Predicting soil salinity in response to different irrigation practices, soil types and rainfall scenarios

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Abstract

A model was developed to predict rootzone salinity under different irrigation practices on different soil types, with similar rainfall but different monthly distributions. A rootzone daily water and salt balance was performed using eight scenarios: two soil types (coarse-textured v. fine-textured), two multi-year series of actual rainfall data and two irrigation practices (surface with fixed number of irrigations and ET-based sprinkler irrigation). All factors influenced the mean electrical conductivity (EC) of the rootzone in the growing season (EC_{eS}): (i) Surface irrigation led to lower EC_{eS} than sprinkler irrigation; (ii) Winter-concentrated rainfall caused lower EC_{eS} than rainfall distributed uniformly throughout the year; and (iii) Coarser textured soil usually resulted in lower EC_{eS} than the finer textured. The EC_{eS} was related to the total precipitation of the hydrologic year and to the annual leaching fraction (LF), but surprisingly not to the seasonal LF. In most cases the model predicted lower EC_{eS} than the FAO steady-state approach. Therefore considering these site-specific features could lead to lower leaching requirements and the safe use of higher salinity water.

Introduction

Irrigation is essential in arid and semi-arid climates to optimize crop production but it unavoidably leads to off-site environmental problems such as higher salinity of irrigation return flows (Tanji and Kielen 2002) and increases in nutrient, pesticide and sediment loads (Ongley 1996) resulting in the deterioration of water quality. At the same time, irrigation can have on-site effects such as waterlogging, salinization and sodification of agricultural lands (Skaggs and van Shilfgaarde 1999).

In the context of global competition for water resources, there is a need to understand the complex dynamics of water management including crop evapotranspiraton (ET), water quality and leaching requirements, all of which depend upon site-specific conditions (i.e. crop type, irrigation method, climate, and soil type). This site-specific determination of water needs and required water quality would improve large scale water management and policy decisions.

Soil salinity has been predicted as a function of the salinity of the irrigation water and the leaching fraction in the traditional steady-state model described in FAO 29 (Ayers and Westcot 1985; Rhoades et al. 1992). While this model is a good first approximation, it does not account for soil properties, rainfall patterns or various climates where ET changes throughout the year. These factors will have a profound influence on soil salinity throughout the crop season (Ayers and Westcot 1985). The irrigation method is only considered in FAO 29 by assigning different root-water uptake patterns in relation to high frequency and conventional irrigation and by assuming that the electrical conductivity (EC) of the soil solution must be weighted to account for root-water uptake in high frequency irrigation systems (Ayers and Westcot 1985).

Many steady- and transient-state models (ranging in complexity from bucket-type to numerical solutions of the Richards equation) have been used to model water movement through the soil and associated processes of crop uptake and solute movement (Bastiaansen et al. 2007). Letey and Feng (2007) concluded that steady-state models tend to overestimate the adverse effects of irrigating with saline waters, thus pointing to water quality standards for salinity higher than necessary. The same results were found by Corwin et al. (2007), but they also found that in some instances, accounting for salt precipitation-dissolution processes may be more important than using a dynamic model. Both papers agree in the benefits of using

transient-models to estimate leaching requirements (and thus irrigation volumes) and to develop irrigation management guidelines.

However, sophisticated transient-state models often require highly trained modeling experts and input data are sometimes difficult to obtain. There are also issues with spatial variability that limits the application of the models on a large-scale basis for management purposes (Bastiaansen et al. 2007). Therefore, the use of advanced models for management purposes may need the development of less data-intensive and more user-friendly transient models (Bastiaansen et al. 2007).

A simple, daily time-step soil salinity model, based on soil water storage in four rootzone quarters was developed and applied to long records of meteorological data to take into account a number of site-specific factors. The objectives of this paper were: (i) to develop a straightforward water and salt balance model based on available data (meteorological daily records, crop evapotranspiration (ET) and soil textural parameters) that could be used by regulators to set water quality criteria for electrical conductivity (or chloride); (ii) to incorporate local soil properties, rainfall patterns, crop type and type of irrigation into the model, and establish the effect of these factors on soil salinity during the growing season; (iii) to determine the influence of these site-specific parameters on irrigation water – soil salinity relations and (iv) to compare the results of the application of the model with the current, steady-state FAO 29 approach.

Material and Methods

Model development

The model we developed performs a water and salt balance in the root zone under similar root water-extraction assumptions to the Ayers and Westcot model. The root zone is divided in four quarters of equal depth and the water inputs and outputs in each layer are calculated on a daily basis (precipitation and temperature records for ET calculations that are widely available and that capture the temporal variability of the soil water processes) and the salt concentrations of each flow component are calculated assuming complete mixing and no chemical dissolution or precipitation of salts. While accounting for chemical dissolution and precipitation is valuable and would be an important addition to the model, this model expands on the FAO 29 approach, which is based on EC and evapoconcentration only and does not account for these processes.

Water Balance

The inputs for the first quarter (top soil layer) are the applied irrigation (I) and rainfall (P), and the outputs, the drainage above field capacity (D, from layer 1 to layer 2), and evapotranspiration (ET) from the layer. For the underlying layers, the only input is the drainage (D) from the overlying layer and the outputs are the drainage to the underlying layer and ET from that layer. For the fourth quarter (deepest layer), the drainage represents the total drainage from the crop rootzone. Drainage was only allowed from a layer when its volumetric water content was higher than field capacity. Additionally, water flow at water contents below field capacity (U) was considered between layers and calculated in daily steps too. This unsaturated flow is related to the difference in the water content between the layers and is either upward or downward in direction depending upon the water potential gradient between adjacent layers.

Each soil layer was assigned a saturation water content (S), wilting point (WP), field capacity (FC) and total available water (TAW = FC – WP) according to the soil characteristics for the soil texture chosen. The volumetric water contents (θ_S, θ_{FC} and θ_{WP} available for each soil layer or estimated from texture) were transformed to water contents (S, FC and WP in mm) by multiplying the layer depth RD/4 and the fine earth fraction of the material, where RD (mm) was taken about 75-85% of the rooting depth for the modeled crop, the depth which is usually taken for salinity control and where most of the water uptake takes place (Ayers and Westcot 1985).

The daily ET_c was calculated using appropriate data for K_c and the duration of the crop stages (Goldhamer and Snyder 1989) and ET_o data calculated by the Hargreaves formula (corrected by regression to match local Penman-Monteith estimates) (Hargreaves and Allen 2003):

$ET_{Har}(mm/d) = 0.0029 \cdot R_a \cdot (T_m) \cdot (T_{max} - T_{min})^{0.4}$ where T_{max} (T_{min}) was the maximum (minimum) daily temperature, T_m was the mean daily temperature and the extraterrestrial radiation (R_a) was calculated in MJ m^{-2} d^{-1} from the latitude and the day of the year and converted to mm/d dividing by the latent heat of evaporation (Allen et al., 1998). These daily ET_o estimates (ET_{Har}) based on the Hargreaves formula were corrected by regression to match the ET_o estimates by the Penman-Monteith method presented by Goldhamer and Snyder (1989). The model allows for the introduction of other linear regression coefficients specific to a location to convert ET_{Har} estimates into locally more reliable ET_o estimates.

The achievable, non water-stressed crop ET is calculated as $ET_c = K_c \cdot ET_o$. Between cropping seasons, all ET [or evaporation (E) since there is no established crop on the soil] was assumed to take place from the upper layer. For this period, the K_c was calculated from

the mean interval between precipitation (wetting) events of each month, the mean precipitation per event in each month and the ET_o (Allen et al. 1998). The K_c for the initial development stage (Stage 1) was also calculated in this way including irrigations to establish the interval between wetting events and mean irrigation or precipitation per event. During the non-growing season and the first stage of crop development, ET was reduced according to the soil water content of an upper evaporation layer (with user defined depth, always lower than first layer) calculated through the soil water balance following Allen et al. (1998).

The crop coefficients for the full development stage ($K_{c\,mid}$, Stage 3) and for the end of the growing season ($K_{c\,end}$) were taken from Goldhamer and Snyder (1989). For the crop development stage (Stage 2), K_c was interpolated linearly between K_c of the last day of the initial stage and $K_{c\,mid}$ (constant K_c of Stage 3, full crop development). The K_c was also interpolated linearly between $K_{c\,mid}$ and $K_{c\,end}$ for the late season stage (Stage 4).

Similar to the assumptions by Ayers and Westcot (1985), during the growing season the extraction pattern for each descending quarter-layer of the rootzone was taken as 40%-30%-20%-10% (usual pattern for long irrigation intervals or conventional irrigation). Therefore the achievable crop ET from layer "k" is $ET_c(k) = C_k\, ET_c$ where $C_1 = 0.4$, $C_2 = 0.3$, $C_3 = 0.2$, and $C_4 = 0.1$.

In each layer, the actual crop ET [$ET_r(k)$] can be lower than $ET_c(k)$ due to water stress, which depends on the soil water content and the sensitivity of the crop to low water contents, accounted for through the crop-specific parameter p: the ratio of readily available soil water (RAW) to TAW (p = RAW/TAW) (Allen et al. 1998). When the soil water content [$W(k)$] in a layer fell below $We(k) = WP + (1-p)\, TAW$, the ET from that layer [$ET_r(k)$] dropped below the $ET_c(k)$ and the actual ET of the layer was calculated as $ET_r(k) = K_s \cdot ET_c(k)$, where K_s is a stress coefficient (Allen et al., 1998):

$$K_s = \begin{cases} 1 \dots\dots\dots\dots\dots\dots\dots & if \quad W(k) > We(k) \\ \dfrac{W(k)-We(k)}{We(k)-WP(k)} & if \quad WP(k) < W(k) < We(k) \\ 0 \dots\dots\dots\dots\dots\dots & if \quad W(k) < WP(k) \end{cases} \qquad \text{[Eq. 1]}$$

Also, when one layer was stressed during the growing season [$W(k) < We(k)$] the model allowed to increase the extraction coefficient of the lower layer C_{k+1} to supply the ET demand of the day; thus assuming that the crop can extract water from deeper soil layers when there was water stress in a given soil layer.

