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Crop Water Use From Shallow Groundwater —Simulation Using Field Measured Soil and Climatic Parameters—

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The SWAP93 model was used to predict how much capillary rise would occur in cropped fields. The experimental fields were located in a humid climate and it was thought that contribution from groundwater sources to total water use could be significant. In one field planted with soybean, the model predicted an average daily uptake of 1.3 mm; in another field planted with pumpkin, there was average daily uptake of 0.3 mm; and yet in a third field located in a vinyl house there was average daily uptake of 0.03 mm. These predictions represent about 38, 7 and 1% contribution to total water use respectively. Even though there were no measured data to compare with, the results lie within the range of other works reported in the literature.

Keywords: Crop water use; capillary rise; SWAP93 model; groundwater

1. INTRODUCTION

Water is essential to plant growth and food production. Water for plant growth is obtained from rainfall, irrigation, shallow water table or a combination of these. When water table exists close to the root zone, crops may extract water from the capillary fringe, or water may flow upward into the crop root zone. Upward flow can be significant in areas where the required irrigation rate is low due to rain or a mild climate. In areas where saline irrigation water is used, leaching is necessary to remove salts from the crop root zone. Generally that water should not be counted on for crop water use. However, water tables that are within one meter of the bottom of the root zone, can provide a substantial fraction of the *ET* needs even if water quality is marginal.

The rate of upward flow depends on the depth to the water table and the soil type. Shallow water tables supply water more rapidly than deep water tables. The soil type has two influences. First, the capillarity of the soil provides the energy or potential for upward movement. Second, the conductivity of the soil determines the rate of upward flow. Sandy soils have a high conductivity when nearly saturated, but the conductivity drops very quickly with distance above the water table as the soil becomes unsaturated. Sandy soils are usually irrigated to prevent large soil water potentials which provides less energy for upward flow. Therefore, sandy soils usually have small rates of upward flow. Clay soils can produce large potentials for upward flow; however, their low hydraulic conductivity limits the rate of upward flow. Upward flow is generally most significant for medium textured soils where the soil water potential and conductivity together produce usable rates.

Japan is located in a region described as being humid. Aside from the obvious difference in rainfall, climate in humid regions may be unique in several other ways, many of which are caused by generally higher humidity associated with more available water. Cloudiness reduces total solar iiradiance, and the cloud type, typically cumulus,

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causes high variability in irradiance on a short time scale. Dew forms frequently, and wet leaf conditions may continue for several hours after sunrise.

The combined effects of the local geology, topography, and climate has created high water table regimes in most of the cultivated areas in Japan. Most current irrigation scheduling techniques, however, ignore shallow groundwater contributions to crop water requirements. Under some conditions use from the water tables will reduce net irrigation requirements. The long-term effect may be a lowering of the water table.

On the other hand, existing shallow water tables can be maintained or controlled to provide an additional water source for areas where water quality is good and water tables move vertically into and out of the crop root zone. Crops have different rooting habits and thus have different drainage requirements; i.e., depth to water table during the growing season. "Optimum drainage requirement" refers to the degree of drainage that must be maintained to provide optimum crop growing conditions. Thus that requirement defines the minimum water-table depth that must be sustained to meet crop needs regarding such factors as soil temperature, rooting volume, nutrients, and soil aeration within imposed conditions of trafficability, irrigation management, water resource conservation, soil salinity and environmental quality. "Perfect drainage" is the nonexistence of a water table, or a water table that is deep enough to never come into contact with the crop roots. However, "perfect drainage" may not be good economy, because - with such drainage - crops must obtain all of their water needs from precipitation, stored water, and irrigation; and irrigation is becoming progressively more expensive. Crops' use of water from a water table will reduce irrigation costs.

The objective of this study is to estimate the contributions of high (perched) water tables to the water requirements of some commonly grown crops in the Chugoku region of Japan. Estimation was done using a simulation model and field measured parameters.

