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WATER REQUIREMENTS FOR FLATWOODS CITRUS

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Abstract. **Water requirements of citrus trees depend on tree characteristics (size and health) as well as weather parameters (temperature, humidity, and wind velocity). During extended droughts, the typical combination of warmer than average temperatures, lower than average humidity, and often times higher wind velocities tend to result in higher than normal evapotranspiration (ET) rates. As a result, calculations based on monthly averages tend to under estimate water use during dry periods. This paper summarizes important factors relating to water use by citrus trees grown on flatwoods soils: soil physical properties, root systems, rainfall patterns, irrigation uniformity and application efficiency, upflux from the water table, and salinity. The daily historical rainfall records at the Indian River Research and Education Center over the last 50 years were evaluated to determine frequency and extent of droughts. There were 33 periods of 4 weeks or more that had less than 0.25 inch of rainfall, 34 periods with less than 0.05 inch of rain, and 52 periods with less than 1.0 inch of rain. Rainfall analysis of the spring dry season revealed that 34% of the years had periods of 4 weeks or longer during March-May that received 0.25 inch of rain or less. In addition, 48% of the years had periods of 4 weeks or more with 0.5 inch or less, and 68% with 1.0 inch or less. Calculations show that the combination of shallow root systems, sandy soils, and lack of perched water table during the dry season results in an irrigation frequency of 1-2 d during peak ET periods to provide adequate soil moisture for optimum production. Therefore, irrigation systems for citrus should be designed for complete ET replacement during the critical March to mid-June period. If saline irrigation water is used, additional water will be required for frequent irrigations to leach salts below the root zone.**

Water applied to a citrus tree is used in several ways. A small portion of the water taken up is assimilated and stored. Most of the water utilized in a grove is through the process of evaporation and transpiration, which together are termed evapotranspiration (ET). Direct evaporation moves water from the soil and plant surfaces into the atmosphere. The process of transpiration moves water vapor from plant leaves into the atmosphere.

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In addition to the water directly used in the ET process, water is required for additional uses (Clark et al., 1993). In most systems, extra water must be applied to offset the effects of non-uniform watering and irrigation application inefficiencies. Non-uniformity results in different amounts of water being applied in various locations throughout the grove. These variations are generally due to pressure differences within the system resulting from pipe and tubing diameters that are too small for the flow rate, poor system design, improper installation, alterations to the system, and wear on system components, or from emitter clogging. Non-uniformities in the emitter discharges in combination with soil variability can result in water moving below the root systems in some areas, while other areas within the grove are under-irrigated.

Water is often required for purposes other than just for sustaining trees in a grove. For example, water is required as a transport medium for chemigation, and applications may be required during the wet season when irrigations are not required. In addition, most systems require periodic maintenance, and extra water is required for emitter cleaning and system flushing. During cold winters, irrigation for freeze protection is a major use of irrigation water. In areas of Florida that have irrigation water with high salinity levels, proper water management requires extra irrigation water to leach salts from the soil.

In the flatwoods areas of Florida, the soils are highly variable. The surface soils are generally sandy in texture, but are underlain with slowly-permeable horizons that result in perched water table conditions. As a result, root systems are commonly restricted to the top 18 inch of soil or less. The combination of shallow roots and low water holding capacity in the sandy surface soils make water management critical to achieve optimum crop production. The objective of this paper is to discuss important factors that affect flatwoods citrus water use and irrigation management. These factors include: evapotranspiration, soil physical properties, root systems, salinity, rainfall patterns, irrigation uniformity and efficiency, and depth to water table.

Evapotranspiration

Evaporation of water requires relatively large amounts of energy, either in the form of sensible heat or radiant energy. Therefore the evapotranspiration (ET) process is governed by energy exchange at the vegetation surface and is limited by the amount of energy available. Because of these limitations, it is possible to predict the evapotranspiration rate using mathematical expressions and measured weather parameters. Reference crop evapotranspiration (ETo) refers to ET from a uniform green crop surface, actively growing, of uniform height, completely shading the ground, and under well-watered conditions. A standard that has been accepted for use as a reference crop is grass maintained at a 3-6 inches height. Actual ET for a crop (ETc) is calculated by multiplying ETo by a crop coefficient (Kc) which relates the water use properties of that crop to the reference level of ET (units for ET, ETc, and ETo are inch/d):

$$ETc = Kc \times ETo \quad \text{Eq. 1}$$

Several methods utilizing a wide range of parameters have been developed to predict ETo. These methods range from simple equations that only require daily temperature (Thornthwaite method) to complex methods (i.e., modified Penman method) that require several meteorological parameters. Jones et al. (1984) recommended the Penman equation (an energy based method) for calculating ETo for Florida. The Penman approach combines two components to estimate ETo, a radiation (sunlight) component and an advective (wind) component. Typical inputs to the model are daily maximum and minimum temperature, solar radiation, wind run, and relative humidity. Current and historical weather data and Penman ETo estimates for Florida can be obtained for several sites throughout the state via the Florida Automated Weather Network (FAWN) at: http://fawn.ifas.ufl.edu/.

ET rates vary from day to day and even throughout the day, depending on the temperature, wind, humidity, cloud cover, and location within the state. In general, winter ET rates are less than half of summer ET rates (Table 1). In many years, highest ET rates will occur in May when there are hot, dry, clear days. Typically, summer rains will begin to increase humidity and increase cloud cover by mid-June. As a result, average daily ET rates will be somewhat moderated. However, the days are longer and hotter in the summer, and when typical summer rains fail to materialize and hot, dry weather is prevalent, ET rates in June or July can be the highest of the year.