When the soil water content in layer "k" [W(k)] was above FC(k), the excess water [Ex(k) = W(k)-FC(k)] drains to the lower layer over a two-day period, so that W dropped to FC in two days and with higher flow in the first day than the second. The fraction "α" of the excess water that drained the first day ($0 < \alpha < 1$) was calculated from the soil texture in the layer through an empirical relation obtained to match the results presented by Hillel and van Bavel (1976) for three soil types (approximately, $\alpha \sim 0.9$ for sand, $\alpha \sim 0.75$ for loam and $\alpha \sim 0.6$ for clay). For that purpose, two arbitrary water contents in excess of FC, Wa and Wb, were defined from the FC and saturation (S) of the soil layer and the fraction α:

$$Wa = FC + (1 - \alpha) \cdot (S - FC) < Wb = FC + \frac{1 - \alpha}{\alpha}(S - FC) \text{ and D is calculated as:}$$

$$D = \begin{cases} \alpha \cdot (W - FC) \ldots \ldots \ldots if \quad W > Wb \\ (1 - \alpha) \cdot (S - FC) \ldots \ldots if \quad Wa < W < Wb \\ W - FC \ldots \ldots \ldots \ldots if \quad W < Wa \end{cases} \qquad \text{[Eq. 2]}$$

With the drainage (D) defined above, neither upward movement of water (redistribution of water throughout the profile) nor drainage with W < FC were allowed. In order to account for the slow water movement between layers for low W, a slow upward/downward flow (U; dependent upon the difference in matric potential between soil layers) was introduced. This term was only considered when $W < FC + 0.5 \cdot (Wa - FC)$, so that when W was well above FC, water movement depended only on W. On the other hand, for lower W, water movement depended on the water content (matric potential) of adjacent layers and their soil properties. This term allowed for the redistribution of water in the profile, such as the wetting of the upper layer from lower layers when soil water is depleted by ET. The model allows the user to make use of U or not.

The term U was defined empirically so that it can be inferred from the texture of the soil layers alone. For each textural class, representative values of K_s were selected (Rawls and Brakensiek 1989; Clapp and Hornberger 1978) and simulations of water movement under varying differences of matric potential between layers (from FC in one layer to different W above WP in the other) were performed. For each of the simulations (performed with 10-minute time steps and 10 cm distances between layers), the cumulative water flows after one day (the model time step: $\Delta\theta_{1 \text{ day}}$) were expressed as a fraction of the total difference in water content (x) at the beginning of the simulation, where $x = (\Delta\theta_{1 \text{ day}}) / (\theta_1 - \theta_2)$ with θ_1 and θ_2 being the initial water contents in both simulation layers ($\theta_1 = \theta_{FC}$ and $\theta_{WP} < \theta_2 < \theta_{2FC}$). With all the simulations performed, the logit regressions (Ashton 1972) between x and the clay (C)

and sand (S) weight fractions of the soil and the difference in matric potential between the layers ($\Delta\psi = \psi_1 - \psi_2$ where ψ_1 and ψ_2 are the initial matric potentials in both layers in cm) are fitted. The fitted logit regression yielded x as a linear function of C, S and $\Delta\psi$:

$$x = 1/[1 + \exp(0.489 + 0.00003\ \Delta\psi + 1.289\ S + 2.854\ C)]; \quad (R^2 = 0.78) \qquad \text{[Eq. 3]}$$

always bound between 0 and 1 ($0 < x < 1$) so that the water transfer between two layers never reaches the difference in water content between the layers ($\theta_1 - \theta_2$), a problem found when applying the water movement equations to long one-day time steps.

To perform the aforementioned simulations, the soil matric potential (ψ) was related to the volumetric water content (θ) by means of the equation (Clapp and Hornberger 1978):

$$\psi = \psi_S \cdot \left(\theta \middle/ \theta_S \right)^{-b} \qquad \text{[Eq. 4]}$$

where θ_s was the volumetric water content at saturation, ψ_s is the water entry potential or "saturation" water potential, and b is the slope of the water retention curve on a logarithmic plot. For each soil type, b and ψ_s were calculated from the volumetric water content at field capacity and wilting point (θ_{FC} and θ_{WP}) and their respective potentials in absolute value [$\psi_{FC} = 316$ cm and $\psi_{WP} = 15849$ cm; so that pF(FC) = 2.5 and pF(WP) = 4.2]. Taking logarithms, the expression of the potentials for FC and WP become linear equations

$$\begin{aligned} \log(\psi_{FC}) &= 2.5 = \log\psi_S - b \cdot \log(\theta_{FC}/\theta_S) \\ \log(\psi_{WP}) &= 4.2 = \log\psi_S - b \cdot \log(\theta_{WP}/\theta_S) \end{aligned} \qquad \text{[Eq. 5]}$$

from which b and ψ_s are estimated. The unsaturated hydraulic conductivity for a given θ was given by (Clapp and Hornberger 1978)

$$K = K_S \left(\theta/\theta_S \right)^{2b+3} \qquad \text{[Eq. 6]}$$

where K_S is the saturated hydraulic conductivity (available for that layer material or estimated from texture). Thus, the flow between the layers (U) can be calculated as

$$U = K\ (\Delta\psi/\Delta Z) \qquad \text{[Eq. 7]}$$

where $\Delta Z = 10$ cm (the distance selected for the simulations) neglecting the gravitational gradient.

Water is allowed to flow out of layer 4 ($U_{4\rightarrow}$) by gravitational potential only, assuming that there were no water tables or impervious layers beneath that would affect drainage. The

gravitational flow out of the root zone is taken as: $U_{4\rightarrow} = K_S\left(\theta/\theta_S\right)^{2b+3}$ where the parameters K_S, θ_S and b correspond to layer 4 and θ is the volumetric water content in layer 4. Like U, the model allows the option for including this low W flow out of the root zone.

All the water flows are assigned a plus sign when directed downwards (so that drainage is positive) and minus sign for upward flow. The W in a layer "k" on day 1 (t + 1) [$W(k)_1$ with k = 1, 2, 3, or 4] was calculated from the W in day 0 (or t) $W(k)_0$ and the water flows into and out of layer "k" estimated on day 1:

$W(1)_1 = W(1)_0 + I(1)_1 + P(1)_1 - D(1)_1 - ET_r(1)_1 - U(1)_1$

$W(2)_1 = W(2)_0 + D(1)_1 - D(2)_1 - ET_r(2)_1 - U(2)_1$

$W(3)_1 = W(3)_0 + D(2)_1 - D(3)_1 - ET_r(3)_1 - U(3)_1$

$W(4)_1 = W(4)_0 + D(3)_1 - D(4)_1 - ET_r(4)_1 - (U_{4\rightarrow})_1$ [Eq. 8]

where the D is calculated with the W prior to ET_r and U is calculated with the water content in the layers after all the other terms had been considered. The net drainage from a given layer "k" is obtained as $D(k) + U(k)$, and it is this value from layer 4 that is used as soil drainage in the results section.

Although preferential flow and irrigation non-uniformity are also important features that could be addressed empirically, these processes are complex and remain beyond the scope of this paper.

In addition, the model does not incorporate capillary rise or restriction of water flow downwards by an impervious layer; as the flow out of profile is based on excess water above FC [D(4)] or gravity unsaturated flow ($U_{4\rightarrow}$). Thus this model cannot be used in the presence of shallow water tables or impeded drainage and cannot simulate soil salinity when derived from a shallow, saline water table.

Salt Balance

The salt balance was performed in conjunction with the water balance assuming complete mixing of water entering each layer with that already stored in that layer. The electrical conductivity of water (EC) was used as an indicator of salinity, assuming implicitly that there was a unique relationship between EC and total dissolved solids (TDS) in these dilute solutions and that the EC behaves like a non-reactive solute. Salinity of the input waters [irrigation water (EC_w) and precipitation (EC_p)] must be known even though salt inputs are low. The mass of salts in layer k [Z(k)] is estimated from the product $EC_{sw}(k) \cdot W(k)$, where EC_{sw} is the electrical conductivity of the soil water in that layer. The mass of salts in layer k

in day 1 (t+1) results from the salinity in day 0 (or t) and the salt fluxes in day 1 that are added sequentially:

1. The salts in I and P are added to the salt mass in layer 1 to obtain $Z^a(1)_1$. Salts leaving layer 1 (D) are inputs to the layer 2 and so on such that ($Z^a(x)_1$, x = 2-3-4):

$$Z^a(1)_1 = Z(1)_0 + EC_w \cdot I(1)_1 + EC_p \cdot P(1)_1 \qquad \text{for layer 1 or}$$

$$Z^a(x)_1 = Z(x)_0 + 1 + EC_{sw}(1)_0 \cdot D(1)_1 \qquad \text{for layers 2, 3 and 4} \qquad \text{[Eq. 9]}$$

This results in a soil water concentration of

$$EC^a_{sw}(1)_1 = Z^a(1)_1 / [W(1)_0 + I_1 + P_1] \qquad \text{in layer 1 or}$$

$$EC^a_{sw}(x)_1 = Z^a(x)_1 / [W(x)_0 + D(x-1)_1] \qquad \text{in layers 2, 3 and 4} \qquad \text{[Eq. 10]}$$

2. The drainage from any layer (y = 1-2-3-4) takes place with concentration EC^a_{sw} so that the new mass of salts in layer "y" is:

$$Z^b(y)_1 = Z^a(y)_1 - EC^a_{sw}(y)_1 \cdot D(y)_1 \qquad\qquad \text{[Eq. 11]}$$

and the new soil water concentration is

$$EC^b_{sw}(1)_1 = Z^b(1)_1 / [W(1)_t + I_1 + P_1 - D(1)_1] \qquad \text{for layer 1 and}$$

$$EC^b_{sw}(x)_1 = Z^b(x)_1 / [W(x)_t + D(x-1)_1 - D(x)_1] \qquad \text{for layers x = 2-3-4..} \qquad \text{[Eq. 12]}$$

3. The soil water at this stage is evapo-concentrated by the crop water uptake (ET_r):

$$EC^c_{sw}(1)_1 = Z^b(1)_1 / [W(1)_t + I_1 + P_1 - D(1)_1 - ET_r(1)_1] \quad \text{for layer 1}$$

$$EC^c_{sw}(x)_1 = Z^b(x)_1 / [W(x)_t + D(x-1)_1 - D(x)_1 - ET_r(x)_1] \quad \text{for layers 2,3 and 4} \quad \text{[Eq. 13]}$$

