MODIFICATION OF THE FAO-56 SPREADSHEET PROGRAM FOR SCHEDULING SUPPLEMENTAL IRRIGATION OF WINTER CROPS IN A MEDITERRANEAN CLIMATE

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ABSTRACT. *Population growth and urbanization are increasing demands on limited renewable water resources in the Mediterranean region. Irrigation is a major water user, and so there has been increased effort to improve its efficiency. Using supplemental irrigation to increase and stabilize the yield of rain-fed crops is potentially an efficient use of water, but scheduling irrigation is difficult because of the unpredictability of the weather. The objectives were: (1) to develop a simple irrigation* decision *support tool based on the irrigation scheduling spreadsheet program presented in FAO Irrigation and Drainage Paper 56 (Allen et al., 1998), but with modifications that allow its use in supplemental irrigation; and (2) to evaluate the effect of uncertainties in the input parameters using a 27-year daily climate record for northern Syria. Modifications to the FAO model were incorporated that allow infiltrated rainfall to be stored within the potential root zone so that it can be accessed by the crop later in the season when the root depth has increased. The modified model was tested using a 4-year data set on supplemental irrigation of wheat at Tel Hadya in which a neutron probe was used to measure soil water content in 15 cm increments within the soil profile. The modified model predicted the depth of water within a 1.2-m root zone with a mean absolute error of 23 mm compared to the measured values. Applying the irrigation schedule developed by the model for each year of the climate record and a specified set of conditions to a range of conditions typical for the local area reduced the ratio of actual crop ET to non-stressed crop ET by a maximum of 0.03 at most, from 0.93 to 0.90. This model has potential for use as an irrigation decision support tool at the farm level and also at the level of strategic planning on irrigation water use.*

Keywords. *Rain, Evapotranspiration, Weather, Soil water, Irrigation scheduling.*

The Mediterranean region, which includes countries from southern Europe, North Africa, and the Middle East, experiences a climate characterized by cool temperatures, low reference evapotranspiration (ET_0), and rainfall during the winter; and high temperatures, high ET_0, and little or no rainfall during the summer. Annual rainfall is significantly lower than annual ET_0. Cropping systems encompass the entire range from rain-fed to fully irrigated. Irrigation enables more profitable crop production, but uses large amounts of water. Increasing population, urbanization, and industrialization within the region is putting pressure on the often limited water resources. Because irrigation consumes a large portion of the regions total water use (Allen et al, 1998) and because water will be increasingly taken away from agriculture for use in other sectors, any reduction in irrigation water use through improvements in efficiency will help to maintain production levels with less water.

An example of a Mediterranean climate, which shows cumulative rainfall and crop evapotranspiration (ET_c) for wheat for Tel Hadya, Syria is presented in figure 1. The cumulative daily crop evapotranspiration deficit remains negligible from November (the beginning of the growing season) until March, but after March ET_c increases rapidly and rainfall decreases, resulting in a rapid increase in the deficit. One of the most efficient uses of water is to supplement winter rainfall in areas such as this where rain-fed production is possible but where yields are limited by water stress in the latter part of the growing season. For example, the increase in yield made possible by supplemental irrigation (SI) of wheat in Syria can result in irrigation water productivity (increase in wheat yield per unit volume of irrigation water) of more than 2 kg/m^{-3} (Oweis and Hachum, 2006). Deficit SI can result in even higher irrigation water productivity, although at the expense of lower yield (Zhang and Oweis, 1999).

Although well-managed irrigation has national and regional benefits from a water productivity viewpoint, farmers worldwide tend to apply excess water in order to eliminate the risk of yield losses from applying too little. This is particularly so where the incremental cost of applying irrigation water is relatively low compared with the economic return realized from increased yield. Surface water supply systems often provide water on a fixed schedule at low cost, and groundwater is often available for the cost of pumping it without regard to its sustainable use. Other factors

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may also impact irrigation decisions, such as equipment and labor availability.

In Syria, wheat production currently accounts for more than half of the irrigated land and more than 30% of the non-irrigated land (MAAR, 2006). The fraction of the total wheat production area that is irrigated has increased substantially, from 14% in 1981 to 45% in 2005. However, during the same period the total land irrigated by groundwater more than tripled, from 250,000 to 860,000 ha (MAAR, 2006), and this has led to excessive drawdown in some aquifers. The MAAR has adopted a plan for reducing water use by irrigated agriculture that provides economic incentives and technical assistance to farmers to help them convert from surface irrigation to potentially more efficient sprinkler and drip irrigation (NAPC, 2003). Schweers et al. (2004) found that farmers in the Khanasser Valley in northern Syria who applied supplemental irrigation to wheat by surface irrigation applied more than double the required water needs. However, regardless of the type of irrigation, it is often the on-farm management and irrigation decisions that determine whether water is used efficiently.

In the case of supplemental irrigation of winter crops in Mediterranean countries, the soil profile, particularly near the surface, is very dry in the fall. When the crop is planted, typically in November, the first rains have wetted the surface to allow germination. A relatively light irrigation at planting is an option farmers consider if necessary to ensure adequate crop establishment. There are usually no more irrigations until the spring. Rainfall during the winter is generally sufficient to meet crop water requirements and provide some recharge to the soil profile for later use by the crop. However, the depth of wetting may not be sufficient to allow root development at the same rate as under full irrigation. During dry years or when rain is poorly distributed, stress occurs during winter and early spring. There are also practical constraints that might not apply to a fully irrigated production system, such as that farmers will not usually apply frequent light irrigations because of the labor required to do so. Instead, once the weather starts warming up and rainfall events become less frequent, farmers will apply a few large irrigations sufficient to refill the root zone.

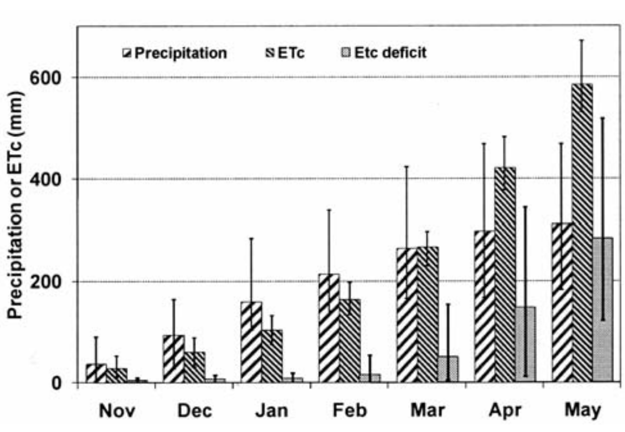

Figure 1. Cumulative daily precipitation, wheat evapotranspiration and evapotranspiration deficit during the growing season at Tel Hadya, Syria. The bars show the value at the end of each month averaged over the 27 seasons from 1979/80 to 2005/06 The error bars show the corresponding minimum and maximum values.

Making regular direct in-field measurements of soil water content (SWC) to schedule irrigation is usually too laborious, time consuming, difficult, or expensive for individual farmers. A more feasible approach is to estimate SWC based on parameters that can be more easily measured. A large effort has been made to model the various processes that determine SWC and movement. Models of SWC range from the simple to the complex. Bastiaanssen et al. (2007) provide a comprehensive review and reference source for many of the models developed for irrigation and drainage during the last quarter century. The simplest models are based on the water balance approach, in which irrigation, rainfall, and sometimes upward movement from below the root zone all increase SWC while evaporation, transpiration, and drainage decrease it. More complex models take account of water fluxes within the soil profile, but they often require more parameters and knowledge on the part of the user. The simpler a model is in terms of the required data and parameters, the easier it is to use. However, if the model is too simplistic in terms of physical processes and/or requires site specific empirical coefficients to perform satisfactorily, it may be of limited value as a practical tool.

