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SIMETAW# - a Model for Agricultural Water Demand Planning

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Abstract A successful water management scheme for irrigated crops requires an integrated approach, which accounts for water, soil, and crop management. SIMETAW# is a user friendly soil water balance model that assesses crop water use, irrigation requirements, and generates hypothetical irrigation schedules for a wide range of crops experiencing full or deficit irrigation. SIMETAW# calculates reference evapotranspiration (ET_o), and it computes potential crop evapotranspiration (ET_c), and the evapotranspiration of applied water (ET_{aw}), which is the amount of irrigation water needed to match losses from the effective soil root zone due to ET_c that are not replaced by precipitation and other sources. Using input information on crop and soil characteristics and the distribution uniformity of infiltrated irrigation applications in full or deficit conditions, the model estimates the mean depth of infiltrated water (IW) into each quarter of the field. The impact of deficit irrigation on the actual crop evapotranspiration (ET_a) is computed separately for each of the four quarters of the cropped field. SIMETAW# simulation adjusts ET_o estimates for projected future CO_2 concentration, and hence the model can assess climate change impacts on future irrigation demand allowing the user to propose adaptation strategies that potentially lead to a more sustainable water use. This paper discusses the SIMETAW# model and evaluates its performance on estimating ET_c, ET_a, and ET_{aw} for three case studies.

Keywords Soil water balance · Crop coefficient · Crop water requirement · Evapotranspiration of applied water · Yield reduction · Adaptation strategies

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1 Introduction

Agriculture is vulnerable to weather conditions and future climate change can be detrimental (Jiménez Cisneros et al. 2014). Especially in those areas already affected by water scarcity, the need for more water resources could grow, and increasing water scarcity will necessitate a more sustainable approach to water resource management. An accurate computation of the seasonal crop water requirement (CWR) is important for water resource planning, and the assessment of the evapotranspiration of applied water (ET_{aw}) is even more important for developing crop management strategies that are economically convenient in terms of water usage, crop yield, and profits. The CWR is the amount of water that a crop needs for optimal production, which was defined by Doorenbos and Pruitt (1977) as the volume of water needed to meet the water loss from the root zone through evapotranspiration, whereas the ET_{aw} is the volume of required irrigation water to infiltrate into the quarter of the cropped field receiving the least amount of water to achieve optimal production.

Water shortages are common in the State of California, and in the early 2000s, this led the University of California, Davis (UCD) and the California Department of Water Resources (DWR) to develop the Simulation of Evapotranspiration of Applied Water (SIMETAW) application program (Snyder et al. 2004; Snyder et al. 2012a), which is a user friendly soil water balance model that is able to estimate the CWR, generate hypothetical irrigation schedules for a wide range of irrigated crops, and output ET_{aw} for use in water resources planning. The SIMETAW application is used to assess the ET_{aw} of crops in a microclimate area having approximately the same evaporative demand over the entire region. Later, a program to apply SIMETAW to all microclimatic regions in California, i.e., Cal-SIMETAW, was developed (Orang et al. 2013).

While SIMETAW and Cal-SIMETAW are useful for irrigation planning in California, where adequate water supplies are available in most years, it is likely that water deficit will occur in the future. Also, deficit irrigation is common in many arid and semi-arid climates and rain-fed agriculture is common in many developing counties. Consequently, the SIMETAW model was modified and renamed "SIMETAW#" in collaboration with the University of Sassari (Italy). The improvements include revised crop coefficient (K_c) values to ET_c, and stress coefficient (K_s) values to account for water deficit effects on evapotranspiration and yield. In addition, SIMETAW# corrects midseason K_c values for the effect of climate, which was not included in SIMETAW or Cal-SIMETAW. SIMETAW# also addresses the impact of rising CO_2 concentration on reference evapotranspiration (ET_o), so it is useful for planning responses to climate change. The earlier models stopped with the calculation of ET_{aw}, and the seasonal irrigation water diversion was calculated separately. The ability to compute the seasonal water diversions for irrigation based on the distribution uniformity fraction (D_u) of the irrigation systems and estimated surface runoff (R_{off}) was added to SIMETAW#.

The ET_{aw}, or irrigation requirement, represents the portion of CWR that is supplied by irrigation and not by water tables, effective precipitation, i.e., rainfall, dew, and fog (Moratiel et al. 2013), and the reduction in water storage in the crop root zone from pre- to post-season. Determining ET_{aw} requires a daily water balance throughout the season to estimate effective precipitation, contributions from water tables, and the change in soil water content during the season. In SIMETAW#, the ET_{aw} is calculated as the sum of the mean depth of water infiltrating into the low quarter of the irrigated field, but ET_{aw} is also equal to the difference between the seasonal CWR and sources of water other than irrigation.

For the irrigated crop, the mean depth of infiltrated water (IW) over the field is calculated as the quotient of ET_{aw} and the D_u. Then, the gross application (GA), or diverted irrigation water, is calculated as the sum of the IW and R_{off}, if any. Using this approach results in a net application (NA) depth that matches the mean infiltration of water into the low quarter of the soil. When adequate water is available, the NA should return the soil water content in the low quarter back to near field capacity. The remaining 75 % of the cropped soil infiltrates more water than needed to refill to field capacity, and the excess water mainly contributes to deep percolation of water below the rooting zone. For most crops, this approach to scheduling is likely to result in the highest productivity. This paper discusses the processes and features of the SIMETAW# model, assesses its potential applications, and reports on its performance.