4. The mass of salts in the slow flow U are then added/removed to obtain the final mass of salts in the layer [$Z(k)_1$]:

$$Z(1)_1 = Z^b(1)_1 - (U_{1\text{-}2})_1 \cdot EC^c_{sw}(2)_1 \quad \text{if} \ \ U_{1\text{-}2} < 0 \qquad\qquad \text{or}$$

$$Z(1)_1 = Z^b(1)_1 - (U_{1\text{-}2})_1 \cdot EC^c_{sw}(1)_1 \quad \text{if} \ \ U_{1\text{-}2} > 0 \qquad\qquad \text{for layer 1 ;}$$

$$Z(2)_1 = Z^b(2)_1 + (U_{1\text{-}2})_1 \cdot EC^c_{sw}(2)_1 - (U_{2\text{-}3})_1 \cdot EC^c_{sw}(3)_1 \quad \text{if } U_{1\text{-}2} < 0 \text{ and } U_{2\text{-}3} < 0 \ \ \text{or}$$

$$Z(2)_1 = Z^b(2)_1 + (U_{1\text{-}2})_1 \cdot EC^c_{sw}(1)_1 - (U_{2\text{-}3})_1 \cdot EC^c_{sw}(3)_1 \quad \text{if } U_{1\text{-}2} > 0 \text{ and } U_{2\text{-}3} < 0 \ \ \text{or}$$

$$Z(2)_1 = Z^b(2)_1 + (U_{1\text{-}2})_1 \cdot EC^c_{sw}(2)_1 - (U_{2\text{-}3})_1 \cdot EC^c_{sw}(2)_1 \quad \text{if } U_{1\text{-}2} < 0 \text{ and } U_{2\text{-}3} > 0 \ \ \text{or}$$

$$Z(2)_1 = Z^b(2)_1 + (U_{1\text{-}2})_1 \cdot EC^c_{sw}(1)_1 - (U_{2\text{-}3})_1 \cdot EC^c_{sw}(2)_1 \quad \text{if } U_{1\text{-}2} > 0 \text{ and } U_{2\text{-}3} > 0 \ \ \text{or}$$

for layer 2 (exchange 1-2-3 by 2-3-4 for layer 3); and

$$Z(4)_1 = Z^b(4)_1 + (U_{3\text{-}4})_1 \cdot EC^c_{sw}(3)_1 + U_{4\rightarrow} \cdot EC^c_{sw}(4) \qquad \text{if } U_{3\text{-}4} > 0 \ \ \text{or}$$

$$Z(4)_1 = Z^b(4)_1 + (U_{3\text{-}4})_1 \cdot EC^c_{sw}(4)_1 + U_{4\rightarrow} \cdot EC^c_{sw}(4) \qquad \text{if} \ \ U_{3\text{-}4} < 0$$

for layer 4. $\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad$ [Eq. 14]

which allows for calculating the final soil water concentration in layer k:

$$EC_{sw}(k)_1 = Z(k)_1 / W(k)_1 \qquad \text{[Eq. 15]}$$

Then, the EC of the saturation extract $[EC_e(k)_t]$ of layer k in day t is calculated from the EC of the soil solution and the water content in the layer on that day $[EC_{sw}(k)_t$ and $W(k)_t]$ as

$$EC_e(k)_t = EC_{sw}(k)_t \ \frac{W_t(k)}{SP(k)} \qquad \text{[Eq. 16]}$$

where SP(k) is the water content of the saturated paste of that layer. The SP(k) is a sensitive parameter and should be assessed whenever possible; when not available, the traditional rule for most mineral soils is $SP = 2 \cdot FC$.

The arithmetic mean $[EC_e]$ and the uptake weighted mean of the 4 layers $[EC_e(w)]$ of the daily $EC_e(k)$ were calculated for every day t:

$$EC_{e_t} = \frac{1}{4}\sum_{k=1}^{4} EC_{e_t}(k); \qquad EC_e(w)_t = \frac{\sum\limits_{k=1}^{4} ET_{r_t}(k) \cdot EC_{e_t}(k)}{\sum\limits_{k=1}^{4} ET_{r_t}(k)} \qquad \text{[Eq. 17]}$$

Generally crops respond to the mean salinity of the root zone over the entire growing season (Ayers and Westcot 1985). Therefore the daily values of EC_e [and $EC_e(w)$ as well] were averaged over the entire growing season:

$$EC_{eS} = \frac{\sum\limits_{Growing\ Season} EC_{e_t}}{Number\ of\ days\ in\ the\ growing\ season} \qquad \text{[Eq. 18]}$$

which gives the seasonal-average rootzone EC_e (EC_{eS}). This value can be compared with the crop salt tolerance EC_e values to determine the yield loss (if any) due to salinity. It is generally assumed that crops respond to the mean seasonal soil salinity but in reality crop salt tolerance changes with growth stage. Since salt-tolerance response functions in relation to changing growth stage are lacking, the model assumes that crops respond to the average rootzone salinity. The model can be used also to adjust the EC_w that results in a seasonal average EC_e low enough to prevent salinity induced yield losses for that crop, which is particularly attractive to policy makers.

The mean daily EC_e was also averaged over the whole hydrologic year (EC_{eHY}) and can be averaged over any other period of interest. The seasonal uptake weighted EC_e [$EC_e(w)$] is better related to crop response in high frequency irrigation systems (drip irrigation) (Ayers and Westcot 1985).

Model application

The model was applied to eight irrigated corn scenarios resulting from the combination of two soils, two rainfall distribution records, and two irrigation methods (sprinkler and basin). These scenarios were intended to provide information about the resulting EC_e during the growing season (EC_{eS}, the main objective of this paper), and the hydrologic year (EC_{eHY}) under a wide range of climatic, management and soil conditions.

The selected soils were the series *Hesperia fine sandy loam moderately deep* (Hst) and *Capay soils flooded* (Cc) (National Resources Conservation Service 1968), both uniform down to 75 cm deep (the selected rooting depth for corn; Hanson et al. 1996). These soils varied drastically in textural class. The Cc soil series are silty-loam soils with low permeability whereas the Hst series are sandy loam soils with a 30-fold higher K_s (Table 1). The clay content (C in weight fraction), K_S and textural class were taken from the National Resources Conservation Service (NRCS) soil surveys of Yolo and Fresno counties. These soils were selected for their homogeneity (absence of textural or conductance discontinuities) and their different hydraulic properties (K_S and TAW). Soil properties required for model application (sand and silt content, wilting point, field capacity, porosity and saturated paste water content) inferred from the soil surveys are reported in Table 1.

Table 1 Soil properties considered for the soil water and salt balance: Sand (S), Clay (C) and Silt (Si) content, textural class, hydraulic conductivity (K_s), water content of the saturated paste (SP), field capacity (FC, cm^3/cm^3), permanent wilting point (WP) and total available water (TAW)

Soil	Weight fraction			Texture	K_s cm/d	SP	FC cm^3/cm^3	WP	TAW cm^3/cm^3	mm
	S	C	Si							
Cc	0.075	0.475	0.45	Si-C	7.9	0.529	0.364	0.223	0.141	105.8
Hst	0.65	0.125	0.225	S-L	241.9	0.429	0.198	0.119	0.079	59.6

To test the influence of rainfall distribution, two precipitation records (having similar annual rainfall averages but different distributions throughout the year) were selected: Davis CA (470 mm/yr; 1951 to 2006) and Almudévar, Spain (457 mm/yr; 1964 to 2006). The model was applied to all the available meteorological data (56 years in Davis and 43 years in Almudévar) (Fig. 1). The temperature (T) and ET_c values were assumed to be the same for both locations (Davis data) in order to test models influence by rainfall distribution only. The meteorological records for Davis were taken from the National Climate Data Center (2004) and the data for Almudévar were facilitated by the Agencia Estatal de Meteorología of Spain.
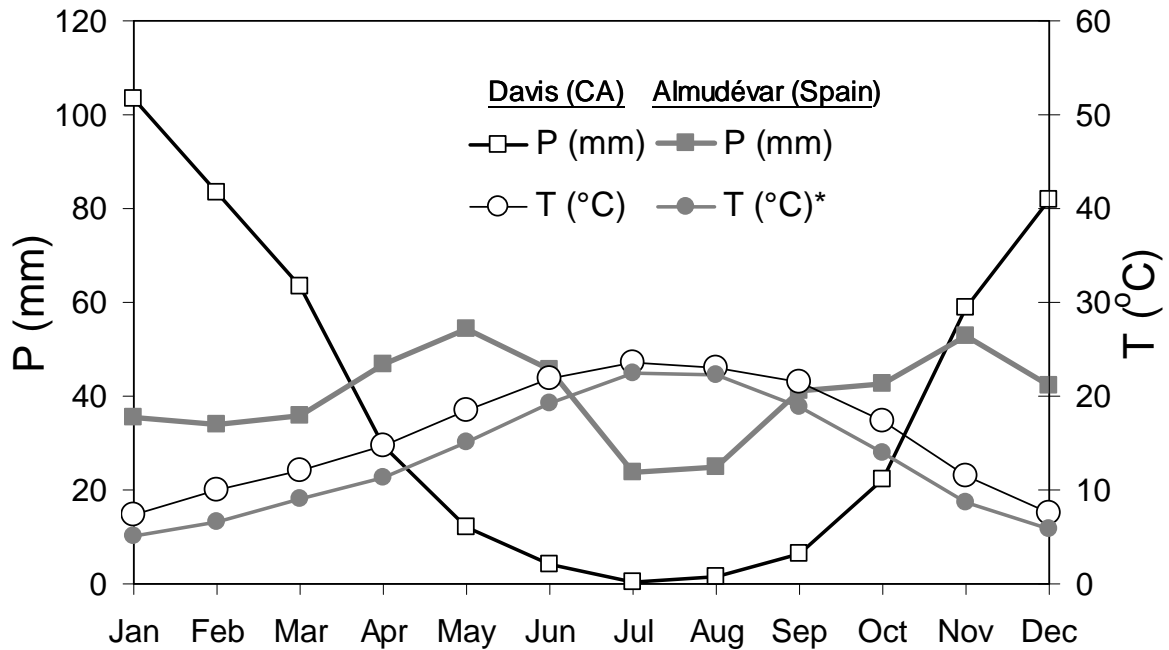
Fig. 1 Mean monthly rainfall (P) and temperature (T) in the stations of Davis and Almudévar (* T data from Almudévar were not used and are presented here only for comparison purposes)

In Davis, rainfall was concentrated in winter (88% of rainfall took place from October to March), whereas in Almudévar rainfall was more uniformly distributed throughout the year (only 51% from October to March). Total annual rainfall was almost the same in both locations but slightly more variable in Davis (ranging from 143 mm to 969 mm, $CV = 33.6$ %) than in Almudévar (from 228 mm to 819 mm, $CV = 26.8$ %).

Finally, two irrigation management scenarios were tested: In the Sprinkler method, the irrigation amounts were calculated based on 11-day (fine-textured soil; Cc) or 6-day (coarse-textured soil; Hst) ET_c forecasts and the dates of irrigation were chosen when the crop reached stress (W < We). This is the case of a sprinkler irrigation system where the date of irrigation can be chosen freely and the amount adjusted to forecasted needs. The adjustment of the amounts to the ET_c forecast and the choice of the irrigation dates based on W assumed that there was an adequate knowledge of soil properties and good management was practiced. The amount of water applied in each location was based only on predicted ET_c and did not consider in-season precipitation or any leaching fraction. The leaching in each scenario stems from irrigation applications above the actual soil water deficit and from seasonal rainfall. This leaching occurs because applications are calculated based on ET_c forecasts which are usually different from the actual soil water deficit.

Under the Surface irrigation method, the number of irrigations along the season was fixed at 9 in both soils. Each irrigation event took place when the cumulative ET_c reached a tenth of the seasonal ET_c and the amount applied was always the same: 1/9 of the seasonal ET_c (with 9 irrigations, the growing season is divided into 10 ET events; one before the first irrigation and one after the final irrigation). As it was assumed to be a rigid irrigation system, no differences were introduced in the Surface method between the two soil types. In both irrigation methods, no irrigation was allowed in the last 15 days of the growing season, to follow normal grower practices.

