Precision Irrigation Technology _ Behnaz Molaei

Slide 1: This presentation will provide an overview of soil water relationship and different sensors and technologies that can be used for irrigation scheduling and precision water management. I also provide some examples that show the practical use of these technologies.

Slide 2: To know more about the irrigation scheduling and precision water management we need to know basics of soil and water relationship. The four main components of soil are mineral material, organic material, air and water. Typical agricultural soil has 50% minerals and organic matter, and the other 50% is pore space occupied by water and air (Optimum condition for plant growth occurs when about 25% is air and 25% water). Size and distribution of soil pores have significant influence on the amount of water that a soil can store which I will explain more about it in future slides.

Slide 3: Soil texture refers to the degree of fineness or coarseness of soil particles, which is vital for irrigation scheduling. Represented graphically by the soil triangle, it categorizes textural classes based on the proportions of sand, silt, and clay present in the soil. Determining soil texture involves drying, sieving, and analyzing a soil sample to identify the percentage of each particle size group. This information helps understand water holding capacities and drainage properties, influencing water movement and availability to plant roots.

Slide 4: Soil structure is the arrangement of soil particles into larger units or aggregates, which impacts plant growth through moisture retention, aeration, heat transfer, and nutrient availability. By evaluating and preserving healthy soil structure, farmers can enhance soil fertility, water penetration, and crop productivity, while reducing erosion and environmental harm.
<u>Major soil structures:</u>
Single Grain: Soil particles act independently, typical of soils with high sand contents.
Platy: Aggregates are thin and form like a stack of plates
Massive: Soil particles cling together, but they don't break into similar structural units
Prismatic/Columnar: Tall and column-like, prismatic tops are often flat and may not be distinct, columnar tops are rounded and distinct.
Blocky: Irregular aggregates.
Question: What is the most desirable soil structure for **irrigation?**
Answer: Crumb and Granular that has the most desirable pore size for soil water movement and storage

Slide 5: This illustration highlights how soil structure impacts water movement downward. It emphasizes that a fine granular structure is optimal for seedbeds, while cracks and pores aid in air movement, influencing root penetration and water intake. Agricultural activities like tillage and irrigation can alter soil structure, especially with heavy overhead or flood irrigation, potentially causing surface sealing.

Slide 6: Small pores store water effectively, while large pores aid in drainage and soil aeration. Large soil particles enhance drainage, while small particles promote water retention. Additionally, higher humus content in soil enhances water retention capacity. Humus, resulting from organic matter decomposition, improves soil structure and water retention, thus enhancing soil health and fertility.

Slide 7: ETc, or crop water use, is independent of soil type. This is evident in the figure, which shows varying reservoir sizes for different soil textures; deep soil holds more water than deep sand soil. Despite soil differences, ET remains constant across all types. In a large field with diverse soil conditions, optimal irrigation scheduling is crucial to prevent crop water stress. To address sandy soil, manage irrigation by increasing pivot speed and frequency to prevent deep percolation and water stress in sandy areas.

Question: Which soil needs MORE water? **Answer:** The plants use the same amount of water regardless of soil type.

Question: Where will you see water stress first? **Answer:** In sandy soil. This is why people mistakenly believe that sandy soils need more water, which is not true. Sandy soil requires more FREQUENT watering in smaller amounts.

Question: If you have variable soil types in a single field and you want to manage for maximum production (no stress), which soil type should you manage to? (Where should you place your sensors?) **Answer:** Manage to the shallow sand, or the soil with the lowest water holding capacity.

Question: If you want to impose water stress (e.g., for red wine grapes), in which soil type will plants respond most quickly? **Answer:** Shallow sand.

Question: In which soil type will you have trouble imposing water stress? **Answer:** Deep silt.

Slide 8: Saturation: Porous full of water, no air. Adding more water = runoff or deep percolation

Field capacity (θ_{FC}): Maximum amount of water that a soil can hold against gravity without any loss due to drainage. The soil water content where the drainage rate, caused by gravity, becomes negligible.

