ADVANCED IRRIGATION TECHNIQUES AND CONSERVATION STRATEGIES

Site-Specific Irrigation Scheduling

Using technology like soil-moisture sensors can give superintendents a better understanding of turfgrass water needs throughout a golf course. (USGA/Kyle LaFerriere)

SNAPSHOT

This strategy deals with using weather data and sensors to better estimate turfgrass water needs for irrigation scheduling. It is a high-impact, medium-cost strategy applicable for many golf courses.

Expected cost	< $25K per acre
Ease of implementation	Additional resources needed
Potential water savings for affected area	10% to 30%
Highest potential impact areas	Nationwide

OVERVIEW

One of the most challenging aspects of golf course irrigation is estimating the water requirements of different grasses, under different management regimes and stresses, throughout many different growing environments across hundreds of acres. Varying soil types, sun exposure, traffic patterns and countless other variables affect turfgrass water use in a particular area, and superintendents are inevitably forced to make assumptions about irrigation scheduling. Visually inspecting the course and relying on experience with how turf reacts during different weather conditions is the most basic approach, but leaves lots of room for error and often results in overwatering as superintendents sensibly err on the side of caution. Using a soil probe in representatively wet or dry areas before scheduling irrigation adds information, but the touch and feel aspect of soil sampling is inaccurate and imprecise.

In the past several decades, sensor technology has played an increasing role in golf course maintenance – especially when it comes to irrigation decisions. Many golf courses now have an on-site weather station or at least follow readily available local weather data. Recent USGA and Golf Course Superintendents Association of America (GCSAA) surveys indicate that about half of golf courses use hand-held moisture sensors to guide irrigation decisions (Shaddox et al., 2022; Thompson et al., 2021). However, fewer respondents reported using evapotranspiration (ET) data to schedule irrigation and only 6% of GCSAA survey respondents reported having in-ground soil-moisture sensors, so these technologies are still emerging in terms of their adoption on golf courses. Using sensor technology to enhance a superintendent's understanding of soil moisture and plant water needs has clear potential to improve irrigation decisions over a visual survey of the course, but there are obstacles to adoption. Cost of equipment and data services, and how well certain sensors estimate soil moisture are still challenges. However, research has shown that there is potential to use sensor-based approaches to significantly reduce water use and improve overall turf health and playing conditions. Learning more about these technologies in a turfgrass context and taking results from research settings and applying them to the larger and highly variable environment of a golf course are ongoing efforts. This chapter will review the most common tools currently used to guide site-specific irrigation and will explain the benefits, limitations and ways to implement these tools to advance water conservation goals.

TOOLS FOR SITE-SPECIFIC IRRIGATION

ET-Based Irrigation

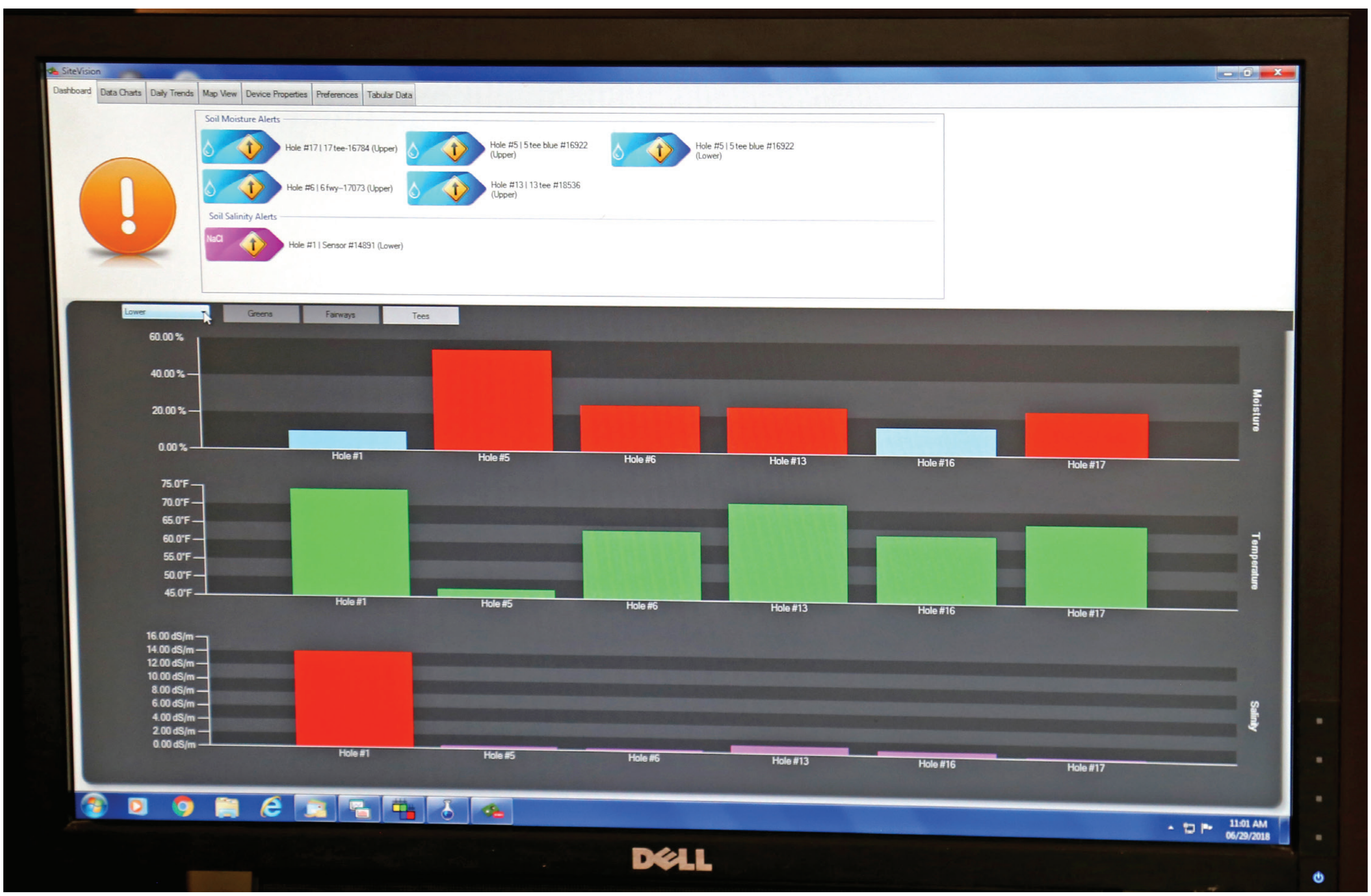
The overarching goal of site-specific irrigation is to precisely deliver only the amount of water necessary for turfgrass growth. Fundamental to this goal is understanding how weather affects turfgrass water requirements. One established method is to schedule irrigation based on ET, which combines estimates of water loss through evaporation from soil and leaves with plant transpiration. By quantifying ET, irrigation inputs can be refined.

To get the most out of ET, it is necessary to appreciate both what it is and what its limitations are. The objectives for this section are to first define and describe ET in simple, everyday language and address common misconceptions and barriers to adoption. We will then discuss key considerations used to refine ET values and maximize their effectiveness as part of site-specific irrigation practices. A key theme to this section is that ET-based irrigation should be seen as a complement to other water-conservation strategies, and that ET data can be used in conjunction with the other site-specific irrigation techniques.

First and foremost, ET-based irrigation is an improvement over runtime- or calendar-based irrigation scheduling as it more precisely incorporates environmental conditions into the amount of water being applied. Furthermore, the inherent flexibility of ET-based irrigation offers the opportunity to adapt a single ET value to different turfgrass species, maintenance practices and microclimates on a golf course. Yet, the adoption of ET-based irrigation on golf courses remains surprisingly low. Less than 20% of respondents from a recent GCSAA survey report scheduling irrigation using ET data from either a weather service or on-site weather station (Shaddox et al., 2022). USGA research indicates that many golf courses still plan to adopt ET-based irrigation scheduling (Thompson et al., 2021), and promoting a practical understanding of ET and associated terminology may enhance adoption.

Soil-Moisture Sensors

Soil-moisture sensors (SMS) have been around for about 40 years, but their use in turfgrass has been primarily in the last 20 years, mostly for scientific research (Bremer & Ham, 2003; Schiavon & Serena, 2023). More recently, SMS have gained traction for use on golf courses, although there is much room for expansion of their use.



In-ground soil-moisture sensors provide data that helps superintendents make more-objective decisions about when and how much to irrigate.

"Controlling an irrigation system without soil-moisture data is like driving a car without a gas gauge," said Dana Lonn, former managing director for technology at The Toro Company. Using this analogy, when driving without a gas gauge you would tend to fill up your tank earlier than necessary because you don't want to run out of gas. Similarly, without SMS in turfgrass, most turf managers will irrigate earlier than necessary because they don't want their turfgrass to run out of water and become drought stressed. The result is often excessive irrigation.

Soil-moisture sensors estimate the amount of water in soil, thus providing the superintendent with data regarding water available to turfgrass plants. This is an advantage over other irrigation scheduling methods such as calendar-based, ET-based, or "look-and-feel" approaches. Because none of these methods use soil-moisture measurements, they often result in improper irrigation amounts and/or timing that wastes water and money. For example, although ET-based irrigation is generally an improvement over calendar-based irrigation, ET values rely on equations that model ET from weather data, and those models are not always accurate. Similarly, factors other than soil moisture may affect the appearance of turfgrass, including pest infestations or abiotic stresses like traffic, soil compaction or nutrient deficiencies. Even obvious wilt may not be for lack of soil moisture. Therefore, turf appearance alone is not always a good guide for irrigation scheduling.

Remote Sensing

Remote sensing is the process of measuring plant characteristics without coming into physical contact with the plants. In turfgrass, remote sensing is typically used to detect stress-related issues, such as the effects of drought, and can be useful for irrigation management. Technically, remote sensing could include standard digital images or videos of turfgrass, such as those taken with a smartphone and evaluated with an app (e.g., to measure green cover), or aerial views from cameras mounted on drones. However, more-complex spectral cameras that measure light reflectance at multiple wavelengths and thermal cameras that measure turfgrass surface temperatures provide additional information about drought and other turfgrass stresses. For example, spectral and thermal cameras may be used to create colorful, detailed maps of stress patterns in turfgrass. Research has shown that these maps can be used to detect some forms of plant stress in controlled settings, including early drought stress in turfgrass before it becomes visible to the naked eye (Hong et al., 2019a & 2019b; Bremer et al., 2023). However, these technologies still have limitations for a large-scale application, including high cost and the potential need for site-specific calibration to improve accuracy.

These technologies should be viewed as an enhancement to the superintendent's knowledge and experience, not a replacement for it.

