Chapter 4
Water Management and Conservation

Plants typically contain between 75 and 85 % water by weight, and begin to die if their water content drops to 60–65 % within a short period of time. Water acts as a buffer in plants against extreme temperature fluctuations, ensuring damage from high or low temperatures occur slowly.

Unfortunately, rainfall does not occur frequently enough in most cases to provide adequate water to sustain turfgrasses, especially with the limited root systems associated with most closely-mowed turf areas and soils used with low water-holding capacity. This situation is further intensified by warm weather and the high aesthetic demands by clientele. To ensure efficient watering, turf facilities require well-designed irrigation systems based on soil infiltration rates, soil water-holding capacity, anticipated annual rainfall, plant water-use requirements, depth of rootzone, conveyance losses from the surrounding area, and desired level of turfgrass appearance and performance.

Water loss from a turf area occurs through evaporation, transpiration, run-off, leaching, and conveyance losses. Turf managers have a degree of control over these water-loss mechanisms; therefore, they should have a good understanding of each mechanism in order to maximize water conservation. In addition to water quantity, water conservation also encompasses irrigation water quality which will also be covered in this chapter.

4.1 Water Use

Determining When to Irrigate

There are a number of methods used to determine how much water turf requires at any given time, under any given environmental conditions. Several are indirect and base their estimates on measuring soil moisture. Others simulate evapotranspiration from the canopy, while yet others make direct soil measurements.

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Fig. 4.1 Turfgrass discoloration such as a *blue-green* to *grayish* color is a key indicator of drought occurrence

Visual Symptoms

A simple method used to determine when to irrigate is to observe visual symptoms of moisture stress. Moisture-stressed grass appears blue-green or grayish-green in color (Fig. 4.1), recuperates slowly (>1 min) after walking or driving across it ("foot-printing") (Fig. 4.2), or wilts continuously. These symptoms occur when plant moisture is insufficient to maintain turgor pressure, due to more water being lost than taken up. As a result, the plant rolls its leaves to minimize exposed leaf surface and wilts to conserve moisture. Golf course managers should avoid prolonged moisture stress, especially on greens. This method is best used for low-maintenance turf such as golf course roughs, out-of-play sports fields, or home lawns.

While visual observation for stress symptoms may be the simplest method, it does have some drawbacks. Waiting for wilting symptoms is a good method of determining when the turf needs water, but not necessarily how much water is needed. Turf managers also cannot afford to wait until drought symptoms appear on putting greens since this causes unacceptable turf quality. Certain areas or patches of turf will tend to wilt prior to others due to poor irrigation distribution, localized dry spots, poorly developed root systems, or variation in soil texture. Watering the whole turf area to eliminate these "hot spots" will waste water; thus, extensive hand watering is often needed.

Fig. 4.2 Foot printing or traffic patterns as an indicator of drought occurrence

Evaporatory Pans

Another method of irrigation scheduling is the use of evaporatory pans. A U.S. Weather Service Class A Evaporatory Pan is 122 *cm* in diameter, 25 *cm* deep, and is supported 15 *cm* above the ground (Fig. 4.3). Evaporatory pans are filled with water and placed in a representative location, where water loss is measured over time. The amount of water evaporating from the pan correlates to that lost by evapotranspiration (ET). This correlation is generally accurate except during windy conditions which tends to exaggerate the amount of water lost by the evaporatory pan compared to actual ET rates.

The water quantity lost through evaporation correlates with turfgrass ET, but is not exactly the same; turfgrasses use less water than the quantity evaporated from the pan. A crop coefficient (K_c) value is needed to adjust this correlation (Table 4.1). Warm-season grasses use 55 to 65 %, and cool-season grasses use 65 to 90 %, of pan evaporation. Thus, if the evaporative pan shows a 1 *in* (2.5 *cm*) water loss, a bermudagrass turf would actually have lost approximately 0.60 *in* (1.5 *cm*) while bentgrass would have lost approximately 0.85 *in* (2.2 *cm*).

Soil Moisture Measuring Devices

Soil moisture measuring devices have been developed with the goal of indicating how much moisture is available to plants. Soil moisture is measured in two

Fig. 4.3 Evaporatory pan used to measure daily evapotranspiration water losses

Table 4.1 Crop coefficient (K_c) values for a class A evaporative pan or the Penman-Monteith equation

Grass	Class A-evaporative pan K_c values	Penman-Monteith K_c values
Bermudagrass	0.55 to 0.65	0.70 to 0.80
Tall Fescue	0.65 to 0.75	0.75 to 0.95
Perennial Ryegrass	0.65 to 0.75	0.80 to 1.0
Kentucky Bluegrass	0.70 to 0.80	0.85 to 1.0
Creeping Bentgrass	0.75 to 0.90	0.95 to 1.0

distinctly different methods—*quantitatively* (or *volumetric*), the actual amount of moisture in the soil, and *qualitatively* (or *tensiometric*), how tightly water is held by soil. Though numerous means of measuring these exist, the more common ones including gravimetric water content, TDR, tensiometers, and FDR (or hand-push) probes.

The water content of different soils varies due to large differences between soils in their total particle surface areas. For example, moisture levels at field capacity for sands may be as low as 7 % whereas clays may have as much as 40 % moisture content at field capacity. In another example, the permanent wilting point volumetric water content may range from 1 to 2 % for sandy soils to 25 or 30 % for clay (finer-textured) soils. This variation demonstrates that a measure of soil water (volumetric) content does not necessarily indicate the amount of water available to plants. A better indicator of a plant's soil-water availability is the energy status of water (called tensiometric or water potential) which measures the relative amount of work (or energy) needed to remove a unit of water from a particular soil.

Quantitative Methods

Quantitative methods for measuring soil moisture include gravimetric sampling, neutron probe (or scatter), and dielectric constant (Time Domain Reflectometry and Frequency Domain Reflectometry, TDR and FDR) probes. The most accurate is the gravimetric water content method where a volume of soil is weighed, dried, and then reweighed (Table 4.2). The impracticality of this method and expense (>$5000) for neutron probes have led to the development of other techniques.

Dielectric constant methods measure the soil's ability to transmit electricity (electro-magnetic waves or pulses) with the value increasing as the water content of the soil increases (Fig. 4.4). The permittivity constant for air is approximately 1; dry soil between 3 and 5; and about 80 for water. Values are related through calibration to known soil moisture content determined using either a neutron probe or the gravimetric sampling technique. The equipment consists of an electronic meter connected to 2 to 4 rods placed into the ground. The instrument sends an electrical signal through the soil and the rods serve as the transmitter and receivers. TDR and FDR probes are currently the most commonly used dielectric devices. Although these devices are able to detect the amount of moisture in the soil, they do not determine how much of it is available to plants.

Advantages of using dielectric devices to quantify soil moisture include:

- ability to leave soil moisture sensors in place to continuously monitor soil moisture content,
- repeatability of measurements,
- sensitivity to small changes in soil moisture content,
- precise resolutions with depth due to the narrow vertical zone of influence.

Disadvantages include:

- need for soil specific calibration for best accuracy,
- relatively small zone of measurement,
- possibility of soil salinity influencing probe reading,
- sensitivity to air gaps,
- probe length should equal rooting depths.

Time Domain Reflectometry (or TDR)

These systems measure the travel time of an electromagnetic wave between sending the pulse and receiving it, and is the preferred tool for researchers. With TDR, a pair of parallel metal rods connected to a signal receiver is inserted into the soil. The rods serve as conductors while the soil is the dielectric (a nonconductor of

Table 4.2 Comparison of common techniques of soil moisture content measurement

Technique	Measurable range	Advantages	Disadvantages
Gravimetric water content. Measures soil moisture by weighing-drying-reweighing.	Full range of water content (%).	– simple equipment needs, – highly accurate, – easy interpretation.	– destructive sampling, – labor intensive, – collection, transport, and time restraints.
Time Domain Reflectometry (TDR). Measures time for an electromagnetic wave to travel using soil medium as a dielectric. Moisture slows this down.	Up to 50 % volumetric water content (0.50 kg water kg^{-1} soil)	– accurate, – minimal soil disturbance, – soil specific-calibration is optional, relatively insensitive to temperature, – also estimates, with limited accuracy, soil EC.	– expensive, – accuracy decreases in high saline ($>25\,dS\,m^{-1}$) conditions or heavy clay soils, – relatively small sensing volume (~ 1 in, 2.5-cm, radius around probe).
Frequency Domain Reflectometry (FDR) or **Hand-push probes**. Measures the change in frequency of a capacitor using soil medium as a dielectric.	Up to 70 % volumetric water content (0.70 kg water kg^{-1} soil) or to $-7.0\,MPa$	– relatively inexpensive, – can be automated with irrigation, – stable in different soil types and over a large range of moisture contents.	– needs soil-specific calibration for accuracy, – samples small volume of soil (~ 4 in, 10 cm, radius around probe), – sensitive to soil air gaps, saline soils and temperature.
Tensiometers. Measure how tightly (the "tension") water is held by soil.	0 to $-0.08\,MPa$ or 0 to $-80\,kPa$	– direct readout of soil water potential (or tension), – inexpensive, – can be automated with irrigation, – relatively reliable, – good accuracy, – unaffected by soil salinity.	– soil moisture retention curve needed to relate to soil water content, – samples a small area near cup, thus, multiple samples are needed in larger areas, – doesn't measure soil salinity content, – exposed gauges, sensitive to disturbance and soil air gaps.
Unit conversions: $1\,bar \approx 1\,atm = 14.7\,psi$; $1\,kPa = 0.001\,MPa = 0.01\,bar = 1\,cb = 10\,cm\,H_2O$			

Fig. 4.4 Soil moisture dielectric probe with two sets of probes used to measure quantitative levels of soil moisture near the soil surface and several inches (turfgrass rootzone) below this

electricity). The presence of water (higher dielectric constant) proportionally slows the speed of the electromagnetic wave. Traditionally, TDR instruments were more expensive due to the advanced electronics needed to provide this series of precisely-timed electrical pulses and ability to read these. However, recent technology has allowed TDR moisture sensors to be priced closer to the less accurate FDR based alternatives.

Frequency Domain Reflectometry (or FDR)

These are also known as *hand-push probes* and as *dielectrical capacitance probes*. Like TDR systems, FDR are also dielectric sensors as their electrodes are separated by the dielectric (soil). One or two pairs of electrodes (either an array or parallel spikes or circular metal rings) form a capacitor, with the soil acting as the dielectric in between. This capacitor works with the oscillator to form a tuned circuit and changes in soil water content are detected by changes in the reflected frequency. Most of these sensors operate at low frequencies (100 *MHz* or less) compared to higher (~250 *MHz*) operating frequency for TDR probes. The high frequency used for TDR probes allows less dependency on soil specific properties like texture, salinity or temperature. The greater the soil moisture content, the smaller (or greater change in) the frequency. The dielectric reading is then converted to volumetric water content (m^3 water m^{-3} soil or θ_v) with readout in percentage (% volume).

In general, FDR probes perform best in coarser-textured, non-saline soils and often require specific soil calibration, limiting their use or comparison between different soils or locations. Less precise electronics are needed vs. TDR, thus FDR probes are cheaper. All electronic resistance probes are influenced by temperature, soil composition and bulk density, and the solute concentration (EC) of the soil solution and since moisture content is a non-linear curve, calibration equations are required for specific soils. Probes should also be at least $6\,in$ ($15\,cm$) in length to reduce wavelength reflection which produces erroneous readings as do EC levels at and above $25\,dS\ m^{-1}$.

Electrical Conductivity Probes

These are a commonly available low-cost means of measuring soil moisture in the soil based on the soil's ability to pass a current of electricity between two probes. In many ways the concept is similar to resistance blocks but the probes (electrodes) have direct contact with the soil and are not buffered as in resistance blocks (discussed below). The more moisture in soil the better the conductivity or the lower the electrical resistance. This method is very sensitive to probe spacing as well as being influenced by soil type and salts, primarily in the form of fertilizers. Because of this strong correlation, these probes are more commonly used to measure salt content in soils.

Qualitative Methods

These methods measure how tightly soil moisture is held by soil particles but do not directly measure the quantity of water contained in it. As the tension increases, water extraction becomes more difficult for the plant. Tensiometers and porous blocks (i.e., gypsum, ceramic, nylon, and fiberglass) are qualitative methods.

Tensiometers

These are sealed, water-filled tubes with a vacuum gauge on the upper end and a porous ceramic tip on the lower end (Fig. 4.5). Water in the tensiometer comes to equilibrium with water in the soil and provides an indication of how difficult it is (or tension required) for the plant to obtain water from the soil, but does not directly provide information on soil water content. To obtain this, a soil moisture release curve is needed. A lower reading indicates more available water. Though very accurate when scheduling irrigation, tensiometers are often not practical in turfgrass applications as their presence disrupts play and/or maintenance practices.

Electrical Resistance Blocks

Electrical resistance blocks measure soil moisture tension with two electrodes imbedded in a porous material such as gypsum, nylon, fiberglass, or a sand-ceramic

Fig. 4.5 Tensiometer used to determine how much tension is required for plants to extract soil moisture

mixture. Gypsum or similar material is used to buffer against salts that would affect resistance readings. Moisture is allowed to move in and out of the blocks as the soil dries or becomes moist. The electrodes measure resistance to electric current when electrical energy is applied. The more moisture in the block, the lower the resistance reading indicating more available moisture. These are accurate when measuring low soil moisture content and can be left in place for extended periods. They are, however, sensitive to saline conditions, and like tensiometers, measure soil moisture only at the area immediately surrounding them. They also are not as accurate in predominately sandy soil.

Calibrating Soil Moisture Devices

When using any soil moisture measuring device for irrigation purposes, three critical soil moisture levels need to be quantified: (1) gravitational water; (2) field capacity; and, (3) wilting point. A SMRC will indicate these (Fig. 1.25) but they

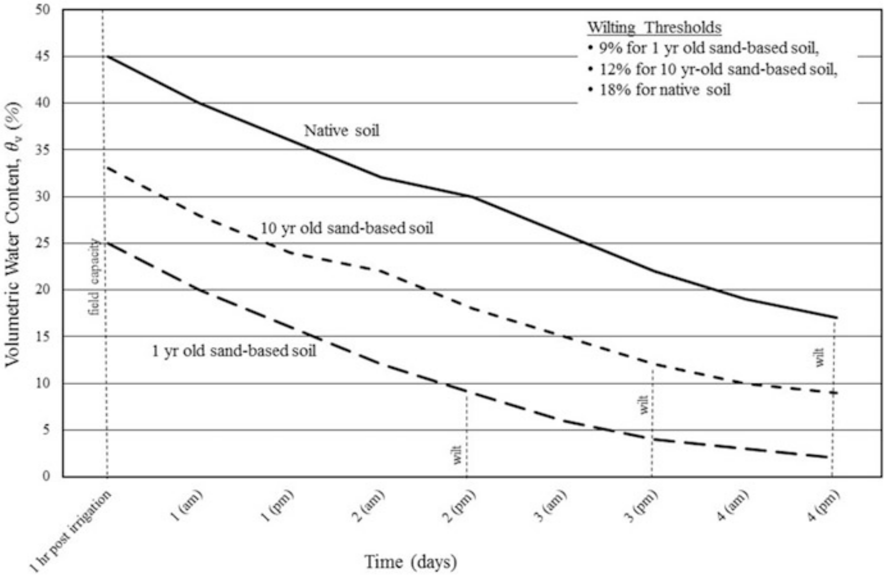


Fig. 4.6 Moisture levels often vary with different soils. Shown are differences in volumetric moisture content for three different soils at field capacity and wilting points. Field capacity was highest for the native soil at approximately 45 % and lowest at 25 % for a 1 year old sand-based rootzone. Wilting occurred earliest for the 1 year old sand-based rootzone (2 days after irrigation) while it was latest for the native soil (4 days after irrigation). Redrawn and modified from Karcher (2013)

also should be confirmed with field readings. Moisture levels typically vary with soil type and uniformity and readings vary between soil measuring devices (Fig. 4.6). Therefore, it is highly recommended soil moisture measuring devices be calibrated for the particular soil in consideration.

The amount of moisture between field capacity and wilting is that available for plant use. Gravitational water is typically that in the soil following heavy rainfall and puddle disappearance. About 24 *h* later, a reading should approximate field capacity. Field capacity is also the amount of soil moisture present about 1 *h* following heavy irrigation. Multiple readings should be taken over the whole area and the probe length should extend to just below the average rooting depth. Readings should be taken at least twice daily until significant plant wilting is observed.

Example From the use of a hand-held TDR probe, determine how much water is needed to return the total moisture levels to field capacity once it reaches wilting point for two sands with volumetric soil water content at field capacity (θ_{fc}) of 0.35 and 0.25 $cm^3\ cm^{-3}$ and volumetric water content at wilting point (θ_{wp}) of 0.025 and 0.015 $cm^3\ cm^{-3}$ for sands 1 and 2, respectively. The TDR probe measures moisture in the top 10 *cm* (4 *in*) of the soil profile.

Determine available water for each sand using the equation:

$$\mathrm{D_e} = soil\ depth\ \left(\theta_{\mathrm{f}c} - \theta_{\mathrm{w}p}\right)$$

where:

$\mathrm{D_e}$ = equivalent depth of available water in the top 10 *cm* (4 *in*),
θ_{fc} = volumetric water content at field capacity,
θ_{wp} = volumetric water content at wilting point

$$\begin{array}{ll} \text{For sand 1 :} & \mathrm{D_e} = \text{soil depth}\left(\theta_{\mathrm{f}c} - \theta_{\mathrm{w}p}\right) = 10\ (0.35 - 0.025) = 3.25\ cm\ (1.28\ in) \\ \text{For sand 2 :} & \mathrm{D_e} = \text{soil depth}\left(\theta_{\mathrm{f}c} - \theta_{\mathrm{w}p}\right) = 10\ (0.25 - 0.015) = 2.35\ cm\ (0.93\ in) \end{array}$$

Therefore, for sand 1, 3.25 *cm* would be needed to bring the soil moisture level back to field capacity once it reach wilting point while 2.35 *cm* would be required for sand 2.