Crop stress point: Amount of water in the soil that plant can't extract enough water and experience damage.

Permanent wilting point (θ_{PWP}): Amount of water remaining in the soil after plants can no longer extract water from the soil (wilt & die)

Available Water Content (AWC)= (θ_{FC}- θ_{PWP})

Slide 9: Soil is like a water reservoir. The ideal situation to grow crops is figure 3 and 4 where we have enough water available in the soil reservoir to grow crops. When we use soil moisture sensors, we try to keep the volumetric water content of the soil at this range and level. Figures 5 and 6 indicate low water availability in the soil profile that crop shows water stress at that level.

Slide 10: Near field capacity (FC), crops reach optimal conditions for yield. Management Allowable Depletion (MAD) denotes the safe water depletion from a plant's root zone before irrigation becomes necessary to prevent stress. Exceeding the MAD threshold leads to reduced crop production. MAD varies based on soil type, crop, climate, and growth stage. Effective MAD management is essential for water use efficiency and sustaining crop productivity.

Slide 11: The table illustrates different percentages of MAD for various crops. For example, potatoes exhibit a low % MAD, indicating their high susceptibility to water stress, whereas Alfalfa demonstrates a higher % MAD. These values are utilized in determining the water requirements for each irrigation event.

Slide 12: Root Zone refers to the potential rooting depth of the crop, indicating the maximum depth at which the plant's roots can extend. The Effective Root Zone, on the other hand, constitutes the upper half of the actual maximum rooting depth. This portion of the root zone is where approximately 70% of the plant's water uptake occurs, as it is densely populated with active roots crucial for water absorption and nutrient uptake.

Slide 13: We have three different types of soil: sand, silt loam, and clay. In each scenario:

- The planting distance of the crops in the row remains consistent.
- The distance between emitters in the dripline is constant (12 inches).
- The amount of applied water (0.5 inches) and the duration of irrigation (3 hours) remain unchanged.

However, we can observe variations in the wetting patterns within the soil. This figure illustrates that silt loam soil exhibits the most favorable wetting pattern, characterized by a significant overlap of each wetting circle with the next one, ensuring uniform irrigation across the entire field.
Question: Which field experiences water stress? The sandy soil, as the spacing of the emitters does not facilitate a sufficient overlap of the wetting circles, resulting in non-uniform irrigation throughout the field.

Slide 14: Understanding the depth of the root zone is crucial for accurately estimating the water requirements of crops for irrigation scheduling. For instance, lettuce generally possesses shallower roots compared to corn and vines.
Applying the same amount of water to all crops during each irrigation event may not yield optimal results. When providing 0.5 inches of water for lettuce in a single irrigation event, much of the water may surpass the crop's shallow root zone, leading to deep percolation. However, this same amount of water might adequately moisten the root zones of vines.

Slide 15: Uniformity in irrigation systems ensures even water distribution across the entire field, while efficiency measures the ratio of water used to meet crop needs to the total water diverted for irrigation. The figures depict various scenarios of uniformity and efficiency, offering insights into underground processes. In the top left figure, both uniform and efficient irrigation are achieved, distributing water evenly without excessive deep percolation. Conversely, the top right figure shows non-uniform and inefficient irrigation, with some areas over-irrigated and others under-irrigated. The bottom left figure demonstrates uniform but inefficient irrigation, where excess water percolates beyond the root zone. Similarly, the bottom right image depicts non-uniform and inefficient irrigation, with disparities in water distribution across the field.

Slide 16: Precision Irrigation Management entails employing advanced technologies and techniques to enhance the efficiency, uniformity, and effectiveness of agricultural irrigation practices. This approach involves precise measurement and control of factors like soil moisture, crop water needs, weather conditions, and irrigation system performance. By utilizing sensors, data analytics, automation, and other tools, Precision Irrigation Management aims to deliver optimal water amounts at the right times and locations, maximizing crop yields, conserving water, minimizing environmental impacts, and reducing operational costs. Various irrigation scheduling methods, including soil-based, plant-based, weather-based, remote sensing-based, and their combinations, can be utilized in this approach.