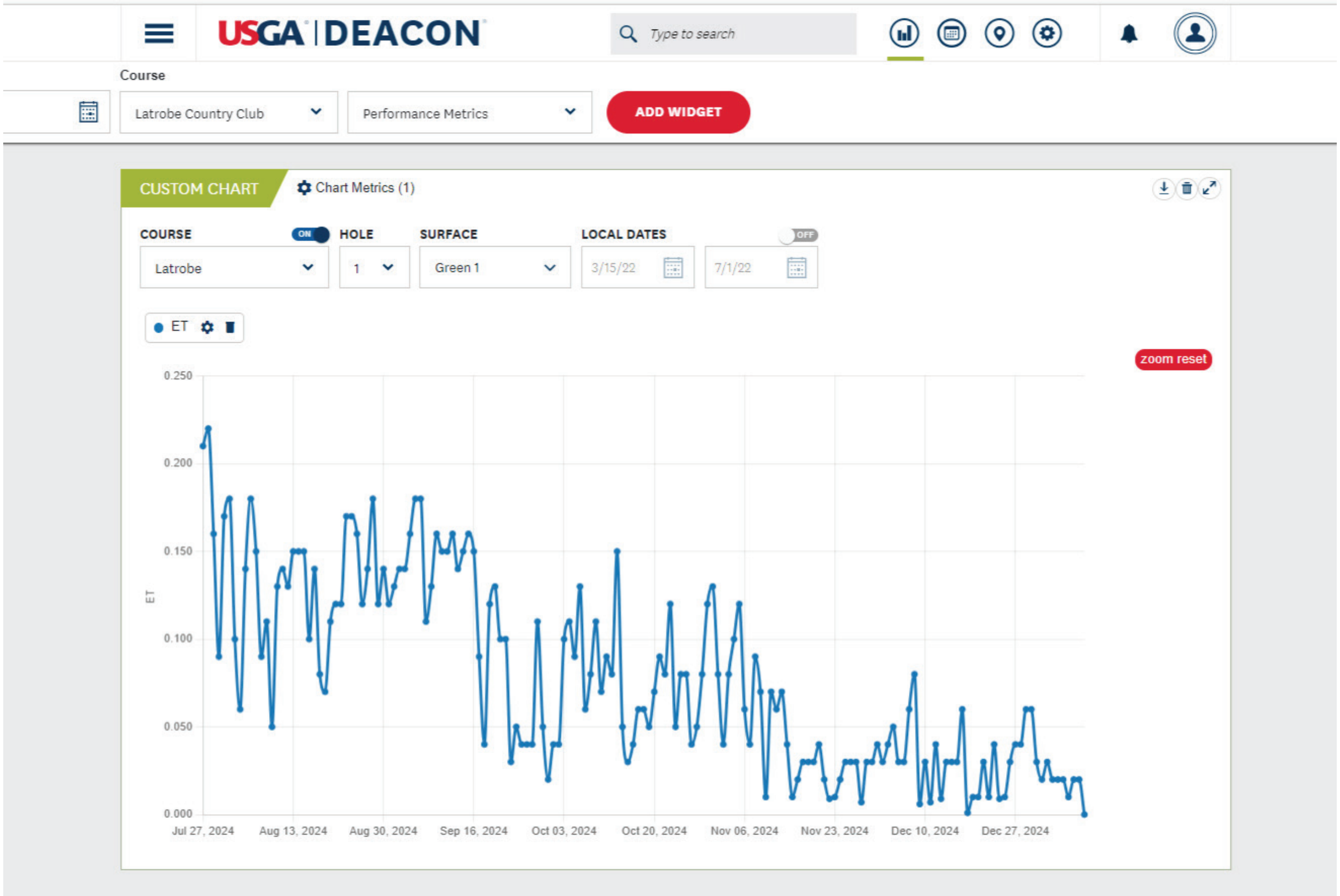
Although remote sensing has been around for about 50 years, it is still considered an emerging technology in golf course and turfgrass settings as it has been used primarily in research. In turfgrass research, remote sensing has typically been utilized with hand-held or vehicle-mounted sensors. However, with the increasing availability and affordability of remote sensing platforms comes a greater ability to evaluate large areas of turfgrass on golf courses (Bremer et al., 2023). Using aerial platforms such as small drones or even data acquired from satellites, turfgrass vegetation and stress maps can be developed relatively rapidly and frequently, providing more timely information for scouting and management decisions. Consultation between the superintendent and a remote sensing specialist may be needed, at least initially, for accurate interpretation of these maps. Nevertheless, there is significant opportunity for more widespread use of remote sensing by the turfgrass industry, including for improved irrigation management.

Summary

Given the increasing water costs and potential limitations in water availability faced by many golf courses, the need for reducing water consumption in the golf industry will continue. Therefore, as ET-based, SMS, and remote sensing technologies are continually improved, their use for irrigation management on golf courses is predicted to increase. These site-specific irrigation tools may be used alone, in tandem, or with other data streams such as weather forecasts. While the ultimate goal is for highly precise and potentially automated irrigation management, the superintendent's input and ability to control the system will remain critical. These technologies should be viewed as an enhancement to the superintendent's knowledge and experience, not a replacement for it.

USING ET-BASED IRRIGATION

ET-based irrigation technology is useful for any type of golf course in any environment, without any particular limitations. It can also be adapted to golf course areas with various irrigation requirements, such as greens, fairways or shaded areas.



Using ET data to guide irrigation scheduling is a proven way to improve water-use efficiency.

In practice, ET data is obtained either from weather services or on-site weather stations. This data is adjusted for cool- or warm-season grasses to better approximate actual turfgrass water requirements. While ET is proven to improve water-use efficiency, adoption on golf courses is still relatively low, likely due to unfamiliarity with the process or misconceptions about its complexity. There can also be challenges adjusting the irrigation control system to properly implement ET-based scheduling, even though nearly all modern systems have the capability. Increasing understanding of ET and its benefits for irrigation scheduling, and integrating it with existing irrigation practices, could lead to broader use and significant water savings on golf courses.

ET Terminology

Evapotranspiration can be measured and calculated with several methods, each offering different ways to represent the water loss from turfgrass systems. Common terminologies used to report and discuss ET are: ET_p, ET_o, ET_{os} and Et_a.

Potential ET (ET_p)

Definition: ET_p refers to the amount of water loss that would occur under ideal conditions with an unlimited water supply, such as from a body of water or a well-irrigated landscape.

Use: ET_p is a theoretical value that assumes no limitations on water availability. It is mainly used as a reference point to understand how much water plants would lose if they had unrestricted access to water.

Measurement: ET_p can be estimated using empirical models that consider weather factors like solar radiation, temperature, wind speed and humidity. Direct measurements and use are less common for ET_p since it assumes unlimited water availability.

Reference ET (ET_o)

Definition: ET_o refers to the amount of ET from a well-watered “reference crop,” which is often a forage crop such as alfalfa or a cool-season grass maintained at a certain height (Allen et al., 1998). It represents the theoretical maximum water loss under current or recent field conditions.

Use: ET_o serves as the baseline for calculating irrigation needs. It is typically reduced by specific percentages to estimate how much water certain turfgrass species would need.

Measurement: ET_o is typically calculated using the same weather data as ET_p. It is often presented in daily or weekly values and is reported in units of depth (inches or millimeters).

Reference ET for short grass (ET_{os})

Definition: ET_{os} is used when ET_o is calculated using a "short crop" reference. It typically refers to the amount of ET from a well-watered cool-season grass (often tall fescue) maintained at or below 4.75 inches. It is a more precise evolution of ET_o that is adapted for turfgrass systems. In practice, ET_{os} and ET_o are often used interchangeably.

Use: ET_{os} serves as the baseline for calculating irrigation needs in turfgrass.

Measurement: Same as ET_o calculation.

Actual ET (ET_a), ET crop (ET_c) or ET turf (ET_t)

Definition: ET_a and ET_c, or less-commonly ET_t, refer to the amount of water lost from a specific turfgrass system, potentially under specific conditions. This value is generally an adjustment from ET_o that better represents water use estimates for cool- or warm-season grasses broadly. It can be more accurate when species- or cultivar-level information is available, or when estimates have been made for specific turfgrasses regionally, seasonally or under different levels of irrigation. Another way to improve ET_a is to more accurately estimate ET_o based on site-specific weather data from several microclimates within a golf course.

Use: ET_a is most useful for site-specific irrigation scheduling when determined in a way that accounts for specific grasses grown in specific microclimates throughout a golf course. It provides a more accurate estimate of water loss based on current or recent conditions, and it is the best ET value for scheduling irrigation.

Calculation: ET_a is calculated by multiplying ET_o by a crop coefficient (K_c), which accounts for the specific characteristics of the turfgrass being grown (e.g., cool-season vs. warm-season grasses). Typically, K_c values are determined through research under controlled conditions.

$$ET_a = ET_o * K_c$$

K_c Values: Generally, warm-season turfgrasses have a K_c value of 0.6, while the K_c value for cool-season grasses is 0.8. These values are only a starting point and can be further refined based on species, cultivars, microclimate and soil conditions. Recently, some studies have looked at seasonal adjustment for K_c values in turf.

An on-site weather station is the best way to obtain ET data that is site-specific to a particular golf course.

ET Measurement

On-site weather stations

On-site weather stations are tools installed directly on a golf course or property to provide hyperlocal weather data that can be used to calculate

ET. These stations allow for real-time, site-specific ET estimation, which can be used to adjust irrigation schedules more precisely.

ET gauges

ET gauges are instruments that mimic water loss from turfgrass systems to estimate ET directly. These gauges are often used for more-direct measurements and can be set up on-site at relatively low cost (around $500). They are helpful for capturing the combined effects of evaporation and transpiration in specific areas. Although popular in the scientific community and for smaller areas, these are typically impractical for golf courses.

Weather networks and ET prediction

State and local networks like AZMET (Arizona), CIMIS (California) or Mesonet (Kansas) provide historical ET_o data. These are typically accurate and reliable values and can be automatically synchronized to the irrigation control system. The National Weather Service (NWS) and National Oceanic and Atmospheric Administration (NOAA) also provide forecasted ET_o (FRET), which predicts ET_o for the next day or week based on forecasted weather data. Research has shown that FRET is a very accurate predictor of ET_o calculated with data from an on-site weather station (Hejl et al., 2022). Although currently limited in use, FRET has great potential to further improve ET-based scheduling.

Where Is the Strategy Typically Used?

On a golf course

On a golf course, ET-based irrigation is typically used to estimate how much water is needed to replace what has been lost through ET to prevent drought stress. In can be used to manage water more precisely across different areas such as greens, fairways and roughs. This is achieved by using data from on-site weather stations or local weather networks to monitor real-time ET rates. Adjustments are made based on specific turfgrass species, microclimates and other localized environmental factors.

Regionally

ET-based irrigation is most commonly used in areas where water conservation is crucial, such as in drought-prone or arid regions like the southwestern United States. In places like Arizona and California, regional weather networks like AZMET and CIMIS provide ET_o data to support large-scale irrigation management. Municipalities, agricultural producers, golf courses and others utilize this data to manage water resources more efficiently.