2 The SIMETAW# Model Description

In SIMETAW#, ET_{aw} (mm) is determined as the sum of the net irrigation applications, but it can also be estimated as the seasonal cumulative total of daily crop evapotranspiration (CET_c, mm) minus effective rainfall during the season, as well as the decrease in soil water content from the beginning to the end of the season, and any contributions to ET_c (mm) coming from fog, dew, light rainfall, and water tables. Crop and soil characteristics, climate data, water contributions from all sources, and irrigation system distribution uniformities are the basic inputs needed to compute ET_{aw}.

2.1 Climate Input Data and ET_o Computations

SIMETAW# computes ET_o (mm d^{-1}) using the daily (24-h) standardized reference evapotranspiration equation for short canopies (Allen et al. 1998; Allen et al. 2005b, 2006).

At the time when the Penman-Monteith equation (Monteith 1965) was developed, the global CO_2 concentration was about 372 ppm and it is projected to reach about 550 ppm by 2050 and more than 800 ppm by 2100 considering the most critical CO_2 concentration pathway scenario (IPCC 2013). Studies have shown that the stomatal conductance (g_s, mm s^{-1}) of many C3 plants decrease by about 20 % when the CO_2 concentration increases from 372 to about 550 ppm (Drake et al. 1997; Long et al. 2004; Ainsworth and Long 2005). Therefore, if the CO_2 concentration changes from 372 to 550 ppm, the stomatal conductance of 0.12 m tall C3 species grass with a stomatal resistance (r_s) of 100 s m^{-1} should decrease from about 10 mm s^{-1} to 8 mm s^{-1}. Assuming the relationship remains linear beyond the 550 ppm concentration, Snyder et al. (2011) expressed the canopy resistance (r_c, s m^{-1}) as a function of CO_2 concentration (ppm) as:

$$r_c = \frac{1000}{1.44(14.18 - 0.0112\ CO_2)} \quad (1)$$

This equation is used in SIMETAW# to adjust the canopy resistance for the effect of projected CO_2 concentration.

2.2 Crop-Soil Input Data

Soil characteristics and crop-irrigation management practices are input to the model to calculate the soil water balance and determine hypothetical irrigation schedules. The SIMETAW# model follows the basic soil water balance concepts as described in Snyder et al. (2012a) and Orang et al. (2013). The potential crop rooting depth (mm), the allowable depletion (AD, %) of available water, and the volumetric available water holding capacity (θ_A, mm mm^{-1}) are input or selected and used to determine the plant available water (PAW, mm) within the soil rooting depth. There is a 50 % default value for AD which is widely used for many field and horticultural crops, but it can be overridden.

A user can select whether to use only precipitation, deficit irrigation, or full irrigation. Default values for application rate (AR, mm h^{-1}) and D_u of infiltrated water (Center for Irrigation Technology 2011) are included in the program.

2.3 Crop Coefficient Values and Corrections

In SIMETAW#, the seasonal crop coefficient trends are determined following a similar approach as was presented in Doorenbos and Pruitt (1977) and Allen et al. (1998). Default crop coefficient values are included in SIMETAW# using information provided by the FAO 24 (Doorenbos and Pruitt 1977), FAO 56 (Allen et al. 1998), and several recent papers. The SIMETAW# K_c method differs from the FAO methods in that the ends of the growth periods are identified as a percentage of the length of the season (Snyder et al. 2012a), whereas FAO uses estimates of the number of days within each growth periods to identify the end points. The advantage from using the percentages is that the number of days within growth periods is unknown for many crops and regions, and growers often have little or no information to identify when the trend changes from the midseason to late-season period.

Initially, SIMETAW# extracts the tabular midseason K_c values from data stored in the program. Midseason K_c values, however, are known to vary depending on the climate (Doorenbos and Pruitt 1977; Allen et al. 2005a), so a climate correction was included. The climate correction equation is:

$$K_{cmid} = K_{ctab} + 0.261(ET_o - 7.3)(K_{ctab} - 1) \quad (2)$$

where K_{cmid} is the corrected midseason crop coefficient and K_{ctab} is the tabular midseason K_c value that is expected during midseason in a climate with $ET_o = 7.3$ mm d^{-1} (Guerra et al. 2014). The SIMETAW# model also has corrections to determine the K_c values for immature trees and vines as percentage shading of the ground in relation to the growth date, and it has corrections for cover crops between the rows of orchards and vineyards as described in Snyder et al. (2012a).

2.4 Crop Evapotranspiration

During the off-season and the initial-growth period, the SIMETAW# model estimates ET_c as the product of ET_o and K_e, which is the bare soil evaporation coefficient (Snyder et al. 2012a). Afterwards, based on crop data input, soil, and irrigation information, a K_c curve from the beginning of rapid growth to the end of late season is determined, and the daily crop evapotranspiration is calculated as the product of ET_o and K_c.

2.5 Water Balance Calculations

The SIMETAW# model computes the daily soil water balance for major crops. Because the soil water balance is calculated each day, rainfall runoff is ignored. The assumption is that storms with sufficiently heavy precipitation to have runoff are also likely to recharge the soil water content to field capacity after a heavy rainfall. The soil water depletion (SWD, mm) is updated daily using:

$$SWD_i = SWD_{i-1} + ET_{ci} + P_{cpi} + C_i - D_i - R_{offi} + I_i \quad (3)$$

The variable ET_c is the potential crop ET, P_{cp} is precipitation, C is capillary rise from water tables, D is deep percolation below the root zone, R_{off} is runoff, I is irrigation depth, the subscripts i and i-1 represent the current and previous day, respectively, and all units are in mm. In the model the SWD_i is defined as θ_{fc}-θ_i, where θ_{fc} and θ_i are the soil water holding contents at field capacity and on the i^{th} day (mm mm^{-1}), respectively. For deficit irrigated crops, ET_a is substituted for ET_c in Eq. 3.