The internet has enabled easy access to up-to-date weather information and evapotranspiration estimates from automated climate stations, making the use of evapotranspiration-driven water balance models for irrigation scheduling more generally applicable. Examples of online networks include CIMIS (California Irrigation Management Information System, www.cimis.water.ca.gov); AGRIMET (www.usbr.gov/pn/agrimet/) in the northwest states; and AEMN (Automated Environmental Monitoring Network, www.griffin.uga.edu/aemn) in Georgia, all from the United States, and www.agric.wa.gov.au in Western Australia. Climate station networks may also include irrigation scheduling programs that can directly use the climate data, such as WISE (Washington Irrigation Scheduling Expert, www.sis.prosser.wsu.edu/wise.htm); AZSCHED (Arizona Irrigation Scheduling System, www.ag.arizona.edu/crops/irrigation/azsched/azsched.htm) and Wateright (www.wateright.org). Another approach is to use a spreadsheet, such as Kansched and KISCORN from Kansas (www.oznet.ksu.edu/mil/ToolKit.htm). But it should be noted that these programs are generally set up to schedule full irrigation. However, in Syria, as in most other countries in the Mediterranean region, there is currently no system and little services to assist farmers with their day to day irrigation decisions. There is a clear need for simple and robust methods that can be used by agricultural research and extension personnel to provide farmers with real-time irrigation scheduling advice and to help make sound water allocation decisions.

FAO Irrigation and Drainage Paper 56 (Allen et al., 1998) is a standard reference for crop evapotranspiration. It provides a comprehensive description of the widely accepted Penman-Monteith method for estimating ET_0 from data on air temperature, humidity, wind speed, and solar radiation; and procedures for computing ET_c under standard and non-standard (stressed) conditions. This publication also includes a spreadsheet program (available from the University of Idaho web site, www.kimberly.uidaho.edu/water/fao56/index.html) for irrigation scheduling under standard conditions. In this spreadsheet program the root zone is treated as a single layer from which water is depleted by the crop. The root zone increases linearly to its maximum value as a function of time, while water depletion from the root zone determines how much irrigation is needed to refill it to field capacity. The spreadsheet was developed for full irrigation and cannot be directly used for supplemental irrigation because of some of the explicit and implicit assumptions. One of these assumptions is that the complete profile is at field capacity, except for a user-specified deficit in the surface layer due to evaporation. Thus, the moisture content in the root zone increases when it expands downward due to root growth, and any drainage from the current root zone leaches directly from the profile and is therefore not available for later use.

A multi-layer model can better account for the movement of water and the growth of roots within the profile, but it will be more complex. But even some of the more advanced irrigation scheduling and soil water balance models that have been used for supplemental irrigation of wheat (e.g. Oweis et al., 2003) do not include a dynamic root growth function. If sufficient data are available, crop models (e.g. Pala et al., 1996) could also be used to provide additional management and production information. We sought a compromise between the potentially higher accuracy but greater complexity of multi-layer and crop models, and the less realistic but greater simplicity of a single layer model such as the FAO-56 spreadsheet-based model. Our goal was to provide agricultural research and extension personnel in the Mediterranean region with a robust and user-friendly tool to help farmers make daily irrigation scheduling decisions and to aid with the development of water management and allocation strategies.

Our specific objectives were to build upon the FAO-56 spreadsheet program to (i) modify and evaluate it for scheduling of supplemental irrigation in a rain-fed Mediterranean environment; (ii) evaluate the effect of uncertainties in the model's input parameters on its usefulness as an irrigation and water management tool in the region.

Materials and Methods

Soil Water Balance Model

The FAO-56 spreadsheet program estimates actual crop water use (ET_a) from the reference evapotranspiration (ET_o), using a crop coefficient (K_c); a soil evaporation coefficient (K_e) to account for evaporation directly from a moist soil surface; and a stress coefficient (K_s) to account for reduced crop water use when SWC is limiting. The model uses the dual crop coefficient method that separates evaporation from transpiration. This process can be expressed as:

$$ET_a = (K_s\, K_{cb} + K_e)\, ET_o \qquad (1)$$

where ET_a is the actual crop evapotranspiration (mm); ET_o is the reference evapotranspiration (mm); K_s is a stress coefficient with values from 0 (fully stressed) to 1 (not stressed); K_{cb} is the basal crop coefficient; and K_e is the soil evaporation coefficient. K_e is a function of the evaporation reduction coefficient (K_r), the maximum and basal crop coefficient, and the exposed and wetted soil fraction (Allen et al., 1998).

Irrigation is automatically initiated when soil water in the root zone falls below the readily available water level (RAW). The readily available water is indicated by p, the threshold at which stress starts to occur, expressed as a fraction of the total available water (TAW), the water held between field capacity (FC) and wilting point (WP). Hence RAW = p TAW, and under well-managed full irrigation SWC should be maintained above the stress level and the value of K_s should never decrease below its maximum value of 1.0. However, when SWC does fall below p, K_s decreases linearly towards its minimum value of 0.0 at WP. Similarly, the soil evaporation reduction coefficient (K_r) is at its maximum value of 1.0 until the readily evaporable water (REW) has evaporated, and then decreases linearly to 0.0 as evaporation approaches the soil's total evaporable water (TEW).

To model rain-fed and supplemental irrigation production systems, we modified the FAO-56 spreadsheet program by dividing the potential root zone into two dynamic layers (fig. 2). Layer 1 extends from the surface down to the current root depth, with the remainder of the potential root zone being layer 2.

Roots are allowed to grow downwards only when the SWC in either layer 1 or layer 2 is above a user-specified threshold value, defined as a percentage of available water content. When water content is above the threshold, the daily increase in root depth is a constant, subject to the defined maximum root depth and the user-specified period of root growth.

The initial depth of layer 1 should be sufficiently large (at least equal to or larger than the depth of the soil from which water evaporates) to be able to store some water before it drains into the usually much dryer layer 2. Because roots start growing from the actual planting depth, layer 1 only starts expanding after the roots have reached the bottom of the initial value of layer 1. This process is expressed as follows

$$\begin{aligned}\Delta RZ_i &= RG \text{ for } SWC1_{i-1} \geq (q \times TAW1_{i-1}) \\ &\text{or } [SWC2_{i-1} \geq (q \times TAW2_{i-1}) \text{ and} \\ &L1_{i-1} < RZ_{max} \text{ and } T_{PL} \leq i \leq T_{RG}]\end{aligned} \qquad (2a)$$

$$\Delta RZ_i = 0 \text{ if all above conditions are not met} \qquad (2b)$$

where ΔRZ_i is the change in root depth on day i (mm); RG is the vertical root growth rate (mm/d); $SWC1_{i-1}$ and $SWC2_{i-1}$ are the water contents in layers 1 (root zone) and 2, respectively, on day i-1 (mm); q is the threshold for root growth, expressed as a fraction; $TAW1_{i-1}$ and $TAW2_{i-1}$ are the total available water contents in layers 1 and 2, respectively (mm) on day i-1; $L1_{i-1}$ is the depth of layer 1 on day i (mm); RZ_{max} is the maximum potential root zone depth (mm); and T_{PL} and T_{RG} are the planting date and the date that root growth ceases, respectively. Thus, the root zone is computed as:

$$RZ_i = RZ_{i-1} + \Delta RZ_i \qquad (3)$$

where RZ_i and RZ_{i-1} are the root zone depths on day i and day i-1 (mm). The depth of layer 1 is given by:

$$L1_i = RZ_i \text{ for } RZ_i \geq L1_{PL} \qquad (4a)$$

$$L1_i = L1_{PL} \text{ for } RZ_i < L1_{PL} \qquad (4b)$$

where $L1_i$ is the depth of layer 1 on day i (mm); and $L1_{PL}$ is the initial depth of layer 1 at planting (mm).