Slide 17: The neutron probe sensor measures soil water content by lowering a radioactive source into a vertically installed access tube in the soil. The source emits high-speed neutrons, which are slowed down by hydrogen ions in soil water. The rate of slowing is proportional to the water content. A detector near the source counts the slow-moving neutrons over a brief period, typically 30 seconds to 2 minutes. There is a strong correlation between the count of slow-moving neutrons and soil water content (θv).
Advantages: More accurate than other soil water sensors (within 1%), Measures soil water, Size volume of soil sample (6-10 inches), Unaffected by salinity or temperature

Disadvantage: High initial cost (around $14K), Required license for operator, Calibration curve is necessary, Can't leave it in the field, take to field and return it, Required installed access tubes for measurements, No real-time log data

Slide 18: TDR is a method for measuring soil water content. It uses two rods in the soil to send and receive electromagnetic waves. The time it takes for the wave to travel reflects the soil's apparent dielectric permittivity (εa), which is influenced by water content (θv). Dry soil results in a faster travel time and lower εa, while wet soil has a slower travel time and higher εa. The strong correlation between εa and θv makes TDR an accurate way to measure soil water content, typically within a 2% margin of error.

Slide 19: Capacitance probes measure soil water content by indirectly estimating the soil's apparent dielectric permittivity (εa) and its correlation with volumetric water content (θv). Capacitance probes determine εa by assessing capacitance and frequency. These probes use the soil as a dielectric and pulse it with high-frequency radio waves. The measured frequency helps calculate capacitance, which is then used to determine εa and, consequently, θv. While capacitance probes are easy for trend monitoring, accurate measurements require calibration specific to the soil they are installed in. There are two forms of capacitance probes:
1- The top pictures sensors require an access tube, similar to neutron probes. This allows soil water to be determined at multiple depths in the soil profile; however, the sensing volume is much smaller since the sensor is not in direct contact with the soil.
2- It has two or three electrodes which are inserted directly into the soil. The probe can be permanently installed at the desired depth in the soil profile. The meas
Advantages: Measures soil water content (θv), easy-to-use option for monitoring trends in θv, Accuracy 3% IF installed correctly and calibrated for the soil
Disadvantage: Small sample area, Inconsistent (highly variable), Dependent on soil structure, require proper installation, affected by salinity and temperature.
Slide 20: The tensiometer is an old method for measuring soil water tension (matric potential, ψm) directly. It consists of a water-filled tube with a porous cup at one end and a vacuum gauge at the other. The tube is sealed at the gauge end. To use it, the tensiometer is placed in the soil with the cup at the desired depth. As the soil dries, water is pulled out of the tensiometer, creating a vacuum in the tube. The vacuum gauge shows the soil water tension, usually in centibars (cb) from 0 to 100 cb. The reliable range is 0 to 75 cb, with zero indicating saturated soil.
0 cb = Saturated soil , 8 cb = FC for fine sand, 20 cb = FC for silt loam soil
For fine sand: 70% of AWC is depleted for silt loam at 75 cb
By using Figure, we are able to demonstrate that, for fine sand, about 70% of the AWC has been depleted at 75 cb (the upper limit of the instrument),
but only about 45% of the AWC has been depleted for silt loam at 75 cb.
Advantages: Measures soil water tension, Not affected by salinity, Cheaper than other sensors
Disadvantage: Small sample area, Limitation for irrigation management on finer-textured soil
Slide 21: Electrical resistance blocks have two embedded electrodes in porous gypsum material. Buried at a desired depth, they need good contact with the surrounding soil. An ohmmeter with AC current measures resistance between electrodes when the soil water reaches equilibrium with the block. The resistance relates to gypsum water content, and the water tension in the gypsum reflects soil water tension (Ψm). Embedding electrodes directly into the soil is avoided due to electrolytes affecting resistance in the soil. Gypsum helps buffer this effect, ensuring more

accurate estimates of matric potential, especially in saline soils where salts can distort measurements.
Advantages: Inexpensive, Give soil water potential (same parameter as plant sees)
Disadvantage: Low accuracy, Small sample area, Affected by salinity