Opportunities to expand use

There are significant opportunities to expand the use of ET-based irrigation nationwide. While especially crucial in areas where water is increasingly scarce and expensive, ET data is less used in areas that typically don't worry about water scarcity and this should change. As the management of golf courses and other large landscapes becomes more data-driven, integrating ET data with advanced technologies like soil-moisture sensors and remote sensing can provide even more precise irrigation control. Beyond golf courses, expanding this technology into residential and commercial landscaping, parks and sports fields presents a substantial opportunity to improve water conservation on a broader scale.

BENEFITS OF ET-BASED IRRIGATION

Water Efficiency and Savings

ET data is used to adjust irrigation schedules to optimize irrigation for turf health and playing conditions and reduce the risk of overwatering. This approach can lead to significant water savings. Recent research has demonstrated water savings in the 20% to 50% range compared to turfgrass plots irrigated based on a constant runtime, depending on turfgrass species and the environment (Serena et al., 2020).

Site-Specific Adjustments

Using a single ET_a estimate to inform irrigation for a golf course is a mistake. One of the major advantages of ET-based irrigation is the ability to adapt it to the specific conditions of a given site. It accounts for factors like turfgrass species, microclimates, soil conditions and type of playing surface. This allows for more-precise irrigation tailored to the unique needs of different areas on a golf course, which promotes turf health while minimizing water waste.

Data-Driven Decision Making

ET-based irrigation guides decision-making with measurable factors such as temperature, wind speed, solar radiation and humidity to determine how much water is needed. This removes some of the guesswork involved in traditional irrigation scheduling methods, making irrigation decisions more consistent and reliable.

Enhanced Turf Health

By providing a better approximation of water needs, ET-based irrigation helps maintain healthy, high-performing turfgrass. This can prevent common problems associated with overwatering, such as turf disease, waterlogged soils and inefficient nutrient uptake, while helping grass stay as healthy as possible during periods of drought stress.

Flexibility Across Turf Types

ET-based irrigation can be customized for different types of cool-season or warm-season turfgrass by adjusting K_c. This flexibility allows superintendents to fine-tune irrigation amounts based on specific grass species or cultivars, helping optimize water use without sacrificing turf quality.

Integration With Other Technologies

ET-based irrigation can be easily integrated with other water-saving technologies such as soil moisture sensors, remote sensing and smart irrigation controllers. This creates opportunities for even more refined water management, leading to automated systems that dynamically adjust irrigation based on multiple data inputs.

Better Playing Conditions

ET-based irrigation helps superintendents to better estimate the amount of water necessary to sustain turfgrass health on their golf course. Reducing the number of instances where water is overapplied will result in better playing conditions.

LIMITATIONS OF ET-BASED IRRIGATION

Generalization of ET_o and K_c Values

While ET-based irrigation adjusts the ET_o using K_c values, these coefficients are often generalized for broad categories like cool-season or warm-season turfgrass. They do not account for specific species or cultivars. Further, ET_o is commonly calculated and used as a single value, without accounting for variations within a golf course. Superintendents need to refine these estimates based on local conditions to achieve true site-specific irrigation, which can be challenging and requires expertise.

A single daily ET estimate cannot account for the many different microclimates and growing environments on a typical golf course. Scouting is still necessary to assess actual turfgrass water requirements.

Initial Setup Costs

Implementing ET-based irrigation can involve significant up-front costs, especially if on-site weather stations or ET gauges are needed. While national and state weather networks can provide free ET_o data, the most accurate, site-specific ET values come from on-site equipment, which can range in cost from around $500 for basic ET gauges to upward of $12,000 for high-end weather stations.

Complexity and Learning Curve

Despite its benefits, ET-based irrigation can seem complex to those unfamiliar with the technology. Superintendents and staff may need training to understand ET data and how to adjust irrigation schedules accordingly. Misconceptions, such as the belief that ET-based irrigation conflicts with a superintendent's feel for their course, can also act as barriers to adoption.

Weather Variability

ET-based irrigation relies heavily on weather data, which can vary significantly within a region or even across a single golf course. If the ET data used does not accurately reflect the specific conditions of a course, the irrigation schedule may not be optimal. On-site weather stations help address this issue, but they also add complexity and cost to the system.

Adjustment Needs for Seasonal Changes

ET values and crop coefficients need to be adjusted not only for different areas of a course but also for seasonal changes in weather patterns and turfgrass growth rates. For example, warm-season grasses go dormant in some areas during winter, while temperature and moisture fluctuations in the spring and fall can create unique ET challenges. Superintendents must continually monitor and adjust ET data to ensure proper water application all year round.

Weather stations should be placed in representative areas on the golf course rather than hidden near the maintenance facility.

Integration Challenges

While ET-based irrigation systems can integrate with other irrigation management technologies, ensuring smooth integration with existing irrigation hardware, software and weather data systems can be a challenge. Each system must be properly calibrated and maintained to realize the full benefits of ET-based irrigation.

IMPLEMENTATION OF ET-BASED IRRIGATION

One of the most effective ways to implement ET-based irrigation involves installing on-site weather stations that directly monitor weather on the golf course property. These stations provide hyper-localized ET data, which can then be used to fine-tune irrigation scheduling. It may be advisable to install more than one weather station if there are distinct microclimates around the property. Otherwise, estimates of ET will not be as accurate as possible. Weather stations should be placed in representative areas on the golf course rather than hidden near the maintenance facility.

Many modern irrigation control systems can use ET data to control water application automatically. These systems allow superintendents to input ET values and adjust irrigation schedules based on real-time data. This integration reduces manual intervention and makes it easier to optimize water use across different areas of a golf course. It is important to recognize that irrigation scheduling will still need continual refinement based on conditions in the field, regardless of ET integration into scheduling.

TIPS FOR SUCCESS: ET-BASED IRRIGATION

Determine precipitation rates for irrigation zones.

Using ET begins with having accurate precipitation rate information for irrigation zones. Perform regular audits, adjust irrigation system components as needed, and enter any changes into the irrigation control system. Without this information, adjusting runtimes based on changes in ET only perpetuates the guesswork of irrigation scheduling.

Start small and then scale up.

Begin by following ET data and observing how the course changes with consistent irrigation and varying ET. Next, implement ET-based scheduling on a limited part of your course, such as a few fairways, before expanding to other areas. Begin with simpler fairways and then compare the process to fairways with unique or challenging microclimates. Remember that many variables will affect moisture uniformity and the superintendent's intuition and soil-moisture sensors can further inform scheduling. Refine your process before scaling up to the entire course.

Invest in on-site weather stations.

While regional weather data is useful, on-site weather stations provide more accurate, localized ET values, helping you make better irrigation decisions. Though the up-front cost is higher, the long-term savings in water and improved turf health justify the investment.

Regular calibration of sensors is necessary.

Successful data-driven decision making depends on collecting accurate and consistent data. To optimize ET readings, regularly check, clean and calibrate your weather stations and sensors. This will help avoid data drift, which can lead to over or under watering.

Refine the K_c values used for your course.

Don't rely on generalized crop coefficients for cool- and warm-season grasses. Customize K_c values based on the specific species, cultivars and microclimates of your course to better reflect the actual water needs.

Use a combination of data sources.

Integrate ET data with other available technologies such as soil-moisture sensors and remote sensing tools. This multisource approach will provide a more complete picture of your turf's water requirements, helping you refine your irrigation scheduling.

Train your staff.

Ensure your team understands ET-based irrigation concepts and how to use the system effectively. Training on topics like ET terminology, weather data interpretation, and irrigation controller adjustments will empower them to manage the process confidently.

Monitor weather patterns regularly and carefully.

Weather conditions fluctuate throughout the year, affecting ET rates. Regularly review weather data to adjust irrigation schedules, and be particularly mindful of transitions during spring and fall when ET rates can change quickly.

Incorporate your expertise, knowledge and feel as a superintendent.

Balance ET data with your experience and knowledge of the course. Use ET-based scheduling as a complement to your feel for the turf's needs, adjusting for localized factors like shade, airflow and soil conditions that data alone may not fully capture.

USING SOIL-MOISTURE SENSORS

When observing data from soil-moisture sensors (SMS) frequently and over time, superintendents will become familiar with how their turfgrass looks and performs at various levels of soil moisture. They learn that at or below a certain level of soil moisture, turfgrass will begin to experience wilt or other undesirable symptoms from drought stress. The soil moisture level at which this occurs becomes a threshold for initiating irrigation. This threshold may vary from one location to another – even within a single green, fairway or rough area – and may change slightly over a growing season and from year to year. Nevertheless, the real-time information provided by SMS becomes invaluable to the water management program.

In-ground soil-moisture sensors help superintendents track moisture trends and identify thresholds for irrigation.

Managers often build in a buffer, which means irrigating at a slightly higher soil moisture level than the threshold where turfgrass begins to show early signs of drought stress. The amount of buffer will vary based on the superintendent's experience and comfort with visible signs of drought stress on their course. Without a buffer, turfgrass quality may decline over time due to the slight drought stress experienced every time the soil dries to the threshold between irrigation events. Other factors such as soil type, slope, traffic and salinity may affect the desired buffer. For example, sandy soils or south-facing slopes may require slightly greater buffers. A more precise strategy for the development of thresholds is called a "field calibration" and is described in the Tips for Success section later.

Although there are many different types of SMS, dielectric sensors, such as time-domain reflectometers (TDRs) or capacitance sensors, are most common and estimate soil moisture by measuring the dielectric constant of soil, which is highly dependent on soil moisture. The most common type of SMS used on golf courses are portable hand-held units often used to help manage water on putting greens (Whitlark et al., 2023). There are also fixed, in-ground sensors that can be placed throughout a golf course. In-ground sensors have the advantage of providing continuous readings from a consistent location, so changes over time can be easily observed. However, there are practical limits to where and how many in-ground sensors can be placed around a golf course.

Where Is the Strategy Typically Used?

On a golf course

Portable SMS are most commonly used to manage water on putting greens. They are well-suited for this application because of the relatively small area involved and the elevated desire for precision and consistency in putting green playing conditions. Some courses have expanded the use of portable SMS units to tees, approaches and even fairways. While collecting the data across large areas such as fairways is time consuming, golf course superintendents report improved soil moisture consistency and playability resulting from scheduling changes made to individual sprinklers.

The first instinct of new users of in-ground SMS often is to place them in putting greens. While a few in-ground SMS can help generally compare specific greens over time, the flexibility and spatial resolution offered by portable SMS makes them a better fit for the nuances of putting green irrigation. In-ground SMS are better suited for larger areas such as fairways, which are also better targets for water conservation. Because in-ground SMS can't be placed everywhere on a golf course, superintendents must identify locations that are representative of the various growing conditions and playing surfaces on the course. For example, you may want to place in-ground sensors in several fairway locations that tend to get dry, tend to stay wet, or tend to have moderate soil moisture. In that way, the information from a handful of sensors can be extrapolated throughout the course. If the representative dry areas all have inadequate soil moisture, but moderate areas have adequate soil moisture, chances are good that only drier areas of the course require irrigation at that time.