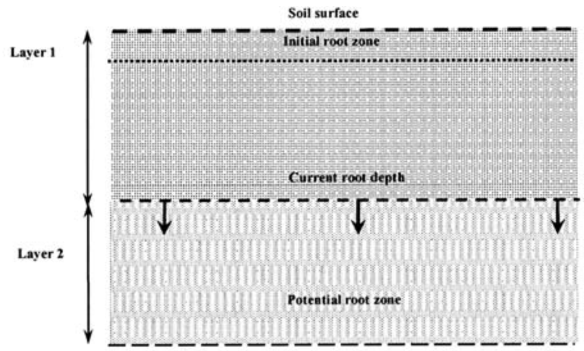

Figure 2. Division of the root zone into two layers under rain-fed conditions.

This process represents a simplified model of the growth of roots following downward water movement through cracks and macropores. In an earlier version of the model (Bruggeman et al., 2005), the root depth was constrained to the zone that had been fully recharged to FC. However, the simulated root depths were often smaller than the root depths ascertained from the pattern of soil water extraction shown by the measurements of soil water with depth.

Rainfall and irrigation replenish layer 1, while evaporation, transpiration, and drainage deplete it. Following a rainfall or irrigation event large enough to cause layer 1 to exceed field capacity, the excess will drain into layer 2 and be stored there, thereby increasing layer 2 water content. If the drainage from layer 1 into layer 2 causes layer 2 to exceed field capacity, the excess will drain out of layer 2 and the profile. The total water content in the profile is the sum of the water content of layers 1 and 2. If SWC permits sufficient root growth, layer 2 will eventually decrease to zero with layer 1 occupying the entire profile. This process is expressed by:

$$SWC1_i = SWC1_{i-1} + PPT_i + IRR_i - ET_i - DRN1_i + (\Delta RZ_i \times \theta 2_{i-1}) \quad (5)$$

$$DRN1_i = SWC1_i - (L1_i \times FC) \quad \text{for } SWC1_i > (L1_i \times FC) \quad (6a)$$

$$DRN1_i = 0 \text{ for } SWC1_i \leq (L1_i \times FC) \quad (6b)$$

$$SWC2_i = SWC2_{i-1} + DRN1_i - (\Delta RZ_i \times \theta 2_{i-1}) - DRN2_i \quad (7)$$

$$DRN2_i = SWC2_i - (L2_i \times FC) \quad \text{for } SWC2_i > (L2_i \times FC) \quad (8a)$$

$$DRN2_i = 0 \text{ for } SWC2_i \leq (L2_i \times FC) \quad (8b)$$

where PPT_i, IRR_i, and ET_i are rainfall, irrigation, and evapotranspiration on day i (mm) and $SWC1_{i-1}$ and $SWC2_{i-1}$ are the water contents of layer 1 and layer 2, respectively, on the previous day (day i-1) (mm); ΔRZ_i is the change in layer 1 on day i resulting from root growth (mm); $\theta 2_{i-1}$ is the water content of layer 2 on day i-1 (volumetric fraction); $DRN1_i$ and $DRN2_i$ are drainage from layers 1 and 2, respectively, on day i (mm), $L1_i$ and $L2_i$ are the depths of layer 1 and 2 on day i (mm); and FC is the field capacity of the soil (volumetric fraction).

Model Evaluation Using Field Trials

To evaluate the modified spreadsheet program, a data set from a multi-year experiment on supplemental irrigation of durum wheat (*Triticum turgidum* L.) was used (Oweis et al., 1999). The experiment was conducted at ICARDA's main research station at Tel Hadya, near Aleppo in northern Syria (36.01° N, 36.93° E; 284 m above sea level) where the soil is a deep red clay, classified as a Calcixerollic Xerochrept, and representative of soils in the region (Ryan et al., 1997). The data set includes the four consecutive cropping seasons 1992/1993, 1993/94, 1994/95 and 1995/96. In all years, wheat was planted in early November and received no irrigation until spring (March or April). The wheat was adequately fertilized with 40 to 50 kg P/ha and 100 kg N/ha. Daily climate data from an automatic station at this location were used to compute ET_0. The crop was irrigated at a rate sufficient to replenish the root zone to field capacity based on a p value of 50%.

The values we used for the variables required by the model came from Allen et al. (1998) (see table 1). In all years, the development stage began around 1 January and continued to approximately 1 April, followed by the mid stage which lasted until 15 May, and the end stage which lasted until the end of the crop season on 25 May. The total length of the growing season was 200 days.

Soil water content was measured during the season in 15-cm increments down to at least 1.50 m using a neutron probe, while SWC in the top 15-cm was determined using cored soil samples. Soil water content below 1.2 m did not change much over the season, indicating that this would be a reasonable estimate of maximum effective rooting depth or depth of water infiltration. The field capacity (FC) of this soil is in the range 36 to 40% while the wilting point (WP) is 20 to 24%. Analysis of the measured volumetric soil water data indicated that a value of 38% for FC and 22% for WP would best represent the soil at the field sites used during this study.

The value of TEW for the top soil was computed from the FC and WP, as specified by Allen et al. (1998), considering an effective depth of the soil evaporation layer of 20 cm. Although the depth to which evaporation takes place in these cracking clay soils is deeper, soil moisture observations indicate that evaporation during the majority of the crop season is restricted to the top 15 cm. The depth of the initial root zone should be equal or larger than the soil evaporation layer. If the depth of the initial root zone is too small the amount of water it can hold will also be small and rapidly depleted by evaporation. It will also drain after a relatively small rainfall and this drainage into the correspondingly larger and usually much dryer layer 2 will not have much effect in raising its water content. If the depth of the initial root zone is too large the average water contents will be too low and the roots won't grow.

Barraclough and Leigh (1984) found root growth rates for adequately irrigated winter wheat in the UK of 6 mm/d when planted in October and 12 mm/d when planted in September and related the differences to temperature. They quoted similar wheat root growth rates of 5 to 6 mm/d in winter (Gregory et al., 1978; Ellis and Barnes, 1980) and 18 mm/d in spring (Gregory et al., 1978). Sato et al. (2006) monitored

Table 1. Model input parameter values.