The total amount of irrigation water needed by a fully grown citrus grove for optimum yield depends on the daily rate of ET, rainfall distribution, and tree characteristics (variety, tree size, and tree health). Large, vigorous, healthy trees require more water than young or non-productive trees. In a study conducted on a developing grove (with Bahia grass cover) over a 10-year period at Ft. Pierce, average annual ET was reported to be 48 inches (Rogers et al., 1983). Daily water use by the trees in Rogers et al. (1983) peaked at about 45 gal/d during the June-July period. Boman (1994) reported water use from 6-year-old Valencia orange trees with a peak ET of 15 gal/d during June-July.

Water use rates and irrigation requirements are usually presented in terms of depth (inch). Conversion of depth to volume (gal) is required for the management of microirrigation systems that water only a portion of the ground surface. Detailed conversions from irrigation depth to irrigation volume requires knowledge of tree planting density, size, and vigor. As a rule of thumb, however, ETc rates expressed as depths can be converted to volume by the following equation:

$$\text{Volume (gal/tree per day)} = \text{ETc (in/d)} \times \text{tree spacing } (\text{ft}^2) \times 0.622 \text{ gal/in-ft}^2 \qquad \text{Eq. 2}$$

For example, to convert an ETc of 0.18 in/d in May (Table 1) to gal/tree per day for citrus trees planted at a 12 ft in-row × 24 ft across-row spacing, ETc = 0.18 in/d × 12 ft × 24 ft × 0.622 gal/in-ft^2 = 32 gal/tree per d. The conversion should only be used as a starting point with the actual water estimates based on the size and condition of trees in each block. The water use per tree for mature citrus trees in high density plantings will be less than that in low density plantings due to tree size.

Root Systems

Most flatwoods commercial plantings of citrus are on raised beds that are constructed to expedite drainage and provide a better-drained root zone relative to non-bedded soils. Even so, Bauer et al. (2003) reported that roots are concentrated near the surface, and often are found only in the top 10-15 inches of the soil profile in the most common flatwoods soils (Immokalee, Myakka, Riviera, Pineda, Winder, Oldsmar, etc.). Exceptions are more upland soil series such as Wabasso and Oldsmar, where roots may be found at depths of 24-30 inches.

Soil Water Holding Capacity

The amount of water that a soil can hold against gravity is termed field capacity (FC). The FC varies with soil texture, organic matter content, and depth in profile. However, not all the water held in the soil is available to plants. The plant available water (PAW) is defined as the amount of water available between FC and wilting point (WP). The WP is the water content of the soil below which the plant cannot extract water.

Table 1. Typical ETc calculated from long-term data for West Palm Beach and the Penman equation (Jones et al., 1984) and crop coefficient values (Kc) for flatwoods citrus (Rogers et al., 1983) compared to ET measured at Ft. Pierce Soil Water Atmosphere Plant (SWAP) site (Rogers et al., 1983).

	Citrus ET calculated with Penman ETr and Kc[z]				Measured at SWAP site	
		Penman ETr	Citrus ETc (ETr × Kc)		Citrus ET	
Month	Citrus Kc	(inch/d)	(inch/d)	(inch/month)	(inch/d)	(inch/month)
Jan	0.90	0.10	0.09	2.8	0.07	2.3
Feb	0.90	0.13	0.12	3.4	0.09	2.4
Mar	0.90	0.16	0.14	4.3	0.11	3.3
Apr	0.90	0.19	0.17	5.1	0.12	3.7
May	0.95	0.19	0.18	5.6	0.17	5.1
Jun	1.00	0.18	0.18	5.4	0.20	5.9
Jul	1.00	0.18	0.18	5.6	0.18	5.5
Aug	1.00	0.18	0.18	5.6	0.17	5.1
Sep	1.00	0.16	0.16	4.8	0.16	4.8
Oct	1.00	0.14	0.14	4.3	0.13	4.0
Nov	1.00	0.12	0.12	3.6	0.09	2.8
Dec	1.00	0.10	0.10	3.1	0.08	2.4

[z]Kc developed from measured ET for citrus and calculated Penman ETr at SWAp site.

The units for FC, PAW and WP are expressed as depth (inch) of water for a given depth of soil (inch).

Typical values of PAW reported in the county soil surveys for citrus soils vary from 0.02-0.05 in/in for coarser soils (i.e., Pineda, Wabasso, Oldsmar, etc.) to 0.06-0.10 in/in for finer textured soils such as Winder (Watts and Stankey, 1980). Typical PAW and other information on most of the common soils used for citrus production in Florida can found in Obreza and Collins (2002).

The allowable soil water depletion is defined as the fraction of the PAW that will be used to meet ET demands before being replenished. As ET occurs, the soil water begins to be depleted. As the soil dries, the remaining water is bound more tightly to the soil, making it more difficult for trees to extract it. As a result, water stress begins and ET is reduced. With prolonged water deficit in the soil, trees will wilt. Lower ET generally results in smaller fruit, lower overall total soluble solids (TSS) production, and lower fruit yields. Therefore, irrigations should commence before the root zone water content reaches a level that restricts ET.