Portable soil-moisture sensors are well suited for use on putting greens because you can take many readings in a relatively small area to optimize watering. (USGA/Kyle LaFerriere)

Regionally

Nationally, about half of all respondents to a recent Golf Course Superintendents Association of America (GCSAA) survey reported using hand-held SMS units, regardless of region (Shaddox et al., 2022). Only 6% of respondents reported using in-ground SMS. Early adopters of SMS in fairways and roughs have been primarily in the southwestern U.S., where water scarcity and costs are a constant factor in golf course management.

Opportunities to expand use

Few golf courses have utilized SMS in fairways and roughs. However, in-ground SMS on fairways and roughs offer an excellent opportunity for the golf industry to reduce water use because these areas make up the majority of irrigated golf course acreage (Gelernter et al., 2015; Whitlark et al., 2023), and there is inherent difficulty in estimating irrigation needs over large areas. Using in-ground SMS in representative locations can be a valuable tool to conserve water and improve playing conditions.

Interestingly, water savings from SMS are often larger in wetter regions and years than they are in arid regions and dry years, indicating that golf courses in all climates can benefit from using SMS. In wetter locations or years, SMS-based irrigation scheduling often increases the duration between irrigation events relative to traditional calendar-based irrigation. The result is more bypassed irrigation events and greater water savings.

In arid regions, reports of water savings among golf courses using SMS are mixed, ranging from 20% less water applied to no significant change. Within an individual golf course, experience has shown that SMS reduce irrigation frequencies or run times primarily in wetter areas, while irrigation scheduling does not change as much in dry areas. Therefore, it is recommended that superintendents in arid regions carefully evaluate the potential for water savings with SMS placement across their course, perhaps in consultation with SMS experts, before implementing an SMS program.

BENEFITS OF SOIL-MOISTURE SENSORS

Expected Water Savings

Turfgrass studies have revealed significant water savings when using in-ground SMS to guide irrigation decisions compared with calendar-based and ET-based irrigation (Cardenas-Lailhacar & Dukes, 2012; Chabon et al., 2017; Dyer et al., 2021). Water savings have typically ranged from 20% to more than 80%, with greater savings typically seen in wetter regions, as discussed above. Most research has been conducted on small plots and residential lawns, but early reports from ongoing studies also indicate significant water savings (24%-46%) on golf course fairways when using in-ground SMS compared to traditional and ET-based irrigation (Straw et al., 2022b).

Water savings should begin immediately after incorporating SMS data into irrigation decision-making. However, establishing thresholds for triggering irrigation and their associated buffers may take a few days or weeks after SMS installation – depending on climate, soils, turfgrass species, superintendent experience and other factors. Furthermore, thresholds will change throughout the year based on day length, sun angle, and other plant- or soil-related factors.

Better Playing Conditions

Using SMS will improve the precision of water management, which will translate to improved playing conditions. Recent research has shown the inevitable soil-moisture variability within and over different fairways from nine traditionally irrigated golf courses (Straw et al., 2022a). Leveraging SMS data is a good way to reduce that variability and improve playing conditions.

The technology associated with SMS is also evolving in ways that will make them even more valuable for optimizing water use on areas like greens, even if the water savings is limited. For example, real-time digital mapping of locations where moisture readings are taken is a valuable feature that helps superintendents understand what areas need water and allows the staff responsible for irrigation to communicate more effectively.

Data from soil-moisture sensors allows for more-precise watering, which leads to better playing conditions and healthier, more-consistent turf.

LIMITATIONS OF SOIL-MOISTURE SENSORS

Sampling Challenges

Soil-moisture sensors can only be used to sample very limited areas on a golf course and there can be a high degree of variability in soil moisture even within a small space. Measurements from portable moisture meters on greens can vary widely within a few inches, and these are taken in areas with relatively consistent soil media and generally more precise irrigation. When you consider the soil and microclimatic variability across large fairway and rough areas, the challenges of sampling are evident. While more data is always better, there are cost and practical limitations to how much coverage SMS can provide across a course. Research has shown that a minimum of three to four samplings per 1,000 square feet would be necessary to sufficiently account for the spatial variability in soil moisture (Magro et al., 2022). Therefore, developing an effective, representative sampling method to establish hydrozones prior to installing SMS is an important challenge to overcome.

Calibration

The data coming from SMS is only useful if it is accurate. Portable and in-ground SMS may require calibration initially and potentially on an ongoing basis, depending on manufacturer specifications. Deterioration of the rods of portable units commonly reduces accuracy and these components must be monitored and replaced as needed. These sensors are exposed to the environment and are also vulnerable to other types of damage that can affect their measurements. Soil salinity is another factor that can affect the quality of soil-moisture estimates. Research has demonstrated that common SMS options accurately track soil moisture up to salinity levels of 4 or 5 deciSiemens per meter (Dukes, 2020; Serena et al., 2020). Higher salinity levels may reduce accuracy of some SMS, so selecting ones that are accurate at higher salinities, or at least can also measure salinity, is crucial in such areas.

Improper Installation and Damage

In-ground SMS must be installed properly to deliver accurate data, but it can be easy to make small errors like failing to fully insert the sensor rods into the soil or not installing sensors at a consistent depth in each location. The risk of minor installation mistakes reducing data quality is something superintendents need to be aware of. Improper installation can also lead to signal loss or poor reception, which ultimately leads to data loss.

Depending on where in-ground SMS are installed, they may also be at risk for damage during aeration. This is especially true on greens, which are aerated on a regular basis. The maintenance team must be aware of sensor locations and will have to either remove them from the ground prior to aeration or use shallower aeration techniques that can pass over the sensors without damaging them. Skipping aeration and other cultural practices in the area around the sensor is not recommended because that can potentially lead to long-term agronomic issues.

IMPLEMENTATION OF IN-GROUND SOIL MOISTURE SENSORS

Using portable SMS is a well-understood process in the golf course maintenance industry. They are most often used on putting greens to optimize soil-moisture uniformity and putting green playability. Portable SMS can also be used to map other areas of a golf course to identify soil-moisture hydrozones and determine where to place in-ground SMS.

Successfully using in-ground SMS involves several decisions and steps, including deciding on the number of sensors to use, selecting a type or brand, deciding whether to use wireless SMS or SMS connected to the irrigation system with underground cables, the depth and location within and among irrigation zones, and field calibrations to develop irrigation thresholds. The assistance of a consultant who is experienced with in-ground SMS is recommended for most circumstances. A good place to start is to install sensors in areas field staff have identified as “wet,” “moderate” and “dry” on several fairways, preferably based on actual soil moisture measurements taken with a hand-held SMS unit. Another consideration is the platforms and software associated with SMS. The ability to view SMS data across locations and time may impact how readily data can be implemented into irrigation decision making.

Within each irrigation zone where SMS are installed, placement must be at a representative location for the data to be broadly applicable.

Placement of Soil-Moisture Sensors Within an Irrigation Zone

In most situations, proper installation of in-ground SMS will require consultation with experts experienced in using SMS in turfgrass. Improper installation of the SMS may result in significant errors in function and accuracy, leading to poor results from the SMS system.

Within each irrigation zone where SMS are installed, placement must be at a representative location for the data to be broadly applicable. The recommended method for deciding on representative locations is to measure soil moisture in a series or grid pattern across each irrigation zone with a portable, GPS-enabled SMS or specialty sensing systems (Straw et al., 2022b). For example, several courses in Arizona used portable SMS to measure soil moisture every 12 paces along lines (traverses) spaced 12 paces apart, yielding 30 to 80 measurements a grid pattern across sampled fairways. Alternately, a protocol developed by researchers at the University of Minnesota recommends collecting data every eight to 10 steps, while following a serpentine pattern through the fairway, for up to 150 measurements per fairway.

Data from this sampling effort can then be used to generate a soil moisture map for each fairway. Specialized software can expedite this process. The range of observed soil moisture across fairways can then logically be divided into three or more sub-ranges for soil moisture classes, and maps should be used to classify each irrigation zone into one of the defined classes. Typically, at least one in-ground SMS should be placed to represent each soil-moisture class.

If this approach is not feasible, then in-ground SMS placement may be determined with teamwork between the SMS consultant and irrigation manager, who should have a good sense about general soil-moisture classifications and representative locations for each irrigation zone. Placement may be more straightforward in zones that are level and have relatively consistent soils. If a zone has undulating slopes or variations in soil type, compaction or microclimate, then SMS placement will be more complicated. At the very least, some type of soil-moisture measurement across these locations would be extremely helpful for guiding irrigation decisions.

If irrigation heads can be controlled individually across a golf course, superintendents can create “hydrozones” in their irrigation programming by grouping the irrigation heads into categories based on the relative wetness or dryness of soils surrounding each head (Straw et al., 2022b). For example, Hydrozone 1 could be fairway heads surrounded by relatively wet soils (high soil moisture), Hydrozone 2 could be those surrounded by relatively dry soils (low soil moisture), and Hydrozone 3 could be those surrounded by relatively average soil moisture (medium soil moisture). More than three irrigation hydrozones may be required to improve precision. An advantage to this approach is that only one SMS per hydrozone might be required, assuming irrigation heads get classified correctly and the soil moisture is similar around the heads in each zone.

If the irrigation heads are controlled in blocks rather than individually, it is recommended that each block of heads be evaluated and grouped with other blocked zones that have similar soil moisture values. Using this method, a single SMS could be used to represent all irrigation blocks with similar soil moisture. While there will likely be some variation in soil moisture within each sprinkler block, the limitations in irrigation control make it difficult to find a better solution. It is not practical to put a SMS in each block of sprinklers and using some SMS is better than using none. A typical number of SMS used across a course is 10 to 30, but the number of SMS required for any given course could fall outside that range. An SMS consultant can help courses find the best solution for their unique site characteristics.

After in-ground SMS are installed, there could be air pockets or lose soil around the SMS rods. The first heavy irrigation or rainfall will help to “seat” soil around the SMS, allowing for proper soil-to-sensor contact. Shortly after installation, it may be worth comparing moisture readings from a portable SMS and in-ground SMS to make sure there are no large discrepancies. Note that moisture values would not be expected to be identical between the two sensors because they are measuring slightly different soil depths and locations. In some instances, it may be necessary to relocate SMS if the superintendent determines they are not representative of soil moisture in their immediate vicinity based on portable SMS measurements and other indicators like visual observations of turfgrass quality. Regardless of location, we recommend that all in-ground SMS on the course measure at the same soil depth.

In-ground soil-moisture sensors should be installed at a consistent depth throughout the course to make measurements directly comparable.

Field Calibration of Sensors

All SMS are calibrated by the manufacturer for accuracy of soil moisture measurements, most likely in a laboratory, before being distributed to customers. However, a number of factors in the field affect the measurements and desired irrigation thresholds compared to what might be found in a laboratory setting. These include soil type, soil compaction, slight variations in SMS installation, and the amount of organic material or plant roots adjacent to the sensors. Furthermore, irrigation thresholds will be impacted by turfgrass species, different microclimates, and cultural practices such as mowing height and aerification. Therefore, it is recommended to conduct a calibration in the field after the SMS are installed to account for these factors. After the field calibration, low value warnings and irrigation thresholds can be adjusted accordingly. This field calibration may be required at least at the beginning of each year and perhaps more frequently if conditions change during the growing season.