2. LITERATURE REVIEW

Several investigators have measured the use of shallow groundwater by agricultural crops, under both irrigated and dry land conditions. Groundwater use, as a percentage of total water use by a crop, can be affected by water-table depth, soil type, crop, climate, and the quality of the groundwater. Variations in crops, soils, depth and fluctuations of water tables, climate, and irrigation regimes make it difficult to extend and generalize the results.

Studies show that under favorable conditions crops can draw water from water tables 2 m or more deep. Namken et al. (1969) studied cotton in lysimeters and found that water tables at 0.91, 1.83, and 2.74 m contributed 54, 26, and 17% of total water used by the crop under a high moisture treatment. Doorenbos and Pruitt (1977) reported upward rates of flow from water table of 2 to 6 mm/d for water-table depths from 2 to 4 m below the root zone.

Groundwater contributions to crop water needs can be significant, even under irrigated conditions. Benz et al. (1984, 1985a) investigated four shallow, constant water-table depths for alfalfa in the U.S. The water table provided a sizable contribution to evapotranspiration (ET), ranging from 0.6 to 38.4%, decreasing as irrigation was increased. For low irrigation levels, groundwater use exceeded 50% of total ET, even for water tables as deep as 2.1 m. Kruse et al. (1985, 1986) determined that irrigation applications can be decreased when corn or alfalfa is grown over shallow water tables. Depth to groundwater was found to be the primary determinant of how much is used by the crop. Lysimeter studies in Australia (Meyer, 1987; 1988) showed that a water table at 1-m depth in a loam soil contributed 28 to 36% of the water requirement of spring wheat. In a less permeable clay loam soil, only 10 to 15% of the water requirement was met by a water table at the same depth. However, Marston and Guitjens (1988) concluded that there was no support for the concept that shallow groundwater would sustain alfalfa growth without irrigation in the Newlands Project bottomlands in the U.S.

Some research has shown a linear relation between groundwater use and decreasing depth to water table. Tovey (1964) measured alfalfa *ET* in lysimeters, using three soil textures, and constant water-table depths of 0.60, 1.20, and 2.40 m. For non-irrigated treatments, *ET* decreased almost linearly with increasing depth to water table. Grismer and Gates (1988), reviewing results of studies in the U.S and Egypt, found that results were adequately represented by a linear relation between rate of upward flow from the water table and depth to water table, with the proportionality depending only on soil type.

Crop use from groundwater decreases with increasing surface water applications, either irrigation or rainfall. Benz et al. (1985b) found that subirrigation from shallow water tables contributed to *ET* in sizable quantities if rainfall and surface irrigation were inadequate. The water table contribution to *ET* was significantly increased, with no loss in productivity, when irrigation frequency for cotton and alfalfa was reduced (Grimes and Henderson, 1986).

In summary, studies of the use of shallow groundwater by irrigated crops show considerable variation because of different soil hydraulic properties, crop rooting patterns and salinity tolerances, and the irrigation regimes imposed. Shallow groundwater can reduce irrigation requirements and enhance yields.

3. MATERIALS AND METHODS

3.1 *The Field site*

Water use from high (perched) water tables was studied at the Okayama University Research farm at Tsushima; and a private farm located at Soja (Okayama Prefecture). A description of the field site at the Okayama University Research farm has been given by Abenney-Mickson et al., (1995). The climatic conditions of Soja is similar to that of the University Research farm (i.e. humid), with mean annual precipitation, temperature, relative humidity, and wind velocity of 1500 mm, 15°C, 85%, and 2.5 ms^{-1} respectively.

The physical and hydraulic properties of the soils at the Okayama University Research farm and that for the soil at the Soja site is presented in Table 1. It is significant to note that all the sites were located on reclaimed rice fields. Generally, differences in the physical and hydraulic properties will reflect the differences in the reclamation methods used and also the source or nature of the transported topsoil. A specific difference that was observed in the field related to the soil at the Soja site. The topsoil (up to about 40 cm) was mixed with rice straw (plant material) at various stages of rottenness. This feature enhanced aggregation in the topsoil giving it quite a different physical and hydraulic characteristic from the subsoil. This is observed in Table 1 where the topsoil has low bulk density values coupled with high saturation water content and saturated hydraulic conductivity.