All the scenarios were tested with an irrigation water EC (EC_w) of 0.7 dS/m because under the classic FAO 29 steady-state approach a mean EC_{eS} of 1.0 dS/m (a value considered non-growth limiting even for the most salt-sensitive crops) results from using an irrigation water with an $EC_w = 0.7$ dS/m and leaching fraction (LF) between 0.15 to 0.20. The EC of the precipitation water ($EC_p = 0.007$ dS/m) was averaged from data of the National Atmospheric Deposition Program (2005) for Davis.

The model was applied to both meteorological series assuming the same management practices for all years, selected from the typical corn cropping practices in Yolo County. The growing season was assumed to be from May 1st to September 27th (150 days: 30 for Stage 1, 40 for Stage 2, 50 for Stage 3, and 30 for Stage 4). The objective was not to actually simulate a 56 year continuous cropping of corn (43 for the Alm rainfall series), but to provide a multiple-year record of seasonal or annual EC_e averages (and related parameters).

The hydrologic and management parameters calculated for each scenario were the precipitation (P), the volume of drainage [D, where D stands for both D and U down the fourth layer: $D = D(4) + U_{4\rightarrow}$], the leaching fraction [$LF = D / (I + P)$], and the mass of salts leached [estimated as Salt (kg/ha) = $7 \cdot EC_d$ (dS/m) $\cdot$ D (mm); i.e. assuming a factor of 700 (mg·L^{-1}) · (dS·m^{-1}) to convert EC into TDS, Rhoades et al. 1992] for both the whole year and the irrigation season; the volume of irrigation (I), the number of irrigations (N), and the seasonal ET deficit (1 - ET_r/ET_c) that determines the yield loss due to water stress (Doorenbos and Kassam 1979).

Results and discussion

Water and salt balance

The results of the first-year simulation (1951) for the Davis rainfall series is presented under this section for illustration purposes of the models outputs. The simulated water contents in

each layer are presented in Fig. 2 along with daily rainfall and irrigation for a sandy loam soil (Hst) in Davis using surface irrigation. The water content in the four layers stayed above WP and for most days below FC: only in days when $W(k) > FC(k)$ did drainage (D) take place from layer k. On the other hand, the water movement term that depends upon soil water potentials (U) occurred with lower water contents and was responsible for the slow W decrease in layers 2, 3 and 4 during the non growing season, when these layers produced drainage (downward flow) and when water also moved towards the upper layer (upward flow) which contributed to the non seasonal $ET_r(1)$ (Fig. 3).
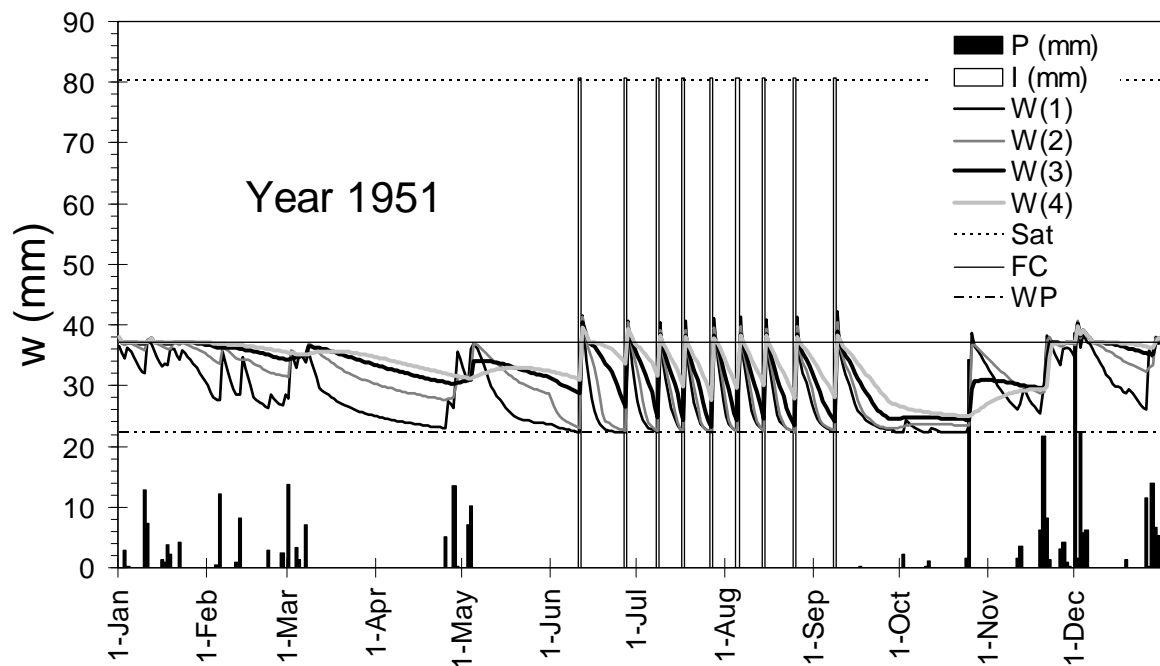

Fig. 2 Soil water content in the four soil layers [W(1) to W(4)], precipitation (P) and irrigation (I) along the first-year (1951) simulation for a surface irrigated corn crop using the Davis rainfall series on soil Hst (sandy loam). The water contents at saturation (Sat), field capacity (FC) and wilting point (WP) of the layers are also shown

In some years, particularly for low TAW soils and long interval irrigations, the calculated ET (ET_r) was clearly lower than ET_c showing that the crop experienced water stress (Fig. 3). The ET deficit during the growing season ($ET_{def} = 1 - ET_r/ET_c$,) is related to the yield loss induced by water stress (Doorenbos and Kassam 1979). Figure 3 also indicates that ET_r took place only from the upper soil layer during the non-growing season and the initial stage of crop growth.

The mean daily EC_e for the same soil selected in Figs. 2 and 3 under surface irrigation is illustrated in Figure 4. Each irrigation event adds some salts that are leached as drainage following the irrigation, causing the spikes during the growing season. The reduction in

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salinity in the winter and early spring is due to rainfall leaching (Fig. 2). During the non-growing season and the first stage of crop development, the $EC_e(1)$ is taken as EC_e.
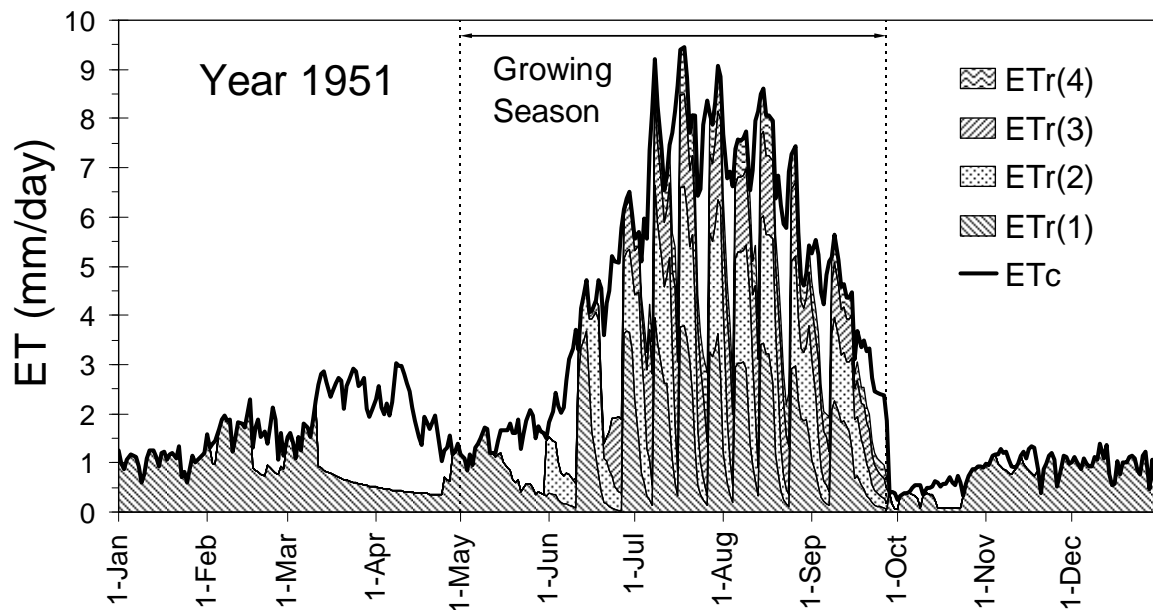
Fig. 3 Simulated ET from the each soil layer [$ET_r(1)$, $ET_r(2)$, $ET_r(3)$, and $ET_r(4)$] and maximum achievable crop ET of corn (ET_c) along the first year of simulation for the Davis rainfall series with surface irrigation on soil Hst (sandy loam). The fraction of unshaded area below the ET_c curve during the growing season represents the ET deficit
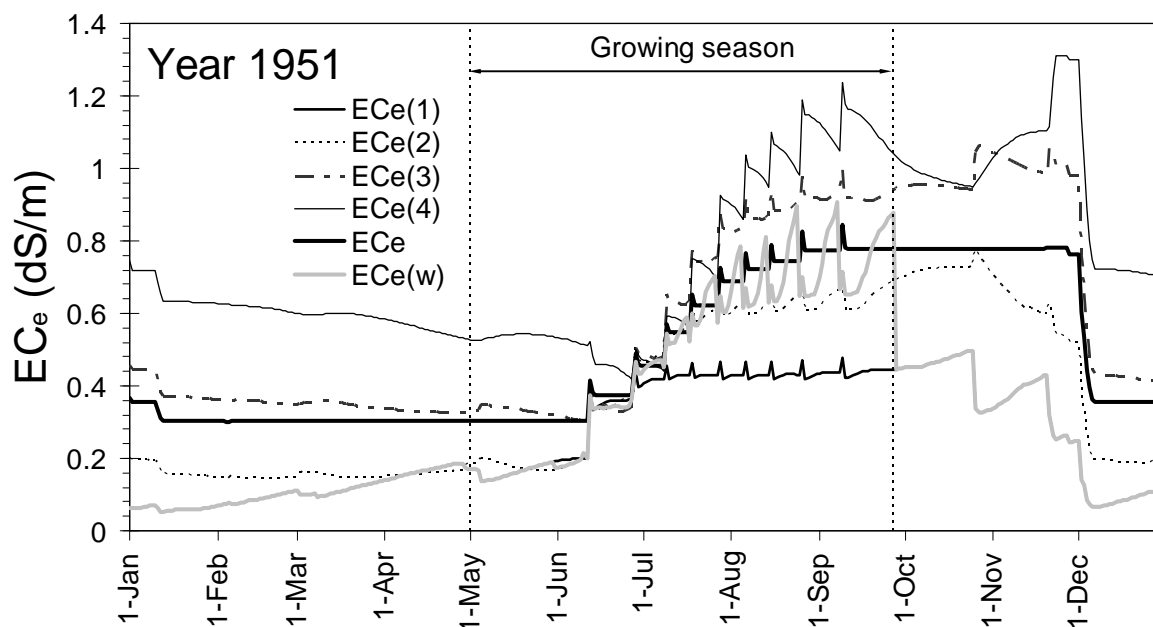
Fig. 4 Simulated daily electrical conductivity of the saturated paste extract of each soil layer [$EC_e(1)$ to $EC_e(4)$], mean EC_e of the soil profile (EC_e) and root water uptake weighted mean EC_e of the 4 layers [$EC_e(w)$] along the first year of simulation (1951) for a surface irrigated corn crop using the Davis rainfall series on soil Hst

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Comparison of the different scenarios

Irrigation method and soil textual class

Both the method of irrigation and soil textural class had a strong influence on the model results. The volume of irrigation applied (I) was slightly higher for the surface irrigation method (712 mm) than the sprinkler method (626 mm) and within the sprinkler method, slightly higher for the Davis rainfall series (671 mm) than the Almudévar rainfall series (568 mm) due to the higher summer precipitation of Almudévar (Table 2). The differences in I between soils within each rainfall series in the sprinkler method were much smaller; but the number of irrigations required in the coarse-textured soil (Hst; lowest TAW) doubled the number in the fine-textured soil, Cc (in the surface method, both I and N were defined equal).