Predictive Models or Evapotranspiration Feedback

Predictive models, such as the modified Penman-Monteith ET (also known as FAO 56) model, based on weather station data and soil types also are available. These are often referred to as Irrigation or ET Controllers in the industry. They estimate or predict ET of the turf. These are relatively accurate and applicable, especially as long-term predictors of yearly turf water requirements. Models, however, are only as effective as the amount of data collected and the number of assumptions made. Weather data such as rainfall, air and soil temperature, relative humidity, and wind speed are incorporated into certain model formulae, and estimated soil moisture content is made. Accessible weather data, as well as specialized computer equipment and programs, must be available (Fig. 4.7).

Evapotranspiration feedback strategies are also used to schedule irrigation. Weather station or evaporative pan data can be used to calculate water use. This value is referred to as potential ET ($\mathrm{ET_p}$) and is used as a reference point. Actual turf water use usually is not quite as high as $\mathrm{ET_p}$, so a factor called the **crop coefficient** ($\mathrm{K_c}$) is used to convert $\mathrm{ET_p}$ to actual turf ET (as discussed in the previous section on evaporative pans). Crop coefficients are fairly constant for a given species, but vary considerably between species (Table 4.1). For example, the $\mathrm{K_c}$ of bermudagrass is about 0.75. This means bermudagrass will use about 75 % as much water as is predicted from using environmental data to calculate $\mathrm{ET_p}$. If environmental data indicates the theoretical reference crop used 2.2 *in* (5.6 *cm*) of water for a given week in the summer, multiply 2.2 by 0.75 indicates 1.65 *in* (4.2 *cm*) of water is actually used by bermudagrass. Most cool-season grasses have a $\mathrm{K_c}$ of approximately 0.85, indicating cool-season grasses actually require 1.87 *in* (4.75 *cm*) of water in the previous situation. These calculated water use rates

Fig. 4.7 Automatic weather station used to construct predictive models on how much soil moisture is present

are the "feedback" used to determine irrigation rates. Using the site information and weather data, ET feedback controllers run a "water balance" that keeps track of how much water is in the soil. Controllers then adjust the run timers (or amount) of water applied to the turf.

Atmometer

The atmometer (also referred to as the "ET gauge" or Bellani plate) also can be used to estimate evaporative demand (Fig. 4.8). This relatively inexpensive device consists of a water reservoir connected to a porous plate covered by green fabric designed to simulate a leaf surface. Water from the reservoir is wicked through the plate to the fabric, where it evaporates. The drop in the reservoir is then easily measured on a daily basis, much like checking a rain gauge. Rates of water loss are directly related to weather conditions, especially temperature, wind, and humidity, and have been found to correlate very well with turfgrass water demand. Atmometers may be an attractive alternative to the more costly weather station-based system while still supplying similar information.

Fig. 4.8 Atmometer which is a water-filled container connected to a porous plate covered by green fabric to estimate evapotranspiration rates of turfgrasses

The atmometer should be located in a sunny turf-covered area representative of the majority of the golf course. Additional units may be necessary for varying microclimates such as shady, windy, or stagnant areas, and irrigation rates should be adjusted accordingly. Atmometers require calibration and provide only an estimation of watering needs.

4.2 Evapotranspiration Rates

Plants absorb water from the soil and lose water to the atmosphere. Only about 5 % of all water consumed by turf is used in photosynthesis, carbohydrate synthesis, and other metabolic reactions. About 95 % of this water is lost as vapor from the leaves to the atmosphere, by the process of **transpiration**. Water is also lost by **evaporation** from soil and leaf surfaces. Evaporation is typically much lower than transpirational losses in a mature turf. The combined total of water lost through transpiration and evaporation is termed **evapotranspiration**, abbreviated ET. Evapotranspiration is usually expressed in inches or millimeters per day, week, or month. Since ET is the total water lost from the turf system, it represents the water demand, or the total amount that must be replaced to maintain a healthy turf. Environmental parameters largely controlling ET are light intensity and duration, relative humidity, wind velocity, and temperature. Increasing solar radiation, temperature, and wind increases ET, while increasing relative humidity decreases ET. Other parameters affecting ET to a lesser extent include soil-water content, turf-root system development, inherent turf water needs and dehydration avoidance mechanisms, and turf cultural practices.

Transpiration occurs through tiny pores in the leaf, called the **stomata**. Stomata are usually open, allowing water vapor and oxygen to move out of the leaf and carbon dioxide to move in for photosynthesis. To conserve water, stomata often close during periods of peak water demand (hot, windy afternoons), but will usually reopen after environmental conditions moderate. Under prolonged stress, however, stomata may close for extended periods, which in turn affects other plant functions.

Although it might seem like transpiration is just a waste of water, it is in fact critically important as it cools the leaf. If not for transpirational cooling, a leaf could reach 120 °F (49 °C) or higher during midsummer, a lethal temperature for most plants. Fortunately, transpiration keeps leaves much cooler, usually below 90 °F (32 °C), due to the **latent heat of vaporization** for water, or the large amount of energy needed to convert liquid water to water vapor via evaporation. For example, for every *calorie* of solar energy absorbed by the plant, $1\,g$ of turfgrass tissue (mainly water) will increase in temperature by nearly 2 °F. Ten *calories* of solar energy could warm $1\,g$ of turf tissue by about 18 °F. However, it takes a lot of energy, $539\,cal$, to evaporate $1\,g$ of water. By transpiring only $1\,g$ of water, a turf plant loses enough energy to cool $539\,g$ of plant tissue by roughly 2 °F. Multiply this by the millions of grams of water a turfgrass area loses daily and the incredible cooling capacity of transpiration becomes evident. Humans use a similar process when perspiration evaporates, cooling their bodies.

Transpiration is also directly involved in mineral nutrition, both by causing soluble nutrients to be drawn to the roots along with soil water and by moving nutrients and certain hormones from roots to shoots. It is the diffusion of water through the stomata that creates a lower pressure potential, allowing water to overcome gravitational potential and move upward from the soil, into the plant roots, and upward in the plant. When the transpiration stream is lacking, as when plants are grown in a saturated atmosphere ($100\,\%\ RH$, $\Psi_t \sim 0\,MPa$), nutrient deficiency symptoms, especially for nitrogen and iron, often develop or a term called **wet wilt** occurs where plants collapse in the presence of water when evaporation exceeds root water uptake.

Environmental Influence on Evapotranspiration

Environmental parameters that control plant ET include relative humidity, temperature, solar radiation, and wind. Of these, solar radiation is the driving force for evaporative demand by stimulating stomata opening. Cloudiness can decrease ET by blocking incoming radiation.

Atmospheric relative humidity and wind velocity also influence ET rates. As air becomes more saturated at higher humidities, the vapor pressure gradient between leaves and air is reduced, resulting in less ET. Under calm air conditions, the existing vapor pressure tends to form an external layer of still air adjacent to the leaf called the **boundary layer**. The boundary layer, if not disturbed, acts as an insulator by protecting the leaf from sudden vapor pressure changes, and thus reduces ET. The boundary layer thickness is determined by wind speed. With increasing wind, the boundary layer decreases and ET increases. As a result, ET rates tend to increase with higher temperatures, light, and wind, but decrease with higher atmospheric relative humidity and cloud cover. Minimal ET rates occur when dark, cloudy days with high relative humidity, low temperatures, and little wind occur. Conversely, the highest ET rates occur on bright sunny days with low relative humidity, high temperatures, and moderate-to-high winds.

Turfgrass Water-Use Rates

Water-use rates are usually expressed in inches or centimeters of water lost per day or per week. In general, warm-season grasses use less water due to their greater resistance to water stress compared to cool-season grasses (Table 4.3). This ranges between 35 and 50 % less water required to maintain desirable warm-season grass color compared to cool-season grasses. Bermudagrass ET is between 0.3 and 0.9 cm water day^{-1}, while tall fescue water use ranges from 0.4 to 1.3 $cm\ day^{-1}$. Lower values are associated with cooler or more humid regions of the United States, while higher values are typical of warm arid regions. Tall fescue has the highest potential

Table 4.3 General mean summer turfgrass evapotranspiration (ET) rates

	Summer ET rates			
Turfgrass	$in\ day^{-1}$	$mm\ day^{-1}$	$in\ week^{-1}$	$cm\ week^{-1}$
Bahiagrass	0.25	6.2	1.75	4.4
Bermudagrass	0.12–0.30	3.1–8.7	0.84–2.10	2.1–5.3
Buffalograss	0.20–0.30	5.3–7.3	1.40–2.10	3.6–5.3
Centipedegrass	0.15–0.33	3.8–8.5	1.05–2.31	2.7–5.9
Creeping bentgrass	0.19–0.39	5.0–9.7	1.33–2.73	3.4–6.9
Kentucky bluegrass	0.15–0.26	3.7–6.6	1.05–1.82	2.7–4.6
Perennial ryegrass	0.15–0.44	3.7–11.2	1.05–3.08	2.7–7.8
Seashore paspalum	0.25–0.31	6.2–8.1	1.75–2.17	4.4–5.5
St. Augustinegrass	0.13–0.37	3.3–9.6	0.91–2.59	2.3–6.6
Tall fescue	0.15–0.50	3.6–12.6	1.05–3.50	2.7–8.9
Zoysiagrass	0.14–0.30	3.5–7.6	0.98–2.10	2.5–5.3

Low values within a range represent humid conditions; high values are for arid conditions (compiled from Beard 1985; Carrow 1995; McCarty 2011). ET rates during non-summer months generally are much lower

ET rates, but avoids drought stress due to its deep and extensive root system and ability to go dormant for short periods without lethal consequences.

Potential Evapotranspiration (ET_p) Rates

As previously discussed, another method to schedule irrigation is the development of ET feedback systems based on an estimate of the potential ET (indicated as ET_p) developed from climatic data or weather pan evaporation. The ET is then adjusted to actual plant ET use with an appropriate crop coefficient (K_c) that more accurately reflects actual ET for the particular turfgrass under irrigation:

$$\mathrm{E}T_{\mathrm{p}} = \mathrm{K_c} \times \mathrm{p}an \quad \mathrm{e}vaporation$$

Currently, K_c for warm-season grasses ranges from 0.60 (moderate stress) to 0.90 (nonstressed) and from 0.80 to 0.85 for cool-season grasses. General estimates of ET_p may be calculated using the following values for $K_{c:}$

$$\text{Warm-season grasses} : \mathrm{ET_p} = 0.75 \times \text{pan evaporation rate}$$

$$\text{Cool-season grasses} : \mathrm{ET_p} = 0.85 \times \text{pan evaporation rate}$$

Scheduling Irrigation Based on ET Rates

Potential ET rates can be calculated from a variety of equations. In general, by using historical climatological data as a reference and incorporating this in the modified Penman or McCloud equation to determine specific ET rates, potential ET rates have been calculated at various locations throughout the country. From this, normal net irrigation requirements to maintain low-to-medium maintenance grass are estimated.

When using any predictive equation to determine ET rates or net irrigation requirements to maintain grass, a series of assumptions must be made. These assumptions influence actual amounts of net irrigation requirements since each location and golf operation is designed and built differently. Allowances are needed to account for these and to adjust for any differences.

1. The net irrigation requirement is affected by irrigation system efficiency or **distribution uniformity** (designated DU). To determine the actual irrigation quantity needed to provide the minimum intended amount uniformly across the turf, the following equation is used:

$$\text{actual irrigation needed} = \frac{\mathrm{ET_p}}{\text{Distribution Uniformity}}$$

For example, if 1.0 *in* (2.54 *cm*) of water is needed as determined by multiplying pan evaporation rate by K_c to achieve ET_p with a 75 % efficient (or DU) system, then 1.33 (1.0 ÷ 0.75) in of total "applied" water is required to uniformly apply this minimum 1.0 *in* (2.5 *cm*) over the whole turf area.

2. Environmental parameters at the time of application also influence the amount of water delivered to plants. Applications made during hot temperatures, windy conditions, and when relative humidity is low, as well as with fine mist irrigation nozzles, can result in extensive evaporation (up to 30 to 50 %) of irrigation prior to reaching the turfgrass. Irrigation should not be scheduled during such periods. However, special practices such as establishing new turf areas, and watering-in fertilizer or pesticide applications, often necessitate irrigation during adverse conditions.
3. Net irrigation requirements listed are for taller-mowed grass. Closely maintained grass, such as golf greens and tees, have significantly less rooting depth compared to taller-mowed plants; thus, they require more frequent, shallow irrigations and have less room for error if not properly and adequately watered during periods of heat and drought stress.
4. Rainfall amounts used in these calculations are averages based on historical climatological data. Deviations from these averages usually occur, and net irrigation amounts during exceptionally dry years will have to be increased to compensate for this. Values listed also assume even rainfall distribution over the entire period. If uniform rainfall distribution does not occur, irrigation amounts higher than those listed in Table 4.3 are required.
5. "On-site" computer-assisted ET-predicted models calculate water needs based on local conditions. Generally, a range of ET models are used that estimate between 0.8 and 1.2 of actual ET.

4.3 Irrigation Strategies

With potential shortages of irrigation water, it is in the best interest of a turf facility to conserve water whenever possible and to design irrigation programs that provide quality turf with minimum water use. Irrigating too heavily not only wastes valuable water, but it invites the potential for increased disease incidence, turf thinning, shallow rooting, reduced stress tolerance, and increased soil compaction and turf wear. Inefficient use of electricity and excessive wear and tear on the irrigation pumps and other components of the system also are reasons to maximize water use.

Playing conditions are also influenced by watering practices. Overwatered golf courses tend to play much longer and have slower putting greens. Conversely, drier turf results in quicker putting surfaces and more bounce and roll; in effect, shortening the course. However, if allowed to dry excessively, this increases the risk of losing turf from moisture stress and causing a reduction in aesthetic quality. Many courses also are restricted in the amount of water they can use and may be mandated to irrigate based on ET data, soil moisture levels, or other water need indicators.

Steps in formulating an irrigation strategy include:

1. Calibrate an irrigation system's output and distribution uniformity (or DU).
2. Determine daily ET rates or soil moisture status by one of the methods discussed. A reasonable estimate of daily summer mean ET rates for various grasses are provided in Table 4.3.
3. Accurately track daily rainfall and ET rates so a water budget can be set-up and followed.
4. When irrigation is needed, use the appropriate crop coefficient to find daily ET rate and incorporate distribution uniformity (DU) of the irrigation system as shown earlier and below.
5. Make adjustments for rainfall, varying microclimates, and forecasted weather.

Irrigation System Calibration

The first step in irrigation scheduling is to determine how much water the irrigation system applies, typically expressed as inches per hour (*in* h^{-1}). This information is central to water management. The easiest and most common way to determine application rate is by "canning" the turf area. For small areas, a dozen or so empty tin cans are placed in a grid system across the turf with the location of each catch-can recorded (Fig. 4.9). It is important the cans are the

Fig. 4.9 Conducting a distribution uniformity test when calibrating an irrigation system to determine how uniform water is being applied

same size, have a consistent cross-section, and are fairly tall; soup or vegetable cans work well. The irrigation system is then activated for a timed period, usually 15 to 30 min, to let the cans collect a ¼ to ½ *in* (6.4 to 13 *mm*) of water. The average amount of water in each can is then measured with a ruler and adjusted to the amount of water caught per hour. These cans are all emptied into a single can and the water depth is measured with a ruler. The depth is then divided by the total number of cans to get the average depth per can. This value must be divided by the time period to calculate the application rate. For example, assume 12 cans were used to collect irrigation for a 30-min period. The total depth of all cans was 4.4 *in* (11 *cm*). Dividing 4.4 *in* (11 *cm*) by 12 gives 0.37 *in* (0.94 *cm*) per can. Now multiply the average depth, 0.37 *in* (0.94 *cm*) per one-half hour, by 2 to calculate the application rate of 0.74 $in\ h^{-1}$ (1.9 $cm\ h^{-1}$).

The canning method also helps indicate the distribution uniformity (DU) of the irrigation system which is the ratio of under-watered area to the average applied within the sprinkler coverage area. The most common measure of distribution uniformity is the "low-quarter" method. With this method, distribution uniformity is determined by identifying the depth of irrigation applied to the driest 25 % of the test area and dividing it by the mean depth of water in all cans. The equation of DU involves:

$$\text{distribution uniformity (DU)} = \frac{\begin{array}{c}\text{average } \textbf{least} \text{ amount of water depth}\\ \text{collected in 25 \% of all cans}\end{array}}{\text{average depth of water collected for all cans}}$$

Typical DU values range from 55 to 80 %; even rainfall is not 100 % uniform. The lower the value, the less uniformity with which an irrigation system applies water; thus, the more water and energy requirements are needed to uniformly meet plant needs. Obtaining 80 % DU is considered excellent (achievable), 70 % as good (minimum) and 55 % or less as poor. Means of improving existing DU values include: (1) changing sprinklers and sprinkler nozzles; (2) pressure changes (increases); and, (3) changing sprinkler spacing.

Example

1. Determine the distribution uniformity (DU) of the following conditions. A can test was performed with 20 cans evenly spaced 5 *ft* (1.5 *m*) apart in a grid system. After a 15-min run cycle, the average depth in the five **least**-filled cans was 0.2 *in* (0.5 *cm*). The average depth measure in all cans was 0.33 *in* (0.84 *cm*). The irrigation rate is then adjusted from inches per 15-min to inches per hour by multiplying the 0.33-*in* (0.84-*cm*) and 0.2-in (0.5-*cm*) by 4 to achieve 1.32-$in\ hr^{-1}$ (3.36-$cm\ hr^{-1}$) and 0.8-$in\ hr^{-1}$ (2.0-$cm\ hr^{-1}$) respectively. The DU value is then determined:

$$\text{distribution uniformity (DU)} = \frac{\text{average } \textbf{least} \text{ amount of water depth collected in 25\% of all cans}}{\text{mean depth collected for all cans}}$$
$$= \frac{0.8\,in}{1.32\,in}$$
$$= 0.61\,(\text{or } 61\,\%)$$

2. How much water would be needed to apply 0.5 *in* (1.3 *cm*) over the entire area? $\frac{0.5\ in}{0.61\ \text{DU}} = 0.82\ in\ (2.1\ cm)$ of irrigation needed to apply at least 0.5 in (1.3 cm) over the area.
3. How long would the irrigation system need to run to apply 0.88 *in* (2.2 *cm*)?