Symbol	Parameter	Value	Units
PD	Planting date	5-10 Nov	
$K_{cb\ ini}$	Crop coefficient in initial stage	0.15	
$K_{cb\ mid}$	Crop coefficient at mid stage	1.10	
$K_{cb\ end}$	Crop coefficient at end stage	0.40	
L_{ini}	Duration of initial stage	57	d
L_{dev}	Duration of development stage	90	d
L_{mid}	Duration of mid stage	44	d
L_{late}	Duration of late stage	10	d
FC	Field capacity	38	% by volume
WP	Wilting point	22	% by volume
p	Water depletion at which crop stress starts	50	% (of TAW)
REW	Readily evaporable water	8	mm
TEW	Total evaporable water	54	mm
RZ_{ini}	Initial root zone	0.20	m
RZ_{max}	Maximum potential root zone	1.20	m
RG	Root growth rate	11	mm/d
q	Threshold for root growth	50	% (of TAW)
Ht_{max}	Maximum crop height	0.75	m

root growth of bread wheat planted on 23 December in Tel Hadya and found that, under non-water limiting conditions, roots had reached the 45- to 60-cm layer after 56 days, indicating an approximate root growth of 10 mm/d. Also for wheat at Tel-Hadya, but in a much drier year with a 50-mm irrigation applied at planting, Izzi et al. (2007) measured an average downward root growth of 7 mm/d during the first 74 days after emergence. Although roots are generally considered to reach their maximum depth at anthesis, Brown et al. (1987) and Gregory et al. (1992) found that the roots of barley and wheat still increased in weight between anthesis and maturity. Considering the above, we used a vertical root growth rate of 11 mm/d, with roots growing from 5-cm depth at planting down to a maximum potential effective root depth of 120 cm. We used a SWC value of 50% of available water as the threshold above which root growth can proceed. This threshold corresponds to the same SWC as specified by the stress threshold. Root growth was assumed to cease towards the end of April, halfway between anthesis and maturity.

The measured values of SWC were screened to identify measurement errors. There were a total of 71 measurement days during the 4-year period. Average daily ET between adjacent measurement dates was calculated as the residual of the soil water balance, including irrigation, rainfall, and the change in SWC measured to the depth of the neutron probe access tube. The calculated daily ET on 5 of the 71 dates was found to be an unrealistic 200% greater or less than ET_0, as estimated from climate data, and so these dates were eliminated. (three in 1992/1993 and two in 1995/96).

To evaluate the model, we used the mean absolute difference between measured and predicted values, and the modified index of agreement (Legates and McCabe, 1999), which uses absolute instead of squared differences to reduce sensitivity to extreme values.

Sensitivity Analysis

A sensitivity analysis was conducted to assess the effect of uncertainties in the crop and soil parameters on the seasonal crop evapotranspiration and irrigation needs, using a 27-year daily climate record from ICARDA's Tel Hadya climate station. The parameter values for the base scenario were similar to those used for the Tel Hadya field trials, which represent fairly average conditions for the 300- to 400-mm rainfall zone in northern Syria. However, similar to farmer's practices, if the soil moisture in the top layer (20-cm) had not exceeded the soil moisture stress level (RAW) within 1 week of planting, an initial irrigation of 50 mm was given.

To estimate the soil moisture conditions at planting, simulations were started on 1 September, which is usually before the beginning of the rainy season. The initial soil moisture content on this date, after the hot and dry summer months, was assumed to be 11% in the initial root zone (0-20 cm) and 24.5% in the soil profile below. Initial moisture conditions depend not only on the soil but also on the preceding crop, management and irrigation practices, but the values represent typical conditions for the clay soils in the region, which generally exhibit dry, cracking conditions in the top 30 to 45 cm of the profile, higher moisture contents (26% to 32%) in the layers below 75 to 90 cm, and wilting point in between. The use of an average moisture content for such a variable profile is more or less compensated for by the fact that the dryer layers in the upper part of the profile are recharged first.

Selected parameters were changed, one at the time, to their expected minimum and maximum values. The relative sensitivities (RS) of the 27-year averages were computed as:

$$RS = [(O - O_b)/O_b] / [(I - I_b)/I_b] \qquad (10)$$

where O and O_b are model output parameter values of the current test run and the base run, respectively, and similarly I and I_b are the input parameter values of the test run and the base run. A fortran-version of the spreadsheet program was made to facilitate long-term analysis and data processing.

Irrigation Scheduling

To evaluate the use of the model for providing real-time irrigation scheduling advice for a larger area surrounding a climate station, the effect of applying a generic schedule to soils with different physical properties was tested. When applying the same irrigation advice to a variety of fields, it is more appropriate to develop a schedule for a soil with low water storage capacity and apply it to soils with higher storage capacities so that the irrigations will not cause drainage from the profile. Therefore, considering the soils in the area, an irrigation schedule was simulated for each of the 27 years of climate data for a relatively shallow soil (90 cm) with a relatively low water holding capacity (12%, FC = 36% and WP = 24%), thus providing a total available water capacity of 108 mm. The initial SWC below the initial root zone and evaporation layer was set at 27%, halfway between the wilting point and the crop stress level (30%). All other conditions were kept similar to those of the previous simulations. This is referred to as the *test* case.

The irrigation schedule developed for the test case was applied to the soils at Tel Hadya, which have a greater water holding capacity. Assuming a profile depth of 120 cm and a water holding capacity of 16% (FC of 38% and WP of 22%), the total available water capacity is 192 mm (78% larger than the test case). To also assess the effect of dryer or wetter initial SWC in the profile below the initial root zone, SWC from 20 to 120 cm was set either at 22% (wilting point) or at

30% (crop stress level). These are referred to as the *dry* and *wet* cases, respectively. Irrigation schedules were simulated for the dry and wet cases, and also for the dry and wet cases but imposing the same schedule developed for the test case.

Results and Discussion

Model Evaluation Using Field Trials

A summary of ET_a as estimated by the model, along with precipitation and irrigation for the four cropping seasons, is shown in table 2. The largest total irrigation amount was in the 1992/1993 season, during which rainfall was low. However, the individual irrigations were likely excessive because the model predicted that three of the four irrigations resulted in significant drainage from the profile (178 mm over the season). No drainage was predicted in the other three seasons. In all four seasons the sum of irrigation and rainfall exceeded estimated ET_a . In the 1993/1994, 1994/1995, and 1995/1996 seasons the excess was in the range 70 to 140 mm, and this was stored within the profile at the end of the season. In the 1992/1993 season the excess was about 300 mm, which could not all be stored within the profile and so resulted in drainage.

Measured and predicted values of SWC in the top 1.2 m of soil for full supplemental irrigation are presented in figure 3 for each year. The mean absolute error of 23 mm appears acceptable considering potential sources of error from other factors, such as in the soil water measurements made by the neutron probe, and in the model inputs, such as amount of rain or irrigation water applied. For example, a systematic error in the volumetric moisture content reading of 0.02 m^3/m^3 would result in an error of 24 mm over the entire 1.2-m profile at the site. Similarly, a stationary sprinkler irrigation system with good performance and operating under low wind conditions may have a coefficient of uniformity (CU) of 85%. This implies that, for 100 mm of irrigation, there will be an average absolute deviation of 15 mm in the amount of water applied anywhere in the field.

Measured and predicted values of SWC in the entire profile during both the rain-fed and irrigated periods in the 1993/1994 season are presented in figure 4. This relatively wet season (360-mm rain between 1 November and 31 May) caused SWC to increase to close to FC by the end of February. The stored soil water was then extracted by evapotranspiration until the first of three irrigations replenished the profile to close to FC again. By this time the rate of soil water extraction was increasing as a result of higher evapotranspiration rates. Soil water content before the final irrigation had declined to below the desired p level of 50%, likely causing some stress. At the end of the season the model predicted some residual water in the profile that the crop may not have been able to use but which might be available to a subsequent crop.

Table 2. Estimated ET_a, precipitation (PPT), and irrigation (IRR) from 1 November to 31 May during the four cropping seasons.

