**INSTITUTIONS FOR SUSTAINABLE WATERSHED MANAGEMENT: RECONCILING PHYSICAL
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REAL-TIME SOIL WATER MONITORING FOR OPTIMUM WATER MANAGEMENT

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ABSTRACT: Effective and efficient water resource management is undoubtedly one of the most important policy issues facing agriculture in Hawaii in the years ahead. Substantial amount of water could be saved through optimizing plant water uptake and minimizing excess water losses below root zones. Capacitance sensors have been successful in monitoring water content at multiple depths and at different locations in near real-time. The objectives of this work are to use real-time data from capacitance sensors to: i) determine field soil physical properties, i.e., soil hydraulic conductivities and soil water holding capacity; ii) determine irrigation scheduling setting points, i.e. full points and refill points. Six capacitance probes were used to monitor the soil water content in real-time (every 10 minutes) across the field. Each probe has four soil moisture sensors that monitor the water content at 10, 20, 30 and 50 cm below the soil surface. Soil hydraulic conductivity at 10 and 40 cm was determined across the field. Rain and irrigation were also monitored during the period of the study. Among the three investigated tomato plant varieties, Toro variety treatment had lowest water content in all investigated soil depths compared with the two other treatments. This variety seems to have higher water uptake than Ruby and Atila F1 varieties.

INTRODUCTION

When written history began, irrigation has been a well-established practice since the dawn of civilization (James, et al., 1982). Today, irrigation is one of the most dynamic issues in the world of agriculture due to its function to optimize agricultural yield, especially in the water resource limited areas. In fact, some parts of the world are facing water shortage. In some cases, water shortage is so severe that basic human needs, such as drinking and showering can not be satisfied. Shortage of water is one of the most limiting factors in crop production worldwide.

In the United States, irrigation remains the largest user of freshwater with total 137 billion gallons day⁻¹ for the year 2000, which represent about 65% of total fresh water withdrawals. In the State of Hawaii, irrigation is leading in water usage with more than 60% of fresh water was used for this purposes in the year 2000 (Hutson et al., 2000). Concurrent with the agriculture extension and intensification in the future, the water withdrawals for agriculture are predicted to increase.

As fresh water resources become scarce, the efforts to preserve fresh water resources should be intensified by optimizing water use and reducing water waste. When water is applied on the soil surface, assuming little or no surface runoff, a portion of water is utilized by plants or retained in the soil, and the excess water drains through the vadose zone into the ground water which contributes to aquifer recharge. This excess water may contain agricultural chemical or soluble nutrients (Fares and Alva, 2000a). Better irrigation scheduling does not only reduce the production of the crops of interest cost but also minimize economic losses due to effects of under and over irrigation. In order to achieve the maximum benefit of irrigation, it is essential to quantify the effects of soil, climate, and crop factors on the amount and timing of irrigation (James et al., 1982). A commonly encountered problems related to any irrigation system is the way to determine the timing and duration of irrigation events (Fares and Alva, 2000b). Most often, growers assess the time to irrigate by considering the visual crop responses. Such visual assessments frequently correspond to levels of water stress that may affect the plant growth adversely. Moreover, the dynamic of soil moisture can change so rapidly that watering may be required before growers notice the visual symptoms (Fares and Alva, 2000b).

During plant growing season, the availability of water is critical. The impact of soil moisture deficit on plant growth and production is closely related to crop growth stages. Usually, in the period of flowering and fruit enlargement, plants are more

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sensitive to moisture deficit than other growing periods. While in period of ripening, less water is needed. Additional water is necessary if the frequency and intensity of precipitation is inadequate to meet the water crop requirement (Holzapfel et al. 2004). Non-uniformity of rainfall is also the reason for using supplemental irrigation (Fares and Alva, 2000b).

The main objectives of this work are: i) determine field soil physical properties, i.e., hydraulic conductivities and soil water holding; ii) determine irrigation scheduling setting points, i.e. full points and refill points.

Irrigation management in agriculture

The growers are expected to harmonize amount of water applied and crop water demand through continuous monitoring of available water. Maintaining adequate soil water content through most growing period is necessary to support optimum plant growth and yields. By continuous measurement of soil moisture levels, the desirable upper and lower limits of water availability in the soil profile can be determined, available soil moisture is determined as the different between the water content at field capacity and permanent wilting point.

Field capacity is defined as the water content at which internal drainage become essentially negligible. Samples subjected to -0.1 and -0.33 bar pressure are used to determine water content at field capacity for coarse/medium and fine-textured soil, respectively. Since no laboratory system is capable of duplicating soil-water dynamics in the field, it is highly desirable to measure field capacity in the field whenever possible (Fares and Alva, 2000b).

Permanent wilting point is defined as the water content at which plants can no longer extract soil water at a sufficient rate to meet physiological demands imposed by loss of water to the atmosphere, and thus irreversibly wilt and die (Or and Wraith, 1999). Determination of water content at permanent wilting point is based on laboratory measurement of water content of a soil sample that subjected to -15 bars matric potential. Plant-available soil water storage is an important factor in the determination of irrigation scheduling. For practical purposes, irrigation amounts in excess of field capacity are lost to deep percolation, and thus, should be avoided (Or and Wraith, 1999).