Any in-season P_{cp} that is stored in the root zone and potentially contributes to evapotranspiration is called effective rainfall (R_e). If rainfall occurs and the P_{cp} exceeds the SWD, the R_e = SWD and the soil returns to field capacity. If the P_{cp} event does not exceed the SWD, the $R_e = P_{cp}$ and the SWD is reduced by an amount equal to the R_e.

Identifying the net irrigation application (NA_c, mm) for a well-watered crop is the first step for the water balance computation. The NA_c is estimated at the beginning of midseason (date C) as:

$$NA_c = (1 - R_{off}) \cdot RT \cdot AR \cdot D_u \quad (4)$$

where RT is the irrigation system runtime (hh).

During initial-growth (from date A to B), the NA_c depends on the mean ET_o rate, the crop coefficient for bare and nearly bare soil (K_e), and the days between irrigation. The K_e values were determined using the method of Ventura et al. (2006) with a typical soil hydraulic factor 2.6, mean daily ET_o rates ranging from 1 to 10 mm d^{-1}, and wetting frequencies of 2, 4, 7, 10, and 20 days. The equation for K_e based on the cumulative ET_o (CET_o, mm) is:

$$K_e = \frac{2.54}{\sqrt{CET_o}} \quad (5)$$

Assuming that the ET_c during initial-growth, i.e., with ground shading less than 10 %, is nearly equivalent to the evaporation from bare soil, the NA_c during initial-growth is estimated as:

$$NA_c = \overline{ET_o} \cdot K_e \cdot d_e \quad (6)$$

where d_e is the number of days from one irrigation to the next during initial-growth, and $\overline{ET_o}$(mm) is the mean daily ET_o rate during initial-growth.

One option in SIMETAW# is to select if a crop is pre-irrigated or not. If a crop is pre-irrigated, then the SWD is set equal to zero on the day preceding the season. If it is not pre-irrigated, then the SWD on the day preceding the season is determined by the soil water balance during the off-season before planting or leaf-out. Some crops are frequently irrigated with sprinklers during the initial-growth period, and the irrigation frequency and mean ET_o rate affect the initial-growth crop coefficient as was discussed earlier. Following the initial-growth period, irrigation events occur whenever the SWD reaches the "management allowable depletion" (MAD, mm). This approach forces the soil water depletion to generally fall between the yield threshold depletion (YTD, mm) and the permanent wilting point (PWP, mm) at the end of the season.

A pressurized irrigation system normally maintains similar distribution uniformity regardless of the water amount applied, so during deficit water conditions, the best management practice is to maintain the same irrigation timing and reduce the depth applied for each irrigation event. Deficit irrigation will generally increase the application efficiency because less applied water goes to deep percolation and runoff. However, this may be untrue for surface irrigation if insufficient water is applied to obtain an even infiltration. SIMETAW# keeps the same irrigation dates for full and deficit irrigations, but less irrigation water is applied at each irrigation event. To do this, the program first calculates a schedule assuming there is adequate water available to avoid water stress. In this process, the model 'estimates' the ET_{aw} for a well-watered crop (ET_{awe}, mm) considering CET_c during the season, (i.e., from growth date A to E for field crops or date B to E for orchard and vine crops) as:

$$ET_{awe} = CET_c - \left(YTD_c - \frac{YTD_{os}}{2}\right) \quad (7)$$

where YTD_c and YTD_{os} (mm) are the maximum yield threshold depletion estimates during midseason and off-season, respectively.

During the off-season, it is assumed that only half of the PAW in the top 0.30 m of soil can be depleted, so the YTD_{os} is estimated as the product of the θ_A and 300 mm. Because the seasonal water balance is unknown prior to the end of the season, it is impossible to determine the real ET_{aw} until the seasonal soil water balance is computed. However, Eq. 7 provides an early estimate for ET_{aw} assuming that there is little effective rainfall and the soil is fairly dry at the end of the season.

The ideal number of irrigation events (N_{ic}) for a fully irrigated field is computed as:

$$N_{ic} = \frac{ET_{awe}}{MAD_c} \quad (8)$$

where the MAD_c (mm) is the management allowable depletion for a well-watered crop during the midseason period, which is equal to NA_c.

Since water application to a cropped field is non-uniform, the SIMETAW# program divides the field into four quarters. The low (1^{st}) quarter application is the mean depth of water applied to the one quarter of the field receiving the least amount of water. The high (4^{th}) quarter application is the mean depth of water applied to the one quarter of the field receiving the most water, and the 2^{nd} and 3^{rd} quarters are the mean depths of water applied to the intermediate quarters of the field.

After computing the MAD_c and N_{ic}, the program calculates the soil water balance for a well-watered crop and the ET_{aw} as:

$$ET_{aw} = \sum_{i=1}^{n} NA_{c,i} \quad (9)$$

for $i = 1$ to n, where n is the number of irrigation events and $NA_{c,i}$ (mm) is the net application or mean depth of water infiltrated into the low quarter on the i^{th} day. Therefore, ET_{aw} is equivalent to the seasonal mean depth of irrigation water infiltrated into the low quarter.