	Cropping Season			
	1992/93	1993/94	1994/95	1995/96
ET_a (mm)	520	610	513	503
PPT (mm)	276	360	294	395
IRR (mm)	548	323	354	180

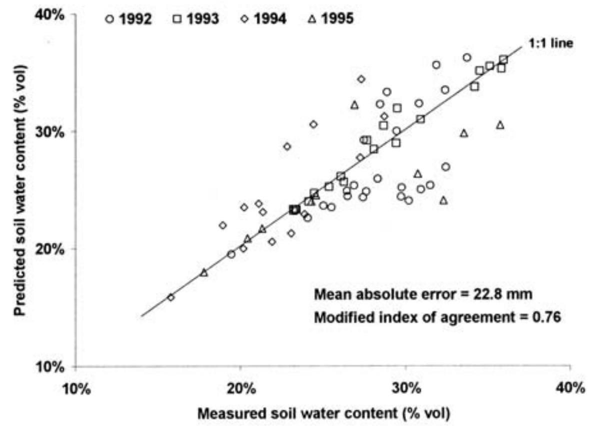

Figure 3. Measured and predicted volumetric soil water content under full supplemental irrigation during the 1992/93, 1993/94, 1994/95 and 1995/96 cropping seasons.

Soil water content in the current root zone of the crop is important for irrigation scheduling. However, measuring the root zone over the course of the season is difficult and so is rarely done. Measurements of SWC with depth at intervals over time can sometimes help in determining root depth. For example, a decrease in SWC in the upper part of the profile between two dates, but not at deeper depths between the same dates, can indicate water extraction by roots from the upper zone. However, this becomes more difficult to quantify when rain or irrigation also adds water to the same upper part of the profile.

An example from the 1994/1995 season is shown in figure 5, in which the change in measured SWC is plotted (at the midpoint of the depth increment) for a period during which there was neither irrigation nor significant rainfall but which was also long enough for significant changes in SWC from crop uptake. The change in measured SWC between the beginning of the period on 22 April 1995, and the two subsequent measurement dates before the next irrigation, 29 April and 4 May is shown. A positive change at the same depth between the dates means that SWC at the beginning of the period was higher than on subsequent measurement dates. A reduction in SWC (positive change) should primarily be due to extraction by roots. Where the change is close to zero there may be no root extraction. However, there may also be water movement within the profile, but unless data are logged continuously the two processes cannot be separated. The root depths predicted by the model at the beginning (0.91 m) and end of the period (1.04 m) are shown. These predictions are consistent with the depth at which SWC does not change significantly.

Because the actual root zone is not known, a direct comparison between measured and predicted values is not possible and so the predicted root zone must be used instead. Examples of measured and predicted SWC within the predicted root zone for 1992/1993 (a relatively dry season with 276-mm rainfall between 1 November and 30 May), and 1993/1994 (a wetter season with 360-mm rainfall) are presented in figure 6. Also shown are rainfall and irrigation, as well as the water content at WP and FC as the predicted root zone increases over the season. There is reasonable

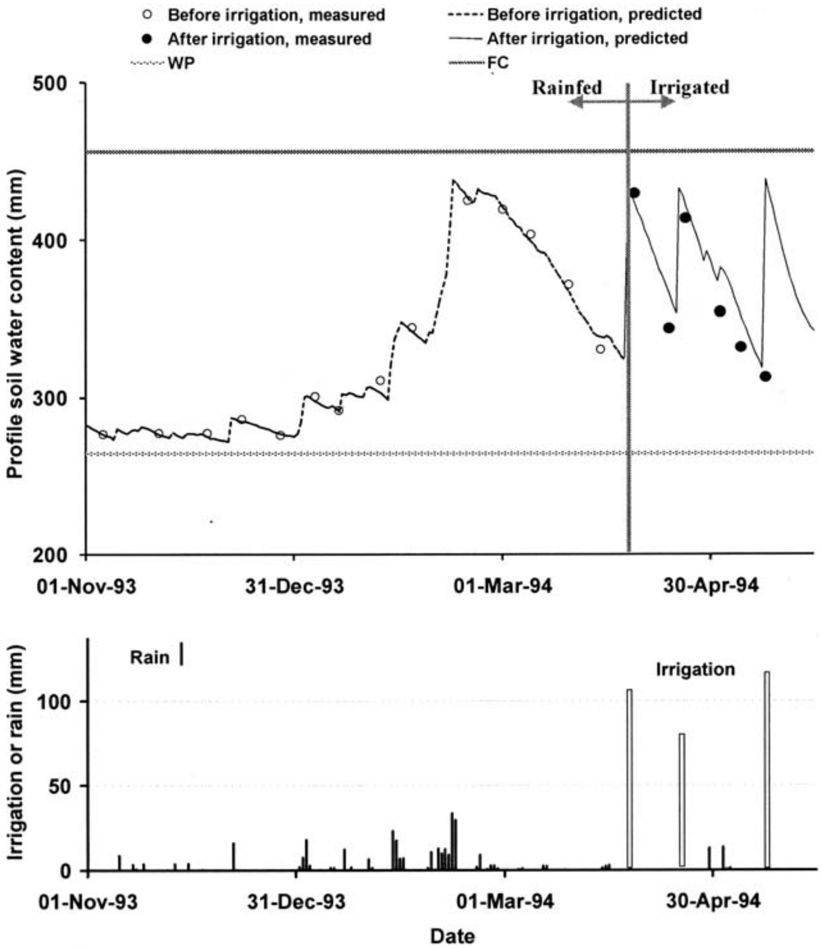

Figure 4. Measured and predicted volumetric soil water content in the 1993/94 cropping season during the rain-fed period and subsequently under full supplemental irrigation.

agreement between the measured and predicted values, such that the model would be useful in scheduling supplemental irrigation. The lower rainfall amounts in the 1992/1993 season did restrict predicted root zone development prior to the first irrigation.

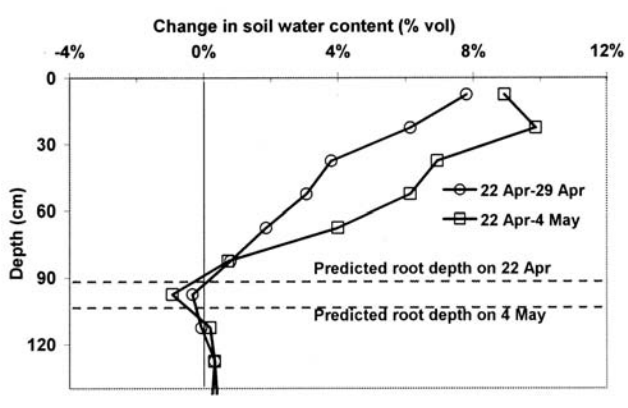

Figure 5. Change in measured soil water content with depth between 22 April and 29 April, and between 22 April and 4 May 1995, during which time there was no irrigation and negligible rainfall. The root depths predicted by the model on these days are also shown.

Sensitivity Analysis

The results of the sensitivity analysis are presented in table 3. The relative sensitivity, calculated using equation 10, is shown for two essential output values in this model, namely ET and the number of irrigations scheduled by the model. Because the input parameter values being tested were set at their potential extremes, it is also useful to look at the resulting differences in the average values of the water balance components for the 27-year period. As expected, both ET and the number of irrigations are highly sensitive to changes in the length of the crop development stage, which in this case was also assumed to change the total length of the crop season by the same number of days. The crop evapotranspiration was also relatively sensitive to the value of the crop coefficient during mid stage, but the average difference between values for the 27-year record remained relatively small.

