.22	10.34	15.26
Bicarbonates meq/L	21.20	5.51	11.39
Chlorides meq/L (ppm)	16.75 (594)	6.66 (236)	11.96 (424)
RSC	−5.04	−0.29	−2.36
P ppm	1.41	0.21	0.42
K ppm	21.3	13.1	17.3
Nitrate ppm	44	14	16
Sulfate ppm (meq/L)	168 (3.5)	89 (1.85)	132 (2.75)
B ppm	0.13	0.14	0.16

Points of concern:

1. Water pH > 8.0 will be concern with nutrient availability.
2. Ca concentrations are low compared to Na.
3. Mg concentration is higher than Ca.

4. Blend between reject concentrate and well water is loading high total salts into the main irrigation lake.
5. Bicarbonate levels are extremely high and complexing all the calcium.
6. Sodium is high enough to load into the soil profile and eventually cause sodic soil problems and foliar feed into the turfgrass shoots to disrupt nutritional balances.
7. Chlorides are high enough to potentially affect nitrogen nutrition.
8. Fines being applied with each irrigation application.
9. P and K levels are quite low.

Optional management decisions:

1. Acidification of bicarbonates,
2. Calcium injection into the water; granular gypsum applications to soil; Ca levels must equal and surpass the Na levels to manage that salt ion.
3. Ca concentrations need to be higher than Mg to stabilize nutrition and maintain grass color.
4. Possible supplemental use of liquid nitrogen applications.
5. Blend higher percentage of the well water in the blended water going into the irrigation lake.
6. Screen more fines out of the reject concentrate water source.
7. Proactively monitor P levels in the soil and in the plant tissue.
8. Spoon-feed K regularly and monitor tissue sufficiency levels.

CASE STUDY 3: LAKE (NEVADA)

pH	8.0	
Hardness	904.2	
pHc	7.24	
Bicarbonates ppm (meq/L)	122 (2.0)	
ECw mmhos/cm or dS/m	3.02	Impact on general turf plant growth and soil structure
TDS ppm	1933	
Sodium ppm (meq/L)	355 (14.57)	Impact from root contact
Chloride ppm	403	
Boron ppm	1.0	
adjSARw	10.48	Impact on soil structure
SAR	4.85	
Nitrates	6.20 ppm	0.44 meq/L
Phosphates	0.01 ppm	0.00 meq/L
Potassium	30 ppm	0.77 meq/L
Magnesium	108 ppm	8.88 meq/L
Calcium	184 ppm	9.18 meq/L
Sulfates	882 ppm	18.38 meq/L
Sodium	355 ppm	14.57 meq/L
Chlorides	403 ppm	11.35 meq/L

Points of concern:

1. Sodium levels are higher than the calcium levels.
2. Sulfates are extremely high and could potentially lead to black layer problems.
3. Chlorides are potentially high enough to affect N nutrition.
4. pH at 8.0.
5. 5228 lb salt being applied to the irrigated area with each 325,851 gal of water.

Optional management decisions:

1. Calcium concentrations need to exceed Na + sulfates to properly manage those salts (1 meq/L Ca will bind with 2.43 meq/L sulfates to form gypsum).
2. Regularly scheduled aeration to minimize potential black-layer problems; periodic application of lime to form gypsum in black-layer prone areas.
3. Apply micronutrient packages regularly and monitor tissue for sufficiency levels.
4. Supplemental liquid N applications periodically.
5. Regularly scheduled aeration to manage high salt deposition from the water.

CASE STUDY 4: HAWTHORN AQUIFER WELL WATER (SW FLORIDA)

pH	7.10	
Hardness ppm	1692.09	
Conductivity mmhos/cm or dS/m	8.66	
TDS ppm	5542.40	
SAR	15.38	
adjSAR	33.24	
pHc	7.24	
RSC	−30.94	
Bicarbonates ppm (meq/L)	174.24	(2.86)
Calcium ppm (meq/L)	281.33	(14.04)
Magnesium	240.30	(19.76)
Sodium	1453.86	(63.21)
Chlorides	2605.88	(73.49)
Sulfur as sulfates	1009.81	(21.02)

Points of concern:

1. 14,990 lb of salt deposited on irrigated area with each 325,851 gal of water.
2. Sodium levels 4.5 times higher than calcium levels.
3. Mg levels higher than calcium levels (meq/L basis).
4. Chlorides will completely affect *Nitrosomonas* conversion of granular urea-N and ammonium-N products to nitrates.
5. Exceptionally high sulfates.

Optional management decisions:

1. Only the most salt-tolerant grasses can be grown.
2. Inject calcium into the irrigation water and regularly apply granular calcium to soil surface with an aeration event.
3. Weekly to biweekly aeration to facilitate adequate leaching of chlorides and high total salts.
4. Proactive monitoring at least monthly on soil, water, and tissue samples.
5. Careful adjustments in fertility program; more supplementation with liquid products as needed.
6. Look for lower salinity water resource for blending.
7. Flush at least every 2–4 weeks.
8. Monitor leachate emerging from bottom of greens drainage lines to enhance leaching program.

CASE STUDY 5: LAKE BLENDED WITH HAWTHORN AQUIFER WELL WATER (SW FLORIDA)

		Desired Range
pH	7.50	>6.0–<8.0
Hardness ppm	1162.26	
Conductivity mmhos/cm or dS/m	5.74	<2.35
TDS ppm	3673.60	<1504
SAR	12.39	<10
adjSAR	27.61	<10
pHc	7.17	
RSC	−19.24	<1.0
Bicarbonates ppm (meq/L)	241.33 (3.96)	<122 (2.0)
Calcium ppm (meq/L)	220.81 (11.02)	(= to Na + Mg + SO_4)
Magnesium	148.12 (12.18)	
Sodium	970.61 (42.20)	<92 (4.0)
Chlorides	1955.69 (55.15)	<355 (10.0)
Sulfur as sulfates	593.80 (12.36)	<180 (3.75)

Points of concern:

1. High total dissolved salts (9935 lb of salt per 325,851 gal of water).
2. Bicarbonates will complex about 4 meq/L of the calcium, forming an insoluble and unavailable compound for turfgrass root uptake.
3. Mg levels higher than Ca levels (meq/L basis).
4. Na levels 3.9 time higher than Ca levels.
5. Chlorides high enough to affect nitrogen nutrition.
6. Sulfates high enough to cause concern about potential for black-layer problems.

Optional management decisions:

1. Weekly aeration to facilitate adequate leaching of high total salts and chlorides.
2. Inject calcium into the water and apply calcium to the soil surface to increase Ca as the counter ion to high Na and high sulfate levels.
3. Adjust the N fertility program in include regular liquid N applications.
4. Proactively monitor soil, water, and tissue at least monthly.
5. Collect leachate from drainage lines to improve leaching program.
6. Flush greens at least every 2–4 weeks.
7. Periodic applications of lime following an aeration event to chemically form gypsum and stabilize the high sulfur loading into the soil and minimize potential black-layer problems.

CASE STUDY 6: ORANGE COUNTY (SOUTHERN CALIFORNIA) POTABLE VERSUS RECYCLED WATER QUALITY

Two neighboring facilities were studied in Orange County, located approximately 7 miles apart and serviced by different wastewater and potable sources. Primary source of potable water at course 1 is groundwater; potable source near course 2 is a blend of surface water originating from the Colorado River (average 800 ppm TDS) and the California State Water project (average 300 ppm TDS). It is known that the potable supply at Course 2 is hard, and a high percentage of residences in the community use water softeners, hence the dramatic increases of sodium, chloride, ECw, and TDS.

	Course 1		**Course 2**	
Source	**Potable**	**Recycled**	**Potable**	**Recycled**
pH	8.1	7.2	8.2	7.43
ECw mmhos/cm	0.99	1.32	0.65	1.73
TDS ppm	770	954	416	1104
SAR	2.46	4.32	2.22	3.30
adjRNaw	2.83	4.88	2.22	4.26
adjSARw	NR	NR	3.40	7.47
Ca meq/L	3.99	3.79	1.85	7.11
Mg meq/L	2.63	2.47	1.39	4.06
Na meq/L	4.48	7.65	2.83	7.79
Bicarbonates meq/L	3.10	3.00	1.55	4.53
Chlorides meq/L	2.34	4.51	2.73	7.10
RSC	−3.52	−3.26	−1.69	−6.64
P ppm	<0.01	3.01	NR	1.18
K ppm	5.1	22.0	3.20	16.73
NO3-N ppm	2.0	46.0	2.0	1.19
NH3-N	NR	NR	NR	7.14
Sulfate ppm	276	258	132	491
B ppm	0.14	0.44	0.13	0.51

Points of concern: California water code requires recycled water use for landscape irrigation. Likely, a high amount of water softeners are used in the area.

1. Regular leaching of greens required.
2. Note increases of sodium and chlorides most significant between potable and recycled samples.
3. Bicarbonates will be complexing a large part of the Ca concentration.
4. Sulfate levels >180 ppm are a concern and potential problem for black-layer.
5. Sodium levels are higher than Ca levels in all cases.

Optional management decisions:

1. Occasional applications of gypsum made during fall/winter to promote improved infiltration of ultrapure rainwater and optimize leaching by natural rainfall.
2. Ca levels need to be higher than the Na + sulfate concentrations.
3. Regular aeration events should be scheduled.
4. Proactive monitoring to balance nutrition and manage the salts.

CASE STUDY 7: CALIFORNIA/NEVADA STATE LINE GROUNDWATER QUALITY—VARIABILITY OF THREE WELLS

Well 1 is located at higher elevation near the base of a nearby mountain; wells 2 and 3 are located on a desert valley floor.

Source	**Well 1**	**Well 2**	**Well 3**
pH	6.43	7.47	7.43
ECw mmhos/cm	0.89	2.30	6.58
TDS ppm	571	1472	4211
SAR	2.71	9.63	43.60
adjRNa	2.75	11.54	43.60
adjSARw	3.96	17.28	56.43
Ca meq/L	2.58	3.75	1.84
Mg meq/L	1.83	1.38	1.04
Na meq/L	4.02	15.51	52.31
Bicarbonates meq/L	1.62	2.89	2.63
Chlorides meq/L	3.31	17.47	47.28
RSC	−2.79	−2.24	−0.25
P ppm	NR	NR	NR
K ppm	5.74	6.07	12.85
NO3-N ppm	NR	NR	NR
NH3-N	NR	NR	NR
Sulfate ppm	220	37	121
B ppm	0.22	0.18	0.73

Points of concern:

1. Volume of water that can be withdrawn from well 1 is restricted by county authority, forcing occasional blending with wells 2 and 3 during the irrigation season.
2. Bicarbonates will complex about half or more of the calcium, allowing Na to start to dominate the CEC.
3. Sodium levels are higher than Ca levels.
4. Chlorides could be a problem with wells 2 and 3 and potentially affect N nutrition.
5. Sulfates in well 1 will need to be monitored.

Optional management decisions:

1. Use well 3 for blending only when there is an emergency due to the high salt load in the water.
2. Blending should be predominately between wells 1 and 2 to minimize salt accumulation problems.
3. Increase the application of calcium amendments.
4. Regularly schedule aeration events.
5. Proactively monitor soil, water, and tissues at least monthly.

CASE STUDY 8: TPC, SCOTTSDALE, ARIZONA

Data in the table below relate to the following:

Lake irrigation water: The recycled water used for irrigation was deposited into the primary irrigation lake and monitored in February, April, July, and August 2007. Note the pH, TDS, sodium, chloride, and salt loading changes between the first two months (high people occupancy rate; peak golf play months) and the last two months (hottest time of the summer months).

Head (sprinkler) water actually being applied to the golf course: With a few exceptions, the salts being deposited on the golf course were at higher concentrations than was actually found in the irrigation lake.

Leachate collected from drainage lines in the greens: TDS concentrations ranged from 3.5–7 times higher in the leachate fraction, demonstrating that salts will build up to high concentrations in USGA specification greens, but those salts can be effectively leached down to the drainage lines. Sodium levels ranged from 2.6–5.5 times higher in the drainage lines than the irrigation water that was applied on the grass, but the calcium amendment program was sufficient to promote good Na leaching down to the drainage lines. Chlorides, which are highly mobile and highly soluble, ranged from 3.7–17.5 higher in the leachate than in irrigation water. Bicarbonates, which are generally difficult to leach, ranged from 0–13 times higher in the leachate fraction, compared to the irrigation water. Total salts (lb/acre-foot) ranged from 2.6–7.3 times higher in the leachate, again demonstrating that the leaching program on the site is quite effective in moving the salts through the soil profile.

Conclusion: Collecting leachate from drainage lines at strategic sites on the golf course is an excellent strategy for monitoring how effective the leaching program might be during the year and how often any flushing might be needed.

Source	pH	TDS (ppm)	Sodium (meq/L)	Chloride (ppm)	Bicarbonates (meq/L)	Salt loading (lb/acre-foot)
2/07 Lake	8.7	1030	7.0	244	2.6	2803
4/07 Lake	9.0	538	4.2	118	2.8	1462
7/07 Lake	8.1	973	7.7	240	2.0	2646
8/07 Lake	8.1	1082	8.1	287	2.6	2942
2/07 Head	6.8	1146	7.2	286	0.4	3116
4/07 Head	7.7	922	7.8	236	2.4	2507
7/07 Head	6.9	480	7.9	257	3.8	1306
8/07 Head	6.6	1101	8.0	301	1.8	2994
2/07 Drain	7.0	4198	34.5	1380	5.2	11,420
4/07 Drain	6.9	2438	20.2	877	4.1	6632
7/07 Drain	7.0	3507	26.8	1070	3.8	9540
8/07 Drain	6.9	5549	43.8	5270	6.4	15,093

Source: Courtesy of Jeff Plotts, Superintendent at TPC, Scottsdale Arizona.

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Appendix

SALT- AND BORON-TOLERANT ORNAMENTAL PLANTS

The salt and boron tolerance tables that follow were assembled from various online and published sources. Very little salt and boron tolerance research has been done specifically on ornamental plants; the majority of information available is based on field observation. Much of the original information originated from arid or coastal regions, where salinity problems are most prevalent; however, some plants that are adapted to northern climates where highway salting affects roadside plantings is also included.

Different sources have used different data to report observed salt and boron tolerance levels. They include numerical values for electrical conductivity of irrigation water (EC_w) and saturated paste extracts of soils (EC_e), or just general descriptions such as "low," "moderate," "high or poor," "good," and "very good." Where soil EC_e is reported, it was often noted to relate to the most active part of the root zone. Some sources also included rankings for foliar (coastal airborne or irrigation spray) salt tolerance. Boron concentrations reported in mg/L typically reflect threshold concentrations where foliar damage may become noticeable. The following key distinguishes the specific designations of reported salt and boron tolerances provided in the tables:

X = General classification of salt tolerance, soil versus foliar tolerance was not distinguished.
S = General classification of soil salt tolerance as reported.
F = General classification of foliar, aerial, or salt spray tolerance reported.
ECw 1–2 = Example of a reported numerical range of irrigation water electrical conductivity tolerance.
ECe 2–4 = Example of a reported numerical range of electrical conductivity of soil saturated paste extract.

Varying tolerances reported for the same genus and species can be related to regional influences such as differences of soil drainage and climate extremes. Where different results were reported by various sources, each has been provided. Therefore, consider these tables as anecdotal information for use as a general guideline in plant material selection and evaluation.

Salt Tolerance

Botanical name	Common name	Tree, shrub, groundcover, flower, palm, fruit, vine, cycad	Low tolerance	Moderate tolerance	High tolerance	Source
Abelia grandiflora	Glossy abelia	Shrub		ECw 2–4		11
Abelia grandiflora	Edward goucher abelia	Shrub	F/S			18
Abelia grandiflora	Glossy abelia	Shrub	ECe 2–3			10, 16
Abies balsamea	Balsam fir	Tree	Intolerant			15
Acacia acuminata	Jam	Shrub		ECe 4–8		5
Acacia ampliceps	Salt wattle	Shrub			ECe >16	5
Acacia collectoides	Spine wattle	Shrub		ECe 4–8		5
Acacia cyclops	Coastal wattle	Shrub			ECe >16	5
Acacia farnesiana	Sweet acacia	Tree		X		2, 6
Acacia farnesiana		Tree			S	12
Acacia greggii	Catclaw acacia	Shrub			X	3, 8
Acacia greggii		Shrub			S	12
Acacia iteaphylla	Flinder's range wattle	Shrub		ECe 4–8		5
Acacia longifolia	Sydney golden wattle	Shrub	EC_W .75–1.5			4
Acacia longifolia	Sydney golden wattle	Shrub		ECe 4– 8		5
Acacia longifolia	Sydney golden wattle	Shrub	S			12
Acacia merrillii	Merrill's wattle	Shrub		ECe 4–8		5
Acacia pendula	Weepling myall	Tree		ECe 4–8		5
Acacia pendula		Tree		X		8
Acacia prainii	Prain's wattle	Shrub		ECe 4–8		5
Acacia redolens	Redolen acacia	Shrub			X	3
Acacia redolens	Revensthorpe source	Shrub		ECe 4– 8		5
Acacia redolens Desert Carpet	Ongerup	Groundcover			X	8

Acacia redolens Maslin	Prostrate acacia	Shrub			F/S	18
Acacia salicina	Cooba	Tree			X	8
Acacia saligna	Willow acacia	Tree			X	8
Acacia smallii	Sweet acacia	Tree			X	8
Acacia spp.		Tree/shrub		X		12
Acacia stenophylla	River cooba	Tree			ECe >16	5
Acacia stenophylla	Shoestring acacia	Tree			X	8
Acalypha wilkesiana	Copper leaf	Shrub	X			2
Acalypha wilkesiana	Copper leaf	Shrub		X		6
Acalypha wilkesiana	Copper leaf	Shrub		ECw 2–4		11
Acalypha wilkesiana	Copper leaf	Shrub	S			12
Acalypha wilkesiana	Copper leaf	Shrub	F/S			18
Acer buergerianum	Trident maple	Tree			X	3
Acer campestre	Hedge maple	Tree			Salt spray	1
Acer campestre	Hedge maple	Tree			X	3
Acer campestre	Hedge maple	Tree		F		7
Acer ginnala	Amur maple	Tree		F		7
Acer ginnala	Amur maple	Tree		ECe <6		15
Acer ginnala	Amur maple	Tree		S		17
Acer negundo	Boxelder	Tree		ECe <6		15
Acer negundo	Boxelder	Tree		S		17
Acer nigrum	Black maple	Tree		F		7
Acer platanoides	Norway maple	Tree		ECe <8		15
Acer platanoides	Norway maple	Tree			S	7, 17
Acer pseudoplatanus	Sycamore maple	Tree			S/F	7
Acer pseudoplatanus	Sycamore maple	Tree			Salt spray	1, 7
Acer pseudoplatanus	Sycamore maple	Tree	F/S			18
Acer rubrum	Red maple	Tree		X		6
Acer rubrum	Red maple	Tree	Intolerant			15

(continued)

Salt Tolerance (continued)

Botanical name	Common name	Tree, shrub, groundcover, flower, palm, fruit, vine, cycad	Low tolerance	Moderate tolerance	High tolerance	Source
Acer rubrum	Red maple	Tree	F/S			18
Acer saccharinum	Silver maple	Tree		F		7
Acer saccharinum	Silver maple	Tree		S		17
Acer saccharinum		Tree	S			12, 15
Acoelorraphe wrightii	Paurotis palm	Palm			ECw 4–5.5	11
Acoelorrhaphe wrightii	Paurotis	Palm		X		2, 6
Acoelorrhaphe wrightii	Paurotis palm	Palm		F/S		18
Adiantum spp.	Maidenhair fern	Groundcover		F/S		18
Aesculus hippocastanum	Horsechestnut	Tree			F	1, 7
Aesculus hippocastanum	Common horsechestnut	Tree		ECe <8		15
Aesculus hippocastanum	Horse chestnut	Tree			S	17
Aesculus octandra	Yellow buckeye	Tree		F		7
Aesculus pavia	Red buckeye	Tree			S	1
Agapanthus africanus	African lily	Groundcover		ECw 2–4		11
Agave (most species)		Shrub			S	12
Agave americana	Century plant	Shrub			X	6
Agave americana	Century plant	Shrub			F/S	18
Agave attenuata	Thin-leaved agave	Shrub		EC$_W$ 1.5–3		4
Agave attenuata	Thin-leaved agave	Shrub		S		12
Agave spp.		Shrub			X	3, 8
Ageratum houstonianum	Ageratum	Flower		ECw 2–4		11
Agropyron cristatum	Crested wheatgrass	Groundcover		ECe 4–8		15
Agropyron cristatum	Fairway wheatgrass	Grass		F/S		18