The critical PAW level depends on several components, including: crop factors (rooting density and tree age/size), soil factors (PAW and effective root depth), and atmospheric factors (ET rate, temperature, radiation level, wind velocity, and humidity). Therefore, no single level can be recommended for all situations. Allowable depletions of to 50% to 67% of PAW are commonly used in scheduling irrigations during the non-sensitive periods. Lower depletion levels should be used during sensitive stages such as at bloom and fruit set. As a rule of thumb, soils should be allowed to deplete no more than 33% of PAW from February through the "June drop" and no more than 50-67% depletion of PAW during other times of the year.

For Riviera series soil with an 18-inch root zone and 0.08 inch/ inch of PAW, the root zone could hold 0.08 inch/inch × 18 inch = 1.44 inch. During the spring bloom, fruit set, and early development period, irrigations should commence before 0.33 × 1.44 inch = 0.48 inches are depleted (about 2 d of ET). Typically, the sandy soils and shallow root zones in flatwoods soils require 1-2 d irrigation intervals in order to minimize water stress on trees during the normal dry spring months (Table 2).

Irrigation Efficiency and Uniformity

As the soil dries during extended dry periods, it is important that irrigation water be supplied at the appropriate frequency and volume in order to minimize stress. During extended droughts, nearly all of the water used by the trees will come from the area wetted by the irrigation system. Wetted area normally varies from 12-15 ft diameter for microsprinklers to 2-3 ft wide bands for drip systems. The low PAW and shallow root zones make frequent irrigation necessary to supply tree water needs while minimizing water movement below the root zone.

It is not possible to apply the exact amount of irrigation water required with perfect uniformity because of variations in soil properties, variations in irrigation system components, pressure losses in systems due to friction and elevation changes, or other causes. Even when the correct average amount of water is applied, non-uniform water applications can result in excess applications (wasted water and nutrient leaching) in some areas and under-irrigation in other areas (tree stress).

Application efficiencies of microirrigation systems are typically high (Smajstrla et al., 1991). The primary causes of nonuniformity include pressure losses in the system due to elevation changes and friction in mains and laterals. Other factors such as clogged emitters can also result in nonuniform applications. Wind drift and evaporation losses from drip systems are relatively low. However, microsprinkler efficiencies can be quite low due to wind drift and evaporation on hot, dry, windy days. To compensate for these losses, increased run times and/or operation at night may be required to maintain optimum soil moisture. These management strategies can be adopted to achieve high application efficiencies.

In order to compensate for losses from wind drift and evaporation, soil moisture should be monitored. Tensiometers (Smajstrla et al., 1988) or more modern soil moisture sensors (e.g., capacitance probes) can be used to determine the soil moisture status and better manage irrigation (Zazueta and Xin, 1994).

Salinity

In some flatwoods areas (e.g., the Indian River, Shell Creek, Joshua Creek, and Prairie Creek areas), irrigation wa-

Table 2. Estimated irrigation interval (d) on typical Pineda and Riviera series soils for healthy, mature trees (116 tree/acre) based on average soil water holding capacity, root zone depth, 33% depletion of PAW from February through June, 67% depletion for the other months, and ETc for citrus calculated with the Penman equation from long-term data for West Palm Beach (Jones et al., 1984).

Month	ETc (ETo × Kc) (inch/d)	ETc (ETo × Kc) (gal/tree/d)	Allowable depletion (%)	Riviera[z] 12-inch root zone, PAW = 0.08 inch/inch (d)	Pineda[y] 15-inch root zone, PAW = 0.05 inch/inch (d)
Jan	0.09	20	67	7.1	5.6
Feb	0.12	27	33	2.7	2.1
Mar	0.14	33	33	2.2	1.7
Apr	0.17	39	33	1.9	1.4
May	0.18	42	33	1.8	1.4
Jun	0.18	41	33	1.8	1.4
Jul	0.18	41	67	3.6	2.8
Aug	0.18	41	67	3.6	2.8
Sep	0.16	37	67	4.0	3.1
Oct	0.14	32	67	4.6	3.6
Nov	0.12	27	67	5.4	4.2
Dec	0.10	23	67	6.4	5.0

[z]Riviera is a finer textured sand with higher PAW.
[x]Pineda is a coarser textured sand with lower PAW.

ter supplies have high salinity. The salinity of these surface and ground water supplies can vary from month to month and from year to year. However, highest salinity levels typically occur during dry periods (April and May), the most critical irrigation months.

When irrigation water has over 1200 ppm total dissolved solids (TDS), high concentrations of salt may accumulate near the soil surface in the absence of sufficient irrigation or rainfall to maintain vertical water flow to leach out salts. The increase in salinity results from plant transpiration and soil surface evaporation which selectively removes relatively salt-free water and concentrates the salts in soils. Salt accumulation in the soil is generally only removed by leaching below the crop root zone. Therefore, the key to salinity control is to provide a net downward flow in the root zone. Even in well-managed groves, the soil water will be several times more saline than the irrigation water. With insufficient leaching and soil drying, this ratio can easily increase ten-fold or more, resulting in tree injury. Therefore, the irrigation strategy to minimize salt damage is to irrigate frequently (often daily) with sufficient quantity to ensure downward flushing of salts from the root zone (Boman and Stover, 2002).

In Florida, accumulation of salts over the years is not a problem in most cases due to abundant rainfall at sufficient

Table 3. Monthly rainfall (inch) at IRREC, Ft. Pierce.

