Maximizing Effective Agronomics in Landscapes with Soil Moisture Sensors

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Abstract. *The key information required to make agronomically sound irrigation decisions is reviewed, including the relative relationships of soil type, soil water holding characteristics, and plant water requirements. Optimal water management and the agronomic relationship between plants and soils is discussed. The relative benefits and challenges of weather based and soil moisture based irrigation decision making are reviewed. Specific capabilities of soil moisture based irrigation controls are discussed with implications for long term performance, control, and effectiveness. Relative performance of various soil moisture measurement techniques are reviewed, and an overall summary of agronomic benefits of various smart watering approaches is provided.*

Keywords. Smart controller, smart irrigation, ET, evapo-transpiration, soil moisture sensor, SMS, agronomy, soil science, water management, irrigation scheduling, sprinkler, sprinkler controller, irrigation controller, rain sensor

Introduction

The purpose of this white paper is to provide a short overview of landscape irrigation watering issues associated with irrigation controls, and review the various alternatives for improving watering performance in landscape applications.

This white paper references a breadth of original and derivative research in North America and worldwide. While this paper merely scratches the surface of historic and recent research conducted in the area of landscape and agricultural irrigation efficiency, it is the intention of the author to illustrate the potential value of new technologies available to the irrigation industry to affect widespread reduction in outdoor water use while maintaining or improving the quality of residential and commercial landscapes.

The intent of this paper is to focus on the agronomic issues associated with the plant-soil-water system with respect to the various new technologies, including soil moisture sensors (SMS). The availability of inexpensive, highly accurate, and reliable soil moisture sensors is possibly the most agronomically important landscape irrigation development of the last 20 years.

Overview of Landscape Irrigation Water Waste Issues

The use of irrigation water for urban landscapes has grown materially in the United States over the last two decades in conjunction with the increase in automated irrigation systems.

It is important to note that automated irrigation systems provide meaningful benefits to the U.S. and International consumers. These benefits include, but are not limited to:

- Convenience
- Consistent health and beauty of landscapes
- Ability to support landscapes in arid climates

However, it is also clear that one unanticipated result of this proliferation of automated irrigation systems is the consistent and epidemic overwatering of most North American landscapes.

The problem: Overwatering, Not Water Use

The purpose of this paper is to focus on overwatering behaviors and their agronomic implications. However, the author feels it necessary to state very clearly that the problem is over-watering, not water use. Appropriate water use to support landscapes is a significant factor in the North American quality of life, and a social expectation of most citizens of the United States.

While appropriate changes in planting materials, application technologies, local regulations and local restrictions are appropriate limits on water use, the focus of this paper is on overwatering. This is both a technical and behavioral issue for commercial and residential landscape management in the United States.

Scope of the Overwatering Problem in Landscapes

The most commonly accepted urban water use statistic come from the American Water Works Association, which estimates that water use for U.S. domestic landscapes averages 58%.

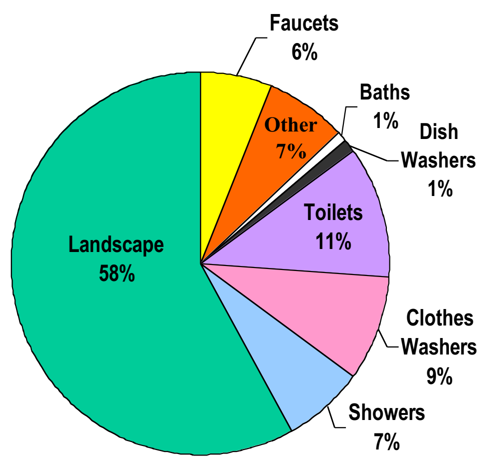

Figure 1. Domestic Water Use in the United States.
Source: AWWA End Uses of Water, 2001.

Of this water applied to domestic landscapes, the Environmental Protection Agency estimates that as much as 50% is wasted. This results in roughly 3.5 billion gallons of water waste per day in the United States alone. While concrete measures of the actual cost of wasted water in the United States, most sources size the total U.S Dollar value of the waste as between $2.0B and $2.4B, annually.

Other Effects of Overwatering

While there are many social and environmental effect from overwatering irrigated landscapes, most sources classify the affects as follows:

- Energy consumption for pumping and distribution
- Capital costs for treatment and management
- Runoff issues, including impacts to wetlands and costal coral reef systems
- Plant health

The conclusion is obvious and difficult to ignore: overwatering is not only a tangible multi-billion dollar problem in the United States, but has significant social and environmental impacts as well.