Sprinkler irrigation always provided enough water to practically avoid crop stress (ET deficit < 2% in all scenarios). Surface irrigation on the fine-textured soil provided similar results (ET deficit < 3%); but on course-textured soil, the long irrigation intervals combined with the low TAW led to crop water stress: 12 % for the Almudévar rain series and 20% for the Davis series, which presented lower summer precipitation (Table 2).

Table 2 Indicators of the irrigation performance under the different irrigation methods (Sprinkler or Surface) tested under different rainfall series [Davis or Almudévar (Alm)] and different soil classes (Fine textured Capay or Coarse textured Hesperia): volume of irrigation (I) and number (N) of irrigations applied; deficit ET ($ET_{def} = 1 - ET_r/ET_c$) and volume of drainage (D), leaching fraction (LF), mass of salts leached (Salt) and mean concentration of the leachate for both the growing season (S) and the whole hydrologic year (HY)

Method	Rain	Soil	I mm	N	ET_{def} %	D Mm S	HY	LF S	HY	Salt (kg/ha) S	HY	Leachate (mg/L) S	HY
Sprinkler	Davis	Fine	667	11	1	38	257	0.06	0.21	456	3310	1189	1288
		Coarse	675	22	2	26	259	0.04	0.21	371	3336	1431	1290
	Total Dav		**671**	**16**	**2**	**32**	**258**	**0.05**	**0.21**	**414**	**3323**	**1286**	**1289**
	Alm	Fine	564	8	1	71	131	0.09	0.12	1375	2767	1932	2108
		Coarse	572	17	2	70	138	0.09	0.13	1255	2835	1800	2052
	Total Alm		**568**	**13**	**1**	**70**	**135**	**0.09**	**0.13**	**1315**	**2801**	**1867**	**2079**
Total Spr			**626**	**15**	**2**	**49**	**204**	**0.07**	**0.17**	**805**	**3097**	**1650**	**1515**
Surface	Davis	Fine	713	9	3	76	305	0.10	0.24	950	3531	1252	1157
		Coarse	713	9	20	191	424	0.26	0.35	2062	3513	1079	828
	Total Davis		**713**	**9**	**12**	**133**	**365**	**0.18**	**0.30**	**1506**	**3522**	**1129**	**966**
	Alm	Fine	712	9	1	203	273	0.22	0.23	2515	3525	1240	1293
		Coarse	712	9	12	281	351	0.31	0.30	2828	3533	1006	1005
	Total Alm		**712**	**9**	**6**	**242**	**312**	**0.27**	**0.26**	**2672**	**3529**	**1104**	**1131**
Total Surf			**712**	**9**	**9**	**181**	**342**	**0.22**	**0.28**	**2012**	**3525**	**1114**	**1031**
Total			669	12	5	115	273	.14	0.23	1409	3311	1228	1212

Drainage and LF were clearly higher for the surface method (181 mm and 0.22) than the sprinkler irrigation method (49 mm and 0.07) during the growing season, but the difference was tampered for the hydrologic year: 342 mm (0.28) for the surface method and 204 mm (0.17) for the sprinkler method (Table 2). The Almudévar rain series produced seasonal D about twice as high as the Davis series in both methods (70 mm vs. 32 mm in the sprinkler method and 242 mm vs. 133 mm in the surface method) due to its higher seasonal precipitation; but the hydrologic year D was higher for the Davis series (258 mm vs. 135 mm in the sprinkler method and 365 mm vs. 312 mm in the surface method), showing that drainage was more concentrated during the winter for the Davis series (Table 2). In fact, the ratio of seasonal D to yearly D in Davis was 1 to 8 in the sprinker method (only 1 to 1.9 for the Alm series) and 1 to 2.7 in the surface method (only 1 to 1.3 for the Alm series) (Table 2). The seasonal drainage from the fine-textured soil (Cc) with the Davis rainfall series and surface method (76 mm) was much lower than that from the coarse-textured soil (191 mm), or from both soils within the Almudévar rainfall series (mean 242 mm). Between soils, there were no apparent differences in seasonal or annual D in the sprinkler; but in the surface, D was much higher from fine-textured soil than from the same soil from the Alm series (281 mm vs. 203 mm) and especially for the Davis series (191 mm vs. 76 mm).

Generally, the leaching fractions presented a very similar behavior (Table 2): higher LF in the season for the Alm series than the Davis series (0.09 vs. 0.05 in sprinkle irrigation and 0.27 vs. 0.18 under surface irrigation and higher LF during the year for the Davis series than for the Alm series (0.21 vs. 0.13 in the case of sprinkler irrigation and 0.30 vs. 0.26 for surface irrigation). But the Almudévar rain series in surface irrigation resulted in the same LF in the season (mean 0.27) than in the whole year (mean 0.26) for both soils. Under surface irrigation, the LF was higher for the coarse-textured soil than soil Cc (during the season and the hydrologic year) but there were no differences between soils for the sprinkler method.

The mean seasonal LF for the 8 scenarios ranged from 0.04 to 0.13 (0.12 to 0.35 for the annual LF), but the individual LF obtained in the simulated series ranged from 0.03 to 0.40 for the season (from 0.02 to 0.53 for the year). Furthermore, this variability took place even though the irrigation volume (I) was defined, in both methods, to provide approximately the seasonal ET_c in each season; showing the power of the capacity-based model to account for irrigation inefficiency (i.e. the same 'I' can give rise to many different LF's) and the influence of the irrigation methods, soil type and, especially, of the random distribution of rainfall on the resulting LF.

The mass of salts leached during the season or the hydrologic year varied in the same fashion as D, though the actual masses were also influenced by the concentration of the drainage water (Table 2). The mass of salts leached was higher in the surface method (2012 kg/ha) than with the sprinkler method (805 kg/ha) during the season and to a lesser extent during the hydrologic year (3525 kg/ha vs. 3097 kg/ha). There were no apparent differences in the annual masses of the soils or rain series using the surface method (mean 3525 kg/ha) whereas in the sprinkler method, the mass was higher for the Davis series (3323 kg/ha) than for the Alm series (2801 kg/ha) and very similar for both soils within each rain series.

The concentration of salts in the leachate during the season was higher for the Alm series (1867 mg/L) than the Davis (1286 mg/L) series in using the sprinkler method and similar when using the surface method (mean 1114 mg/L) (Table 2). For the hydrologic year, these differences increased. For all the cases and soils, the Davis rainfall series (winter concentrated) gave rise to higher D along the hydrologic year with lower concentration than the Almudévar series; and it was this higher D that led to a higher mass of salts exported. But during the growing season, both the mass of salts and D were higher for the Almudévar series than the Davis series in all soils and cases.

Rainfall distribution

The variability in the results (in the irrigation characteristics of the previous section and the resulting mean EC_{eS} in the following section) within each scenario is due to the yearly differences in meteorological properties (mainly rainfall distribution but also, to a lesser extent, temperatures and ET) within each rainfall series. Each rainfall series utilized (Davis and Almudévar) resulted in a time series of EC_{eS} for each combination of irrigation method and soil type, which are different in their mean values (differences between scenarios) and also in their distribution (Fig. 5).

For the Davis rainfall series the differences between sprinkler and surface irrigation were very low for the fine-textured soil (higher TAW) indicating that the leaching achieved by both methods of irrigation was quite similar and very clear for coarse-textured soil (lower TAW), showing that the leaching caused by the surface irrigation was much higher in the surface irrigation scenario [Fig. 5(a)].
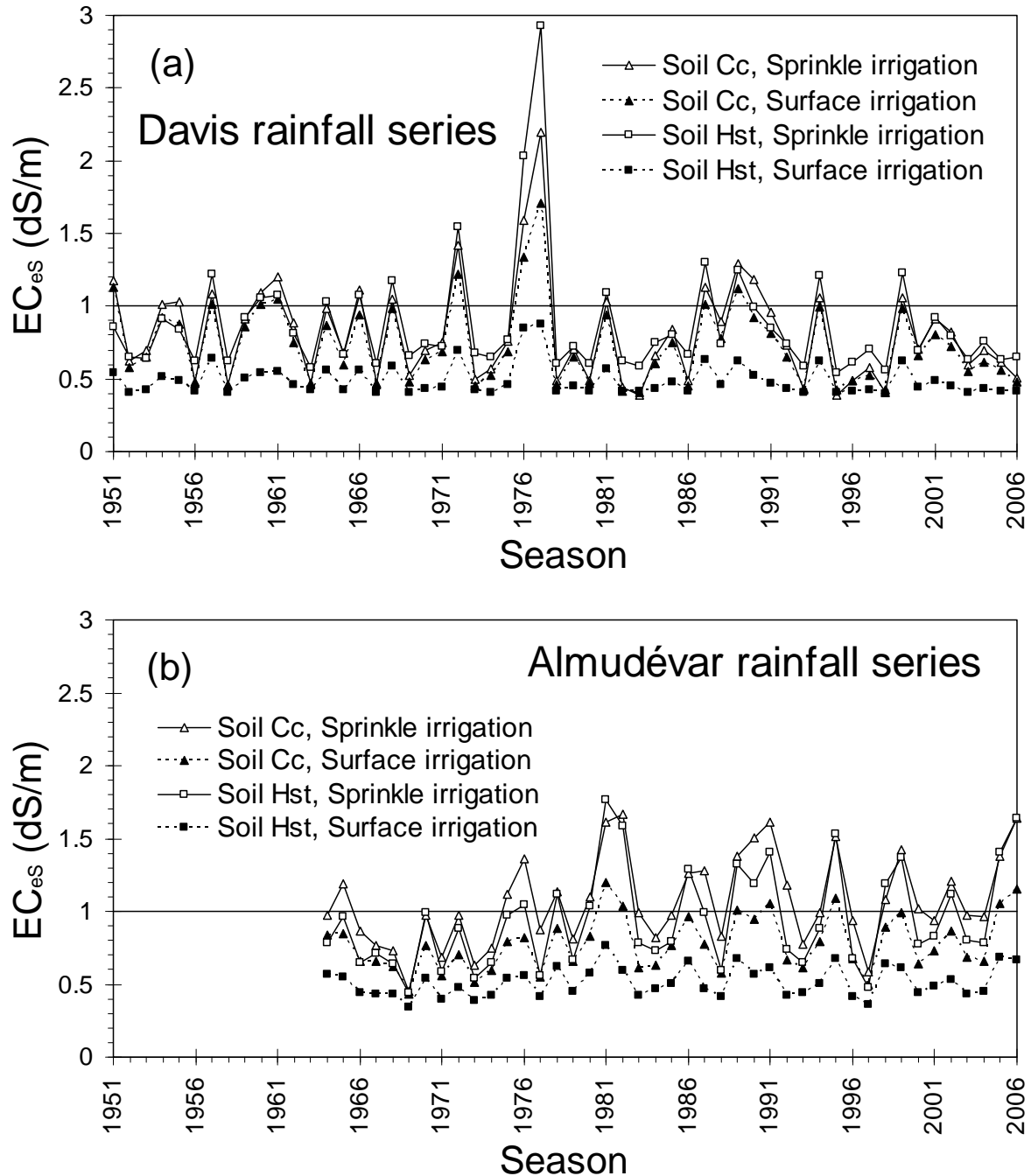
Fig. 5 Mean electrical conductivity of the saturated paste extract during the growing season (EC_{eS}) for the simulated years in the 8 scenarios considered. The $EC_{eS} = 1$ dS/m line is presented for comparison purposes

