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Citrus Irrigation Scheduling

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ABSTRACT

As the major water user, irrigated agriculture is expected to make substantial changes to optimize its water use. Ample research findings in the literature show that an efficient irrigation scheduling reduces production cost, improves crop yield, limits erosion and sediment loading, and enhances environmental quality. A successful irrigation water management program optimizes water availability, while ensuring the best crop yield and quality at the lowest cost to the producer. Irrigation scheduling is generally meant to calculate the exact amount and timing of irrigation to be applied to the field based on the crop irrigation water requirements. This review manuscript discusses the following sections: i) soil and its major physical properties that influence irrigation scheduling, ii) measurement of some of soil physical properties iii) rainfall characteristics (amount, intensity and distribution) and their effect on irrigation scheduling, iv) citrus crop properties that influence water uptake (root system and crop growth stages and parameters, crop water uptake across the growing season), v) irrigation techniques used in citrus, vi) different citrus irrigation scheduling techniques, and vii) an outlook of future research in citrus irrigation scheduling.

Keywords: crop and root growth stages, rainfall distribution, soil water

Abbreviations: ASW, available soil water; **D**, drainage; **ER**, effective rainfall; **ET**, evapotranspiration; **FC**, field capacity; **IRR**, irrigation requirements; **LAI**, leaf area index; **MCP**, multi-sensor capacitance probes; **NS**, neutron scattering; **P**, rainfall; **PVC**, polyvinyl chloride; **PWP**, permanent wilting point; **RO**, surface runoff; **S**, soil water storage; **TDR**, Time Domain Reflectometry

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INTRODUCTION

Water is critical for optimal growth and production of all crops. The optimum amount of irrigation applied at the right time allows the crop to grow and produce at its best. With the exception of arid and semi-arid conditions, rainfall is the main source of water supply for most field crops. However, supplemental irrigation has been proven to increase crop yield even in areas with relatively high annual rainfall that is distributed irregularly throughout the growing season. It is widely known that crop growth increases with actual crop evapotranspiration until it maximizes at potential evapotranspiration. This is expected because of the close relationship between crop transpiration and photosynthesis.

A growing worldwide demand for food, fiber, and biofuel coupled with an unprecedented increase in the cost of energy are enough reasons to optimize our finite water resources through improved irrigation water efficiency. Optimum crop production requires efficient irrigation scheduling programs that optimize crop water uptake while minimizing excess water losses. Supplemental citrus irrigation significantly increases crop yield (Koo 1978). Gross crop irrigation requirements throughout the growing season are a function of the rainfall characteristics (distribution, amount, and intensity), evapotranspiration, soil physical and hydro-

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Invited Review

logical properties (mineral composition, particle size distribution, water holding capacity, infiltration, drainage, and surface runoff), irrigation system efficiency, and crop characteristics (crop coefficient, root distribution).

This review discusses the following sections: i) soil and its major physical properties that influence water management, ii) measurement of some of soil physical properties iii) rainfall characteristics (amount, intensity and distribution) and their effect on irrigation scheduling, iv) citrus crop properties that influence water uptake (root system and crop growth stages and parameters, crop water uptake across the growing season), v) irrigation techniques, vi) different irrigation scheduling techniques, and vii) an outlook of future research in irrigation scheduling.

Soil major physical and hydrological properties

Soil is a porous heterogeneous media composed of solid, liquid, and gaseous phases. The liquid phase is mainly composed of water containing dissolved nutrients. The sum of the liquid and gaseous phases makes up total the soil total porosity. The solid fraction of soil is composed of different particles (i.e., sand, silt, clay, and loam) and organic matter (humus) which acts as the skeleton of the soil and as a porous medium. There is a strong relationship between physical characteristics of soil i.e., porosity, water holding capacity, soil texture, mineral composition, and infiltration and chemical properties i.e., cation exchange capacity and pH.

Soil texture refers to the relative proportions of sand, silt, and clay in a soil matrix; whereas, the arrangement of these particles into a soil aggregate determines soil structure. Soil texture determines soil type (i.e., sandy, silty, clayey or loam) and soil structure determines the pore spaces through which soil water and gases move. The measure of total pore space in a soil matrix determines the total soil porosity that is measured as a percentage of the total soil volume. A soil medium comprised of coarser particles has lower porosity than that comprised of fine particles. The degree of compactness of soil solids defines soil bulk density, ρ_b, which is the ratio of the mass of soil solids to the total soil volume. Bulk density is generally higher in low profile layers indicating high compactness of soil solids in a soil matrix. For soils with shrinking and swelling capabilities, bulk density varies according to their water content. Fares *et al*. (2004) quantified this effect on a duplex soil with a shrinking/swelling clay and reported that the ρ_b varied with the sampling depths. They showed that except for the 20 cm sampling depth, the top 50 cm of the soil profile had the lowest bulk density as compared with the lower 50 cm portion of the profile. They attributed the pronounced increase in ρ_b in the upper 10 cm horizon to the soil compaction. They also reported on a negative correlation between ρ_b and water content in the 30 to 100 cm depth layers, reflecting the shrinking and swelling properties of the fine textured subsoil. Soil bulk density is also affected by the amount of organic matter present in the soil. Fares *et al*. (2008a) reported on the effect of soil organic matter produced as result of livestock manure amendment on soil bulk density (ρ_b) and soil total porosity (θ_t) of a highly weathered Hawaii tropical soil. They found that increased manure amendments significantly decreased ρ_b and consequently increased θ_t.

Soil major hydrological properties include infiltration and hydraulic conductivity. Infiltration rate is the rate at which water enters the soil from its cross-sectional area. Understanding the infiltration process helps quantify the amount of water (from irrigation or rainfall) entering into and moving through the soil. Tension infiltrometer (SMS, n.d), double ring infiltrometer (Reynolds *et al*. 2002), and Guelph permeameter (Elrick *et al*. 1984) are the most common instruments used to measure the steady state infiltration rates that are then used to determine hydraulic conductivity of a soil. These instruments have been used to determine soil hydraulic conductivity under various conditions. A detailed description of these techniques can be found in Casey and Derby (2002) and in Bouwer (1986).