Sources of Overwatering in Irrigated Landscapes

There are clearly a variety of sources of overwatering in irrigated landscapes. For the purposes of treatment, the root causes for landscape overwatering are most often classified as follows:

Table 1. Most Common Root Causes of Overwatering in the United States

System Design	Examples:
	• Poor distribution uniformity
	    o Improper application technology chosen
	    o Improper head placement
	    o Mixing of application technologies
	• Mixing of plant materials with different water needs
	• Improper design for topography and slopes

Installation Quality	Examples: • Improper placement of heads, plant materials, and or landscape features • Failure to comply with manufacturer's instructions • Improper or incomplete inspections
Maintenance	Examples: • Broken or unadjusted sprinkler heads • Blocked heads due to grow in or landscape changes • Leaks
Programming/Scheduling	Examples: • Excessive, unmeasured watering times • No seasonal adjustments • Application rates in excess of soil infiltration rates • No adjustments based on actual soil moisture conditions • Failure to water deeply and infrequently to promote deep root growth and drought tolerance

It is increasingly clear that all of these areas must be treated, and programs from the Irrigation Association and the U.S. Environmental Protection Agency have begun to address all the root causes listed above.

The remainder of this paper will focus on the last item: automated irrigation system programming and scheduling. While technical advances in other areas have facilitated potential improvements, the low cost and high efficacy of scheduling technologies makes this an area of specific interest to affect wide scale in the United States and world-wide.

Restrictions: A Temporary Solution With Costs

Watering restrictions are a common and increasing technique for water purveyors to control landscape irrigation use at the state and local level. Broad use of watering restrictions, in most areas with associated fine structures, has grown dramatically U.S. wide over the last 10 years.

However, watering restriction programs are rarely founded on sound, if any, agronomics. Most watering restriction programs are effectively a position of last recourse for the municipalities involved, and have the generalized effect of stressing or even permanently damaging

While the scope of landscape damage due to watering restrictions has not been well studied, the author suspects that the total cost in landscape damage may exceed the total value of water saved. Further study in this area is suggested.

The author further posits that, given a choice between spending a modest amount on appropriate technologies to treat overwatering problems or suffering damage and degradation to landscape quality, most Americans would opt for the former.

Potential Solutions to Overwatering in Irrigated Landscapes

As has been covered elsewhere at length, there are many potential solutions to overwatering issues in irrigated landscapes. As with the root causes listed in Table 1 above, most classify the potential solutions as follows:

Table 2. Potential Solutions to Overwatering in Irrigated Landscapes

System Design	Examples: • Matched precipitation rate application technologies • Increased use of micro and subsurface drip technologies • Increased use of pressure regulation • Proper pipe sizing and hydrological design • Use of native or area appropriate plant materials • Restrictions on total turf areas as a percentage of landscapes • Restrictions on inappropriate application designs (e.g. spray heads on steep slopes)
Installation Quality	Examples: • Certifications or licensing for irrigation installers • Increased manufacturer training and certification programs • Increased inspection programs
Maintenance	Examples: • Maintaining proper maintenance schedules • Keeping heads and other equipment properly adjusted • Replacing worn or broken equipment • Detecting and fixing leaks
Programming/Scheduling	Examples: • Deployment of smart control technology to better determine when and how much water to apply • Match application rate to infiltration rate • Minimize evaporation loss • Minimize leaching loss • Minimize runoff • Minimize disease and parasites

	• Avoid landscape use damage due to over-wet or over-dry conditions for multi-use landscapes

Clearly, all of these areas should be considered and evaluated when attempting to address overwatering issues.

The key question is: which technologies and approaches will be the most effective in changing watering behavior in the United States and world-wide?

Programming/Scheduling Factors for Landscape Irrigation

The purpose of this section is to review the scheduling factors typically used to control landscape irrigation, and the key questions that must be answered to optimally apply landscape water.

Studies in wet climates such as Florida and the South Eastern U.S. indicate that scheduling solutions alone, independent of other treatments, can result in a 70% reduction in outdoor water use.

Studies in dry climates such as Utah indicate that residential systems in these regions over-water by at least 50%, irrespective of rainfall.

The potential for water use reduction through the reduction or elimination of overwatering due to irrigation scheduling should not be underestimated. Based on research to date, the author estimates that water savings from simply improving irrigation controls to be as follows:

Table 3. Potential Water Savings From Landscape Irrigation Scheduling Changes Alone

Wet Climate	Up to 70% of landscape water use can be reduced by making smart control (scheduling) changes alone, independent of additional improvements in application uniformity and system design.
Dry Climate	Up to 40% of landscape water use can be reduced by making smart control (scheduling) changes alone, independent of additional improvements in application uniformity and system design.

While these claims may seem bold, the author is excited to see a growing body of supportive literature and is excited to see the results of these ongoing investigations.