Typical values for D_u and R_{off} values are used to estimate the seasonal sum of gross application amounts (applied water) for the fully watered crop from the ET_{aw} as:

$$\sum GA_c = \frac{ET_{aw}}{D_u} / \left(1 - \frac{R_{off}}{100}\right) = \frac{\Sigma NA_c}{D_u} / \left(1 - \frac{R_{off}}{100}\right) \quad (10)$$

where R_{off} is the percentage of ΣGA_c (mm) that contributes to runoff. For well-designed sprinkler, drip, and micro-sprinkler systems, the R_{off} should equal zero.

The water allocation (WA, mm) is the mean depth of water that is available for the irrigation during a season. It is computed from the depths of infiltrated water (IW, mm) to the four quarters (IW_1, IW_2, IW_3, and IW_4):

$$WA = \frac{IW_1 + IW_2 + IW_3 + IW_4}{4} = \sum GA_c \left(\frac{PIR}{100}\right) \quad (11)$$

where PIR is the percentage of the full irrigation requirement for the crop that is allocated for the cropping season. The user can set PIR = 100 for full irrigation, PIR < 100 % for water deficit conditions, and PIR = 0 for rain-fed crops. The low quarter mean depth applied is computed as:

$$IW_1 = WA \cdot D_u \quad (12)$$

The high (4th) quarter mean depth applied is computed as:

$$IW_4 = WA + (WA - IW_1) \quad (13)$$

The 2nd quarter mean depth applied is equal to the sum of IW_1 and 1/3 of the difference between the high and low quarter mean depths applied, so:

$$IW_2 = IW_1 + 1/3(IW_4 - IW_1) \quad (14)$$

The 3rd quarter mean depth applied is equal to the sum of the low quarter depth and 2/3 of the difference between the high and low quarter mean depths applied:

$$IW_3 = IW_1 + 2/3(IW_4 - IW_1) \quad (15)$$

When water deficit conditions are considered, the water allocation is less than for a fully irrigated crop (PIR < 100 %). Thus, the sum of the irrigation depths to the low quarter of a deficit irrigated crop (ΣNA_a, mm) is computed as:

$$\Sigma NA_a = \sum GA_c \left(\frac{PIR}{100}\right) = WA \cdot D_u \quad (16)$$

When using pressurized irrigation systems, the number of irrigation events in water deficit conditions (N_{ia}) is equal to N_{ic}, and the MAD for the deficit irrigation (MAD_a, mm) is estimated as function of the PIR and MAD_c as:

$$MAD_a = MAD_c \left(\frac{PIR}{100}\right) \quad (17)$$

Because the distribution uniformity of surface (gravity) irrigation depends greatly on the opportunity time to infiltrate water across the field, it is difficult to change the application amount for any given irrigation event. Therefore, SIMETAW# forces surface irrigation to have a similar management allowable depletion as the fully irrigated crop. During deficit water supply conditions, the number of irrigation events is reduced, but the depth of water applied is similar for each irrigation event. Therefore, for gravity irrigation, $MAD_a = MAD_c$ and $N_{ia} < N_{ic}$, where N_{ia} is the sum of the net applications in deficit condition divided by the management allowable depletion for the fully irrigated crop as:

$$N_{ia} = \frac{\Sigma NA_a}{MAD_c} \tag{18}$$

2.6 Determination of the Stress Coefficient and Fraction of Potential Yield

Since the SIMETAW# program is able to compute the soil water balance in full irrigation and water deficit conditions, ET_a is computed as the product of ET_c and the stress coefficient.

The K_s is computed as function of the SWD under deficit water conditions as:

$$K_s = 1 - \frac{100\left(\frac{SWD}{PAW}\right) - AD}{100 - AD} \tag{19}$$

If $K_s = 1.00$, there is no water deficit, while a $K_s < 1.00$ implies a water deficit. The CET_c and cumulative actual crop evapotranspiration (CET_a, mm) are computed by summing the daily ET_a rates from the first through the last day of the season.

Since water application to a cropped field is non-uniform, the SIMETAW# program estimates yield separately to each of the four quarters of the field based on infiltrated water. For a fully irrigated crop, with $CET_a = CET_c$, then $IW_1 = ET_{aw}$. When there is stress, $CET_a < CET_c$ and $IW_1 < ET_{aw}$. SIMETAW# calculates the seasonal CET_a for the deficit irrigated crop of the low quarter. The difference between CET_a and IW_1 is the amount of CET_a coming from sources other than irrigation, e.g., effective precipitation, water table, dew and fog, and stored soil water. The ratio of CET_a to CET_c is computed for each quarter of the field, and reductions in yield due to water stress are computed for each of the four quarters of the field following the procedures in FAO 33 (Doorenbos and Kassam 1979). For each quarter, the actual to potential yield ratio (Y_a/Y_c) is computed as:

$$\frac{Y_a}{Y_c} = 1 - K_Y\left(1 - \frac{CET_a}{CET_c}\right) \tag{20}$$

where K_Y is a coefficient that relates the relative reduction in cumulative ET to the relative reduction in yield. Finally, the mean of the four yield ratios is computed to provide an estimate of yield as affected by deficit irrigation. This approach accounts for the irrigation system in addition to the irrigation deficit.

The FAO 33 publication contains K_Y values for several crops, but K_Y values are not known for all crops. If the K_Y value is unknown for a particular crop, then $K_Y = 1.0$ is used in SIMETAW#. For crops with unknown K_Y values, assuming $K_Y = 1.0$ is equivalent to assuming that a 1 % reduction in transpiration due to stress will lead to a 1 % reduction in biomass production. For crops that produce reproductive parts rather than biomass alone, this is still a fair assumptions because, unless there is a severe irrigation deficit, the reduction in transpiration typically occurs later in the season when biomass is accumulating more in the reproductive parts. Thus, this modified version of the FAO 33 approach provides estimates of the actual to potential yield ratio for a large number of crops.