   From the above information, it was determined the irrigation system delivered $1.32\,in\ hr^{-1}$ ($3.4\,cm\ hr^{-1}$), therefore,

$$0.88\ in \times \frac{1\ hr}{1.32\ in} \times \frac{60\ min}{hr} = 40\ min$$

Irrigation system calibration, but not DU, can also be determined by knowing the amount (gal) of water applied per irrigation head, the sprinkler spacing (*ft*), and by using one of the formulas listed in Table 4.4. Different formulas are needed depending on whether the sprinkler head design is on square spacing, triangular spacing, or single row design. For example, to determine inches of water applied per hour for an irrigation system designed with triangular spaced heads 50 *ft* apart that apply $30\,gal\ min^{-1}$ of water per head, use the following equation from Table 4.4.

$$\text{in water applied}\,h^{-1} = \frac{96.3 \times gal\,min^{-1}\text{ per head}}{(\text{sprinkler spacing, } ft)^2 \times 0.866}$$
$$= \frac{96.3 \times 30\,gal\,min^{-1}\text{ applied per head}}{(50ft)^2 \times 0.866}$$
$$= 1.33\,in\ h^{-1}\left(3.4\,cm\ h^{-1}\right)$$

Table 4.4 Irrigation application rates per head based on the head spacing pattern

Square spacing head design
$\frac{96.3 \times gal\ min^{-1}\text{applied per full circle head}}{(\text{sprinkler spacing, } ft)^2} = in\,h^{-1}$
Triangular spacing head design
$\frac{96.3 \times gal\ min^{-1}\text{applied per full circle head}}{(\text{sprinkler spacing, } ft)^2 \times 0.866} = in\,h^{-1}$
Single row spacing head design
$\frac{96.3 \times gal\ min^{-1}\text{applied per full circle head}}{\text{sprinkler throw diameter } (ft) \times 0.80 \times \text{sprinkler spacing } (ft)} = in\ h^{-1}$

Table 4.5 Conversions and calculations for determining turfgrass irrigation needs

1 *ac-in* (water needed to cover 1 *ac* to 1 *in* depth)	$= 27,154\,gal$ $= 43,560\,in^3$ $= 3,630\,ft^3$	1 *ac-ft* (water needed to) cover 1 *ac* to 1 *ft* depth)	$= 325,851\,gal$ $= 43,560\,ft^3$
$1\ in\ 1,000\,ft^{-2}$	$= 623.33\ gal$ $= 83.33\,ft^3$	7.48 *gal*	$= 1\,ft^3$ $= 1728\ in^3$
1 *gal*	$= 0.134\,ft^3$ $= 231 in^3$ $= 8.34 lb$ water	1 *ft*3 1 *psi* 1 *ft* of head	$= 7.4805\ gal$ $= 2.31\,ft$ of head $= 0.433\ psi$
1 *lb* of water	$= 0.1199\ gal$ $= 27.7\ in^3$	1 million *gal*	$= 3.07$ *ac-ft*

Example

1. If 46 *ac* (18.6 *ha*) of turf were to receive 1 *in* (2.5 *cm*) of water, what is the total amount of water, in gallons, needed? From Table 4.5, 1 *ac-in* of water equals 27,154 *gal*; thus, 27,154 *gal* × 46 *ac* = 1,249,084 total *gal* water needed (4.7 million *L*).
2. If water costs are $\$0.03\,ft^{-3}$ of water, what is the total cost of this volume? From Table 4.5, $1\,ft^3$ equals 7.48 *gal* of water; thus,

$$\frac{1ft^3}{7.48} \times 1,249,084gal \quad total \times \frac{\$0.03}{ft^3} = \$5,010$$

Determining Irrigation Rates and Frequency

In addition to the application rate and uniformity, the turf manager should know how much water the turf is using. This can be determined using reference ET from a weather station/computer system plus a crop coefficient specific for the turf species from data in Table 4.3, or with data from an atmometer or other devices as previously discussed. Historical weather information may also provide reasonable estimates of average water use. Managers also need to know where the roots are in the soil profile and approximately how much available water is held by the soil.

The amount of water needed to moisten the soil to a given depth depends on soil type, water infiltration and percolation rates, and surface slope. Figure 4.10 presents the amount of water needed to wet different soils to various depths. Soils severely sloped, compacted, or clayey in nature may have low infiltration rates. As a result, the soil may not be able to absorb the required amount of irrigation at one time. Managers may have to irrigate using multiple cycles until the desired amount is applied. After an irrigation event, managers should double-check the depth of moisture penetration using a soil probe or screwdriver so they can fine-tune their timing.

As previously noted, evaporation during hot, windy, and dry periods can reduce irrigation efficiency. Superintendents can avoid this by irrigating early in the morning before the temperature rises and humidity drops. Early morning irrigation also removes dew from the leaves, and helps prevent diseases favored by irrigating in the evening.

Fig. 4.10 Approximate penetration depth of water applied to three types of soil

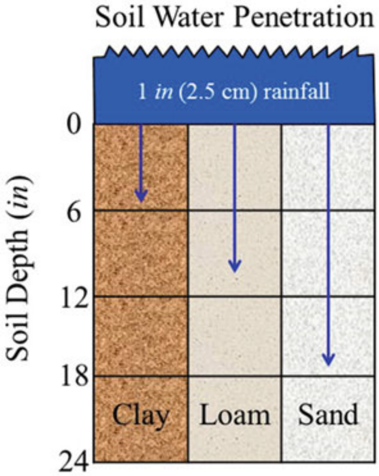
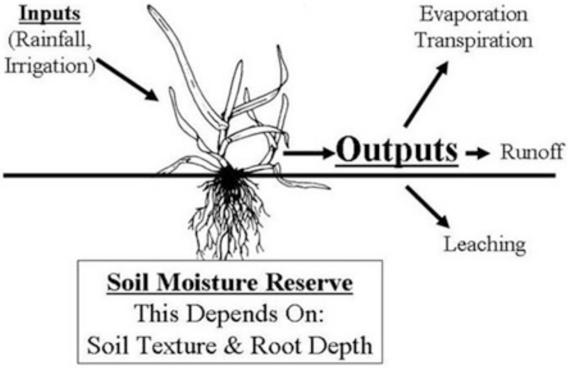


Fig. 4.11 Inputs and outputs when developing a water budget to determine irrigation needs



Water Budgeting

Budgeting water is analogous to handling money in a checking account (Fig. 4.11). There are inputs (deposits), outputs (withdrawals), and a certain amount of water in the soil (standing balance). The flow of water (money) into and out of the "checking account" (the rootzone) is simply followed over time. If the roots penetrate 12 *in* (30 *cm*), the checking account is the water held in 12 *in* (30 *cm*) of soil. If the roots penetrate only 2 *in* (5 *cm*), the checking account is considerably smaller. Irrigation is applied to wet the rootzone, no more, no less. Generally, most of the roots on putting greens and tees are in the top 6 *in* (15 *cm*) of soil, whereas roots on fairways and roughs often penetrate 12 *in* (30 *cm*) or more.

Consider a silt-loam soil at field capacity, which is roughly 2.0 *in* (5 *cm*) of water per foot of soil (see Chap. 1). A 12 *in* (30 *cm*) deep bermudagrass root system growing in this soil will have access to 2.0 *in* (5 *cm*) of available water.

Weather station data and a predictive model estimate over a 6-day period that 1.8 *in* (4.6 *cm*) of water was used by the theoretical reference crop. Correcting this reference value using a K_c of 0.7 for bermudagrass, estimates the turf actually uses about 1.3 *in* of water ($1.8 \times 0.7 = 1.26\,in$, $3.2\,cm$). Subtracting this from the original 2.0 *in* (5 *cm*) of available water gives about 0.7 *in* (1.8 *cm*) of water left in the soil. Should the turf go another day before irrigating? No, it's time to water, since it is never a good idea to deplete most of the available water. Approximately 1.5 *in* (3.8 *cm*) of irrigation should be applied to replace the 1.3 *in* (3.3 *cm*) lost from the system. The soil is returned to field capacity without irrigating excessively and wasting water.

For most turfgrass examples, the amount of water at wilting point is negligible. Turfgrass rooting depth should be used instead of soil rootzone depth since most moisture obtained by plants in a reasonable time frame will be in the rooting depth and not below it.

Determining Approximate Intervals (in Days) Between Irrigation Cycles

$$\text{irrigation interval (days)} = \frac{\text{soil water content at field capacity} \times \text{rooting depth } (in)}{\text{daily ET rate } (in\ day^{-1})}$$

Example Determine the time between irrigation cycles for a sand soil with a volumetric water content of 15 % at field capacity, a rooting depth of 4 *in* (10 *cm*), and a summer daily ET rate of 0.20 $in\ day^{-1}$ (5 $mm\ day^{-1}$):

$$\frac{0.15 \times 4\,in}{0.20\,in\,day^{-1}} = 3 \text{ days between irrigation cycles, which brings the soil back to field capacity}$$

If rainfall occurs and it is more than the amount of water depleted during the period (1.3 *in*, 3.3 *cm*), the rootzone is returned to field capacity and any excess is ignored since it will drain and not be stored in the rootzone. If it rains less than actual ET, the running deficit is calculated over several days, and irrigation is scheduled when ET has depleted the soil moisture to a bit more than 50 % of the 0.6 *in* ($0.15 \times 4\,in$) of available water. A good rain gauge is needed to keep track of precipitation, and it is a good idea to use automatic pump shutdown switches to prevent irrigation after a significant precipitation. Conversion factors in Table 4.5 indicate gallonage required to apply certain amounts.

Example From the use of a hand-held TDR probe, determine a soil moisture management program including when to irrigate and how much water is needed to return the total moisture levels to field capacity for two sands with $\theta_{fc} = 0.32$ and $0.22\,cm^3\ cm^{-3}$ and $\theta_{wp} = 0.02$ and $0.01\ cm^3\ cm^{-3}$ for sands 1 and 2, respectively. The TDR probe measures moisture in the top 10 *cm* (4 *in*) of the soil profile.

step 1: Determine available water for each sand using the equation:

$$\mathrm{D_e} = s\mathit{oil\ depth}\ \left(\theta_{\mathrm{fc}} - \theta_{\mathrm{w}p}\right)$$

where:

$\mathrm{D_e}$ = equivalent depth of available water in the top 10 *cm* (4 *in*),
θ_{fc} = volumetric water content at field capacity,
θ_{wp} = volumetric water content at wilting point

$$\text{For sand 1}: \quad \mathrm{D_e} = \text{soil depth}\left(\theta_{\mathrm{fc}} - \theta_{\mathrm{wp}}\right) = 10\ (0.32 - 0.02) = 3.0\,cm(1.18\,in)$$

$$\text{For sand 2}: \quad \mathrm{D_e} = \text{soil depth}\left(\theta_{\mathrm{fc}} - \theta_{\mathrm{wp}}\right) = 10\ (0.22 - 0.01) = 2.1\,cm(0.83\,in)$$

step 2: If the effective rootzone is 10 *cm* (4 *in*) deep and the turfgrass being used has an average ET rate of 0.2 *in* day^{-1} (0.5 *cm* day^{-1}), the days between watering for each sand would be:

$$\text{sand 1}: \quad 3.0\,cm\,\text{rootzone moisture} \times \frac{1\,\text{day}}{0.5\,cm\,\text{moisture used}} = 6\,\text{days}$$

$$\text{sand 2}: \quad 2.1\,cm\,\text{rootzone moisture} \times \frac{1\,\text{day}}{0.5\,cm\,\text{moisture used}} = 4.2\,\text{days}$$

Therefore, for sand 1, 3.0 *cm* of water would be needed every 6 days while for sand 2, 2.1 *cm* would be needed every 4.2 days to return each to field capacity.

With information on ET rates and sprinkler calibration available, each sprinkler's run time can be calculated. The daily ET rate is divided by the sprinkler output. For example, if the day's ET rate is 0.3 *in* (7.6 *mm*) and the sprinkler output is 0.01 $in\ min^{-1}$ (0.25 $mm\ min^{-1}$), the irrigation time needed would be 30 *min*. However, this is adjusted according to the appropriate crop coefficient (e.g., 0.85 for bentgrass); therefore, 30 *min* is multiplied by 0.85 to give 25 *min* of run-time needed. Distribution uniformity considerations should then be incorporated to ensure enough water is being applied uniformly across the turf area.

Example Water use engineers employed at a municipality require a golf course to justify their water use permit in terms of total amount of water requested and how they determined this value (patterned after Green 2005).

A: Determine average yearly ET rate from one of the methods listed previously. In this example, 56.37 *in* (4.7 *ft*, 1.4 *m*) is used.
B: Determine normal yearly precipitation rate. In this example, 10.67 *in* (27 *cm*) is used.
C: Area of irrigated turfgrass. In this example, 110 *ac* is used (3.1 *ac* for greens, 3.7 for tees, 43.7 for fairways, and 59.5 for roughs).
D: Determine the irrigation efficiency (DU). In this example, 70 % is used.

	Greens	Tees	Fairways	Roughs
E. turf area (*ac*)	3.1	3.7	43.7	59.5
F. Turfgrass	Bentgrass	Bermuda overseeded Oct–May	Bermuda overseeded Oct–May	Bermuda
G. K_c (crop coefficient)	0.8	0.75	0.75	0.65
H. Turf Water Use [A × G] (which is ET × K_c)	45.1	42.3	42.3	36.6
I. 25 % precipitation (*in*): [B × 0.25][a]	2.7	2.7	2.7	2.7
J. Water use adjusted for 25 % precipitation (in): [*H-I*]	42.4	39.6	39.6	33.9
K. Irrigation water use (*in*): [J/D]	60.6	56.6	56.6	48.4
L. K converted to feet: [K/12] (12 *in* = 1 *ft*)	5.1	4.7	4.7	4.0
M. Annual irrigation use (*ac-ft*): [E × L]	15.8	17.4	205.4	238.0
N. Annual irrigation water use: [sum of M for all turf areas]	477 *ac-ft* (or 155,430,927 *gal*)			

[a] Water use regulators often use a precipitation efficiency adjustment value to reflect the amount (percentage) of usable precipitation by plants. Rainfall is often at inefficient amounts (too high or low) or at the wrong agronomic time.

In the above example, to compare calculated annual irrigation use to the overall formula, ET × area, the following was determined:

O. ET × 110 *ac*: *A* (*ft*) × *C* (total turfgrass area) or 4.7 *ft* × 110 *ac* = 517 *ac-ft* predicted by the simple formula,

P. Calculation efficiency for water budget: *N*/*O* × *100* or 477 *ac-ft* ÷ 517 *ac-ft* × 100 = 92 %. This value indicates the simple formula of ET × area overestimated water needs by 8 % compared to the Water Budgeting process above.

4.4 Managing Irrigation Water Quality Problems

Turf facilities are increasingly using poorer quality irrigation sources. Wells, ponds, retention ponds, canals, streams, rivers, lakes, and waste treatment plants are common water sources for irrigation. Water from waste treatment plants may contain elevated nutrient and trace element concentrations. Successful irrigation management requires regular monitoring of both soil and water chemistry, especially salt content. The following tests provide information concerning soil and water quality:

- **Water soluble salts** (or **Salinity drought hazard**)—Total salt content as measured by the electrical conductivity (EC_W) or total dissolved salts (TDS) of water. Excessive salts produce plant physiological drought.

- **Sodium status**—Soil sodium level proportionally to Ca and Mg ions as measured by sodium adsorption ratio (SAR), exchangeable sodium percentage (ESP), or adjusted SAR (adj. SAR). SAR also is used to assess the sodium levels of water. Excessive sodium causes soil structure deterioration.
- **Specific ions toxicity**—Toxic ion levels, especially boron, chloride, fluoride, sulfate and nitrate-nitrogen.
- **Alkalinity**—Bicarbonates and carbonates as measured by residual sodium carbonate (RSC).
- **pH and lime requirement.**
- **Suspended solids**, as measured by total suspended solids (TSS).
- **Soil nutrient imbalance based on**:
  - Sufficiency levels of available nutrients and cation ratio.
  - Soil cation exchange capacity (CEC).
  - Percent base saturation.
  - Percent organic matter.

Salts

A salt is a combination of positively charged ions (cations) and negatively charged ions (anions). Cations include calcium, magnesium, sodium, ammonium, and potassium; while anions include carbonates, bicarbonate, nitrate, sulfate, chloride, and boron. Table salt (sodium chloride) is found in some soils. Insoluble salts (i.e., gypsum and lime) occur, but excessive soluble salts are the primary ones that may impede plant growth rather than the insoluble ones. High soluble salts in the soil solution reduce water availability, causing the turfgrass to be prone to drought stress. This is the most important or most common salt problem involved with turfgrasses.

The amount of salt in water determines the degree of salinity and, to a large extent, the overall water quality. The following equation determines the amount of salt applied when irrigating with saline water:

$$\begin{aligned} lb\,\text{salt applied}\,ac^{-1} &= \text{irrigation water salinity level}\ \left(ppm\,\text{or}\,mg\ L^{-1}\right) \\ &\quad \times 2.72\ \text{million}\,lb(\text{weight of water per}\,ac\text{-}ft) \\ &\quad \times ac\text{-}ft\,\text{water applied} \end{aligned}$$

Example How much salt is applied, if 1 *in* (2.5 *cm*) of water with salinity levels of 640 *ppm* is used? 1 *in* = 0.083 *ft*.

$$\frac{640\,parts}{1{,}000{,}000} \times \frac{2{,}720{,}000\,lb}{ac\text{-}ft\,\text{water}} \times 1\,ac\text{-}in\,\text{water} \times \frac{1ft}{12\,in} = 144\,lb\,\text{salt applied per acre}$$

To determine the amount of salt applied per $1000ft^2$, divide 144 *lb* salt ac^{-1} by 43.56 = 3.3 *lb* salt applied per $1000ft^2$, when 1 *in* (2.5 *cm*) of irrigation water with a salinity level of 640 *ppm* is used.

