Fairbanks Ranch Country Club (Rancho Santa Fe, California) successfully demonstrates that, with careful maintenance practices, a quality golf course can be achieved despite having been built on a salt lake bed.

Understanding Water Quality and Guidelines to Management

An overview of challenges for water usage on golf courses for the 21st century.

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WITH GLOBAL demand for fresh or potable water doubling every 20 years, competition for this valuable resource will increase in the 21st century. Potable water reserves comprise only 2.5% of the total available global water supply, with groundwater reserves averaging about 1.7% of that total. For groundwater, only 45% is fresh water, and this source supplies 30% of the human and industrial users, with the remainder from surface water resources. This potable water dilemma will result in turfgrass managers having no choice but to irrigate with recycled and other non-potable alternative water resources of lesser quality that contain increased levels of dissolved salts.

Several overriding issues will change 21st-century turfgrass management strategies. A primary concern is water quality and the consistency of that water quality. Non-potable water can be referred to as brackish, effluent, recycled, wastewater, reclaimed, regenerate, or grey water. Water released from sewage plants can vary from primary to secondary to tertiary treatment levels, and quality will be partially dictated by the 1) quality of the original source prior to potable use, 2) salts and solids added by first-time users (e.g., discharges from factories or byproducts of other manufacturing facilities), and 3) contamination of salts and solids added via surface runoff into treatment facilities.

Quality factors include the presence of:

1. Solids (sand-silt-clay and organic particles) that potentially can clog the irrigation delivery system, plug soil micropores, and cause excess wear on sprinkler nozzles and pumping components.

2. Biological (nematodes, weed seeds, algae, fungal spores) and chemical

(pesticides, fertilizers, other salt residues, pollutants) materials that can affect turfgrass performance.

3. Salt-related problems such as total salinity, sodium permeability hazard (impact on soil structure), specific toxic ions, and nutrient balance.

Water quality variability is site-specific and can change seasonally or, in extreme cases, on a daily basis. The focus of this article is on assessment of water for these salt-related problems.

Water Quality Assessment

Water quality assessment is one of the most confusing and complex problems facing turf managers. The types and quantities of chemicals that are applied to the turf system through irrigation water have a dramatic influence on soil chemical/physical aspects and turf performance. Variable levels of salts and extreme environmental conditions (high prolonged heat and humidity, severe drought, and traffic) magnify water quality problems. Water samples submitted to laboratories for analysis often come back with data in confusing units or with no reference points. Do you have a problem with the water on your course? How do you assess the data? What are the critical points to look for? How can you adjust your management to prevent a potential future problem? These are all valid questions that will be addressed in this article.

Problems

Four critical problem categories must be considered from the data presented in a water analysis report: *total salt content, sodium permeability hazard, specific ion toxicity,* and *critical nutrient levels.* Each category is a salt problem but differs from the other three problem areas in specific effects on soil traits and turf performance. In addition to these salt problems, inorganic or organic suspended solids need to be consistent. The four problem areas can result in many different combinations and degrees of stress.

High total salts or total salinity concentrations will often reflect the potential for a saline soil problem to develop. Saline conditions inhibit water uptake by turfgrasses and cause a salt-induced drought stress. This is the most common salt-related water issue that occurs and must be managed on golf courses. Total salinity problems are site-specific and must be assessed on that basis, and management strategies involving grass selection, cultivation, and irrigation scheduling must be developed accordingly.

Continuous use of saline water sources without leaching the soils can lead to serious salt accumulations and ultimately turfgrass decline.

High sodium concentrations, especially in conjunction with high bicarbonates and relatively low calcium (Ca^{+2}) and magnesium (Mg^{+2}) levels identified in the water analysis, can potentially cause a *sodium permeability hazard.* This hazard must be assessed, and high values have the potential for developing serious soil structural deterioration and water infiltration problems. Assessment and management strategies must be 1) based on site-specific soil and water conditions and 2) aggressively monitored and frequently adjusted to address specific constraints involving grass selection, amendments to the water and/or the soil, regular cultivation, and careful irrigation scheduling (leaching).

Specific toxic ions must be assessed as to their level of toxicity and their potential impact on the turf root system as well as foliar damage. Finally, *nutrient load* in the irrigation water is a fourth problem that can contribute a substantial amount of fertilizer to the turfgrass and can often induce deficiencies of other critical nutrients in salt-challenged turfgrass systems.

Calculations and Unit Conversions

Development of an effective management program starts with collection of a representative water sample and submission of that sample to a reputable analytical laboratory for analysis. What data should you ask for, and in what specific units should these data be presented?

Quality Factor	*Preferred Units*
Water	pH
Carbonates and Bicarbonates	mg/L, ppm, or meq L^{-1}
Total Salinity (impact on plant growth from higher total salts)	
Electrical conductivity (EC)	dS/m
Total dissolved salts (TDS)	ppm
Ion Toxicity (impact on root and foliar contact)	
Na	meq/L and ppm
Cl	ppm
B	ppm
Na Permeability Hazard (impact on soil structure)	
Sodium adsorption ratio (SAR)	meq/L
Adjusted SAR (adj SAR)	meq/L
Residual sodium carbonate	meq/L
Nutrients	ppm and meq L^{-1}

Often, the laboratory analysis comes back with confusing units for some of the data values. The conversion factors can be found in Table 1.