3.2 *Measurements*

The suction potential of the soil water was monitored suing mercury manometer tensiometers with porous ceramic cups at the Okayama University Research farm sites. At the Soja site, an automatic recording tensiometer (i.e.

pressure transducer attached to porous cup) was used. Except for the Soja site where the installed depths of tensiometer is 10, 20, 30, and 40 cm, at the other sites the tensiometer was installed at depths of 5, 15, 25, 35, 50, and 70 cm. In the case of the mercury manometer attached tensiometers measurements were made daily at 18:00 o'clock (local time); even though the automatic recording tensiometer had the ability to give measurements at short intervals (say, every minute), the measurement value corresponding to 18:00 o'clock (local time) was used in all analysis of data. For the determination of soil water contents, laboratory determined soil moisture retention curves were indirectly used.

Based on the soil moisture characteristic curves determined at the different depths of measurement the soil profile was divided into different layers at the various sites (see Table 1) for the purposes of simulation. The basic criteria for this division into layers was based on the dry bulk density because it was thought that its effect on the hydraulic properties was great. The micrometeorological data used as driving variables in the model (i.e. temperature, humidity, precipitation, net radiation, and wind velocity) were measured at the experimental site. With the exception of the Soja site where monitoring took place in a vinyl house, the others took place in open fields. Potential evapotranspiration was calculated based on the Penman (1948) equation and since the vinyl house was enclosed, a constant value of 0.5 ms^{-1} was used as the wind velocity (this parameter was not measured). This value was chosen arbitrarily taking into consideration the fact that in the vinyl house the wind velocity cannot be said to be zero.

Leaf area index (LAI) and soil cover ratio were also measured and used as input in the water balance model. The Energy balance - Bowen ratio approach was used in measuring daily evapotranspiration from the open fields. In the vinyl house the Energy balance - Bowen ratio method could not be applied and it was thought that the actual evapotranspiration was equal to the potential. Root development (i.e. rooting depth) was observed in the field every two weeks till a maximum depth of rooting was achieved by selecting two plants at each observation time at all sites.

For the Soybean experiment, the initial groundwater level was 67 cm from the surface but this increased after about three weeks beyond the maximum level of a 1 m piezometer installed in the field. Monitoring was therefore discontinued. The groundwater level fluctuated between 99 cm and 128.8 cm with an average of 120.7 cm from the surface in the case of the Pumpkin experiment over the period of measurement. At the Egg Plant site, even though the groundwater level was not monitored in this particular season, it fluctuated between 50 cm and 100 cm with an average of 60 cm during the following cropping season.

3.3 *Simulation model*

The SWAP93 model (Wesseling et al., 1994), which predicts water contents and actual evapotranspiration with good resolution was used in this work to simulate water movement in the field. The model is based on numerical solution to the one-dimensional Richards' equation for vertical flow. Lateral movement due to drainage is evaluated using approximate equations that are imposed as boundary conditions on the solutions to the Richard equation. The model can consider up to five soil layers having different physical properties. Climatological data including daily rainfall and potential evaporation and transpiration are used to specify the boundary condition at the top of the profile. Flux in the saturated zone at the bottom of the profile is calculated by a steady state equation developed by Ernst. Six other bottom boundary conditions can be considered. A detailed description of the model is given by Wesseling et al. (1990) and Abenney-Mickson et al., (1995). For this particular study the Neumann condition, where flux is specified as the lower boundary was applied. In the case of Soybean free drainage at the bottom, and for Pumpkin and Egg Plant no-flux boundary was applied.