2.7 Rain-fed Agriculture

When a crop is grown in rain-fed conditions, the SIMETAW# program still calculates the daily water balance for a fully irrigated crop because the CET_c information is needed to determine the well-watered yield for the crop. However, the stress function is determined using the SWD, AD, and PAW as previously discussed. The CET_c and CET_a are determined as in the deficit irrigated crop case. Finally, the Y_a/Y_c is still determined using the CET_a and CET_c calculations.

3 Materials and Methods

3.1 Datasets

The SIMETAW# model was designed to estimate the irrigation needs, thus its performance was tested employing data from three field studies.

3.1.1 Site 1

The first experimental study used in this paper was carried out by Bryla et al. (2005) in a peach field [*Prunus persica* (L.) Batsch], planted at the University of California Kearney Agricultural Research and Extension Center near Fresno, California (Johnson et al. 2002). The soil was fine sandy loam, and the rooting depth was around 1 m. Irrigation was applied by furrow and drip systems, and the schedule was based on ET_c measured hourly on two well-watered peach trees growing in the same weighing lysimeter. The lysimeter contained trees of the same variety, age, and planting density as trees in the orchard. Furrow irrigation was applied to the orchard weekly while drip irrigation was applied every day. Irrigation application occurred from the beginning of April through mid-October. The research project was conducted during 2002 through 2004 and the results were used to assess the accuracy of the SIMETAW# model in estimating monthly ET_c and ET_{aw}. Weather data necessary to estimate ET_o (Allen et al. 2005b) were obtained from the California Irrigation Management Information System (CIMIS) station (Snyder and Pruitt 1992) nearby the experimental site (Parlier, 36°35′52″N; 119°30′11″W; 103 m a.s.l.). The development dates were B (1 Mar), C (23 Jun), D (22 Set), and E (15 Oct), and the percentages for each growth stage from data B were 50 % (A-C), 90 % (A-D), and 100 % (A-E) and the K_c values were K_{c1} = 0.55 on date B, K_{c2} = 1.05 on dates C and D, and K_{c3} = 0.65 on date E. Using crop, soil, and management data reported in the experimental study, ET_{aw} and the monthly ΣNA_c for furrow and drip irrigation were estimated.

3.1.2 Site 2

The second experiment was carried out by Snyder and O'Connel (2007) on navel orange orchard [*Citrus sinensis* (L.) Osbeck] near Lindsay, California. The soil was a fine sandy loam, and the rooting depth was around 1.2 m. Irrigation was applied with micro-sprinklers every 4–6 days during summer. There was no irrigation from October/November through mid-March. Evapotranspiration was measured using the residual of the energy balance where the sensible heat flux was determined using the calibrated surface renewal method (Snyder and O'Connel 2007). A surface renewal (SR) station was set up inside the orchard to measure daily ET_c, while weather data used to calculate ET_o (Allen et al. 2006) came from the CIMIS station at the University of California Lindcove Field Station (36°21'26″N; 119°03'31″W; 146 m a.s.l.). The percentages for each growth stage from data B were 33 % (A-C), 67 % (A-D), and 100 % (A-E) and the K_c values were K_{c1} = 1.00 on date B, K_{c2} = 1.00 on dates C and D, and K_{c3} = 1.00 on date E. Results of daily ET_c, monthly ΣNA_c, and monthly number of irrigation events for the 2003 and 2004 seasons were used to assess the performance of the SIMETAW# model.

3.1.3 Site 3

The third experimental study was carried out by Snyder et al. (2012b) at the Campbell Tract at the University of California, Davis. Wheat (*Triticum aestivum* L.) was cultivated in rain-fed conditions from November 2011 until June 2012. The soil was a Yolo silty clay loam with infiltration rate of about 28.6 mm h^{-1} and θ_A = 0.20 mm mm^{-1}. Rooting depth was about 1.7 m. The development dates were A (26 Nov), B (10 Jan), C (20 Mar), D (15 May), and E (10 Jun), and the percentages for each growth stage from data A were 23 % (A-B), 58 % (A-C), 87 % (A-D), and 100 % (A-E) and the K_c values were K_{c1} = 0.33 on date B, K_{c2} = 1.05 on dates C and D, and K_{c3} = 0.15 on date E. The ET_a was computed by using data from a weighing lysimeter and a combination of the SR and eddy covariance (EC) methods. During initial-growth, because of the low ET_a values, precipitation, and fog, data were only collected by the lysimeter. From mid-February on, the EC and SR methods were also used to estimate ET_a. In early May, ET_a from the lysimeter dropped dramatically. The EC and SR methods did not measure a drop in ET_a until about two weeks later. The crop was not irrigated, and the early decrease in ET_a observed in the lysimeter running out of water earlier than in the deeper soil surrounding the lysimeters. The wheat inside the lysimeter clearly senesced approximately two weeks prior to the wheat outside of the lysimeter. Thus, considering that the EC and SR observations clearly showed that the season was longer than indicated by the lysimeter data, an accurate computation of the ET_a was possible by using the EC and SR data at the end of the season.

Weather data and ET_o estimates came from the CIMIS station (Davis, 38°32'09″N; 121°46'32″W; 18 m a.s.l.). Observed daily ET_a data from the lysimeters (early growth), SR and EC (end of the season) where compared with those estimated by the SIMETAW# model.