Fares *et al*. (2000) used the Instantaneous Profile method, the Guelph permeameter, and the van Genuchten hydraulic functions to determine the steady state infiltration rates, and saturated and unsaturated hydraulic conductivity of a Candler fine sand soil, a typical soil of Florida's ridge citrus area. Using the van Genuchten hydraulic functions (Mualem 1976; van Genuchten 1980), they were able to predict the unsaturated hydraulic conductivity at the different depths. The saturated hydraulic conductivity (K_s), measured at five soil depths (10, 20, 40, 70 and 110 cm), varied between 6.1 and 10.0 m day^{-1}. However, the unsaturated hydraulic conductivity of this soil decreased exponentially as the volumetric water (θ_V) decreased to 0.10 m^3 m^{-3}.

Fares *et al*. (2008a) determined saturated hydraulic conductivity from the steady state infiltration rates measured with tension and double ring infiltrometers in a study that quantified the effect of manure amendment rates, levels, and types (chicken, dairy and swine manure) on major soil physical and hydrological properties of a highly weathered Hawaii tropical soil. Their results show that the increased manure amendment rates and levels significantly decreased bulk density and consequently increased total porosity. The values of the K_s of this soil increased significantly with increase in chicken and dairy manure amendment rates and levels. However, for swine manure treatments, K_s decreased with increase in manure amendment rates and levels. They attribute this behavior to the clogging effect of swine manure that was applied as slurry. They also reported that K_s calculated from double ring infiltrometer data were slightly greater than those from tension infiltrometer. However, the K_s values from the two techniques for individual measurements were reasonably correlated. Larger K_s values from double ring infiltrometer data as compared with tension infiltrometer data may be attributed to the differences in the infiltration measurement areas of the two techniques. Tension infiltrometer measurements cover a small area, while double ring infiltrometer data represents the conductivity of the larger area of soil that might include large pores. With double ring infiltrometer, a significant fraction of the water may infiltrate through a few large cracks.

Soil water release curve

Soil water release curve, the relationship between soil water content and soil water suction, is a fundamental part of characterization of the soil hydraulic properties (Klute 1986). Soil water release curves can be determined in the laboratory using disturbed and undisturbed soil cores (Klute and Dirksen 1986) or in the field using *in-situ* method called Instantaneous Profile method (Elrick *et al*. 1984; Fares *et al*. 2000). This method has been used by several researchers with different soil types (Bruce and Luxmoore 1986; Dane and Puckett 1992). It requires frequent and simultaneous measurements of soil water content at different depths and matric potential at the required depths of a soil profile.

Fares *et al*. (2000) used the Instantaneous Profile method in combination with capacitance probes, tensiometers, and the van Genuchten hydraulic functions to determine the water content-pressure head relationships for five soil depths (10, 20, 40, 70 and 110 cm) of a Candler fine sand soil in a citrus grove in Florida. Data from their study demonstrate the low water-holding capacity of the Candler fine sand, as evidenced by its loss of more than 50% of its water within 8 to 10 h following saturation. These properties of Candler fine sand, presented in this section and that above it, influence the irrigation practices for this soil. Low volume irrigation is the most appropriate method for this type of sandy soil since it will not increase the water content substantially over a short duration, and, thus, it will facilitate increased retention of water by minimizing excessive water drainage. Accordingly, frequent short duration irrigation events are recommended for this soil to minimize drainage below the rootzone, which can act as carrier of nutrients and other agrochemicals.

SOIL WATER

Soil water content is expressed as the ratio of the volume of the liquid water in a soil (V_W) to the total volume of the soil solids including pores (V) and is expressed as $\theta_V = V_W/V$. Soil water content has been used as a practical indicator of plant water availability.

The ability of soil to hold water despite gravity forces is called soil water holding capacity. Since water is held around the soil particles by adsorption, the surface area of the soil particle determines the water holding capacity of a soil. Smaller particles having larger total surface area hold larger amounts of water and vice versa. At saturated condition, all the pores of a soil are filled with water. As the soil loses water due to surface evaporation, gravity and/or plant uptake and thus become unsaturated when most of the excess water is drained due to gravitational forces, the soil water content is said to be at field capacity (FC). In sandy or coarse-textured soils, the applied water drains off quickly because of the relative large size of the soil pores and gravity. For fine-textured soils, i.e., clayey or silty, the applied water drains off slowly because of the relative small size of soil pores and enhanced adsorption on larger surface area. Therefore, sandy soils hold less water than silty and clayey soils, reflecting the lesser FC water content of sandy soils than those of silty and clayey soils. Permanent wilting point (PWP) refers to the situation when there is no water available for plant uptake and the plants wilt and die beyond this point. The water is available to the amount between FC and PWP and is calculated as follows:

$$\text{ASW} = \theta_{\text{FC}} - \theta_{\text{PWP}}$$

where ASW is available soil water, and θ_{FC} and θ_{PWP} are the volumetric water contents at FC and PWP, respectively.

The soil with larger pores i.e., sandy soils, have less ASW than those with smaller pores i.e., clayey soils. Loamy soils have the largest quantity of ASW since for the clayey soils the water is held tightly and is not easily extractable by the plants. The water that is tightly bound to soil particles in the form of a thin film and is not easily removed for plant use referred to as hygroscopic water (Haman and Izuno 2003). The hygroscopic water is chemically bound to soil particles by adhesive forces.

Soil water dynamics

Optimal citrus production requires maintaining soil water content above 25 to 33% depletion of ASW during the period from February to May to avoid potential adverse effects of water stress on flowering and fruit set (Koo 1969). However, during the remaining part of the growing season, ASW can be allowed to deplete by 50 to 67% before replenishment of the soil water back to field capacity (Fares and Alva 2000; Morgan *et al*. 2006). Irrigation scheduling is based on the evaluation of ASW and as such, soil water content should be continuously monitored through the growing season.

Measurement of soil water content

There are direct and indirect soil water content (θ) measuring methods. The thermo-gravimetric method is the most known direct method of soil water content measurement. However, there are several indirect soil water content measuring methods including neutron scattering, electrical resistance, Time Domain Reflectometry (TDR), and capacitance probes. Extensive details can be found in Dane and Topp (2002) about these different soil water content measuring methods. However, brief description is given to some of these methods and devices used to measure soil water content.