Slide 22: Now, imagine you have soil moisture sensors in your hand. It's crucial to determine the optimal locations for placing these sensors in the field.
Best location for sensor installation: Avoid placing the sensor right on the edge of the field, consider the average soil conditions and decide on the installation location accordingly, Ideally, install the sensor in an area with the lowest water holding capacity (such as sandy soil), where crops exhibit signs of water stress sooner compared to other parts of the field with different soil textures. **Regarding installation depths:** First, ascertain the depth of the roots and divide it into four sections, as depicted in the figure. If you have only one sensor and intend to manage field irrigation based solely on this sensor, install it in the middle of the root zone. With two sensors, install one at the 1/3 mark (middle) and the other at the bottom of the root zone. For three sensors, place them at the top, middle, and bottom of the root zone. In general: Top sensors indicate when watering is needed, while bottom sensors reveal more severe stress and provide insights into the water holding capacity of the soil.

Slide 23: Now that we have the soil moisture sensor in the field, we can compare two fields with different irrigation management practices. The figure depicts a scenario of effective irrigation management, where growers kept the soil water content within the range between field capacity and the MAD (Management Allowed Deficit) line, ensuring that the crop does not experience water stress. Each pick in the soil water content happens after each irrigation event or rainfall.

Slide 24: This figure illustrates poor irrigation scheduling, as the soil water content has exceeded the MAD (Management Allowed Deficit) level. As a result, the crop could potentially exhibit symptoms of water stress in the field following these occurrences. When soil sensors indicate that the soil moisture level has dropped below the MAD level, it signifies that the crop is experiencing stress. In this graph, we can observe two instances of water stress events.

Slide 25: "Soil water balance" refers to the equilibrium between the water entering and leaving the soil system over a specific period. It involves tracking the inputs and outputs of water within the soil profile to assess water availability for plants and other soil-dependent processes. The inputs typically include precipitation, irrigation, and groundwater recharge, while the outputs consist of evaporation, transpiration (water uptake by plants), and drainage. By monitoring the soil water balance, farmers can make informed decisions about irrigation scheduling, crop management, and water conservation practices to optimize agricultural productivity and sustain soil health.
Here are the abbreviations explaining each term defined in the figure.
P = Precipitation, Rainfall, I = irrigation, CP = Capillary rise, E = Evaporation, T = Crop Transpiration
RO = Run off, DP = Deep Percolation, $\Delta\theta$ = Soil Water storage

Slide 26: This summary outlines a soil water balance study conducted on Spearmint at WSU-IAREC. RGB drone imagery was captured at a height of 60 feet above ground level, with irrigation managed by a linear system moving in a rectangular pattern. Various irrigation levels were applied using different nozzles, with yellow circles indicating locations of neutron probe access probes under each treatment. TEROS-10 sensors from METER group were installed at Block 3 under 100%

irrigation levels at two depths for continuous soil water monitoring. Efforts were made to minimize runoff by adjusting irrigation rates. Deep soil moisture sensors were utilized to monitor soil water content and assess deep percolation. The graph depicts soil water content measured by neutron probe sensors at each irrigation level, with neutron probe readings used to validate TEROS-10 sensor accuracy.

Slide 27: Weather stations play a crucial role in irrigation scheduling by providing essential data on weather conditions that influence crop water requirements. These stations are equipped with various sensors to measure key meteorological parameters such as temperature, humidity, wind speed, solar radiation, and precipitation. Additionally, some advanced weather stations may also include sensors for measuring soil moisture levels and leaf wetness.