Table 1. Conversion factors

		To convert ppm to meq/L, multiply by:	To convert meq/L to ppm, multiply by:
Sodium	Na^{+1}	0.043	23.0
Calcium	Ca^{+2}	0.050	20.0
Magnesium	Mg^{+2}	0.083	12.2
Chloride	Cl^{-}	0.029	35.4
Potassium	K^{+1}	0.026	39.0
Sulfate	SO_4^{-2}	0.021	48.0
Carbonate	CO_3^{-2}	0.033	30.0
Bicarbonate	HCO_3^{-}	0.016	61.0

Note: 1 mg L^{-1} = 1 ppm

For example, to convert 220 mg L^{-1} Na^{+} to meq L^{-1}:
(220 mg L^{-1}) × (0.043) = 9.46 meq L^{-1} Na^{+}

	Convert ECw	Multiply by:
Electrical Conductivity of Water	mSm^{-1} to dSm^{-1}	0.01
	dSm^{-1} to mSm^{-1}	100
	mScm^{-1} to mSm^{-1}	100
	mSm^{-1} to ppm	6.4
	dSm^{-1} to ppm	640
	mScm^{-1} to ppm	640
	ppm to dSm^{-1}	0.0016

Other Conversion Factors:

1 mmhos cm^{-1} = 1 dSm^{-1} = 1,000 umhos cm^{-1} = 0.1 Sm^{-1}
1 umhos cm^{-1} = 0.001 dSm^{-1} = 0.001 mmhos cm^{-1}
1 ppm = 1 mg L^{-1} (solution) = 1 mg kg^{-1} (soil)
1% concentration = 10,000 ppm
1 mmolc L^{-1} = 1 meq L^{-1}
1 ECw (dSm^{-1}) = 640 ppm (TDS = Total Dissolved Salts)
TDS (ppm) = ECw × 640; TDS (lb./ac.-ft.) ≈ TDS (ppm × 2.72)
ppm = grains per gallon* × 17.2
(grains/gallon is still used by domestic effluent water purveyors to report hardness)
Sum of cations and anions (meq L^{-1}) ≈ EC (dSm^{-1}) × 10

Total Salinity

The most common salt problem on turf is accumulation of high total salts leading to a saline soil condition. Saline soils can cause salt-induced or physiological drought. Turfgrass symptoms include reduced growth, discoloration, wilting, leaf curling, and eventually leaf firing or desiccation. Drought or water stress symptoms can occur a) if salt from irrigation water is allowed to accumulate within the rootzone, b) if accumulated salts in the rootzone (previously added by salt-laden irrigation water) rise up into the active rootzone by capillary action, or c) when both occur simultaneously during hot, dry periods.

In USGA greens, the perched water table zone, located below the normal rootzone, is an area of potential salt accumulation where salts could rise by capillary action into the rootzone during high ET periods. To avoid capillary rise, sufficient surface water must be applied to break tension in a USGA-type green and periodically flush out excess salts. In a native soil, a net downward movement of salts beyond the active turf rooting area must be maintained by ample irrigation.

Excess salts inhibit water uptake by turfgrass roots and cause wilting. Salts literally prevent water uptake even in a moist soil, and the turf can change color rapidly (sometimes overnight) to a yellowish brown and purplish color, depending on turf species. Salt crystals may actually form on the soil surface, especially in bare-soil areas. Salts that contribute to total salinity include calcium, potassium, magnesium, sodium, chloride, sulfate, nitrate, ammonium, and bicarbonate.

Electrical conductivity (ECw) is the extent to which water conducts electricity, which is directly proportional to the concentration of dissolved salts. ECw is used to estimate the total dissolved salts (TDS) in water (TDS ÷ 640 = ECw). TDS will occasionally be referred to as total soluble salts (TSS) or total dissolved solids (TDS) by analytical laboratories. Irrigation water containing high total salts such as sewage effluent can lead to saline soil conditions and poor turfgrass performance. Most sewage effluent ranges from 200 to 3,000 ppm TDS or ECw = 0.30 – 4.7 dSm^{-1} (Feigin et al., 1991).

Irrigation quantity, leaching duration and frequency, drainage requirements, and turf species/cultivar selection requirements increase as ECw or TDS increases (Table 2). Water quality monitoring must be used to predict future soil salinity problems and to adjust management strategies to minimize deterioration of turfgrass performance.

Management Strategies for Total Salinity

Indicators of total salinity impact on turfgrass growth will be ECw and TDS, and both measurements are interrelated. When a water analysis indicates that total soluble salts (> 0.75d Sm^{-1} ECw or > 500 ppm TDS) are the primary problem, *irrigation scheduling* and *cultivation plus leaching* become the predominate management options. Sodium (Na), chlorine (Cl), and boron (B) levels may be high, and if ECw > 1.50 dSm^{-1} and TDS > 1,000 ppm, selection of salt-tolerant turf species and specific cultivars within that species becomes increasingly important.

Drainage requirements also increase since leaching frequency and the water quantity needed for leaching escalates as the total salinity hazard increases. Leaching directly affects nutrient availability, particularly with mobile ions such as potassium (K), magnesium (Mg^{+2}), nitrate (NO_3^{-}), iron (Fe), and manganese (Mn). Fertilizer programs must be adjusted accordingly, and this topic will be discussed in the section on "Nutrient Variability."

The success or failure of the management strategy for dealing with high total

Excess suspended solids can plug water-conducting pores at the soil surface. Low-quality effluent irrigation sources are notorious for containing high loads of suspended organic solids.

Table 2. Total salinity hazard classification guidelines for variable quality irrigation water based on ECw and TDS (Carrow and Duncan, 1998)

Salinity Hazard Class	ECw (dSm^{-1})	TDS (ppm)	Management Requirements
Low	< 0.75	< 500	No detrimental effects expected
Medium	0.75 - 1.50	500 - 1,000	Moderate leaching to prevent salt accumulation
High	1.5 - 3.00	1,000 - 2,000	Turf species/cultivar selection, good irrigation, leaching, drainage
Very High	> 3.00	> 2,000	Most salt-tolerant cultivars, excellent drainage, frequent leaching, intensive management

salts is predicated on one key aspect of turf management, namely *water management*. In particular, good irrigation scheduling and adequate volumes that promote leaching are essential. Cultivation is an integral part of regular management in salt-affected environments, encompassing both deep aeration (8-12 inches) once or twice each year and shallow aeration (3-6 inches) as needed, depending on soil texture. Infiltration, percolation, and drainage will dictate how effectively total salts are moved away from the turfgrass root system and are not allowed to build up in subsoil layers where they could potentially rise to the rootzone during periods of inadequate leaching.