Scheduling Questions:

When scheduling irrigation, the key questions that should be considered include the following:

- When to irrigate?
    - Is nighttime application recommended to reduce evaporation
    - What restrictions apply?
    - What landscape use is expected?
- How much water to apply?
- How quickly can water infiltrate into the soil?
    - How quickly does water run off sloped areas?
- How quickly does the application technology apply water?
- How much variability (distribution uniformity) is there in application rates due to system design or condition?
- What is the plant water requirement?
- How much water can the soil hold?

- What is the health of the plant material?
- What nutrition levels are currently available in the soil?

Various “smart control” technologies attempt to answer some or all of these questions. This paper will contrast the most prevalent technologies and solutions as to their ability to answer these key scheduling questions.

However, it is clear that there are significant differences between the capabilities of the different approaches.

Soil Water Holding Characteristics

By way of analogy, the soil is the plant’s “drinking water storage tank”. Like any storage tank, soil water holding comes in many shapes and sizes. Some tanks can be filled faster than others. The time between fillings (to keep the tank from becoming completely empty) depends on how fast the water is being used and the total holding capacity of the tank.

Likewise, soil systems have natural capability to store and hold water. Also, most plants have evolved to tolerate significant variation in soil moisture conditions as driven by common weather patterns in their native region(s).

In order to optimally schedule irrigation, precise knowledge of the holding capacity of the soil is highly desired. To return to the tank analogy – if you were designing a tank-filling system, would you want to know when the tank was empty and/or full?

Modern technologies such as soil moisture sensors are capable of providing exactly this information.

Soil Moisture Terminology

Soil moisture content is typically described with the following terms:

Table 4. Soil Moisture Content Terms and Definitions

Saturation	When a soil is saturated, the soil pores are completely filled with water and nearly all of the air in the soil has been displaced by water. Gravity will exert force on the water contained in saturated soils, moving it deeper into the ground (if possible). This is known as “gravitational water”.
Field Capacity	The level of soil moisture left in the soil after drainage of the gravitational water. Irrigation to levels above field capacity will result in runoff or drainage as gravitational water.
Managed/Maximum Allowed Depletion (MAD)	The desired maximum soil moisture deficit at the time of irrigation. Soil moisture levels below MAD are not desired, and may result in stress or permanent wilting of plant materials. Most systems use a safety factor to set MAD above the permanent wilt point.
Oven Dry	When soil is dried in an oven, nearly all water is removed. This moisture content is used to provide a reference for measuring saturation, field capacity, and MAD.

A key soil holding capacity concept is that soil saturation is greater than field capacity. Imagine a sponge dipped in a bucket. When removing the sponge from the bucket, water will drip from the sponge for a period of time. When this dripping has stopped, the sponge will be at its field capacity. Squeezing the sponge will result in additional water running out.

Likewise in soil systems, within the area of interest for the roots of the plants in the landscape, application of water above field capacity is excess irrigation, and will gravitationally move through the root level into deeper soil.

A second key concept is that the amount of water required to change the soil moisture level from MAD to field capacity is constant. If precise irrigation can be timed to occur when and every time the MAD has been reached, the exact same amount of water application will result in filling the soil to field capacity and no further. This is regardless of season, temperature, or plant need.

Soil Types and Water Holding Characteristics

The USDA defines soil textures via relative composition of particle sizes. Particle sizes are roughly grouped in the following categories:

- Gravel
- Sand
- Silt
- Clay

Figure 2 shows the relative sizes of these particles.