Field calibrations are conducted over one or two soil dry-down periods to help determine the soil moisture level at which irrigation should be applied for each irrigation zone. The best approach for field calibration is to begin immediately after a rainfall that fills the soil profile to field capacity. If in an arid region where little or no rainfall has occurred or is expected, then the turfgrass should be irrigated until soils are wet at the depth of the SMS. Using this method, the soil moisture will likely be less uniform than after rainfall, which could affect the precision of irrigation threshold values compared to field calibrations developed after rainfall. Regardless, the irrigation threshold for each SMS should be developed based on the general turfgrass quality desired by the superintendent across the zone.

After the dry down begins, the superintendent should monitor soil moisture values for each SMS and the associated turfgrass quality and appearance across the irrigation zone over the next few days. The soil moisture value at which the turfgrass begins to show signs of wilt or drought stress will become the initial irrigation threshold, although adjustments like added buffers can be made according to the superintendent’s comfort level. Turfgrass quality should be carefully monitored during the next few irrigation cycles to determine if the soil moisture threshold needs adjustment. Remember that the absolute value of the threshold will likely differ among hydrozones and may change over time.

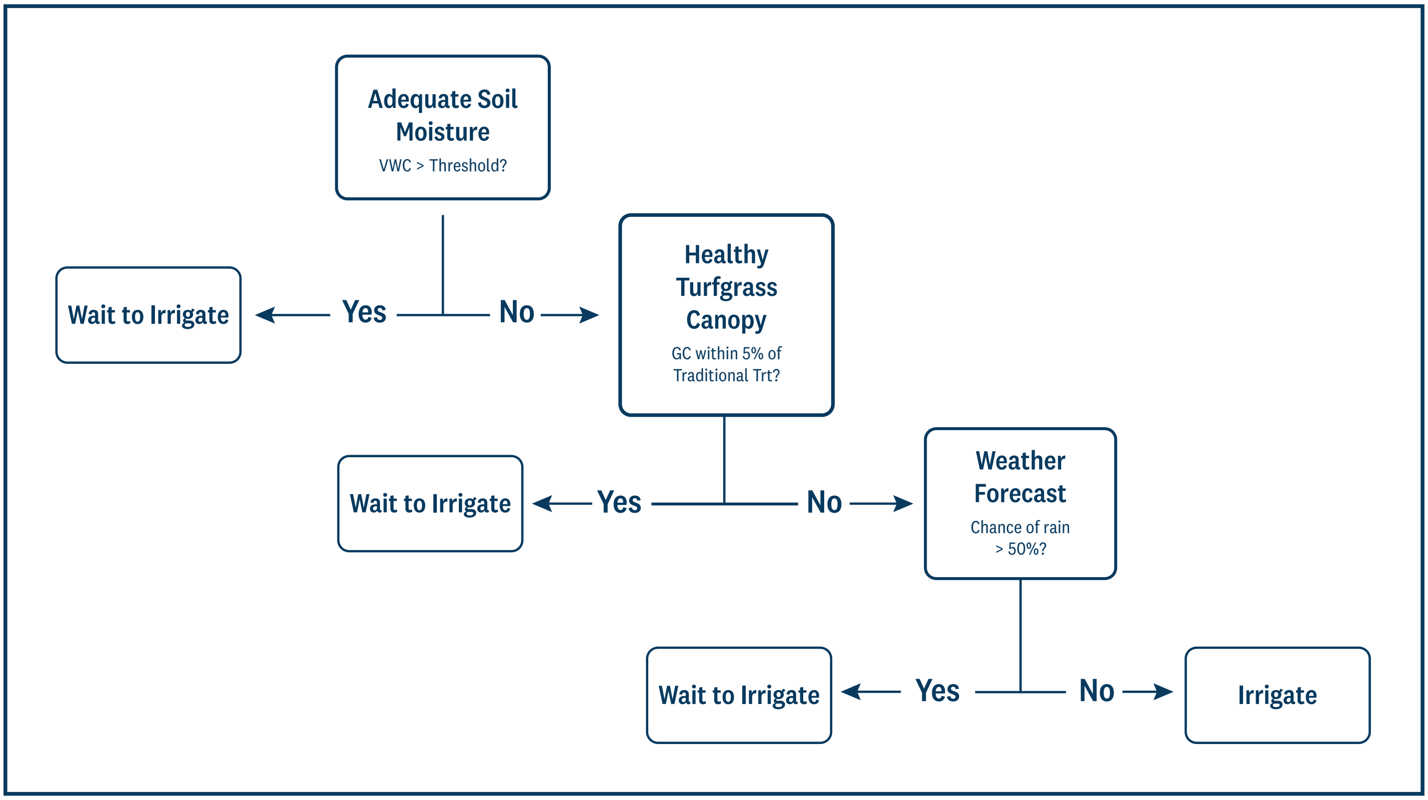
If a slight decrease in turfgrass quality is unacceptable, then a slightly higher threshold or buffer may be necessary. This can be accomplished by adding a few percentage points to the initial soil moisture threshold and continuing to monitor turfgrass quality when using this level as a trigger for irrigation. Incremental adjustments can be made if the first buffer is insufficient to maintain the desired turfgrass quality. Golf courses have found that the threshold will change from season to season and oftentimes a larger buffer is necessary during summer months or in chronically dry areas such as crests of south-facing slopes.

Maximizing Sensor Efficiency

Use a decision tree

If more water savings are desired, the relatively simple irrigation decision tree shown in Figure 1 may be used (Dyer et al., 2021). More research is needed to evaluate this method, but initial results indicate an additional 15% water savings compared with using SMS thresholds alone.

Figure 1: A decision tree for making irrigation decisions based on SMS data and additional criteria.



VWC = volumetric water content; GC = turfgrass green cover; Traditional Trt = traditional well-watered turfgrass. Source: Dyer et al., 2021.

The decision tree requires three criteria to be evaluated before irrigation is applied:

1. Soil moisture declines to the irrigation threshold as described above. Irrigation is then delayed further until a second criterion is met.

2. Turfgrass quality is allowed to decrease to a lower threshold that can be determined in a couple of ways. The most practical way is to set this lower threshold based on the turfgrass appearance at the point of maximum allowable decline. A second way is to set the lower threshold based on a certain percentage of decline in green cover below that of well-watered turfgrass. In Figure 1, a threshold of 5% decline in green cover is used as an example. To utilize this approach, a method for measuring turfgrass green cover is required. There are various apps that can be used. Also, an

area of well-watered turfgrass of the same species and mowing height may be useful as a reference point. Either way, after this second threshold is reached, irrigation is delayed again until a third criterion is evaluated.

3. If the forecasted probability of rainfall is greater than 50% within the next 24 hours, irrigation can be delayed to allow for the possibility of benefitting from rainfall, which could save additional water. The exact forecasted rain probability can be adjusted according to the superintendent's preference.

When using the decision tree, thresholds for the first criteria (soil moisture level) and second criteria (maximum allowable decline in turfgrass appearance or green cover) should be developed cautiously, especially where highly manicured green turfgrass is the expectation. If the turfgrass experiences too much drought stress when these thresholds are reached, the result could be a decline in turfgrass quality over time. Conversely, if greater water savings are necessary and some reduction in turfgrass quality is acceptable, then there may be more incentive to adjust the thresholds to lower levels of soil moisture, turfgrass appearance or green cover, and possibly forecast rainfall probability.

Common Mistakes

Installation issues

Proper installation of SMS should avoid air gaps between the sensor and the surrounding soil. The sensors should also be oriented according to the manufacturer's specifications – e.g., horizontal or vertical placement. Sensors should be installed at the proper depth within the rootzone and at a consistent depth. It is also important to ensure a successful connection with a base station or the internet, depending on whether you are using wireless or buried electrical cable connections.

Improper SMS data is often used for scheduling

A common misconception is to manage irrigation scheduling according to the average soil moisture across all SMS. However, managing irrigation according to average soil moisture is almost always a mistake. It is critical to manage irrigation scheduling according to the SMS that represents each hydrozone, blocked zone or group of blocked zones – not an average of all SMS across the property.

It is recommended that the hydrozones or grouped blocked zones represented by a single SMS be reevaluated several times per year – e.g., seasonally due to changes in sun angle and day length. It is not unusual for the high, medium and low soil-moisture areas to change, especially on courses with tall trees or slopes. While this may not require SMS to be moved, it may require installing additional SMS to capture the changes in soil moisture status.

Damage to SMS during aeration

SMS and any associated buried cables can be damaged by aeration. Marking the locations of SMS and any buried cables with GPS during installation will help to locate and avoid them when aerating turfgrass. Keep in mind that continuously skipping aeration above or near SMS may eventually result in thatch or compaction issues that could significantly alter soil moisture and turf health in those areas. In some instances, less-disruptive aeration immediately surrounding or even above the SMS may be necessary periodically, but at a shallower depth to avoid damage.

It is important to know the precise location of all in-ground soil-moisture sensors to make sure they are not damaged by aeration, drainage projects or other maintenance practices.

TIPS FOR SUCCESS: IN-GROUND SOIL-MOISTURE SENSORS

Using in-ground SMS in large areas like fairways and roughs results in the most water savings.

Large areas such as fairways and roughs account for the most water use on a golf course. It is also difficult to estimate water requirements on these surfaces because there is so much variability in soil type, sun exposure and many other factors. Installing in-ground SMS in these areas, rather than focusing solely on greens, can significantly reduce water consumption across the course and improve playing conditions.

Classify irrigation zones by water needs to create categories of “hydrozones.”

Not every part of a golf course needs the same amount of water. By classifying areas into hydrozones – e.g., wet, moderate and dry – you can strategically place in-ground SMS in representative areas of each zone to monitor soil moisture accurately. The key is to reduce the number of sensors required by using one SMS to represent the average conditions in each zone. However, it's crucial to regularly monitor these zones and recalibrate the zones if needed, especially as turfgrass demands change seasonally.

Field calibration is required for developing accurate irrigation thresholds.

While manufacturers calibrate SMS for general accuracy in a lab setting, the unique conditions on your course can impact soil moisture estimates. Conducting a field calibration immediately after installation is vital for tailoring SMS to your specific site conditions.

Consult with experts to ensure proper selection, installation and setup.

Consulting with an experienced professional during the setup of your in-ground SMS network can help avoid common pitfalls such as improper sensor placement, depth errors or misalignment with irrigation zones. Experts can also guide you in selecting the right SMS model. For courses using recycled or high-salinity water, selecting SMS models that can accurately measure salinity is crucial to ensure the system remains reliable and delivers actionable data under those conditions.

Seasonal adjustments to thresholds will be needed in certain areas.