Except for TEW, all the other parameters had almost no effect on ET. However, even for a 50% increase in TEW (from 54 to 81 mm), with a corresponding increase in the initial root zone to 30 cm, the maximum soil water deficit in the evaporation layer never exceeded 71 mm (corresponding to a SWC of 14%) during the crop season. In half of the years (13 out of 27) deficits never exceeded 60 mm, and only in 2 years did the deficit exceed 60 mm before May. When TEW

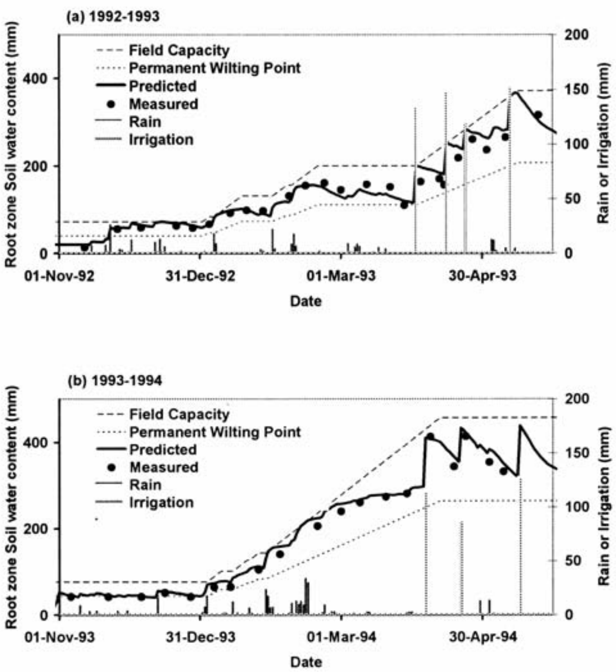

Figure 6. Predicted and measured soil water content in the predicted root zone in (a) 1992 (a relatively dry year and (b) 1993 (a relatively wet year), along with rainfall and irrigation, and the soil water contents at field capacity and permanent wilting point.

was set equal to 41 mm, deficits in the 15-cm evaporation layer did not exceed 36 mm before May in 17 of the 27 years (corresponding to a SWC of 14%). Allen et al. (2005) proposed a two-step linear process to simulate the evaporation of cracking clay soils, but the low sensitivity of this parameter indicates that this may not be necessary for supplemental irrigation of winter crops in this environment.

A change in the net average total irrigation did not always result in the same change in ET_a. Some of the differences in irrigation amounts were partially compensated for by other water balance components, as shown in table 3. For the base run, the SWC in the profile averaged 70 mm higher at harvest than at the start of the simulation period on 1 September. This occurred because SWC in the profile at the beginning of the rainy season was close to WP while at the end of the season it was higher because crop water use or evaporation had not yet depleted it back down to its initial value. The simulations indicated that the change in soil water storage between the beginning and end of the season was most affected by the timing and size of the final irrigation. However, there was also a change in the average seasonal evapotranspiration ratio (ET_a/Et_c) for the 27-year period. The lower this ratio, the more the crop experienced periods of water stress. The minimum ratio, 0.88, occurred when the root growth was low (5 mm/d), while the maximum ratio of 0.97 occurred for simulations with high initial water content (30%) in the profile below the initial root zone.

Table 3. Relative sensitivities and differences for the 27-year averages of the model's water balance components caused by changes in selected model parameters.

Parameter	Base Value	Test Value	Relative Sensitivity: ETc	Relative Sensitivity: Irrigations	Difference [Test-Base]: ETc (mm)	Irrigation (mm)	Irrigations (No.)	Evaporation (mm)	Leaching (mm)	Moisture Change (mm)
Duration of development stage[a] (d)	90	76	1.04	0.92	-101	-65	-0.6	-16	0	13
Duration of development stage[a] (d)	90	104	1.24	1.22	120	72	0.8	17	-1	-14
Crop coefficient at mid stage	1.1	1	0.23	0.26	-13	-11	-0.1	23	1	-2
Crop coefficient at mid stage	1.1	1.2	0.34	0.26	19	11	0.1	-17	-1	-3
Available water content (vol %)[b]	16	12	-0.02	-1.05	4	-9	1.1	4	6	-3
Available water content (vol %)[b]	16	20	-0.02	-0.67	-3	1	-0.7	-3	-4	-1
Depletion level at which stress occurs (% TAW)[c]	50	40	0.01	0.24	-1	-9	-0.2	-1	1	3
Depletion level at which stress occurs (% TAW)[c]	50	60	0.01	0.24	1	9	0.2	1	0	-1
Readily evaporable water (mm)	8	6	0.01	0.00	-2	2	0.0	-2	1	2
Readily evaporable water (mm)	8	12	0.01	0.00	4	5	0.0	4	-1	1
Total evaporable water[d] (mm)	54	40.5	0.06	0.10	-10	-10	-0.1	-10	-1	-2
Total evaporable water[d] (mm)	54	81	0.03	-0.05	10	12	-0.1	10	1	-1
Maximum potential root zone (m)	1.2	0.9	-0.02	-0.29	3	-3	0.3	3	10	-19
Maximum potential root zone (m)	1.2	1.5	0.00	-0.10	-1	-1	-0.1	-1	-7	10
Root growth (mm/d)	10	5	-0.02	-0.95	6	-18	2.0	6	-2	4
Root growth (mm/d)	10	18	0.00	-0.15	-2	8	-0.5	-2	4	1
Root growth moisture threshold (% TAW)	50	30	0.01	0.36	-2	12	-0.6	-2	5	2
Root growth moisture threshold (% TAW)	50	70	0.01	0.77	3	-16	1.3	3	-1	-3
Initial soil moisture below root zone (vol %)	24.5	22	-0.01	-0.47	1	-2	0.2	1	-5	14
Initial soil moisture below root zone (vol %)	24.5	30	-0.01	-0.85	-1	-5	-0.8	-1	15	-47
Base run (results in mm)					620	320	4.2	167	8	70

[a] The change in the length of the development stage also changed the total length of the crop season by the same number of days.
[b] Both the wilting point and the field capacity were adjusted by 2%. The initial volumetric soil moisture content was kept similar to that of the base run.
[c] A lower depletion level (p) indicates that the crop transpiration becomes stressed at a lower level of soil moisture depletion, which is a higher level of available soil moisture (the fraction is taken backwards from field capacity). Irrigation, in the third crop stage, was applied as soon as the soil moisture fell below the depletion level.
[d] With the TEW also the depth of the evaporation layer and initial root zone was changed to 15 and 30 cm, respectively. The initial soil moisture in this layer was set equal to the TEW, but the total soil moisture in the profile remained the same as for the base run.

The average total number of irrigations required per year during the 27-year period was highly sensitive to almost all changes in the soil's water holding properties as well as root growth and crop parameters. The change in the number of irrigations required was highest when the root growth rate was low (5 mm/d); the soil water threshold required for root growth was high (70% of TAW); and when the TAW was low (12%). These parameters all affect the depth of the root zone, with a smaller root zone requiring more irrigations (but lower water amounts per irrigation). Increases in the root growth rate beyond 10 mm/d had a less dramatic effect on the depth of the root zone and the resulting irrigation schedule. The simulated average depth of the root zone by the time of the first irrigation in early April was 91 cm for the base simulation, but was only 53 cm for the low root growth rate, and 67 cm for the high root growth moisture threshold. These last two depths may be low considering the measured soil moisture extraction patterns, but this cannot be confirmed without appropriate measurements of SWC.