Two types of salt problems exist: (1) those associated with the total salinity, and (2) those associated with sodium. Water with high salinity becomes toxic to plants and poses a **salinity hazard**. As mentioned, soil salt accumulation is the most common cause of plant injury from poorer quality water but normally must occur over an extended period of time before this is seen. Combinations of saline irrigation use, low precipitation, poor soil drainage, and the use of cool-season turfgrasses increase the likelihood of salinity problems. Salt soils may cause direct injury to turfgrass growth or indirect injury due to soil physical properties. Direct stresses include moisture stress as roots are unable to absorb tightly held soil moisture, ion toxicity, or nutrient (ion) imbalances. In saline soils, water moves from an area of lower salt concentration (plant roots) to an area of higher salt concentration (the soil). This causes plant water stress and wilt even though the soil may be wet. Indirect stress occurs from high soil sodium by destroying soil structure, thus, reducing water infiltration, drainage, and soil oxygen levels. Salinity problems are less likely to develop with high rainfall and cooler climates, use of salt-tolerant warm-season grasses, and soils that are well-drained.

Drought stress symptoms from salinity stress include turf developing bluish-green color, wilting, leaf rolling or folding, and eventual leaf firing (yellowing and death) (Fig. 4.12). Direct ion toxicity to plants can occur from excessive soil levels of sodium (Na^+), chloride (Cl^-), boron (B^-), bicarbonate (HCO_3^{-2}), and high pH

Fig. 4.12 Direct salinity damage to turf resembles drought symptoms or fertilizer burn. Shown is salt-damaged turf from an ocean storm surge across a golf course fairway

Fig. 4.13 Salt and bicarbonate build up on a soil surface from inadequate flushing and soil drainage

[hydroxyl (OH^-)] ions. Nutrient imbalance from high soil levels of sodium, chloride and other ions can also occur. High levels of these can cause deficiencies of calcium (Ca^{+2}), potassium (K^+), nitrates ($NO_3{}^-$), magnesium (Mg^{+2}), manganese (Mn^{+2}), and phosphorus (P).

Salts also can move upward from groundwater. Water is drawn to the surface when evaporation exceeds the amount of water being applied and is deposited on the soil and plant surface through the process of capillary rise. Formation of a white crust on the soil surface indicates salt accumulation, as does shoot browning (Fig. 4.13). Many arid and semiarid soils, especially when annual rainfall is $<15\,in$ ($38\,cm$), are salt affected due to insufficient leaching to remove salts that accumulate from the weathering of minerals, groundwater, and rain. In arid and semiarid regions, sodium and sulfate salts (Na_2SO_4, K_2SO_4, $CaSO_4$, and $MgSO_4$) usually dominate, reflecting the composition of the soils parent material.

Measuring and Classifying Irrigation Salinity

Salinity hazard is determined by measuring the ability of water to conduct an electrical current. Salty water is a good conductor of electrical current, whereas pure water is a relatively poor conductor. Salinity is expressed in two different ways, either as **electrical conductivity** (EC_w) or **total dissolved salts** (TDS) (also reported as **total soluble salts**, TSS). There are several units commonly used to express EC_w: deciSiemens per meter ($dS\ m^{-1}$), millimhos per centimeter ($mmhos\ cm^{-1}$), or micromhos per centimeter ($\mu mhos\ cm^{-1}$). The relationship between these units is:

$$1 dS\ m^{-1} = 1\ mS\ cm^{-1} = 0.1\ S\ m^{-1} = 1\ mmhos\ cm^{-1} = 1000\ mmhos\ cm^{-1}$$
$$= 640\, ppm\, \mathrm{TDS}$$

Total dissolved salts are expressed in parts per million (*ppm*) or milligrams per liter ($mg\ L^{-1}$) and are generally not measured directly, but calculated from an EC_w measurement.

$$\mathrm{TDS}\ \left(mg\ L^{-1}\ \mathrm{or}\ ppm\right) = EC_w\left(mmhos\ cm^{-1}\ \mathrm{or}\ dS\ m^{-1}\right) \times 640$$

Individual components of salinity (such as sodium) may also be reported in milliequivalents per liter ($meq\ L^{-1}$). To convert ppm to $meq\ L^{-1}$, divide the *ppm* of the ion by its equivalent weight. The ratio of total dissolved salt to EC_w of various salt solutions ranges from 550 to 740 *ppm* per $dS\ m^{-1}$. The most common salt in saline water, sodium chloride, has a TDS of 640 *ppm* at an EC_w of 1 $dS\ m^{-1}$. Most laboratories use this relationship to calculate TDS from EC_w, but some multiply the amount by 700.

Example

1. An irrigation source has an EC_w of 0.53 $mmhos\ cm^{-1}$. What would the EC_w be in $dS\ m^{-1}$, $\mu mhos\ cm^{-1}$, and *ppm* TDS?
   (a) Since 1 $dS\ m^{-1} = 1\ mmhos\ cm^{-1}$, then 0.53 $mmhos\ cm^{-1} = 0.53\ dS\ m^{-1}$
   (b) Since 1 $mmhos\ cm^{-1} = 1000\ \mu mhos\ cm^{-1}$, then

$$0.53\ mmhos\ cm^{-1} \times \frac{1,000\ \mu mhos\ cm^{-1}}{1\ mmhos\ cm^{-1}} = 530\ \mu mhos\ cm^{-1}$$

   (c) To convert $mmhos\ cm^{-1}$ to *ppm*, multiply by 640:

$$0.53\ mmhos\ cm^{-1} \times 640 = 339\ \ ppm\ \ \mathrm{TDS}$$

2. The salt content of a water sample is 1121 $mg\ L^{-1}$ TDS. What is the salt content in $dS\ m^{-1}$ and $\mu mhos\ cm^{-1}$?
   (a) To convert TDS ($mg\ L^{-1}$ or *ppm*) to $dS\ m^{-1}$, divide by 640:

$$1,121\ mg\ L^{-1} \div 640 = 1.75\ \ dS\ m^{-1}$$

   (b) To convert $dS\ m^{-1}$ (or $mmhos\ cm^{-1}$) to $\mu mhos\ cm^{-1}$, multiply by 1000:

$$1.75\ \ dS\ m^{-1}\left(\mathrm{or}\ mmhos\ cm^{-1}\right) \times 1,000 = 1,750\ \mu mhos\ cm^{-1}$$

Table 4.6 Salt concentration hazard levels for irrigation water

Hazard	EC_w ($dS\ m^{-1}$)	Total dissolved salts (*ppm*)
Low	0.75	500
Medium	0.75–1.5	500–1000
High	1.5–3.0	1000–2000
Very high	>3.0	>2000

3. Convert 100 *ppm* Ca to $meq\ L^{-1}$. The equivalent weight of Ca^{+2} is 20.

$$100\,ppm\ \text{Ca} \div 20 = 5\,meq\ L^{-1}\ \text{of Ca}$$

Water sample salinities are often compared to those of seawater with an average EC_w of 54 $dS\ m^{-1}$ or about 34,500 *ppm* dissolved salts.

Irrigation water is classified based on the salinity hazard, which considers the potential for damaging plants and the level of management needed for utilization as an irrigation source (Table 4.6). Water with EC_w readings of less than 0.75 $dS\ m^{-1}$ is suitable for irrigation without problems. Successful use of water with EC_w values above 0.75 $dS\ m^{-1}$ depends upon soil conditions and plant tolerance to salinity. Generally, higher salinity levels can be used on sandy soils where salts can be flushed. Similar values on poorly draining clay soils that may cause problems. Under typical summer stress, EC_w of turfgrass irrigation should ideally not exceed 1.25 $dS\ m^{-1}$soluble salts. Salinity levels above 3.0 $dS\ m^{-1}$ are unsuitable for any length as an irrigation source.

Water Sodium Hazard

The primary cause of sodic or saline-sodic soil is using high sodium (Na^+) content irrigation water. While EC_w is an assessment of all soluble salts in a sample, **sodium hazard** (termed sodic or saline-sodic soil) accounts for sodium's specific detrimental effects on soil physical properties. The potential for irrigation water to have poor infiltration properties or sodium hazards is assessed by determining the **sodium adsorption ratio** (SAR) and the electrical conductivity (EC_w) of the water. The sodium adsorption ratio relates the concentration of sodium to the concentration of calcium and magnesium. Calcium and magnesium counter the negative effects of sodium on soil structure. The higher the sodium level in relation to calcium and magnesium, the higher the SAR, the poorer the water infiltration, and the more increased problems with soil deflocculation (deterioration—swelling, dispersion, and permeability reduction). The collapse of aggregates from dispersion of clay tends to clog large pores, particularly at the soil surface. Salt concentration and exchangeable sodium percentage then become problems with the loss of permeability. Calcium will hold soil together (or flocculate), while sodium pushes (or disperses) soil particles apart. The dispersed soil readily crusts and poses water infiltration and permeability problems.

SAR is defined as:

$$\mathrm{SAR} = \frac{\mathrm{N}a^{+}}{\sqrt{\frac{\mathrm{C}a^{+2} + \mathrm{M}g^{+2}}{2}}} \quad or \quad \frac{\mathrm{N}a^{+}}{\sqrt{\mathrm{C}a^{+2} + \mathrm{M}g^{+2}}}$$

Ion concentrations in the equation above left are expressed in milliequivalents per liter (*meq* L^{-1}) while those in the equation above right are expressed in millimoles per liter (*mmol* L^{-1}). Milliequivalents describe the molecular weight adjusted for the valence number (number of positive charges) of the ion. The SAR is determined by the number of milligrams per liter (*mg* L^{-1} or *ppm*) of Na^{+}, Ca^{+2}, and Mg^{+2} in a water sample. To convert *ppm* (or *mg* L^{-1}) to *meq* L^{-1}, use the following equation and equivalent weights for Na^{+}, Ca^{+2}, and Mg^{+2} of 23, 20, and 12.2 *mg* meq^{-1}, respectively. Use of the saturated paste extract method, rather than other soil test extraction methods, is necessary for determining soil Na^{+}, Ca^{+2}, and Mg^{+2} levels for the SAR equation.

$$meq L^{-1} = \frac{\text{concentration}\left(ppm\,\text{or}\,mg L^{-1}\right)}{\text{equivalent weight}\left(mg\,meq^{-1}\right)}$$

Example A water sample test reports 1000 *mg* L^{-1} Na^{+}, 200 *mg* L^{-1} Ca^{+2}, and 100 *mg* L^{-1} Mg^{+2}.

Find the SAR value in *meq* L^{-1}.

step 1: Calculate the concentration (*meq* L^{-1}) of each ion:

$$\begin{aligned} \mathrm{Na}^{+} &: 1000\,mg L^{-1} \div 23\,mg\,meq^{-1} = 43.5\,meq L^{-1} \\ \mathrm{Ca}^{+2} &: 200\,mg L^{-1} \div 20\,mg\,meq^{-1} = 10\,meq L^{-1} \\ \mathrm{Mg}^{+2} &: 100\,mg L^{-1} \div 12.2\,mg\,meq^{-1} = 8.2\,meq L^{-1} \end{aligned}$$

step 2: Place these values into the SAR equation:

$$SAR = \frac{\mathrm{N}a^{+}}{\sqrt{\frac{\mathrm{C}a^{+2} + \mathrm{M}g^{+2}}{2}}} = \frac{43.5}{\sqrt{\frac{10 + 8.2}{2}}}$$
$$= 14.4\ meq\ L^{-1}$$

Example A water analysis indicates a Na^{+} concentration of 85 *meq* L^{-1}, a Ca^{+2} concentration of 33.3 *meq* L^{-1}, and a Mg^{+2} concentration of 7.1 *meq* L^{-1}. What is the SAR value for this water?

Table 4.7 SAR values, categories, and precautions for irrigation sources with $EC_w \geq 1\ dS\ m^{-1}$

SAR or adj SAR ($meq\ L^{-1}$)	Category	Precaution
0–10	Low sodium water	Little danger from structure deterioration to almost all soils. For ornamentals, water SAR values should be <10.
10–18	Medium sodium water	Problems on fine-textured soils and sodium-sensitive plants, especially under low-leaching conditions. Soils should have good permeability.
18–26	High sodium water	Problems on sodium accumulation on most soils. Good salt-tolerant plants are required along with special management, such as good drainage, the use of gypsum, and leaching. Generally, high and very high EC water should not be used for irrigating turfgrasses long term.
>26	Very high sodium water	Unsatisfactory except with high salinity ($EC_w > 2.0\ dS\ m^{-1}$), high calcium levels, and the use of gypsum.

$$\mathrm{SAR} = \frac{\mathrm{N}a^{+}}{\frac{\sqrt{Ca^{+2} + \mathrm{M}g^{+2}}}{2}} = \frac{85}{\frac{\sqrt{33.3 + 7.1}}{2}} = 18.9 \quad meq\ L^{-1}$$

Since salts and sodium do not act independently, the effect of sodium on soil particle dispersion, thus permeability, is counteracted by high concentrations of soluble salts (measured as EC_w) in the irrigation water. The effects of high SAR on irrigation water infiltration are dependent on the electrical conductivity of the water (Table 4.7). For a given SAR, the lower the EC_w, the greater dispersion or poorer infiltration properties; the higher the EC_w, the better the infiltration. For example, irrigation water with a $SAR = 15\ meq\ L^{-1}$ has poor infiltration properties with an $EC_w = 0.5\ dS\ m^{-1}$, but good infiltration properties with an $EC_w = 2.0\ dS\ m^{-1}$. As a rule-of-thumb, if the SAR is more than ten times greater than the EC_w, then poor water infiltration is likely to occur. When the $EC_w = 0.5\ dS\ m^{-1}$ or less, the water has very few minerals to flocculate soil particles. Thus, irrigating with this **pure water** strips minerals from cation exchange capacity (CEC) sites, causing dispersed particles to settle closely next to each other. The result is a compacted soil surface which forms a thin crust layer, impeding water flow into the soil. Problems can develop quickly when $EC_w \leq 0.2\ dS\ m^{-1}$. In the case of pure water, the problem exists regardless of the SAR value since very few minerals are present to begin with.

Clay-textured soils can have structural permeability problems if a water $SAR > 9\ meq\ L^{-1}$ is used over an extended period that reduces infiltration, percolation, and drainage, often causing low soil oxygen problems. In the earlier example where the water sample had an SAR of $14.4\ meq\ L^{-1}$, problems could occur if this water source was used long term on finer-textured soils.

Example A superintendent has two water sources to choose from based on their sodium hazard.

Sample 1. $SAR = 5.0$ and $EC = 0.5$.

Sample 2. $SAR = 5.0$ and $EC = 1.5$.

Which one is more suitable?

Sample 1. Water infiltration problems may occur, especially on finer textured clay or silt-based soils.

Sample 2. This sample is less likely to cause soil water infiltration problems.

Soil Sodium Permeability Hazard

Although high sodium levels in irrigation water can be directly toxic to plants (especially ornamentals), its most deleterious effect is on soil structure. Since sodium ions (Na^+) are monovalent (have only one positive charge), two sodium ions are needed to displace divalent (two positive charged) ions such as calcium (Ca^{+2}) or magnesium (Mg^{+2}). This concern is greater on fine-textured soils such as clays and silt loams. Salts often accumulate in high, exposed sites such as hilltops while low areas may accumulate salts from runoff.

High soil sodium causes finer-textured soil clays and organic matter to disperse (termed **deflocculation**) to where aggregates break down into smaller units and smaller clay minerals and organic particles plug soil pores, reducing water infiltration and soil aeration. Soil then seals and becomes hard and compacted, reducing soil water and oxygen movement. The higher the clay and organic matter content of the soil, the greater the effects of sodium. Typically, for soil structure breakdown, sodium levels exceed calcium levels by more than 3 to 1. These soils are characterized by pools of standing water after irrigation. To counteract the negative effects of sodium, increasing calcium and magnesium concentrations in clay soils will cause the soil to flocculate (have good structure). A key management step is to prevent soil structure breakdown.

Soil structure can be destroyed by continued use of water containing high levels of sodium. This results in reduced water infiltration, drainage, and soil oxygen. The sodium ions replace calcium and magnesium ions on the clay CEC sites, destroying its structure plus reducing pore continuity, thus reducing infiltration, percolation, and drainage.

Assessing Soil Salinity

Saline soils are classified based on two criteria: (1) the **total soluble salt** or **salinity content** based on electrical conductivity of a saturated extract (EC_e), and (2) **exchangeable sodium percentage** (or, more recently, **sodium adsorption ratio**). Additional information is also often used, such as carbonate content and potential toxic ions.

Soluble salts are measured in soils by the same basic method as used for water samples. A conductivity instrument measures electrical conductivity in an extract

(EC_e) either from a **saturated paste** (preferred method) or from a **soil:water dilution**. As total salt concentration increases, EC_e also increase. The SAR is a calculated value from a saturated paste extract sample based on milliequivalents per liter of Ca, Mg, and Na. The saturated paste extract is the most precise method to determine soil EC, SAR, and boron levels. A soil sample is brought just to the point of saturation using the irrigation source, allowing it to equilibrate for several hours, and then is subjected to vacuuming to extract the soil solution through filter paper. Spectrophotometers and other analytical equipment are then used to quantify the soil solution. Using the saturated paste extract, soils with EC_e readings $<1.5\, dS\ m^{-1}$ are considered to have low salt levels. Soils with EC_e readings of 1.6 to $3.9\, dS\ m^{-1}$ have medium levels. When soil readings are above $4.0\, dS\ m^{-1}$, soils are considered to have high salt levels and only salt-tolerant turfgrasses normally survive.