Slide 28: This equation serves to enhance your understanding of how researchers and scientists utilize weather data to estimate crop water usage and facilitate irrigation scheduling.
The data collected from weather stations is utilized to calculate reference evapotranspiration (ET_0 or ETr), which quantifies the amount of water lost from soil and plant surfaces due to evaporation and transpiration under standardized conditions. ET_0 acts as a foundational measure for estimating crop water requirements, incorporating factors such as crop type, growth stage, and environmental conditions. Alfalfa-reference ET is defined as the ETr rate from an expansive, uniform surface of dense, actively growing alfalfa, approximately 20 inches tall and adequately supplied with soil water. ETo represents the evapotranspiration rate from a reference surface that is not deficient in water. A vast, uniform grass field is recognized worldwide as the reference surface. This reference crop fully covers the soil, is maintained at a short height, adequately irrigated, and is actively growing under optimal agronomic conditions.

Slide 29: The crop coefficient (Kc) is a dimensionless factor used in irrigation and agriculture to estimate the water requirements of a specific crop relative to the reference evapotranspiration (ET_o). It represents the ratio of the actual evapotranspiration (ETc) of the crop to the reference evapotranspiration (ET_o). The crop coefficient accounts for the stage of crop growth, canopy development, and physiological activity, which influence the crop's water needs. It varies throughout the growing season, reflecting changes in the crop's water consumption as it progresses from initial growth stages to maturity.

Slide 30: By multiplying the reference evapotranspiration (ET_o) by the crop coefficient (Kc), one can determine the crop's actual water requirement (ETc) at any given stage of growth. This information is valuable for effective irrigation scheduling, helping farmers optimize water use efficiency and maximize crop yields while minimizing water waste and environmental impact. These are the basic concepts that are used in the irrigation scheduling.

Slide 31: Leaf water potential is the negative pressure or tension found in plant leaves.
The LWP of the well water plants is higher (less negative in value) than that of plants under water stress. LWP values provide information on the moisture status of the plant.
This measurement is made by detaching a leaf from the plant and inserting it into a chamber with its petiole protruding from a small hole. Gaseous nitrogen is allowed to enter the chamber, increasing the pressure within the chamber. When the internal pressure of the chamber is as positive in value as the leaf and petiole are negative in tension, small water bubbles can be seen on the incised edge of the petiole, and this equilibrium pressure if recorded as the LWP value.

Slide 32: Sap flow: movement of water, nutrient in the roots, stems, and branches of the plants
This is something like blood pressure measurement of the human.
It wraps around the stem or branches, apply fixed heat to the stem, and temperature sensors resolve the flowrate.
Limitation of Sap flow Sensors: Not applicable for all plant species, plants have different sap flow pattern, External environmental conditions like Ta, WS, RH can influence sap flow, Accuracy depends on proper sensor installation, Stem diameter dependency.

Slide 33: Plant transpire, cooler than ambient air during daytime
IRT sensors are available at reasonable prices. Spot-check canopy temperature to know about soil moisture condition, require maintenance and calibration, Applicable for full canopy condition, Early season irrigation scheduling is not possible (soil background not removable from crop canopy)

Slide 34: Energy balance models are mathematical representations utilized across various fields to quantify the exchange of energy between different components of the Earth's surface and the atmosphere. These models consider the fluxes of energy, including solar radiation, sensible heat, latent heat, and ground heat flux, at the Earth's surface and within the atmosphere. Energy balance models typically involve equations that account for incoming and outgoing energy fluxes, as well as energy storage within the system. By solving these equations, energy balance models can offer valuable insights into various processes, such as surface temperature dynamics, evapotranspiration, soil heat flux, and radiation budget.

Slide 35: ETc mapping is one of the products of energy balance models that can be utilized to generate prescription maps for uploading onto the control panels of center pivot systems, aiding in variable rate irrigation systems.
There are two types of variable rate irrigation systems: (1) Variable speed, which allows for controlling the speed of the pivot. Increasing the speed at one location results in reduced water application in that area, while decreasing the speed increases water application. (2) Variable zone irrigation system, where nozzles turn on and off at specific locations within the field to irrigate water according to the prescription map. Nowadays the control panel of the center pivot irrigation systems has the capability of uploading prescription maps on it and applying different levels of water to different parts of the field.