Agropyron elongatum	Tall wheatgrass	Grass			ECe 14–18	15
Agropyron elongatum	Tall wheatgrass	Grass		F	S	18
Agropyron intermedium	Intermediate wheatgrass	Grass		F/S		18
Agropyron riparium	Streambank wheatgrass	Groundcover		ECe 4–8		15
Agropyron sibiricum	Siberian wheatgrass	Grass		F/S		18
Agropyron smithii	Western wheatgrass	Grass			ECe 14–18	15
Agropyron smithii	Western wheatgrass	Grass		F/S		18
Agropyron trachycaulum	Slender wheatgrass	Grass		ECe 4–8		15
Agropyron trachycaulum	Slender wheatgrass	Grass		F/S		18
Agrostis palustris	Creeping bentgrass	Grass		F/S		18
Agrostis palustris var. seaside	Creeping bentgrass (seaside)	Grass			F/S	18
Agrostis tenuis	Colonial bentgrass	Grass		F/S		18
Ailanthus altissima	Tree of heaven	Tree		ECe <8		15
Ajuga repens	Carpet bugle	Groundcover	F/S			18
Albizia distachya		Tree			S	12
Albizia julibrissin	Silk tree	Tree	F/S			18
Alnus glutinosa	Black alder	Tree		S		17
Allamanda blanchetti	Purple allamanda	Vine		F/S		18
Allamanda cathartica	Allamanda	Vine		S		12
Allamanda cathartica	Allamanda	Vine			F/S	18
Allamanda spp.	Allamanda	Vine		ECw 2–4		11
Allamanda spp.	Allamanda	Vine		X		2, 6
Allamanda cathartica		Vine		S		12
Allocasuarina leuhmannii	Buloke			ECe 4–8		5
Allocasuarina verticillata	Drooping sheoak			ECe 4–8		5
Alopecurus pratensis	Meadow foxtail	Grass	F/S			18
Almond	Almond	Tree	S			12
Aloe arborescens		Shrub			S	12
Aloe spp.		Shrub			X	3, 6, 8

(continued)

Salt Tolerance (continued)

Botanical name	Common name	Tree, shrub, groundcover, flower, palm, fruit, vine, cycad	Low tolerance	Moderate tolerance	High tolerance	Source
Aloe vera		Perennial			S	12
Aloe vera	Aloe	Perennial			F/S	18
Alopecurus pratensis	Meadow foxtail	Groundcover	ECe <4			15
Alternanthera ficoidea	Joyweed	Groundcover		F/S		18
Alternanthera spp.	Joseph's coat	Flower		ECw 2–4		11
Alternanthera spp.	Blood leaf	Groundcover		X		2, 6
Ambrosia deltoidea	Triangleleaf bursage	Groundcover			X	8
Ambrosia dumosa	White bursage	Groundcover			X	8
Amelanchier canadensis	Shadblow	Tree		ECe <8		15
Amelanchier grandiflora	Apple serviceberry				F	7
Ananas comosus	Pineapple	Tree		X		14
Anisacanthus spp.		Shrub		X		8
Annona cherimola	Cherimoya	Tree	X			14
Antigonon leptopus	Queen's wreath	Vine			X	8
Antigonon leptopus var. hookerii	Coral vine	Vine	F	S		18
Antirrhinum majus	Snapdragon	Flower			ECw 4–5.5	11
Apple	Apple	Tree	S			12
Aptenia cordifolia	Sun rose	Groundcover		ECw 2–4		11
Aptenia cordifolia	Red apple iceplant	Groundcover			F/S	18
Aquilegia micrantha	Cliff columbine	Flower		ECe 6–8		15
Araucaria heterophylla	Norfolk island pine	Tree			ECw 4–5.5	11
Araucaria heterophylla	Norfolk island pine	Tree			EC_W >3	4
Araucaria heterophylla	Norfolk island pine	Tree			X	6

Araucaria heterophylla	Norfolk island pine	Tree			S	12
Araucaria heterophylla	Norfolk island pine	Tree			F/S	18
Arbutus unedo		Tree			S	12
Arbutus unedo	Strawberry tree	Tree			X	3
Arbutus unedo	Strawberry tree, cv. Compact	Tree	ECe 3–4			10, 16
Arctostaphylos densiflora	Vine hill manzanita	Shrub			F/S	18
Arctostaphylos densiflora var. lynne	Lynne's vine hill manzanita	Groundcover		F/S		18
Arctotheca calendula	Arctotheca	Groundcover			EC$_W$ >3	4
Arctotheca calendula	Cape weed	Groundcover			S	12
Ardisia escallonioides	Marlberry	Shrub			X	6
Ardisia escallonoides	Marlberry	Shrub			X	2
Arecastrum romanzoffianum	Queen palm	Palm		X		2, 6
Arecastrum romanzoffianum	Plumosa palm	Palm	S			12
Arelisia paniculata				S		12
Arenga engleri	Dwarf sugar palm	Palm		ECw 2–4		11
Argemone spp.	Prickly poppies	Flower	ECe 2–4			15
Aronia arbutifolia	Red chokeberry	Shrub			S/F	1
Arrhenatherum elatius	Tall meadow oatgrass	Groundcover		ECe 4–8		15
Arrhenatherum elatius	Oat grass	Grass	F/S			18
Artemisia cana	Silver sagebrush	Shrub	ECe <4	X		15
Artemisia frigida	Fringed sage	Shrub			X	8
Artemisia frigida	Fringed sage	Shrub		ECe <6		15
Artemisia pycnocephala	Sandhill sage	Shrub			X	3, 9
Artemisia spinescens	Bud sagebrush	Shrub		ECe <6		15
Artemisia tridentata	Big sagebrush	Shrub			X	8
Artemisia tridentate	Basin big sagebrush	Shrub		ECe <6		15
Arundo donax		Shrub			S	12
Asclepias subulata	Desert milkweed	Shrub			X	8
Asparagus meyeri	Foxtail fern	Groundcover			ECw 2–4	11

(continued)

Salt Tolerance (continued)

Botanical name	Common name	Tree, shrub, groundcover, flower, palm, fruit, vine, cycad	Low tolerance	Moderate tolerance	High tolerance	Source
Asparagus spp.	Asparagus fern	Groundcover			X	6
Asparagus sprengeri	Asparagus fern	Groundcover			ECw 2–4	11
Aspidistra elatior	Cast iron plant	Groundcover			ECw 2–4	11
Athyrium filix-femina	Lady fern	Groundcover	F/S			18
Atriplex amnicola	River saltbush	Shrub			ECe >16	5
Atriplex bunburyana	Silver saltbush	Shrub			ECe >16	5
Atriplex canescens	Fourwing saltbush	Shrub			ECe <10	15
Atriplex cinerea	Grey saltbush	Shrub			ECe >16	5
Atriplex confertifolia	Shadscale saltbush	Shrub			ECe <10	15
Atriplex corrugate	Mat saltbush	Shrub			ECe <10	15
Atriplex lentiformis var. breweri		Shrub			S	12
Atriplex lentiformis	Quailbrush	Shrub			ECe >16	5
Atriplex muelleri		Shrub			ECe >16	5
Atriplex nummularia	Old man saltbush	Shrub			ECe >16	5
Atriplex nuttalli	Nuttall saltbush	Shrub			ECe <10	15
Atriplex nuttalli var. cuneata	Caste valley clover	Shrub			ECe <10	15
Atriplex nuttalli var. gardneri	Gardner saltbush	Shrub			ECe <10	15
Atriplex paludosa	Saltbush	Shrub			ECe >16	5
Atriplex rhagodioides	Saltbush	Shrub			ECe >16	5
Atriplex semibaccata	Creeping saltbush	Groundcover		ECe 4–8		5
Atriplex semibaccata	Australian saltbush	Groundcover			X	8
Atriplex spp.	Saltbush	Shrub			X	9
Atriplex spp.	Saltbush	Shrub			X	3

Atriplex spp.	Saltbush	Shrub			X	8
Atriplex undulate	Wavy-leafed saltbush	Shrub			ECe >16	5
Atriplex vesicaria	Saltbush	Shrub			ECe >16	5
Avacado	Avocado	Fruit Tree	S			12
Averrhoa carambola	Carambola	Tree		X		6
Averrhoa carambola	Carambola, starfruit	Tree	F	S		18
Azadirachta indica	Neem tree	Tree		X		8
Baccharis emoryi	Emory baccharis	Shrub			ECe <10	15
Baccharis glutinosa	Seep-willow	Shrub			ECe <10	15
Baccharis halimifolia	Groundselbush, Eastern baccharis	Shrub			X	6
Baccharis halimifolia	Saltbrush	Shrub			S/F	1
Baccharis pilularis	Dwarf coyote brush	Shrub			X	3
Baccharis pilularis	Coyote bush	Groundcover			EC$_W$ >3	4
Baccharis pilularis	Coyote bush				S	12
Baccharis pilularis consanguinea		Shrub			S	12
Baccharis sarothroides		Shrub			S	12
Baccharis sarothroides (male)	Desert broom	Shrub			X	8
Baccharis viminea		Shrub			S	12
Bambusa spp.	Bamboo	Shrub		X		6
Bambusa spp.	Bamboo	Shrub		F/S		18
Bauhinia purpurea	Orchid tree	Tree		X		6
Bauhinia purpurea	Orchid tree	Tree		ECe 4–6		10, 16
Bauhinia purpurea	Orchid tree	Tree	S			12
Bauhinia purpurea	Orchid tree	Tree	F	S		18
Bauhinia spp.	Orchid tree	Tree		ECw 2–4		11
Berberis fremontii	Fremont barberry	Shrub	ECe <4	X		15
Berberis julianae	Wintergreen barberry	Shrub	X			2
Betula alleghaniensis	Yellow birch	Tree		ECe <6		15
Betula lenta	Sweet birch	Tree		ECe <6		15

(continued)

Salt Tolerance (continued)

Botanical name	Common name	Tree, shrub, groundcover, flower, palm, fruit, vine, cycad	Low tolerance	Moderate tolerance	High tolerance	Source
Betula nigra	River birch	Tree		F		7
Betula papyrifera	Paper birch	Tree			F	1
Betula papyrifera	Paper birch	Tree		ECe <6		15
Betula papyrifera	Paper birch	Tree			S	17
Betula populifolia	Gray birch	Tree			F	1
Betula populifolia	Grey birch	Tree		ECe <6		15
Betula verrucosa		Tree	S			12
Bischofia javanica	Toog	Tree		X		6
Bismarckia nobilis	Bismarckia	Tree			ECw 4–5.5	11
Bontia daphnoides	Bontia	Tree			X	2, 6
Bougainvillea glabra	Bougainvillea	Shrub		S		12
Bougainvillea glabra Choisy	Bougainvillea	Shrub			F/S	18
Bougainvillea spectabilis	Bougainvillea	Shrub			X	3
Bougainvillea spectabilis	Bougainvillea	Shrub			EC_W >3	4
Bougainvillea spectabilis	Bougainvillea	Shrub			S	12
Bougainvillea spectabilis	Bougainvillea	Shrub			ECe >8	10, 16
Bougainvillea spp.		Shrub			EC_e >8	4
Bougainvillea spp.	Bougainvillea	Shrub			ECw 4–5.5	11
Bougainvillea spp.	Bougainvillea	Shrub			X	2, 6, 8
Bouteloua gracilis (H.B.K.) Lag. Ex Steud.	Blue grama	Grass		F/S		18
Brahea armata	Mexican blue palm	Tree			X	8
Brassaia actinophylla	Schefflera	Tree		X		6

Breynia disticha	Snowbush	Shrub		X		6
Breynia nivosa	Snow bush	Shrub	X			2
Breynia disticha	Snow on the mountain	Shrub			ECw 4–5.5	11
Bromeliaceae spp. L.	Bromeliads	Groundcover		F/S		18
Bromus carinatus	California brome				X	3
Bromus carinatus Hook. Et Arm.	California brome	Grass		F/S		18
Bromus inermis	Smooth brome	Groundcover		ECe 4–8		15
Bromus inermis Leyss.	Bromegrass, smooth	Grass		S	F	18
Bromus marginatus	Mountain brome	Grass			ECe 8–12	15
Bromus marginatus Nees	Bromegrass, mountain	Grass		S	F	18
Bromus unioloides Willd.	Rescue grass	Grass		S	F	18
Buchloe dactyloides	Buffalograss	Grass		ECe 4–8		15
Buchloe dactyloides	Buffalograss	Grass		F/S		18
Bucida buceras	Black olive	Tree			X	2, 6
Bucida buceras	Black olive	Tree			ECw 4–5.5	11
Buddleia officinalis	Butterfly bush	Shrub	X			2
Buddleia officinalis	Butterfly bush	Shrub		X		6
Buddleia spp.	Butterfly bush	Flower		ECw 2–4		11
Buddleia spp.	Butterfly bush				S	12
Buddleja daviddi Franch.	Butterfly bush	Shrub	F/S			18
Bursera simaruba	Gumbo-limbo	Tree		X		2
Bursera simaruba	Gumbo limbo	Tree			X	6
Butia capitata	Pindo palm	Palm			X	3
Butia capitata	Pindo palm	Palm		X		2, 6
Butia capitata	Pindo/jelly	Palm			ECw 4–5.5	11
Butia capitata	Pindo palm	Palm			F/S	18
Buxus microphylla	Boxwood	Shrub			S/F	1
Buxus microphylla	Boxwood	Shrub		ECe <6		15
Buxus microphylla	Boxwood	Shrub		S	F	18

(continued)

Salt Tolerance (continued)

Botanical name	Common name	Tree, shrub, groundcover, flower, palm, fruit, vine, cycad	Low tolerance	Moderate tolerance	High tolerance	Source
Buxus microphylla v. japonica	Japanese boxwood	Shrub		EC_W 1.5–3		4
Buxus microphylla v. japonica	Japanese boxwood	Shrub		S		12
Buxus microphylla v. japonica	Japanese boxwood	Shrub		ECw 1.5–3		12
Buxus microphylla v. japonica	Japanese boxwood	Shrub		ECe 4–6		10, 16
Buxus microphylla var. japonica	Japanese boxwood	Shrub			X	3
Buxus microphylla var. japonica	Japanese boxwood	Shrub		EC_e 3–8		4
Buxus sempervirens	English boxwood	Shrub	S			12
Caesalpinia gilliesii	Mexican bird of paradise	Shrub			X	8
Caesalpinia pulcherrima	Barbados flower-fence	Shrub		X		2, 6
Caesalpinia pulcherrima	Red bird of paradise	Shrub			X	8
Caladium spp. Vent.	Caladium	Groundcover	F/S			18
Calendula officinalis	Calendula	Flower		ECw 2–4		11
Calliandra haematocephala	Powderpuff	Shrub		X		6
Calliandra haematocephala Hassk	Powderpuff tree	Shrub	F/S			18
Callicarpa americana	Beautyberry	Shrub			S/F	1
Callistemon citrinus	Crimson bottlebrush	Shrub			X	3, 6
Callistemon citrinus Curtis	Lemon bottlebrush	Shrub		S	F	18
Callistemon paludosis	River bottlebrush	Shrub		ECe 4–8		5
Callistemon phoeniceus	Lesser bottlebrush	Shrub		ECe 4–8		5
Callistemon rigidus	Bottlebrush	Shrub		X		2, 6
Callistemon rigidus	Stiff bottlebrush	Shrub			X	9
Callistemon rigidus	Bottlebrush	Shrub		S		12
Callistemon rigidus	Bottlebrush	Shrub		F/S		18

Callistemon spp.	Bottlebrush	Shrub			X	8
Callistemon spp.	Bottlebrush	Shrub		ECw 2–4		11
Callistemon viminalis	Weeping bottlebrush	Shrub			X	3
Callistemon viminalis	Weeping bottlebrush	Shrub		EC_W 1.5–3		4
Callistemon viminalis	Weeping bottlebrush	Shrub			S	12
Callistemon viminalis	Weeping bottlebrush	Shrub		S		12
Callistemon viminalis	Weeping bottlebrush	Shrub		ECw 1.5–3		12
Callistemon viminalis	Weeping bottlebrush	Shrub			EC_e 8.0	4, 12
Callistemon viminalis	Weeping bottlebrush	Shrub		ECe 6–8		10, 16
Calocephalus brownii	Cushion bush	Shrub			X	3
Calocephalus brownii	Cushion bush	Shrub			S	12
Calochortus spp.	Mariposa lilly	Flower	ECe 2–4			15
Calophyllum oliviforme	Mastwood	Tree			X	6
Calotropis gigantea	Giant milkweed	Shrub		X		2, 6
Camellia japonica	Camellia	Shrub	S			12
Camellia japonica	Camellia	Shrub	F/S			18
Campsis radicans	Trumpet creeper	Vine			X	8
Campsis radicans	Trumpet creeper	Vine	F/S			18
Canna generalis	Canna lily	Shrub		F/S		18
Caragana arborescens	Siberian peashrub	Shrub		ECe <8		15
Carica papaya	Papaya	Shrub		F/S		18
Carica papaya	Papaya	Tree		X		6, 14
Carissa arduina				S		12
Carissa macrocarpa	Natal plum	Shrub			X	2, 3, 6
Carissa macrocarpa	Natal plum	Shrub			ECw 4–5.5	11
Carissa macrocarpa	Natal plum	Shrub			S	12
Carissa macrocarpa	Natal plum	Shrub			ECw >3.0	4, 12
Carissa macrocarpa	Natal plum	Shrub			F/S	18
Carissa macrocarpa	Natal palm	Shrub			ECe >8	4, 10, 16

(continued)

Salt Tolerance (continued)

Botanical name	Common name	Tree, shrub, groundcover, flower, palm, fruit, vine, cycad	Low tolerance	Moderate tolerance	High tolerance	Source
Carpobrotus edulis	Hottentot fig	Groundcover			X	2, 6
Carpobrotus edulis	Hottentot fig	Groundcover			F/S	18
Carya cordiformis	Bitternut hickory	Tree			S/F	7
Carya illinoensis Koch	Pecan	Tree		F/S		18
Carya ovata	Shagbark hickory	Tree			F	7
Caryota mitis	Fishtail palm	Palm		ECw 2–4		11
Caryota mitis lour	Fishtail palm	Palm		F/S		18
Casimiroa edulis	Sapote, white	Tree	X			14
Cassia (Senna) artemisioides	Feathery cassia				X	3
Cassia (Senna) spp.		Shrub		X		8
Cassia artemisioides					S	12
Cassia fistula	Golden-shower	Tree	X			2
Cassia fistula	Golden-shower	Tree		X		6
Cassia spp.		Tree			S	12
Casuarina cunninghamiana	River sheoak	Tree		ECe 4–8		5
Casuarina equisetifolia	Horsetail tree	Tree		EC_W 1.5–3		4
Casuarina equisetifolia	Australian pine	Tree			X	6
Casuarina equisetifolia		Tree			S	12
Casuarina equisetifolia	Horsetail tree	Tree		S		12
Casuarina glauca	Grey buloke				ECe >16	5
Casuarina obesa	Salt sheoak				ECe >16	5
Casuarina cunninghamiana	Horsetail tree	Tree			X	3
Casuarina spp.	Beefwood	Tree			X	3, 9