Soil water dilution ratios are either a 1:2 dilution (one part dry soil:two parts water) or a 1:5 dilution (one part soil:five parts water). Electrical conductivity readings from these three methods are not comparable, so the method used must be known in order to interpret the EC_e reading. Soil testing laboratories frequently use a 1:2 dilution method because it is more rapid than obtaining a saturated paste extract. The EC_e of a 1:2 extract is on average 20 % of the EC_e of a saturated paste extract, on sand-based greens. To estimate the EC_e of a saturated paste from a 1:2 extract, multiply the EC_e of the 1:2 extract by 5.

Assessing Soils for Sodium Problems

Sodicity refers to high concentration of sodium (Na^+) while **salinity** refers to high concentrations of total salts including NaCl, Ca^{+2}, Mg^{+2}, and SO_4^{-2}. Salt-affected soil can be classified as **saline**, **sodic**, and **saline-sodic** soils. **Saline soils** are the most common type of salt-affected soil and the easiest to reclaim. Saline soils are plagued by high levels of soluble salts, primarily chloride (Cl^-), sulfate (SO_4^{-2}), and sometimes nitrate (NO_3^-). Salts of low solubility, such as calcium sulfate or gypsum ($CaSO_4$) and calcium carbonate ($CaCO_3$), may also be present. Because exchangeable sodium is not a problem, saline soils are usually flocculated with good water permeability. Saline problems generally occur when: (1) there is insufficient rainfall to leach salts through the soil profile, (2) drainage is impaired, or (3) irrigation water contains high levels of salts.

Sodic soils, or soil structure deteriorated soils, have high levels of exchangeable sodium and low total soluble salt content, $HCO_3 > 120\, mg\ L^{-1}$ or $CO_3^{-2} > 15\, mg\ L^{-1}$. These soils tend to disperse, reducing water infiltration. Sodic soils also have a pH between 8.5 and 10 and are often called black alkali soils because the organic matter in the soil tends to disperse creating black-colored puddles (Fig. 4.14). Calcium and magnesium ions in sodic soils tend to form insoluble calcitic lime, leaving low soluble calcium and magnesium levels to displace sodium ions, allowing the sodium problems. The high sodium concentration of a sodic soil not only injures plants directly, but also degrades the soil

Fig. 4.14 Black-colored soil resulting from dispersed soil organic matter in sodic soils. This condition is referred to as **black alkali**

structure, termed "sodium hazard." Sodic soil cannot be improved by leaching the sodium from the soil profile alone. Soil amendments are required to replace the sodium in the soil, commonly a calcium containing amendment, in conjunction with leaching with acidified water.

Saline-sodic soils contain both high soluble salts and high exchangeable sodium. Saline-sodic soils, like sodic soils, are best reclaimed by adding a calcium-containing amendment and then leaching to remove excess soil sodium ions.

Two laboratory measurements are used to assess whether soils contain excessive sodium levels and if poor drainage and aeration are likely to occur. These measures are the **exchangeable sodium percentage** (ESP) and the **sodium adsorption ratio (SAR)**. The ESP identifies the degree or portion of the soil cation exchange capacity (CEC) occupied or saturated by sodium, and is calculated as follows:

$$\mathrm{ESP}\,(\%) = \frac{\text{exchangeable sodium }(meq\,100\,g^{-1})}{\text{cation exchange capacity }(meq\,100\,g^{-1})} \times 100$$

ESP does not consider the quantity of calcium and magnesium ions relative to sodium ions present like SAR does.

Example A soil test indicates the Na^+ content of a soil is $6.9\,meq$ 100 g^{-1} and the CEC of the soil is $17.3\,meq\,100\,g^{-1}$. Find the exchangeable sodium percentage (ESP) of this soil.

$$\begin{aligned}\text{ESP} &= \frac{\text{exchangeable sodium } (meq\,100\,g^{-1})}{\text{cation exchange capacity } (meq\,100\,g^{-1})} \times 100\\ &= \frac{6.9\,meq\,100\,g^{-1}}{17.3\,meq\,100\,g^{-1}} \times 100\\ &= 40\,\%\end{aligned}$$

Soil SAR is a second, more easily measured property, analogous to the irrigation water SAR discussed earlier which considers calcium and magnesium ion content in the soil. Soil SAR is calculated from soil-test extractable levels of sodium, calcium, and magnesium (expressed in $meq\,100\,g^{-1}$ or $mmol\,L^{-1}$).

ESP indicates the probability a soil will disperse, thereby reducing the permeability of soil to water and air. In the environment, salts and sodium do not act independently. High-soluble salt concentration can negate the soil particle dispersal (thus, impermeability) effects of sodium. Usually, little or only minor problems occur when ESP values are less than 13–15 %. An ESP $>15\,\%$ or a soil SAR $>13\,meq\,100\,g^{-1}$ indicates a **sodic** soil, where sodium causes soil colloids to disperse and plug the soil's drainage pores, thereby reducing the permeability of the soil to water and air. Sodic soils become saturated with sodium ions compared to calcium and magnesium ions, especially if bicarbonate ions are present. Symptoms of reduced permeability include waterlogging, reduced infiltration rates, crusting, compaction, disease occurrence, weed invasion, and poor aeration. Sodic soils often have considerable amounts of clay that is sticky due to the sodium. ESP and SAR are related and can be estimated by:

$$\text{ESP} = \frac{1.475 \times \text{SAR}}{1 + (0.0147 \times \text{SAR})}$$

Managing Poor Quality Water Use Sites

Managing salinity, sodicity, and alkalinity problems requires constant attention (Table 4.8). Management practices that aid in remedying these problems include:

1. Site assessment to determine which, if any, water and soil treatments are best.
2. Utilizing salt-tolerant grasses—warm-season turfgrasses generally are less salt-sensitive compared to cool-season turfgrasses, while most ornamentals are more salt-sensitive.
3. Diluting or blending poor quality water with good quality water.
4. Leaching excess salts by applying extra water.
5. Modifying soils with various amendments to replace and leach sodium from the soil.
6. Amending irrigation water to correct sodium and bicarbonate problems.

Table 4.8 Water and soil salinity problems with potential management solutions

Soil salinity problem	Potential solutions
Total Irrigation Salt Content (EC)	– Leaching; blending water sources; increase drainage and aeration; use salt tolerant varieties.
Soil SAR/adj. SAR	– Apply calcium amendment; apply sulfur alone (in calcareous soils) plus lime (in acidic soils); blending water sources; acid or sulfur irrigation injection in severe cases.
Exchangeable Sodium Percentage (ESP)	– Apply calcium amendment such as gypsum; apply sulfur alone (in calcareous soils) plus lime (in acidic soils); or sulfur irrigation injection in severe cases.
Soil Residual Sodium Content (RSC)	– Irrigation acid injection; sulfur generator; sulfur application in calcareous soils; blending water sources.
Soil Infiltration/Permeability (EC_w plus SAR)	– Gypsum additions to either: (a) low EC_w plus low SAR water; or, (b) low to moderate EC_w plus high SAR water; blending water sources.
Specific Ion Toxicity	– Establish tolerant varieties (especially ornamentals); blending water sources.
Total Suspended Solids	– Irrigation line filtration; use of settling ponds.
Nutrient Imbalances	– Adjusting fertility programs.

7. Enhancing soil drainage by using sands and installing subsurface drain lines plus intensive cultivation to enhance infiltration, percolation, and drainage of salt-laden water (see earlier).
8. Using cytokinin and iron-containing biostimulants as salt-stressed plants often exhibit low cytokinin activity, as well as using wetting agents and appropriate fertilizers.
9. Raising the mowing height to promote more stress-tolerant plants.
10. Routine use of wetting agents to help maintain good water infiltration and percolation to flush salts and sodium below the rootzone.

Blending Water Sources for Reducing Salinity

High salinity water that is unacceptable for use can be made suitable as an irrigation source by diluting it with nonsaline water. Enough nonsaline water must be available to create a mixed water of acceptable quality (i.e., not making a less-saline water that is still unacceptable). The quality of a poor water source should improve proportionally to the mixing ratio with better quality water. For example, a water source with an $EC_w = 5\,dS\ m^{-1}$ mixed equally with a source with an $EC_w = 1\,dS\ m^{-1}$ should reduce salinity in the blend to approximately $3\,dS\ m^{-1}$. A chemical analysis of the blend should be performed to confirm this. The salinity of the mixture can be calculated with this equation:

$$EC_w(\text{blend}) = \frac{\text{volume (water A)} \times EC_w\ \text{(water A)} + \text{volume (water B)} \times EC_w\ \text{(water B)}}{\text{volume (water A)} + \text{volume (water B)}}$$

Example Two water sources are available for irrigation. One has an EC_w of $3.0\,dS\ m^{-1}$ and the other, $0.6\,dS\ m^{-1}$. The water will be blended in equal amounts. What would the resulting EC_w of the blended water be?

$$\begin{aligned} EC_w(\text{blend}) &= \frac{\text{volume (water A)} \times EC_w\ \text{(water A)} + \text{volume (water B)} \times EC_w\ \text{(water B)}}{\text{volume (water A)} + \text{volume (water B)}} \\ &= \frac{[1\,gal \times 3.0\ dS\,m^{-1}] + [1\,gal \times 0.6\ dS\,m^{-1}]}{1\,gal + 1\,gal} \\ &= \frac{3.6\ dS\,m^{-1}}{2} \\ &= 1.8\ dS\,m^{-1} \end{aligned}$$

Mixing of irrigation sources can occur in irrigation ponds or within the irrigation system itself. When mixing water sources in irrigation ponds, the nonsaline water should be added immediately prior to being used so as to reduce evaporative losses. Evaporation of surface water is not only an inefficient use of water, but it also increases the salinity of the water remaining in the pond. If blending is not an option, alternating irrigating with saline followed by fresh water helps leach salts.

Leaching or Flushing Soils to Remove Salts

Salt buildup from salt-laden irrigation water occurs when rainfall is low and evaporative demand is high (Fig. 4.13). As water evaporates from the soil surface, salt deposits are left behind. Applying water in an amount greater than ET to cause the applied water to flow (or leach) through the rootzone and wash away salts is the goal of leaching salt-laden soil. Steps involved when leaching or flushing soils to remove salts include:

1. Perform soil and water test to determine the extent of salinity levels present.
2. Aerify or vent the soil. Soils which do not drain well will not benefit greatly from flushing as the salts must be removed by leaching. Also, standing water in summer is often detrimental to certain plants, such as bentgrass. Aerifying or venting the soil by slicing are two ways of improving internal soil drainage. If drainage is still inadequate, then "pulse" irrigation may work. Pulse irrigation is a series of short-run irrigation cycles where water is to match infiltration rates or added until puddling occurs. Once the surface water drains, another pulse of irrigation is applied.
3. Apply gypsum (calcium source) to replace soil sodium ions removed and also add wetting agents to improve water infiltration and assist in soluble salt removal from the rootzone.
4. Perform leaching or flushing. Several techniques to determine the amount of water needed to accomplishment the goal(s) of leaching/flushing are presented.
5. Add leached nutrients. Leaching/flushing to remove salts also often removes other elements, especially nitrogen and potassium. Add a scheduled fertilizer

Fig. 4.15 Flushing (excessive irrigation) is the best means of overcoming irrigation salinity problems. Excess moisture must be applied and excellent soil drainage are needed for this strategy to succeed

following leaching/flushing to ensure sufficient potassium levels are maintained to help combat future added sodium ions.

Measuring the EC of the soil is the best way to determine the extent of salt accumulation. When the EC exceeds the tolerance level of the turfgrass, the soil should be leached to move the salt below the rootzone. For example, 6 *in* (15 *cm*) of water is required to leach 80 % of salt out of the top 1 *ft* (30 *cm*) of a sand loam soil and about 1.5 *ft* (45 *cm*) of water is required to leach 80 % of the salt out of the top 1 *ft* (30 *cm*) of a clay loam. Typically, a course should plan on an additional 10–20 % of water needed yearly for turf growth to provide water for adequate leaching.

Frequent flushing of the soil with good quality irrigation water or rainfall is the best method of preventing excessive salt accumulation (Fig. 4.15). Unfortunately, low salinity irrigation sources are not always available and frequently saline irrigation water must be used to manage soil salinity. However, as long as the salinity of the irrigation water is acceptable, it can be used to leach accumulated salts from the turf rootzone. The goal is to maintain a soil salinity level that is not increased through salts added by irrigation and yet can support turfgrass growth. The use of soil amendments, such as gypsum, should be considered in conjunction with leaching irrigation applications in saline-sodic soils.

If saline water is used to reduce the salt level of the soil, irrigation must be applied at rates exceeding evapotranspiration to leach (or flush) excess salts out of the rootzone. Leaching of soluble salts in the soil solution is much more rapid and easier than removing sodium on the CEC sites of sodic soils. On sodic soils, the sodium is chemically bonded and must be replaced by calcium before the sodium can be leached from the soil solution. Soluble salts are already in the soil solution, thus, are more easily leached. To determine the amount of excess water required to leach salt below the rootzone, the following **leaching requirement** equation is often used.

Leaching requirement is the amount of extra water needed to leach salts from the rootzone and is defined as:

$$\text{leaching requirement} = \frac{\text{EC}_\text{w}}{\text{EC}_\text{dw}} \times 100\,\%$$

EC_w equals the electrical conductivity of the irrigation water and EC_dw is electrical conductivity of a saturated paste extract that can be tolerated by the turfgrass being grown.

Example An irrigation water source has a salinity level of $2\,dS\ m^{-1}$. The turfgrass being grown has a tolerance of $4\,dS\ m^{-1}$. What would be the recommended amount of water needed to leach salt from the rootzone?

step 1: Determine the leaching requirement for this sample and turfgrass.

$$\begin{aligned}\text{leaching requirement} &= \frac{\text{EC}_\text{w}}{\text{EC}_\text{dw}} \times 100\,\% \\ &= \frac{2}{4} \times 100\,\% \\ &= 50\,\%\end{aligned}$$

step 2: Fifty percent additional water above that normally applied would be needed to leach the salt from the soil. If $2\,in$ ($5\,cm$) of water are normally used, adding $50\,\%$ would equal $3\,in$ ($7.6\,cm$). Table 4.9 lists these irrigation guidelines for leaching salts from soil with saline water.

Table 4.9 Irrigation guidelines for leaching salts from soil with saline water

Irrigation water EC_w ($dS\ m^{-1}$)	Maximum plant EC_dw tolerance level, measured by saturated soil paste extract ($dS\ m^{-1}$)		
	4 (low)	*8 (medium)*	*16 (high)*
	(in water to replace weekly ET losses and provide adequate leaching in rootzone[a])		
0.00	1.5	1.5	1.5
1.00	2.0	1.7	1.6
2.00	3.0	2.0	1.7
3.00	6.0	2.4	1.8

[a] Multiply inches by 2.54 to convert to *cm*

Leaching requirements depend on the salt levels of the irrigation water, ET rates, and the salt tolerance of the affected plants. As the irrigation water becomes saltier or the soil heavier, the leaching requirement becomes larger, meaning more water must be added for leaching to avoid salt accumulation. A guideline is for about 70 % of the total soluble salts to be removed by leaching, 3 *in* (7.6 *cm*) of water is needed per 12 *in* (30 *cm*) of soil depth of a sandy soil, 6 *in* (15 *cm*) of water per 12 *in* (30 *cm*) of a medium-textured loam soil, and 9 *in* (23 *cm*) of water per 12 *in* (30 *cm*) of a clay (fine-textured) soils. Leaching Na^+ also removes nutrients such as K^+, Mg^{+2} and others. These should be monitored and replaced, if necessary, following leaching. Heavy Ca^{+2} applications may also cause other cations imbalances, such K^+ or Mg^{+2}, thus they may need replacing. It generally is better to have periodic leaching events (i.e., 2 to 4 times monthly at 0.2 to 0.4 *in*, 5 to 10 *mm*, per application) compared to heavier, infrequent events (i.e., once monthly) which may cause puddling.

If saline water is the only source of water available for irrigation, it is helpful to predict how the leaching fraction of known irrigation water salinity will influence soil salinity over an extended period of time. Applying a leaching fraction of 10 % will lead to an EC_e of $EC_w \times 2.1$, 15 to 20 % will lead to an EC_e of $EC_w \times 1.5$, and 30 % will lead to an $EC_e = EC_w$.

Finally, plants tolerate higher soil salinity levels if water stress is avoided by maintaining soil moisture. Adequate surface moisture also prevents capillary rise of subsurface water and salts.

Flushing Steps

1. Aerify to break hardpans or organic zone surface tension.
2. Add green's grade gypsum at 7 to 12 *lb* 1000 ft^{-2} (3.4 to 5.9 *kg* 100 m^{-2}).
3. Start flushing, usually about an hour. If puddling occurs, stop, allow it to percolate, then resume.
4. Assess flushing length of time by measuring EC_w of discharged water with a portable meter. Once readings stabilized or fall below pre-set thresholds, stop.
5. Afterwards, N and K may need to be added as they are commonly stripped by flushing.

Good Soil Percolation and Drainage

As previously mentioned, leaching works well only with soils possessing good drainage (Fig. 4.16). If compacted zones or abrupt changes in soil texture exist, less leaching occurs as water movement through the soil is reduced. Good soil drainage through modifying rootzones, increased deep tine aerification, and use of drain lines are used for carrying away salty water. Drain lines, spaced no more than 20 *ft* apart (6.1 *m*), are used on golf greens for this purpose. Aerification also initiates deep root development prior to summer heat and salt stress by reducing soil compaction and

Fig. 4.16 Salinity problems will be magnified in areas of insufficient drainage as salts will remain at or on the soil surface

disrupting soil layering. Native (or pushup) greens with limited drainage often fail when effluent water is used unless these techniques are aggressively incorporated (Fig. 4.17).