Theoretically, sandy soil profiles are easier to leach than heavier clay soils. However, both soil types often require regularly scheduled deep and shallow cultivation followed by adequate leaching to move the excess salts downward. If aeration is regularly performed, but irrigation is scheduled for only 5-10 minutes daily (i.e., light, frequent irrigation), salts can move back up through the soil micropores by capillary action, form a concentrated layer in the rootzone, and limit water uptake or even kill the turf root system. This usually occurs when evapotranspiration (ET) exceeds the amount of water applied to the turf during prolonged high temperature or windy conditions. Also, if large diameter aeration holes are not backfilled with topdressing sand prior to leaching, large volumes of water can run into the holes and beyond the surface, while leaving behind a salt-laden zone between holes.

High salt levels from even low volume total salt applications (TDS = 600-800 ppm) can build up in subsoil layers over time in sand-based greens during prolonged dry periods. These salt layers usually can be found at depths corresponding to how deep the irrigation water percolated into the sand profile. If only a low volume (< 0.50 inch) of irrigation water is applied, the salt accumulation zone is often located just below the root system at about 6-8 inches depth, unless total salts are leached deeper by a periodic heavy flushing from rainfall or irrigation. Any zone of salt accumulation on sandy soils should be at least 12-16 inches deep, and on fine-textured soils, at least 16-24 inches deep to limit a possible rapid capillary rise of salts when irrigation volume is not sufficient for net leaching.

At shallower depths, salts can rise within two or three days through capillary action and evapotranspiration during extreme hot and prolonged dry, windy conditions. The salts may have been added through irrigation water at 600-800 ppm levels (which is normally not a problem), but the subsurface salt accumulation zone will be at much higher concentrations that can quickly desiccate and kill the turfgrass root system. Thus, net downward water movement is essential to avoid salt layers near the turfgrass rootzone. A heavy nighttime leaching program followed by an afternoon hand-watering of localized dry areas on sand-based greens may be necessary to prevent turfgrass collapse when temperatures exceed 90-95°F for one to two weeks or more. *The rule of thumb to minimize salt accumulation is to increase water volume applied by 12.5% for each 640 ppm rise in total dissolved salts (TDS) in the irrigation water.*

Additionally, high total salts can have a growth regulator effect on turfgrasses because water uptake is limited. Regardless of the level of salt tolerance, all turfgrass cultivars will experience some growth reduction from high salt accumulations. The most salt-tolerant cultivars (for example, seashore paspalum cultivars Sea Isle 1, Sea Isle 2000) have high inherent growth rates so that they maintain adequate growth for recovery from injury and for long-term performance when under persistent salt stress. Less salt-tolerant cultivars can be significantly affected when other stresses such as low mowing height (< ¼ inch), high salt-index soluble fertilizers, shade, and excessive traffic/wear/compaction negatively affect long-term turf performance. Sites continually irrigated with salt-laden irrigation water should restrict cart traffic on the golf course to cart paths only, especially on turf species and cultivars with low salt tolerance.

Sodium Permeability Hazard

The sodium concentration in conjunction with the quantity and type of other salts in irrigation water have a major influence on a) water infiltration into and percolation through soil profiles by directly affecting soil permeability, b) the leaching fraction, or the quantity of water required to leach excessive Na or other salts, c) whether the water should be treated prior to application to enhance infiltration/percolation into the soil, and d) the options available to adjust management scenarios to maintain or enhance turf performance. Two key water component relationships must be determined before management decisions can be made: Sodium adsorption ratio and bicarbonate/carbonate levels.

The SARw, or sodium adsorption ratio, is used to assess the sodium status and permeability hazard (Table 3). Sodium, calcium (Ca), and magnesium concentrations (in meq L^{-1}) are used to compute SARw:

$$\mathrm{SARw} = \frac{\mathrm{Na}}{\sqrt{(\mathrm{Ca} + \mathrm{Mg})/2}}$$

When bicarbonate (HCO_3^-) and carbonate (CO_3^{-2}) concentrations are > 120 and 15 ppm, respectively, calculate adj SARw and *residual sodium carbonate* (RSC) according to Table 4.

Table 4. Calculation for adjusted sodium adsorption ratio and residual sodium carbonate

adj SAR or adjusted sodium adsorption ratio

a) adj SARw = SAR [1 + 8.4 – pH_c]
(refer to Carrow and Duncan 1998, and Ayers and Westcot 1985)

b) adj SARw is also calculated by the Hanson et al. (1999) method

RSC or residual sodium carbonate

RSC = (CO_3 + HCO_3) – (Ca + Mg), in meq L^{-1}

Table 3. Sodium permeability hazard and specific toxic ion reference points
(Adapted from Harivandi and Beard, 1998; Carrow and Duncan, 1998)

Irrigation Water Components		**Degree of Problem**		
Sodium permeability hazard (Na^+-induced soil structural deterioration, and low water/oxygen permeability)				
SARw or adj SARw (sodium adsorption ratio) by clay type (ppm)				
		Low	**Moderate**	**High**
Clay type unknown		< 10	10 - 18	> 18
Montmorillonite (2:1)*		< 6	6 - 9	> 9
Illite (2:1)*		< 8	8 - 16	> 16
Kaolinite (1:1)**		< 16	16 - 24	> 24
Sands with ECw > 1.5 dSm^{-1}		< 10	10 - 18	> 18
Sands with ECw < 1.5 dSm^{-1}		< 6	6 - 9	> 9
RSC (residual sodium carbonate)		< 1.25	1.25 - 2.50	> 2.50
Specific Toxic Ions				
Sodium Content		**Low**	**Moderate**	**High**
Toxicity to roots	SARw	< 3	3 - 9	> 9
	ppm	< 70	70 - 210	> 210
Toxicity to leaves	meq L^{-1}	< 3	> 3	
	ppm	< 70	> 70	
Chloride Content				
Toxicity to roots	meq L^{-1}	< 2	2 - 10	> 10
	ppm	< 70	70 - 355	> 355
Toxicity to leaves	meq L^{-1}	< 3	> 3	
	ppm	< 100	> 100	
Residual Chlorine (Cl_2)	ppm	< 1	1 - 5	> 5
Boron toxicity on roots	ppm	< 0.7	0.7 - 3.0	>3.0
Bicarbonate content	meq L^{-1}	< 1.5	1.5 - 8.5	> 8.5
	ppm	< 90	90 - 500	> 500