Casuarina stricta					S	12
Catalpa speciosa	Catalpa	Tree			F	1
Catalpa speciosa	Northern catalpa	Tree			S/F	7
Catalpa speciosa	Northern catalpa	Tree	ECe <4			15
Catalpa spp.			S			12
Catharanthus roseus	Vinca rosea/Madagascar periwinkle	Flower		ECw 2–4		11
Catharanthus roseus	Periwinkle	Groundcover		S	F	18
Ceanothus arboreus	Wild lilac	Shrub			S	12
Ceanothus gloriosus	Pt. Reyes Ceanothus	Shrub			X	3
Ceanothus gloriosus	Wild lilac	Shrub			S	12
Ceanothus thyrsiflorus	Blue blossom	Shrub			X	3
Ceanothus thyrsiflorus	Wild lilac	Shrub			S	12
Ceanothus thyrsiflorus	Blue blossom	Shrub		S	F	18
Cecropia palmata	Cecropia	Tree		X		6
Cedrus deodara	Deodar cedar	Tree			X	3
Cedrus deodara	Deodar cedar	Tree			S	12
Cedrus deodara	Deodar cedar	Tree		F/S		18
Celtis laevigata	Hackberry	Tree			F	1
Celtis occidentalis	Hackberry	Tree		S/F		7
Celtis occidentalis	Hackberry	Tree		X		8
Celtis occidentalis	Hackberry	Tree	ECe <4			15
Celtis pallida	Desert hackberry	Shrub			X	8
Celtis reticulata	Canyon hackberry	Tree			X	8
Celtis reticulata	Netleaf hackberry	Tree		X		8
Celtis reticulata	Netleaf hackberry	Tree	ECe <4			15
Celtis sinensis Pers.	Chinese hackberry	Tree	F/S			18
Ceratoides lanata	Winterfat	Shrub			X	8
Ceratoides lanata	Common winterfat	Shrub			ECe <10	15
Ceratozamia spp.	Mexican horncone	Cycad		ECw 2–4		11

(continued)

Salt Tolerance (continued)

Botanical name	Common name	Tree, shrub, groundcover, flower, palm, fruit, vine, cycad	Low tolerance	Moderate tolerance	High tolerance	Source
Cercidium floridum	Blue palo verde	Tree			X	3
Cercidium floridum	Blue palo verde	Tree			S	12
Cercidium spp.	Palo verde	Tree			S	12
Cercis canadensis	Eastern redbud	Tree	Intolerant			15
Cercis occidentalis	Western redbud	Tree			X	3
Cercis occidentalis	Western redbud	Tree		X		8
Cercis occidentalis	Western redbud	Tree			S	12
Cercis occidentalis	Western redbud	Tree	ECe <4			15
Cercis spp.	Redbud	Tree	S			12
Cercocarpus betuloides	Hardtack	Tree			X	3
Cercocarpus montanus	Mountain mahogany	Tree		X		8
Cercocarpus betuloides	Mountain mahogany	Tree			S	12
Cereus peruvianus	Hedge cactus	Shrub		X		2, 6
Cereus peruvianus	Cactus	Shrub		S		12
Cestrum aurantiacum	Orange cestrum	Shrub		F/S		18
Cestrum nocturnum	Night cestrum	Shrub		X		2, 6
Cestrum nocturnum	Night blooming jasmine	Shrub		ECw 2–4		11
Chaenomeles speciosa	Flowering quince	Shrub	ECe <2			15
Chamaecyparis pisifera	False cypress	Shrub			S/F	1
Chamaerops humilis	European fan	Palm		X		2, 6
Chamaerops humilis	European fan palm	Palm		ECe 6–8		10
Chamaerops humilis	European fan	Palm			ECw 4–5.5	11
Chamaerops humilis	Mediterranean fan palm	Palm			X	3, 8

Chamaerops humilis	European fan palm	Palm		ECe 6–8		16
Chamaerops humilis	Mediterranean fan palm	Palm			F/S	18
Chilopsis linearis	Desert willow	Tree		X		8
Chionanthus virginicus	White fringetree	Tree			S	1
Chloris gayana	Rhodes grass	Grass		ECe 4–8		5
Chloris gayana Kunth	Rhodes grass	Grass		S	F	18
Chlorophytum comosum	Spider plant	Groundcover		F/S		18
Chrysalidocarpus lutescens	Areca palm	Palm		X		2, 6
Chrysalidocarpus lutescens wendl	Areca palm	Palm		F/S		18
Chrysanthemum spp.		Shrub			S	12
Chrysobalanus icaco	Coco plum	Shrub			X	6
Chrysobalanus icaco		Shrub		S		12
Chrysophyllum oliviforme	Satin leaf	Tree			X	2, 6
Chrysothamnus albidus	Alkali rabbitbrush	Shrub		ECe <8		15
Chrysothamnus greenei	Greene rabbitbrush	Shrub			ECe <10	15
Chrysothamnus linifolius	Flaxleaf rabbitbrush	Shrub			ECe <10	15
Chrysothamnus nauseosus	Rabbitbush	Shrub			X	8
Chrysothamnus nauseosus	Rubber rabbitbrush	Shrub		ECe <6		15
Chrysothamnus viscidiflorus	Douglas rabbitbrush	Shrub		ECe <6		15
Chrysopsis villosa	Hairy goldenaster	Flower	ECe 2–4			15
Chrysalidocarpus lutescens	Areca palm	Palm		ECw 2–4		11
Cinnamomum camphora	Camphor tree	Tree		X		6
Citrus	Orange	Tree	S			12
Citrus	Grapefruit	Tree	S			12
Citrus	Lemon	Tree	S			12
Citrus aurantiifolia	Lime	Tree	X			14
Citrus limon	Lemon(e)	Tree	X			14
Citrus limon L.	Lemon	Tree	F/S			18
Citrus maxima	Pummelo	Tree	X			14

(continued)

Salt Tolerance (continued)

Botanical name	Common name	Tree, shrub, groundcover, flower, palm, fruit, vine, cycad	Low tolerance	Moderate tolerance	High tolerance	Source
Citrus paradisi	Grapefruit(e)	Tree	X			14
Citrus paradisi Macf.	Grapefruit	Tree	F/S			18
Citrus reticulate	Tangerine	Tree	X			14
Citrus reticulata var. blanco	Tangerine	Tree	F/S			18
Citrus sinensis	Orange	Tree	X			14
Citrus sinensis var. osbeck	Orange	Tree	F/S			18
Citrus spp.	Citrus	Tree		X		6
Clerodendrum thomsoniae	Glory bower vine	Shrub		X		6
Clerodendrum thomsoniae	Bleeding heart vine	Vine	F/S			18
Clethra alnifolia	Summersweet	Shrub			S/F	1
Clusia rosea	Pitch apple	Tree			X	6
Clytostoma callistegioides	Painted trumpet	Vine	X			2, 6
Clytostoma callistegioides	Violet trumpet vine	Vine	F/S			18
Coccoloba diversifolia	Pigeon plum	Tree			X	6
Coccoloba laurifolia	Pigeon plum	Tree			X	2
Coccoloba uvifera	Sea grape	Shrub			X	2, 6
Coccoloba uvifera	Sea grape	Shrub			ECw 4–5.5	11
Coccoloba uvifera	Sea grape	Tree			F/S	18
Coccolobis floridana					S	12
Coccolobis uvifera	Sea grape	Tree		S	S	12
Coccothrinax argentata	Silver palm	Palm			X	2, 6
Coccothrinax argentata	Silver palm	Palm		S		12
Coccothrinax spp.	Silver palm	Palm			ECw 4–5.5	11

Cocos nucifera	Coconut palm	Palm			X	2, 6
Cocos nucifera	Coconut palm	Palm			ECw 4–5.5	11
Cocos nucifera	Coconut palm	Palm		S		12
Codiaeum punctatus					S	12
Codiaeum variegatum	Croton	Shrub	X			2
Codiaeum variegatum	Croton	Shrub		X		6
Codiaeum variegatum	Croton	Shrub		ECw 2–4		11
Codiaeum variegatum Blume	Croton	Shrub	F/S			18
Coleonema spp.	Breath of heaven				X	3
Coleonema spp.					S	12
Coleus blumei	Coleus	Groundcover	X			2
Coleus blumei	Coleus	Groundcover		X		6
Congea tomentosa	Woolly congea	Vine		X		2, 6
Conocarpus erectus	Silver button-bush	Tree			X	2, 6
Copernicia alba	Wax palm	Palm			ECw 4–5.5	11
Coprosma repens	Mirror plant	Shrub			EC_W >3	4
Coprosma repens	Mirror plant	Shrub			S	12
Coprosma spp.	Mirror plant	Shrub			X	3
Cordia parvifolia	Little leaf cordia	Shrub		X		8
Cordia sebestena	Geiger tree	Tree			X	2, 6
Cordia boissieri	Texas wild olive	Tree		ECw 2–4		11
Cordyline indivisa	Blue dracaena	Shrub			X	3
Cordyline indivisa	Blue dracaena	Shrub		ECe 6–8		10, 16
Cordyline terminalis	Ti plant	Shrub		X		6
Cornus mas	Cornelian cherry	Tree	F/S			18
Cornus racemosa	Grey dogwood	Shrub	Intolerant			15
Cornus sericea	Red osier dogwood	Shrub			S/F	1
Cornus stolonifera	Red-osier dogwood	Shrub	Intolerant			15
Cortaderia selloana	Pampas grass	Shrub			EC_W >3	4

(continued)

Salt Tolerance (continued)

Botanical name	Common name	Tree, shrub, groundcover, flower, palm, fruit, vine, cycad	Low tolerance	Moderate tolerance	High tolerance	Source
Cortaderia selloana	Pampas grass	Shrub			X	6
Cortaderia selloana	Pampas grass	Shrub			ECw 4–5.5	11
Cortaderia selloana	Pampas grass	Shrub			S	12
Cortaderia selloana var. pumila	Dwarf Pampas grass (sterile)	Shrub			X	8
Cotoneaster congestus	Pyrenees Cotoneaster	Shrub	F/S			18
Cotoneaster congestus	Pyrenees Cotoneaster	Shrub	ECe 1–2			10, 16
Cotoneaster divaricatus	Spreading Cotoneaster	Shrub			S/F	1
Cotoneaster horizontalis	Rock Cotoneaster	Shrub/ groundcover	EC_W .75–1.5			4
Cotoneaster horizontalis	Rock Cotoneaster		S			12
Cotoneaster lacteus	Parney Cotoneaster	Shrub			X	3
Cotoneaster microphylla	Rockspray Cotoneaster	Shrub	S	F		18
Cotoneaster microphyllus	Rockspray or Littleleaft Cotoneaster	Tree		F/S		18
Cotoneaster pameyi					S	12
Crassula argentea	Jade plant	Shrub	EC_W .75–1.5			4
Crassula argentea	Jade plant					
	Shrub		X		2, 6	
Crassula argentea	Jade plant	Shrub	S			12
Crataegus crus-galli	Cockspur hawthorn	Tree		ECe <8		15
Crataegus lavallei	Lavalle hawthorne	Tree			F	1
Cryptomeria japonica	Japanese cedar	Tree			F	1
Cryptostegia grandiflora	Rubber vine	Vine			X	2, 6

Coccoloba uvifera	Sea grape			S		12
Cupaniopsis anacardiopsis	Carrotwood	Tree			ECw 4–5.5	11
Cuphea hyssopifolia	Cuphea	Shrub	X			2
Cuphea hyssopifolia	Cuphea	Shrub		X		6
Cuphea hyssopifolia	Fals heather	Groundcover		F	S	18
Cupressocyparis leylandi	Leyland cypress	Tree			X	3
Cupressus arizonica	Arizona cypress	Tree		X		8
Cupressus sempervirens	Italian cypress	Tree			X	3
Cupressus sempervirens	Italian cypress	Tree			S	12
Cupressus sempervirens	Italian cypress	Tree		F/S		18
Cycas circinalis	Queen sago palm	Shrub		X		6
Cycas circinalis	Queen sago	Cycad		ECw 2–4		11
Cycas media	Australian bread nut	Cycad		ECw 2–4		11
Cycas revoluta	Sago palm	Shrub		X		6
Cycas revolute	King sago	Cycad			ECw 4–5.5	11
Cynodon dactylon	Common bermudagrass	Grass			X	3
Cynodon dactylon	Common bermudagrass	Grass		X		6
Cynodon dactylon	Common bermudagrass	Grass			F/S	18
Cyperus alternifolius	Umbrella sedge	Groundcover		F/S		18
Cytisus scoparius	Scotch broom	Shrub			S/F	1
Cytisus scoparius	Scotch broom	Shrub		ECe <8		15
Dactylis glmerata	Orchardgrass	Grass		ECe 4–8		15
Dactylis glomerata	Orchardgrass	Grass	F/S			18
Dalbergia brownei				S		12
Dalbergia sissoo	Indian rosewood	Tree		ECw 2–4		11
Dalbergia sissoo	Sissoo	Tree		X		6, 8
Dasylirion spp.		Shrub			X	8
Delonix regia	Royal Poinciana	Tree		X		2, 6
Delonix regia	Royal Poinciana	Tree		ECw 2–4		11

(continued)

Salt Tolerance (continued)

Botanical name	Common name	Tree, shrub, groundcover, flower, palm, fruit, vine, cycad	Low tolerance	Moderate tolerance	High tolerance	Source
Delosperma alba	White iceplant	Groundcover			EC_W >3	4
Delosperma alba	White iceplant	Groundcover			S	12
Delosperma alba	White iceplant	Groundcover			F/S	18
Delosperma alba	White iceplant	Groundcover			ECe >10	10, 16
Delosperma alba	White iceplant	Groundcover			X	3
Deschampsia caespitosa var. Beauv.	California hairgrass	Grass	S	F		18
Deschampsia elongate	Slender hairgrass	Grass			X	3
Deschampsia elongate	Slender hairgrass	Grass		S	F	18
Dianthus spp.	Dianthus	Flower		ECw 2–4		11
Dichondra carolinensis	Dichondra	Groundcover			X	2
Dichondra micrantha	Dichondra	Groundcover			X	6
Dictyosperma album	Hurricane palm	Palm			X	2, 6
Dietes iriodes	Fortnight lily				X	3
Dietes spp.	African iris	Groundcover		F/S		18
Dietes vegeta	African iris	Groundcover		ECw 2–4		11
Dioon edule	Mexican cycad	Cycad			ECw 4–5.5	11
Dioon spinulosum	Mexican cycad	Cycad		ECw 2–4		11
Diospyros digyna	Black sapote	Tree		F/S		18
Diospyros kaki	Japanese persimmon	Tree		X		6
Diospyros virginiana	Common persimmon	Tree			S/F	1
Diospyros virginiana	Persimmon	Tree		F		7
Diospyros virginiana	Persimmon	Tree	X			14
Diospyros virginiana	American persimmon	Tree	F/S			18

Dipladenia sanderia	Dipladenia	Vine	ECw 2–4		11
Distichlis spicata	Saltgrass	Grass		ECe 14–18	15
Distichlis spicata	Saltgrass	Grass		F/S	18
Dodonaea viscosa	Hopbush	Shrub	X		8
Dodonaea viscosa		Shrub		S	12
Dodonaea viscosa	Dodonaea, cv. atropurpurea	Shrub	ECe 4–6		10, 16
Dodonaea viscosa v. atropurpurea	Dodonea	Shrub	S		12
Dodonaea spp.		Shrub/ groundcover		ECe >8	4
Dodonaea viscosa v. atropurpurea	Dodonea	Shrub	ECw 1.5–3		4, 12
Dracaena deremensis Engler	Dracaena	Shrub	F/S		18
Dracaena spp.			S		12
Dracaena spp.		Shrub		EC_e >8	4
Dracena endivisa	Dracaena	Shrub		EC_W >3	4
Drosanthemum hispidum	Rose iceplant	Groundcover		X	3
Drosanthemum hispidum	Lavender pink iceplant	Groundcover		EC_W >3	4
Drosanthemum hispidum	Lavender pink iceplant	Groundcover		S	12
Drosanthemum hispidum	Rosea iceplant	Groundcover		F/S	18
Drosanthemum hispidum	Rosea iceplant	Groundcover		ECe >10	10, 16
Drosanthemum speciosum	Iceplant	Groundcover		X	8
Echium fastuosum	Pride of Madeira			S	12
Echium fastuosum	Pride of Maderia			X	3
Elaeagnus angustifolia	Russian olive	Tree		X	9
Elaeagnus angustifolia	Russian olive	Tree	ECe <8		15
Elaeagnus angustifolia		Tree		S	12, 17
Elaeagnus commutate	Silverberry	Shrub	ECe <8		15
Elaeagnus multiflora	Cherry elaeagnus	Shrub	ECe <8		15
Elaeagnus pungens	Silverberry	Shrub	EC_e 3–8		4
Elaeagnus pungens	Eleagnus	Shrub		ECw 4–5.5	11

(continued)

Salt Tolerance (continued)

Botanical name	Common name	Tree, shrub, groundcover, flower, palm, fruit, vine, cycad	Low tolerance	Moderate tolerance	High tolerance	Source
Elaeagnus pungens	Silverberry	Shrub		S		12
Elaeagnus pungens	Silverberry	Shrub		ECw 1.5–3		4, 12
Elaeagnus pungens	Silverthorn, silverberry	Shrub			F/S	18
Elaeagnus pungens	Thorny elaeagnus	Shrub		ECe 4–6		10, 16
Elaeis guineensis	African oil palm	Palm		X		2, 6
Elymus angustus	Altai wildrye	Grass			F/S	18
Elymus canadensis	Canadian wildrye	Grass			F/S	18
Elymus giganteus	Mammoth wildrye	Groundcover		ECe 4–8		15
Elymus glaucus	Blue wildrye	Grass			X	3
Elymus glaucus	Blue wildrye	Grass		S	F	18
Elymus junceus	Russian wildrye	Grass		ECe 4–8		15
Elymus junceus	Russian wildrye	Grass			F/S	18
Elymus triticoides	Beardless wildrye	Grass			ECe 14–18	15
Elymus triticoides	Beardless wildrye	Grass			F/S	18
Encelia farinose	Brittlebush	Groundcover			X	8
Encephalartos spp.	African cycad	Cycad		ECw 2–4		11
Ephedera spp.	Mormontea	Shrub			X	8
Ephedra nevadensis	Nevada mormontea	Shrub		ECe <6		15
Ephedra spp.	Mormon teas	Shrub			ECe <10	15
Ephedra torreyana	Torrey ephedra	Shrub			ECe <10	15
Epipremnum spp.	Pothos	Vine		F/S		18
Eragrostis spp.	Love grass	Grass	S	F		18
Eranthemum pulchellum	Blue sage	Shrub		X		2, 6

Eremochloa ophiuroides	Centipedegrass	Grass		F/S		18
Eriobotrya japonica	Loquat	Tree		ECw 2–4		11
Eriobotrya japonica	Loquat	Tree		X		2, 6
Eriobotrya japonica	Loquat	Tree	S			12
Eriobotrya japonica	Loquat	Tree	X			14
Eriobotrya japonica	Loquat	Tree		F/S		18
Eriogonum arborescens	Santa Cruz Island buckwheat	Shrub			S	12
Eriogonum fasciculatum	California buckwheat	Shrub			S	12
Eriogonum fasciculatum	California buckwheat	Shrub			X	3
Erythea annata		Shrub			S	12
Erythrina spp.	Coral tree	Tree	X			2
Erythrina spp.	Coral tree	Tree		X		6
Escallonia rubra	Escallonia	Shrub			X	3
Escallonia rubra	Escallonia	Shrub		S	F	18
Eucalyptus aggregate		Tree		ECe 4–8		5
Eucalyptus anceps		Tree		ECe 4–8		5
Eucalyptus angustissima		Tree		ECe 4–8		5
Eucalyptus astringens	Brown mallet	Tree		ECe 4–8		5
Eucalyptus botryoides	Southern mahogany	Tree		ECe 4–8		5
Eucalyptus brachycorys	Comet vale mallee	Tree		ECe 4–8		5
Eucalyptus brockwayi	Dundas mahogany	Tree		ECe 4–8		5
Eucalyptus camaldulensis	River red gum	Tree		ECe 4–8		5
Eucalyptus camaldulensis	Red gum	Tree			X	9
Eucalyptus camaldulensis	Red gum	Tree			S	12
Eucalyptus campaspe	Silver top gimlet	Tree		X		8
Eucalyptus cinerea	Silverdollar eucalyptus	Tree		X		6
Eucalyptus citriodora	Lemon-scented gum	Tree			S	12
Eucalyptus cladocalyx	Sugar gum	Tree			S	12
Eucalyptus coolabahs		Tree		ECe 4–8		5