Turfgrass water needs change with the seasons, especially during transitions from cool to warm months or during periods of high heat or humidity. Regularly reevaluate your SMS settings, including moisture thresholds, to ensure they reflect current turf conditions. For example, during the summer turf may need more frequent irrigation and a larger buffer may be necessary to prevent stress during extended dry periods. Conversely, turfgrass water needs decrease during cooler months, allowing a lower buffer or extended intervals between irrigation events. Additionally, factors like changing shade patterns or seasonal wind shifts can influence how much water is required in different areas. Parts of the course that are dry in one season may become wet in another, so continual evaluation is needed, and sensors may have to be added or moved over time to account for these variables.

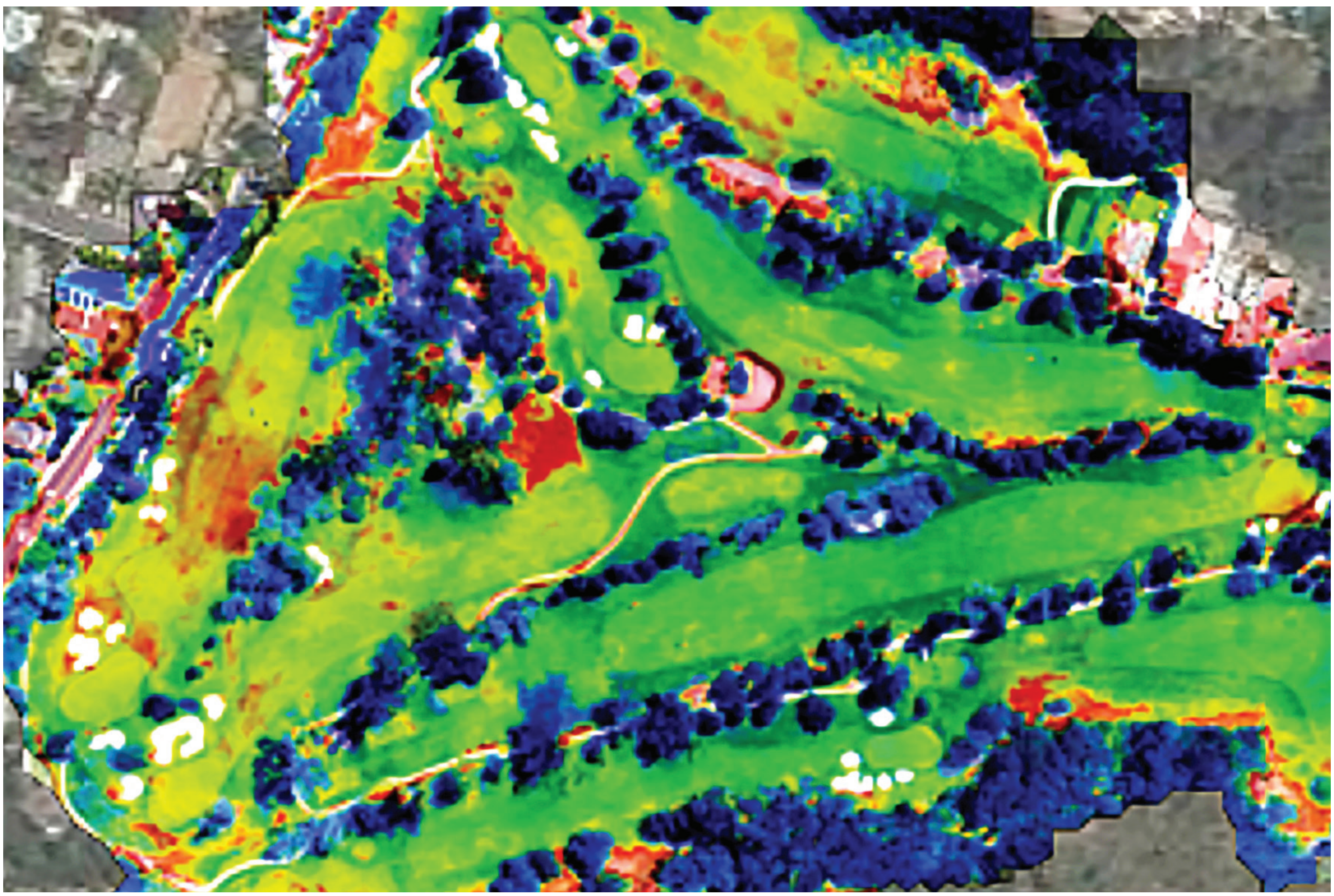
Implement a decision tree for additional water savings.

For superintendents looking to maximize water savings, employing a decision-tree method can save additional water over using soil-moisture thresholds alone by adding criteria like visual turf quality and probability of rainfall. This approach can lead to an additional 15% water savings (Dyer et al., 2021). This is especially useful for courses located in regions where water restrictions or high water costs necessitate extra conservation efforts.

USING REMOTE-SENSING TECHNOLOGY

The use of remote-sensing technology for irrigation management in the turfgrass industry is emerging, with various methods that differ in complexity and expense. The challenge with many remote-sensing tools is that, without continual calibration and "ground truthing," it's difficult to relate data directly to soil moisture, which is essential for making accurate and improved irrigation decisions. Images taken with mobile apps are a type of remote sensing that is relatively simple and inexpensive. For example, smartphone apps are available that estimate green cover of a turfgrass surface. This technology is typically used for fertility management but could also be used to evaluate the effects of drought or other stresses on the reduction in green cover (Patrignani & Ochsner, 2015). This technology could potentially be used in the decision-tree technique described in the SMS section above, where a decline in green cover is required before irrigation is triggered.

It is critical to note that nearly any issue that causes turfgrass stress – e.g., high traffic, soil compaction or pest infestations – may also result in elevated turfgrass canopy temperatures. On pocketed greens with poor air circulation, higher turfgrass temperatures may indicate heat stress rather than drought stress, especially if soil moisture is high. In



Remote-sensing technology can be used to map various indications of turf stress and soil moisture content, but this information must be verified in the field to make the best possible decisions about watering.

this scenario, steps to improve airflow are more beneficial than additional irrigation, but you would not recognize that from the remote sensing output alone. For the foreseeable future, where high turfgrass temperatures are observed using remote-sensing technology, ground truthing is necessary to confirm the cause, whether it is drought related or otherwise.

Hand-held infrared meters or thermal cameras mounted on poles near greens can be used to monitor drought or heat stress and enhance irrigation management. As turfgrass begins to undergo drought or heat stress, transpiration slows and leaf temperature begins to rise, which is detected by the technology. Dry spots on a green that require hand watering can be identified by the colored temperature maps created by these tools – often before stress is visible to the human eye.

Ground-based, vehicle-mounted spectral cameras that measure reflectance indices, such as the normalized difference vegetation index (NDVI), give a scale of relative turf health that can also be used to develop colored vegetation or “heat” maps of a golf course. This can help identify stressed areas of turfgrass prior to traditional methods of scouting. Hand-held NDVI meters are also available for comparative spot measurements between healthy turfgrass and areas of suspected or obviously stressed turfgrass.

Commercial drones with standard, infrared or hyperspectral cameras are increasingly being used in golf course management, including for irrigation scouting. Some superintendents utilize drones themselves, whereas others take a more comprehensive and expensive approach and hire companies to fly drones and create color-coded vegetation or heat maps from acquired data. Spectral images from drones may be useful in detecting drought-stress patterns in turfgrass across a golf course that may not be evident at ground level, such as when irrigation heads are defective or need adjustment.

Hyperspectral and thermal cameras may identify areas of turf stress that are not evident from images taken with a standard camera. This is because spectral cameras measure reflectance, and thermal cameras measure longwave emissions (temperature) from the turfgrass in wavebands outside the visible spectrum. From a practical perspective, these cameras detect important plant properties not necessarily visible to the naked eye (Bremer et al., 2023).

Another important aspect of remote sensing is the frequency of measurements. To identify or monitor early or progressing drought stress – or other issues such as pest infestations – frequent flights are necessary. Daily flights are likely required to collect actionable information and identify trends, but it can be extremely difficult to collect and process data at this frequency. Data from these flights may also be useful for delaying irrigation events, possibly in tandem with soil-moisture sensors. Potential benefits include water savings, directing hand watering staff toward stressed areas of turfgrass, identifying malfunctioning irrigation heads, and detecting other issues such as soil compaction or turfgrass damaged from high traffic.

Maps from frequent drone flights also provide valuable historical records that can be referenced in the future. Some superintendents have benefitted from knowledge gained about problematic areas of their course by using drone-mapping services for one or two years and then discontinuing the service. The decision to discontinue may be based on budgetary or other constraints. However, such a strategy would not likely be useful for identifying or managing any new issues that may appear in future years, whether related to irrigation or other causes of turfgrass stress.

A note about vegetation or heat maps provided by some drone services

Developing these maps requires significant postprocessing, which typically involves uploading images from the drone for the company to create maps and return them, usually within a few hours. Superintendents will likely require some initial training to properly interpret the maps, which contain much useful information but also a significant amount of "noise" that must be filtered out. Also, at present, ground truthing is usually required to understand the specific cause of the stress identified on colored vegetation maps. Colored vegetation or heat maps are useful for identifying stressed areas of turfgrass, but the cause is not necessarily evident from the map. This is true of both spectral and thermal images.

Colored vegetation or heat maps are useful for identifying stressed areas of turfgrass, but the cause is not necessarily evident from the map.

Where Is the Strategy Typically Used?

On a golf course

Remote sensing may be focused on known problem areas that require intensive evaluation or diagnosis – e.g., temperature maps of greens on hot days. Remote sensing can also include mapping the whole golf course on a routine basis, which can help guide broader irrigation management decisions and identify trouble areas that require further investigation.

Regionally

The use of off-the-shelf commercial drones for golf course management is increasing across the U.S. Hiring companies that provide drone-based services for frequent flights and vegetation maps is more common at golf courses with higher budgets.