For fairways, deep aerification has become standard on effluent-using courses to increase soil drainage and provide deep channels for incorporation of soil amendments. On tees and greens, deep aerification in spring and fall are typical along with supplemental monthly venting by spiking, slicing, quadratining, hydrojetting, or other techniques. For soils with limited infiltration properties, pulse irrigation is more effective where water is applied and allowed to infiltrate before reapplying.

Clay type also influences sodium tolerance. Nonexpanding or 1:1 kaolinite, hydrous oxide clays tolerate high soil sodium content better than expanding or 2:1 vermiculite or montmorillonite clays. The percolation in expanding 2:1 clay initially is high until the cracks seal with clay swelling. Illite is intermediate in sodium sensitivity.

Salt damage also is typically experienced in low-lying areas where water accumulates. Drain line installation helps remove this excessive water, preventing toxic accumulation of salts and sodium. Sand topdressing of fairways is also becoming more prevalent to improve playing conditions, degrade thatch, and to help remove excess surface water.

Leaching is typically performed monthly during high-stress summer months but soils should be checked periodically if problems develop. Soil salinity levels should be monitored before and after leaching to determine if salts have sufficiently been moved below the rootzone. Finally, routine leaching will also remove certain soil nutrients such as nitrogen and potassium. Although most effluent sources contain small levels of these and others, monitoring of soil nutrients should occur following a leaching cycle.

Fig. 4.17 Turf replacement in areas of insufficient drainage and use of high salinity irrigation water

4.5 Water Conservation

Daily water conservation practices integrate many of the previously mentioned practices and technology. Using computerized irrigation systems to better pinpoint irrigation needs for various soil types or turfgrass use, utilizing weather stations to determine daily ET rates, installing soil moisture sensors to monitor soil moisture levels, and using automatic pump shutdown switches when significant rainfall occurs are examples of water conservation techniques.

A holistic approach to water conservation is required. If not, turf water conservation will probably be mandated by governing bodies and may include: (a) changing the grass species, (b) allowing only native grasses and Xeriscape designs, (c) reducing the area of irrigated turf, or (d) improving (updating and expanding) current irrigation designs to become more efficient. Steps to develop best management practices (BMPs) for turfgrass water conservation include:

1. Site assessment and initial planning (i.e., documenting grasses, soils, microclimate, and existing management practices).
2. Evaluating and implementing water conservation strategies.
3. Analyzing benefits and costs of water conservation measures.

Site Assessment and Initial Planning

An extensive irrigation/water audit is needed to assess current water usage rates and efficiencies. This includes identifying currently implemented water conservation measures, estimating their costs to implement, and how they have improved water-use efficiency for the facility. This helps indicate to regulatory agencies that water conservation BMPs have been in place at considerable cost and effort and the course is committed to as efficient use of available resources as possible. Examples of current conservations measures can include:

- Irrigation scheduling based on scientific principals and experiences which measure plant water requirements.
- Providing educational and demonstration opportunities for the crew and course membership.
- Irrigating in early morning or at night to reduce wind losses and to take advantage of efficient water pressure.
- Using required irrigation backflow preventers, valves, heads, and permit requirements as per local code.
- Periodically checking valve boxes for leaks or disconnected wires and open and close valves manually to confirm proper operations. Also, inspecting for and eliminating pipe leakage.
- Use a pilot tube and gauge to check pressure at the head to ensure maximum efficiency and to regulate water use.
- Periodically check the height of heads to prevent mower and other equipment damage and to check coverage, water-discharge patterns, and to raise low heads.
- Use low-maintenance turf, landscape plants, and native grasses whenever possible.
- Use mulch ($>3\,in$, $7.6\,cm$ deep) around landscaping to reduce evaporation and weeds.
- Use drip irrigation or low emitter heads for landscapes.
- Use multiple irrigation cycles to allow infiltration without surface runoff.
- Have water harvesting and collection sources feeding into irrigation ponds.
- Having access to color weather radar or other devices to track and predict local showers.
- Matching the application rate to the soil infiltration rate.
- Using an irrigation company with local service support and readily available parts.
- Identifying cultivations programs (i.e., mowing heights, fertility programs, aerifications) and equipment which improve water infiltration and enhance rooting.
- Use of appropriate soil amendments and wetting agents to provide efficient water infiltration, water retention, and to minimize runoff.
- Reducing or eliminating irrigation in low priority play areas.

Following identification of existing water conservation measures, the next step is to assess the current resources and infrastructure available. This can be a time-consuming and costly assessment, especially if alternative irrigation sources are explored or when major irrigation system design changes are needed.

- Hire an irrigation design specialist.
- Use an irrigation system design that provides uniform application to minimize wet and dry areas and limits run-off or leaching.
- Identify and provide cost considerations of alternative water sources such as reclaimed water.
- Identify irrigation design changes necessary for improved efficiencies.
- Assess current soil, microclimatic, and plant conditions affecting irrigation system design including zoning and scheduling issues.
- Add sufficient wire in the irrigation system to accommodate future expansions or added heads per zones.
- Provide single-head irrigation control.
- Use a variable frequency drive pump to gradually reduce water flow after pump shut-off and gradually increase water flow when turned on to reduce strain on the pipe. These motors only expend enough energy to meet the demands of the pumps.
- Have an on-site weather station or access to regional weather information to calculate daily ET rates and possibly use soil moisture sensors to monitor irrigation efficiency.
- Safeguard against water hammer when systems are pressurized by installing check values where water drains from low heads to prevent damage.
- Consider using ductile fittings and gasketed joints instead of glue due to their longer life expectancy.
- Consider looping the irrigation system to allow watering from two directions.
- Use multirow irrigation design systems compared to single rows for better coverage and less water waste.
- Using multiple short duration irrigation cycles to reduce runoff compared to single, heavy-use cycles.
- Zone irrigation heads of similar areas together (greens, tees, bunkers, fairways, and roughs).
- Isolate as many areas of the golf course as possible with individual shut-off valves from the main line.
- Use low-volume heads when possible and low trajectory heads in windy areas.
- Use the biggest irrigation pipe that is affordable—ideally, pipes should be sized for water velocities of about $3 ft\,\mathrm{s}^{-1}$ ($0.9\, m\, s^{-1}$).
- Mainline pipe should be a minimum of 4 to $6\, in$ (10–$15\, cm$) in diameter, preferably larger. Successive branches of an irrigation line should be reduced by $2\, in$ ($5\, cm$).
- Have controller flexibility to develop the most efficient irrigation program.
- Avoid placing heads in a depressed area as seepage or bleeding may occur. Use seals if this is unavoidable.

- Use part-circle pattern heads and proper design to place water only on intended turf areas and not on unintended natural areas, mulched areas, water bodies, edges of fairways or primary rough, off-property, and other such areas.
- Incorporate efficient drainage designs that allow water harvesting or recapturing in ponds or catch basins.
- Consider a remote (radio) controller to enable quicker response time to a problem.
- Using appropriate soil amendments which are known to help retain soil moisture without negatively affecting the turf.
- Use pressure-regulating stems on spray heads to prevent water waste when operated outside the designated window of pressure.

Evaluating and Implementing Water Conservation Strategies

Once existing and potential irrigation practices have been identified, they must be sorted through and the ones practical for a specific course can be implemented. These strategies are generally site-specific, driven by water-allowances and conservation goals, member expectations, and of course, financial and other resources available or required. Key components of water conservation strategies include:

- Alternative irrigation water sources, their availability, costs, quality, reliability, use requirements, suitability for a particular site, and long-term effects. Probably the major problem with effluent water is not quality but quantity. Courses find themselves having to accept a certain amount per day, whether it is needed or not. Storage of this water is a concern and must be addressed early in the planning process of using effluent water.
- Practical extent of implementing efficient irrigation design, scheduling, operations, and monitoring devices as discuss previously.
- Considerations on selecting turfgrass and landscape plants, such as the quality they can produce, their water use requirements, and quality of water needed.
- Changes in management practices which enhance water conservation as discussed previously.
- Holistic course water conservation, including landscaped areas, club house use, pool water conservation, etc.
- Educating the crew, owners, and membership on water conservation and management plans to obtain these.
- Developing a formal written water BMP conservation plan for the course and for regulatory agencies.
- Monitoring and revising the conservation plan periodically to assess the success of the plan and to identify limiting factors to achieving water conservation goals.
- Inform members, owners, crew, and concerned citizens of water conservation efforts with proper signage and other communication avenues.

Assessment of Water Conservation Costs and Benefits

To track costs and benefits which are critical information to demonstrate the facility has developed and is implementing long-term BMP water conservation efforts, a follow-up detailed review and documentation phase is necessary. Costs include labor, facility costs as outlined in evaluating and implementing water conservation strategies section, and costs associated with more stringent water restrictions, such as revenue loss, job loss, reduced and possible hazardous turf quality, etc.

The following is an example of questions to answer when developing Best Management Practices for Water for a particular golf facility (modified from the Georgia Golf Course Superintendent's Association; 2015, http://www.ggcsa.com/best-management-practices-for-water-conservation).

Best Management Practices for Water Use and Conservation

1. Site Assessment for greens, tees, fairways, roughs, landscapes, and club grounds, including
    a. Area size involved, (*ft*^{2}, *ac*, *m*^{2}, or *ha*).
    b. Turf (plant) species involved.
    c. General factors such as mowing height, soil type, special technology, other pertinent information.
    d. Irrigation Audit:
        - Pump station—year, type, pump size(s), gallonage, safety features, condition, maintenance schedule, other information.
        - Controls—year, system type, number of field controllers, condition, other information.
        - Irrigation system—year, type, valves, output and distribution efficiency (DU) for greens, tees, fairways, roughs, plus other information.
2. Overall Water Needs
    a. Metering—number of meters, location(s), other information.
    b. Record keeping—yearly usage, scheduling, other information (attach 1 year of records).
    c. Water testing—schedule, other information (attach most recent tests).
    d. Reservoir—size, type of water, source of water, other information.
    e. Alternative water sources (yes or no), If yes, explain.
    f. Future needs—explain in detail.
3. Best Management Practices and Current Conservation Measures
    a. Current Irrigation Control/Costs—for pump station, controllers/computer, irrigation system components (sprinklers, pipe, valves, fittings, etc.), preventative maintenance of all these, other.

b. Staffing Control/Maintenance Costs—supervisor time, irrigation technician time, other assistance time (include diagnosis, repairs, recordkeeping, inventory, scheduling, etc.).
c. Scouting Costs—daily scouting time (explain).
d. Hand Watering Costs—daily hand watering time (explain).
e. Night Watering Capability—explain how this reduces loss and reduces disease occurrence.
f. Rain, Leak Loss Costs.
g. Traffic Controls/Costs—daily traffic control time (explain).
h. Management for Water Conservation (describe each):

  - Mowing heights.
  - Soil cultivation (number times yearly for greens, tees, and fairways).
  - Evapotranspiration utilization—List source for monitoring weather data to schedule irrigations events based on ET values.
  - Landscape material selection explanation.
  - Natural areas.
  - Fertilization—yearly rates, slow vs. quick release, stress nutrient use.
  - Pest management (explain IPM programs).
  - Wetting agent use (explain products, timings, etc.).
  - Soil moisture sensors—calibrating and determining thresholds (saturation, field capacity, wilting point).

i. Record Keeping:

  - Scouting labor hours and costs.
  - Hand watering hours and costs.
  - Irrigation repair hours and costs.
  - Repair parts costs.
  - Water usage weekly, monthly, and yearly.
  - Water quality tests.
  - Pesticide and fertilizer applications (in relation to irrigation).
  - Other methods.

j. Irrigation Methods—combination of plant based, soil based, atmosphere based, and budget report.
k. Goal Setting—explain.

Education: for example.

  - Benefits of Golf Course and Turf—i.e., economic contributor, carbon dioxide exchange for oxygen, temperature moderation, erosion control, water filtering for improved water quality, wildlife sanctuary, recreational benefits, community outreach (i.e., First Tee Programs), others.
  - Publish this Best Management Plan for use at Club—articles in the Club newsletter or web page explaining proper water use and efforts towards water conservation.

l. During drought, display water conservation plans (posters) in the pro shop and locker rooms and to patrons for use at home.

4. Water Conservation Plan

   a. List reasons for Water Conservation, for example:

      - Proper water management dictates that overwatering is unacceptable.
      - Economic considerations that inefficient watering costs money.
      - Depleted water supplies and reduced water quality.
      - Other reasons.

   b. List Measures Implemented by the Course to Reduce Drought Effects, for example:

      - Raise mowing heights where possible.
      - Stop mowing non-irrigated areas.
      - Increase hand watering and wetting agent use.
      - Improve uniformity by improving pressure regulations, leveling heads, etc.
      - Other reasons.

   c. Irrigation Upgrades Implemented by the Course for Increased Water Conservation.

      - List possible options and costs.

   d. List and Describe Actual Plans for Water Conservation at Various Mandated Drought Levels.

5. Attachments, for example:

   - Pump station records.
   - Most recent water quality test results.
   - Man-hour records.
   - Budgets.
   - Repair records.
   - Copies of publications.

4.6 Hydrophobic Soils and Their Management

Hydrophobic Soils

Hydrophobic (or “water-hating”) soils such as those associated with localized dry spots, occur as organic matter decomposes and humic and fulvic acids (nonpolar) produced eventually coat individual sand grain particles. Sands are more prone to develop water repellency than finer soil textural classes due to the low or smaller

Fig. 4.18 Typical localized dry spots occurring on a golf course putting green. Powder dry soil is typically adjacent to moist soil, reflecting unhealthy and healthy plants

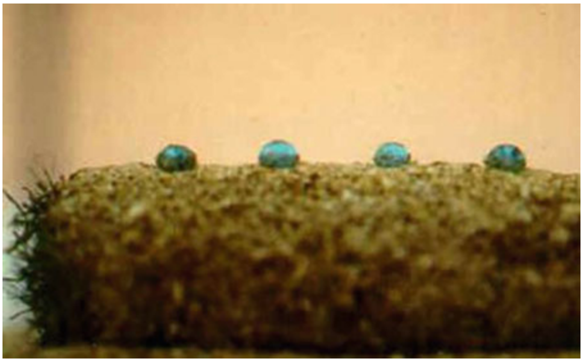
surface area to volume ratio of sand particles. Certain fairy ring fungi also produce a mat of below-ground hyphae which often becomes hydrophobic. These acids have extruding non-polar ends which repel water particles, much like wax, leading to the dry spots. These conditions can be so severe that normal irrigation is often ineffective in restoring adequate soil moisture. Repeated wet and dry soil cycles aggravate hydrophobic soils. Other potential sources of organic acids which coat soil particles include exudates from turfgrass roots, lipids from decomposing organic matter, surface waxes from cuticles of turfgrass plant leaves, and fungal or soil microbial by-products.

Hydrophobic soils can cause problems on golf courses (especially golf greens) and other turf areas, in nurseries and greenhouses, and in open fields (Fig. 4.18). Localized dry spots tend to be a surface phenomenon, in the top 2 *in* (5 *cm*), but can occur up to 6 *in* (15 *cm*) deep. Nursery operators sometimes encounter hard-to-wet media in pots and greenhouse beds. Farmers who work organic soils or "salt-and-pepper" soils complain that the soil wets too slowly, reducing crop productivity. Problems with hydrophobic soils are also commonly associated with citrus production areas, where mine spoils have been deposited, and with burned-over forestland and grassland.

If water cannot readily penetrate and wet the soil, the availability of moisture to plants is reduced, decreasing the germination rate of seeds, the emergence of seedlings, and the survival and productivity of plants. Lack of sufficient water in the soil also reduces the availability of essential nutrients to plants, further limiting

Fig. 4.19 Hydrophobic soils typically repel water, decreasing the efficiency of a water management program

Fig. 4.20 Hydrophobic soils are often quantified using a water droplet test. With this test, the amount of time necessary for a drop of water to penetrate a soil profile is used to determine the degree of hydrophobicity of a soil



growth and productivity. In addition, water that cannot penetrate the soil runs off the surface and increases soil erosion (Fig. 4.19).

A soil water repellency water drop penetration test is used to measure how hydrophobic a soil may be (Fig. 4.20). Droplets of water are placed every inch down a soil core and the time required for the droplet to penetrate the soil reflects the soil's degree of repellency (Table 4.10).

Table 4.10 Degree of soil hydrophobicity (or repellency) based on the water drop penetration test

Water drop penetration time (*s*)	Degree of repellency
0 to 5	None
5 to 60	Slight
60 to 600	Moderate to high
600 to 3600	Severe
>3600	Extreme

Adjuvants

An adjuvant is a spray additive that helps modify the surface properties of liquids to enhance their performance and handling. 'Adjuvant' is a broad term and includes surfactants, wetting agents, crop oils, crop oil concentrates, activators, anti-foaming agents, detergents, drift control agents, emulsifiers, fertilizers, spreaders, sticking agents, dispersing agents, penetrants, pH modifiers and compatibility agents.

Surfactants

Surfactants are adjuvants that produce physical or chemical changes at the interface of a liquid and another liquid, solid, or gas. These typically lower the surface tension of a liquid, allowing easier spreading, and lower the interfacial tension between two liquids. Since this occurs at the surface, the term "surfactant" is short for surface active agents. These facilitate emulsifying, dispersal, wetting, spreading, sticking, penetrating, or other surface-modifying properties of liquids into plants and soil (Fig. 4.21). Surfactants are widely used in everyday life in medicines, medical care, fire extinguishers, paints, inks, adhesives, waxes, laxatives, hair conditioners, and agriculture. Surfactants include emulsifiers, detergents, dispersants, penetrants, soaps, spreaders, stickers, and wetting agents.