Yr	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1953	2.29	2.42	5.27	3.03	0.88	7.15	9.31	10.06	9.00	10.24	3.18	2.01	64.84
1954	0.62	2.70	1.91	7.48	8.76	9.98	7.08	5.45	12.01	6.98	4.28	0.83	68.08
1955	2.34	0.78	2.48	2.13	5.80	9.99	3.25	6.73	4.23	7.18	0.83	3.76	49.50
1956	0.33	2.24	0.13	2.42	2.42	4.72	6.18	9.05	7.65	12.33	1.09	1.38	49.94
1957	2.09	5.24	4.43	7.45	6.77	6.82	10.55	12.51	9.98	6.75	1.00	3.41	77.00
1958	8.34	1.12	3.74	2.77	6.02	3.93	4.63	9.90	3.85	4.68	1.46	4.44	54.88
1959	2.24	0.74	8.14	2.60	4.17	17.72	5.95	3.75	11.19	12.57	3.37	2.35	74.79
1960	0.16	7.86	4.73	5.22	4.10	10.56	13.60	5.48	17.43	3.75	0.94	0.75	74.58
1961	2.13	0.62	2.80	0.67	8.82	6.11	4.38	4.21	3.31	5.89	0.94	0.46	40.34
1962	0.38	1.11	3.17	2.30	1.27	1.95	9.77	12.31	5.81	3.75	4.55	0.26	46.63
1963	0.58	4.15	2.53	0.66	6.33	3.59	5.48	4.11	11.20	6.73	4.06	6.09	55.51
1964	2.25	6.13	0.93	3.81	2.98	4.24	7.26	13.26	8.31	8.75	0.89	1.67	60.48
1965	0.51	5.83	2.49	0.58	1.02	6.08	7.92	2.56	6.27	6.62	1.77	1.40	43.05
1966	4.16	6.93	1.92	3.87	6.59	11.35	7.95	3.96	6.08	5.41	1.82	1.35	61.39
1967	1.82	3.07	0.95	0.54	0.35	11.23	8.40	7.07	4.17	6.90	0.45	1.59	46.54
1968	0.82	1.73	1.54	0.40	5.29	17.45	7.26	3.57	8.98	7.24	2.49	0.15	56.92
1969	2.16	1.11	8.19	0.75	13.35	2.76	7.25	9.73	8.89	9.95	4.97	3.05	72.16
1970	3.97	2.80	6.30	0.14	3.81	3.21	1.61	5.41	7.93	15.20	1.45	0.40	52.23
1971	0.20	2.90	1.44	0.67	3.39	9.28	5.47	7.33	5.14	6.11	1.72	3.05	46.70
1972	1.84	4.42	4.05	2.13	6.68	12.43	5.10	6.57	1.89	4.52	3.02	1.17	53.82
1973	2.86	1.94	2.22	1.84	5.40	6.51	7.34	8.14	7.19	7.70	0.76	1.38	53.28
1974	2.36	0.59	0.54	1.96	4.15	11.31	8.10	5.47	4.75	3.27	1.31	1.93	45.74
1975	0.37	4.30	1.61	1.62	10.14	4.07	3.53	3.20	9.11	2.14	2.95	1.15	44.19
1976	0.77	1.36	0.98	3.23	8.06	11.42	3.06	5.82	4.54	0.71	3.84	2.25	46.04
1977	2.08	2.26	0.51	0.73	5.05	3.68	8.63	5.46	11.27	3.72	3.32	3.79	50.50
1978	2.52	2.37	3.26	1.66	7.17	9.36	5.66	4.60	3.62	6.95	1.98	7.26	56.41
1979	4.14	0.18	1.44	2.31	13.98	5.46	6.88	3.87	20.36	1.87	2.26	1.75	64.50
1980	3.67	2.59	2.62	2.82	2.90	5.63	8.18	2.14	4.59	3.62	5.61	2.35	46.72
1981	0.56	2.64	0.91	0.44	4.01	1.08	4.44	11.45	7.45	2.61	2.67	0.36	38.62
1982	1.39	2.41	7.84	6.95	11.15	11.15	9.62	5.68	5.34	1.74	8.04	1.22	72.53
1983	4.11	7.14	5.52	2.08	1.39	6.67	3.82	11.99	5.70	9.77	1.12	2.89	62.20
1984	1.47	3.00	3.80	0.50	7.58	5.14	6.23	3.60	7.42	2.19	6.68	1.37	48.98
1985	0.86	0.14	4.80	4.38	5.16	3.02	13.90	5.84	20.94	2.75	3.73	2.07	67.59
1986	3.22	0.81	7.69	0.05	1.45	9.15	8.19	8.48	9.95	7.31	1.98	2.62	60.90
1987	1.54	1.90	6.43	0.34	2.21	2.86	6.77	2.98	9.15	10.13	5.04	0.25	49.60
1988	2.88	2.74	4.20	1.63	3.30	1.33	10.37	5.87	1.46	1.76	2.33	2.67	40.54
1989	2.00	0.47	2.88	4.44	2.61	3.40	2.66	5.67	5.91	5.03	1.07	2.67	38.81
1990	1.15	1.90	1.08	1.02	2.77	4.24	9.28	5.20	10.84	3.95	2.65	0.22	44.30
1991	3.31	2.91	2.47	5.52	3.69	9.51	13.39	6.71	5.50	4.13	1.69	1.11	59.94
1992	0.75	3.06	1.44	2.94	0.93	14.75	3.02	5.80	6.13	4.03	8.41	2.10	53.36
1993	7.32	3.07	8.41	0.70	4.34	3.31	3.92	6.94	6.38	8.46	5.33	1.08	59.26
1994	4.59	5.90	1.81	3.90	5.33	5.58	5.21	7.27	14.26	11.87	5.60	6.96	78.28
1995	2.06	3.75	2.04	1.70	1.42	3.84	6.28	15.25	8.80	13.88	0.38	0.29	59.69
1996	2.41	1.11	10.79	0.74	3.90	4.99	5.56	4.56	7.21	6.35	2.55	1.65	51.82
1997	2.98	1.36	1.22	7.40	2.12	6.69	6.68	11.29	3.75	2.13	3.37	0.64	49.63
1998	0.00	4.49	4.87	2.47	2.42	3.14	3.43	11.77	7.00	1.79	8.67	0.91	50.96
1999	1.00	1.45	0.57	3.52	5.20	10.63	1.06	9.96	9.92	11.52	1.60	1.14	57.57
2000	1.81	1.29	2.68	2.38	0.83	6.33	5.85	3.57	3.83	6.29	0.24	2.85	37.95
2001	1.03	0.29	1.20	1.12	6.19	6.43	9.83	6.62	6.50	6.23	4.10	0.55	50.09
2002	1.47	4.13	0.58	5.44	3.05	6.94	8.26	5.90	2.67	0.95	1.66	5.31	46.36