Maintaining optimal soil moisture content in the soil can be difficult without continuous monitoring of the soil moisture status (Alva and Fares, 1998). Multisensor capacitance probe is an effective apparatus for in-situ soil water content measurement. Multisensor capacitance probe measures the dielectric constant of the soil-water-air mixture. This apparatus works based on the difference of dielectric constant of water, soil and air. The dielectric constant of water (80) is large compared to those of the soil matrix (<10) or air (1). Any changes in water content will influence the dielectric of the soil-water-air mixture that is measured by capacitance probe (Fares and Alva, 2000b). Soil type and frequency range of the measuring apparatus are the main factors that may influence the relationship between the change in water content and the dielectric constant. The Sentek EnviroSCAN capacitance probe used in this study was developed by Sentek PTY Ltd. (Environmental Innovations, Kent Town, South Australia). It has been used by growers and researchers as a tool to monitor soil water content as basis for irrigation of several annual and perennial crops in Australia and North America (Buss, 1993)(Alva and Fares, 1998).

These sensors work at an operating frequency in excess of 100 MHz to overcome interfacial polarization effect including salinity, which affect most of the capacitive-based measuring devices (Dean et al. 1987; Fares and Alva, 2000b). A calibration curve of the measured electrical values against volumetric content is generally a power function for the majority of the soil (Mead et al. 1995; Fares and Alva, 2000b).

Tomato in Hawaii

The tomato, *Lycopersicon lycopersici*, is the number one vegetable crop in Hawaii in terms of popularity and market value (Valenzuela et al., 1993). Tomatoes led all individual vegetables and melons in farm value with a record high \$10.2 million in 2003, a 5%-increase from 2002 (Hudson, 2004). As a member of the family Solanaceae, tomato is a native of Central and South America (Valenzuela et al., 1993).

The tomato is a self-pollinated crop. Flowers are located on the stem between nodes, they are borne in clusters. Most of the tomato varieties are sensitive to high night-time temperatures, which may lead to lower fruit set or smaller fruit size. The optimum temperature for fruit set is around (15-20°C) (Valenzuela et al., 1993).

The optimum pH is 6.0-6.5, therefore liming is needed in the acidic soil (Valenzuela et al., 1993). The application of fertilizer should be based on the crop nutrient demands, stage of crop growth and amount of nutrient that already exist in the soil. Excessive fertilizer application beyond crops needs may result in salt buildup, phytotoxic effects on plant growth. In terms of nitrogen fertilizer, to obtain a yield of over 100 ton ha⁻¹, a tomato plant had to absorb about 100 mg N day⁻¹, and the optimum nutrient concentration should be around 140 ppm N (Asian Vegetable Research and Development Center, 1979). Phosphorus in combination with N and K improves peel and pulp coloration, taste, hardness, vitamin C content and hastens maturity. Adequate calcium supply is necessary to prevent blossom-end rot in tomatoes (Valenzuela, 1993).

In Hawaii, tomatoes are best grown year-round at 1,000-3,000 ft (300-1,000 m) elevation, from March through August at 3,000-4,500 ft (1,000-1,500 m), and from September through May from sea level to 1,500 ft (500 m) (Valenzuela, 1993). Plowing is needed if the soil seems compacted. Bedding, fertilizing and fumigating may also be conducted at pre-planting.

A study on the root distribution of mature tomato plants grown in a sandy loam soil under furrow irrigation, through soil-block washing method by Spencer (1950) resulted that nearly 75% of the tomato vertical root distribution was concentrated in the top 40cm of soil. Therefore, monitoring soil moisture dynamics in the top 40cm of the soil is necessary to establish tomato best irrigation management.

In Hawaii, drip irrigation is popular because of its efficiency of water use and its ability to allow the application of fertilizers and pesticides with the irrigation water (Valenzuela, 1993). This irrigation system enables tomato farmers to synchronize the application of water and nutrient rates with the corresponding stage of crop development.

MATERIAL AND METHODS

The study was conducted at the University of Hawaii-Manoa Poamoho research station, Waialua Oahu, HI, approximately 53 km from University of Hawaii at Manoa campus. The elevation of the site is 116-215m from sea level, with average annual temperature around 20-28°C and 1270 mm of mean annual rainfall. This study was part of a tomato variety trial (*Lycopersicon lycopersici*) grown under drip irrigation on a Wahiawa silty clay soil. This soil series has Ap1 (0-15cm), Ap2 (15-30 cm), B21 (30-40 cm), B22 (40-80 cm), B23 (80-115 cm), and B24 (115-150 cm) horizons (National Cooperative Soil Survey, 1978). Bulk densities range from 1.10-1.30 g cm⁻³ for 0-35 cm depths, permeability ranges from 1.5-5 cm hr⁻¹ for depths of 0-5 cm and 0.6-1.5 cm hr⁻¹ for depths of 5-35 cm. As reported by Gavenda, et al. (1996), soil water release curve data for a typical Wahiawa silt clay loam soil are presented in Figure 1.