*2:1 clays are shrink-swell clays
**1:1 clays do not shrink (crack) on drying or swell on wetting
Other 1:1 types are Fe/Al oxides and allophanes

Sodic and Saline-Sodic Soil Formation

The relative quantities of soil Ca, Mg, and Na are extremely important. Calcium is the primary ion that stabilizes soil structure. Magnesium offers secondary structural stability. When excess Na (> 200 ppm) is applied through irrigation water, the Na content builds up over time and eventually will displace the Ca^{+2} ions that are the building blocks and that enhance the structural integrity of the clay fraction in the soil profile. This "push-and-shove" relationship, which is dominated by a larger Na^+ ion with a weaker force or charge for holding clay particles together, eventually results in soil structure breakdown. The result is a sodic soil. It is sometimes referred to as *black alkali*, since the excess sodium precipitates out the organic matter fraction in the soil, which in turn rises to the soil surface. The deposit on the surface is black with a slick, oily appearance. Where excess Na^+ and high total salts are both present, it is called a saline-sodic soil and is characterized by having both white salt deposits and black decomposed organic matter deposits on the surface.

Very few turfgrasses can survive these sodium hazard conditions since the soil structural breakdown results in a sealed soil with little or no water permeability. Classic symptoms on golf courses are heavily compacted areas, areas with long-standing puddles, and dead turf. A secondary symptom can be surface algae and black layer formation caused by the constant moist conditions and the lack of oxygen in the turf root system. Sodium adsorption ratios (SAR or adj SAR) exceeding 6 meq L^{-1} indicate that the Na^+ levels are high enough to cause structural deterioration in some soils.

A more subtle symptom often occurs in sand-based greens or on fairways and tees where clay soil profiles have been capped with sand. On greens, short duration (5-10 minute) daily irrigation scheduling when using high Na irrigation water may eventually result in a layer forming in the sand profile. This layer normally will be as deep as the water percolates downward each day (usually somewhere between 4 and 12 inches deep). While sands often contain few clay colloids, Na^+ can cause organic matter of colloidal size to migrate to this depth and start to seal the soil pores, eventually leading to black layer formation. High sulfur or sulfate concentrations in the water will enhance the process.

The salts and excess Na congregate in this zone and, with normal evaporation, the salt concentration will gradually increase. When evapotranspiration exceeds irrigation, coupled with prolonged hot, dry, and/or windy conditions, these concentrated salts will move back up into the turf rootzone, cause salt-induced drought, root dessication, and may even kill the turf. The turfgrass will turn purple or yellow to yellowish-brown to brown, usually within 24 hours, depending on the turf species.

A similar scenario can develop on fairways, roughs, or tees where sand (4-10 inches in most cases) is used to cap a heavy clay soil. The high Na irrigation water will usually result in a concentration of excess Na ions at the interface of the sand cap and clay. Unless the excess Na^+ moves laterally under the sand cap (drainage lines can help), it will eventually break down the clay structure and the subsoil will seal off. Symptoms during wet periods will be continuously damp, boggy areas with possible standing water. In dry periods, salts may rise into the rootzone.

The type of clay soil has a profound influence on the amount of Na that will eventually cause soil structural deterioration. Soils that crack open when they dry (montmorillonite, illite) tolerate a much lower Na concentration before soil structural deterioration, mainly because Na^+ easily enters between clay platelets, and because of the increased exposure of the clay particle exchange sites to excess Na as these soils expand and contract. Soils that have non-swelling clays (kaolinite, Fe/Al oxides) tolerate much higher Na concentrations before structural breakdown because the Na ion has more difficulty migrating into these non-expanding soils and in-between clay platelets.

Regardless of clay type, once a soil has deteriorated into a sodic condition, turning this condition around will require a program of aeration, application of Ca^{+2} source amendments, high-volume leaching, and careful turfgrass selection. Calcium amendments should be applied immediately following aeration to avoid acceleration of permeability problems in the soil profile at the depth of the aeration treatments. This scenario is the most complex and difficult salt stress to overcome and may take several months to several years to accomplish. With poor quality, salt-laden water as the only irrigation source, management at a high level will have to be constant to prevent the sodic soil condition from reoccurring.

Bicarbonate and Carbonate Influence

Another set of water data factors is also important in influencing Na^+ activity — namely, relative levels of bicarbonates (HCO_3^-) and carbonates (CO_3^{-2}) in relation to Ca^{+2} and Mg^{+2} concentrations (Tables 3 and 4). When high HCO_3^- and CO_3^{-2} levels (> 120 and 15 ppm, respectively) are applied through the irrigation water, these ions react with Ca^{+2} and Mg^{+2} to form insoluble $CaCO_3$ and $MgCO_3$. The decreased levels of Ca^{+2} and Mg^{+2} from this reaction process reduce the amount of these ions that can compete with Na^+ for exchange sites on the clay particles. As the Na^+ content increases through daily irrigation applications, the Na^+ dominates these exchange sites and causes soil structural breakdown. The soil becomes sealed, water does not percolate into the soil profiles, and the turf eventually dies. The insoluble Ca/Mg carbonate forms precipitate out into the soil, and remaining bicarbonates reduce the effectiveness of gypsum or sulfur treatments to the soil.

Acid injection and sulfur burners can be used to treat water with excess bicarbonate levels. Acidifying irrigation water to a pH of 6.5 reduces bicarbonates by approximately 50%.

The sodium permeability hazard in irrigation water is usually assessed by SARw values when HCO_3^- is < 120 ppm and CO_3^{-2} is < 15 ppm. The SARw value incorporates the influence of Na^+, Ca^{+2}, and Mg^{+2} concentrations. Above these levels, adj SAR is preferred since these values incorporate the influence of HCO_3^- and CO_3^{-2}.