The thermo-gravimetric method determines the water content by removing it from a given volume through heating at 105°C for 24 to 48 hrs. It is considered as the most accurate method of soil water measurement; its accuracy depends on sampling procedure and handling of the samples. For example, the soil samples should be sealed off right after collection to avoid water loss due to evaporation and transported to lab for further steps. Water should not be dripping from the samples in case of the saturated/we conditions. This method is not used for scheduling irrigation at large farm scale because of the large number of the required samples and the time it takes. It is not suited for frequent sampling as it is destructive and for rocky and gravelly soils because of the stone fraction involvements (Fares *et al*. 1997).

Most early indirect measurements of the water content were made with neutron moisture meters, often referred to also as neutron scattering (NS). First introduced in the 1950s (e.g., Gardner and Kirkham 1952), NS proved to be very popular as a research and teaching tool within the scientific community, and also for application to a wide range of practical agricultural (i.e., irrigation scheduling), environmental, and engineering problems. Its widespread use resulted partly from the ease and speed of measurement and the nondestructive nature of its water content measurement as compared with conventional gravimetric methods. A NS device generally consists of a probe containing radioactive source that emits high energy fast neutrons, a detector of slow neutrons, and a scaler to electronically monitor the flux of slow neutrons (Hignett and Evett 2002). When the fast neutrons encounter hydrogen nuclei in the surrounding soil, they are slowed down or thermalized. Most of the hydrogen in the soil is associated with soil water. The electronic scaler is used to measure the number of thermalized neutrons which is proportional to the soil water content. Over the years, many NS calibration equations have been proposed (e.g., Allen and Segura 1990; Corbeels *et al*. 1999). One of the first guides on how to use the neutron probe was written by Greacen *et al*. (1981); recent guides were also published by Hignett and Evett (2002) and by the IAEA (2003).

Since the release of the first prototype, the NS methods has seen several improvements such as weight and size reductions and the introduction of more efficient detectors that also used safer radioactive sources. However, despite these improvements, safety regulations requiring costly licensing and training of users and considerable regulation have caused the NS method to remain expensive to maintain and difficult or impossible to use in some situations, particularly it may not be left unattended for automatic monitoring (Evett 2000).

A considerable advancement has been made in TDR method during the past two decades (Heathman *et al*. 2003). The TDR method measures in-situ profile soil water content from soil dielectric constants. A TDR unit consists of a pulse generator, a sampling head, and an oscilloscope to record voltage amplitudes and transit times (Rhoades and Oster 1986). The TDR measured dielectric response (ϵ) is calibrated to the θ_V. For this, a calibration curve is constructed relating θ_V and ϵ. The form of this curve for a wide range of mineral soils (Topp and Davis 1982) is as follows:

$$\theta_V = -5.3{*}10^{-2}\ 2.91{*}10^{-2}\,\epsilon - 5.5{*}10^{-4}\,\epsilon^2 + 4.3{*}10^{-6}\,\epsilon^3$$

Soils with high organic content or high clay content may need a unique calibration curve for each soil series or soil type (Kutilek and Nielsen 1994).

The capacitance method for water content estimation was introduced to the scientific community as early as the 1930s (Smith-Rose 1933). However, it was only in the late 1980s that commercial capacitance probe prototypes were developed and tested under laboratory (Dean *et al*. 1987) and field (Bell *et al*. 1987) conditions. During the 1990s several capacitance sensors were commercialized. The capacitance method is now increasingly being used for soil water content measurements for a variety of applications (Fares *et al*. 2004; Thompson *et al*. 2007) including citrus irrigation scheduling (Fares and Alva 1999, 2000; Morgan

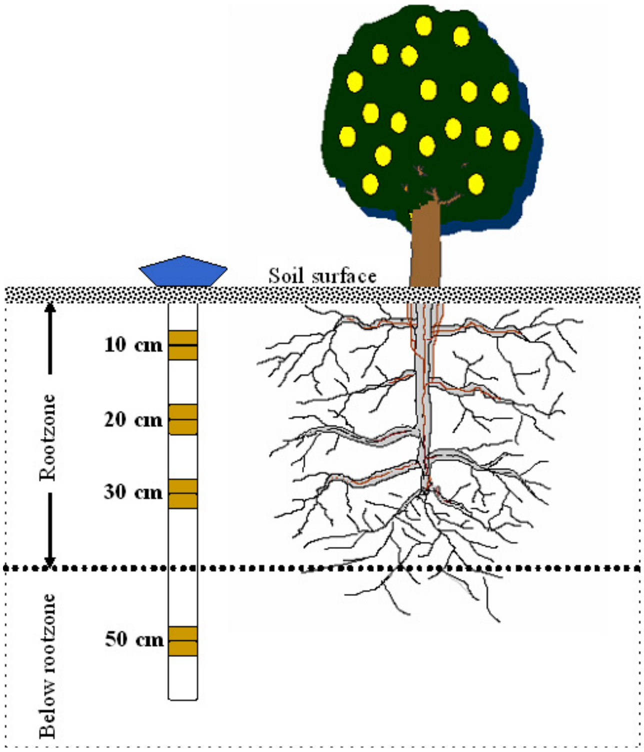

Fig. 1 A Schematic representing a multisensor capacitance probe installed near a citrus tree. The sensors are shown at 10, 20, 30, and 50 cm depths.

et al. 2006; Fares *et al.* 2008b). In addition to the manufacturer's calibration, capacitance systems have been calibrated in the laboratory (Baumhardt *et al.* 2000; Fares *et al.* 2007) and under field conditions (Morgan *et al.* 1999; Fares *et al.* 2004). A description of the different capacitance systems, and their principles of operation are given by Fares and Polyakov (2006).