To understand how surfactants work, it helps to understand how water works. Each water molecule is bipolar, meaning it has a negative and a positive charge, similar to a magnet. When several water molecules come into contact with each other, these positive and negative forces attract each other. This attraction of water molecules for each other is termed cohesion. The molecules on the surface of a water droplet are held together with more force than those of the interior water molecules. This causes surface tension, which causes the droplet to behave as if a thin, flexible film covered its surface, tending to keep the water molecules apart from other substances, and can prevent many things from going into solution and getting wet. This surface tension is the tendency of the water surface molecules to be attracted toward the center of the liquid, causing a water droplet with a dense, elastic membrane around it. Wetting agents help break this surface tension, thus the water droplets break down allowing dispersal. Adhesion, the attraction of water

Fig. 4.21 Wetting agents are often used to reduce the angle of beading water molecules possess. Areas outside the green rectangular areas have not been treated with a wetting agent, retaining dew as large droplets of water

molecules to other substances, is the force causing water molecules to adhere to other objects, such as soil particles.

The effects of these forces can be illustrated by placing a drop of water on a napkin and another drop on a piece of waxed paper or newly waxed vehicle. On the napkin, the force of adhesion between the water molecules and the paper molecules is greater than the force of cohesion that holds the water molecules together. As a result, the water droplet spreads out and soaks into the paper. Certain organic substances such as wax, however, do not have an adhesive force for water. On the waxed paper, therefore, the water "beads up"—that is, the droplet remains intact. The water molecules are not attracted to the wax that coats the paper's surface; instead, the water molecules cohere to each other. When the adhesive forces between water molecules and an object are weaker than the cohesive forces between water molecules, the surface repels water and is said to be hydrophobic (Fig. 4.22).

Surfactants are composed of two parts, a water-soluble end which is polar or hydrophilic, meaning it is attracted to water, and an oil soluble hydrocarbon chain which is lipophilic or nonpolar, meaning it is attracted to oil and not water. Water forms bonds with polar molecules but does not bond to non-polar molecules and is repelled by these. Chemists manipulate the ratio of the hydrophilic (polar) portion

Fig. 4.22 Severe localized dry spots on a golf course putting green. Managing consistent playing surfaces and turf health are challenges under such severe conditions

Fig. 4.23 Demonstration of unwanted run-off of untreated water (*left*) on a hydrophobic soil compared to water infiltration by a water source treated with a wetting agent

of the molecule to the lipophilic (nonpolar) to produce different surfactants, with different molecular weights, and different characteristics. Thousands of potential combinations exist, thus the reason for the hundreds of surfactants available. These components of a surfactant molecule help break water surface tension, allowing the solution to be more evenly dispersed on a surface and to reach its target (Fig. 4.23). Two major types of surfactants are emulsifiers and wetting agents.

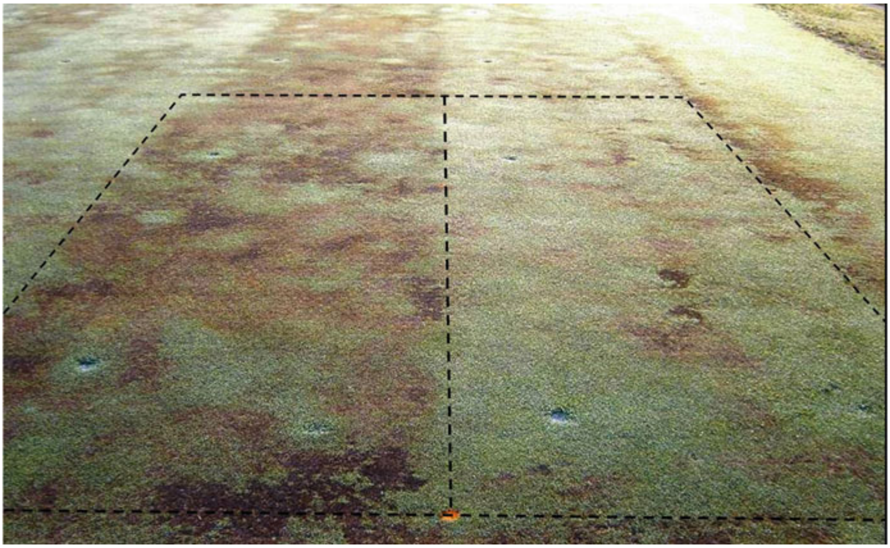


Fig. 4.24 Healthier turf (*right*) that has been treated with a wetting agent compared to severe localized dry spots which has not (*left*)

Wetting Agents

Wetting agents are a type of adjuvant that reduce interfacial tensions and cause a liquid to spread more easily over, or to penetrate, a solid surface, thus making more contact with treated surfaces (Fig. 4.24). They can reduce this surface tension by 50 to 60 % or more. In plant and soil sciences, wetting agents have a number of uses including reducing soil hydrophobicity (i.e., localized dry spots), reducing dew and frost formation, firming bunker sand, improving irrigation efficiency, reducing vehicle path dust, improving soil water infiltration, improving pesticide efficacy, and others.

Wetting agents are classified based on how they ionize or separate into charged particles in water. Four types of wetting agents are:

1. **Anionic**—negatively charged. These are often used for dispersion of clays in wettable dry granulars as well as detergents, and degreasers. They may burn plants.
2. **Nonionic**—neutrally charged. Also referred to as polyoxyethylene or alkylphenol ethoxylate. Often used to enhance water movement into soil.
3. **Cationic**—positively charged, often used as biocides (disinfectants), soaps, shampoos, and fabric softeners. Strongly adsorbed to soil particles with high plant burn potential. Rarely used.
4. **Amphoteric**—charge is pH dependent of the solution. Little use on plants.

Nonionic surfactants do not ionize, thus remain uncharged. This is the most commonly used type of surfactant and is compatible with most pesticides. They are unaffected by water containing high levels of calcium, magnesium, or ferric ions. They also can be used in strong acid solutions. Anionic wetting agents ionize with water to form a negative charge while cationic ones ionize with water to form a positive charge. Anionic wetting agents may deleteriously impact soil structure (negative soil charges repel the negatively charged anionic wetting agents) and are often phytotoxic to plants. Amphoteric surfactants can be either anionic or cationic depending on the acidity of the solution. Cationic materials are strongly adsorbed to soil particles and may become ineffective. If used in hard water, anionic and cationic surfactants can cause an insoluble precipitate or foam to form. These are only occasionally used. Soaps and detergents are types of surfactants but typically are anionic and react with salts in hard water and form a precipitate (scum), foam, or are phytotoxic to plants.

As mentioned, chemists are able to manipulate the ratio of the hydrophilic (polar) portion of the molecule to the lipophilic (nonpolar) to produce different surfactants, with different molecular weights, and different characteristics. Within the nonionic surfactant chemistry, two main groups of wetting agents are currently available: soil penetrants and water retainers.

1. *Soil Penetrants.* These are often characterized as “water-moving” chemistry, characterized by having ethylene oxide terminal functional groups. Ethylene oxide groups are hydrophilic, being able to attract or disperse water molecules. Soil penetrating wetting agents generally increase water infiltration and percolation through the rootzone, providing more uniform soil moisture distribution within the profile, leading to “fast and firm” playing conditions.
2. *Soil water retainers.* These are often characterized as “water-holding” chemistry, containing propylene oxide terminal functional groups. Propylene oxide groups are hydrophobic, thus repel water molecules. These are used where moisture retention is needed, especially sand-based rootzones with little organic matter and high infiltration and percolation rates. These are especially useful to help retain moisture during drought periods.

To take advantage of both types of wetting agents, many newer commercial products are blends of each. Extensive research has been conducted on hydrophobic soils and on the effectiveness of wetting agents. Localized dry spots in turf grown on naturally sandy soils, and on formulated materials high in sand content, become a serious turf management problem during the summer months, especially during periods of drought, windy weather, and low humidity. Despite frequent irrigation, the soil in these spots resists wetting, resulting in patches of dead or severely wilted turf. The water applied wets the turf but does not adequately penetrate the soil surface to reach the rootzone. Wetting agents or surfactants do not aid in decomposing thatch, alleviating black layer, or reducing soil compaction.

When a wetting agent is applied, its non-polar ends react (or align) with the non-polar (“water-hating”) ends of the acid coated sands. The polar (“water-loving”) ends of the wetting agent then are exposed outward and can attract water, restoring wettability. Wetting agents, however, do not substantially remove the hydrophobic acid coating. For most products, to minimize phytotoxicity, irrigation after wetting agent application is critical as well as not treating when temperatures are extreme. When soil organic matter content exceeds 3.5 %, this organic matter may dry down slower when treated with a wetting agent. Increasing the use rates above label recommendations generally does not increase the longevity or effectiveness of products and increases the chance of plant damage. Wetting agents can improve the efficiency of irrigation and when water repellent soil conditions occur, wetting agent use may improve root growth and survival. Efficacy differences and length of control does vary between wetting agents. Soil organisms and natural breakdown of the materials eventually occur, causing the need for repeat applications for extended results. When treating golf greens, it generally is best to treat the whole green versus just treating the hot spots. Wetting agents do not solve a subsurface drainage problem but may help leach salts from the rootzone under certain situations.

In general, studies have shown that the extent of improvement in infiltration rate is affected by the type of wetting agent used, its dilution, previous use of wetting agents on the soil, and the water content of the soil at the time water is applied. Several studies have shown that the infiltration rate of a hydrophobic soil, once it has been wetted, remains higher than it was before it was wetted, even if it is allowed to dry out again. Applying wetting agents often reduces the severity of the condition, but best use is in combination with coring—making small holes in the soil surface to allow water to pass through the hydrophobic surface layer. Also, keeping the soil moist seems to be the best defense against the development of dry spots as allowing the soil to dry out intensifies the problem. For maximum efficiency, if your goal is to rewet a dry, hydrophobic soil, the area should be aerified, followed by pre-wetting the area, applying the wetting agent or soil surfactant, and then watering it rapidly and liberally into the soil profile.

4.7 Questions

1. Soil moisture measuring devices have been developed with the goal of indicating how much moisture is available to plants. List and discuss the major means by which soil moisture is currently measured.

Quantitatively (or volumetric):

Gravimetric water content*—Measures soil moisture by weighing-drying-reweighing to provide a full range of water content (%). Simple equipment is needed, it is highly accurate, and data is easy to interpret. However, it involves destructive sampling, is labor intensive, and involves collection, transport, and time restraints.*

Time Domain Reflectometry (TDR)*—Measures time for an electromagnetic wave to travel using soil medium as a dielectric. Moisture slows this down.*

Up to 50 % volumetric water content (0.50 kg water kg^{-1}*soil) can be measured. TDR is accurate, has minimal soil disturbance, soil specific-calibration is optional, relatively insensitive to temperature, and also estimates, with limited accuracy, soil EC. Limitations include being expensive, accuracy decreases in high saline (>25 dS* m^{-1}*) conditions or heavy clay soils, and involves relatively small sensing volume (about 1 in, 2.5 cm, radius around probe).*

Frequency Domain Reflectometry (FDR) or Hand-push probes*—Measures the change in frequency of a capacitor using soil medium as a dielectric. Up to 70 % volumetric water content (0.70 kg water kg* $^{-1}$*soil) can be measured. It is relatively inexpensive, can be automated with irrigation, and is stable in different soil types and over a large range of moisture contents. It requires soil-specific calibration for accuracy, samples only a small volume of soil (about 4 in, 10 cm, radius around probe), and is sensitive to soil air gaps, saline soils and temperature.*

Other quantitatively methods of determining soil moisture include neutron (or scatter) probe (expensive) and electrical conductivity probes (limited accuracy).

Qualitatively (or tensiometric):

Tensiometers*—Measure how tightly (the "tension") water is held by soil from a range of 0 to −0.08 MPa (0 to −80 kPa). It provides a direct readout of soil water potential (or tension), is inexpensive, can be automated with irrigation, relatively reliable, good accuracy, and unaffected by soil salinity. Limitations include soil moisture retention curve needed to relate to soil water content, samples a small area near cup thus multiple samples are needed in larger areas, doesn't measure soil salinity content, and involves exposed gauges, sensitive to disturbance and soil air gaps.*

2. The following water content values were generated for two sands being used for a 30 *cm* (12 *in*) rootzone. If the $ET_p = 0.5$ *cm* day^{-1} (0.2 *in* day^{-1}), approximately how many days' supply of water would be expected to be stored in each?

	Moisture content at		
Sand sample	Field capacity	Wilting point	Rooting depth (*cm*)
1 (medium)	0.400 $cm^3\,cm^{-3}$	0.050 $cm^3\,cm^{-3}$	20
2 (course)	0.400 $cm^3\,cm^{-3}$	0.150 $cm^3\,cm^{-3}$	12

Available water = (rooting depth, cm) × (FC–WP, $cm^3 cm^{-3}$*)*

Sand 1*: 20 cm × (0.400–0.050* $cm^3\,cm^{-3}$*) = 7.0 cm (or 2.8 in).*
Sand 2*: 12 cm × (0.400–0.150* $cm^3\,cm^{-3}$*) = 3.0 cm (or 1.2 in).*

Days of Water Stored:
For Sand 1: 7.0 cm available water ÷ 0.5 cm $day^{-1} ET_p \approx 14$ *days.*

For Sand 2: 3.0 cm available water $\div$ *0.5 cm* $day^{-1} ET_p \approx$ *6 days.*

Even though both sands held similar amounts of moisture at field capacity, the medium-sized sand has a deeper rooting depth and should not wilt until soil reached a lower moisture content (0.050 $cm^3\ cm^{-3}$*) compared to the shallower rooting depth in the coarser sand sample which has a higher moisture content at its wilting point (0.150* $cm^3\ cm^{-3}$*).*

3. A golf green 5495 ft^2 (510 m^2) in area, 1 ft deep (30.5 cm) with a bulk density of 1.40 $g\ cm^{-3}$ starts to wilt when the TDR probe averages 12 % volumetric water content. If the superintendent wishes to increase the soil moisture content to 16 % of the whole soil depth, how many gallons of water are necessary?

$$
\begin{aligned}
\text{equivalent depth of water, } D_e \text{ at } 12\,\% &= \text{soil depth} \times \text{volumetric water content} \\
&= 30.5\ cm \times 0.12\ cm^3 \text{ water } cm^{-3} \text{ soil} \\
&= 3.66\,cm \\
\text{equivalent depth of water, } D_e \text{ at } 16\,\% &= 30.5 \times 0.16\ cm^3 \text{ water } cm^{-3} \text{ soil} \\
&= 4.88\,cm \\
\text{additional depth } (cm) \text{ of water needed} &= 4.88\ cm - 3.66\ cm \\
&= 1.22\ cm (0.48\,in) \\
\text{additional water } (gal) \text{ needed} &= 0.48\,in \times \frac{ac}{43{,}560\,ft^2} \times \frac{5495\,ft^2}{\text{green}} \times \frac{27{,}154\,gal}{ac\text{-}in} \\
&= 1645\,gal\ (6227\,L)
\end{aligned}
$$

4. The can test was performed with 20 cans spaced 5 ft (1.5 m) apart in a grid system. After a set time period (15 min), the depths in all cans were recorded. Calculate the irrigation system's distribution uniformity from the following values (in *inches*) caught:

1. 0.40	6. 0.25	11. 0.34	16. 0.39
2. 0.22	7. 0.28	12. 0.19	17. 0.37
3. 0.15	8. 0.30	13. 0.23	18. 0.35
4. 0.41	9. 0.31	14. 0.25	19. 0.34
5. 0.33	10. 0.21	15. 0.35	20. 0.33

After a 15-min run cycle, the average depth in the 5 ***least*** *filled cans was 0.20 in (0.5 cm). The average depth measured in all cans was 0.33 in (0.84 cm). The DU value is determined by the formula:*

$$
\begin{aligned}
DU &= \frac{\textit{average } \textbf{\textit{least}} \textit{ amount of water depth collected in } 25\,\% \textit{ of all cans}}{\textit{average amount of water collected in all cans}} \\
&= \frac{0.2\,in}{0.3\,in} \\
&= 0.67\,(or\ 67\,\%)
\end{aligned}
$$

The irrigation application rate may then be calculated as:

$$\frac{0.3\,in}{15\,\text{min}} \times \frac{60\,\text{min}}{1} = 1.25\,in\ h^{-1}\ \left(3.2\ in\ hr^{-1}\right)$$

5. If pan evaporation is measured at $1.60\,in\ week^{-1}$, using a K_c value for bermudagrass of 75 % and a DU value for the irrigation system of 60 %, determine the actual irrigation amount needed to uniformly apply the weekly water requirement.

   a) *Calculate weekly potential evapotranspiration (ET_p) for this turf.*

$$ET_p = pan \times K_c = 1.60\,in \times 75\ \% = 1.20\,in$$

   b) *Calculate total irrigation depth needed to apply minimum ET_p over entire area.*

$$\begin{aligned} actual\ irrigation\ needed &= \frac{ET_p}{Distribution\ Uniformity} \\ &= \frac{1.20\,in}{60\%} \\ &= 2.0\,in \end{aligned}$$

   Therefore, 2.0 in (5.0 cm) of total 'applied' water is required to uniformly apply a minimum of 1.2 in (3.0 cm) over the whole turf area.

6. A sand soil has a volumetric water content of 11 % at field capacity, a rooting depth of $5\ in$ ($12\ cm$), and a summer daily ET rate of $0.22\ in\ day^{-1}$ ($5.6\ mm\ day^{-1}$). Determine the appropriate time (days) between irrigation cycles.

$$\begin{aligned} irrigation\ interval\ (days) &= \frac{soil\ water\ content\ at\ field\ capacity \times rooting\ depth\ (in)}{ET\ rate\ (in\ day^{-1})} \\ &= \frac{0.11\ \times 5\ in}{0.22\ in\ day^{-1}} \\ &= 2.5\ days\ between\ irrigation\ cycles,\ which\ brings \\ &\quad the\ soil\ back\ to\ field\ capacity \end{aligned}$$

7. List and briefly discuss the steps in formulating an irrigation strategy.

   a. *Calibrate an irrigation system's output and distribution uniformity (or DU).*
   b. *Determine daily ET rates or soil moisture status by one of the methods discussed. A reasonable estimate of daily summer mean ET rates for various grasses are provided in* Table 4.3
   c. *Accurately track daily rainfall and ET rates so a water budget can be set-up and followed.*

d. *When irrigation is needed, use the appropriate crop coefficient (0.75 to 0.85) to find daily ET rate and incorporate distribution uniformity (DU) of the irrigation system as shown earlier and below.*
e. *Make adjustments for rainfall, varying microclimates, and forecasted weather.*

8. An irrigation zone applies 0.66 *in* h^{-1} and the projected ET rate for the next 24 *h* is 0.22 *in*. After doing an irrigation audit, you determined its distribution uniformity is 73 %. Calculate how long the irrigation system should run to uniformly apply the 0.22 *in*.