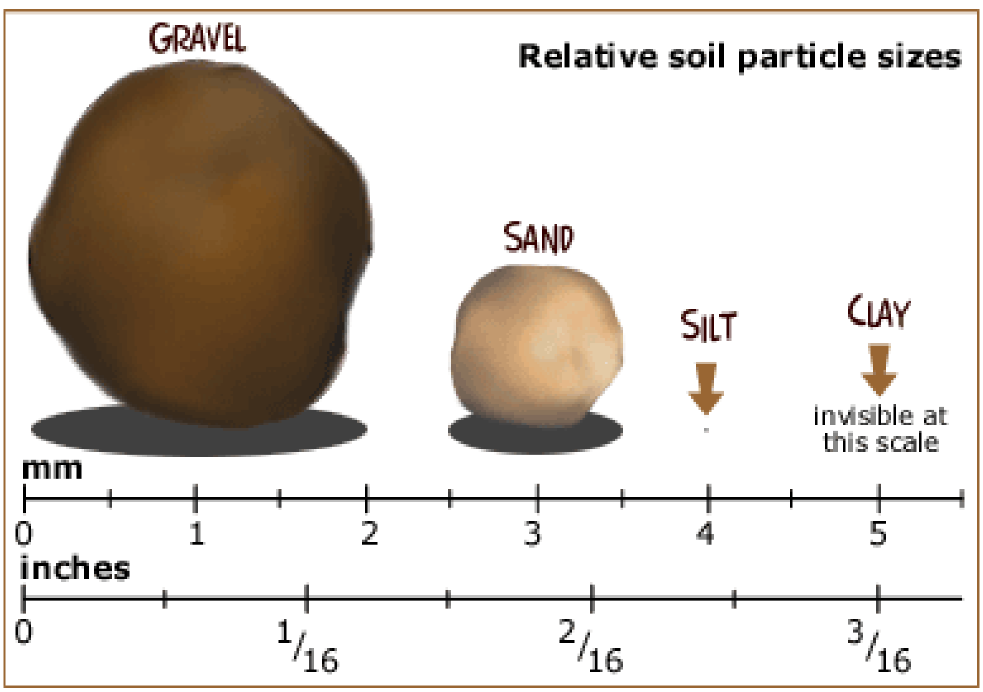

Figure 2. Relative sizes of soil particles
Chart courtesy of IFAS, University of Florida

Specific soil typing is generally accomplished using the USDA Soil Textural Triangle:

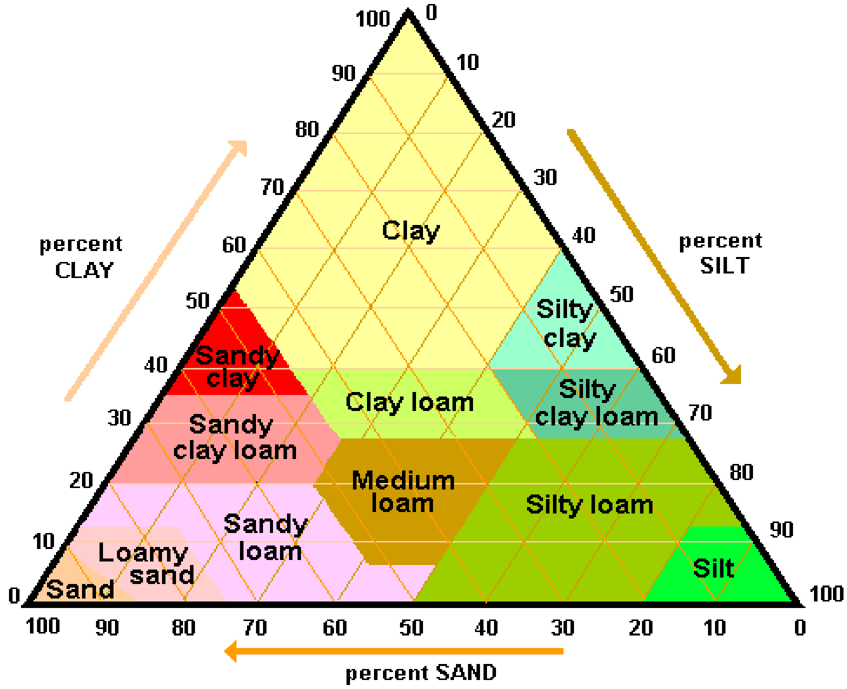

Figure 3. USDA Soil Textural Triangle
Chart courtesy of the USDA

The most significant irrigation issue with respect to soil type is that most irrigators have no idea what soil type they have. This makes optimum irrigation scheduling difficult if not impossible.

Careful analysis of soil moisture data provided by modern soil moisture sensors can determine field capacity for any soil type. This capability enables irrigation control functions such as automated determination of field capacity and MAD for specific hydrozones in an irrigated landscape.

Key Point: Automated irrigation control systems with soil moisture sensors can be configured not only to apply more or less water per application, but also to appropriately vary the time between irrigations. Irrigation is required more frequently in sandy soils than in heavy or clay soils.

Soil Condition Also Affects Holding Capacity

In addition to the particulate sizes in the soil, conditions of the soil can also affect water holding capacity. While an exhaustive review of these conditions is beyond the scope of this white paper, two specific common conditions affecting irrigated landscapes are mentioned here.

First, soil density can have a very significant affect on water holding capacity of soils. This is particularly an issue for new construction projects, where the soil has been significantly perturbed as a part of the construction and landscaping process.