Capacitance soil water sensors operate at a narrow band frequency and use dielectric constant of soil–water–air mixture to estimate soil water content. Water molecules, being permanent dipoles, respond to the electrical field by becoming polarized. The ϵ of water (78.54 at 22°C) is large compared with those of soil matrix (<10) and air (1); thus, a change in soil water content will strongly influence the ϵ of soil–water–air mixture. However, the great variability of the ϵ of soil minerals (6) and soil organic matter (<4) makes it necessary to calibrate these sensors for a particular soil (Baumhardt *et al.* 2000) and, if practical, for each soil horizon. In most cases, the relationship between the capacitance sensor output and volumetric soil water content is a three-parameter power function (Fares *et al.* 2004).

There are a number of capacitance probe designs, which differ from each other by electrode configuration and geometry, range of operating frequencies (50-150 MHz), ease of use and accuracy. Conceptually, capacitance sensor systems can be subdivided into single and multi-sensor systems. They also have different electrode designs: rod, flat, or cylindrical types. Capacitor sensors are either permanently buried at desired soil depths or are inserted into a PVC access tube buried in the soil (Fares *et al.* 2006; **Fig. 1**). Commercially available capacitive sensors are logged with different data loggers at different logging time as short as one second and can be as long as many days. Most of the capacitance probes come with software to display the information as total water content of the selected or all the sensors. These data can be downloaded and converted, using a utility program (Fares and Alva 1997), into spread-sheet for further analysis. The direct water content measuring methods are more accurate (± 0.01 $cm^3\ cm^{-3}$) than the indirect methods of water content measurement (Muñoz-Carpena 2004).

Components of water potential measurement

Soil water potential is an expression of the energy status of water in soil. There are several components of the water potential including mainly, matric potential, gravitational potential and osmotic potential. In the majority of cases, the osmotic potential is neglected except for soils of high salt content (Jury and Horton 2004). Soil water potential is useful for describing the availability of water to plants and the driving forces which cause water movement (Kar and Oswal 2004).

RAINFALL QUANTITY AND DISTRIBUTION

Rainfall is vital for any agriculture production system under arid and semi-arid conditions. Rainfall is expressed as equivalent depth (mm or inch). It is characterized by its total amount over some period (daily, monthly, yearly), intensity (depth per unit time), and its spatial and temporal distribution. In many humid and tropical locations, annual rainfall is higher than the evapotranspiration; therefore, the crops need to be irrigated for optimal production.

Although Florida citrus production areas average around 1300 mm of rain annually, supplemental irrigation is still required for intensive citrus production because: (1) rainfall is irregularly distributed, with 70% of the annual amount occurring during the summer months; (2) the water holding capacity of Florida's sandy soils (>96% sand) is extremely low and (3) intensive citrus production requires maintenance of soil water content near field capacity especially during the flowering and fruit setting period which coincides with the dry period of the year (Fares *et al.* 2008b).

Before reaching the soil surface, some or all of the rain may be intercepted by the canopy of the citrus tree and/or weed species covering the row middles; thus, irrigation scheduling needs to account for this canopy interception as it might substantially impact our local hydrologic budget calculations. Li *et al.* (1997) reported that neither "Marsh" grapefruit nor "Hamlin" orange tree canopies significantly influenced rainfall distribution in the edge between the irrigated and the non-irrigated area. Alva *et al.* (1999) studied rainfall and soil moisture distribution under "Valencia" citrus trees as affected by canopy interception and found that the canopy intercepted 21 to 53% of incident rainfall, which consequently altered soil water distribution substantially.

Fares *et al.* (2008b) evaluated rainfall interception by a citrus canopy and its effect on effective rainfall (ER) estimation. Soil water content was monitored every 30 min at 10, 20, 40, and 80 cm depths in the rootzone both under and outside of citrus tree canopies. Micro-irrigation, rainfall and weather data were used to calculate effective rainfall, plant water uptake, and deep drainage. They found that tree canopy intercepted 35 and 50% of the incoming high (≥ 5 mm) and low (< 5 mm) intensity rainfalls, respectively. Effective Rainfall (ER) calculated without accounting for the canopy interception effect was overestimated by about 30 and 5% for the dry and wet periods, respectively.

Some portion of the canopy interception may reach soil as stemflow (a concentrated flow through tree trunk). Brooks *et al.* (2003) reported that stem flow is usually less than 2% of gross annual precipitation. Crockford and Richardson (2000) stated that accurate measurement of stemflow is very difficult so that in some studies it was not measured, e.g. Liu (1997). Asdak *et al.* (1998) found stemflow to be 1.4% in an unlogged plot in a rainforest in Indonesia. The low stemflow values for tropical rainforests probably result from a combination of high rainfall intensities and a large leaf area index (LAI). Citrus trees have high LAI and Florida has generally high intensity rainfalls, therefore the stemflow of citrus trees in Florida is expected to be considerably low.

Effective rainfall (ER) is defined as the portion of rainfall that plants use to meet daily evapotranspiration requirements (USDA 1970). Some of the rainfall may be unavoidably lost due to the combined effect of rainfall intensity, frequency, and amount. Effective rainfall varies along with total rainfall. Water regulating agencies require accurate estimates of crop water budget components in order to fairly allocate irrigation water resources to growers. Effective rainfall is an important component of the irrigation requirement calculations.

The USDA Technical Release No. 21, known as TR-21 (USDA 1970), has been widely used to estimate ER and predict irrigation requirements. Improvement in real-time soil water monitoring sensors provided a good opportunity to test the accuracy of TR-21 estimation. Obreza and Pitts (2002) developed a spreadsheet soil water budget model to calculate daily water table upflux, soil water storage, plant water uptake, drainage, and effective rainfall for the irrigated and non-irrigated rootzones of citrus groves. However, their model did not include canopy interception loss, which is one of the major components of the water budget of crops with sizeable canopy. The canopy of intensive-production citrus orchards covers, on average, half of the land area. Ignoring canopy interception may result in overestimation of the ER due to erroneous higher rainfall input. Therefore, canopy interception should be included to improve the accuracy of irrigation requirements (IRR) and ER estimations for the water resource allocation to citrus growers.