3.2 Statistics

The performance of the model in estimating the ET_c, ET_a, and ET_{aw} was determined by statistical analyses. Several indexes, including the calculation of correlation and differences between estimated and measured series, were used. The simulated data were analyzed calculating the Pearson's correlation coefficient (r), root mean squared error (RMSE), and mean relative error (MRE).

The Pearson's correlation coefficient provides a measure of how strong is the correlation between simulated and observed series, and its range is between −1 and 1.

The RMSE, which is a measure of how closely two variable match (Loague and Green 1991; Xevi et al. 1996) was used to test the accuracy of the model:

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\hat{Z}_i - Z_i\right)^2} \quad (21)$$

where n is the number of samples and Z_i and $\hat{Z}_i$ are the observed and estimated values for n observations.

The MRE was used to measure the absolute error between simulated and observed data:

$$\mathrm{MRE} = \frac{1}{n}\sum_{i=1}^{n}\frac{|Z_i - \hat{Z}_i|}{Z_i} \quad (22)$$

The MRE statistic indicates the match of estimated to observed values, but the value is relative to the observed data.

4 Results

4.1 Site 1

It was assumed that the peach orchard was irrigated with sufficient frequency and depth of water applied to avoid water stress, so the symbol ET_c rather than ET_a is used here. The SIMETAW# model estimated the CET_c for peach equal to 1026, 1020, and 1058 mm, while the observed values were equal to 1100, 1081, and 1041 mm, in 2002, 2003, and 2004, respectively. As shown in Fig. 1, the estimated and observed monthly ET_c values followed a similar trend. For all three seasons, the model tended to overestimate ET_c values during April through June and to the under predict ET_c during July through September. The early difference is likely due to a later leaf out and, therefore, lower ET_c than the default input value in the model (March 1). The midseason ET_c difference is clearly related to the choice of midseason K_c. If the model midseason K_c were increased, to what was observed, the model prediction would be nearly perfect. In general, the match between predicted and observed ET_c values during the irrigation season was good. Nearly perfect ET_c estimates were observed during May and June 2002 (Fig. 1a) and July and August 2004 (Fig. 1c).

Results of the statistical analysis of peach ET_c estimates are shown in Table 1. The Pearson's coefficient values were significant to less than 0.025. Taking into account the indices based on differences between expected and measured data, a relatively low RMSE was observed for ET_c. The highest RMSE value was observed in 2003 (32.69 mm month^{-1}), while the lowest value was 16.51 mm month^{-1} in 2004. These results confirm a good predictive efficiency of the model. The model showed a tendency to underestimate ET_c in 2002 and 2003. On the contrary, a slight overestimation of ET_c was observed in 2004. These relationships would change if the model crop coefficients and growth dates were modified to better match the observed values.

The estimated ET_{aw} in 2002 was 990 and 1005 mm for drip and furrow irrigation, respectively, compared with an observed ET_{aw} = 1029 mm. For this example, the observed ET_{aw} was set equal to the depth of water applied to the lysimeter, so distribution uniformity

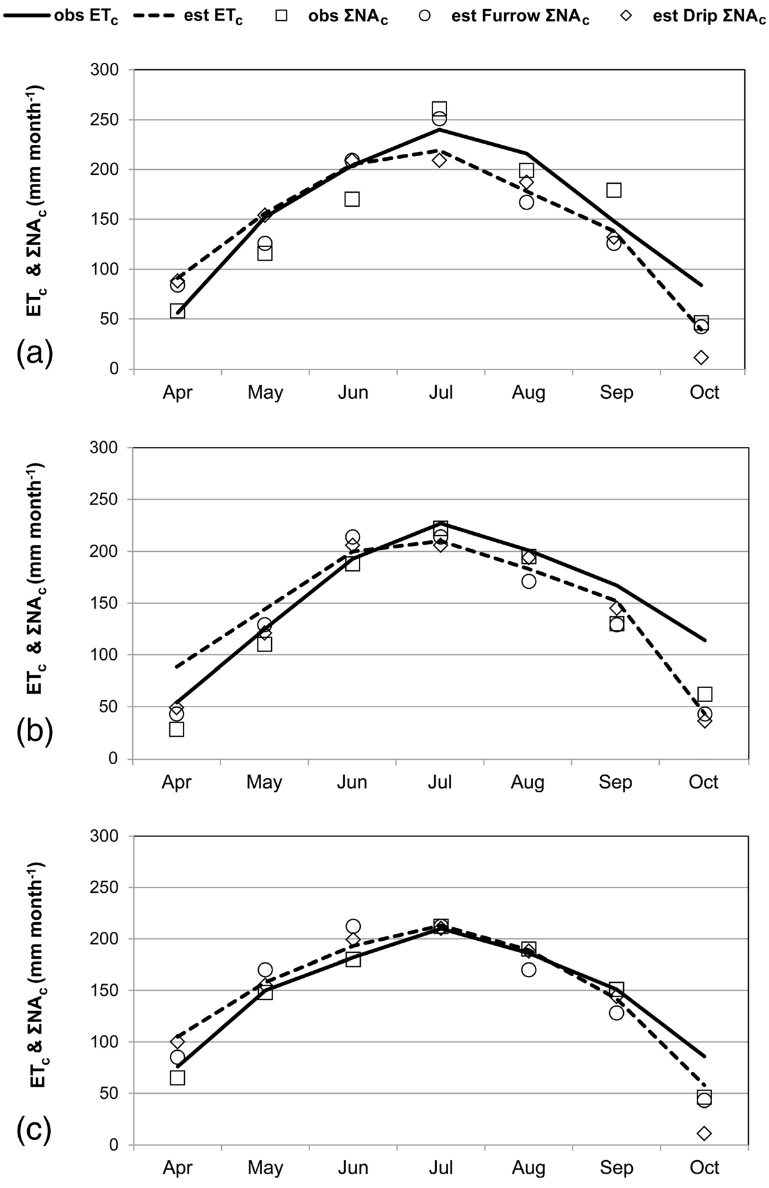

Fig. 1 Monthly observed (obs) and estimated (est) crop evapotranspiration (ET_c) and applied water (ΣNA_c) data for peach orchard in 2002 (**a**), 2003 (**b**), and 2004 (**c**)