Residual sodium carbonates (RSC) also are used to assess the sodium permeability hazard, and this value includes the influence of HCO_3^- and CO_3^{-2} as compared to Ca^{+2} and Mg^{+2} (Tables 3 and 4). As a general rule, whenever HCO_3^- exceeds 120 ppm, it is a good idea to calculate RSC. *It is not the absolute levels of HCO_3^- and CO_3^{-2} present in the irrigation water that are important, but the relative concentrations of HCO_3^- and CO_3^{-2} compared to Ca^{+2}, Mg^{+2}, and Na^+ levels.*

When HCO_3^- and CO_3^{-2} concentrations exceed soluble Ca and Mg concentrations, water acidification may be needed if residual sodium carbonate and adjusted sodium adsorption ratios (adj SARw) exceed 1.25 and 6 meq L^{-1}, respectively (Table 3). If HCO_3^- and CO_3^{-2} concentrations are < 120 ppm, RSC < zero, *and* adj SARw < 6 meq L^{-1}, then acidification of irrigation water should not be needed. *Know all three values before deciding to purchase a sulfur generator or acid injection system for water treatment!* (Carrow et al., 1999)

If the RSC is > 0, indicating residual carbonates remain above those removed by Ca and Mg precipitation, another option is to add gypsum or a soluble Ca^{+2} source to prevent Na^+ accumulation in the soil. One meq L^{-1} Ca must be added for each meq L^{-1} HCO_3. However, any previously precipitated Ca and Mg tied up by the excess bicarbonates (positive RSC value) will not be active or available. Thus, acidification will remove the bicarbonate and will make available the Ca and Mg contained in or added to the irrigation water to react with the excess Na adsorbed to soil CEC sites. Additional Ca could be supplied by adding gypsum or a soluble Ca source. The amendments are intended to improve soil water infiltration and percolation. (Refer to Carrow et al., 1999, *Green Section Record*, 37(6):11-15 for more information on water treatment options to improve infiltration.)

SAR/ECw Interaction

The interaction of SARw and ECw on soil water infiltration is presented in Table 5. High total (salt) electrolyte concentrations in the irrigation water can counteract the adverse effects of Na on causing soil deterioration. When irrigation water is very low in salts (ECw < 0.5 dSm^{-1}), permeability problems can arise at the soil surface even at low SARw (1-10 meq L^{-1}). All irriga-

Table 5. Interaction of sodium adsorption ratio (SARw) and electrical conductivity (ECw) on soil water infiltration

(Harivandi and Beard, 1998)

	Salt-Laden Irrigation Water (dSm^{-1}) Influence on Soil Permeability*		
SARw and ECw	**No Restriction**	**Slight to Moderate Restriction**	**Severe Restriction**
SARw =	0 - 3	0 - 3	0 - 3
ECw =	> 0.7	0.7 - 0.2	< 0.2
SARw =	3 - 6	3 - 6	3 - 6
ECw =	> 1.2	1.2 - 0.3	< 0.3
SARw =	6 - 12	6 - 12	6 - 12
ECw =	> 1.9	1.9 - 0.5	< 0.5
SARw =	12 - 20	12 - 20	12 - 20
ECw =	> 2.9	2.9 - 1.3	< 1.3
SARw =	20 - 40	20 - 40	20 - 40
ECw =	> 5.0	5 - 2.9	< 2.9

*Soil permeability = ability of water to infiltrate into the soil and percolate/drain. Gas exchange is reduced by low soil permeability.

tion water should contain at least 20 ppm or 1 meq L^{-1} Ca and have a minimum ECw = 0.5 dSm^{-1} to prevent soil dispersion (Petrie 1997). At high ECw (> 3 dSm^{-1}), the high electrolyte (salt) concentration can function in maintaining soil permeability even with a high SARw (15-30 meq L^{-1}). Thus, a high Na hazard in the soil can be reduced by irrigation water with a high ECw (see Table 3).

(Refer to Duncan and Carrow, 1999, *Golf Course Management*, May: 58-62, or Carrow and Duncan, 1998, for the gypsum requirements to reduce soil exchangeable sodium percentage.)

Specific Ion Toxicity

Irrigation water may contain toxic levels of certain ions that affect turfgrass in 1) root tissues due to soil accumulation, 2) shoot tissues due to uptake by the turf roots and accumulation in leaves, and 3) directly on the foliage of landscape plants due to sprinkler irrigation. *The ions that cause toxicity problems include Na, Cl, B,* HCO_3*, and pH (*H^+ *or* OH^- *ions).* 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 root systems.

The specific ion toxicity guidelines (Table 2) apply to sensitive turf and landscape plants, but soil accumulation of these ions can eventually cause damage to even tolerant turfgrass. Over time, sodium can become toxic to turf roots, since it accumulates in the soil and leaves of susceptible turf genotypes at SAR > 3 meq L^{-1} or 70 ppm. Chloride (Cl) can accumulate at potentially toxic levels for roots and leaves at 2-3 meq L^{-1} or 70-100 ppm, and can restrict N uptake. Excess Cl normally accumulates in the tips of leaves. In turf, regular mowing plus collection and disposal of clippings removes these high concentrations from the turf and soil system. But leaf removal is normally not a management option for landscape plants, or may be limited on turf under non-mowed conditions, such as in naturalized roughs.

Residual chlorine (Cl_2) that is used to disinfect wastewater becomes toxic at > 5 ppm. HCO_3 concentrations are not toxic at > 8.0 meq L^{-1} or 500 ppm, but can cause unsightly deposits on leaves and equipment and can contribute to excess Na^+ deterioration of soil structure.