rates to leach the salts from the root zone. Accumulated salts in typical flatwoods soils are generally leached out with the first inch of rainfall. However, in some poorly drained heavier soils (such as depressional soils), salt accumulation can still be a problem. These soils require more careful monitoring of salinity levels and may need improved drainage systems.

Water Table

Most flatwoods citrus soils have a restrictive layer that can perch the water table and significantly affect tree water relations. A high water table can exist close enough to the root zone to have a direct influence on the vigor and productivity of citrus trees when planted on raised beds. Rainfall and irrigation can quickly raise the water table, while slope, topographical elevation, depth to the restrictive layer, and the ability of the artificial drainage system to remove water influence how quickly the water table declines.

The upward movement of water within the soil profile from the water table is called upflux (Obreza and Boman, 1992). As water is removed from the soil by tree roots and by evaporation at the ground surface, water content of the soil decreases. By capillary action, water moves from the water table into the drier soil above. Water adheres to soil particles due to surface tension between adjacent particles. Smaller soil particles have smaller voids (pore spaces) compared to coarse textured soils. The smaller particles provide greater surface areas upon which water can adhere. In addition, the smaller pores allow water to be retained at higher surface tensions, giving them the ability to move water greater distances by capillary action. The upflux process can move water into the root zone from a much deeper water table in clay soils than in coarser sandy soils.

For operational considerations and annual water use estimates, water table upflux is an important consideration for flatwoods citrus. The combination of a shallow water table and frequent summer rains provides adequate soil moisture for many flatwoods groves during the wet season of typical years. However, the contribution of upflux to meet ET requirements should generally not be considered when designing a system to meet peak ET rates. During extended droughts, the water table generally drops to levels where its contribution to citrus ET is minimal. Therefore, it is generally ignored for peak ET design estimates. Typically, systems are designed to meet the peak ETc expected to occur over a short period of time (weeks).

Rainfall Patterns

Due to the sandy soils and shallow root systems of citrus grown on flatwoods soils, frequent irrigation or rainfall is required to maintain adequate soil moisture for optimum production. When calculating irrigation requirements, it is essential to look at long-term rainfall patterns in order to identify the length and duration of rain-free periods when irrigation will be necessary.

The daily rainfall record at the Indian River Research and Education Center at Ft. Pierce (IRREC) was analyzed for the period from 1953-2002. Rainfall averaged about 55 inches per year over the last 50 years (Table 3). Eight out of the 50 years (16%) had less than 45 inches of annual rain. Monthly averages ranged from a low of 2.1 inch in December and January to 7.7 inches in September (Fig. 1). However, there was considerable variation from year to year, with the standard deviation of monthly rainfall typically being 1.5-2.0 inches in the winter to 3-4 inches in the summer months (Table 4). In spite of the ample rain in most years, the distribution of rain is extremely important for citrus on flatwoods soils with shallow root zones.