Opportunities to expand use

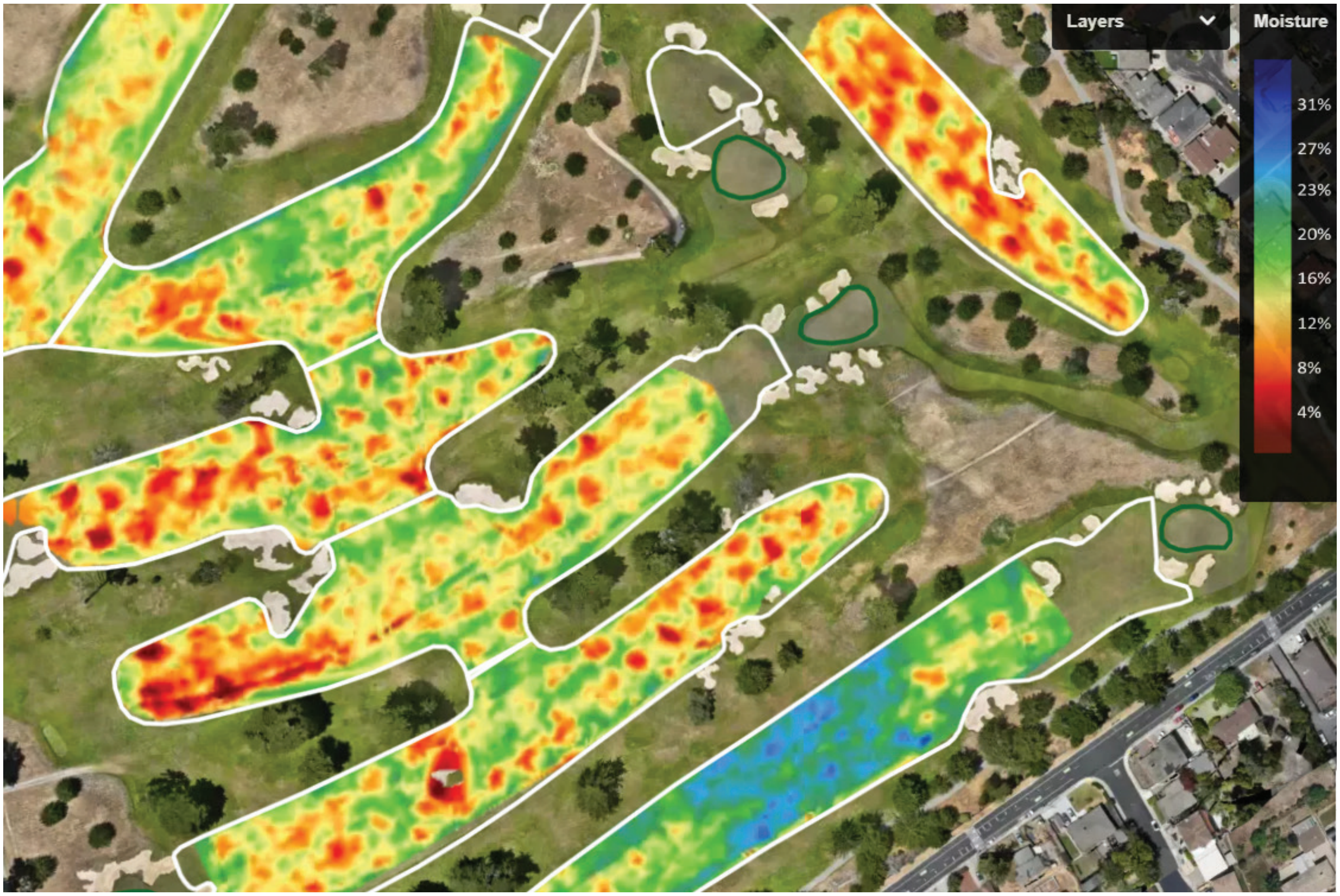
The use of autonomous drone flights with no on-site pilot is an emerging industry. Autonomous drones are available on the market, but federal regulations are still being developed and must be adhered to. Presumably, daily or otherwise frequent autonomous flights over a golf course may become more practicable and affordable in the near future. This approach has the advantage of allowing for increased frequency of flights with minimal staff time required.

The availability and affordability of satellite data is increasing. Satellite data can be obtained periodically during the season, from which turfgrass vegetation and stress or heat maps can be developed. The current frequency and sensitivity of publicly available satellite imagery is a hurdle for the type of precision required in making golf course irrigation decisions.

L-band radiometers, which can be mounted on mowers or other golf course vehicles to map soil moisture, have received much attention recently (Houtz et al., 2023). While the L-band radiometer may hold promise for improving turfgrass irrigation management, more research is necessary before it can be recommended for widespread use.

Ongoing research indicates that, as with other remote-sensing technologies, on-site calibration is required for data to be accurate and useful for irrigation scheduling (Leinauer et al., 2023).

The use of thermal imaging from drones, possibly combined with spectral imaging from drones, may enhance the establishment of irrigation hydrozones. Such images may also aid in optimizing SMS placement within irrigation zones.



Radiometers can be mounted on mowers or other vehicles to efficiently gather and present information about soil moisture. Calibrating and assessing this information with soil-moisture sensor data is important.

BENEFITS OF REMOTE SENSING

Expected Water Savings

Anecdotal reports of 10% water savings have been reported on golf courses that use various remote-sensing technologies, and some companies claim 15% to 20% water savings, but little scientific research has been conducted to validate such claims. Presumably, water savings could begin shortly after implementation of remote sensing applications and last as long as measurements continue. There will be a period of learning in terms of becoming familiar with map interpretation, ground truthing areas identified as potentially drought-stricken on maps, and developing irrigation management practices based on data from the maps. This process may require consultation between the superintendent and a remote sensing specialist.

Improved Scouting

One of the primary potential advantages of remote-sensing technologies as they currently stand is improved scouting. It is possible to gather information about large areas of the course in a relatively short amount of time, and to potentially see problems and patterns that may not be visible to staff on the ground. However, routine scouting by the staff will still be necessary for the many issues these technologies cannot detect, and any potential problem spots identified through remote sensing will have to be visited by staff to diagnose the issue. There will also be an ongoing process of calibration and ground truthing the imagery that comes from remote-sensing technologies, which is an added step.

Ease of Use and Implementation

Ease of use will depend upon the form of remote sensing being implemented. Smartphone apps to identify reductions in green cover are relatively simple and could be used by anyone with a smartphone. Using drones with standard video cameras requires a drone and an experienced pilot with an Unmanned Aircraft Systems (UAS) license. Such a license from the Federal Aviation Administration (FAA) is required when flying drones for any commercial purpose, including evaluating the condition of turfgrass by a golf course superintendent using their own drone. Using drones equipped with spectral and thermal cameras have the same legal requirements, but in most cases will also require some postprocessing of data. Typically, this would be accomplished by hiring a company to make flights with the appropriate drones and return the colored vegetation or temperature maps (and their interpretation) to the superintendent. In general, using remote sensing technology is fairly simple if the budget is available. Interpreting and acting on the information is often the bigger challenge.

LIMITATIONS OF REMOTE SENSING

The Technology is Relatively New in Golf

The use of remote sensing for irrigation management in turfgrass is emerging. Spectral and thermal cameras, both ground and aerial, have been used widely in turfgrass research and have been very effective at identifying drought stress in controlled settings (Bremer et al., 2023). Ongoing research is being conducted to develop specific guidelines for irrigation management on golf courses using remote sensing, but much work remains to be done (McCall & Roberson, 2022). Early results in some of these studies have not shown a strong relationship between known soil moisture and estimates from certain technologies, so golf course superintendents must be cautious about product claims at this point in the development and application of remote-sensing technology in golf course maintenance (Isom, 2024).

Physical and Legal Restrictions

Drones have performance and legal limitations that may affect the ability to utilize remote sensing at a desired time and location. For example, drones cannot be flown during windy or rainy weather. Flights may also not be allowed over residential areas or within 5 miles of airports or controlled airspace without authorization from the FAA and possibly local authorities as well.

Drones with spectral or thermal cameras have additional limitations (Bremer et al., 2023; McCall et al., 2022). These flights should not occur during periods of intermittent clouds, which can diminish data quality. Flights should also be limited to midday, when the solar angle is highest. Flights during low sun angles or periods with wet turfgrass surfaces may result in diminished data quality. Maps may contain significant "noise," such as tree (and even turfgrass canopy) shadows, mowing patterns that affect light reflectance and mowing height variations that can make interpretation difficult. The assistance of a remote-sensing specialist will be helpful in differentiating the signal from the noise. Data from satellites may also be unavailable during periods with cloud cover or when the satellite does not pass over a given golf course at the desired time.

Ongoing research is being conducted to develop specific guidelines for irrigation management on golf courses using remote sensing, but much work remains to be done.

Image Resolution

Image resolution increases from satellites to small drones to ground-based vehicles and higher resolution results in finer detail and more-actionable information. For example, resolution from satellites may be as low as 100 square feet per pixel, but newer low-Earth-orbit satellites may have resolutions closer to 11 square feet per pixel. The image resolution of maps derived from drone data can be in the range of 1 to 3 square inches, while ground-based vehicles may offer sub-inch resolution. High-resolution images from drones and ground-based vehicles generate large files that are good for turfgrass research, but data processing time could be a bottleneck for field applications, especially if data must be uploaded for analysis and limited bandwidth is available (Bremer et al., 2023). Consulting with a remote sensing specialist is recommended to determine appropriate image resolution for the purposes of irrigation management.

IMPLEMENTATION OF REMOTE SENSING

For most golf courses, using remote sensing will require the assistance of an experienced consultant, at least initially. The consultant provides expertise in remote sensing applications and interpretation of data, but the superintendent's knowledge of the golf course and ability to ground truth potential issues identified on maps is also critical.

The use of remote sensing for golf course water management is in its infancy, so few specific protocols have been developed for successful application. However, the following are a few strategies a superintendent could consider. In each of these strategies, consultation with a remote sensing specialist is advised to guide selection of sensor type, spatial resolution requirements and whether to use aerial, ground or hand-held devices to collect measurements. A consultant can also help the superintendent accurately interpret the data, determine the optimal frequency of measurements, develop thresholds for irrigation and help calibrate the sensors.

Initially, scouting the entire golf course using remote sensing may be useful to identify areas of turf that may be under or over watered, or that are suffering from some other type of stress. A rudimentary survey could be conducted using a drone equipped with a standard video camera to view the golf course from an aerial perspective. A more detailed evaluation could be conducted with spectral or thermal cameras mounted on a drone or a ground vehicle. If only one survey is possible and water management is the focus, ideal timing would be during a period of high drought stress when limitations in the irrigation system and water management program would be most visible. If additional surveys with a drone or ground vehicle are conducted, which is recommended, the series of maps will help evaluate the mitigation or progression of drought stress or other turf stressors. Such maps can also be used to modify irrigation scheduling, improve soil moisture consistency, conserve water and improve playing conditions.

Imagery from aerial drones can identify areas of turf stress and potential irrigation issues, making scouting more efficient.

If surveying the entire golf course with remote sensing technology is not feasible due to budgetary or other factors, then remote sensing could be used to target areas of concern or areas that may have known or suspected drought-related issues. For example, using hand-held or pole-mounted infrared cameras on greens can identify specific hot spots for hand watering, which could conserve water.

Using remote sensing data in combination with other sensors, such as SMS, can help confirm whether drought stress is truly affecting turfgrass (Bremer et al., 2023). For example, when remote sensing indicates the turfgrass is under some type of stress and a SMS in the same vicinity indicates the soil is relatively dry, then most likely the turfgrass is experiencing drought stress. Weather data could also be used to confirm if drought stress is the likely problem, such as during windy and hot conditions with high rates of ET or when rainfall has been insufficient.

Golfer Impacts

The effects of implementing remote sensing should be minimal on a golf course. If drones are used, it may be desirable to avoid flights during times of heavy play and to avoid flying over people for safety purposes. Drones can illicit varying responses from individuals and may evoke privacy concerns, so communication with golfers about what information is being collected is important to alleviate any concerns. Golfers may also be interested in how new technology is being used on the course and the imagery is often visually appealing, so remote sensing can be a good chance to educate golfers about various golf course maintenance efforts, including water conservation.

TIPS FOR SUCCESS: REMOTE SENSING

Set clear goals for water conservation.