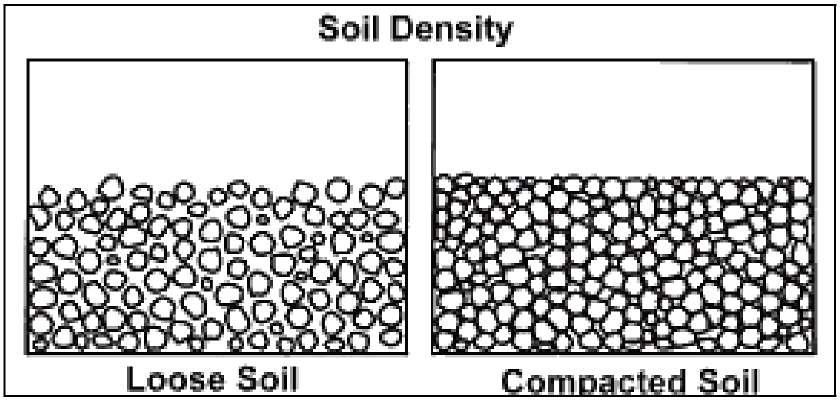

Figure 4. Soil Density
Image courtesy of the University of Minnesota Agricultural Extension

Water holding affects of uncompacted or compacting soils are difficult to estimate. Technologies such as soil moisture sensors, when installed in similarly disturbed soil conditions, provide the best insight into changing holding characteristics.

A second common soil condition affecting holding capacity in irrigated landscapes is soil layering.

Figure 5. Soil Layering Example
Image courtesy of the USDA

Soil layering is most specifically an issue when amended soils (i.e., top soil) has been applied over a layer of heavier compacted soil. This creates a barrier to gravitic water movement, and may also create a barrier to deeper root growth.

In these cases, the mechanical motion of water, and the resultant affects on field capacity and MAD can be difficult to estimate.

Key point: Soil moisture sensors can be an effective tool for monitoring actual moisture conditions even in the event of complex compaction or soil layering scenarios.

Optimum Irrigation Scheduling vs. Soil Moisture Content

The target of optimum irrigation is to keep the soil moisture (plant available water) between the soil's Field Capacity and a Maximum Allowed Depletion point. With the exception of specialty irrigation applications such as syringe cycling or post fertilization watering, all applied irrigation, regardless of the technique or technology used attempts to accomplish this.

However, as outlined in the section above, both Field Capacity and MAD vary by soil composition. A simplified graph of the relationship soil moisture content and soil composition is show in Figure 6.