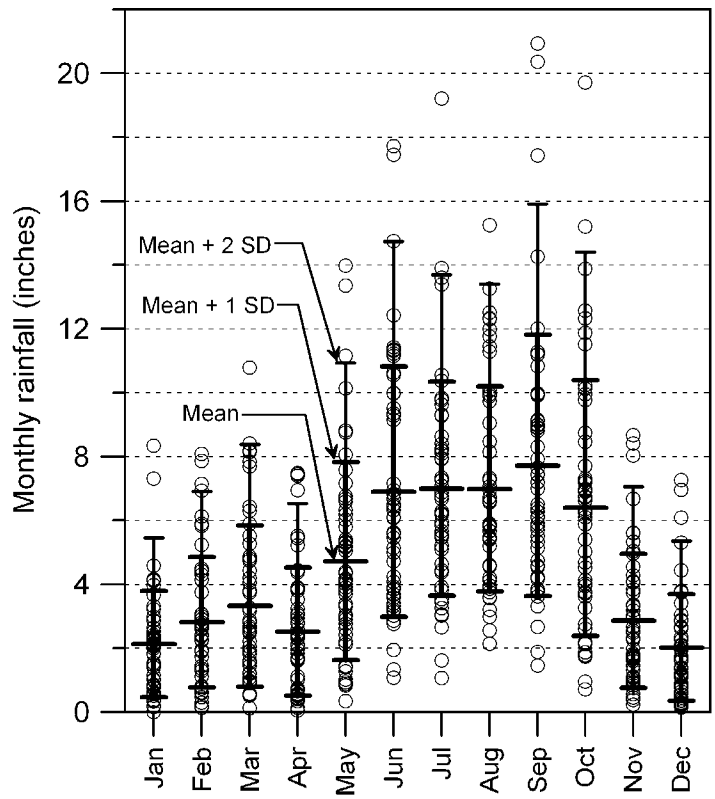

Fig. 1. Distribution of monthly rainfall for 1953-2002 period at IRREC.

Minimum monthly rainfall was less than 0.25 inch for January, February, March, April, November, and December, while the minimum for May and October was 0.35 inch and 0.71 inch, respectively. In the normal wet season months, there were years when rainfall was less than 1.1 inches/month (June and July, Table 4). Periods of 3-weeks or longer were identified that had cumulative rainfall of less than 0.25, 0.50, and 1.0 inch. The analysis did not consider contributions from upflux from a shallow water table. However, during extended droughts of several weeks, the water table generally drops well below levels where it can supply significant water to the root zone. Figure 2 shows the periods of 21 d or more when 0.25 inch or less of rainfall were received. There were 7 periods of 6+ weeks with less than 0.25 inch of cumulative rainfall (Table 5). Many years had several periods with limited rainfall. There were 33 periods of 4+ weeks that had less than 0.25 inch of rainfall, 34 periods with less than 0.50 inch of rain, and 52 periods with less than 1.0 inch of rain. There were no periods of 3+ weeks receiving 0.25 inch or less or rain in 1953, 1978, 1982, and 1994. In 6% of the years, there was at least 1 period of 4+ weeks with less than 0.25 inch of rain. All of the years had periods of 3+ weeks with less than 0.25 inch of cumulative rain, and 80% of the years had periods of 4+ weeks with less than 0.5 inch of rain.

The rainfall data were further analyzed to determine periods with extended drought when the average long-term citrus ET was 0.15 inch/d or more (late March to mid-October). Un-

Table 4. Statistical summary for monthly rainfall (inch) at IRREC, Ft. Pierce (1953-2002).

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Minimum	0.00	0.15	0.13	0.05	0.35	1.08	1.06	2.14	1.46	0.71	0.24	0.15
95%[z]	0.18	0.24	0.53	0.24	0.86	1.64	2.14	2.77	2.28	1.35	0.42	0.24
90%[z]	0.37	0.59	0.58	0.44	1.02	2.86	3.06	6.57	3.62	1.79	0.76	0.29
80%[z]	0.62	1.11	1.08	0.67	2.12	3.40	3.92	3.96	4.23	2.61	1.00	0.64
Median	2.00	2.41	2.49	2.13	4.10	6.08	6.68	5.84	7.00	6.11	2.26	1.40
Mean	2.12	2.71	3.27	2.51	4.73	6.96	6.75	6.88	7.70	6.13	2.90	2.05
Maximum	8.34	8.09	10.79	7.48	13.98	17.72	19.21	15.25	20.94	19.72	8.67	7.26
SD[y]	1.66	2.05	2.53	2.01	3.10	3.92	3.35	3.21	4.09	4.00	2.10	1.67

[z]Monthly rainfall exceeded in 95%, 90%, or 80% of years.
[y]SD = Standard deviation of monthly rainfall (n = 50).

der these conditions, there were 43 periods of 3-4 weeks, 15 with 4-5 week duration, and 26 periods that were longer than 5 weeks. These data emphasize the frequent occurrence of extended periods where rainfall is less than citrus ET demands.

Thirty-four percent of the years had periods of 4+ weeks during March-May that had 0.25 inch of rain or less. In addition, 48% of the years had periods of 4+ weeks with 0.5 inch or less, and 68% with 1.0 inch or less. Typically during spring drought periods, irrigation does not stop when scattered showers provide small amounts of rainfall (<0.5 in). These small rains generally do not penetrate very deep into the soil and much of the moisture is often lost to evaporation within a day.

Analysis of the 50-year historical rainfall data at IRREC reveals that the timing of rainfall events was such that some of the wetter years had longer drought periods. There was no correlation between rainfall in the spring dry season (March-May) and the duration of drought, demonstrating the importance of rainfall timing for irrigation design and operation. The March to May rain totaled from less than 2 to over 18 inch during years when there were periods of 4 weeks or more with less than 0.5 inch of rainfall. The longest drought in the spring dry season occurred in 1985, which had 14.3 inch of rain from March to May, but over 10 weeks with less than 0.5 inch of cumulative rainfall.