(continued)

Salt Tolerance (continued)

Botanical name	Common name	Tree, shrub, groundcover, flower, palm, fruit, vine, cycad	Low tolerance	Moderate tolerance	High tolerance	Source
Eucalyptus diptera	Two-winged gimlet	Tree		ECe 4–8		5
Eucalyptus erythrocorys	Red cap gum	Tree		X		8
Eucalyptus famelica		Tree		ECe 4–8		5
Eucalyptus ficifolia	Red-flowering gum	Tree			S	12
Eucalyptus foliosa		Tree		ECe 4–8		5
Eucalyptus globulus compacta	Blue gum	Tree			S	12
Eucalyptus halophila	Salt lake mallee	Tree			ECe >16	5
Eucalyptus kondininensis	Kondinin blackbutt	Tree			ECe >16	5
Eucalyptus largiflorens	Black box	Tree		ECe 4–8		5
Eucalyptus lehmannii	Bushy yate	Tree			S	12
Eucalyptus leptocalyx	Hopetoun mallee	Tree		ECe 4–8		5
Eucalyptus microtheca	Coolibah	Tree			X	8
Eucalyptus polyanthemos	Siler dollar gum	Tree			S	12
Eucalyptus pulverulenta	Silver mountain gum	Tree		S		12
Eucalyptus rudis	Desert gum	Tree			X	9
Eucalyptus rudis	Desert gum, swamp gum	Tree			S	12
Eucalyptus sargentii	Salt river gum	Tree			X	8
Eucalyptus sideroxylon var. rosea	Red ironbark, pink ironbark	Tree			S	12
Eucalyptus spathulata	Narrow leaf gimlet	Tree		X		8
Eucalyptus spp.	Gum tree	Tree			X	3
Eucalyptus tereticomis	Square-fruited mallee	Tree		S		12
Eucalyptus torquata	Coral gum	Tree			X	8, 9
Eucalyptus woodwardii	Lemon-flowered gum	Tree		X		8

Eugenia spp.		Shrub			S	12
Eugenia uniflora	Surinam cherry	Shrub		X		6
Eugenia uniflora L.	Surinam cherry	Shrub	F/S			18
Eugenia unifora	Surinam cherry	Shrub		ECw 2–4		11
Euonymus fortunei	Running strawberry bush	Groundcover			X	2
Euonymus japonica	Evergreen euonymus				X	3
Euonymus japonica	Spindle tree, cv. Grandiflora	Shrub		ECe 6–8		10
Euonymus japonica	Spindle tree	Shrub		ECe <8		15
Euonymus japonica v. grandiflora	Euonymus	Shrub		S		12
Euonymus japonica v. grandiflora	Euonymus	Shrub			ECw >3.0	12
Euonymus japonica var. grandiflora	Euonymus	Shrub			EC_W >3	4
Euonymus spp.		Shrub/ groundcover			EC_e >8	4
Euphorbia lactea	Candelabra cactus	Shrub			X	2, 6
Euphorbia lactea	Spurge				S	12
Euphorbia milii	Crown of thorns	Shrub			ECw 4–5.5	11
Euphorbia milii	Crown-of-thorns	Shrub			X	6, 18
Euphorbia pulcherrima	Poinsettia	Shrub	X			2
Euphorbia pulcherrima	Poinsettia	Shrub		X		6
Euphorbia pulcherrima "Barbara Ecke"	Poinsettia	Shrub	S			12
Euphorbia pulcherrima wild	Poinsettia	Shrub	F/S			18
Euphorbia tirucalli	Pencil tree	Tree	X			2
Euphorbia tirucalli	Pencil tree	Tree		X		6
Euphorbia tirucalli		Tree			S	12
Euphorbia pulcherrima	Poinsettia		S			12
Euryops pectinatus	Golden marguerite	Tree	F/S			18
Euryops pectinatus	Golden shrub daisy	Shrub		S	F	18
Euryops pettinatus		Shrub			S	12
Eustoma grandiflora	Lisianthus	Flower			ECw 4–5.5	11

(continued)

Salt Tolerance (continued)

Botanical name	Common name	Tree, shrub, groundcover, flower, palm, fruit, vine, cycad	Low tolerance	Moderate tolerance	High tolerance	Source
Evolves glomeratus	Blue daze	Groundcover			ECw 4–5.5	11
Fabiana imbricate					S	12
Fallugia paradoxa	Apache plume	Shrub			X	8
Fallugia paradoxa	Common apache	Flower		ECe 4–6		15
Fatsia japonica	Fatsia	Shrub		X		2, 6
Fatsia japonica	Japanese Aralia	Shrub	S			12
Feijoa sellowiana	Pineapple guava	Shrub	X			2
Feijoa sellowiana	Pineapple guava	Shrub/ groundcover	EC_W .75–1.5			4
Feijoa sellowiana	Pineapple guava	Shrub/tree	EC_e <3			4
Feijoa sellowiana	Pineapple guava	Shrub		X		6
Feijoa sellowiana	Pineapple guava	Shrub		ECw 2–4		11
Feijoa sellowiana	Pineapple guava	Shrub	EC_e 2.0			12
Feijoa sellowiana	Pineapple guava	Shrub	S			12
Feijoa sellowiana	Pineapple guava	Shrub	ECw .75-1.5			12
Feijoa sellowiana	Pineapple guava	Tree	ECe 2–3			10, 16
Felicia aethiopica	Felicia	Shrub	EC_W .75–1.5			4
Felicia aethiopica	Felicia		S			12
Festuca arundinacea	Tall fescue	Grass		ECe 4–8		15
Festuca arundinacea	Tall fescue	Grass		S	F	18
Festuca californica	California fescue	Grass			X	3
Festuca californica	California fescue	Grass		S	F	18
Festuca elatior	Meadow fescue	Grass	ECe <4			15

Festuca elatior	Meadow fescue	Grass		F/S		18
Festuca longifolia	Hard fescue	Grass		F/S		18
Festuca ovina glauca	Blue fescue	Ornamental grass	EC_W .75–1.5			4
Festuca ovina glauca	Blue fescue	Ornamental grass	S			12
Festuca rubra	Red fescue	Grass	ECe <4			15
Festuca rubra	Creeping fescue	Grass		F/S		18
Ficus benjamina	Weeping fig	Tree		X		2, 6
Ficus carica	Fig	Tree			X	6
Ficus carica	Edible fig	Fruit tree		S		12
Ficus carica	Fig	Tree		X		14
Ficus carica	Edible fig	Tree			F/S	18
Ficus elastica	Rubber plant	Tree		X		2, 6
Ficus pumila	Creeping fig	Vine		X		2
Ficus pumila	Creeping fig	Groundcover			X	2, 6
Ficus pumila	Creeping fig	Groundcover		ECw 2–4		11
Ficus pumila	Creeping fig	Groundcover/vine			F/S	18
Forsythia x intermedia	Showy border forsythia	Shrub		ECe <6		15
Forsythia x intermedia Zabel	Hybrid forsythia	Shrub		F/S		18
Fortunella margarita	Kumquat	Tree		X		6
Frankenia spp. *(F. ambita, F. brachyphylla, F. fecunda)*					ECe >16	5
Fraxinus americana	White ash	Tree			S/F	1, 7
Fraxinus americana	White ash	Tree		ECe <6		15
Fraxinus americana	White ash	Tree			S	17
Fraxinus anomala	Singleleaf ash	Tree	ECe <4			15
Fraxinus excelsior	European ash	Tree			F	1, 7
Fraxinus excelsior	European ash	Tree	ECe <4			15
Fraxinus oxycarpa	Raywood ash	Tree		F/S		18
Fraxinus pennsylvanica	Green ash	Tree			F	1

(continued)

Salt Tolerance (continued)

Botanical name	Common name	Tree, shrub, groundcover, flower, palm, fruit, vine, cycad	Low tolerance	Moderate tolerance	High tolerance	Source
Fraxinus pennsylvanica	European ash	Tree			S/F	7
Fraxinus pennsylvanica	Green ash	Tree	ECe <4			15
Fraxinus pennsylvanica	Green ash	Tree		S		17
Fraxinus quadrangulata	Blue ash	Tree		F		7
Fraxinus velutina	Arizona ash	Tree			X	3
Fraxinus velutina	Arizona ash	Tree			S	12
Fraxinus velutina var. modesto	Modesto ash	Tree			X	3
Fraxinus velutina var. modesto	Modesto ash	Tree			S	12
Fremontia mexicana	Southern flannel bush	Tree/shrub			X	3
Fremontia mexicana	Southern flannel bush	Tree/shrub			S	12
Furcraea gigantea					S	12
Gaillardia pulchella	Blanket flower	Groundcover		X		6
Gaillardia pulchella	Gaillardia	Groundcover			ECw 4–5.5	11
Gaillardia pinnatifida	Cutleaf blanketflower	Flower	ECe 2–4			15
Galphimia glauca	Thryallis	Shrub	X			2
Galphimia glauca	Thryallis	Shrub		X		6
Galphimia gracillis	Thryallis	Shrub		ECw 2–4		11
Gamolepis chrysanthemoides	African bush daisy	Shrub			F/S	18
Gardenia augusta Merrill	Cape jasmine, gardenia	Shrub		F/S		18
Gardenia jasminoides	Gardenia	Shrub			S/F	1
Gardenia jasminoides	Gardenia	Shrub		X		6
Gardenia jasminoides	Gardenia	Shrub	S			12
Gardenia jasminoides var. “Belmont”		Shrub	S			12

Gastrococos crispa	Acrocomia	Palm		X		2, 6
Gazania aurantiacum	South African daisy	Groundcover			EC_W >3	4
Gazania aurantiacum	South African daisy	Groundcover			S	12
Gazania rigens		Groundcover		X		8
Gazania spp.	Gazania daisy	Groundcover			ECw 4–5.5	11
Gazania spp.	Gazania	Groundcover			X	3, 9
Gelsemium sempervirens	Carolina jasmine	Vine			ECw 4–5.5	11
Genista spp.					S	12
Gerbera jamesonii	Transvaal daisy	Groundcover	X			2
Gerbera jamesonii	Transvaal daisy	Groundcover		X		6
Ginkgo biloba	Maindenhair tree	Tree			F	1
Ginkgo biloba	Maindenhair tree	Tree		S/F		7
Ginkgo biloba	Maindenhair tree	Tree	ECe <4			15
Ginkgo biloba	Maindenhair tree	Tree	F/S			18
Gleditsia triacanthos	Honeylocust	Tree			S/F	1
Gleditsia triacanthos	Honeylocust	Tree		S/F		7
Gleditsia triacanthos	Honeylocust	Tree		ECe <8		15
Gleditsia triacanthos	Honeylocust	Tree			S	17
Glottiphyllum depressum	Fig-marigold	Groundcover			X	2, 6
Grape spp.	Grape	Vine		S		12
Grevillea banksii					S	12
Grevillea robusta	Silk oak	Tree			X	3
Grevillea robusta	Silk oak	Tree		X		6
Grevillea robusta	Silk oak	Tree			S	12
Grevillea robusta	Silk oak	Tree			F/S	18
Guaiacum sanctum	Lignum-vitae	Tree		X		6
Gymnocladus dioicus	Kentucky coffeetree	Tree			F	1
Gymnocladus dioicus	Kentucky coffeetree	Tree			S/F	7
Hakea suaveolens	Needle bush	Tree		EC_W 1.5–3		4

(continued)

Salt Tolerance (continued)

Botanical name	Common name	Tree, shrub, groundcover, flower, palm, fruit, vine, cycad	Low tolerance	Moderate tolerance	High tolerance	Source
Hakea suaveolens	Needle bush	Shrub		S		12
Halimodendron halodendron	Salt-tree	Shrub			S	12
Halimodendron halodendron	Salt-tree	Shrub		ECe <8		15
Halosarcia spp.	Samphire				ECe >16	5
Hamelia patens	Scarlet bush	Shrub		X		2, 6
Hedera canariensis	Algerian ivy	Groundcover	EC_e <3			4
Hedera canariensis	Algerian ivy	Vine			X	2, 6
Hedera canariensis	Algerian ivy	Shrub	S			12
Hedera canariensis	Algerian ivy	Groundcover	EC_W .75–1.5			4, 12
Hedera canariensis	Algerian ivy	Vine			F/S	18
Hedera canariensis	Algerian ivy	Groundcover	ECe 3–4			10, 16
Hedera canariensis var. variegata	Algerian ivy			S		12
Hedera helix	English ivy	Groundcover			X	2, 6
Hedera helix	English ivy	Groundcover		ECw 2–4		11
Hedera helix	English ivy				S	12
Hedera helix	English ivy	Vine		F/S		18
Helianthus debilis	Cucumberleaf sunflower	Groundcover			X	6
Helianthus debilis	Cucumberleaf sunflower	Groundcover			S	12
Heliconia spp.	Heliconia	Shrub		F/S		18
Hemerocallis spp.	Daylily	Groundcover			X	6
Hemerocallis spp.	Daylily	Groundcover		F/S		18
Hesperaloe parviflora	Red yucca	Shrub			X	8
Heteromeles arbutifolia	Toyon	Shrub			X	3

Heteromeles arbutifolia	Toyon	Shrub			S	12
Hibiscus rosa-sinensis cv. Brilliante	Hibiscus	Shrub	S			12
Hibiscus rosa-sinensis	Hibiscus	Shrub	X			2
Hibiscus rosa-sinensis	Hibiscus	Shrub		X		6
Hibiscus rosa-sinensis	Chinese hibiscus	Shrub	ECe 3–4			10, 16
Hibiscus rosa-sinensis	Hibiscus	Shrub			ECw 4–5.5	11
Hibiscus rosa-sinensis	Hibiscus	Shrub		S		12
Hibiscus rosa-sinensis	Rose of China, garden hibiscus	Shrub		F/S		18
Hibiscus rosa-sinensis var. brilliante	Hibiscus	Shrub	EC_W .75–1.5			4
Hibiscus rosa-sinensis var. brilliante	Hibiscus	Shrub		ECw 1.5-3		12
Hibiscus spp.		Shrub			S	12
Hibiscus spp.		Shrub		EC_e 3–8		4
Hibiscus syriacus	Rose-of-Sharon	Shrub			S/F	1
Hibiscus tiliaceus	Sea hibiscus, Mahoe	Tree			X	6
Hippophae rhamnoides	Sea buckthorn	Shrub		ECe <8		15
Holmskioldia sanguinea	Chinese hat plant	Shrub	X			2
Holmskioldia sanguinea	Chinese hat plant	Shrub		X		6
Homalocladium platycladum	Ribbon bush	Shrub		X		2, 6
Hoya carnosa	Wax plant	Vine		X		2, 6
Hydrangea macrophylla	House hydrangea	Shrub			S/F	1
Hydrangea macrophylla ser.	Hydrangea	Shrub		F/S		18
Hylocereus undatus	Night blooming cereus	Vine			X	2, 6
Hylocereus undatus		Vine		S		12
Hylocereus undatus	Night blooming cereus	Vines		F/S		18
Hymenocallis keyensis				S		12
Hymenocyclus croceus	Croceum iceplant	Groundcover			ECe >10	10, 16
Hyophorbe lagenicaulis	Bottle palm	Palm		ECw 2–4		11
Hyophorbe spp.	Bottle palm	Palm			X	2, 6
Hyophorbe verschaffeltii	Spindle palm	Palm		ECw 2–4		11

(continued)

Salt Tolerance (continued)

Botanical name	Common name	Tree, shrub, groundcover, flower, palm, fruit, vine, cycad	Low tolerance	Moderate tolerance	High tolerance	Source
Hypericum calycinum	St. John's wort	Shrub			S/F	1
Hyphaene thebaica	Gingerbread palm	Palm		X		2, 6
Hyphaene thebaica	Gingerbread palm	Palm			ECw 4–5.5	11
Ilex attenuate	East Palatka holly	Tree		ECw 2–4		11
Ilex cassine	Dahoon	Tree		X		2, 6
Ilex cornuta	Chinese holly	Shrub			S/F	1
Ilex cornuta	Chinese holly cv. Burford	Shrub	ECe 2–3			10
Ilex cornuta	Chinese holly	Shrub	S			12
Ilex cornuta var. burfordii	Burford holly	Shrub/ groundcover	EC_e <3			4
Ilex cornuta var. burfordii	Burford holly	Shrub	S			12
Ilex cornuta var. burfordii	Burford holly	Shrub	ECe 2–3			16
Ilex cornuta var. burfordii	Burford holly	Shrub	EC_W .75–1.5			4, 12
Ilex cornuta var. burfordii	Burford holly	Shrub		F/S		18
Ilex crenata	Japanese holly	Shrub			S/F	1
Ilex glabra	Inkberry	Shrub			S/F	1
Ilex glabra	Inkberry	Shrub		X		6
Ilex glabra	Inkberry	Shrub		S		12
Ilex opaca	American holly	Tree			F	1
Ilex opaca	American holly	Tree	X			2
Ilex vomitoria	Yaupon holly	Shrub			X	2, 6
Ilex vomitoria	Yaupon holly	Shrub			ECw 4–5.5	11
Ilex vomitoria	Yaupon holly	Shrub		S		12

Ilex vomitoria	Yaupon holly	Shrub			S/F	1, 18
Ilex vomitoria var. nana	Dwarf yaupon holly	Shrub			X	6
Ilex vomitoria var. nana	Dwarf yaupon holly	Shrub			F/S	18
Illicium floridanum	Anise	Shrub			S/F	1
Ipomoea pescaprae	Railroad vine	Vine			F/S	18
Ipomoea pescaprae	Beach morning glory	Groundcover			X	6
Ipomoea pescaprae	Beach morning glory	Groundcover			S	12
Ipomoea stolonifera	Seafoam morning glory	Vine			F/S	18
Iris hexagona	Iris			F/S		18
Isomeris arborea	Bladderpod				X	3
Isomeris arborea	Bladderpod				S	12
Iva spp.					S	12
Ixora coccine	Ixora	Shrub	F/S		F/S	18
Ixora coccinea	Ixora	Shrub		X		2, 6
Ixora spp.	Ixora	Shrub			ECw 4–5.5	11
Jacaranda acutifolia	Jacaranda	Tree			X	3
Jacaranda acutifolia	Jacaranda	Tree			S	12
Jacaranda mimosifolia	Jacaranda	Tree		X		6
Jacaranda mimosifolia D. Don	Jacaranda	Tree	F/S			18
Jacquinia armillaris				S		12
Jacquinia keyensis				S		12
Jasminum floridum	Flowering jasmine	Vine			X	6
Jasminum multiflorum	Downy jasmine	Vine	X			2, 6
Jasminum nitidum	Star jasmine	Vine	X			2, 6
Jasminum polyanthum Franch.	Jasmine	Shrub		F/S		18
Jasminum sambac	Arabian jasmine	Shrub		X		6
Jatropha hastate	Jatropha	Shrub		ECw 2–4		11
Jatropha multifida L.	Coral plant	Shrub	F	S		18
Jatropha spp.	Coral plant	Shrub	X			2

(continued)

Salt Tolerance (continued)