Depending on the source, some irrigation effluent can contain high levels of heavy metals and other ions (Carrow and Duncan, 1998). Maximum concentrations of selected heavy metals Zn (2.0 ppm) and Cu (0.2 ppm) are noteworthy since these ions can restrict uptake of iron (Fe) (Table 4). The maximum concentrations for Fe (5.0 ppm) and Mn (0.2 ppm) are important to know since these elements tend to be deficient in salt-affected and highly leached turfgrass systems. These maximum guidelines are based on the potential to achieve toxic levels over time with long-term use of the water.

Soil and Water pH

Water pH and soil pH are additional management considerations. The key reference points are pHs < 5.0 (H^+ dominates on the acidic level) and > 8.5 (OH^- dominates on the alkaline level). When pHs are at or beyond these specific extremes, management levels must be increased accordingly to minimize deterioration in turf performance (Carrow and Duncan, 1998).

The effect of water pH on altering soil pH is often short term because the buffering capacity (CEC) of most clay and loam native soils is so high that many years of irrigation will be required before a significant change will occur. Soils with lower CECs (sands, decomposed granites, crushed lava rock) should be monitored closely for pH changes. Accordingly, acidifying water for the sake of pH modification is questionable when cost analyses are considered. However, when high bicarbonates are supplied in combination with excess Na in the water source (which ties up the Ca/Mg needed to counter the Na), water acidification would be justified. Additionally, when the water pH is in the 8.0-8.5 range, use of acidifying fertilizers (sulfur-based sources) to dissolve some of the free calcium carbonate (lime) can counter some of this alkaline soil pH reaction.

Be aware that extreme water pH and high salt concentrations, when used in the sprayer mix with fungicides, herbicides, or insecticides, can have an effect on efficacy. This is particularly true with organophosphate and carbamate chemistries. Consult with manufacturers regarding each particular product when confronted with this problem.

Critical Nutrient Considerations

All irrigation water will contain a certain level of nutrients in its composition, and wastewater may contain elevated levels of certain nutrients. Due to the nutrient load in effluent irrigation water, fertility programs must be adjusted to maximize turfgrass performance and to minimize environmental impact (King et al., 2000).

Nutrient guidelines in irrigation are compared in Tables 5, 6, and 7. Key ratios to calculate include Ca:Mg, Ca:K, and Mg:K (Table 8), especially in salt-affected sites that are irrigated with salt-laden water. When dealing with these conditions, certain management considerations should be considered.

- Because of the high mobility of K^+ and the propensity of Na^+ to displace K^+ on soil exchange sites, a regular K^+ application may be needed every 2-4 weeks to maintain a nutritional balance in the turf plant.
- Due to high leaching events with salt-laden irrigation water, Fe and Mn may be needed on a regular basis in spoon-feeding format.
- Highly soluble nitrate sources [$Ca(NO_3)_2$] are recommended in a spoon-feeding approach to maximize turf uptake and utilization in a salt-challenged environment.
- Less soluble, slow-release products with lower salt indexes may be more appropriate when planning soil-applied fertilization programs to reduce the total salt load in the turf rootzone.
- Avoid unnecessary sulfur applications (except when in conjunction with lime to form gypsum) because they can lead to black layer and anaerobic problems in turf.
- If P, PO_4^-, and P_2O_5 concentrations are in the normal range, do not apply additional P-based fertilizers since this nutrient is one of the least mobile of nutrients in the soil and can contribute to algal blooms in holding ponds or contamination in surface and subsurface water resources.
- Avoid foliar calcium applications since this element is the least mobile of nutrients and is an element that is more effectively taken up by roots than through foliar tissue.

Total Suspended Solids

Suspended solids are inorganic or organic materials (sand, silt, clay, plant debris, algae) that do not dissolve in water and can only be removed by filtration. While total suspended solids (TSS) is normally not considered a salt problem, it is an important water quality characteristic. Low quality effluents are notorious for containing high volumes of organic solids. The overall effect on hydraulic conductivity is governed by particle size and quantity of suspended inorganic and organic solids. Organic materials include humic substances such as fulvic acid and humic acid that exhibit both soil aggregating and anti-aggregating properties. Excess suspended solids, and particularly sand contamination, often contribute to premature wear or plugging of sprinkler and pumping components as well as increasing the potential for plugging micropores, which conduct soil surface water.

Suspended solids generally have little or no impact on native soils (fairways, roughs, landscaped areas) or pushup soil tees and greens, because the added solids normally are similar in particle size to the native soil. In this case, solids added through the irrigation water in small amounts provide a light topdressing to the native soil.

The primary concern with suspended solids is their effect on newly constructed sand greens that can potentially be contaminated by these fine-particle-size solids delivered during seed germination, establishment, and grow-in. If significant amounts of suspended soil fines are applied at this stage, soil surface micropores can become plugged, function like a layer of

Table 6. Nutrient guidelines in irrigation water (ppm)

Nutrient	Low	Normal	High	Very High
P	< 0.01	0.1 - 0.4	0.4 - 0.8	> 0.8
PO_4^-	< 0.3	0.3 - 1.21	1.21 - 2.42	> 2.42
P_2O_5	< 0.23	0.23 - 0.92	0.92 - 1.83	> 1.83
K	< 5	5 - 20	20 - 30	> 30
K_2O	< 6	6 - 24	24 - 36	> 36
Ca	< 20	20 - 60	60 - 80	> 80
Mg	< 10	10 - 25	25 - 35	> 35
N	< 1.1	1.1 - 11.3	11.3 - 22.6	> 22.6
NO_3^-	< 5	5 - 50	50 - 100	> 100
S	< 10	10 - 30	30 - 60	> 60
SO_4^-	< 30	30 - 90	90 - 180	> 180

Table 7. Reclaimed water guidelines — recommended maximum values
(Adapted from L. J. Stowell, 1999. Pointers on reclaimed water contract negotiations. Fairbanks Ranch meeting. June 7, 1999.)