Fares *et al*. (2008b) reported the influence of canopy interception on ER and drainage by developing a model that estimates all water budget components including tree canopy interception. For instance, without accounting for the canopy interception effect, calculated ER and drainage were overestimated by 12 and 97%, respectively. Since this Florida Candler fine sand has a very low water holding capacity, overestimation of ER was relatively less than with a soil with a much higher water holding capacity. Under such conditions, drainage would have been reduced and ER would have been much higher. The overestimation of ER results in an underestimation of irrigation requirements. This in turn might result in inadequate water allocation for citrus growers. Overestimation of ER in dry seasons was higher than in the wet seasons. Measured and calculated water contents with and without the interception effect showed a similar correlation due to the low soil water holding capacity which causes a low ER. Seasonal variations in ER demonstrated that the canopy interception effect was less significant in the wet season than that in the dry seasons.

IRRIGATION TECHNIQUES

Surface, sprinkler, and drip irrigation are among the major irrigation methods used in citrus production. A brief overview of these irrigation methods is given below.

Surface flooding and sub-irrigation

Despite their low water delivery and application efficiencies, surface irrigation methods (basin, furrow, and flood irrigation) are still used to irrigate citrus orchards in the developing world. This method is best suited for fine or medium textured soils. Surface irrigation was common for citrus on the east coast and southwest of Florida. Most soils in these regions are poorly drained with impervious soil horizon within 90 to 120 cm depth. The most obvious and critical disadvantage of this method is the large volume of water required as compared to other irrigation methods. The average efficiency of surface flooding irrigation is 50% which is low compared to other low volume irrigation systems described in the following sections.

Sprinkler irrigation

This method includes overhead and micro-sprinkler systems where water is applied by spraying it through the air at high and low volumes, respectively. These systems are designed to apply water uniformly, as drops, over the application areas. Overhead sprinklers were popular before the introduction of the micro-sprinkler and drip irrigation systems in the major citrus production areas, i.e., Florida and California. The introduction of sprinkler irrigation systems allowed the use of non-uniform terrains and saved substantial amounts of irrigation water as a result of their higher efficiency as compared to traditional irrigation practices (i.e., basin, furrow or flooding). However, their major disadvantages are: i) their low efficiency in windy conditions and during hot periods due to water loss by evaporation and by evaporation drift, ii) leaf damage of citrus crops as a result of irrigation water spraying, and iii) their high visible application rates that instigate public criticism of agricultural operations as a source of excess water use.

Under-tree micro-sprinklers systems operate at low volumes when compared to overhead sprinkler systems and over shorter intervals to maintain soil water at an adequate level for optimum growth. Mini-sprinklers are used to irrigate citrus nursery and young plants. Their advantages include: i) a higher beneficial use of available water, ii) increased crop yield, iii) decreased energy requirement, iv) limited weed growth, and v) chemical injection of fertilizers and pesticides. However, their major disadvantages are i) clogging of emitters, ii) salinity buildup, and iii) restricted soil water distribution in the rootzone. Rodney *et al*. (1977) and Roth *et al*. (1978) reported that the growth rate of young ‘Campbell Valencia’ trees irrigated with pressurized systems was greater than that of the trees irrigated with the traditional flood systems.

Drip irrigation system

Drip irrigation is a low volume irrigation method that applies water through small emitter openings. A drip system can be laid at the soil surface, above it or buried at a given depth below it. This irrigation system aims at watering the crops frequently to meet consumptive use of the crops. Drip irrigation method is being adapted extensively as water resources are becoming scarce in many agricultural production regions around the world. If designed accurately and used properly, drip irrigation is one of the most efficient irrigation method that minimizes deep percolation, runoff and evaporation losses (Fares *et al*. 1997). Aljibury *et al*. (1977) reported that in California, the fruit yield of ‘Navel’ orange trees on trifoliate rootstock remained the same after the conversion of irrigation method from furrow to drip irrigation. Drip irrigation system is considered a water saving system with high irrigation application efficiency. In addition to the advantages of the micro-sprinkler irrigation system, drip irrigation has the following additional advantages: 1) its efficiency is not impacted by wind, and 2) it can be used with low quality irrigation water.

IRRIGATION SCHEDULING TECHNIQUES

In addition to the traditional visual symptom method, there are other approaches that have been used to determine the proper timing of irrigation (Koo 1975). Irrigation requirements and water use by mature citrus trees have been investigated by several researchers (Koo and Sites 1955; Koo and Hurner 1969; Hoffman *et al*. 1982; Jones *et al*. 1984; Smajstrla *et al*. 1986). Scheduling of citrus irrigation can be based on visual symptoms, water budget calculation, plant water stress, and soil water status. Any of these methods answers the two questions of when to irrigate and how much to irrigated. The goals are i) to start irrigation when the depletion level of the ASW has been reached, and ii) to stop the irrigation when the average water content in the rootzone reaches field capacity. Common irrigation scheduling methods are discussed below.

Visual symptoms

This is the most traditional irrigation scheduling method where growers rely on the appearance of wilting symptoms as an indication of citrus triggering irrigation. However, many crops do not show consistent visual symptoms of low moisture stress until the crops suffer severe stress effects. Furthermore, the soil water status may change rapidly so that watering may be required before growers/crop manager notices visual symptoms. Growth processes slow down or in some cases cease in many crops before visual wilting occurs, thus by the time symptoms for irrigation needs appear, yield reduction might already have occurred (Smajstrla *et al*. 1997).

Checkbook method

This method requires accounting for all water inputs, i.e., rainfall and irrigation and outputs, i.e., evapotranspiration, runoff, and excess water lost below the rootzone as drainage. Changes in soil water content are calculated for a given time interval using the water mass balance equation:

$$S = P + I - D - ET - RO$$

where S is the soil water storage in the rootzone, P is the rainfall, I is the irrigation, RO is the surface runoff, ET is the evapotranspiration, and D is the drainage below the rootzone. Daily monitoring of the soil water balance of a field involves monitoring the growth of the crop and its ET, rainfall received and/or irrigation applied to the field. A daily ET value can be estimated from historical data or using any other ET estimation method, i.e., crop water use table. Irrigation is scheduled when the soil water storage in the rootzone is near the allowable depletion level.