Botanical name	Common name	Tree, shrub, groundcover, flower, palm, fruit, vine, cycad	Low tolerance	Moderate tolerance	High tolerance	Source
Jatropha spp.	Coral plant	Shrub		X		6
Juglans cinerea	Butternut	Tree			F	7
Juglans nigra	Black walnut	Tree			S/F	1
Juglans nigra	Black walnut	Tree			F	7
Juglans nigra	Black walnut	Tree	Intolerant			15
Juniper spp.	Juniper	Shrub/ groundcover			ECw 4–5.5	11
Juniperus californica	California juniper	Tree			X	3
Juniperus californica	California juniper	Tree			S	12
Juniperus chinensis	Chinese juniper	Shrub			S/F	1
Juniperus chinensis	Spreading juniper	Shrub/ groundcover		EC_W 1.5–3		4
Juniperus chinensis	Chinese juniper	Shrub			S/F	7
Juniperus chinensis	Spreading juniper	Shrub		ECe 4–6		10
Juniperus chinensis	Chinese juniper	Shrub			EC_e 8.0	12
Juniperus chinensis	Spreading juniper	Shrub		S		12
Juniperus chinensis	Spreading juniper	Shrub		ECw 1.5-3		12
Juniperus chinensis	Spreading juniper	Shrub		ECe 4–6		16
Juniperus chinensis	Chinese juniper	Groundcover		F/S		18
Juniperus chinensis var. armstrongii	Armstrong juniper	Shrub		EC_e 3–8		4
Juniperus chinensis var. pfitzerana	Pfitzer juniper	Tree			S	12
Juniperus chinensis var. pfitzerana	Pfitzer juniper	Tree		ECe <8		15
Juniperus chinensis var. procumbens	Japanese garden juniper	Groundcover		X		6

Juniperus chinensis var. torulosa	Hollywood juniper	Shrub		EC_W 1.5 –3		4
Juniperus chinensis var. torulosa	Hollywood juniper	Shrub		S		12
Juniperus chinensis varieties		Shrub			S	12
Juniperus communis	Common juniper	Shrub			S/F	1
Juniperus communis	Common juniper	Shrub		ECe <6		15
Juniperus communis “Stricia”		Shrub		S		12
Juniperus conferta	Shore juniper	Groundcover			S/F	1
Juniperus conferta	Shore juniper	Groundcover			X	6
Juniperus conferta	Shore juniper	Groundcover			S	12
Juniperus conferta	Shore juniper	Groundcover			F/S	18
Juniperus horizontalis	Creeping juniper	Groundcover			S/F	1, 7
Juniperus horizontalis	Creeping juniper	Groundcover			F/S	18
Juniperus procumbens	Japanese garden juniper	Groundcover			S	12
Juniperus procumbens	Japanese garden juniper	Groundcover		F/S		18
Juniperus sabina var. tamariscifolia		Shrub			S	12
Juniperus scopulorum var. moffeti	Moffets juniper	Tree	S			12
Juniperus scopulorurn var. moffeti	Moffets juniper	Tree	EC_W .75–1.5			4
Juniperus silicicola	Red cedar	Tree		ECw 2–4		11
Juniperus silicicola	Southern red cedar	Tree			F/S	18
Juniperus silicoola	Southern red cedar	Tree			X	6
Juniperus virginiana	Eastern red cedar	Tree			S/F	1
Juniperus virginiana	Eastern red cedar	Tree			F	7
Juniperus virginiana	Cedar	Tree		S		17
Juniperus virginiana var. skyrocket	Skyrocket juniper	Tree			X	3
Juniperus virginiana var. skyrocket	Skyrocket juniper	Tree			F/S	18
Justicia brandegeana	Shrimp plant	Shrub	F/S			18
Kalancho blossfeldian	Kalanchoe	Groundcover		ECw 2–4		11
Kalanchoe spp.	Kalanchoe	Groundcover		X		2
Kalanchoe spp.	Kalanchoe	Groundcover		S		12

(continued)

Salt Tolerance (continued)

Botanical name	Common name	Tree, shrub, groundcover, flower, palm, fruit, vine, cycad	Low tolerance	Moderate tolerance	High tolerance	Source
Kalanchoe spp.	Kalanchoe	Groundcover		F/S		18
Kochia Americana	Greenmolly summercypruss	Shrub			ECe <10	15
Koelreuteria paniculata	Goldenrain tree	Tree			S/F	1
Koelreuteria paniculata	Goldenrain tree	Tree		F		7
Koelreuteria paniculata	Goldenrain tree	Tree	ECe <4			15
Koelreuteria paniculata	Goldenrain tree	Tree		F/S		18
Kopsia arborea				S		12
Lagerstroemia indica	Crape myrtle	Shrub	X			2
Lagerstroemia indica	Crape myrtle	Shrub		X		6
Lagerstroemia indica	Crape myrtle	Tree	F/S			18
Lagerstroemia indica	Crape myrtle	Tree	ECe 3–4			10, 16
Lagunaria patersonii					S	12
Lampranthus productus	Purple iceplant	Groundcover			F/S	18
Lampranthus productus	Purple iceplant	Groundcover			ECe >10	10, 16
Lampranthus spectabilis	Trailing iceplant	Groundcover			EC_W >3	4
Lampranthus spectabilis	Trailing iceplant	Groundcover			S	12
Lampranthus spp.	Ice plant	Groundcover			ECw 4–5.5	11
Lantana camara	Lantana	Shrub		ECe 3–8		4
Lantana camara	Lantana	Shrub			ECe 8.0	12
Lantana camara	Lantana	Shrub		S		12
Lantana camara	Lantana	Shrub		X		6, 8
Lantana camara	Lantana	Shrub		ECw 1.5-3		4, 12
Lantana camara	Lantana	Shrub			F/S	18

Lantana camara	Yellow sage	Shrub		ECe 4–6		10, 16
Lantana montevidensis	Weeping lantana	Groundcover			X	2, 6
Lantana montevidensis	Trailing lantana	Groundcover		X		8
Lantana montevidensis	Trailing lantana	Groundcover		S		12
Lantana spp.	Lantana	Shrub			ECw 4–5.5	11
Lantana spp.	Lantana	Shrub			S	12
Larix deciduas	Common larch	Tree			F	1, 7
Larix laricina	American larch				F	7
Larrea tridentate	Creosote	Shrub			X	8
Latania spp.	Latan palm	Palm			X	6
Lathyrus japonicus					S	12
Lavatera assurgentiflora	Tree mallow				X	3, 9
Lepidozamia peroffsyana	Scaly zamia	Cycad		ECw 2–4		11
Leptochloa fusca	Kallargrass	Grass			F/S	18
Leptospermum laevigatum	Australian tea tree	Tree	EC$_W$ .75–1.5			4
Leptospermum laevigatum	Australian tea tree	Tree	S			12
Leucaena leucocephala		Tree		S		12
Leucaena spp.		Tree			X	8
Leucophyllum frutescens	Texas ranger	Shrub			X	3
Leucophyllum frutescens	Texas ranger	Shrub			ECe >8	10, 16
Leucophyllum spp.	Texas ranger	Shrub			X	8
Libocedrus decurrens					S	12
Ligustrum amurense	Amur privet	Shrub			S/F	1
Ligustrum japonicum	Japanese privet	Shrub	X			2
Ligustrum japonicum	Japanese privet	Shrub		X		6
Ligustrum japonicum	Japanese privet	Shrub		S	S	12
Ligustrum japonicum	Japanese privet	Tree		F/S		18
Ligustrum lucidum	Glossy privet	Tree		EC$_e$ 3–8		4
Ligustrum lucidum	Glossy privet	Tree		X		6

(continued)

Salt Tolerance (continued)

Botanical name	Common name	Tree, shrub, groundcover, flower, palm, fruit, vine, cycad	Low tolerance	Moderate tolerance	High tolerance	Source
Ligustrum lucidum	Glossy privet	Tree		ECw 2–4		11
Ligustrum lucidum	Glossy privet	Tree		EC_e 5.0		12
Ligustrum lucidum	Glossy privet	Tree		S		12
Ligustrum lucidum	Glossy privet	Tree		EC_W 1.5–3		4, 12
Ligustrum lucidum	Glossy privet	Tree		ECe 4–6		10, 16
Ligustrum spp.	Ligustrum	Shrub		ECw 2–4		11
Ligustrum vulgare	Common privet	Shrub	ECe <2			15
Limonium perezii	Sea lavender	Flower	EC_W .75–1.5			4
Limonium perezii	Sea lavender	Perennial	S			12
Lippia canescens var. repens	Lippia	Flower			EC_W >3	4
Lippia canescens var. repens	Lippia	Flower			S	12
Liquidambar styraciflua	Sweet gum	Tree			F	1
Liquidambar styraciflua	Sweet gum	Tree	X			2
Liquidambar styraciflua	Sweet gum	Tree		X		6
Liquidambar styraciflua	Sweet gum	Tree			S/F	7
Liquidambar styraciflua	Sweet gum	Tree			S	12
Liquidambar styraciflua	Sweet gum	Tree	F/S			18
Liquidambar styraciflua	Sweet gum	Tree		ECe 6–8		10, 16
Liriodendron tulipifera	Tulip tree	Tree	ECe 2–3			10, 16
Liriope muscari	Lilyturf	Groundcover		ECw 2–4		11
Liriope muscari	Lilyturf	Groundcover		F/S		18
Liriope spp.	Lilyturf	Groundcover			X	6
Liriope spicata	Lirope	Groundcover			X	2

Litchi chinensis	Litchi nut	Tree		X		6
Litchi chinensis	Lychi nut	Tree	F/S			18
Livistona austrailis	Australian fan	Palm			ECw 4–5.5	11
Livistona chinensis	Chinese fan palm	Palm		X		6
Livistona chinensis	Chinese fan palm	Palm			ECw 4–5.5	11
Livistona chinensis	Chinese fan palm	Palm		S		12
Livistona decipiens	Weeping fan palm	Palm			ECw 4–5.5	11
Livistona saribus	Asian fan palm	Palm		ECw 2–4		11
Lolium multiflorum Lam.	Annual ryegrass	Grass	F/S			18
Lolium perenne	Perennial ryegrass	Grass			ECe 8–12	15
Lolium perenne	Perennial ryegrass	Grass		F/S		18
Lonicera hildebrandiana	Giant honeysuckle	Vine			X	3
Lonicera hildebrandiana	Giant honeysuckle	Vine			S	12
Lonicera japonica	Japanese honeysuckle	Vine			X	3
Lonicera japonica	Japanese honeysuckle	Vine		ECw 2–4		11
Lonicera japonica	Japanese honeysuckle	Vine			S	12
Lonicera japonica var. halliana	Hall’s honeysuckle	Vine	ECe <4			15
Lonicera sempervirens	Red honeysuckle	Vine		ECw 2–4		11
Lonicera tatarica	Tatarian honeysuckle	Shrub			S/F	1
Lonicera tatarica	Tararian honeysuckle	Shrub		ECe <8		15
Lonicera tataricum var. zabellii	Zabel’s honeysuckle	Vine		ECe <8		15
Lotus corniculatus	Birds foot trefoil	Groundcover			S	12
Lotus corniculatus	Birds foot trefoil	Groundcover			ECe 14–18	15
Lycium fremontii	Wolfberry	Shrub			X	8
Lysiloma thornberi	Desert fern	Tree		X		8
Macadamia spp.	Macadamia	Tree		X		6
Macfadyena unguis	Cat claw vine	Vine			X	8
Machaeranthera xylorrhiza	Common woody aster	Flower		ECe 6–8		15
Maclura pomifera	Osage-orange	Tree	ECe <4			15

(continued)

Salt Tolerance (continued)

Botanical name	Common name	Tree, shrub, groundcover, flower, palm, fruit, vine, cycad	Low tolerance	Moderate tolerance	High tolerance	Source
Magnolia grandiflora	Southern magnolia	Tree			S/F	1
Magnolia grandiflora	Southern magnolia	Tree		X		2
Magnolia grandiflora	Southern magnolia	Tree		ECw 2–4		11
Magnolia grandiflora	Southern magnolia	Tree	S			12
Magnolia grandiflora	Southern magnolia	Tree	F/S			18
Magnolia grandiflora	Southern magnolia	Tree		ECe 4–6		10, 16
Magnolia soulangiana	Saucer magnolia	Tree		F		7
Magnolia spp. (deciduous)		Tree		S		12
Magnolia virginiana	Sweetbay magnolia	Tree			S	1
Mahonia aquifolium		Shrub			S	12
Mahonia aquifolium	Oregon grape	Shrub	F/S			18
Mahonia aquifolium	Oregon grape	Shrub	ECe 1–2			10, 16
Mahonia bealei	Leatherleaf mahonia	Shrub		X		6
Mahonia nevinii					S	12
Mahonia pinnata	California holly grape	Shrub	F/S			18
Mahonia spp.	Grape hollies	Shrub		X		2
Malephora crocea Schwantes	Iceplant	Groundcover			F/S	18
Malpighia coccigera	Holly malpighia	Shrub		X		2, 6
Malpighia glabra	Barbados cherry	Tree		X		6
Malus spp. (most cultivars)	Apple and crabapple	Tree	ECe <2			15
Malus spp. (some cultivars)	Crabapple	Tree		F		7
Malus sylvestris	Apple	Tree	X			14
Malus sylvestris	Crab apple	Tree	F/S			18

Mandevilla splendens	Pink allamanda	Vine		X		2, 6
Mandevilla splendins	Mandevilla	Vine		ECw 2–4		11
Mangifera indica	Mango	Tree		X		2, 6
Mangifera indica	Mango	Tree	X			14
Mangifera indica	Mango	Tree	F/S			18
Manilkara roxburghiana	Mimusops	Tree			X	6
Manilkara zapota	Sapodilla	Tree			X	6
Manilkara zapota	Sapodilla	Tree			F/S	18
Maytenus phyllanthoides	Mangle dulce	Shrub			X	8
Medicago sativa	Alfalfa	Legume groundcover		ECe 4–8		15
Melaleuca armillaris		Tree			S	12
Melaleuca cuticularis	Swamp paperbark, salt paperbark	Tree			ECe >16	5
Melaleuca halmaturorum var. cymbifolia		Tree			ECe >16	5
Melaleuca halmaturorum var. halmaturorum	South Australian swamp paperbark	Tree			ECe >16	5
Melaleuca leucadendra	Cajeput tree	Tree		EC_W 1.5–3		4
Melaleuca leucadendra	Cajeput tree	Tree		S		12
Melaleuca leucadendron	Punk tree	Tree	S			12
Melaleuca nesophila	Pink melaleuca	Tree			X	9
Melaleuca nesophila		Tree			S	12
Melaleuca quinquenervia	Cajeput tree, punk	Tree			X	6
Melaleuca spp.	Melaleuca				X	3
Melaleuca thyoides					ECe >16	5
Melica californica	California melic	Grass		F/S		18
Melilotus alba	White sweet clover	Legume groundcover			ECe 8–12	15

(continued)

Salt Tolerance (continued)

Botanical name	Common name	Tree, shrub, groundcover, flower, palm, fruit, vine, cycad	Low tolerance	Moderate tolerance	High tolerance	Source
Melilotus officinalis	Yellow sweet clover	Legume groundcover			ECe 8–12	15
Mentzelia spp.	Blaxing stars	Flower	ECe 2–4			15
Mesembryanthemum spp.					S	12
Metrosideros excelsus	New Zealand Christmas tree				X	3
Metrosideros tomentosus	New Zealand Christmas tree				X	9
Mitchella repens	Partridge berry	Groundcover	X			2
Mitchella repens	Partridgeberry	Groundcover		X		6
Monstera deliciosa	Swiss cheese plant	Shrub		X		6
Monstera deliciosa	Split leaf philodendron	Shrub	S			12
Morus alba	Fruitless mulberry	Tree		S		12
Morus spp.	Mulberry	Tree		X		6
Muhlenbergia lindheimeri var. autumn glow		Grass			X	8
Muhlenbergia rigens	Deergrass	Grass			X	3, 8
Muhlenbergia rigens	Deergrass	Grass			F/S	18
Murraya paniculata	Orange jessamine	Shrub		X		6
Murraya paniculata	Orange jessamine	Shrub	F/S			18
Musa acuminate	Banana	Tree	F/S			18
Musa paradisiaca	Banana	Shrub		X		6
Musa sumatrana	Red-leaved banana	Shrub	S			12
Myoporum laetum	Myoporum	Shrub			EC_W >3	4
Myoporum laetum	Myoporum	Shrub			X	9

Myoporum laetum	Myoporum	Shrub			S	12
Myoporum parvifolium	Myoporum	Groundcover			EC_W >3	4
Myoporum parvifolium	Myoporum	Groundcover			S	12
Myoporum parvifolium	Myoproum	Groundcover			X	3, 9
Myrica cerifera	Wax myrtle	Shrub/tree			S/F	1
Myrica cerifera	Southern wax myrtle	Shrub/tree			X	2, 6
Myrica cerifera	Wax myrtle	Shrub/tree			ECw 4–5.5	11
Myrica cerifera	Wax myrtle	Shrub/tree			F/S	18
Myrica pennsylvanica	Bayberry	Shrub			S/F	1
Myrica pennsylvanica	Bayberry	Shrub		S		12
Myrtus communis	Tree myrtle	Shrub			X	3
Myrtus communis		Shrub		S		12
Myrtus communis	Tree myrtle	Shrub			F/S	18
Myrtus communis compacta		Shrub			S	12
Nandina domestica	Heavenly bamboo	Shrub	EC_W .75–1.5			4
Nandina domestica	Heavenly bamboo	Shrub		EC_e 3–8		4
Nandina domestica	Heavenly bamboo	Shrub		X		6
Nandina domestica	Heavenly bamboo	Shrub		S		12
Nandina domestica	Heavenly bamboo	Shrub	S			12
Nandina domestica	Heavenly bamboo	Shrub		ECw 1.5-3		12
Nandina domestica	Heavenly bamboo	Shrub	F/S			18
Nandina domestica	Heavenly bamboo	Shrub	ECe 3–4			10, 16
Neodypsis decaryi	Trinangle palm	Palm		ECw 2–4		11
Nephrolepis exaltata	Sword fern	Groundcover			F/S	18
Nerium oleander	Oleander	Shrub			ECe >8	4
Nerium oleander	Oleander	Shrub		ECe 6–8		10
Nerium oleander	Oleander	Tree			ECw 4–5.5	11
Nerium oleander	Oleander	Shrub			ECe 10.0	12
Nerium oleander	Oleander	Shrub		S		12

(continued)

Salt Tolerance (continued)

Botanical name	Common name	Tree, shrub, groundcover, flower, palm, fruit, vine, cycad	Low tolerance	Moderate tolerance	High tolerance	Source
Nerium oleander	Oleander	Shrub			EC_W >3	4, 12
Nerium oleander	Oleander	Shrub		ECe 6–8		16
Nerium oleander	Oleander	Shrub			F/S	18
Nerium oleander	Oleander	Shrub			X	2, 3, 6, 8, 9
Nolina microcarpa	Bear grass	Shrub			X	8
Nolina recurvata	Ponytail palm	Shrub		F/S		18
Noronhia emarginata	Madagascar olive	Tree			X	6
Nyssa sylvatica	Tupelo	Tree			F	1
Nyssa sylvatica	Tupelo	Tree		S/F		7
Ochrosia elliptica	Ochrosia	Tree			X	2, 6
Ochrosia elliptica		Tree		S		12
Oenothera caespitosa	Tufted evening primrose	Groundcover		ECe 4–6		15
Oenothera speciosa	Evening primrose				X	3
Oenothera speciosa childsii					S	12
Oenothera spp.		Groundcover			X	8
Olea europaea	Olive	Fruit tree		S		12
Olea europaea	Olive	Tree		X		14
Olea europaea	Olive	Tree	F/S			18
Olea europaea	Olive	Tree			S	8, 12
Olea europaea var. montra	Dwarf olive				X	3
Ophiopogon japonicus	Lily turf	Groundcover			X	2, 6
Ophiopogon japonicus	Mondo grass	Groundcover		ECw 2–4		11
Opuntia spp.		Cactus			S	12