TDS (ppm)	960	Cl (ppm)	250
ECw (dSm^{-1})	1.5	Na (ppm)	200
SARw	5.7	Fe	5.0
adj SARw	11.6	Mn	0.2
RSC (meq L^{-1})	< 1.25	Zn	2.0
HCO_3 (ppm)	250	Cu	0.2
B (ppm)	0.5	Ni	0.2

Table 8. Nutrient ratios in irrigation water and potential deficiencies*

Ca:Mg	< 3:1	Ca deficiency
	> 8:1	Mg deficiency
Ca:K	< 10:1	Ca deficiency
	> 30:1	K deficiency
Mg:K	< 2:1	Mg deficiency
	> 10:1	K deficiency

*Irrigation water with nutrient concentrations outside these ranges can be used; the fertility program must be adjusted to avoid deficiencies.

foreign soil or incompatible topdressing, and inhibit water infiltration and percolation. If the irrigation water is salt-laden, the fines can settle at the bottom of the wetting zone and develop a layer where excess salts accumulate and concentrate. If ET is higher than the volume of irrigation that is applied, the concentrated salts can rise through capillary action into the turf rootzone to cause salt injury.

Unfortunately, no specific guidelines have been published for predicting the level at which TSS becomes a hazard. Interpret TSS data based on common sense and the potential impact that contaminants may or may not have on soil structure and irrigation system components. Use the following method to evaluate the TSS hazard:

1) The water quality test reports TSS in parts per million (ppm) or milligrams per liter (mg L^{-1}).

2) Multiply the value by a conversion factor of 2.72. The resulting value is equivalent to the pounds of solids per acre-foot (325,852 gallons), or the volume of solids applied to each acre with 12 inches of irrigation water.

For example:

1) Water quality test reports 22 ppm TSS.

2) 22 ppm × 2.72 = 59.84 or 60 lbs. of solids applied per acre-foot of water applied to the turf.

3) Is this a problem? Not likely, since this amount (60 lbs./acre-foot) is equivalent to one bag of cement spread over the golf course with each acre-foot of water applied. Sand, silt, and clay particle residue from a windy day would provide more solids than this water source (Kopec, 1998).

4) If the TSS was 735: 735 ppm × 2.72 = ~2,000 lbs. or 1 ton of solids per acre-foot. This volume of fines could be a problem on sand greens. Filtering the water or providing settling ponds would be options to consider.

Summary

Steps in assessing water quality to determine turfgrass management options:

1. Check for bicarbonates and carbonates in the water. If concentrations are greater than 120 ppm and 15 ppm, respectively, calculate adj SARw and RSC to verify the degree of impact that these ions will have on Ca and Mg activity. Adj SARs > 6 meq L^{-1} and RSCs > 1.25 may indicate that acid treatment plus lime or gypsum applications are needed.

2. Check Na content and calculate SARw or adj SARw and RSC to assess impact on soil structural deterioration (Na permeability hazard). Also, evaluate ECw in conjunction with SAR or adj SAR to estimate the permeability hazard (Tables 3 and 5). Knowledge of the clay type will be useful. These values will determine the level of aerification, amendments, and leaching that will be needed.

3. Check ECw and TDS for their impact on turfgrass (Table 2). High total salinity values in conjunction with low Na^+ and HCO_3^- values would indicate the potential to create a saline soil condition and will determine the degree of aeration and leaching needed as your primary management options.

4. Check S and/or sulfate levels in the water. If S > 60 ppm or SO_4 > 180 ppm, you may need to use lime as an

This patch of seashore paspalum is surviving better than the surrounding bermudagrass in this poorly drained, high-salt-content soil.

amendment. The high sulfates (sulfur) in the water will combine with lime to form gypsum. Removing the excess sulfur and sulfates will help minimize anaerobic problems and black layer formation when regular aeration and leaching are used in management protocols.

5. Check actual Na, Cl, and B values for their specific ion toxicity potential (Table 3). These ions normally will affect landscape plants and susceptible turf cultivars, but continued accumulation can eventually influence even tolerant species. Plants tolerant to high total salinity also are generally tolerant to high levels of these specific ions.

6. Check levels of actual nutrients and make appropriate adjustments in your fertility program to account for nutrient additions or any induced deficiencies (Tables 6 and 7). Calculate Ca:Mg, Ca:K, and Mg:K ratios and adjust the fertility program accordingly (Table 8). Watch for deficient levels of Fe and Mn. With very high Cl$^-$ levels, you may need to increase N by 10-25%. P and K are critical to maintenance of a good root system in a salt-challenged ecosystem. Annual P and K rates may need to be increased 25-50% above non-salt-affected sites, but with a spoon-feeding application regime. High Ca and Mg applications to replace excess Na can depress K uptake. High Na also depresses K uptake. N:K$_2$O ratios should be maintained at 1:1 up to 1:1.5 by light, frequent applications.

7. *Aerate, aerate, aerate* followed by *leach, leach,* and *leach*. Keep the salts moving!

Glossary of Terms

Acid injection: Used to treat water with high HCO$_3$ and CO$_3$ content. Adding an acid evolves the HCO$_3$ and CO$_3$ off as CO$_2$ and water. Commonly used sources include sulfuric, urea-sulfuric, and SO$_2$ gas from sulfurous generators.

B: Boron, a micronutrient, essential at very low concentrations. Can become toxic at soil concentrations of 0.5-6.0 ppm. Most turfgrasses have a good tolerance to boron, while some ornamental species are very sensitive.

Bicarbonate: HCO$_3$ ion.

Ca: Calcium is an essential plant nutrient and cation responsible for good soil structure.

CaCl$_2$: Calcium chloride, a very soluble calcium salt that can be dissolved in irrigation water to lower the SAR or increase the ECw.

CaCO$_3$: Calcium carbonate (lime), insoluble form of calcium precipitated by water high in Ca, HCO$_3$, and CO$_3$. Sometimes naturally occurring in calcareous/caliche soils in arid regions. Insoluble until reacted with an acid.

Without proper management, sodium, in combination with bicarbonates, can cause crusting and sealing of the soil surface.

CaCO$_3$ · MgCO$_3$: Calcium/magnesium carbonate (dolomitic lime), insoluble calcium/magnesium combination precipitated from water high in Ca, Mg, HCO$_3$, and CO$_3$. Sometimes naturally occurring in calcareous/caliche soils in arid regions. Insoluble until reacted with an acid.