Table 1a: Physical properties of the soil at the Soja site together with the optimized parameter values of the soil hydraulic functions

Soil Layer	ρ_b (g.cm^{-3})	Clay (%)	Silt (%)	Sand (%)	Texture*	θ_r	θ_s	K_s	α (cm^{-1})	n
				van Genuchten parameters						
0-25 cm	0.74	14.40	19.10	66.50	SL	0.00	0.62	2073.60	0.0178	1.110
25-45 cm	0.95	14.40	19.10	66.50	SL	0.21	0.46	2073.60	0.0091	1.304
45-135 cm	1.54	31.26	30.22	38.53	CL	0.16	0.36	0.86	0.0032	1.260
Fayer and Simmons modified parameters						θ_a				n_n
0-25 cm						0.20	0.62	2073.60	0.0178	1.337
25-45 cm						0.21	0.46	2073.60	0.0091	1.304
45-135 cm						0.16	0.36	0.86	0.0032	1.260

* : **SL** - Sandy Loam; **CL** - Clay Loam

Table 1b: Physical properties of the soils at the Soybean and Pumpkin sites, together with the optimized parameter values in the soil hydraulic functions

Soil Layer	ρ_b (g.cm^{-3})	Clay (%)	Silt (%)	Sand (%)	Texture*	θ_r	θ_s	K_s	α (cm^{-1})	n
				SOYBEAN SITE						
0-40 cm	1.32	6.89	44.23	48.88	SL	0.14	0.43	416.74	0.0806	1.305
40-100 cm	1.54	8.47	25.42	66.11	SL	0 .12	0.36	458.35	0.0529	1.468
				PUMPKIN SITE						
0-20 cm	1.47	29.29	26.61	44.10	SCL	0.00	0.42	47.13	0.1061	1.036
20-30 cm	1.48	31.26	30.22	38.53	CL	0.22	0.38	31.80	0.1500	1.077
30-40 cm	1.38	31.26	30.22	38.53	CL	0.00	0.45	58.98	0.3974	1.039
40-60 cm	1.58	12.31	6.87	80.83	SL	0.07	0.34	146.93	0.1920	1.154
60-110 cm	1.64	12.31	6.87	80.83	SL	0.05	0.31	110.21	0.2253	1.253

* : **SL** - Sandy Loam; **SCL** - Sandy Clay Loam; **CL** - Clay Loam

3.4 *Soil property inputs*

One of the barriers to the application of all soil water simulation models, including SWAP93, is the difficulty of determining soil property inputs. One of the important properties is saturated hydraulic conductivity, K_s. While there are several methods of measuring K_s, it is often difficult to obtain at the time it is needed (Skaggs, 1976; 1981). Much more difficult to determine are the soil water characteristic (also called soil water retention or pF curve) and the unsaturated hydraulic conductivity function which are needed to calculate the upward flux relationship required as a model input. Either rapid methods measuring these unsaturated functions, or reliable methods of predicting them from more basic soil property data are used. In this study, the analytical expressions of van Genuchten (1978) and Mualem (1976) were used to describe the unsaturated functions mentioned above.

Van Genuchten's expression for the soil water retention characteristics is

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \frac{1}{\left[1 + \left(\alpha|h|\right)^n\right]^m} \qquad [5.1]$$

where S_e is effective saturation, θ_r is the residual volumetric water content (cm^3cm^{-3}), θ_s is the volumetric water content at saturation (cm^3cm^{-3}), and α, n, and m are empirical parameters. Since the topsoil of the Soja site was mixed with a lot of rotten plant material (i.e. implying aggregation), it was found that the van Genuchten approach did not describe the soil water retention characteristic adequately. Even though the Durner's (1992) multimodal model can describe the water retention characteristic with a better accuracy, employing it in the water balance model is a little difficult because of the large number of parameters. A modified function introduced recently by Fayer and Simmons, (1995) was therefore used for the description of retention characteristics for this soil. In the modified function, the residual water content of van Genuchten (1978) is replaced with an adsorption equation (Campbell and Shiozawa, 1992). The modified function retains the form of the original function in the wet range and the form of an adsorption equation in the dry range.