$\frac{0.22 in}{73\%} = 0.30\ in$ needed to apply at least 0.22 *in* over irrigation zone with a DU of 73%.

$$0.30\ in \times \frac{h}{0.66\, in} = 0.46\, h$$

$$0.46\ h \times \frac{60\, min}{h} = 27\, min$$

Therefore, the system would need to operate 27 min to apply 0.30 *in* of water.

9. Water use engineers employed at a municipality require a golf course to justify their water use permit in terms of total amount of water requested and how they determined this value.

A. Determine average yearly ET rate from one of the methods listed previously. In this example, 56.37 *in* (4.7 *ft*, 1.4 *m*) is used.
B. Determine normal yearly precipitation rate. In this example, 10.67 *in*. (27 *cm*) is used.
C. Area of irrigated turfgrass. In this example, 110 *ac* is used (3.1 *ac* for greens, 3.7 for tees, 43.7 for fairways, and 59.5 for roughs).
D. Determine the irrigation efficiency (DU). In this example, 70 % is used.

	Greens	Tees	Fairways	Roughs
E. turf area (*ac*)	3.1	3.7	43.7	59.5
F. turfgrass	Bentgrass	Bermuda overseeded Oct–May	Bermuda overseeded Oct–May	Bermuda
G. K_c (crop coefficient)	0.8	0.75	0.75	0.65
H. Turf Water Use*: [A × G] (which is ET ×* K_c*)*	*45.1*	*42.3*	*42.3*	*36.6*
I. 25 % precipitation (*in*): *[B × 0.25]*[a]	*2.7*	*2.7*	*2.7*	*2.7*
J. Water use adjusted for 25 % precipitation (*in*): *[H – I]*	*42.4*	*39.6*	*39.6*	*33.9*
K. Irrigation water use (*in*): *[J/D]*	*60.6*	*56.6*	*56.6*	*48.4*
L. K converted to feet: *[K/12] (12 in = 1 ft)*	*5.1*	*4.7*	*4.7*	*4.0*

(continued)

	Greens	Tees	Fairways	Roughs
E. turf area (*ac*)	3.1	3.7	43.7	59.5
M. Annual irrigation use (*ac-ft*): *[E × L]*	*15.8*	*17.4*	*205.4*	*238.0*
N. Annual irrigation water use: *sum M for all turf areas*	*477 ac-ft (or 155,430,927 gal)*			

[a] Water use regulators often use a precipitation efficiency adjustment value to reflect the amount (percentage) of usable precipitation by plants. Rainfall is often at inefficient amounts (too high or low) or at the wrong agronomic time.

In the above example, to compare calculated annual irrigation use to the overall formula, ET × area, the following was determined:

O. ET × 110 *ac*: *A* (*ft*) × *C* (total turfgrass area) or 4.7 *ft* × 110 *ac* = 517 *ac-ft* predicted by the simple formula,

P. Calculation efficiency for water budget: *N/O × 100* or 477 *ac-ft* ÷ 517 *ac-ft* × 100 = 92 %. This value indicates the simple formula of ET × area overestimated water needs by 8 % compared to the Water Budgeting process above.

10. List and briefly discuss the necessary laboratory tests for soil and water quality:

- *Water soluble salts (or Salinity drought hazard)—Total salt content as measured by the electrical conductivity (EC_w) or total dissolved salts (TDS) of water. Excessive salts produces plant physiological drought.*
- *Sodium status—Soil sodium level proportionally to Ca^{+2} and Mg^{+2} ions as measured by sodium adsorption ratio (SAR), exchangeable sodium percentage (ESP), or adjusted SAR (adj. SAR). SAR also is used to assess the sodium levels of water. Excessive sodium causes soil structure deterioration.*
- *Specific ions toxicity—Toxic ion levels, especially boron, chloride, fluoride, sulfate and nitrate-nitrogen.*
- *Alkalinity—Bicarbonates and carbonates as measured by residual sodium carbonate (RSC).*
- *pH and lime requirement.*
- *Suspended solids, as measured by total suspended solids (TSS).*
- *Soil nutrient imbalance based on:*
  - *Sufficiency levels of available nutrients and cation ratio.*
  - *Soil cation exchange capacity (CEC).*
  - *Percent base saturation.*
  - *Percent organic matter.*

11. How much salt is applied per *ac* if 1 *in* (2.5 *cm*) of water with salinity levels of 1.0 $dS\ m^{-1}$ (~640 *ppm*) is used? 1 *in* = 0.083 *ft*; 1 *gal* pure water weighs ~8.34 *lb*; 1 *ac-ft* water = 325,851 *gal*.

$$640 \times \frac{2.72}{ac-ft} \times 1 \quad ac-in \times \frac{1}{12\ in} = 145$$

12. An irrigation source has an EC_w of 0.53 *mmhos* cm^{-1}. What would the EC_w be in *dS* m^{-1}, *μmhos* cm^{-1}, and *ppm* TDS?

    a. *Convert mmhos to dS* m^{-1}*: (1 dS* m^{-1} *= 1 mmhos* cm^{-1}*), so 0.53 mmhos* cm^{-1} *= 0.53 dS* m^{-1}

    b. *Convert mmhos* cm^{-1} *to μmhos* cm^{-1}*.*

$$0.53\ mmhos\ cm^{-1} \times \frac{1000\ \mu mhos\ cm^{-1}}{1\ mmhos\ cm^{-1}} = 530\ \mu mhos\ cm^{-1}$$

    c. *Convert mmhos* cm^{-1} *to ppm:*

$$0.53 \quad cm^{-1} \times 640 = 339 \quad TDS$$

13. The salt content of a water sample is 1,121 *mg* L^{-1} TDS. What is the salt content in *dS* m^{-1} and *μmhos* cm^{-1}?

    a) To convert TDS (mg L^{-1} *or ppm) to dS* m^{-1}*, divide by 640 or multiply by 0.0016:*

$$1,121\ mg\ L^{-1} \div 640 = 1.75\ dS\ m^{-1}$$
$$or$$
$$1,121\ mg\ L^{-1} \times 0.0016 = 1.75\ dS\ m^{-1}$$

    b) To convert dS m^{-1} *(or mmhos* cm^{-1}*) to μmhos* cm^{-1}*, multiply by 1000:*

$$1.75\ dS\ m^{-1}\left(or \quad cm^{-1}\right) \times 1,000 = 1,750\ \mu mhos\ cm^{-1}$$

14. What is the TDS and EC of water containing 250 *μmhos* cm^{-1} Ca^{+2}, 325 *μmhos* cm^{-1} Mg^{+2}, and 480 *μmhos* cm^{-1} Na^{+}?

    Convert each value to dS m^{-1} *by dividing by 1000:*

$$ECw = 0.25\ dS\ m^{-1}\ Ca^{+2} + 0.325\ dS\ m^{-1}\ Mg^{+2} + 0.48\ dS\ m^{-1}\ Na^{+} = 1.1\ meq\ \ L^{-1}$$
$$TDS + 1.1\ dS\ m^{-1} \times 640 = 704\ mg\ L^{-1}$$

15. A water sample test reports 1000 *mg* L^{-1} Na^{+}, 200 *mg* L^{-1} Ca^{+2}, and 100 *mg* L^{-1} Mg^{+2}. What is the SAR value for this water?

    step 1: *calculate the number of meq* L^{-1} *of each ion:*

$$meq\ L^{-1} = \frac{concentration\ \left(mg\ L^{-1} or\ ppm\right)}{equivalent\ weight\ \left(mg\ meq^{-1}\right)}$$

$$Na^{+}\ :\ 1000\ mg\,L^{-1} \div \frac{23\ mg}{meq} = 43.5\ meq\,L^{-1}$$
$$Ca^{+2}\ :\ \ 200\ mg\,L^{-1} \div \frac{20\ mg}{meq} = \ 10\ meq\,L^{-1}$$
$$Mg^{+2}\ :\ 100\ mg\,L^{-1} \div \frac{12.2\ mg}{meq} = 8.2\ meq\,L^{-1}$$

step 2: *inset these values into the SAR equation as:*

$$\mathrm{SAR} = \frac{\mathrm{N}a^{+}}{\frac{\sqrt{\mathrm{C}a^{+2}+\mathrm{M}g^{+2}}}{2}} = \frac{43.5}{\frac{\sqrt{10+8.2}}{2}} = 14.4 \quad meq \quad L^{-1}$$

16. A water analysis indicates a sodium concentration of $85\,meq\ L^{-1}$, a Ca^{+2} concentration of $33.3\,meq\ L^{-1}$ and a Mg^{+2} concentration of $7.1\,meq\ L^{-1}$. What is the SAR value for this water?

$$\mathrm{SAR} = \frac{\mathrm{N}a^{+}}{\frac{\sqrt{\mathrm{C}a^{+2}+\mathrm{M}g^{+2}}}{2}} = \frac{85}{\frac{\sqrt{33.3+7.1}}{2}} = 18.9 \quad meq \quad L^{-1}$$

17. An irrigation source containing $75\,mg\ L^{-1}$ Ca^{+2} and $30\,mg\ L^{-1}$ Mg^{+2}. How much each would be supplied in each *ac-ft* of irrigation applied?

    Pounds of salt applied per acre = irrigation water salinity level (ppm or mg L^{-1}*)* × *2.72 million lb (weight of water per ac-ft)* × *ac-ft water applied, therefore for each ac-ft:*

    Ca^{+2}*: 75 mg* $L^{-1} \times 2.72 = 204$ *lb Ca supplied per ac-ft irrigation water applied.*

    Mg^{+2}*: 30 mg* $L^{-1} \times 2.72 = 82$ *lb Mg per ac-ft irrigation water applied.*

18. What is the exchangeable sodium percentage (ESP) of a soil with $15\,meq$ $100\,g^{-1}$ Na^{+} and a CEC of $150\,meq$ $100\,g^{-1}$?

$$\begin{aligned} ESP &= \frac{exchangeable\ sodium\ \left(meq\,L^{-1}\right)}{cation\ exchange\ capacity\ \left(meq\,L^{-1}\right)} \times 100 \\ &= \frac{15\ meq\ 100\ g^{-1}}{150\,meq\ 100\ g^{-1}} \\ &= 10\% \end{aligned}$$

19. The EC of an irrigation water is $0.9\,dS\ m^{-1}$ while the salinity tolerance of tall fescue is approximately $6\,dS\ m^{-1}$. What would be the leaching requirement for this irrigation water to maintain the soil salinity level near its current level?

$$\begin{aligned} \textit{leaching requirement} &= \frac{EC_w}{EC_{dw}} \times 100 \\ &= \frac{0.9\ dS\ m^{-1}}{6\ dS\ m^{-1}} \times 100 \\ &= 15\% \end{aligned}$$

This means 15 % additional water is needed above normal turfgrass water needs to prevent salts from accumulating.

20. From the previous example, 15 % extra water was determined necessary for the tall fescue turf to leach salts from the rootzone. If the "average" ET loss [or ET (target)] for tall fescue in summer is 0.325 $in\ day^{-1}$, determine how much water is needed to meet the needs of the fescue and accomplish the leaching required.

$$\begin{aligned} \textit{Total amount of water to apply} &= \frac{ET(target)}{1 - (\textit{leaching requirement})} \\ &= \frac{0.325\, in\ day^{-1}}{1 - 0.15} \\ &= 0.38\ in\ day^{-1}(9.7\ mm\ day^{-1}) \end{aligned}$$

This indicates 0.38 in day^{-1}*(9.7 mm* day^{-1}*) is needed to meet the summer turfgrass water needs and to prevent salts from accumulating.*

21. Water source 1 has an EC_w of 2.8 $dS\ m^{-1}$ while water 2 has an EC_w of 0.6 $dS\ m^{-1}$.

    (a) If water 2 is mixed in a 3 to 1 ratio to water 1, what would the EC_w of the blended water be?

    (b) If water 2 is mixed equally with water 1, what would the EC_w of the blended water be?

a) $$\begin{aligned} EC_w\ (blend) &= \frac{volume\ (water\,1) \times EC_w\ (water\,1) + volume\ (water\,2) \times EC_w\ (water\ 2)}{volume\ (water\,1) + volume\ (water\,2)} \\ &= \frac{[1 \times 2.8\ dS\ m^{-1} + 3 \times 0.6\ dS\ m^{-1}]}{1+3} \\ &= \frac{4.6\ dS\ m^{-1}}{4} \\ &= 1.15\ dS\ m^{-1} \end{aligned}$$

b) $$\begin{aligned} EC_w\ (blend) &= \frac{volume\ (water\,1) \times EC_w\ (water\,1) + volume\ (water\,2) \times EC_w\ (water\ 2)}{volume\ (water\,1) + volume\ (water\,2)} \\ &= \frac{[1 \times 2.8\ dS\ m^{-1} + 3 \times 0.6\ dS\ m^{-1}]}{1+3} \\ &= \frac{4.6\ dS\ m^{-1}}{4} \\ &= 1.15\ dS\ m^{-1} \end{aligned}$$

22. The following water quality analysis report was generated for a potential irrigation source.

    a. Find the missing SAR value.

    step 1: *The units must be converted to meq* L^{-1}*: Na (78), Ca (6.6), Mg (15.6), P (1.55), K (73),* CO_3*(3.9),* HCO_3*(10)*

    step 2: *Insert the values into the SAR equation:*

$$\mathrm{SAR} = \frac{\mathrm{N}a^{+}}{\sqrt{\frac{\mathrm{C}a^{+2}+\mathrm{M}g^{+2}}{2}}} = \frac{78}{\sqrt{\frac{6.6+15.6}{2}}} = 23.4\, meq\, L^{-1}$$

    b. If 7.5 *ac-in* of water is applied per month, how many pounds of sodium are being applied yearly?

$$\frac{1.8\; g\; Na}{L} \times \frac{1\; lb\; Na}{454\; g\; Na} \times \frac{7.5\; ac{-}in\; water}{month} \times \frac{12\; months}{1\; yr} \times \frac{27,154\; gal}{1\; ac-in} \times \frac{3.785\; L}{1\; gal}$$
$$= 36,674\, Na\; yr^{-1}$$

    c. If your 7.8 *ac* are irrigated on average of 4.5 *ac-in* every month, how much nitrogen is being applied?

    step 1: The amount of nitrogen in nitrate (NO_3*) must be determined: (molecular weights* $N = 14$ *g,* $O = 16$*)*

$$NO_3 = 14 + (3 \times 16) = 62 \quad g \quad \%N = (14 \div 62) \times 100 = 22.6\%\, N$$

    From the analysis, 6 ppm NO_3*is in the water, thus, this is multiplied by 22.6 % to obtain ppm N.*

    6 ppm × 22.6 % = 1.36 ppm N is being applied in the 6 ppm NO_3

    step 2: Now determine how much nitrogen is being applied each month:

$$\frac{1.36\, lbN}{1,000000\, lbH_2O} \times \frac{8.33\, lbH_2O}{gal} \times \frac{27,154\, gal}{ac-in} \times \frac{4.5\, ac\text{-}in}{month} \qquad \text{(or)}$$
$$\times\; 7.8\, ac = \;\sim 11\, lbN \text{ applied monthly over } 7.8\; ac$$

$$\frac{1.36\, mgN}{L} \times \frac{lg}{1,000\, mg} \times \frac{lb}{454\, g} \times \frac{3.755\, L}{gal} \times \frac{27,154\, gal}{ac\text{-}in} \times \frac{4.5\, ac\text{-}in}{month}$$
$$\times\; 7.8\; ac = \;\sim 11\; lb\, N$$

23. Water conservation involves numerous activities and practices. List the three activities when developing BMPs for Turfgrass water conservation.

    (a) *Site assessment and initial planning (*i.e., *documenting grasses, soils, microclimate, and existing management practices).*

Sample no.	Na^+	Ca^{+2}	Mg^{+2}	P	K^+	Cl^-	Carbonate (CO_3)	Bicarbonate (HCO_3)	Nitrate (NO_3)	Sulfate (SO_4)	TDS	pH	Conductivity (*mmhos* cm^{-1})	SAR
	ppm													
1	1800	131	190	1.55	73	6800	117	610	6	86	5120	8.4	8.0	–

(b) *Evaluating and implementing water conservation strategies.*
(c) *Analyzing benefits and costs of water conservation measures.*

24. Define hydrophobic soils and potential cause(s) of their development.

Hydrophobic soils are "water-hating" or -repelling from the coating of sand particles of acids (humic and fulvic). Acids are produced from:

Natural breakdown of soil organic matter.
Certain fairy ring fungi producing a mat of below-ground hyphae which often becomes hydrophobic.
Exudates from turfgrass roots.
Lipids from decomposing organic matter.
Surface waxes from cuticles of turfgrass plant leaves.

25. Within the nonionic surfactant chemistry, two main groups of wetting agents are currently available. List and discuss these.

1. *Soil Penetrants. These are often characterized as "water-moving" chemistry, characterized by having ethylene oxide terminal functional groups. Ethylene oxide groups are hydrophilic, being able to attract or disperse water molecules. Soil penetrating wetting agents generally increase water infiltration and percolation through the rootzone, providing more uniform soil moisture distribution within the profile leading to "fast and firm" playing conditions.*
2. *Soil water retainers. These are often characterized as "water-holding" chemistry, containing propylene oxide terminal functional groups. Propylene oxide groups are hydrophobic, thus repel water molecules. These are used where moisture retention is needed, especially sand-based rootzones with little organic matter and high infiltration and percolation rates. These are especially useful to help retain moisture during drought periods.*