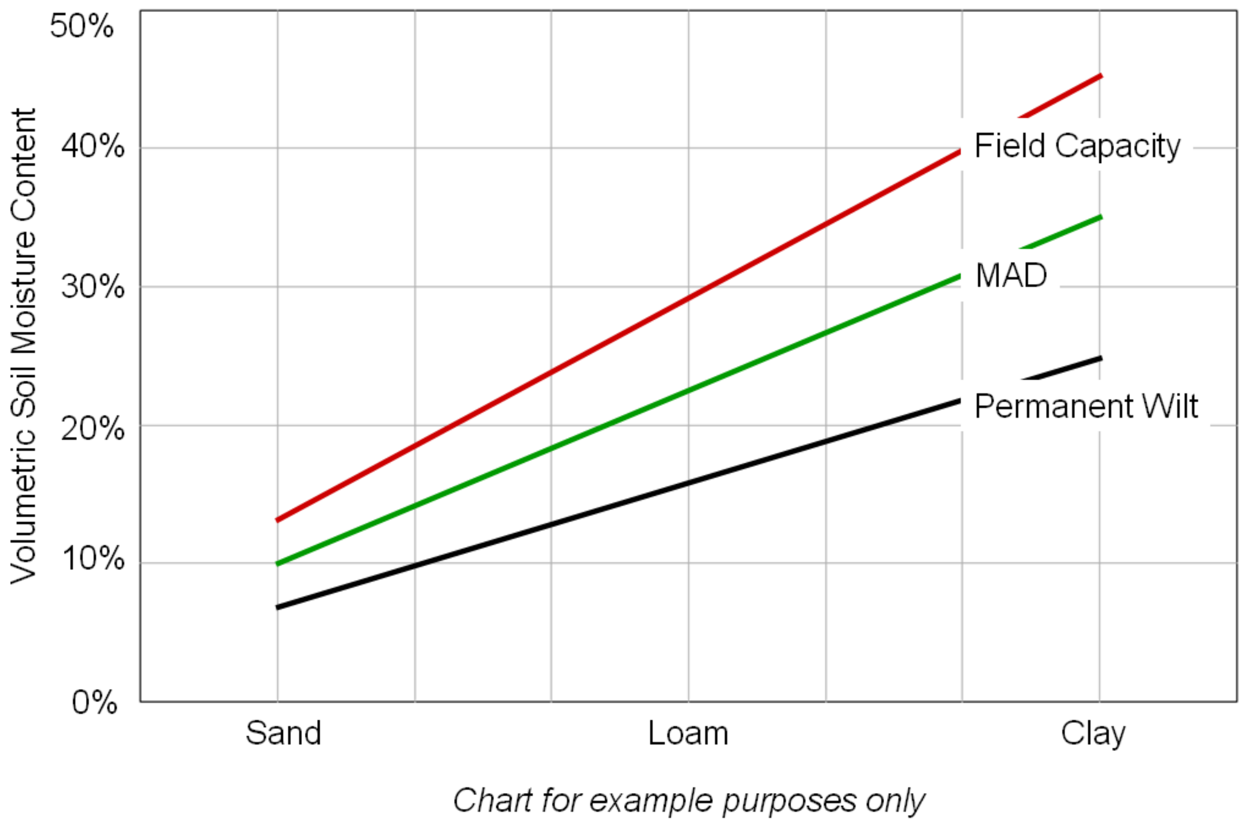

Figure 6. Simplified Example of Soil Holding Characteristics

As stated above, the objective of all artificial irrigation is to dry the soil conditions out to the MAD, then apply the minimum amount of water required to return to Field Capacity. This is true regardless of soil type or plant need.

Key point: Precise measurement of soil moisture simplifies and optimizes the potential for optimal watering behavior, and protects against landscape damage due to inadvertent mis-estimation of field capacity or permanent wilt point.

Plant Water Needs

Another key characteristic of optimal irrigation is understanding plant need. Plant water needs have been studied extensively in Agriculture over the last 70 years. Early work in the field resulted in the articulation and characterization of the plant-soil evapo-transpiration system. Evapo-transpiration ("ET") estimates the soil moisture depletion based on measurable weather or climate data in order to determine how much water to apply. Several different calculations exist, using a superset of subset of a set of key weather variables, including solar radiation, high and low air temperature, wind exposure, and humidity.

This watering model (modification of applied water based on plant water need) is often referred to as “deficit irrigation”.

Key point: Modern soil moisture based control solutions can precisely measure the affects of these same weather variables as they apply to the actual level of moisture in the soil – the very metric that the calculations were invented to estimate.

The basic water need of plants is most strongly affected by the variables used in the ET calculations, but are also affected by many other variables to a lesser degree.

However, one important area of additional impact in landscape applications is from plant nutrition and health. Plant nutrition can, especially when under-fed, result in poor looking plants regardless of how much water is applied. This concept is most clearly explained using Leibig’s Barrel.

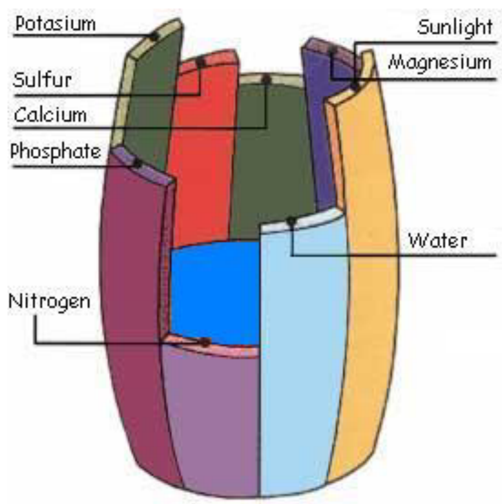

Figure 7. Liebig’s Barrel

Liebig's Law of the Minimum, often simply called Liebig's Law or the Law of the Minimum, is a principle developed in agricultural science by Carl Sprengel (1828) and later popularized by Justus von Liebig. It states that growth is controlled not by the total of resources available, but by the scarcest resource (limiting factor).

This concept was originally applied to plant or crop growth, where it was found that increasing the amount of plentiful nutrients did not increase plant growth. Only by increasing the amount of the limiting nutrient (the one most scarce in relation to "need") was the growth of a plant or crop improved.

Key point: Soil moisture based irrigation control systems automatically account for actual plant water use as limited by the most limited resource. If more fertilizer is applied, and as a result more water is used by the plants, then additional water can be automatically applied.

Key point: Soil moisture based irrigation control systems will not automatically apply additional un-needed water when plant health is compromised due to low nutrient availability, thereby making the problem worse.

Key point: “It is all ET” – (quoted from Brent Mecham, Irrigation Association.) While there often seems to be an argument between weather based and soil moisture based control solutions, the bare truth is that these are all methods for watering to ET. “ET” is the description of the system, not the watering technique.

Root Depth, Drought Tolerance and Plant Health

Most plants, and nearly all turfgrass varietals, respond to mild soil moisture stress with root growth. For this reason, the rule of thumb for watering established lawns, especially in more arid climates, is to water as deeply and infrequently as possible.

Deeper root systems result in healthier plants, more drought tolerance, more disease resistance and more nutrient uptake efficiency. Further, in many cases proper irrigation management can increase plant health and also reduce the use of pesticides. This technique has been used in Agriculture for over 30 years.