In Davis, the EC_{eS} on coarse-textured soils that were surface irrigated were clearly lower than those from the other three method-soil combinations and the behavior of both soils under the sprinkler method were quite similar [Fig. 5(a)]. For the Almudévar rain series, the differences between the two soils for the sprinkler method, and especially between both irrigation methods on coarse-textured soil, were a little more apparent; while the surface method for the coarser soil was again clearly lower than the others [Fig. 5(b)].

Summary Analysis of the EC_{eS} for the different scenarios

The records of yearly means of EC_e along the growing season (EC_{eS}) were taken as samples defining the behavior of soil salinity under the different scenarios. The differences in EC_{eS} between scenarios and the relationship between EC_{eS} and other management (leaching fractions) or hydrologic parameters (rainfall, water content or initial soil water salinity) are presented.

The mean seasonal EC_e (EC_{eS}) for all the cases (396) was 0.77 dS/m, indicating that an irrigation water salinity with an EC_w of 0.7 dS/m results in a 23% lower soil salinity that what is predicted to occur using the steady-state FAO 29 approach (i.e. 1.0 dS/m). These seasonal EC_e however were widely scattered (from 0.34 dS/m to 2.93 dS/m) and depended strongly on the 3 factors defining the scenarios [Soil textual class; Rainfall distribution; Davis or Almudévar; and irrigation method (sprinkler or surface) as well as weather variables.

The analysis of variance for the variable EC_{eS} on the factors Soil, Rain and Method showed that all the single factors were significant ($P < 0.001$) as well as the interactions Soil-Method and Rain-Method ($P < 0.05$; although the significance of the interaction Soil-Method was introduced by the different definition of the irrigation scheme for the two soils using sprinkler irrigation). The interaction Rain-Method followed the fact that the difference between sprinkler and surface irrigation was higher for the Almudévar rainfall series than for the Davis series (Table 3).

The soil salinity along the growing season was always lower for the Davis (0.73 dS/m) rainfall series than the Almudévar (0.82 dS/m) series and for the surface irrigation method (0.63 dS/m) as compared to sprinkler irrigation (0.91 dS/m) (Table 3). Also, EC_{eS} was lower for the coarse-textured soil (Hst; S-L) than for fine-textured soil (Cc; Si-C) except for sprinkler irrigation on the Davis rainfall series (Table 3): in surface irrigation the irrigation intervals are equal for both soil types despite their different TAW leading to a much higher leaching (Table 3), whereas the adjustment of the irrigation dose to the 6-day forecast in coarse-textured soil for sprinkler irrigation led to reduced leaching and to an EC_{eS} similar (slightly higher but not significantly different: $P > 0.05$). Also, the driest years in the Davis rainfall series led to higher EC_{eS} in the coarse-textured soil than in the fine-textured soil Cc (Fig. 5).

Table 3 Means for all the simulations performed of the seasonal EC_e (EC_{eS}) and the leaching fraction of the hydrologic year (LF_{HY}) by irrigation method: Sprinkle or Surface; soil type: Fine or Coarse textured; and rainfall series: Davis or Almudévar (Alm)

Soil	Rainfall	EC_{eS} dS/m Irrigation Method Sprinkler	Surface		LF_{HY} Irrigation Method Sprinkler	Surface	
Fine	Davis	0.810	0.731	**0.771**	0.211	0.244	**0.227**
	Alm	1.068	0.774	**0.921**	0.125	0.228	**0.177**
		0.922	**0.750**	**0.836**	**0.174**	**0.237**	**0.205**
Coarse	Davis	0.874	0.489	**0.682**	0.210	0.347	**0.278**
	Alm	0.943	0.513	**0.728**	0.130	0.297	**0.214**
		0.904	**0.499**	**0.702**	**0.176**	**0.325**	**0.250**
Total		**0.913**	**0.625**	**0.769**	**0.175**	**0.281**	**0.228**

The winter-concentrated rainfall (Davis) was more effective in reducing EC_e, than when a similar amount of rainfall is distributed more evenly throughout the year. The model results indicate that the EC_{eS} for Davis conditions were lower than those for Almudévar (and the leaching fraction higher) for all scenarios (Table 3). But the effect of the fixed-scheduled surface irrigation in lieu of sprinkler irrigation was more conspicuous (higher differences in Table 3) especially for the coarser-textured soil Hst.

The mean EC_{eS} for the different scenarios (Table 3) do not provide information about the actual distribution of the record of EC_{eS} within each scenario or the differences between the distributions in each scenario. The mean EC_{eS} were higher for the Almudévar series [Table 3; Fig. 5(b)] but it showed the highest values for the Davis rainfall series and soil Cc [Fig. 5(a)] because of the more skewed distribution of yearly rainfall in Davis (presenting some very low minimum values causing the highest EC_{eS} records).

Factors affecting the EC_{eS}

The EC_{eS} was not significantly related to the total rainfall or the mass of salts leached during the season, but was strongly related to their annual series (Table 4). Although the EC_{eS} was strongly related to the seasonal D and LF, the correlations were higher (in absolute value) with the annual D and LF (Table 4).

These correlations were different for the different scenarios, though the signs of the coefficients and the general pattern agreed with the general correlations in Table 4. For the Almudévar rain series, the correlations between EC_{eS} and Salt and P during the season were significant ($P < 0.05$) since most of the leaching took place during the season (Table 2).

Table 4 Coefficients of correlation (r) for all the years simulated between the mean electrical conductivity of the saturated paste extract (EC_e) during the growing season (EC_{eS}) and the volume of drainage (D), the mass of salts leached (Salt), the leaching fraction (LF), real evapotranspiration (ET_r), and rainfall (P) during both the season (Season) and the hydrologic year (HY); and the irrigation (I), EC_e at the beginning of the season (EC_{oS}) and the mean EC_e for the whole hydrologic year (EC_{eHY})

	r			r
Variable	Season	HY	Variable	
D	-0.46	-0.79	I	-0.33
Salt	-0.04[NS]	-0.55	EC_{oS}	0.89
LF	-0.50	-0.85	EC_{eHY}	0.94
P	0.03[NS]	-0.60		
ET_r	0.40	0.15		

[NS] not significant (P > 0.05)

In all scenarios, as well as for the overall data there were well-defined relationships between EC_{eS} and the rainfall of the hydrologic year (P_{HY}), the leaching fraction for the hydrologic year (LF_{HY}), and the EC_e at the beginning of the irrigation season (EC_{oS}). The correlation between EC_{eS} and the LF for the irrigation season (LF_S) was low (r = - 0.50; Table 4), a finding that is inconsistent with the traditional assumption that EC_{eS} responds to the LF_S.

The EC_{eS} was also better correlated to the hydrologic year precipitation (i.e. the EC_e of the growing season: May to September was related to P of the hydrologic year: October previous year to September) in Davis (r = -0.66, P < 0.001) than in Almudévar (r = -0.52, P < 0.001) due to the higher winter rain in Davis (Fig. 6). The relationships for Almudévar were weak, while in Davis they could foretell EC_{eS} quite accurately through a multiplicative model, though the parameters of the regressions were significantly different for each scenario (Table 5). In Davis, the EC_{eS} could also be predicted from the P of the non-growing season (October previous year to April) quiet accurately.