This method requires daily values of its input parameters which can become time consuming for multiple fields and locations. However, one of its advantages is that it has been implemented in different computer programs to handle the accounting and provide timely and quick scheduling recommendations. Accuracy of these programs depends on the specificity and reliability of the data input. Fares *et al*. (2004) developed an irrigation scheduling program for citrus, TheHelper, to produce short- and long-term citrus irrigation schedules under different soil types that the user chooses from a menu driven package. The input parameters to this program are historical weather data, soil physical properties and crop rootzone depths. The user chooses model inputs from different menus provided on the model interface.

Weather monitoring method

This method involves measuring evapotranspiration as it represents the net loss of water from the plant and soil surface. There are various methods commonly used to determine or measure evapotranspiration. Lysimeters are usually used to measure evapotranspiration for different field crops. Lysimeters are tanks filled with soil in which crops are grown to measure the amount of water used by the crop. Water use data obtained from lysimeters are reliable provided the lysimeters are constructed, installed and operated so as to be representative of the areas to which the results are to be applied.

Advancements in the field ET measurement have been significant during the past three decades. Now, there is a choice of models based on data type and quality, and suitability of field conditions. Watershed models use different ET submodels (Penman 1948; Priestly-Taylor 1972; Thornthwaite 1948). Penman's (1948) mathematical model combines the vertical energy budget with horizontal wind effects. The ET calculation/measurement has been determined using one of the following methods: i) water budget (Fares and Alva 2000), ii) mass-transfer (Harbeck 1962), iii) combination (Penman 1948), iv) radiation (Priestley and Taylor 1972), and v) temperature based (Thornthwaite 1948). Detailed information on many of these methods is available in the literature (Jensen *et al*. 1990; Morton 1994). Penman model improvements and adaptation were made by many researchers by including the direct net radiation estimates, improved wind profile theory and effect of plants (Monteith 1965; Rijtema 1965). The Penman-Monteith model is probably the most suitable ET model for watershed studies, particularly in tropical islands where high intensity winds have significant effect on ET.

The Penman-Monteith (Penman 1948) approach includes all parameters that govern energy exchange and corresponding latent heat flux (evapotranspiration) from uniform expansion of vegetation. It calculates evapotranspiration ($m\ h^{-1}$) as follows:

$$\lambda ET = \frac{\Delta(R_n - G) + \rho_a C_p \dfrac{(e_s - e_a)}{r_a}}{\Delta + \gamma\left(1 + \dfrac{r_s}{r_a}\right)}$$

where R_n is the net radiation ($MJm^{-2}\ h^{-1}$), G is the soil heat flux ($MJm^{-2}\ h^{-1}$), (e_s-e_a) is the vapor pressure deficit of the air (kPa), ρ_a is the mean air density at constant pressure (kg m^{-3}), C_p is the specific heat capacity of the air ($MJm^{-3}\ °C^{-1}$), Δ is the slope of saturation vapor pressure temperature relationship times air pressure (kPa $°C^{-1}$), γ is the psychometric constant (kPa $^{o}C^{-1}$), λ is the latent heat of vaporization (MJm^{-3}), and r_s and r_a are surface and aerodynamic resistances ($s\ m^{-1}$), respectively.

Soil water status

The status of water in soils is expressed as either water potential or water content. Soil water status is one of the most widely used irrigation scheduling method. Fares and Alva (2000) optimized irrigation scheduling for young citrus trees in Florida using multi-sensor capacitance probes (MCP). The soil water content through the soil profile was monitored in real-time using three MCPs each of which had five sensors at 10, 20, 40, 70, and 110 cm depths. The MCPs were installed within the emitter wetting area under canopy along the tree drip line of randomly selected trees. The first three sensor depths represent the depth of tree rooting, while the last two depths represent the soil profile below the rooting depth. Soil water content data were logged at 10 min intervals with a data logger. Irrigation and rainfall were also monitored throughout the study period. They maintained the soil water content above the 33% depletion of the ASW during the period from February to May to avoid potential adverse effects of water stress on flowering and fruit set. However, during the remaining part of the growing season, ASW was allowed to deplete by 67% before replenishment of the soil water back to field capacity. Each irrigation event delivered the adequate amount of water to replenish the deficit in the top 40 cm of the soil profile to field capacity.

Results of their study demonstrated that monitoring of soil water using capacitance probes can be used to optimize irrigation scheduling for citrus groves on a sandy soil. Given the knowledge of soil water characteristic curves, effective rooting depth, and recommended depletion of ASW content depending on the crop growth stages, the rootzone soil water can be replenished to its optimum level while minimizing drainage and avoiding plant stress. Furthermore, they used the data provided by the MCPs to calculate two of the major daily components of this citrus grove water balance, e.g., evapotranspiration and drainage. They found that annual evapotranspiration and drainage were 920 and 890 mm, respectively.

Paramasivam *et al*. (2000) monitored redistribution and depletion of soil water in a commercial citrus grove grown in Tavares fine sand in Florida using tensiometers. Tensiometers were installed at 15-, 30-, 90-, and 150-cm depths in five clusters along the dripline of 25-year-old Hamlin orange trees on Cleopatra mandarin rootstock. Irrigation was scheduled when the soil water potential at the 15- and 30-cm depths exceeded either -10 KPa (Jan. to June) or -15 KPa

(July to Dec.) to replenish the water deficit (below field capacity) in the top 90 cm of the soil profile. The tensiometers installed at 15- and 30-cm depths responded to changes in soil water regardless of irrigation or rainfall. Tensiometer readings were used to estimate the water content at corresponding depths using the van Genuchten analytical relationship equations. Total soil water contents within the rootzone (0 to 90 cm) and below the rootzone (90 to 150 cm) of the monitoring depth (0 to 150 cm) were also calculated to estimate the water available for the trees and water that drained below the rootzone.

There are several difficulties in using tensiometers in the field to determine soil water suction. Tensiometers are sensitive to temperature gradient between their various parts; thus, the above-ground parts should preferably be shielded from direct sun light. The contact between the tensiometer cups and the soil affects equilibration between soil water and tensiometers water, which is important for proper functioning of the tensiometers. Despite their shortcomings, tensiometers are practical instruments that provide reliable data on the in-situ water potential. To ensure their reliability, more than one tensiometer should be installed at the same plane for a given soil depth.