Key Point: Automated irrigation controllers with soil moisture sensors can safely water more infrequently, allowing MAD to always be reached without the risk of permanent wilt or plant damage. This naturally results in healthier, more drought tolerant, more disease resistant plants.

Evapo-Transpiration and Crop Coefficients

One of the variables in ET calculation is the crop coefficient (Kc). Crop coefficients are generally the result of agricultural study, and are designed to work with maximum growth for maximum harvest. This crop growth model assumes that water availability is not the limiting factor. Colloquial reference to this growth model in turf grass is often termed “bailing mode.”

Since it has been well determined that deficit irrigation improved plant water use efficiency (WUE), it also seems clear that optimal watering will actually require less applied water than estimated by ET using standard crop coefficients.

Further study implies that many landscape cultivars exhibit peak water use curves that do not line up in time with established ETo.

Field testing of modern weather based and soil moisture based irrigation control solutions implies that soil moisture based solutions are not only more likely to easily produce excellent water use reduction results, but in fact may irrigate more optimally than ET calculations would predict.

Key point: Automated irrigation control systems with soil moisture sensors often demonstrate water savings in excess of those predicted by ETo while maintaining excellent plant health and visual quality.

Rainfall and Effective Rainfall

When determining irrigation watering needs, natural rainfall should be accounted for. However, in order to determine the Effective Rainfall, i.e., the amount of natural rainfall that infiltrates the soil and is available to plants, the infiltration rate of the soil must be considered.

Table 5. Estimated Infiltration Rates for Common Soil Types

Course Sand	0.75” to 1.00” per hour
Fine Sand	0.50” to 0.75” per hour
Find Sandy Loam	0.35” to 0.50” per hour

Silt Loam	0.15” to 0.40” per hour
Clay Loam	0.10” to 0.20” per hour

Rainfall at a rate in excess of the soil’s infiltration rate will most often run off if there is any appreciable slope to the landscape.

Key point: One benefit of soil moisture based irrigation control systems is that the water that penetrates to the root zone, i.e., the Effective Rainfall, is automatically detected. When effective rainfall is not sufficient for plant need, the appropriate amount of additional irrigation can be automatically scheduled.

Options for “Smart” Programming/Scheduling

Technology has advanced significantly over the last 10 years in landscape irrigation. In addition to broad application of best practices from Agriculture, new solutions for the landscape irrigation industry have also been developed.

For programming & scheduling optimization, the most important of these developments are the so-called “smart controllers”. The Irrigation Association defines smart controllers as:

> “Smart” sprinkler controllers reduce outdoor water use by monitoring and using information about site conditions (such as soil moisture, rain, wind, slope, soil, plant type, and more), and applying the right amount of water based on those factors—not too much and not too little—to maintain healthy growing conditions. [Courtesy, the Irrigation Association.]

Smart controllers hold great promise to effectively reduce water use and increase plant health. Options for modern irrigation managers available today to do “smart” watering include:

Hands-on water management

- Hose end watering/visual examination of plant materials
- Manual operation of automated systems
- Timer programming using historical “ET” and seasonal adjustments

Climatology/Weather Based Controllers (“ET”)

- On-site weather stations
    - Tipping rain buckets
    - Evaporation devices
- Offsite weather data access

Soil Moisture Based Controllers (“SMS”)

- Newer techniques
    - Time Domain Transmission (“TDT”)
    - Frequency Domain Reflectometry (“FDR”)
- Older techniques
    - Electrical conductivity probes
    - Electrical conductivity in granular matrix
    - Tensiometers

Weather Based Irrigation Control “ET”

Use of automated weather based or “ET” irrigation controls has been common on commercial properties for the last 15 to 20 years. Weather based or “ET” controllers in general are devices which calculate or adjust irrigation schedules based on one or more of the following parameter sets: weather conditions (temperature, rainfall, humidity, wind and solar radiation), plant types (low versus high water use and root depth), and site conditions (latitude, soils, ground slope and shade).

Weather based controllers can get the necessary data to calculate ET from one or more of several sources:

- Historic Evapotranspiration data for the appropriate region or location
- On-site collected weather data
- Remotely collected and/or interpolated weather data

The relative benefits and challenges of these techniques are illustrated in the table below:

Table 6. Benefits and Challenges of Different Weather Based Control Approaches

Approach	Benefits	Challenges
Historical data	• No maintenance • Generally inexpensive • Relatively low tech • Good performance in non-peak water use periods	• Accuracy depends on variables • Does not respond to rapid changes or variability in weather • System uses generalized off site data
Remotely collected weather data	• No local maintenance • Reduction in both peak and non-peak water use • Data is generally from high-quality collection equipment • Can adjust for rapid change or variable weather	• Typically include monthly fees • Does not deal well with micro-climates or site specific performance • Accuracy depends on site-specific input variables
On-site weather station	• Specific on-site weather information • More sensors = more accurate results (temperature, wind, solar, rainfall, etc.) • Reduction in peak and non-peak water use • Can have plant health benefits • Adjust for rapid change or variable weather as seen on site	• Typically require regular maintenance • Accuracy relies on the sensitivity of the sensors, the number of different sensors, and the accuracy of site-specific variables.