The modified function is written in the form of van Genuchten's expression as:

$$S_e = \frac{\theta - \chi\theta_a}{\theta_s - \chi\theta_a} = \frac{1}{\left[1 + \left(\alpha|h|\right)^n\right]^m} \qquad [5.2]$$

where χ is a parameter dependent on soil matric suction h, and θ_a is the new residual representing adsorption soil water content (cm^3cm^{-3}). Both equations [5.1] and [5.2] can be used in conductivity models, thus allowing for the prediction of hydraulic conductivity.

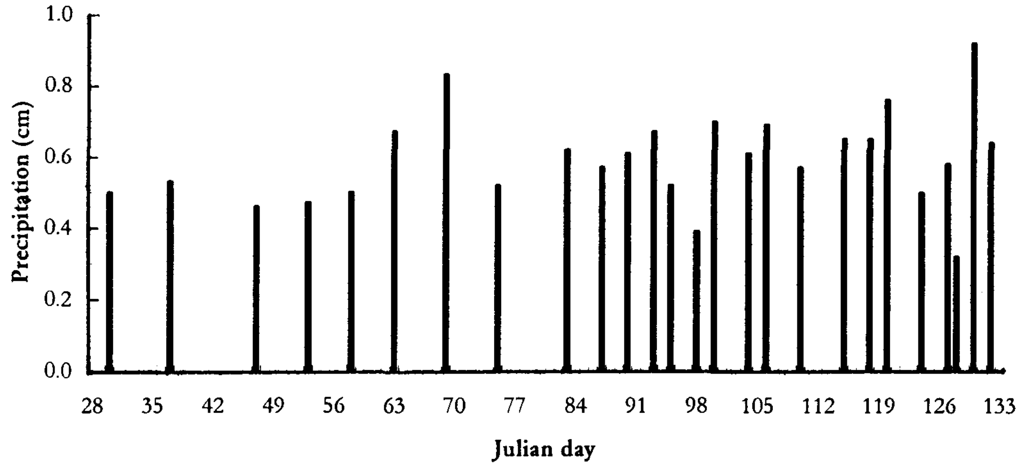
Mualem's expression for the hydraulic conductivity characteristic is

$$K(S_e) = K_s \cdot S_e^l\left[1 - \left(1 - S_e^{1/m}\right)^m\right]^2 \qquad [5.3]$$

where $K(S_e)$ is the unsaturated hydraulic conductivity ($cm.d^{-1}$), K_s is the saturated hydraulic conductivity ($cm.d^{-1}$), and l is an empirical parameter (-).

4. RESULTS AND DISCUSSION

At the Soja site where the experiment took place in a vinyl house, the actual evapotranspiration rate was equal to the potential rate throughout the period under consideration, with the exception of the first three weeks or there-about (Fig. 1). The difference between actual and potential evapotranspiration during the first three weeks is attributed to the fact that the plant had just been transplanted and therefore could not transpire at the potential rate. In the mean time actual soil evaporation, E_s was matching the potential rate. After about three weeks plant growth became vigorous and the actual transpiration rate matched the potential rate. It is important to note that the data as presented in Fig. 1 is based on using the Fayer and Simmons (1995) modified retention model parameters (see Table 1).