Determining the appropriate amount of irrigation

After determining the time of irrigation, the next step in the irrigation scheduling program is to determine how much water to apply through the irrigation system to replenish the depleted water and under semi-arid and arid conditions additional irrigation for leaching requirements to avoid salt build up in the rootzone. Thus, the gross irrigation requirements, GIR, are calculated using the following equation:

$$\mathrm{GIR} = \frac{ASW \bullet DL}{(1-\mathrm{LR})-f_i}$$

where ASW is the available soil water (mm), DL is the depletion level, f_i is the efficiency of irrigation method (e.g., 85 and 50% for drip and flood, respectively) and LR is the leaching requirement to avoid salt built-up in the rootzone.

Fares (2008) developed a site and crop specific, variable scale, GIS-based water allocation decision support system, GIS-IManSys. GIS-IManSys uses the capabilities of GIS (ArcGIS 9.2, ESRI) to integrate the Irrigation Management System (IManSys) software and different spatially variable weather, soil and crop databases., e.g., daily rainfall and evapotranspiration, soil physical and hydrological properties, irrigation system characteristics, and crop parameters. The GIS-IManSys has the following capabilities: i) spatially variable scale from a portion of a field to an entire region, i.e., island, ii) it can be easily adapted to different locations and crops around the world although currently it has data for only Hawaii and 40 crops, iii) results of the analysis are presented as text data or GIS maps at different frequencies (from daily to yearly).

Based on a daily mass balance approaches (following equation), IManSys uses long-term historical daily rainfall, evapotranspiration, irrigation systems specification, soil physical and hydrological properties and crop parameters to calculate daily, weekly, biweekly, monthly and yearly gross irrigation requirement (GIR), which also called irrigation water allocation. In addition, IManSys calculates all the other water budget components at the same frequencies of those of IRR cited above. IManSys calculates the crop irrigation water demand as follows:

$$GIR = \frac{ET_{crop} + \Delta S + Dr + RO + CI - R - Ge}{(1-LR).fs}$$

where ET_{crop} is the crop evapotranspiration, R is gross rainfall, CI is the canopy interception, DR is the excess drainage below the rootzone, RO the is surface runoff, Ge the is groundwater contribution, fs is the efficiency of irrigation method (e.g., 85 and 50% for drip and flood, respectively) and LR is the leaching requirement to avoid salt built up in rootzone. All terms are in mm.

GIS-IManSys has an excellent user-friendly graphical interface with a help menu that defines the input parameters and their appropriate values for different crops using a dropdown menu. A customized version of GIS-IManSys is currently used by the State of Hawaii Commission on Water Resource Management to help determine water allocation to different water users across the state. This model was calibrated and validated for different crops as compared to published data, i.e., the USDA-NRCS Handbook 38. A close agreement was observed between the estimates of the two techniques.

Citrus irrigation water requirements

Irrigation requirements and other water budget components for citrus grown at the University of Hawaii's Waimanalo Agriculture Research Station, Oahu, Hawaii (21° 20′ 15″ N; 157° 43′ 30″ W) were simulated with GIS-IManSys. The long-term average precipitation at Waimanalo is 938 mm yr^{-1} most of which occurs between November and April. Mean annual soil temperature is 23°C. The soil at this location is classified as Waialua gravelly clay variant (*Isohyperthermic Pachic Haplustolls*). This soil has 2 to 6 percent slopes and is similar to Waialua clay variant except the presence of common weathered gravels throughout its profile. Citrus crop parameters including minimum and maximum citrus root depths (Noling 2003), maximum leaf area index (Cohen *et al*. 1987), monthly values of crop coefficients (Petillo and Castel 2007), and those of allowable water dep-

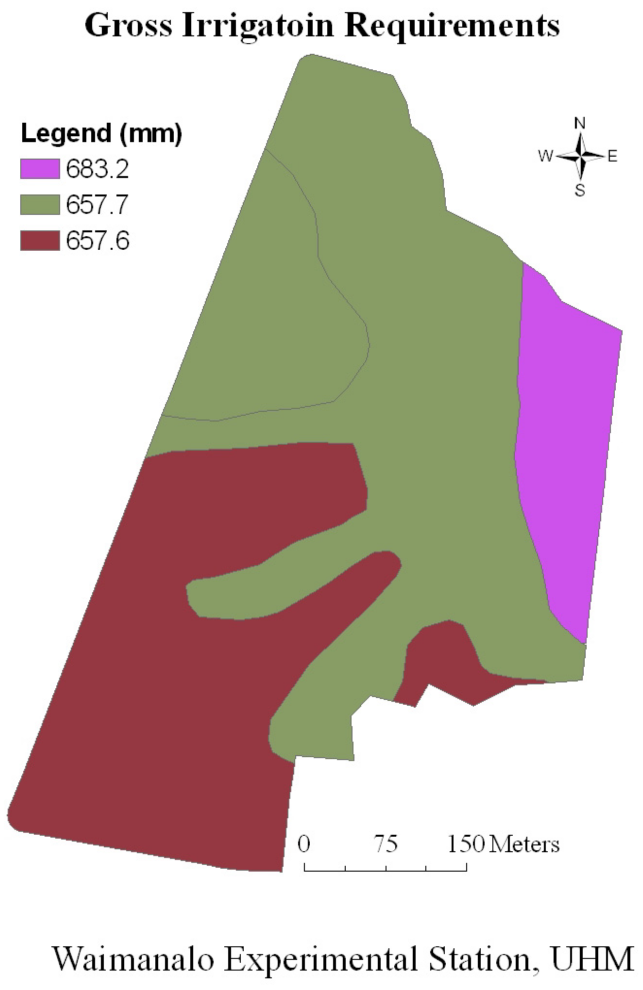

Fig. 2 Spatially distributed gross irrigation water requirement for citrus grown at the University of Hawaii's Waimanalo Agriculture Research Station, Oahu, Hawaii (21° 20′ 15″ N; 157° 43′ 30″ W) calculated using GIS-IManSys based on long-term weather data and site specific crop and soil parameters.