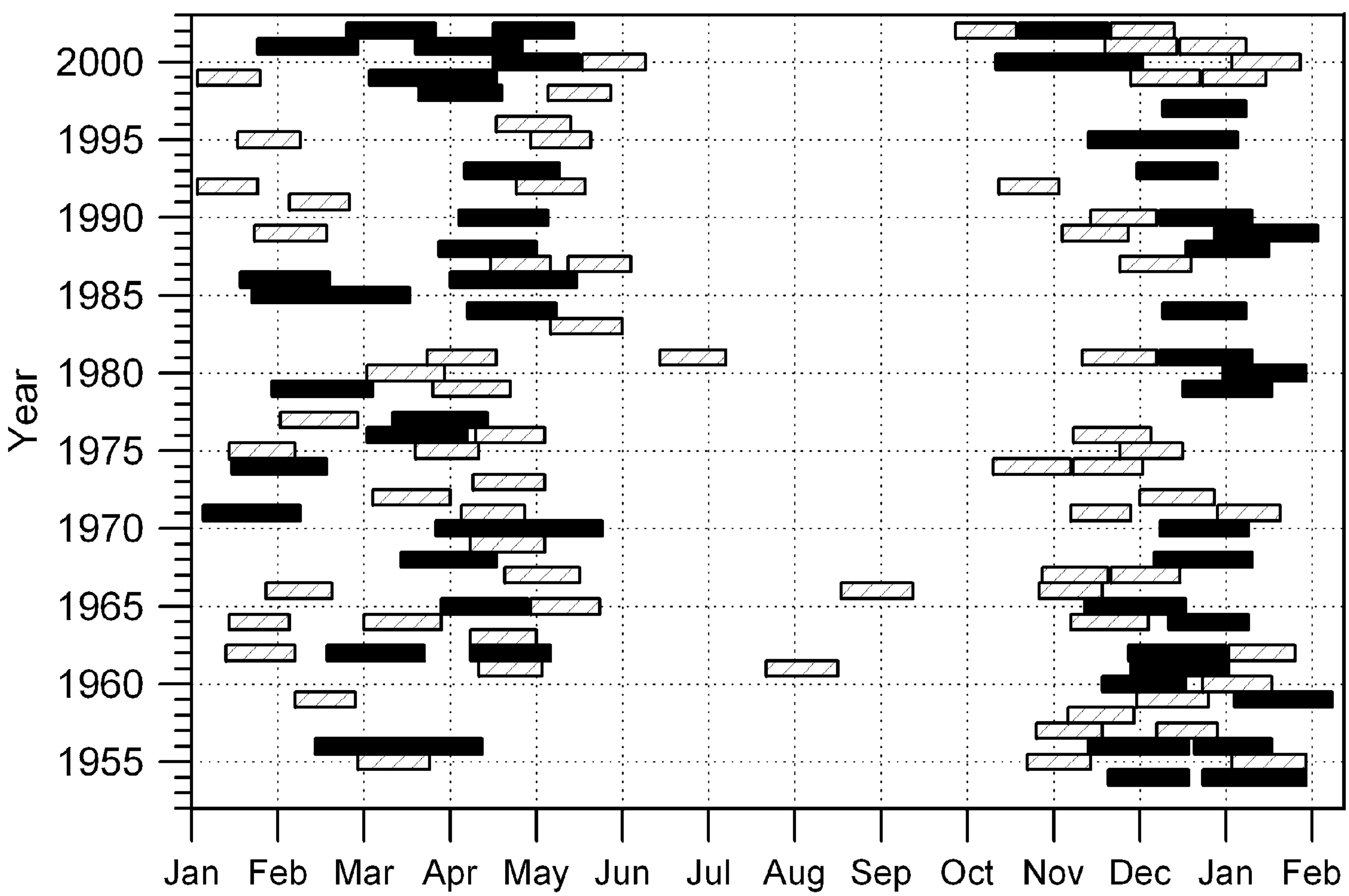

Fig. 2. Periods of 3-4 weeks (hatched bars) or more than 4 weeks (solid bars) for 1953-2002 with less than 0.25 inch of cumulative rainfall IRREC.

Table 5. Number of periods from 1953-2002 at the IRREC where rainfall was less than 0.25, 0.5, or 1.0 inch for various periods.

Period length (weeks)	Number of periods <0.25 inch rain	<0.5 inch rain	<1.0 inch rain
3-4	68	87	96
4-5	33	34	52
5-6	9	27	43
>6	7	17	35

Measured Water Use

Water use data from several experiments conducted in the Indian River area are summarized in Table 6. The annual water use (acre-inch/acre) was calculated using the following equation:

$$\text{acre} - \text{inch}/(\text{acre}) = \frac{\text{trees}/\text{acre} \times \text{gph} \times \text{hours}}{27{,}154\ \text{gal}/\text{acre} - \text{inch}} \qquad \text{Eq. 3}$$

The period covers the 1987-2000 seasons, with the exception of 1995. Annual water use for grapefruit in Table 6 ranged from 0.8 acre-inch/acre in 1994 to 31.1 acre-inch/acre in 2000, averaging 9.4 acre-inch/acre for the 11 seasons. In 2000, the irrigation applied to 'Valencia' oranges on single-row beds (15 × 30 ft spacing) totaled 20.0 acre-inch/acre. Converting this total to a more typical planting density of 145 trees/acre would have resulted in an irrigation application of 29.8 acre-inch/acre, within 5% of that measured for grapefruit that year (Table 6).