was not considered as it would be in a commercial field. The highest mismatch between observed and estimated data was noticed in June and September for both drip and furrow irrigation (Fig. 1a). The difference between observed and estimated monthly ΣNA_c during the following years was less marked (Fig. 1b, c) with a nearly perfect match in 2004 (Fig. 1c). The summary statistics (Table 1) shows that the ET_{aw} estimate in 2002 gave the highest RMSE values for both irrigation methods compared with the following irrigation seasons. The ET_{aw}

Table 1 Summary of predicted and observed monthly peach crop evapotranspiration (ET_c) and sum of the net applications (ΣNA_c) data during three growing seasons, and daily citrus ET_c and monthly ΣNA_c data by year

Crop-variable	Year	n	r	RMSE (mm)	MRE (mm)
Peach ET_c	2002	7	0.92**	27.39	0.22
	2003	7	0.84*	32.69	0.24
	2004	7	0.95***	16.51	0.13
Peach ΣNA_c	Drip 2002	7	0.86*	38.07	0.34
	Furrow 2002	7	0.91**	29.87	0.19
	Drip 2003	7	0.97***	17	0.22
	Furrow 2003	7	0.94**	17.98	0.19
	Drip 2004	7	0.95***	20.41	0.22
	Furrow 2004	7	0.94**	20.16	0.14
Citrus ET_c	2003	184	0.92***	0.60	0.09
	2004	184	0.92***	0.59	0.20
Citrus ΣNA_c	micro-sprinkler 2003	9	0.90***	28.75	0.14
	micro-sprinkler 2004	8	0.86*	42.27	0.42

*$P \leq 0.025$; **$P \leq 0.005$; ***$P \leq 0.001$

was underestimated in 2002, whereas it was overestimated in 2003 and 2004. In fact, the ET_{aw} in 2004 was 1007 and 1013 mm for drip and furrow irrigation, respectively, compared with 992 mm for the observed data. In 2003, ET_{aw} was 959 and 954 mm for drip and furrow irrigation, respectively, compared with 935 mm of the observed data. In general, the observed and predicted monthly ΣNA_c values followed similar trends.

4.2 Site 2

The model estimated CET_c values for citrus were 936 and 972 mm for 2003 and 2004 respectively, whereas the observed CET_c values were 975 and 945 mm, respectively. The model showed some under-prediction of citrus ET_c, especially during October and November in 2003 (Fig. 2a) and during March in 2004 (Fig. 2b). Since a fixed $K_c = 1.00$ was used all year in the SIMETAW# model, the canopy resistance in the ET_o equation is fixed, and the canopy resistance of the crop was reduced when the foliage was wetted by fog or light rainfall, which is common in spring and fall, it likely explains the higher observed than modelled ET_c values from late fall through early spring. In addition, the differences between modelled and observed ET_c might result from measurement errors due to frequent light rainfall and fog interception during these months. In general, observed and predicted values followed the same trend, with a particular good fit when spikes in the ET_c values were observed.

The observed ET_{aw} was estimated as the ΣNA_c during the season assuming no runoff or deep percolation, and the estimated citrus ET_{aw} was determined using SIMETAW#. The model estimated citrus ET_{aw} values were 1060 mm (2003) and 1124 mm (2004) without considering the contribution of November through April fog, dew, and light rainfall; this compares with the observed ET_{aw} values 1153 mm (2003) and 903 mm (2004). The model is predicting an optimal ET_{aw} for the orchard, and the observed ET_{aw} was 93 mm higher than ET_{aw} (2003) and 121 mm lower than ET_{aw} (2004). The yield of top quality fruit from the research orchard was 58 % higher in 2003 than in 2004, and the 2004 yield was considerably higher than the

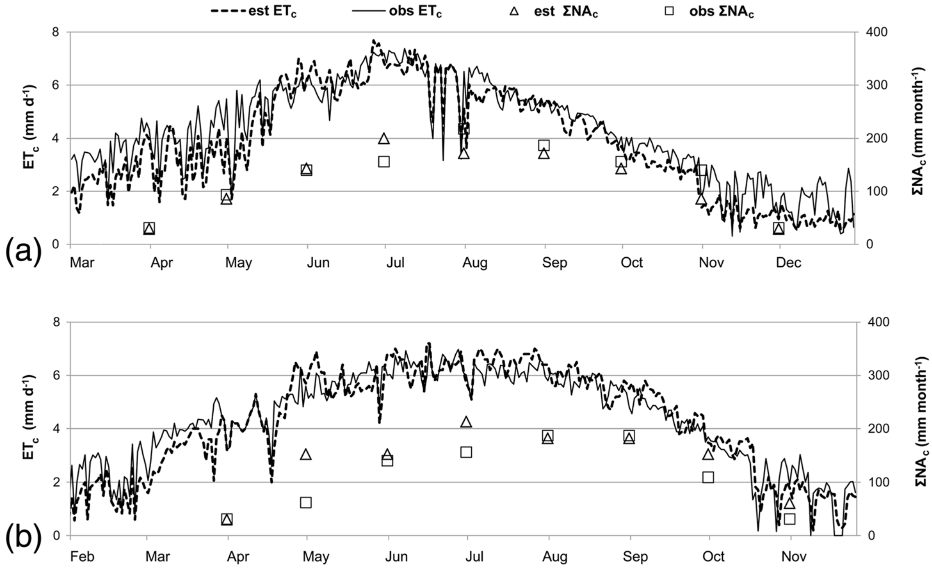

Fig. 2 Estimated (est) and observed (obs) daily crop evapotranspiration (ET_c) and monthly applied water (ΣNA_c) data of citrus in 2003 (**a**) and 2004 (**b**)