The average amount of leaching from the profile simulated by the model for the 27-year period varied between 2 and 15 mm per year for all runs. In 4 out of the 27 years, leaching occurred during the January to March period. One-third of the total leaching occurred during the irrigation season, but this could probably have been prevented if the model (or the user) could have taken the weather forecast into account and thus prevented irrigations when the probability of rainfall is sufficiently high. A sound management practice to reduce the chance of leaching is to not fully refill the root zone to FC but to leave some storage capacity as warranted by the probability of rainfall.

The results of this long-term sensitivity analysis have implications for the potential use of this model as a real-time irrigation scheduling tool:

- The estimation of irrigation needs is clearly very sensitive to the duration of the crop stages. Considering the variability of the climatic characteristics that affect crop growth, it is important to select the crop stage durations based on current field observations of crop development.
- Knowledge of the behavior of the root system under soil moisture limiting conditions is important for improving the efficiency of supplemental irrigation.
- The threshold at which the crop starts experiencing stress (p) was not the most sensitive parameter for irrigation scheduling, but a better understanding of this parameter is needed to quantify the effect of delaying irrigation beyond the optimal date.

Irrigation Scheduling

The results of the irrigation scheduling simulations are presented in table 4 as averages of the individual simulations in each of the 27 years of climate data. In 25 of the 27 years, roots in the test case simulation (90-cm soil profile with TAW of 12%) had reached the bottom of the profile by the time of the first irrigation. The application of the same irrigation schedule to a soil with a higher water storage capacity and dryer or wetter initial SWC in the lower profile (*dry* and *wet* cases, respectively) resulted in a maximum change in the evapotranspiration ratio of 0.02 (from 0.96 to 0.94) for the dry case and 0.03 (from 0.93 to 0.90) for the wet case. Apart from the amount of irrigation water applied, an important consideration for farmers is the number of irrigations because this directly affects their labor input.

For the *dry* case the number of irrigations was reduced or stayed the same in 9 of the 27 years compared to the test case. In 12 of the 27 years one additional irrigation was needed, and in 6 of the years two extra irrigations were needed. For the *wet* case, one additional irrigation was required in 12 of the 27 years, two additional irrigations were required in 13 of the years, and three additional irrigations in 2 of the years.

Soil moisture content in the root zone for the test case, the dry and wet cases, and the dry and wet cases with the test case irrigation schedule are presented in figure 7 for the 1990/91 season. This season ranked among the top 5 seasons in terms of the decrease in the evapotranspiration ratio as a result of imposing the test case irrigation schedule on both the dry and the wet cases. For the dry case (fig. 7a) the schedule applied by the simulations had an evapotranspiration ratio of 0.87, while applying the schedule from the test case resulted in a ratio of 0.84. For the wet case (fig. 7b) the evapotranspiration decreased from 0.97 to 0.95. Imposing the test case irrigation schedule on the dry case (fig. 7a) clearly caused SWC to fall below 30%, (the crop stress level, p) during the second half of April.

The 2001/02 season ranked among the top five seasons for both the dry and the wet case in terms of the increase in the evapotranspiration ratio as a result of imposing the test case irrigation schedule. Figure 8 shows SWC in the root zone for the test case, the dry and wet cases, and the dry and wet cases with the test case irrigation schedule for this season. For the dry case (fig. 8a) the evapotranspiration ratio increased from 0.94 for the simulated schedule to 0.95 for the imposed test case schedule. For the wet case (fig. 8b), the evapotranspiration ratio correspondingly increased from 0.97 to 0.99. However, the reduction in the ratio in both the dry and wet cases when irrigations are scheduled by the model rather than imposing the test case irrigation schedule does not take into account the timing of the increased stress. The main difference occurred at the end of the season due to the timing of the irrigation just before maturity when the crop is not very sensitive to stress.

Table 4. Comparison of simulated average number of irrigations, irrigation amount, and evapotranspiration ratios for a test case and for simulations with a deeper potential root zone (RZ_p), higher total available water fraction (TAW), and different initial water content below the initial root zone (SWC_L) for irrigation schedules as simulated and using the same schedule as the test case. [a]

Case	Irrigation Schedule	RZ_p (cm)	FC (%)	WP	TAW (%)	SWC_L (%)	Irrigations (no.)	Irrigation (mm)	ET_a/ET_c
Test	Simulated	90	36	24	12	27	5.1	303	0.92
Dry	Simulated	120	38	22	16	22	4.4	318	0.90
Dry	As test	120	38	22	16	22	5.1	303	0.89
Wet	Simulated	120	38	22	16	30	3.4	315	0.97
Wet	As test	120	38	22	16	30	5.1	303	0.97

[a] The simulations are based on daily climate data at Tel Hadya for the 27 winter cropping seasons from 1979/80 to 2005/06.

Both figures 7 and 8 illustrate the lower soil water contents in the test case after the initial irrigation or rain at the beginning of the season, due to the lower water storage capacity. Once the root zone starts expanding, root growth is generally more limited for the dry case than for the test case, because the smaller TAW of the test case also results in higher volumetric soil moisture percentages (figs. 7a and 8a). Conversely, root growth for the wet case is more rapid than for the test case. By growing into a relatively wet sub soil, moisture contents generally remained higher for the wet case than for the test case (figs. 7b and 8b).

Summary and Conclusions

A model in spreadsheet form, based on the spreadsheet program of Allen et al. (1998) but accounting for the dynamic development of the root zone in dry soils, was developed for computing net irrigation water needs for supplemental irrigation of winter crops in a homogeneous soil in Mediterranean environments. The dual crop coefficient approach that splits evapotranspiration into crop transpiration and evaporation from the soil was used. Evaluation of the model with a data set on wheat showed that