Opuntia spp.		Cactus			X	6, 8
Opuntia spp.	Opuntia cactus	Cactus			F/S	18
Ostrya Virginian	Ironwood	Tree		F		7
P. Besseyi	Cherry, sand	Tree	X			14
Pachysandra terminalis	Japanese spurge	Groundcover	EC_W .75–1.5			4
Pachysandra terminalis	Japanese spurge	Groundcover	S			12
Pandanus				S		12
Panicum antidotale	Panicgrass	Grass		S	F	18
Parkinsonia aculeata	Jerusalem thorn	Tree	X			2
Parkinsonia aculeata	Jerusalem thorn	Tree		X		6
Parkinsonia aculeata	Jerusalem thorn	Tree			S	12
Parkinsonia aculeate	Mexican Palo Verde	Tree			X	3
Parkinsonia aculeate	Jerusalem thorn	Tree		ECw 2–4		11
Parkinsonia floridum	Blue Palo Verde	Tree		X		8
Parkinsonia hybrida var. desert museum		Tree		X		8
Parkinsonia microphyllum	Foothill Palo Verde	Tree		X		8
Parkinsonia praecox	Palo Brea	Tree		X		8
Parthenium argentatum	Guayule	Tree			X	14
Parthenium argentatum	Guayule	Tree/shrub			F/S	18
Parthenocissus quinquefolia	Virginia creeper	Vine			X	2, 6
Parthenocissus quinquefolia				S		12
Parthenocissus quinquefolia	Virginia creeper — woodbine	Vine		ECe <8		15
Parthenocissus quinquefolia	Virginia creeper	Vine			S	17
Paspalum notatum	Bahiagrass	Grass		F/S		18
Paspalum dilatatum	Dallisgrass	Grass	F/S			18
Paspalum vaginatum	Seashore paspalum	Grass			X	3
Paspalum vaginatum	Saltwater couch	Grass			ECe >16	5
Paspalum vaginatum (seashore ecotype)	Seashore paspalum	Grass			F/S	18
Passiflora edulis	Passion fruit	Tree	X			14

(continued)

Salt Tolerance (continued)

Botanical name	Common name	Tree, shrub, groundcover, flower, palm, fruit, vine, cycad	Low tolerance	Moderate tolerance	High tolerance	Source
Passiflora incarnate	Passion flower	Vines	F/S			18
Pedilanthus tithymaloides	Devil's backbone	Shrub		X		2, 6
Pelargonium spp.	Geranium	Flower			ECw 4–5.5	11
Pelargonium spp.		Flower/vine	S			12
Peltophorum pterocarpum	Yellow poinciana	Tree	X			2
Peltophorum pterocarpum	Yellow poinciana	Tree		X		6
Penstemon spp.		Shrub			X	8
Pentas lanceolata	Pentas	Flower		ECw 2–4		11
Pentas lanceolata	Pentas	Shrub		ECw 2–4		11
Pentas lanceolata	Pentas, Egyptian starcluster	Shrub	F/S			18
Peperomia obtusifolia	Peperomia	Groundcover	F/S			18
Persea americana	Avocado	Tree		X		6
Persea americana	Avocado	Tree	X			14
Persea americana	Avocado	Tree		F/S		18
Persea borbonia	Red bay	Tree			ECw 4–5.5	11
Petrea volubilis	Queens wreath	Vine	X			2, 6
Petunia hybrida	Petunia	Flower		ECw 2–4		11
Phalaris arundinacea	Reed canarygrass	Grass		ECe 4–8		15
Phalaris arundinacea	Canarygrass	Grass		S	F	18
Phalaris tuberose	Harding grass	Grass		F/S		18
Philadelphus coronaries	Mock orange	Shrub			S/F	1
Philadelphus coronaries	Sweet mockorange	Shrub		ECe <6		15
Philodendron bipinnatifidum	Fiddle leaf philodendron	Shrub	S			12

Philodendron williamsii	Philodendron	Vines		F/S		18
Phleum pretense	Timothy	Grass	F/S			18
Phoenix canariensis	Canary island date palm	Palm		X		2
Phoenix canariensis	Canary island date	Palm			ECw 4–5.5	11
Phoenix canariensis	Canary island date palm	Palm			S	12
Phoenix canariensis	Canary Island date palm	Palm			X	3, 6, 8
Phoenix canariensis	Canary island date palm	Palm		F/S		18
Phoenix dactylifera	Date palm	Palm		X		2, 6
Phoenix dactylifera	True date palm	Palm			ECw 4–5.5	11
Phoenix dactylifera	Date palm	Palm			X	3, 8, 14
Phoenix dactylifera	Date palm	Palm			S	12
Phoenix dactylifera	Date palm	Palm			F/S	18
Phoenix humilis		Palm	S			12
Phoenix reclinata	Senegal date palm	Palm			X	6
Phoenix reclinata	Senegal date palm	Palm			ECw 4–5.5	11
Phoenix reclinata	Senegal date palm	Palm		F/S		18
Phoenix roebelenii	Pygmy date palm	Palm		F/S		18
Phoenix roebellini	Pygmy date palm	Palm			ECw 4–5.5	11
Phormium tenax	New Zealand flax	Shrub		EC_W 1.5–3		4
Phormium tenax	New Zealand flax	Shrub			S	12
Phormium tenax	New Zealand flax			S		12
Photinia fraseri	Fraser's photinia	Shrub	EC_W .75–1.5			4
Photinia fraseri	Redtop	Shrub		X		6
Photinia fraseri	Fraser's photinia		S			12
Photinia fraseri	Photinia	Shrub	ECe 1–2			10, 16
Photinia fraseri var. Dress	Photinia	Shrub	F/S			18
Photinia glabra	Japanese photinia	Shrub	F/S			18
Photinia serrulata		Shrub	S			12
Phus typhina	Staghorn sumac	Shrub		ECe <8		15

(continued)

Salt Tolerance (continued)

Botanical name	Common name	Tree, shrub, groundcover, flower, palm, fruit, vine, cycad	Low tolerance	Moderate tolerance	High tolerance	Source
Physaria australus	Twinpod	Flower	ECe 2–4			15
Picea abies	Norway spruce	Tree	ECe <2			15
Picea glauca	White spruce	Tree			S	17
Picea glauca var. densata	Black hills spruce	Tree		ECe <8		15
Picea pungens	Colorado spruce	Tree			F	1
Picea pungens	Blue spruce				X	3
Picea pungens	Blue spruce				S/F	7
Picea pungens	Colorado blue spruce	Tree			S	17
Pinus cembroides	Mexican pinon pine				X	3
Pinus cembroides	Mexican pinon pine	Tree			F/S	18
Pinus clausa	Sand pine	Tree			X	6
Pinus clausa	Sand pine	Tree			F/S	18
Pinus eldarica	Afghan pine	Tree			X	8
Pinus elliottii	Slash pine	Tree		X		6
Pinus elliottii	Slash pine	Tree			ECw 4–5.5	11
Pinus elliottii	Slash pine	Tree		ECw 2–4		11
Pinus elliottii	Florida slash pine	Tree		F/S		18
Pinus halepensis	Aleppo pine	Tree	EC_W .75–1.5			4
Pinus halepensis	Alleppo pine	Tree	S			12
Pinus halepensis	Aleppo pine	Tree	S			12
Pinus halepensis	Aleppo pine	Tree		F/S		18
Pinus halepensis	Aleppo pine	Tree			X	6, 8, 9
Pinus halepensis	Aleppo pine	Tree		ECe 6–8		10, 16

Pinus mugo	Mugo pine	Tree			S/F	1, 7
Pinus mugo	Mugho pine	Tree		ECe <8		15
Pinus mugo	Mugo pine	Tree			S	17
Pinus nigra	Austrian pine	Tree			F	1
Pinus nigra	Austrian pine	Tree		ECe <8		15
Pinus nigra	Austrian pine	Tree			S	17
Pinus palustris	Longleaf pine	Tree			F	1
Pinus pinea	Italian stone pine	Tree			X	3, 8
Pinus pinea	Italian stone pine	Tree			ECe >8	10, 16
Pinus ponderosa	Ponderosa pine	Tree		ECe <6		15
Pinus radiata	Monterey pine	Tree			S	12
Pinus resinosa	Red or norway pine	Tree	Intolerant			15
Pinus strobes	Eastern white pine	Tree	ECe <2			15
Pinus sylvestris	Scot’s pine	Tree	ECe <2			15
Pinus sylvestris	Scotch pine	Tree		S		17
Pinus thunbergiana	Japanese black pine	Tree			S/F	1
Pinus thunbergiana	Japanese black pine	Tree		X		6
Pinus thunbergiana	Japanese black pine	Tree		ECe <6		15
Pinus thunbergiana	Japanese black pine	Tree		F/S		18
Pinus thunbergiana	Japanese black pine	Tree		ECe 4–6		10, 16
Pistacia chinensis	Chinese pistache	Tree			S	12
Pistacia chinensis	Chinese pistachio	Tree			X	8
Pistacia chinensis	Chinese pistache	Tree	F/S			18
Pittosporum crassifolium	Evergreen pittosporum	Shrub/tree			EC_W >3	4
Pittosporum crassifolium	Evergreen pittosporum	Shrub			X	9
Pittosporum crassifolium	Evergreen pittosporum	Shrub			S	12
Pittosporum phillyraeoides	Desert willow	Shrub/tree		EC_W 1.5–3		4
Pittosporum phillyraeoides	Weeping pittosporum	Tree		X		8
Pittosporum phillyraeoides	Willow pittosporum				X	9

(continued)

Salt Tolerance (continued)

Botanical name	Common name	Tree, shrub, groundcover, flower, palm, fruit, vine, cycad	Low tolerance	Moderate tolerance	High tolerance	Source
Pittosporum phillyraeoides	Desert willow			S		12
Pittosporum tobira	Pittosporum	Shrub		EC_W 1.5–3		4
Pittosporum tobira	Pittosporum	Shrub/small tree		ECe 3–8		4
Pittosporum tobira	Pittosporum					
	Shrub			X	2, 6	
Pittosporum tobira	Pittosporum	Shrub			ECw 4–5.5	11
Pittosporum tobira	Pittosporum	Shrub		EC_e 5.0		12
Pittosporum tobira	Pittosporum	Shrub		S		12
Pittosporum tobira	Pittosporum	Shrub	S			12
Pittosporum tobira	Pittosporum	Shrub	ECw .75-1.5			12
Pittosporum tobira	Mock orange	Shrub			F/S	18
Pittosporum tobira	Pittosporum	Shrub	ECe 3–4			10, 16
Platanus acerifolia	London plane	Tree	Intolerant			15
Platanus occidentalis	Sycamore	Tree		S/F		7
Platanus racemosa	California sycamore	Tree			X	3
Platanus racemosa	California sycamore	Tree			S	12
Platanus spp.	Sycamore	Tree			X	8
Platycladus orientalis	Arborvitae	Shrub		EC_W 1.5–3		4
Platycladus orientalis	Oriental arborvitae	Shrub		X		6
Platycladus orientalis	Oriental arborvitae	Shrub			EC_e 8.0	12
Platycladus orientalis	Oriental arborvitae	Shrub		S		12
Platycladus orientalis	Oriental arborvitae	Shrub		ECw 1.5-3		12
Platycladus orientalis	Oriental arborvitae	Shrub		S		12

Platycladus orientalis	Oriental arborvitae	Shrub		ECe 4–6		10, 16
Platycladus orientalis franco	Oriental arbor-vitae	Tree		F/S		18
Platycladus orientalis var. aurea nana	Dwarf golden arborvitae	Shrub		EC_e 3–8		4
Plumbago auriculata	Plumbago	Shrub	X			2
Plumbago auriculata	Cape plumbago	Shrub			X	3
Plumbago auriculata	Plumbago	Shrub		X		6
Plumbago auriculata	Plumbago	Shrub		ECw 2–4		11
Plumbago auriculata	Cape plumbago	Tree			F/S	18
Plumbago auriculata	Cape plumbago	Tree		S	F	18
Plumeria rubra	Frangipani	Tree		S		12
Plumeria spp.	Frangipani	Tree			ECw 4–5.5	11
Plumeria spp.	Frangipani	Tree			X	2, 6
Plumeria spp.	Frangipani	Tree			F/S	18
Poa annua	Annual bluegrass	Grass	F/S			18
Poa pratensis	Kentucky bluegrass	Grass	ECe <4			15
Poa pratensis	Kentucky bluegrass	Grass	F/S			18
Poa scabrella	Pine bluegrass	Grass		S	F	18
Poa trivialis	Rough bluegrass	Grass	F/S			18
Podocarpus macrophyllus	Yew pine	Tree		X		6
Podocarpus macrophyllus	Yew pine	Tree		ECw 2–4		11
Podocarpus macrophyllus	Yew pine	Tree	S			12
Podocarpus macrophyllus	Yew pine	Tree	F/S			18
Podocarpus macrophyllus	Yew pine	Tree	ECe 2–3			10, 16
Podocarpus nagi	Broadleaf podocarpus	Shrub		X		6
Polyscias spp.	Aralia	Shrub	X			2
Polyscias spp.	Aralia	Shrub		X		6
Pongamia pinnata	Pongam	Tree		X		2
Pongamia pinnata	Pongam	Tree			X	6
Populus alba	White poplar	Tree			S/F	1

(continued)

Salt Tolerance (continued)

Botanical name	Common name	Tree, shrub, groundcover, flower, palm, fruit, vine, cycad	Low tolerance	Moderate tolerance	High tolerance	Source
Populus alba	White poplar	Tree		ECe <6		15
Populus alba	White poplar	Tree			S	17
Populus canadensis	Carolina poplar	Tree			S	12
Populus deltoides	Eastern cottonwood	Tree		ECe <6		15
Populus deltoides	Eastern cottonwood	Tree			S	17
Populus fremontii	Western cottonwood	Tree			X	3
Populus fremontii	Fremont cottonwood	Tree			S	12
Populus grandidentata	Large-toothed aspen	Tree		ECe <6		15
Populus nigra	Lombardy poplar	Tree		ECe <6		15
Populus nigra italica	Lombardy poplar	Tree			S	17
Populus spp.	Cottonwood	Tree		X		8
Populus tremuloides	Trembling (quaking) aspen	Tree		ECe <6		15
Portulaca grandiflora	Rose moss				X	3
Portulaca grandiflora	Portulaca	Flower			ECw 4–5.5	11
Portulaca grandiflora	Purslane	Groundcover			ECw 4–5.5	11
Portulaca grandiflora	Purslane (Rose moss)	Groundcover	S	F		18
Portulaca oleracea	Purslane	Flower			ECw 4–5.5	11
Portulaca spp.	Purslane	Groundcover			X	2, 6, 8
Portulacaria afra	Elephant food	Groundcover			X	8
Potentilla fruiticosa var. jackmanii	Jackman's potentilla	Shrub		ECe <8		15
Potentilla fruticosa	Shrubby cinquefoil	Shrub			S/F	1
Pritchardia pacifica	Fiji island fan palm	Palm		X		2, 6
Prosopis alba	Argentine mesquite	Tree			X	8

Prosopis chilensis	Chilean mesquite	Tree			X	8
Prosopis glandulosa Maverick	Texas honey mesquite	Tree			X	8
Prosopis glandulosa var. torreyana	Honey mesquite	Tree			S	12
Prosopis juliflora	Native mesquite	Tree			X	8
Prosopis torreyana	Honey mesquite	Tree			X	8
Prosopis velutina	Arizona native mesquite	Tree			X	8
Prunus	Prune	Fruit tree	S			12
Prunus apricot	Apricot	Fruit tree	S			12
Prunus armeniaca	Apricot	Tree	X			14
Prunus armeniaca	Apricot	Tree	F/S			18
Prunus avium	Cherry, sweet	Tree	X			14
Prunus caroliniana	Carolina cherrylaurel	Tree			S	1
Prunus caroliniana	Cherry laurel	Tree		X		6
Prunus caroliniana	Carolina laurel cherry	Tree	S	F		18
Prunus cerasifera	Cherry plum	Tree		ECe 4–6		10
Prunus cerasifera	Cherry plum	Tree		ECe 4–6		16
Prunus domestica	Plum; prune	Tree	X			14
Prunus dulcis	Almond	Tree	X			14
Prunus dulcis	Almond	Tree	F/S			18
Prunus ilicifolia	Holleyleaf cherry	Tree			X	3
Prunus ilicifolia	Holleyleaf cherry	Tree			S	12
Prunus laurocerasus	Cherry laurel	Shrub			S/F	1
Prunus lyonii	Catalina cherry	Tree			X	3
Prunus lyonii	Catalina cherry	Tree			S	12
Prunus maackii	Amur chokecherry			F		7
Prunus maritima	Beach plum	Shrub			S/F	1
Prunus padus	European bird cherry	Tree		ECe <6		15
Prunus persica	Peach	Tree	S			12
Prunus persica	Peach	Tree	X			14

(continued)

Salt Tolerance (continued)

Botanical name	Common name	Tree, shrub, groundcover, flower, palm, fruit, vine, cycad	Low tolerance	Moderate tolerance	High tolerance	Source
Prunus persica	Peach	Tree	F/S			18
Prunus serotina	Black cherry	Tree			F	1
Prunus serotina	Black cherry	Tree		ECe <6		15
Prunus serotina	Black cherry	Tree		S		17
Prunus spinosa	Blackthorn	Tree		S	F	18
Prunus virginiana	Choke cherry			S/F		7
Prunus virginiana	Choke cherry	Tree		ECe <6		15
Prunus x cistena	Purple-leaf sand cherry	Shrub			S/F	1
Pseuderanthemum atropurpureum	Pseuderanthemum	Shrub		X		2, 6
Pseudotsuga menziesii	Douglas fir	Tree	ECe <2			15
Psidium cattleianum	Strawbwerry guava	Tree			S	12
Psidium guajava	Guava	Tree		X		6
Psidium guajava	Guava	Tree	F/S			18
Psilostrophe bakeri	Paperflower	Flower		ECe 6–8		15
Psilostrophe tagetina	Paper flower	Groundcover			X	8
Ptelea trifoliate	Wafer ash	Tree		ECe <8		15
Puccinellia airoides	Alkaligrass	Grass			F/S	18
Puccinellia ciliate	Puccinellia	Grass			ECe >16	5
Puccinellia spp.	Alkaligrass	Grass			ECe 14–18	15
Punica granatum	Dwarf pomegranate	Tree	EC_W .75–1.5			4
Punica granatum	Dwarf pomegranate	Tree	S			12
Punica granatum	Pomegranate	Fruit tree		S		12
Punica granatum	Pomegranate	Tree		F/S		18

Punica granatum	Pomegranate	Tree		X		8, 14
Punica granatum var. wonderful	Pomegranate	Tree			S	12
Purshia glandulosa	Desert bitterbrush	Shrub		ECe <6		15
Pyracantha coccinea	Pyracantha	Shrub			S/F	1
Pyracantha coccinea	Fire-thorn	Shrub		X		2
Pyracantha coccinea	Firethorn				X	3
Pyracantha coccinea	Pyracantha	Shrub		ECw 2–4		11
Pyracantha coccinea var. roem	Red firethorn	Shrub		F/S		18
Pyracantha fortuneana	Pyracantha, cv. Graberi	Shrub		ECe 4–6		10
Pyracantha fortuneana		Shrub		EC_e 5.0		12
Pyracantha fortuneana	Pyracantha	Shrub		ECe <6		15
Pyracantha fortuneana	Pyracantha, cv. Graberi	Shrub		ECe 4–6		16
Pyracantha fortuneana var. graberi		Shrub		S		12
Pyracantha graberi		Shrub		EC_e 3–8		4
Pyracantha graberi	Pyracantha	Shrub		S		12
Pyracantha graeberi	Pyracantha	Shrub			EC_W >3	4
Pyracantha koidzumii	Formosa firethorn	Shrub		X		6
Pyracantha spp.	Firethorn	Shrub			S	12
Pyrostegia venusta	Flame vine	Vine			X	6
Pyrus calleryana	Callery pear	Tree			X	3
Pyrus calleryana	Callery pear	Tree		F		7
Pyrus communis	Pear	Tree	S			12
Pyrus communis	Pear	Tree	X			14
Pyrus communis	Pear	Tree	F/S			18
Pyrus kawakamii	Evergreen pear	Tree			X	3
Pyrus kawakamii	Evergreen pear	Tree			S	12
Pyrus kawakamii	Evergreen pear	Tree			ECe >8	10, 16
Pyrus spp.	Pear	Tree	ECe <4			15
Pyrus spinosa	Almond-leaved pear	Tree		F/S		18