Carbonate: CO$_3^{-2}$ ion.

CaNO$_3$: Calcium nitrate, a highly soluble source of calcium and nitrogen that can be dissolved in irrigation water to lower the SAR or increase the ECw.

CaSO$_4$: Calcium sulfate, commonly referred to as gypsum. An amendment used to displace sodium from the soil exchange sites and can be added to irrigation water (usually as a suspension) to increase ECw or the ratio of Ca/Na, thereby lowering SAR.

CEC: Cation exchange capacity, the sum total of exchangeable cations that a soil can absorb.

Cl: Chloride is required in small amounts as a plant nutrient; it is a highly soluble salt and toxic in larger quantities (70-100 ppm). Trees and ornamental plants are often more sensitive to chloride than turf, and accumulation is first noted in leaf tips. Most plants are generally more sensitive to chloride salts than sulfate salts.

Cl$_2$: Chlorine, used by water treatment plants to disinfect water of various pathogens. Excess or residual chlorine (> 5.0 ppm) can cause toxicity.

CO$_3$: Carbonate, combines with Ca (calcium) and Mg (magnesium) to form CaCO$_3$ and MgCO$_3$ (calcium carbonate and magnesium carbonate) forms of insoluble lime or calcite.

Cu: Copper, an essential micronutrient, but if concentrations are excessive (> 0.2 ppm) can restrict the uptake of iron.

dS/m$_{-1}$: Decisiemens per meter, the standard measurement used to report electrical conductivity of water (ECw).

ECw: Electrical conductivity of irrigation water. This is a measure of the total salinity or total dissolved salts. 640 ppm TDS = 1.0 dS/m ECw.

ESP: Exchangeable sodium percentage, used to classify sodic and saline-sodic soil conditions. The degree of saturation of the soil exchange complex with sodium as compared to other exchangeable cations occurring from irrigation with sodium-dominated water.

ET: Evapotranspiration, the total amount of water loss from soil evaporation and plant transpiration.

Fe: Iron, essential plant nutrient that tends to become depleted in highly leached, salt-affected soils.

H$_2$SO$_4$: Sulfuric acid, either forms in soil when acidifying amendments/fertilizers are used such as soil sulfur (S), ammonium sulfate, etc., or is injected into irrigation water via a sulfurous generator or acid injection and products such as urea sulfuric acid (NpHURIC).

HCO$_3$: Bicarbonate, combines with Ca (calcium) and Mg (magnesium) to form CaCO$_3$ and MgCO$_3$ (calcium carbonate and magnesium carbonate) forms of insoluble lime or calcite. Can also cause unsightly deposits on ornamentals.

K: Potassium, an essential nutrient that influences rooting, drought, heat, cold, and disease tolerance. Potassium can be displaced by sodium at the cation exchange site.

meq/l: Milliequivalents per liter. Parts per million (ppm) divided by equivalent weight equals milliequivalents per liter.

mg L^{-1}: Milligrams per liter, equals parts per million.

Mg: Magnesium, an essential plant nutrient and cation associated with good soil structure, providing it is not available in excessive quantities in relationship to Ca.

$MgCO_3$: Magnesium carbonate, insoluble form of magnesium precipitated by water high in Mg, HCO_3, and CO_3. Sometimes naturally occurring in calcareous/caliche soils in arid regions. Insoluble until reacted with an acid.

Mn: Manganese, essential plant nutrient that tends to become depleted in highly leached, salt-affected soils.

Na: Sodium, non-essential as a nutrient, a "small" cation with a large hydrated size that disperses soils, thereby affecting infiltration and soil aeration. Can displace potassium on soil exchange sites.

Na_2SO_4: Sodium sulfate, a soluble salt formed when gypsum is used to treat soils with high sodium content.

pH (water): A logarithmic measurement of relative alkalinity or acidity. Water with low pH often reflects higher quantities of sulfates or iron, while high pH tends to reflect high bicarbonates or sodium.

ppm: Parts per million. Milliequivalents per liter multiplied by equivalent weight = parts per million.

RSC: Residual sodium carbonate, like the adj SARw, it is used to determine whether Na will cause soil structure problems. The RSC compares the concentrations of Ca and Mg to HCO_3 and CO_3 and determines when calcium and magnesium precipitation can occur in the soil and result in additional sodium domination of soil cation exchange sites. $RSC = (CO_3 + HCO_3) - (Ca + Mg)$. This calculation is done with all measurements in meq/l.

RSC Value	Potential Irrigation Use
< 1.25	Generally safe for irrigation
1.25 - 2.5	Marginal
> 2.5	Usually unsuitable unless treated

S: Sulfur, a secondary plant nutrient used as a soil amendment to modify pH in alkaline soils. Also used in calcareous and caliche soils (containing high lime) to convert lime into gypsum.

SARw: Sodium adsorption ratio of irrigation water. SARw is used to determine whether sodium (Na) levels of water will cause soil structure to deteriorate. Unadjusted SAR (SARw) considers only Na, Ca, and Mg.

Adj SAR: Adjusted sodium adsorption ratio of irrigation water. Adj SARw predicts the increased influence of sodium (Na) upon soil structure due to the influence of carbonates and bicarbonates.

SO_3 Generator: Sulfurous generator, also known as a sulfur burner. Equipment used to treat irrigation water containing high carbonates and bicarbonates. Burns sulfur at high temperatures to produce sulfurous gas that when combined with water becomes sulfuric acid. This evolves the HCO_3 and CO_3 off as CO_2 and water. This is another method of acid injection.

SO_4: Sulfate, when combined with lime while in an acid form creates gypsum. May also combine with other cations to form various soluble salts.

TDS: Total dissolved salts, normally reported as parts per million (ppm).

TSS: Total suspended solids, organic and inorganic materials (sand, silt, clay, algae, plant debris, etc.) that do not dissolve in water and must be removed by filtration or settling.

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