Soil Moisture Based Irrigation Control “SMS”

The use of soil moisture sensors to monitor irrigation has been common in Agriculture for over 30 years. A variety of attempts have been made over this period to commercialize automated controls for landscape irrigation with little success.

However, over the last ten years with the growing interest in conservation and water management, new and exciting technical developments have opened a new chapter in soil moisture based irrigation control.

Historically, soil moisture sensors have battled problems such as sensitivity to salts and fertilizers, wear-out or expensive maintenance, or poor performance due to insufficient accuracy or resolution. Modern soil moisture sensors have a whole new level of performance previously unseen performance levels.
Different soil moisture sensors utilize different techniques to measure and utilize volumetric soil moisture content. The table below shows the relative performance of a variety of commercialized techniques for measuring soil moisture content.

For the purposes of this paper, “best” is defined as: “least affected by temperature, salts, fertilizers, and soil composition” as observed in commercially available smart control products as-of the writing of this paper.

Table 7. Relative performance of Common Soil Moisture Measurement Techniques

Best	Time Domain Transmissibility (TDT) Time Domain Reflectometry (TDR) • Least affected by temperature, salts, fertilizers and soil composition
Better	Frequency Domain Reflectometry (FDR) High Frequency Capacitance • Less affected by temperature, salts, fertilizers, and soil composition
Good	Soil Conductivity/Electrical Conductivity Low Frequency Capacitance • Most affected by temperature, salts, fertilizers, and soil composition

A note on these conclusions: Performance of specific commercial products utilizing these techniques can vary greatly, possibly more than the relative strengths or weaknesses of the underlying technique. Additionally, product features are greatly variable between different solutions, further requiring careful review of controller functionality independent of sensor accuracy.

Advanced Watering Using Soil Moisture Sensors

As illustrated elsewhere in this paper, systems utilizing soil moisture sensors can have several distinct advantages over any other commercialized irrigation control solution.

Unique advantages of soil moisture based control systems include:

- Ability to automatically determine soil water holding capacity, including Field Capacity and MAD
- Ability to account for complexities of soil, infiltration, plant fertility and plant nutrition no accounted for in weather based solutions
- Ability to measure true effective rainfall (that which infiltrates to the plant root level)
- Ability to measure true irrigation water penetration in slopes and complex landscapes
- Ability to generate alerts or alarms for irrigators prior to plant damage

Testing of soil moisture based landscape irrigation controllers indicates the following benefits:

Benefits of SMS based irrigation controllers:

- Adjusts automatically for on-site climate conditions
- Reduction in both peak and non-peak water us
- Major plant health benefits
- Adjusts for rapid weather changes

- No maintenance required

Challenges for SMS based irrigation controllers include:
- Discontinuous technology
- Sensor placement & burial required
- Slow detection of rainfall (requires water infiltration into the soil)

Conclusion

It is the conclusion of the author that, properly implemented, soil moisture sensor based landscape irrigation controllers have the proven capacity to provide simpler and more effective landscape irrigation performance improvement than competitive techniques.

By way of analogy, the author asks you to consider a similar energy control system: the modern heating and air conditioning (HVAC) system. In this system, a temperature sensor is used with a simple controller (a thermostat) to control the introduction of heated or cooled air into a home or building.

It is conceivable that the system could be controlled by a simple timer. However, manual override would probably be required on an hourly or sub-hourly basis to achieve effective results. It is also possible that historical weather data could be used to set a heating and cooling program. Likewise, daily or hourly intervention would probably be required for effective results.

Finally, a weather station could be connected to the outside of the building, and a calculation including the "R" factor of the windows, the total BTU's provided by the furnace, the total cubic feet of each room, etc., could be used to control the system. Clearly, this last option would perform markedly better than the first option. However, it would be more expensive, and provide lower performance than the simple thermostat.

For this reason, and those articulated throughout this white paper, it is the author's conclusion that soil moisture based solutions, equipped with modern, accurate, and low cost soil moisture sensors will be the preferred method to control landscape irrigation in the near future. History shows that closed-loop control systems, i.e., systems where the performance of the chief variable is directly fed back into the control system, outperform open-loop control systems.

Finally, the author concludes that of all options and alternatives for addressing overwatering as defined in this paper, the introduction of improved control solutions has the potential to provide the most benefit for the lowest actual cost of any alternative option.

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