For the data analyzed, grapefruit yields tended to be inversely related to March-May total rainfall (Fig. 3). Highest yields were measured in 1990, 1992, and 2000. March-May rain totaled for these years totaled less than 5.5 inch. Lowest yields occurred in 1993 and 1994, when March-May rainfall exceeded 15 inches.

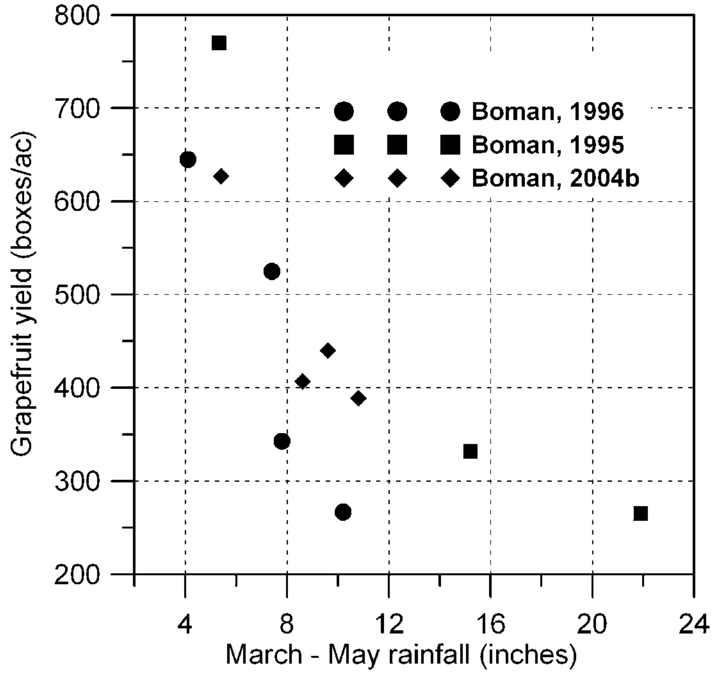

Fig. 3. March-May rainfall versus grapefruit yield from Indian River area experiments where irrigation totals were monitored (note: Boman, 1995 and Boman, 1996 were from same grove).

Discussion

During extended droughts, the typical combination of warmer than average temperatures, lower than average humidity, and often higher wind velocities tend to result in higher than average ETc rates. As a result, calculations based on monthly averages will tend to under-estimate water use during dry periods. Therefore, for design purposes, an analysis of long-term daily weather data should be used to determine

Table 6. Annual rainfall, irrigation, and yields from Indian River area citrus studies.

Rootstock and scion	'Ray Ruby' on Swingle citrumelo and Carrizo citrange				'Valencia' on rough lemon					'Ruby Red' on sour orange				'Ruby Red' on sour orange		
Reference	Boman (2004b)				Boman (2004a)					Boman (1996)				Boman (1995)		
Period	4 seasons (1997-2000)				5 seasons (1996-2000)					4 seasons (1988-1991)				3 seasons (1992-1994)		
Emitter discharge	10.2 gal/h				10.2 gal/h					17.8 gal/h				18.0 gal/h		
Tree spacing	15 × 24				15 × 30					20 × 25				20 × 25		
Tree density	116 trees/ac				97 trees/ac					96 trees/ac				96 trees/ac		
Rows/bed/bed width	2/50 ft				1/30 ft					2/50 ft				2/50 ft		
Year	1997	1998	1999	2000	1996	1997	1998	1999	2000	1988	1989	1990	1991	1992	1993	1994
Rain (inch)	49.7	50.9	57.6	38.0	43.3	57.2	45.9	59.5	37.4	42.1	45.4	46.4	59.3	50.7	74.9	84.3
Irrigation (h)	66	78	304	713	130	42	156	227	548	244	258	171	63	59	75	12
Yield (bx/ac)	389	440	407	627	336	566	509	509	528	525	343	645	267	770	265	332
Avg. annual h of operation	288 h				221 h					184 h				49 h		
Avg. annual depth applied	12.6 ac-in/ac				8.1 ac-in/ac 12.0 ac-in/ac[z]					11.6 ac-in/ac				3.1 ac-in/ac		
Max. annual h operated	713 h (2000)				548 h (2000)					258 h (1989)				75 h (1993)		
Max. annual depth applied	31.1 ac-in/ac				20.0 ac-in/ac 29.8 ac-in/ac[z]					16.2 ac-in/ac				4.8 ac-in/ac		

[z]Estimated irrigation rate for a more typical planting density of 145 trees/ac on double-row beds.

peak irrigation requirements. For irrigation system operation, daily calculations based on current local ET data is recommended.

During droughts, the water table beneath flatwoods groves normally drops to depths where upflux into the root zone is considerable smaller (or negligible). Under these extended drought conditions, nearly all of the ETc is supplied from the areas of the root zone wetted by irrigation. The combination of shallow rooting, sandy soils, and lack of perched water table during the dry season requires irrigation on a 1-2 d frequency during peak ET periods to provide soil moisture for trees. Therefore, irrigation systems for citrus should be designed for complete ET replacement during the critical March to mid-June period. If saline irrigation water is used, additional water will be required for frequent irrigations to leach salts below the root zone.

Water use rates for flatwoods citrus needs to be calculated with daily data to accurately reflect the dynamics of soils, rooting depth, and the infiltration, runoff, and effective rainfall components of each rain event. In addition, microsprinkler irrigation systems should be designed to apply 15-20% additional water to account for application losses (i.e., non-uniform patterns, emitter variation, and wind drift).

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