Slide 36: Leaf temperature serves as a crucial indicator of crop water status, reflecting the level of water stress experienced by plants. When plants undergo water stress due to insufficient water availability or excessive transpiration, their leaf temperatures rise. This increase is attributed to the plant's response to conserving water by closing stomata, reducing transpiration and evaporative cooling. Monitoring leaf temperature enables farmers to assess crop water status in real-time, aiding in informed decisions regarding irrigation scheduling. By identifying areas with elevated leaf temperatures, farmers can implement targeted irrigation strategies to alleviate water stress and enhance crop yields.

Slide 37: In the upcoming slides, I will present practical applications of various sensors used during my PhD and post-doc at WSU. During my post-doc, I worked at the Farm Intelligent Trust of the AgAID Institute, funded by USDA and NSF, focusing on utilizing sensing techniques to develop AI models for irrigation scheduling. My role involved setting up a smart vineyard with sensors to monitor soil-plant-atmosphere interactions and vine water use. The initiative aimed to explore how AI decision support could optimize farm management, mitigate crop losses, and improve product quality. The field map displays four plots, each fully irrigated (FI) and deficit irrigation or water-stressed vines (DI or WS).

Slide 38: These images depict thermal maps of the vineyard captured by a UAS from a 30-meter elevation, using a FLIR DUO R thermal camera. Thermal mapping is commonly used to assess crop water stress levels, with higher temperatures indicating dry soil conditions. Differences in temperature values between fully irrigated and deficit irrigated vines are evident. The right image displays a Crop Water Stress Index (CWSI) map, with a grayscale layer added below to highlight the plots. CWSI is utilized to assess crop stress levels and determine irrigation timing, with a value of 1 indicating water stress and 0 indicating full irrigation.

Slide 39: For the same field experiment that I had during my Ph.D. and I was explained about the treatments in slide 29, I flied drone with two cameras, RedEdge with Multispectral camera with 5 bands, and Thermal camera FLIR DUO PRO R with RGB and Thermal lens over the field twice a week because I was trying to calibrate the UAS-Based METRIC energy balance model that each pixel value show the ET_c or crop water use in mm/day.

Slide 40: These two ETc maps depict crop water use in millimeters per day for two field experiments previously discussed. Each pixel represents specific crop water usage, enabling site-specific irrigation management. The METRIC model, developed by Dr. Rich Allen in 2007, utilizes Landsat imagery to estimate crop water use at a 30-meter resolution. During my PhD at WSU, I contributed to modifying this model to achieve higher resolution using drone imagery. The figure illustrates the application of high-resolution images, with centimeter-scale resolution per pixel, for estimating crop water use and generating ET maps. Although UAS-METRIC models are in the research phase, the satellite-based METRIC model is widely used in the western USA for precision irrigation scheduling.

Slide 41: In the smart vineyard setup for the AgAID institute, a combination of sensors was installed to measure various aspects of water movement in soil, trunk, stem, leaf, and atmosphere. These sensors, including TEROS 12 for soil water content, TEROS 21 and WaterMark sensors for soil water potential, sap flow sensors from Treetoscope and Dynamax, and a dendrometer to monitor trunk diameter changes, were utilized to collect high-quality data for developing AI tools for irrigation scheduling. Additionally, an Apogee infrared temperature sensor was installed over the canopy to detect canopy stress levels.

Slide 42: In addition to installed sensors, drone-based imagery with thermal and multispectral cameras was utilized for periodic measurements over the canopy. A drone equipped with an RGB camera generated a 3D map of the field and monitored canopy structure. Leaf water potential sensors were employed for predawn and afternoon measurements to detect crop stress levels, providing accurate data for calibrating other sensors. Gas exchange sensors were also used for leaf measurements to assess crop stress. These methods aid researchers in predicting irrigation timing and quantity to improve crop yield and quality.