For all the available data, EC_{eS} was estimated from LF_{HY} as $EC_{eS} = 0.25 \cdot LF_{HY}^{-0.641}$ ($R^2 = 0.89$; s = 0.15; N = 396). Assuming a potential relationship between the ratio EC_{eS}/EC_w and the leaching fraction this equation translates into $EC_{eS}/EC_w = 0.36 \cdot LF_{HY}^{-0.641}$, different from the FAO equation below (Rhoades et al. 1992) in the coefficients and in the predictive variable (LF_{HY} instead of LF_S). The parameters of this relationship were significantly different for each scenario and yielded different equations relating EC_{eS} to LF_{HY} generally better in each scenario (Table 5).
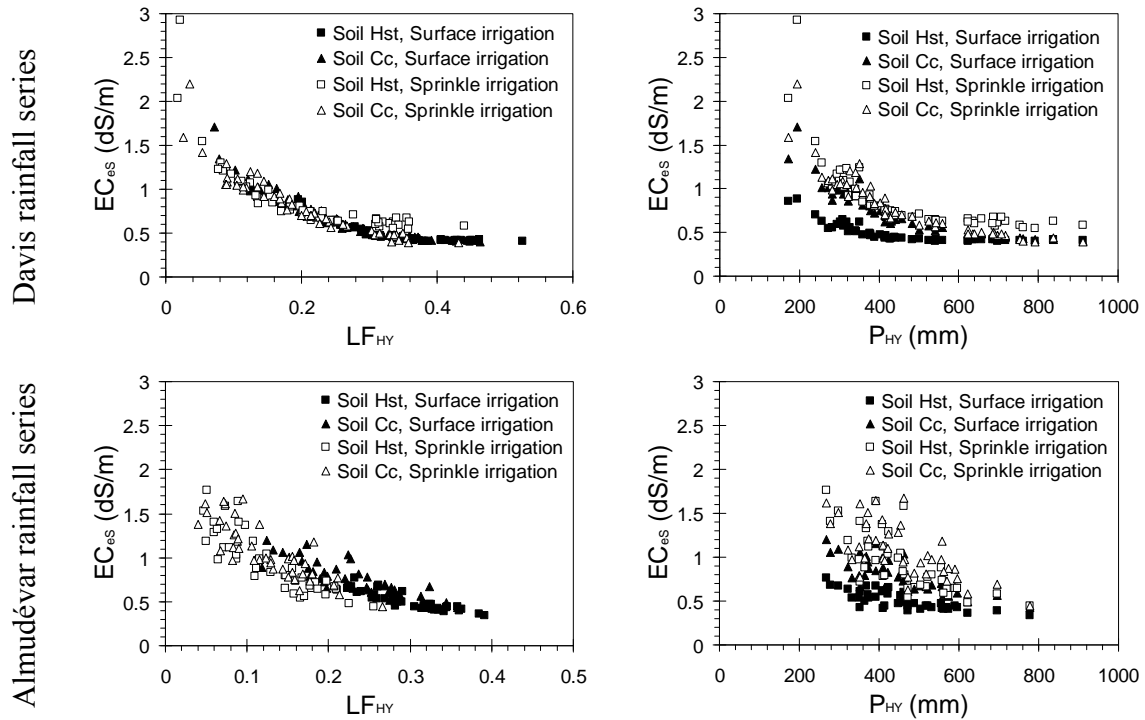
Fig. 6 Electrical conductivity of the saturated paste extract during the growing season (EC_{eS}) versus the leaching fraction (LF_{HY}) and the rainfall (P_{HY}) of the hydrologic year for the 8 scenarios considered

The differences between the parameters of the EC_{eS}-LF_{HY} (like the EC_{eS}-P_{HY}) relationships for each scenario were investigated by the linear regressions between their logarithms. The slopes of the relationships EC_{eS}-LF_{HY} were not different for the 2 soil types or rainfall series (but the intercepts were), with EC_{eS} higher for sprinkler irrigation and fine-textured soil than for surface irrigation and coarse-textured soil, but the response of both soils and irrigation types to growing LF_{HY} were similar (equal slopes). The response to irrigation method was just the opposite: the intercepts were not significantly different but slopes were, with a steeper response for surface irrigation (Table 5).

The response of EC_{eS} to LF_{HY} was steeper for surface irrigation with fixed schedules (higher b) than for sprinkler irrigation. In Davis, where the winter rains are more concentrated, the statistical fits of LF_{HY} and P_{HY} with EC_{eS} were better (higher R^2 and lower *s*) than for the same irrigation method and soil type for the Almudévar series. The parameters (A and b) of the regressions EC_{eS}-P_{HY} were more variable and did not show any clear pattern among the scenarios.

Table 5 Parameters of the multiplicative regressions ($EC_{eS} = A \cdot x^b$) between the mean seasonal electrical conductivity of the saturated paste extract (EC_{eS}) and the leaching fraction ($x = LF_{HY}$) or the precipitation ($x = P_{HY}$) of the hydrologic year fitted for each scenario [irrigation method: Sprinkler or Surface; Rainfall series: Davis or Almudévar (Alm) and Soil type: Fine or Coarse textured] and statistics of the regressions: coefficient of determination (R^2), standard error of the estimate (s) and number of observations (n)

Method	Rain	Soil	A	b	R^2	s	n
		Leaching fraction of the hydrologic year (LF_{HY})					
Sprinkler	Davis	Fine	0.25	-0.640	0.90	0.13	55
		Coarse	0.35	-0.497	0.95	0.08	55
	Alm	Fine	0.30	-0.569	0.69	0.17	42
		Coarse	0.21	-0.677	0.78	0.17	42
Surface	Davis	Fine	0.20	-0.809	0.97	0.06	55
		Coarse	0.21	-0.749	0.86	0.07	55
	Alm	Fine	0.24	-0.759	0.72	0.13	42
		Coarse	0.13	-1.131	0.83	0.08	42
		Precipitation of the hydrologic year (P_{HY})					
Sprinkle	Davis	Fine	336.0	-1.00	0.93	0.10	55
		Coarse	99.8	-0.78	0.81	0.15	55
	Alm	Fine	210.3	-0.87	0.49	0.22	42
		Coarse	7.0	-1.16	0.62	0.17	42
Surface	Davis	Fine	5.0	-0.01	0.94	0.09	55
		Coarse	6.7	-0.43	0.77	0.09	55
	Alm	Fine	104.3	-0.81	0.63	0.15	42
		Coarse	29.3	-0.67	0.65	0.12	42

The poor relationship between EC_{eS} and seasonal LF (LF_S) is largely explained by the different salinity levels at the beginning of the season (EC_{oS}). The multiple regression of the LF_S with the EC_{oS} and EC_{eS} for all the available data ($R^2 = 0.60$; $s = 0.065$; $n = 396$) was calculated to provide a tool for estimating the leaching requirement (LR) given the soil water salinity at the beginning of the season (EC_{oS}, measured in the field) and the required soil salinity during the season ($EC_{e\text{-}req}$, determined by the crop and the expected yield): $LR = 0.379 - 0.507 \cdot EC_{e\text{-}req} + 0.330 \cdot EC_{oS}$ where the EC values are in dS/m and the LR is a fraction. However, this relationship was calculated with $EC_w = 0.7$ dS/m; and specific relationships should be calculated for different EC_w. The scenario-specific relationships between these parameters resulted in better fits (but do not provide a unique general equation for the LR).

The EC_{eS}-LF_S relationship is also affected by the differences in the early and late season soil water contents. In all the scenarios the mean change in the water content along the season was negative, with mean water depletion throughout the growing season of 26 mm. In only

53 out of the 396 simulations did the soil water content increase along the season. The mean seasonal soil water depletion was significantly higher for the Davis (33 mm) than the Alm rain series (18 mm) in the mean (also for each soil-method combination) due to the higher soil water recharge in Davis series during the winter and leading to the poorer EC_{eS}-LF_S relationship for Davis. The differences in the seasonal soil water depletion between the rain series were higher for the Spr case than for the Surf case in soil Cc (with higher TAW) but very similar in soil Hst, due to its lower TAW.

Comparison with FAO 29

One of the goals for developing this model was to expand upon the FAO 29 approach to account for temporal variability in rainfall and irrigation, as well as soil water dynamics, although the differences between both approaches make any comparison difficult. The EC_{eS} series obtained with the model were compared with the results of the FAO formula $EC_{eS}/EC_w = 0.501 \cdot LF_S^{-0.5875}$ (Rhoades et al., 1992) used for conventional (low frequency) irrigation. With the FAO approach, the EC_{eS} is calculated only from the seasonal LF not including rainfall during the winter. Therefore the FAO estimates for EC_{eS}/EC_w were calculated with the LF of the growing season (LF_S calculated by the model for every season) and the mean weighted EC of the seasonal irrigation and precipitation: $EC_{w-p} = (EC_w \cdot I + EC_p \cdot P)/(I+P)$ (Fig. 7). When the model is used with no rainfall, the resulting EC_{eS} is higher than EC_e calculated by the steady state FAO approach (data not shown) suggesting that other factors considered (time distribution of rain and irrigation, actual water extraction pattern, and soil properties) and not rainfall alone, produce the lower-than-FAO approach model estimates below.