(continued)

Salt Tolerance (continued)

Botanical name	Common name	Tree, shrub, groundcover, flower, palm, fruit, vine, cycad	Low tolerance	Moderate tolerance	High tolerance	Source
Quercus agrifolia	Coast live oak	Tree			X	3
Quercus agrifolia	Coast live oak	Tree			F/S	18
Quercus alba	White oak	Tree			F	7
Quercus alba	White oak	Tree		ECe <8		15
Quercus alba	White oak	Tree			S	1, 17
Quercus bicolor	Swamp white oak	Tree		S/F		7
Quercus ellipsoidalis	Northern pine oak	Tree		S/F		7
Quercus imbricaria	Shingle oak	Tree		F		7
Quercus laurifolia	Laurel oak	Tree		X		6
Quercus laurifolia	Laurel oak	Tree	F/S			18
Quercus macrocarpa	Bur oak	Tree			S/F	1
Quercus macrocarpa	Bur oak	Tree		S/F		7
Quercus macrocarpa	Bur oak	Tree			S	17
Quercus palustris	Pin oak	Tree			S	1
Quercus palustris	Pin oak	Tree	ECe <2			15
Quercus phellos	Willow oak	Tree			F	1
Quercus robur	English oak	Tree			F	1, 7
Quercus robur	English oak	Tree		ECe <8		15
Quercus rubra	Northern red oak	Tree			X	3
Quercus rubra	Red oak	Tree		ECe <8		15
Quercus rubra	Red oak	Tree			S	1, 17
Quercus suber	Cork oak	Tree			X	8
Quercus suber	Cork oak	Tree		F/S		18

Quercus virginiana	Live oak	Tree			S/F	1
Quercus virginiana	Live oak	Tree			ECw 4–5.5	11
Quercus virginiana	Live oak	Tree			X	2, 6, 8
Quercus virginiana	Live oak	Tree			F/S	18
Quisqualis indica	Rangoon creeper	Vine	X			2, 6
Quisqualis indica	Rangoon creeper	Groundcover	S			12
Ravenea rivularis	Majesty palm	Palm		ECw 2–4		11
Rhamnus alaternus	Italian buckthorn	Shrub	EC_W .75–1.5			4
Rhamnus alaternus	Italina buckthorn		S			12
Rhamnus californica	Coffeeberry	Shrub			X	3
Rhamnus californica	Coffeeberry	Shrub			S	12
Rhamnus cathartica	Common buckthorn	Shrub		ECe <8		15
Rhamnus frangula	Glossy buckthorn	Shrub		ECe <8		15
Rhaphiolepis indica	Indian hawthorn	Shrub		X		2
Rhaphiolepis indica	Indian hawthorn	Shrub			X	3
Rhaphiolepis indica	Indian hawthorn	Shrub		EC_W 1.5–3.		4
Rhaphiolepis indica	Indian hawthorn	Shrub			ECw 4–5.5	11
Rhaphiolepis indica	Indian hawthorn	Shrub		S		12
Rhaphiolepis indica	Indian hawthorn	Shrub			F/S	1, 18
Rhaphiolepis indica	Indian hawthorn	Shrub		ECe 4–6		10, 16
Rhaphiolepis umbellata		Shrub		S		12
Rhapidophyllum hystrix	Needle palm	Palm			ECw 4–5.5	11
Rhapis excelsa	Lady palm	Palm		X		2, 6
Rhapis excelsa	Lady palm	Palm		F/S		18
Rhapis excesla	Lady palm	Palm		ECw 2–4		11
Rhododendron "Mrs. Fred Sanders"		Shrub	S			12
Rhododendron "sweetheart supreme"		Shrub	S			12
Rhododendron indica		Shrub	S			12
Rhododendron indicum	Satsuki azalea	Shrub		X		2

(continued)

Salt Tolerance (continued)

Botanical name	Common name	Tree, shrub, groundcover, flower, palm, fruit, vine, cycad	Low tolerance	Moderate tolerance	High tolerance	Source
Rhoeo spathacea	Oyster plant	Groundcover		X		6
Rhoeo spathacea	Dwarf oyster plant	Groundcover		ECw 2–4		11
Rhus glabra	Scarlet or smooth sumac	Shrub		X		8
Rhus glabra	Smooth sumac	Shrub		ECe <6		15
Rhus glabra	Smooth sumac	Shrub		S		17
Rhus integrifolia	Lemonade berry	Shrub			X	3
Rhus integrifolia	Lemonade berry	Shrub			S	12
Rhus ovata	Sugar bush	Shrub			X	3
Rhus ovata	Sugar bush	Shrub			S	12
Rhus trilobata	Skunk bush	Shrub			X	8
Rhus trilobata	Skunkbush/squawbush	Shrub		ECe <8		15
Rhus typhina	Staghorn sumac	Shrub			S/F	1
Ribes spp.	Currant/gooseberry	Shrub/tree	X			14
Ricinus communis	Castorbean	Tree		X		14
Robinia neomexicana	New mexican locust	Shrub	ECe <4			15
Robinia pseudoacacia	Black locust	Tree			S/F	1
Robinia pseudoacacia	Black locust	Tree		ECe <8		15
Robinia pseudoacacia	Black losust	Tree			S	12, 17
Rosa	Rose	Shrub	Intolerant			15
Rosa banksiae	Lady Banks rose	Shrub			S/F	1
Rosa hybrid var. grenobile	Hybrid rose (Grenoble)	Shrub	EC_e <3			4
Rosa hybrida					S	12
Rosa rugosa	Rugosa rose	Shrub			S/F	1

Rosa rugosa	Rugosa rose	Shrub	ECe <2			15
Rosa spp. var. grenoble on Dr. Huey root	Rose	Shrub	ECw .75-1.5			12
Rosa spinosissima	Scotch rose	Shrub			S/F	1
Rosa spp.	Rose	Shrub		X		6
Rosa spp.		Shrub	EC_e 2.0			12
Rosa spp.	Rose	Shrub	F/S			18
Rosa spp.	Rose, cv. Grenoble	Shrub	ECe 2–3			10, 16
Rosa spp. var. Grenobie on Dr. Huey root	Rose	Shrub	EC_W .75–1.5			4
Rosa var. “grenoble”			S			12
Rosa woodsii	Wood’s rose	Shrub		X		8
Rosa woodsii	Wood’s rose	Shrub	ECe <4			15
Rosemarinus officinalis	Rosemary	Shrub		S	S	12
Rosemarinus officinalis “prostrata”	Prostrate/Dwarf rosemary	Shrub/ groundcover			S	12
Rosmarinus lockwoodi	Rosemary	Shrub		S		12
Rosmarinus lockwoodi	Rosemary	Shrub/ groundcover			EC_W >3	4, 12
Rosmarinus officinalis	Rosemary	Shrub			X	3
Rosmarinus officinalis	Rosemary	Groundcover			X	8
Rosmarinus officinalis	Rosemary	Groundcover		F/S		18
Rosmarinus officinalis	Rosemary	Groundcover		ECe 6–8		10, 16
Rosmarinus officinalis var. prostratus	Prostrate rosemary	Shrub/ groundcover			ECe >8	4
Roystonea elata	Royal palm	Palm		X		2, 6
Roystonea spp.	Royal palm	Palm			ECw 4–5.5	11
Rubus idaeus	Raspberry	Tree	X			14
Rubus spp.	Blackberry	Tree	X			14
Rubus ursinus	Boysenberry	Tree	X			14
Russelia equisetiformis	Coral fountain	Shrub		X		8

(continued)

Salt Tolerance (continued)

Botanical name	Common name	Tree, shrub, groundcover, flower, palm, fruit, vine, cycad	Low tolerance	Moderate tolerance	High tolerance	Source
Russelia equisetiformis	Firecracker plant	Groundcover			ECw 4–5.5	11
Russelia equisetiformis	Firecracker plant	Shrub		F/S		18
Sabal causiarum	Puerto-Rican hat	Palm			ECw 4–5.5	11
Sabal minor	Dwarf sabal	Palm			ECw 4–5.5	11
Sabal palmetto	Cabbage palm	Palm			X	2, 6
Sabal palmetto	Cabbage plam	Palm			ECw 4–5.5	11
Sabal palmetto	Cabbage palm	Palm		S		12
Sabal palmetto	Cabbage palm	Palm			F/S	18
Salix alba	Weeping willow	Tree			F	1
Salix alba var. tristis	“Tristis”–golden weeping willow	Tree		ECe <6		15
Salix alba var. vitellina	“Vitellina”–golden willow	Tree		ECe <6		15
Salix babylonica	Weeping willow	Tree			S	12
Salix exigua	Coyote willow	Shrub		X		8
Salix exigua	Coyote willow	Shrub	ECe <4			15
Salix matsudana	Corkscrew willow	Tree			F	1
Salix nigra	Black willow	Tree		ECe <6		15
Salix spp.	Willow	Tree		X		6, 8
Salix spp.	Willow	Tree		S		17
Salvia farinacea Benth.	Mealycup sage	Groundcover	F/S			18
Salvia spp.		Shrub		X		8
Salvia spp.	Sage	Annual, biennial, perennial			S	12

Sambucus callicarpa Greene	Coast red elderberry	Shrub		S	F	18
Sambucus canadensis	Elderberry	Shrub			S/F	1
Sanchezia speciosa	Sanchezia	Shrub	X			2
Sanchezia speciosa	Sanchezia	Shrub		X		6
Sanservieria spp.	Mother-in-law's tongue	Evergreen perennial			S	12
Sansevieria spp.	Snake plant	Groundcover		X		6
Sansevieria trifasciata	Mother-in-law's tongue	Subtropical		S		12
Sapium sebiferum roxb.	Chinese tallow tree	Tree			F/S	18
Sarcobatus vermiculatus	Black greasewood	Shrub			ECe <10	15
Sarcocornia spp. *(S. quinqueflora)*	Glassword, samphire				ECe >16	5
Sassafras albidum	Sassafras			F		7
Scaevola frutescens	Hawaiian seagrape	Shrub			ECw 4–5.5	11
Scaevola plumieri	Inkberry	Shrub			X	2, 6
Schefflera actinophylla harms	Schefflera, umbrella tree	Tree		F/S		18
Schefflera arboricola	Dwarf schefflera	Shrub		F/S		18
Schinus molle	California pepper	Tree			S	12
Schinus terebinthifolius	Brazilian pepper	Tree			X	9
Schinus terebinthifolius	Brazilian pepper	Tree			S	12
Sedum spp.	Sedum	Succulent groundcover		S		12
Senecio confusus	Mexican flame vine	Groundcover/vine		X		2, 6
Senecio confusus	Mexican flame vine	Groundcover/vine		ECw 2–4		11
Sequoia sempervirens var. aptos blue	Coast redwood	Tree	F/S			18
Sequoia sempervirens var. los altos	Coast redwood	Tree		F/S		18
Serenoa repens	Saw palmetto	Palm			ECw 4–5.5	11
Serenoa repens	Saw palmetto	Palm			X	2, 6
Serenoa repens		Palm		S		12
Serenoa repens	Saw palmetto	Palm			F/S	18

(continued)

Salt Tolerance (continued)

Botanical name	Common name	Tree, shrub, groundcover, flower, palm, fruit, vine, cycad	Low tolerance	Moderate tolerance	High tolerance	Source
Sesbania punicea	Rattle box	Shrub		X		2, 6
Sesuvium verrucosum	Sea purslane	Groundcover			X	8
Setcreasea pallida	Purple queen	Groundcover		X		2, 6
Setcreasea pallida	Purple queen	Groundcover		ECw 2–4		11
Shepherdia canadensia	Buffaloberry	Shrub		ECe <8		15
Shepherdia rotundifolia	Roundleaf buffaloberry	Shrub		ECe <6		15
Simmondsia chinensis	Jojoba	Shrub			X	3, 8, 14
Solandra guttata	Chalice vine	Vine	X			2, 6
Sophora japonica	Japanese pagoda tree	Tree			F	1
Sophora japonica	Japanese pagoda-tree	Tree			X	2, 3
Sophora japonica	Japanese pagoda tree	Tree		ECe <6		15
Sophora secundiflora	Texas mountain laurel	Tree		X		8
Sorbus aucuparia	European mountain-ash	Tree	Intolerant			15
Sorghum sudanense	Sundangrass	Grass		F/S		18
Spartium junceum	Spanish broom	Shrub			S	12
Spathodea campanulata	African tulip tree	Tree	X			2
Sphaeralcea coccinea	Scarlet globemallow	Flower		ECe 4–6		15
Spiraea bumalda	Bumalda Japanese spirea	Shrub			S/F	1
Spirea bumalda var. froebelii	Froebel's spirea	Shrub		ECe <6		15
Spirea japonica	Japanese spirea	Shrub			S/F	1
Spirea vanhouttei	Van houtte spirea	Shrub		ECe <8		15
Spirea vanhouttei					S	17
Sporobolus airoides	Alkali sacaton	Grass			X	3, 8

Sporobolus airoides	Alkali sacaton	Grass			ECe 14–18	15
Sporobolus airoides Torr.	Alkali sacaton	Grass			F/S	18
Sporobolus virginicus	Marine couch	Grass			ECe >16	5
Sporobolus wrightii	Big Sacaton	Grass			X	8
Stanley pinnata	Prince's plume	Flower		ECe 6–8		15
Stapelia gigantea	Starfish flower	Succulent		S		12
Stenotaphrum secundatum	St. Augustine grass	Grass			X	3
Stenotaphrum secundatum	St. Augustine grass	Grass		X		6
Stenotaphrum secundatum	St. Augustine grass	Grass		S	F	18
Stipa pulchra	Purple needlegrass				X	3
Strawberry	Strawberry	Fruit	S			12
Strelitzia reginae	Bird of paradise	Flowering perennial	EC_W .75–1.5			4
Strelitzia reginae	Bird of paradise	Shrub		S		12
Strelitzia reginae	Bird of paradise	Shrub		F/S		18
Suriana maritima	Baycedar					
	Shrub			X	2	
Suriana maritima	Baycedar	Shrub			X	6
Suriana maritima				S		12
Swietenia mahagoni	Mahogany	Tree			X	2, 6
Syagrus romanzoffiana	Queen palm	Palm		ECw 2–4		11
Syagrus romanzoffiana	Queen palm	Palm		F/S		18
Syagrus schizophylla	Arikury palm	Palm		ECw 2–4		11
Symphoricarpos albus	Snowberry	Shrub			S/F	1
Symphoricarpos albus	Snowberry	Shrub		ECe <8		15
Synadenium grantii	African milkbush	Shrub			X	2, 6
Syringa amurensis	Japanese tree lilac				S/F	7
Syringa amurensis japonica	Japanese tree lilac	Shrub		ECe <8		15
Syringa pekinensis	Peking lilac				S/F	7

(continued)

Salt Tolerance (continued)

Botanical name	Common name	Tree, shrub, groundcover, flower, palm, fruit, vine, cycad	Low tolerance	Moderate tolerance	High tolerance	Source
Syringa reticulate	Japanese tree lilac	Tree			S/F	1
Syringa vulgaris	Lilac	Shrub			S/F	1
Syringa vulgaris	Common lilac	Shrub		ECe <8		15
Syringa vulgaris	Lilac	Shrub		S		17
Syzygium jambos	Rose apple	Tree	X			14
Syzygium jambos alston	Rose apple	Tree	F/S			18
Syzygium paniculatum	Brush cherry				ECe >8	10, 16
Tabebui avellandae	Pink tabebuia	Tree		ECw 2–4		11
Tabebui umbellate	Yellow tabebuia	Tree		ECw 2–4		11
Tabebuia argentea	Tabebuia	Tree			X	2, 6
Tabernaemontana divaricata	Crape jasmine	Shrub	X			2
Tabernaemontana divaricata	Crape jasmine	Shrub		X		6
Tamarindus indica	Tamarind	Tree		X		6
Tamarix africana		Shrub/tree		S		12
Tamarix aphylla	Athel tree	Shrub/tree			S	12
Tamarix gallica	Manna plant–Tamarisk	Shrub		ECe <8		15
Tamarix parviflora		Shrub/tree			S	12
Tamarix pentandra	Five-stamen tamarix, tamarisk	Shrub			ECe <10	15
Tamarix ramosissima	Tamarisk	Shrub			S/F	1
Tamarix spp.	Tamarisk	Shrub/tree			X	9
Taxodium distichum	Bald cypress	Tree		X		6
Taxodium distichum	Baldcypress	Tree			S/F	1, 7
Taxus baccata	English yew	Shrub			S/F	1

Taxus cuspidate	Japanese yew	Shrub/tree			S/F	1
Taxus cuspidate	Japanese yew	Tree/tree	ECe <2			15
Tecoma stans	Yellow elder	Shrub	X			2
Tecoma stans	Yellow elder	Shrub		X		6
Tecomaria capensis	Cape honeysuckle	Vine			ECw 4–5.5	11
Tecomaria capensis	Cape honeysuckle	Vine			X	2, 6, 8
Tecomaria capensis	Cape honeysuckle	Vine			F/S	18
Terminalia catappa	Tropical almond	Tree			X	6
Tetrapanax papyriferus	Rice-paper plant	Shrub	X			2
Tetrapanax papyriferus	Rice-paper plant	Shrub		X		6
Tetrastigma harmandi				S		12
Teucrium chamaedrys	Germander	Shrub		S		12
Thespesia populnea	Seaside mahoe	Tree			X	6
Thevetia peruviana	Lucky nut	Shrub		X		2, 6
Thrinax microcarpa				S		12
Thrinax morrisil	Brittle thatch palm	Palm			X	2
Thrinax parviflora				S		12
Thrinax radiate	Thatch palm	Palm			ECw 4–5.5	11
Thrinax morrisii	Brittle thatch palm	Palm			X	6
Thuja occidentalis	Eastern arborvitae			S/F		7
Thuja occidentalis	American arborvitae	Shrub			S	12
Thuja occidentalis	American arborvitae	Tree		ECe <6		15
Thunbergia erecta	Thumbergia	Vine	S			12
Tibouchina urvilleana	Princess flower	Shrub	X			2
Tibouchina urvilleana	Princess flower	Shrub		X		6
Tigridia pavoinia	Tiger flower	Groundcover		S	F	18
Tilia americana	American linden	Tree	Intolerant			15
Tilia cordata	Littleleaf linden	Tree	Intolerant			15
Toumefortia spp.					S	12

(continued)

Salt Tolerance (continued)