regional average (Snyder and O'Connel 2007). The statistics (Table 1) confirmed the good predictive capability of the model in estimating ET_c and the amount of water necessary during the irrigation season.

The RMSE and MRE values for estimated ET_c, calculated during the main irrigation season, i.e., when ET_o was substantial, were good for both seasons. The model simulation indicated the need for one irrigation event in January and February 2003, however, the contribution of fog, dew, and light rainfall was not included in the calculations. It is likely that the soil water extraction was overestimated during winter because the estimates did not include the contributions of fog, dew, and light rainfall. Because of the inaccuracy in trying to determine ET_o during the winter, when $ET_o < 2.0$ mm d^{-1} was common, we did not attempt to account for the contribution of fog interception, which is appreciable in the San Joaquin Valley from November through March. The irrigation season ended in mid-October 2004 compared with mid-November 2003, however, the model predicted two irrigation events in November 2014 and one irrigation event in November 2003. The actual irrigation events were independently controlled by the grower, but the predicted and actual number of irrigation events over the seasonal were comparable. During the irrigation season of 2003, the model estimated 39 irrigation events and 38 were actually applied. In 2004, the model estimated 38 irrigation events, and there were 36 actual applications.

4.3 Site 3

SIMETAW# estimated the seasonal CET_a for wheat equal to 475 mm, while the observed value was 465 mm. As shown in Fig. 3, the mismatch between observed and simulated values was noted during the end of the growing season. In fact, a relatively small difference of about 20 mm month^{-1} of ET_a was estimated in May. Taking into consideration the simulated daily soil water balance data, the wheat started to exhibit water stress after May 9 and the stress

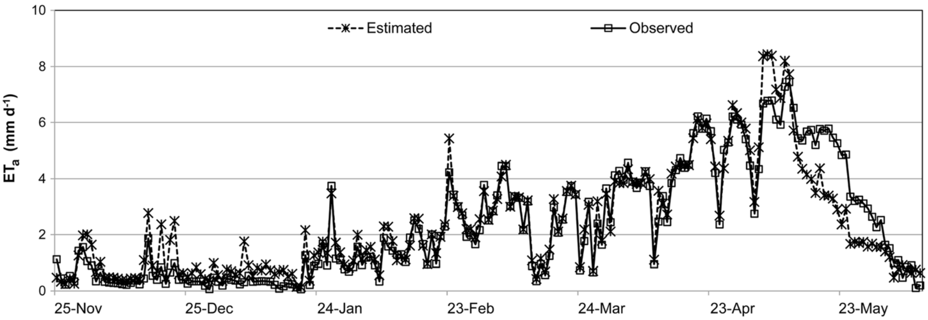

Fig. 3 Daily estimated and observed ET_a data of wheat

factor decreased from 1.00 to 0.42 at the end of the season. Around May 14, the stress factor was $K_s = 0.76$ and the drop of ET_a values became apparent. Overall, the model simulation followed the observed trend well. The statistical analysis showed correlation $r = 0.94$, which was significant at $P \leq 0.001$. The RMSE = 0.70 mm d^{-1} was relatively low and demonstrated a good predictive difference between expected and observed data. As further demonstrated by the MRE (0.51 mm d^{-1}) value, the model showed a good performance for estimating daily ET_a.

5 Discussion

Unlike other soil water balance models, SIMETAW# allows climate corrections for ET_o and crop coefficient data in order to get more reliable water balance calculations. Moreover, SIMETAW# accounts for non-uniformity of the irrigation application, and it can be applied to rain-fed, deficit irrigated, and fully irrigated crops.

SIMETAW# is a model to estimate irrigation water demand, and it provides some potential yield information for a wide number of crops rather than giving detailed crop production information as provided by more specific crop production and growth models. SIMETAW# does not require experimental data for the calibration and evaluation processes that are essential for using crop models.

6 Conclusions

SIMETAW# is a soil water balance model that is able to simulate the evapotranspiration of the applied water. The daily water balance is an essential part of the program because it helps to determine the timing of the first and last irrigation events to insure that the soil water content starts and ends at levels that are reasonable. The model determines when the crop should be irrigated and how much water should be applied in terms of net and gross application depending on the irrigation system. Then, the sum of the computed net applications during a season provides information on how much water is needed to match the seasonal evapotranspiration to produce the crop. The possibility to choose the percentage of the full irrigation requirement to apply to a crop permits the simulation of adaptation strategies aimed to increase the use of irrigation water in an efficient way. Moreover, the application helps to assess irrigation demand in relation to future CO_2 concentration. Results of the ET_{aw} simulation indicate that the SIMETAW# model could be used efficiently to evaluate different irrigation strategies that enhance irrigation planning.

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Compliance with Ethical Standards

Conflict of Interest The authors declare no conflict of interest.

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