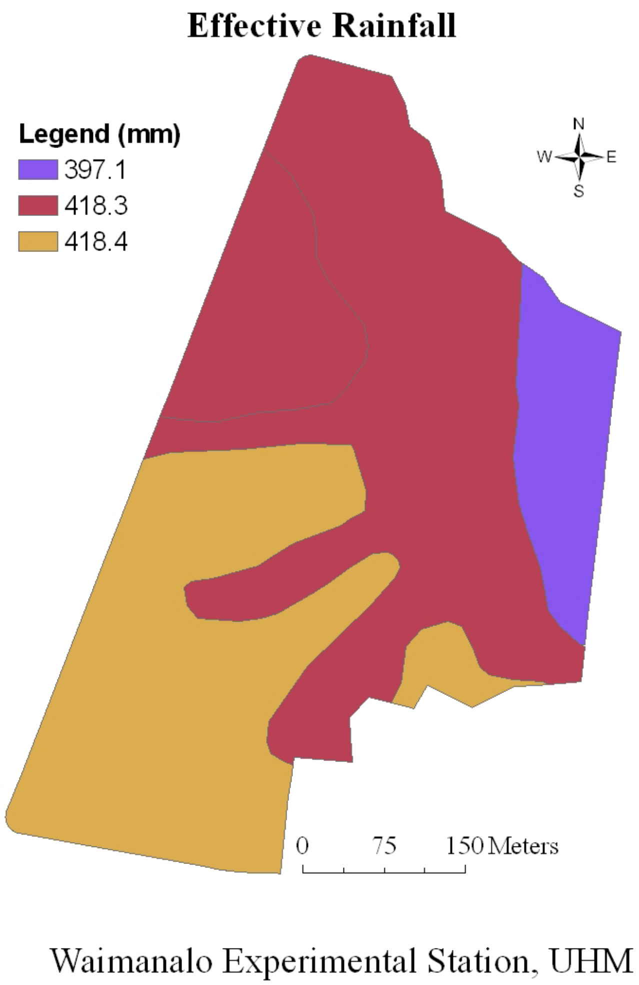

Fig. 3 Map of effective rainfall calculated for a citrus grove at the University of Hawaii's Waimanalo Agriculture Research Station, Oahu, Hawaii (21° 20′ 15″ N; 157° 43′ 30″ W) based on long-term rainfall data and citrus crop parameters and calculated using GIS-IManSys.

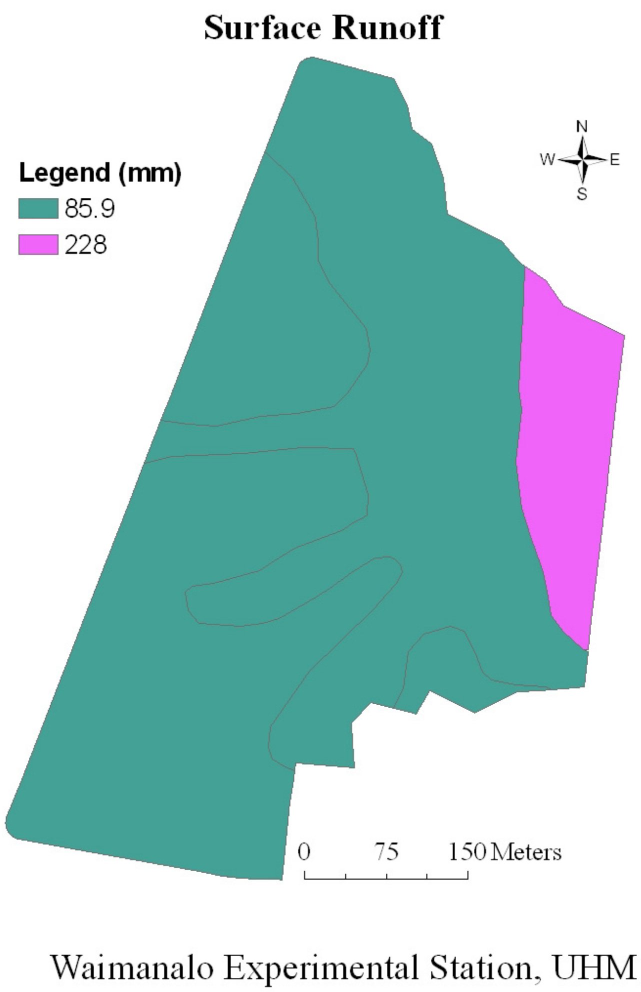

Fig. 4 Map of surface runoff calculated using the United States-Department of Agriculture- NRCS curve number method implemented in GIS-IManSys and based on site specific long-term rainfall from a citrus grove at the University of Hawaii's Waimanalo Agriculture Research Station, Oahu, Hawaii (21° 20′ 15″ N; 157° 43′ 30″ W).

letion (Parsons and Morgan 2008) were collected from literature. 'Drip irrigation' and 'irrigate the crop to field capacity' were chosen as the irrigations system and irrigation practice, respectively. Model simulation produced spatially distributed gross irrigation data (**Fig. 2**) and maps of the major water budget components including effective rainfall (**Fig. 3**), and surface runoff (**Fig. 4**). Knowledge of the reliable estimates of spatially distributed gross irrigation requirements in a given area is of great importance for optimizing water management practices, and thus crucial for managing efficient irrigation scheduling in citrus cultivation.

NEED FOR FUTURE RESEARCH

Increasing demands on our limited water supplies combined with substantial increases in energy costs and fertilizers are major incentives for agriculture to optimize water and nutrient use, lower its production costs to stay competitive and also protect our natural resources. Optimum irrigation scheduling is a key practice that can help meet these goals. The last decades show sharp increase in the numbers of soil water, weather and plant stress monitoring sensors that have been recommended for improving irrigation management. Irrigation scheduling research priorities are recommended to rigorously evaluate these new devices under different cropping systems and edaphic conditions. Further studies of the spatial variability of soil physical, chemical and hydrological conditions and their impact on plant water and nutrient uptake, and excess losses are expected to further develop as the role of precision agriculture increases. There is an urgent need for smart irrigation scheduling methodology; such operations would require integrating various sensing technologies into irrigation scheduling models and controls. There is a need to further investigate the economical impact of citrus irrigation scheduling. Site specific on-farm citrus irrigation scheduling demonstration trials along with strong outreach program would help in the adoption of these important practices.

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