Botanical name	Common name	Tree, shrub, groundcover, flower, palm, fruit, vine, cycad	Low tolerance	Moderate tolerance	High tolerance	Source
Tournefortia gnaphalodes	Sea lavender	Groundcover			X	6
Trachelospermum jasminoides	Star jasmine	Groundcover	EC_W .75–1.5			4, 12
Trachelospermum asiaticum	Dwarf confederate jasmine	Groundcover		ECw 2–4		11
Trachelospermum jasminoides	Star jasmine	Vine/groundcover		EC_e 3–8		4
Trachelospermum jasminoides	Confederate jasmine	Groundcover			X	2, 6
Trachelospermum jasminoides	Confederate jasmine	Vine			ECw 4–5.5	11
Trachelospermum jasminoides	Star jasmine	Vine/shrub		S		12
Trachelospermum jasminoides	Star jasmine	Shrub	S			12
Trachelospermum jasminoides	Star jasmine	Vine			F/S	18
Trachelospermum jasminoides	Star jasmine	Groundcover	ECe 1–2			10, 16
Trachycarpus fortunei	Windmill palm	Palm		X		2
Tradescantia pallida Hunt.	Purple queen	Groundcover			F/S	18
Tribulus terrestris	Caltrops	Groundcover			X	6
Tribulus terrestris					S	12
Trifolium fragiferum	Strawberry clover	Legume groundcover			ECe 8–12	15
Trifolium pretense	Red clover	Legume	ECe <4			15
Trifolium repens	White clower	Legume	ECe <4			15
Tsuga canadensis	Canadian hemlock	Tree	Intolerant			15
Tulbaghia violacea	Society garlic	Groundcover		ECw 2–4		11
Tulbaghia violacea	Society garlic	Groundcover		F/S		18
Ulmus americana	American elm	Tree	S			12
Ulmus americana	American elm	Tree	ECe <4			15

Ulmus americana	American elm	Tree		S		17
Ulmus parvifolia	Drake elm	Tree		ECw 2–4		11
Ulmus parvifolia	Chinese elm	Tree		F/S		18
Ulmus parvifolia var. drake	Chinese elm cv. drake	Tree		F/S		18
Ulmus pumila	Siberian elm	Tree			S	12
Ulmus pumila	Siberian elm	Tree		ECe <6		15
Ulmus regal	Regal elm	Tree			S/F	7
Uniola paniculata	Sea oats	Grass			X	6
Uniola paniculata	Sea oats	Grass			ECw 4–5.5	11
Uniola permiculata		Grass			S	12
Urechites lutea	Wild allamanda	Shrub		S		12
Vaccinium corymbosum	Highbush blueberry	Shrub			S/F	1
Veitchia merrillii	Christmas palm	Palm		X		2, 6
Veitchia spp.	Dwarf royal	Palm			ECw 4–5.5	11
Verbena spp.	Verbena	Groundcover	F/S			18
Viburnum opulus	High bush cranberry	Shrub	ECe <2			15
Viburnum dentatum	Arrowwod	Shrub			S/F	1
Viburnum odoratissimum	Sweet viburnum	Shrub		X		6
Viburnum odoratissimum	Sweet viburnum	Shrub			ECw 4–5.5	11
Viburnum odoratissimum	Sweet viburnum	Shrub		F/S		18
Viburnum opulus	European cranberry bush viburnum	Shrub			S/F	1
Viburnum spp. (others)	Viburnum	Shrub		X		6
Viburnum suspensum	Sandankwa viburnum	Shrub			X	6
Viburnum suspensum	Sandankwa viburnum	Shrub		F/S		18
Viburnum tinus var. robustum	Viburnum	Shrub	S			12
Viburnum tinus var. robustum		Shrub		EC_e 3–8		4
Viburnum tinus var. robustum	Viburnum	Shrub		ECw 1.5-3		4, 12
Viburnum tinus var. robustum	Laurustinus cv. Robustum	Shrub	ECe 3–4			10, 16

(continued)

Salt Tolerance (continued)

Botanical name	Common name	Tree, shrub, groundcover, flower, palm, fruit, vine, cycad	Low tolerance	Moderate tolerance	High tolerance	Source
Viburytim tinus var. robustum		Shrub	EC_e 3.0			12
Vinca major	Periwinkle	Groundcover			S	12
Vinca minor	Dwarf periwinkle	Groundcover	EC_W .75–1.5			4
Vinca minor	Dwarf funning myrtle	Vine groundcover	S			12
Vinca rosea	Vinca	Groundcover			ECw 4–5.5	11
Vitex agnus-castus	Monk's pepper tree	Tree			X	8
Vitex agnus-castus	Chaste tree	Tree		X		2, 6
Vitex angus-castus	Chaste tree	Tree			S/F	1
Vitex trifolia	Vitex	Shrub			ECw 4–5.5	11
Vitex trifolia var. variegata	Vitex	Shrub		X		2, 6
Vitis spp.	Grape	Tree		X		14
Washingtonia filifera	California fan palm	Palm			X	3
Washingtonia filifera	California fan palm	Palm			S	12
Washingtonia robusta	Mexican fan palm	Palm			X	6
Washingtonia robusta	Sky duster	Palm			ECw 4–5.5	11
Washingtonia robusta	Mexican fan palm	Palm			S	12
Washingtonia robusta	Mexican fan palm	Palm			F/S	18
Washingtonia spp.	Fan palm	Palm			X	2, 8
Wedelia trilobata	Wedelia	Groundcover			X	6
Wedelia trilobata	Wedelia	Groundcover		X		8
Wedelia trilobata	Wedelia	Groundcover			ECw 4–5.5	11
Woodwardia spp.	Chain fern species	Tree		S		12
Xylosma congestum	Xylosma	Shrub		EC_W 1.5–3		4

Xylosma congestum	Xylosma	Shrub	ECe 3–8		4
Xylosma congestum	Xylosma	Shrub		S	12
Xylosma congestum	Xylosma	Shrub	ECe 5.0		12
Xylosma congestum	Xylosma	Shrub	S		12
Xylosma congestum	Xylosma	Shrub	ECw 1.5-3		12
Xylosma congestum	Xylosma	Shrub	ECe 4–6		10, 16
Yucca aloifolia	Spanish bayonet	Shrub		X	6
Yucca aloifolia	Spanish bayonet	Shrub		S	12
Yucca aloifolia	Spanish bayonet	Shrub		F/S	18
Yucca brevifolia	Joshua tree	Tree		X	8
Yucca elata	Soaptree yucca	Shrub		X	8
Yucca elata	Yucca	Shrub	ECe 4–6		15
Yucca filamentosa		Shrub		S	12
Yucca glauca	Small soapweed	Shrub		X	8
Yucca glauca	Small soapweed	Shrub	ECe 4–6		15
Yucca smalliana	Adam’s needle	Shrub		X	2, 6
Yucca spp.	Yucca	Shrub		ECw 4–5.5	11
Yucca spp.	Yucca	Shrub		S	12
Zamia furfuracea	Mexican Zamia	Cycad		ECw 4–5.5	11
Zamia integrifolia	Coontie	Groundcover		X	2, 6
Zamia integrifolia	Coontie	Groundcover		F/S	18
Zamia pumila	Coontie	Groundcover		ECw 4–5.5	11
Zamia spp.			S		12
Zanthoxylum fagara		Shrub/tree	S		12
Zebrina pendula	Wandering jew	Groundcover	X		2, 6
Ziziphus jujuba	Chinese jujube	Tree	X		14
Ziziphus jujuba	Chinese jujube			X	3, 8, 9
Zoysia japonica	Zoysiagrass	Grass	F/S		18
Zoysia tenuifolia	Zoysia grass	Grass		X	3
Zoysia tenuifolia	Korean bump grass	Grass		S	12

Boron Tolerance

Botanical name	Common name	Tree, shrub, groundcover, flower, palm, fruit, vine, cycad	Reported threshold range (mg/l B)	General tolerance to boron			Source
				Low	Medium	High	
Abelia grandiflora	Glossy abelia	Shrub	0.5–1.0	X			10, 16
Abelia grandiflora	Glossy abelia	Shrub	1.0–2.0	X			18
Agrostis palustris	Creeping bentgrass	Grass	4.0–6.0			X	18
Agrostis tenuis	Highland bentgrass	Grass	4.0–6.0			X	18
Buxus microphylla	Japanese boxwood	Shrub	2.0–4.0			X	10, 16
Buxus microphylla	Japanese boxwood	Shrub	4.0–6.0			X	18
Calendula officinalis	Marigold	Flowering annual	1.0–2.0		X		10, 16
Callistemon citrinus	Bottlebrush	Shrub	2.0–4.0			X	10, 16
Callistemon citrinus	Bottlebrush	Shrub	4.0–6.0			X	18
Callistephus chinensis	China aster	Shrub	1.0–2.0		X		10, 16
Carissa grandiflora	Natal plum	Shrub	6.0–8.0			X	10, 16
Carissa grandiflora	Natal plum	Shrub	6.0–10.0			X	18
Citrus limon	Lemon	Tree	1.0–2.0	X			18
Citrus paradisi	Grapefruit	Tree	1.0–2.0	X			18
Citrus sinensis	Orange	Tree	1.0–2.0	X			18
Cordyline indivisa	Blue dracaena	Shrub	1.0–2.0		X		10, 16
Cordyline indivisa	Blue dracaena	Shrub	4.0–6.0		X		18
Cynodon dactylon	Bermudagrass	Grass	6.0–10.0			X	18
Delphinium spp.	Larkspur	Perennial	0.5–1.0	X			10, 16
Dianthus caryophyllus	Carnation Dianthus	Flowering annual	2.0–4.0			X	10, 16
Elaeagnus pungens	Thorny elaeagnus	Shrub	<0.5	X			10, 16
Elaeagnus pungens	Thorny elaeagnus	Shrub	4.0–6.0		X		18
Eschscholzia californica	California poppy	Perennial	2.0–4.0			X	10, 16

Euonymus japonica	Spindle tree	Shrub	<0.5	X			10, 16
Euonymus japonica	Spindle tree	Shrub	4.0–6.0		X		18
Euphorbia pulcherrima	Poinsettia	Perennial	1.0–2.0		X		10, 16
Feijoa sellowiana	Pineapple guava	Ornamental	<0.5	X			10, 16
Feijoa sellowiana	Pineapple guava	Shrub	4.0–6.0		X		18
Festuca arundinacea	Tall fescue	Grass	6.0–10.0			X	18
Ficus carica	Fig kadota	Tree	1.0–2.0	X			18
Gardenia spp.	Gardenia	Shrub	1.0–2.0		X		10, 16
Gladiolus spp.	Gladiolus	Shrub	1.0–2.0		X		10, 16
Hibiscus rosa–sinensis	Chinese hibiscus	Shrub	2.0–4.0			X	10, 16
Ilex cornuta	Chinese holly	Shrub	<0.5	X			10, 16
Ilex cornuta	Chinese holly	Shrub	1.0–2.0	X			18
Juglans regia	Walnut	Tree	1.0–2.0	X			18
Juniperus chinensis	Juniper	Shrub	<0.5	X			10, 16
Juniperus chinensis	Juniper	Shrub	1.0–2.0	X			18
Lantana camara	Yellow sage	Shrub	<0.5	X			10, 16
Lantana camara	Yellow sage	Shrub	1.0–2.0	X			18
Lathyrus odoratus	Sweet pea	Vine	2.0–4.0			X	10, 16
Leucophyllum frutescens	Ceniza	Shrub	1.0–2.0		X		10, 16
Leucophyllum frutescens	Texas ranger, ceniza	Shrub	6.0–10.0			X	18
Ligustrum japonicum	Wax-leaf privet	Shrub	<0.5	X			10, 16
Ligustrum japonicum	Wax-leaf privet	Shrub	6.0–10.0			X	18
Lolium perenne	Perennial ryegrass	Grass	6.0–10.0			X	18
Mahonia aquifolium	Oregon grape	Shrub	<0.5	X			10, 16
Mahonia aquifolium	Oregon grape	Shrub	1.0–2.0			X	18
Nerium oleander	Oleander	Shrub	2.0–4.0			X	10, 16
Nerium oleander	Oleander	Shrub	6.0–10.0	X		X	18
Oxalis bowiei	Oxalis	Perennial	6.0–8.0			X	10, 16
Pelargonium hortorum	Geranium	Flowering perennial	0.5–1.0	X			10, 16

(continued)

Boron Tolerance (continued)

Botanical name	Common name	Tree, shrub, groundcover, flower, palm, fruit, vine, cycad	Reported threshold range (mg/l B)	General tolerance to boron			Source
				Low	Medium	High	
Persea americana	Avocado	Tree	1.0–2.0	X			18
Photinia fraseri	Photinia	Shrub	<0.5	X			10
Photinia fraseri	Photinia	Shrub	4.0–6.0		X		18
Pittosporum tobira	Japanese pittosporum	Shrub	<0.5	X			10, 16
Pittosporum tobira	Japanese pittosporum	Shrub	1.0–2.0	X			18
Platycladus orientalis	Oriental arborvita	Shrub	0.5–1.0	X			10, 16
Platycladus orientalis	oriental arbovitae	Shrub	4.0–6.0		X		18
Poa pratensis	Kentucky bluegrass	Grass	1.0–2.0	X			18
Podocarpus macrophyllus	Southern yew	Shrub	1.0–2.0		X		10, 16
Podocarpus macrophyllus	Southern yew	Shrub	6.0–10.0			X	18
Prunus armeniaca	Apricot	Tree	1.0–2.0	X			18
Prunus domestica	Plum	Tree	1.0–2.0	X			18

Puccinellia distans	Puccinellia	Grass	6.0–10.0			X	18
Raphiolepis indica	Indian hawthorn	Shrub	6.0–8.0			X	10, 16
Raphiolepis indica	Indian hawthorn	Shrub	6.0–10.0			X	18
Rosmarinus officinalis	Rosemary	Shrub	0.5–1.0	X			10, 16
Rosmarinus officinalis	Rosemary	Shrub	4.0–6.0		X		18
Sequoia sempervirens	Coast redwood	Tree	1.0–2.0	X			18
Syzygium paniculatum	Brush cherry	Shrub	6.0–10.0			X	18
Syzygium paniculatum	Brush cherry	Tree	1.0–2.0		X		10, 16
Ulmus americana	American elm	Tree	<0.5	X			10, 16
Viburnum tinus	Laurustinus	Shrub	<0.5	X			10, 16
Viburnum tinus	Laurustinus	Shrub	4.0–6.0		X		18
Viola odorata	Violet	Flowering annual	0.5–1.0	X			10, 16
Viola tricolor	Pansy	Flowering annual	0.5–1.0	X			10
Xylosma congestum	Xylosma	Shrub	<0.5	X			10, 16
Xylosma congestum	Xylosma	Shrub	1.0–2.0	X			18
Zinnia elegans	Zinnia	Flowering annual	0.5–1.0	X			10
Zoysia japonica	Japanese lawngrass	Grass	6.0–10.0			X	18

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FIGURE 1 Aerial photography used to monitor irrigation uniformity and/or salinity stress. (Photo courtesy of Angeles National Golf Club, Sunland, CA.)

FIGURE 2 Poor distribution uniformity increases difficulty of managing salts and uniformly leaching them beyond the root zone (Southern CA).

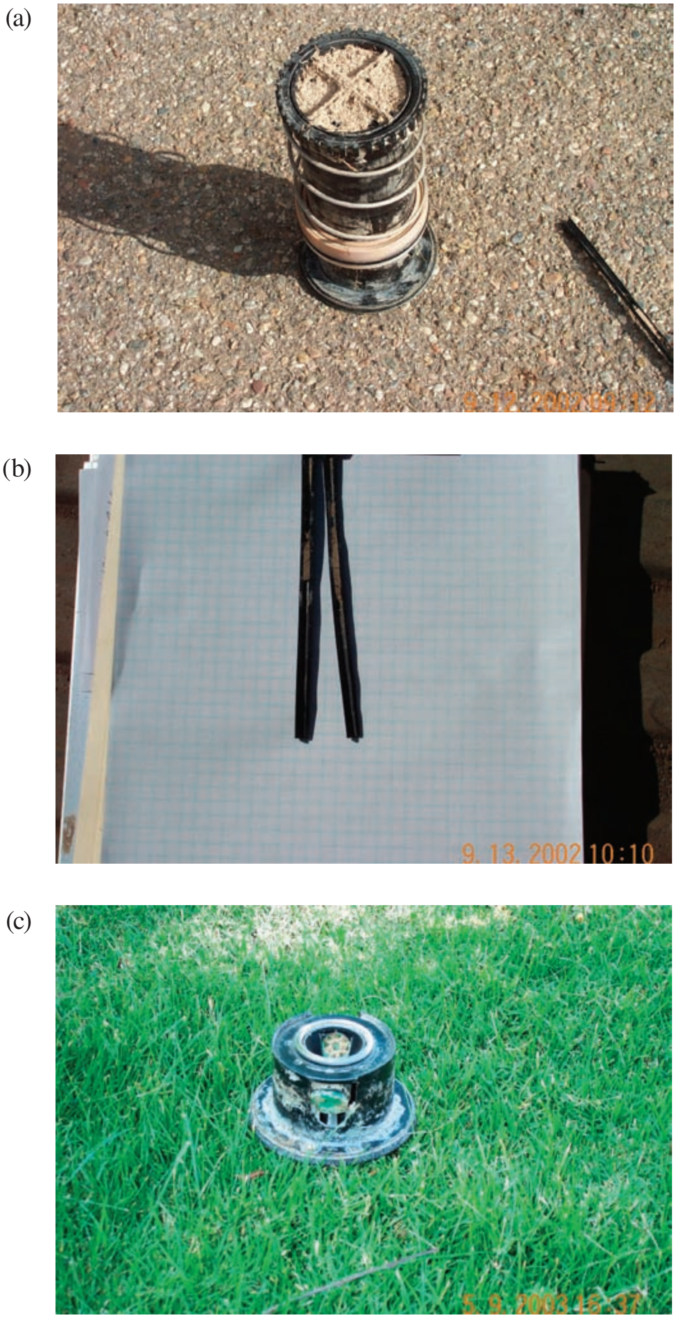

FIGURE 3 Suspended solids (sand, organic, and precipitants) clog a variety of irrigation components: (a) sand and organics in sprinkler gear drive screens, (b) precipitants in hydraulic actuator tubing (c) and organic in sprinkler nozzles and nozzle vanes (Salt Lake City, UT, and Southern CA).

FIGURE 4 Accelerated corrosion by chlorine gas vapors resulting from recycled water being delivered directly into wet well of the pump station. Highly chlorinated recycled water should be delivered into open reservoirs to allow the corrosive vapors to release into the atmosphere (Tampa, FL).

FIGURE 5 Population increase, drought, and climate change will force increased use of alternative irrigation sources. A central California storage and recreational impoundment, normally at 75% capacity in June is at 50% after a dry winter season in 2003.

FIGURE 6 Before and after response from leaching Tifway II hybrid bermudagrass fairways using recycled water (Southern CA).

FIGURE 7 Residue on pine needles contacted by overhead spray of recycled water containing high bicarbonate and calcium. Background—drip irrigated tree shows no residue (Las Vegas, NV).

FIGURE 8 Salt crust and sodic soil conditions of common bermudagrass fairway irrigated with recycled water with varying moderate to high total salts, sodium, chloride, and SAR (Central TX).

FIGURE 9 Chloride leaf tip burn of ornamental plants irrigated with recycled water containing moderate levels of total salts and high sodium (Guadalajara, Mexico).

FIGURE 10 Reddish brown coloration typical of foliar absorbed salts. Salts applied by overhead spray irrigation of saline groundwater containing moderate total salts and high sodium (Denver, CO).

FIGURE 11 Yellow and necrotic pine needles typical of root absorbed salts. Site has high groundwater table containing high total salts, high sodium, and high chloride (Southern CA).

FIGURE 12 Premature defoliation of trees in foreground are irrigated by surface water with TDS varying seasonally from 500 ppm during spring (high flow) to 5500 ppm TDS during summer (low flow) and dominated by high sodium and chloride. Trees in background do not receive irrigation (Toronto, Canada).

FIGURE 13 Seashore paspalum taking over a boggy saline area of high groundwater that remains saturated with soil ECe measuring 22.1 dS/m at the surface (Southern CA).

FIGURE 14 Close up of putting green irrigated with moderately saline recycled water. More salt tolerant creeping bentgrass has established in aeration holes while salt sensitive *Poa annua* has failed in-between where the white salt crust is seen (Southern CA).

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