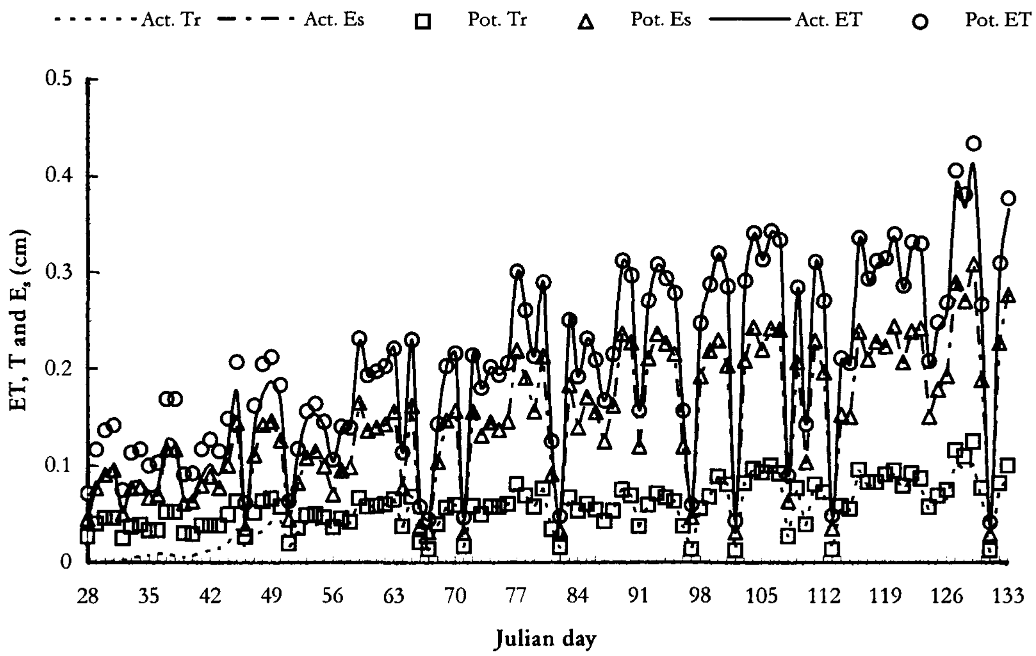


FIG. 1: CALCULATED AND ESTIMATED EVAPOTRANSPIRATION, ET TOGETHER WITH SOIL EVAPORATION, E_S AND TRANSPIRATION, T_R PREDICTED BY SWAP93 [BOTTOM]; AND PRECIPITATION [TOP] AS A FUNCTION OF TIME AT THE SOJA SITE.

Climatic parameters for the growing season and the calculated ET values for all the study years are given in Table 2. Data consists of growing season dates and lengths, measured precipitation, temperatures, relative humidity, solar radiation, wind velocity, calculated reference ET, and estimated actual ET (SWAP93). In the experiment that took place in the open field (Soybean and Pumpkin), average growing season temperatures were 2.1°C higher, rainfall was 20.9 cm higher, and daily solar radiation was 0.36 MJ/m^2 higher for the Pumpkin growth year. As a result, the calculated *ET* for the Pumpkin growth year was higher than for the Soybean growth year. These comparisons were made devoid of the fact that the length of the growing season for the two crops was not the same.

Table 2: Potential *ET* and climatic parameters for the growing season at the study sites.

Parameter	Soybean 1991	Soybean* 1991	Pumpkin 1992	Egg Plant 1994
Growing season (days)	6/05-8/09 (65 days)	6/05-8/09 (65 days)	8/04-9/19 (46 days)	1/28-5/13 (105 days)
Rainfall, cm	11.4	11.4	32.3	15.5
Runoff, cm	0.0	0.0	14.6	0.2
Seasonal avg. daily temperature, °C	25.3	25.3	27.4	17.2
Relative humidity, daily avg., %	67.6	67.6	70.0	86.1
Solar radiation, daily avg., MJ/m^2	10.65	10.65	11.01	7.39
Wind velocity, daily avg., m/s	1.5	1.5	1.3	0.5
Calculated reference ET, cm	20.5	20.5	23.9	21.6
Estimated actual ET, cm	12.6	10.7	14.2	20.8

* — Soybean simulation under which hysteresis was considered.

The low values of estimated actual *ET* compared to the calculated reference *ET* can be attributed to the fact that in some cases (e.g. Pumpkin growing season) there was too much rainfall over a short period leading to water-logging. This created anaerobic conditions in the plant root environment thereby reducing evapotranspiration rate. In yet other cases too (e.g. both Pumpkin and Soybean growing seasons), there were long periods without rainfall or irrigation which led to very low moisture content values. This led to very low moisture availability to the plant and a possible closure of the stomata leading to a reduction in the evapotranspiration rate. For the crop to survive under such conditions water had to move from below the profile into the root zone in order to make up for the water requirement of the crop. (see Table 3 below).