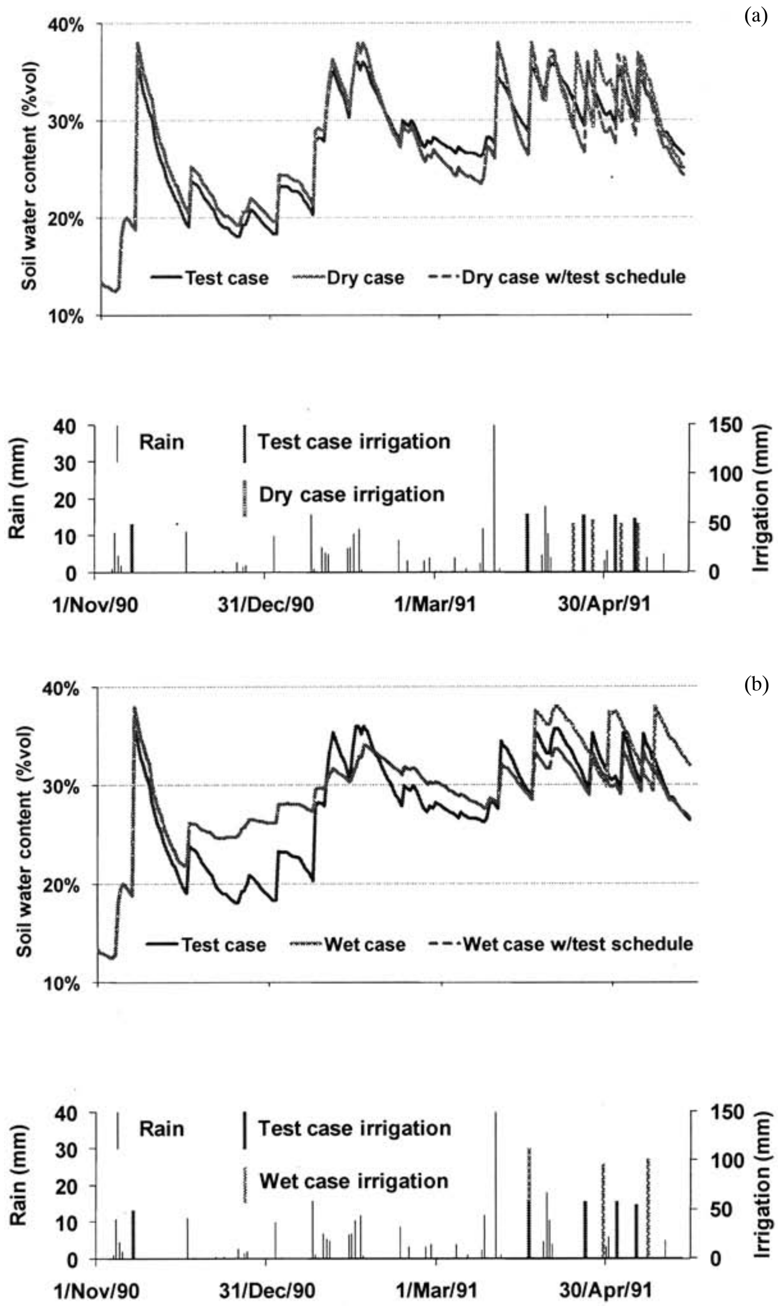

Figure 7. Average soil water contents in the root zone for the *test case* (90cm soil depth, TAW 12%, initial SWC 27% in lower profile); and (a) *dry case* (120-cm soil depth, TAW 16%, initial SWC 24% (WP) in the lower profile along with the *dry case with the test case irrigation schedule*; and (b) the *test case*, the *wet case* (120-cm soil depth, TAW 16%, initial SWC 30% in the lower profile) and the *wet case with the test case irrigation schedule*, for the 1990/91 season. Rainfall and irrigations are also shown. Note: the test, dry, and wet cases all received the same first irrigation at the beginning of the season in November.

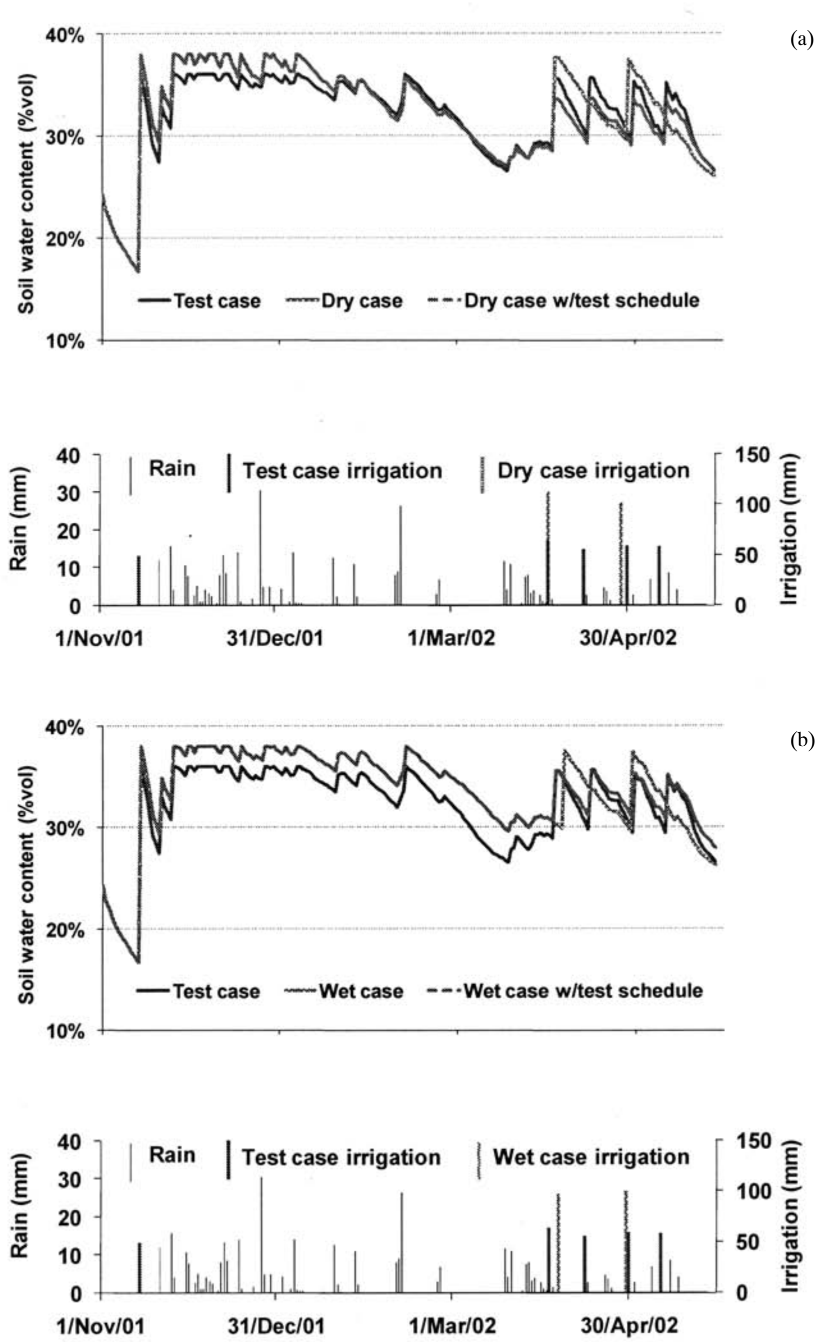

Figure 8. Average soil water contents in the root zone for the *test case* (90-cm soil depth, TAW 12%, initial SWC 27% in lower profile); and (a) *dry case* (120-cm soil depth, TAW 16%, initial SWC 24% (WP) in the lower profile along with the *dry case with the test case irrigation schedule*; and (b) the *test case*, the *wet case* (120-cm soil depth, TAW 16%, initial SWC 30% in the lower profile) and the *wet case with the test case irrigation schedule*, for the 2001/02 season. Rainfall and irrigations are also shown. Note: the test, dry and wet cases all received the same first irrigation at the beginning of the season in November.

it could predict SWC within acceptable error limits. Sensitivity analysis showed that, within the expected parameter value range, computed evapotranspiration for a typical supplemental irrigation scenario for a clay soil in northern Syria was not sensitive to changes in the soil evaporation parameter values over the 27 year climate data record. The resulting computed irrigation schedule was sensitive to changes in all other soil, crop, and root parameters. However, the use of the model to develop irrigation schedules for application to areas where the weather is the same but soil properties and initial moisture conditions may be different produced schedules that resulted in limited crop stress for the different cases.

In Syria, as in many other dry areas, water is the resource that most limits crop production, with irrigation being the major consumer of this resource. In lieu of measuring SWC before making an irrigation decision, this model could be a useful tool to help with the decision because it is simple yet appears to have sufficient accuracy to generate realistic guidelines. Using the model with real-time data from climate stations and rain gauges could help agricultural research and extension services to provide information that would enable farmers to make improved irrigation management decisions. Application of the model for various conditions and scenarios could aid in the development of policies to use irrigation water more effectively in Mediterranean climates. The model is available at www.rec.udel.edu/TopLevel/Research_staff_and_programs.htm or www.icarda.cgiar.org.

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