Begin by identifying the specific outcomes you want to achieve with remote sensing technology. Whether your aim is to detect drought stress, monitor overall turf health or optimize irrigation scheduling, understanding these goals will guide your approach. For example, if you are primarily concerned with spotting early signs of drought stress, you may want to choose specific tools like thermal cameras or NDVI sensors that offer real-time insights into turf stress levels.

Know and adhere to all drone regulations.

Drones offer immense potential for collecting aerial data, but it’s crucial to understand the legal and technical limitations. Ensure that your drone operations comply with local and federal regulations, such as obtaining an FAA UAS license for commercial flights and following registration requirements. Be aware that drones cannot fly in certain conditions, like high winds or rain, and they may require special permissions when operating near airports or populated areas. They also have strict altitude limitations and require special lights for operation around dawn and dusk.

Validate remote sensing data with ground truthing.

Remote sensing technology can provide valuable information about large areas in an efficient manner, but it's important to "ground truth" the data to ensure its accuracy. For example, if remote sensing detects areas of potential drought stress, cross-check that data with soil moisture sensors or a standard soil probe to confirm whether the issue is related to water stress or other factors like compaction or disease. Inconsistency in the environment and in the technology can lead to discrepancies between remote sensing data and actual soil moisture, so it is important to verify conditions on the ground before making irrigation decisions.

Choose the right tools.

Different remote sensing tools serve different purposes, from smartphone apps that assess green cover to more advanced drones equipped with thermal or spectral cameras. Select the tool that best aligns with your course's needs and budget. For example, if you need high-resolution data across large areas, a drone equipped with an NDVI sensor may be ideal. For spot checks of specific turf areas, hand-held infrared temperature meters or thermal cameras may suffice.

Measure as frequently as possible for better data.

Remote sensing is most effective when used regularly. Frequent measurements, whether daily or weekly, help detect the onset of stress or other issues like disease before they become visible to the naked eye. This proactive approach allows you to address problems early, reducing the need for drastic corrective measures. If using drone flights or satellite imagery, plan for regular data collection to create a historical record, making it easier to track trends and respond quickly to emerging issues.

Work with experts to ensure accuracy.

Remote sensing generates large amounts of data, which can be difficult to interpret without expertise. Work with a remote sensing consultant or specialist to ensure your data is correctly calibrated and that maps or imagery are processed accurately. Specialists can help filter out "noise" and make the data more actionable. They can also assist in identifying key trends that can lead to improved irrigation strategies or turf health management. University researchers or other independent scientists will be an important resource. Relatively little research has been conducted on using remote-sensing technologies in turfgrass management or has shown the direct efficacy of most remote-sensing technologies for irrigation scheduling improvements outside of controlled research settings.

Build a record of historical data.

Over time, the data you gather through remote sensing creates valuable historical records that can be used for future planning. By analyzing trends, such as recurring stress patterns in specific areas, you can anticipate problems before they arise and adjust your management practices accordingly. Historical data can also be used to justify resource allocation, adjust irrigation infrastructure or optimize playability across the course.

University researchers and other independent experts are studying remote-sensing technology for use in turfgrass management. Their insight is valuable if your course is thinking about using this technology. (USGA/Bill Hornstein)

BMP CASE STUDIES

"Five Proven Methods to Improve Moisture Uniformity"

USGA Green Section Record, 2021.

A golf course in Palm Desert, California, has been using in-ground soil moisture sensors for more than five years. The superintendent installed four sensors across 40 acres of fairways on one golf course. The sensors were placed into representative "dry," "moderately dry," "moderately wet," and "wet" areas determined by mapping the fairways using the Toro PrecisionSense 6000 system. The turf care team reviewed sensor data daily, in addition to scouting and monitoring ET data, to schedule irrigation. This strategy has yielded more-consistent moisture conditions across fairways and roughs, and has resulted in 10%-14% water savings, which translates into an additional savings in electrical costs associated with pumping.

"Moisture and Salinity Monitoring Through In-Ground Sensors"

USGA Green Section Record, 2015.

In-ground sensors that measure soil moisture, soil temperature and soil salinity were installed strategically throughout Prestwick Country Club in Myrtle Beach, South Carolina, in areas designated as wet, dry, or average moisture. Upgraded irrigation control software displays real-time soil moisture readings from the sensors in an easy-to-read format and allowed each sprinkler head to be correspondingly designated as wet, dry or average. Prestwick's golf course superintendent reported that overall turf conditions improved with the addition of this technology and that the course is seeing about a 25% savings in both water usage and electricity consumption to run the irrigation pumps.

REFERENCES

Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). FAO Irrigation and drainage paper No. 56. *Rome: Food and Agriculture Organization of the United Nations*, 56(97), e156.

Bremer, D.J., & Ham, J.M. (2003). Soil moisture sensors can help regulate irrigation. *Golfdom: Turfgrass Trends*. June, p. 49-54.

Bremer, D.J., Sullivan, D.G., Vines, P.L., McCall, D., Zhang, J., & Hong, M. (2023). Considerations with using unmanned aircraft systems in turfgrass. In M. Fidanza (Ed.), *Achieving sustainable turfgrass management.* Burleigh Dodds Science Publishing, Cambridge, U.K.

Cardenas-Lailhacar, B., & Dukes, M.D. (2012). Soil moisture sensor landscape irrigation controllers: A review of multi-study results and future implications. *Transactions of the ASABE,* 55(2), 581-590.

Cardenas-Lailhacar, B., & Dukes, M.D. (2015). Effect of temperature and salinity on the precision and accuracy of landscape irrigation soil moisture sensor systems. *Journal of Irrigation and Drainage Engineering,* 141(7), 04014076 https://doi.org/10.1061/(ASCE)IR.1943-4774.0000847

Cardenas, B., Migliaccio, K.W., Dukes, M.D., Hahus, I., & Kruse, J.K. (2020). Irrigation savings from smart irrigation technologies and a smartphone app on turfgrass. *Transactions of the ASABE*, 63(6), 1697-1709. https://doi.org/10.13031/trans.13903

Chabon, J., Bremer, D.J., Fry, J.D. & Lavis, C. (2017). Effects of soil moisture-based irrigation controllers, mowing height, and trinexapac-ethyl on tall fescue irrigation amounts and mowing requirements. *International Turfgrass Society Research Journal*, 13(1), 755-760. https://doi.org/10.2134/itsrj2016.04.0242

Dukes, M.D. (2020). Two decades of smart irrigation controllers in U.S. landscape irrigation. *Transactions of the ASABE*, 63(5), 1593-1601. https://doi.org/10.13031/trans.13930

Dyer, W., Bremer, D., Patragnani, A., Fry, J., Lavis, C., & Friell, J. (2021). Integrating canopy dynamics, soil moisture, and soil physical properties to improve irrigation scheduling in turfgrass systems. *USGA Turfgrass and Environmental Research Online Summary*, pp. 214-221.

Gelernter, W.D., Stowell, L.J., Johnson, M.E., Brown, C.D., & Beditz, J. F. (2015). Documenting trends in water use and conservation practices on U.S. golf courses. *Crop, Forage & Turfgrass Management*, 1(1), 1-10. https://acsess.onlinelibrary.wiley.com/doi/full/10.2134/cftm2015.0149

Hejl, R. W., Wherley, B. G., McInnes, K., Straw, C. M., & Fontanier, C. (2022). Evaluation of irrigation scheduling approaches within sand-capped turfgrass systems. Agronomy Journal, 114(3), 1694-1704. https://doi.org/10.1002/agj2.21059

Hong, M., Bremer, D.J., & van der Merwe, D. (2019a). Thermal imaging detects early drought stress in turfgrass utilizing small unmanned aircraft systems. *Agrosystems*, Geosciences & Environment, 2(1), 1-9.

Hong, M., Bremer, D.J., & van der Merwe, D. (2019b). Using small unmanned aircraft systems for early detection of drought stress in turfgrass. *Crop Science*, 59(6), 2829-2844.

Houtz, D.A., Horvath, L., & Schwank, M. (2023). Vehicle mounted L-band radiometer for remote sensing of turfgrass soil moisture. In *IGARSS 2023 - 2023 IEEE International Geoscience and Remote Sensing Symposium*, pp. 4824–4827. IEEE.

Isom, C. (2024). Making sense of remote sensing. *USGA Green Section Record*, 62(14).

Leinauer, B., Egelhoff, T., & Velasco-Cruz, C. (2022). Remote Soil Sensing of Fairways for Irrigation Water Conservation. *USGA Turfgrass and Environmental Research Online Summary*, pp. 238-252

Magro, C., Macolino, S., Pornaro, C., McMillan, M., & Fidanza, M. (2022). Considerations with Determining the Minimum Number of Volumetric Water Content Measurements for Turfgrass Root Zones. Agronomy, 12(6), 1402. https://doi.org/10.3390/agronomy12061402

McCall, D., & Roberson, T. (2022). Optimizing irrigation strategies through remote stress detection. *USGA Turfgrass and Environmental Research Online Summary*, pp. 233-238.

Patrignani, A., & Ochsner, T.E. (2015). Canopeo: A powerful new tool for measuring fractional green canopy cover. *Agronomy Journal*, 107(6), 2312-2320. https://doi.org/10.2134/agronj15.0150

Shaddox, T.W., Unruh, J.B., Johnson, M.E., Brown, C.D., & Stacey, G. (2022). Water use and management practices on U.S. golf courses. Crop Forage & Turfgrass Management, 8(2). e20182

Schiavon, M., & Serena, M. (2023). Advances in irrigation and water management of turfgrass. In M. Fidanza (Ed.), *Achieving sustainable turfgrass management*. Burleigh Dodds Science Publishing, Cambridge, U.K.

Serena, M., Velasco-Cruz, C., Friell, J., Schiavon, M., Sevostianova, E., Beck, L., Sallenave R. & Leinauer, B. (2020). Irrigation scheduling technologies reduce water use and maintain turfgrass quality. Agronomy Journal, 112(5), 3456-3469. https://doi.org/10.1002/agj2.20246

Straw, C., Bolton, C., Young, J., Hejl, R., Friell, J., & Watkins, E. (2022a). Soil moisture variability on golf course fairways across the United States: An opportunity for water conservation with precision irrigation. *Agrosystems, Geosciences & Environment*, 5(4), e20323.

Straw, C., Friell, J., Schwab, R., & Watkins, E. (2022b). Towards advancing precision irrigation on golf courses. *USGA Turfgrass and Environmental Research Online Summary*, pp. 212-221.

Thompson, C. S., Kridel, D. J., & Kenna, M. P. (2021). Economic and sustainability benefits of the United States Golf Association's investment in water, fertilizer, and pesticide management research. *International Turfgrass Society Research Journal*, 14(1), 47-57. https://doi.org/10.1002/its2.91

Whitlark, B., Umeda, K., Leinauer, B.R., & Serena, M. (2023). Considerations with water for turfgrass in arid environments. In M. Fidanza (Ed.), *Achieving sustainable turfgrass management*. Burleigh Dodds Science Publishing, Cambridge, U.K.