In the case of the experiment conducted in the vinyl house, the daily average solar radiation was about 60% of that measured outside the vinyl house (12.17 MJ/m^2). Even though the daily average temperature inside the vinyl house was low compared to the experiment conducted in the open field, the relative humidity was quite high. The estimated actual *ET* was almost equal to the calculated reference *ET*. This could be due to the fact that conditions inside the vinyl house was optimal, allowing the plant to transpire at the maximal rate with the exception of the first few weeks of growth when the plant was still young (see Fig. 1).

Groundwater use by the crops relative to total water use is presented together with the soil profile depth which was considered in Table 3. Consumption of water from water table sources under the Soybean experiment, with hysteresis considered, was greater than the case with hysteresis not considered. This could be due to the fact that the soil hydraulic property with hysteresis considered was capable of utilizing water in the dry zone more effectively because of the use of the dry scanning curve during simulation.

Generally, consumption of water from underground sources was greatest in the Soybean experiment, followed by the Pumpkin experiment, and then the Egg Plant experiment in that order. This might have something to do with the total soil profile depth considered in each experiment. However, the magnitude of water consumption suggests that this is not the only factor or the main one. The possible explanation therefore will be the type of soil at each experimental site, and the kind of crop coupled with the root characteristics.

Table 3: Water use and depth of soil profile.

Crops	Irrg. + Precip. (cm)	Use from GW (cm)	Δ Soil storage (cm)	Total water use (cm)	GW use (% of Total)	Profile depth (cm)
Soybean (no-hysteresis)	11.4	5.5	-8.1	19.4	28.35	100
Soybean (hysteresis)	11.4	7.4	-7.9	19.4	38.14	100
Pumpkin	32.3	1.3	0.2	17.6	7.39	120
Egg Plant	15.5	0.3	-8.4	21.1	1.42	135

The experiments in this study were such that there were no replications, making statistical analysis of the results difficult. In future such studies, at least the yield parameter should be monitored so that the significance of the groundwater use as a percentage of total water use, and water use efficiency can be tested using analysis of variance (Anova) techniques. For the purposes of irrigation scheduling, since the field situation is such that there is variation in the actual water table elevation, one method would be to use flux as the lower boundary where water table depth is not available (as was done in this study using the SWAP93 model). Another alternative would be to monitor water table elevation continuously and adjust the amount of water applied for each irrigation according to the water table depth during the interval preceding that irrigation.

Seasonal use of water from the field sites can be compared with *ET* estimates from the SWAP93 program. The model estimated seasonal *ET* values for Soybean equal to 69% of measured values (non-hysteretic), and 58% of measured values (hysteretic). For Pumpkin, the model estimated *ET* equal to 62% of measured *ET* over identical intervals. The relatively lower estimates of *ET* by SWAP93 can be attributed to particular advective conditions of the field sites, which were small in area. For the Egg Plant, *ET* could not be measured by the energy balance approach but it was thought that optimal conditions existed in the vinyl house for *ET* to be equal to the potential. Under such conditions the estimated actual *ET* equal 99% of the potential reference.

Groundwater use as estimated by SWAP93 for the Soybean growth season was 5.5 cm (non-hysteretic), and 7.4 cm (hysteretic) (Table 3). This amounted to an average of 0.8 and 1.1 mm daily respectively for the non-hysteretic and hysteretic conditions. For the Pumpkin and Egg Plant growth seasons estimated groundwater use was 1.3 and 0.3 cm respectively. This works out to a daily average of 0.3 and 0.03 mm. If these values are to be considered in planning irrigation scheduling for these crops under the conditions above, it is evident that some savings in irrigation water would be possible.

5. CONCLUSIONS

The SWAP93 water balance model has been used successfully to estimate the contributions of high (perched) water tables to the water requirement of some commonly grown crops in the Chugoku region of Japan. A critical look at the values obtained shows some level of reasonability if the soil type and hydraulic properties are taken into consideration. However, the present values can only be used qualitatively as there are no field measured values to compare with. For any quantitative analysis to be made field measured values would have to sought. This was not done in this study as equipment was not available for such kind of measurements to be made.

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