Figure 1. Soil water release curves for a Wahiawa soil (Gavenda, et al., 1996)

Soil water contents were investigated under three tomato varieties: Toro, Ruby and Atila F1. Two tomato plants from each variety were selected randomly for soil water content monitoring. Six EasyAg® (Sentek Sensor Technologies) multisensor capacitance probes, two per treatment, were installed to measure soil moisture content at the depth of 10, 20, 30 and 50 cm. Each probe was installed around 15 cm distance from the tomato stem. Two rain gages equipped with a data logger were used to monitor irrigation and rainfall events. Daily and cumulative rainfalls during the study period are shown in Figure 2.

Figure 2. Rain and cumulative rain for the research site

On the site, soil hydraulic conductivity at 10 and 40 cm below the root surface were measured using Guelph permeameter. This instrument is an in-hole, constant head permeameter which employs the Marriott principle. The result of permeability measurement on the site is shown in the following Table 1.

Table 1. Hydraulic conductivity of the study site

Depth	Hydraulic conductivity (cm/sec)
10	0.025
40	0.006

RESULTS AND DISCUSSION

The data presented in Fig. 3 show the real-time rainfall data and the water content at 10, 20, 30 (rootzone) and 50 cm (below the rootzone) in three different tomato variety treatments: Toro, Ruby and Atila F1. The soil water contents across the study area were determined through standard calibration equation from the sensor manufacturer.

The real-time soil water content among the three variety treatments indicated a dynamic content in every soil depth. The data show that in all of the three variety treatments, water contents in 10cm soil depth were lower than those in deeper soil layers. The water contents in the top 10 cm showed more wetting and drying cycles as compared to all the other depths. The water content at that depth varied between 9.1 and 65.8% as a result of water inputs (rain and irrigation), and water losses through soil evaporation, evapotranspiration, deep percolation below the rootzone and occasional runoff as a result of intense rainfall events. The data shows that in all three treatments, the water content fluctuations in all of the monitored soil depths were influenced by the rainfall variation. A large rainfall event that occurred in March, 8th (day of 67th in the year 2005) significantly increased soil water content across the treatments. The surface layers were substantially affected by precipitation compared with the deeper soil layers.

Figure 3. The daily rain and the water content at 10, 20, 30 and 50 cm below the soil surface

The data also showed that water content in each soil depth did not always show similar variation. This tendency probably occurred due to different hydraulic conductivity in each soil depth, as also investigated across this study area. However, the amplitude of water content variation in the deeper soil layers was lower than that at the upper layers. The water content at the 50-cm depth relatively showed less variability over the entire period.

In addition, among the three investigated tomato plant varieties, Atila F1 treatment had higher soil water content in all investigated soil depths compared with the two other varieties. Soil water contents under Toro treatment had the lowest water content in all investigated soil depths compared with the others. With the assumption that soil physical properties, irrigations, rainfalls and evapotranspiration were uniform, these differences in water content dynamics probably occurred due to the corresponding plant water uptake characteristics. Therefore, Toro variety might have higher water uptake than Ruby and Atila F1 varieties.

The water content data at the four depths, 10, 20, 30 and 50 cm were used to calculate the water content in the rootzone and below it. It was assumed that the majority of the tomato roots are in the top 40 cm; thus, the water content data from the top three sensors were multiplied by 15, 10 and 15 cm, respectively, to determine the total water stored in the rootzone (Fig. 4). The “Full point” and “Refill Point” were defined from available soil water release curve data for Wahiawa series, as the water storage in the rootzone, top 40-cm.

Optimum irrigation management practices should ensure that the storage water in the rootzone would vary between “Full point” and “Refill point”. The sensor at the 50-cm depth was used to represent the water content below the rootzone in the zone between 45 and 55 cm below the rootzone (Fig. 4). These data show that excess water reached the 50-cm depth as a result of the rainfall events shown in Figure 2.

The stored water below the rootzone did not always follow the same pattern as that in the rootzone. The amplitudes of the variation were relatively small; this could be attributed to the low hydraulic conductivity of the deeper soil layers. The variations of the stored water in the rootzone are the results of water input from the rain and occasional irrigation and water output that includes evapotranspiration, excess water losses below the rootzone and potential surface runoff.

Figure 4. Cumulative water in the rootzone and below it

SUMMARY AND CONCLUSIONS

As a major water user, irrigated agriculture in Hawaii is expected to make substantial changes to optimize its water use. Optimum irrigation management should be based on understanding soil water holding capacity and crop water use throughout the growing seasons. Water content within and below the rootzone in a tomato trial was monitored for several months. Real-time soil water content monitoring within and below the rootzone showed substantial variations as a result of water input through irrigation and rainfall and also as a result of water output through evapotranspiration and deep percolations. The future field work should include calibration of the soil moisture sensors. The soil water content data will be necessary to determine the different water budget components for a tomato crop grown under Hawaii leeward conditions.

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