For the Davis rainfall series, the model EC_{eS} estimates were lower than the FAO EC_{eS} estimates (EC_{e-FAO}) for both methods of irrigation and soils except in a few, very dry years [Fig. 7(a)]. For the Almudévar rainfall series, the model EC_{eS} estimates were closer to the EC_{e-FAO}; relationship but only for surface irrigation on soil Cc, the EC_{eS} was higher than EC_{e-FAO} more often than not. Also, only for this scenario were the paired differences $EC_{eS} - EC_{e-FAO}$ positive and significantly different form 0 ($P < 0.05$) (i.e., the model provided higher salinity, more conservative estimates than the FAO formula) [Fig. 7(b)]. For all other scenarios the paired differences $EC_{eS} - EC_{e-FAO}$ were negative and significantly different form 0 ($P < 0.05$): the FAO estimates were more conservative than the model estimates. Thus, the FAO formula estimates were generally more conservative (i.e., higher predicted EC_{eS}) than the model estimates, especially under winter rain conditions in the Davis location.
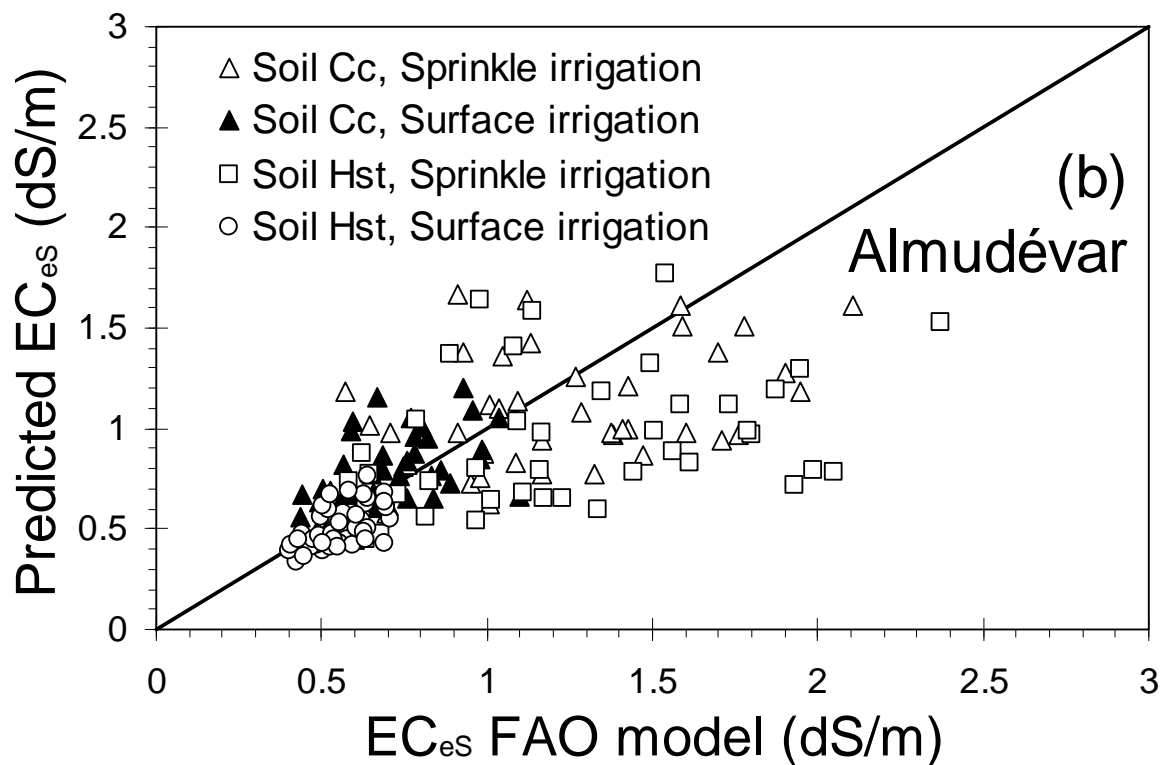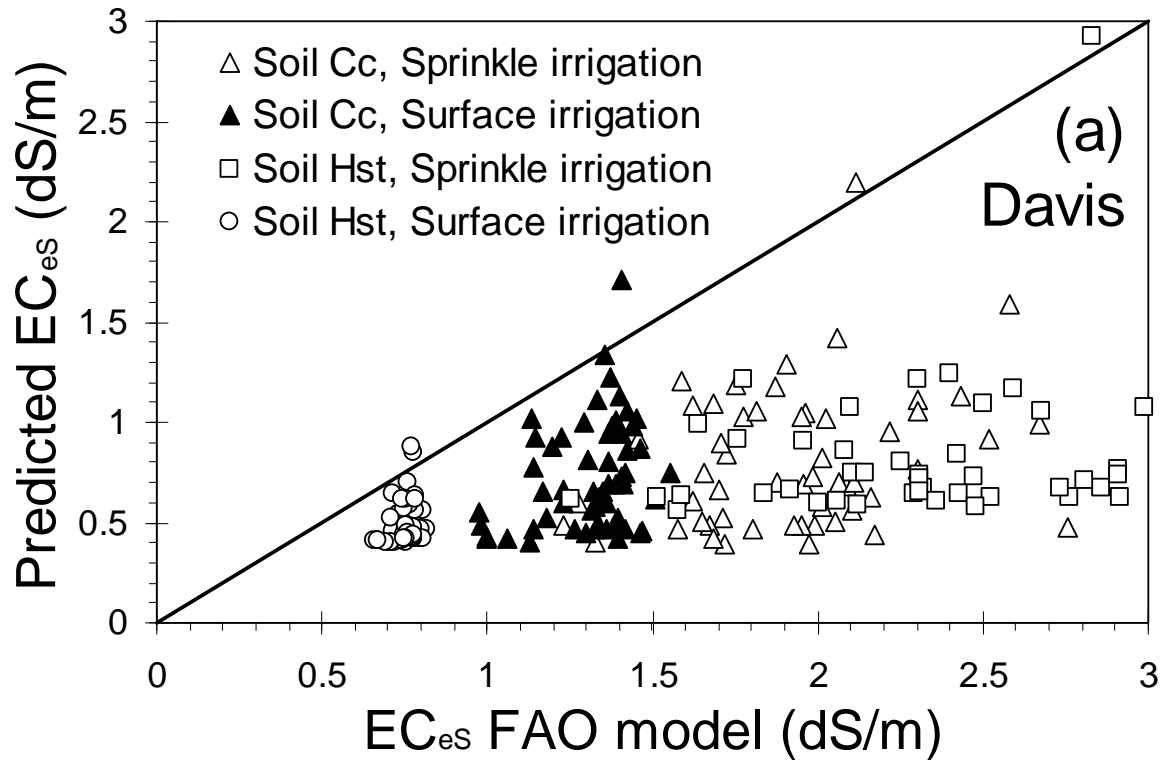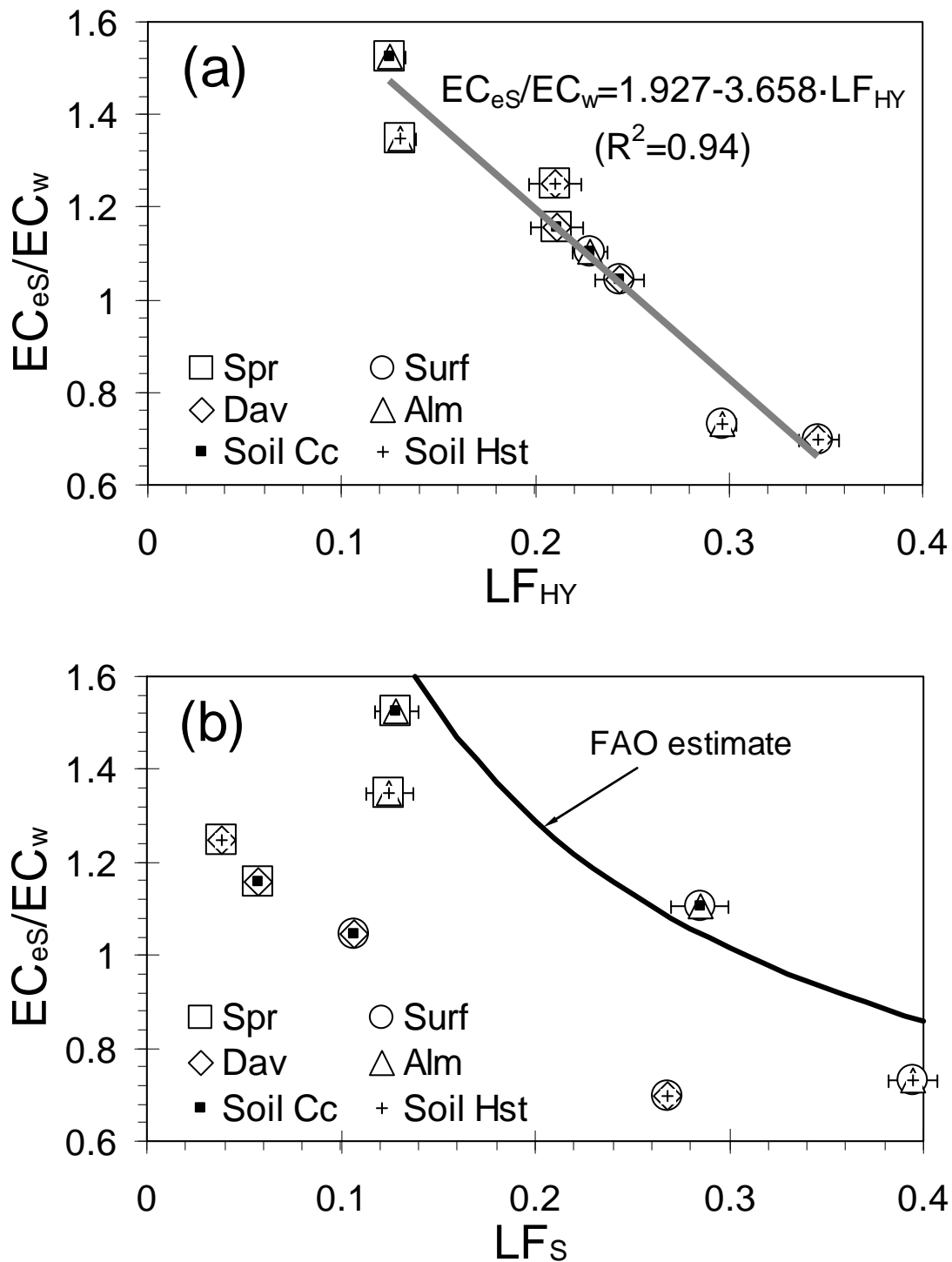
Fig. 7 Mean electrical conductivity of the saturated paste extract during the growing season (EC_{eS}) predicted by the model versus the EC_{eS} predicted by the FAO formulae for all the scenarios considered with the Davis (a) and Almudévar (b) rainfall series

The mean ratios EC_{eS}/EC_w (where $EC_w = 0.7$ dS/m) for each scenario were clearly related to the LF for the hydrologic year (LF_{HY}) but not the seasonal LF (LF_S) (Fig. 8). The relationship

$EC_{eS}/EC_w - LF_{HY}$ was approximately linear [Fig 8(a)], showing that increasing LF_{HY} reduced EC_{eS} regardless of the scenario considered. However, the good potential fits between EC_{eS} and LF_{HY} for each scenario (especially for the Davis series, Table 5) point to the convenience of using specific (irrigation, soil type and rainfall series) relationships to establish EC_{eS} from LF_{HY} when possible. For a given soil and irrigation method, the LF_{HY} was always higher and the ratio EC_{eS}/EC_w lower for the Davis than the Almudévar rain series. The smallest differences between the Davis and Almudévar rainfall series are found f/or surface irrigation on soil Cc and the highest for the sprinkler method on both soils [Fig. 8(a)].

The mean ratio EC_{eS}/EC_w was closer to the FAO estimate from seasonal LF for the Alm rainfall series scenarios, although only for the surface irrigation method and soil Cc was it higher. For all the scenarios with the Dav rainfall series, the ratio EC_{eS}/EC_w was much lower than the FAO estimate [Fig. 8(b)]. Different $EC_{eS}/EC_w - LF_S$ relationships could be established for the Davis and Almudévar series [with lower EC_{eS}/EC_w and better fit for the Davis series, Fig. 8(b)], though the number of scenarios considered did not provide enough simulations to assure this behavior.

Fig. 8 Ratio of the mean electrical conductivity (EC) during the growing season (EC_{eS}) to the EC of the irrigation water ($EC_w = 0.7$ dS/m) as related to the leaching fraction during the hydrologic year (LF_{HY}) and the irrigation season (LF_S) for all the scenarios [Type of irrigation: sprinkle (Spr) or surface (Surf); Rainfall series: Davis (Dav) or Almudévar (Alm) and Soil series: Capay (Cc) or Hesperia (Hst)]. The bars represent one standard error of mean in each scenario (the standard errors of the ratio EC_{eS}/EC_w were too low to be shown)

Conclusions

The model presented here was able to evaluate the differences in soil salinity induced by different rainfall patterns (winter concentrated or year distributed), methods of irrigation (sprinkler and surface with a fixed number of irrigations) and soils (with different total available water, TAW) over a long record of meteorological data. Although the general behavior of soil salinity under these conditions could be outlined by the model, a thorough model evaluation and validation process with a comprehensive set of soil salinity data and daily inputs in the field would be needed to assess the salinity resulting form these scenarios and to determine other factors affecting it. Nevertheless, this model sheds light on a number of relationships that could have a profound influence on predicting soil salinity. Therefore until validation, this model should be used conceptually as a management tool to understand how the soil textural-class and daily inputs (such as rainfall distribution) influence rootzone salinity both within and outside the growing season.

The mean seasonal EC of the saturated paste extract (EC_{eS}, the variable usually related to crop yield) was found to vary widely for the rainfall series, management practices and soil types considered: (i) Surface irrigation produced lower EC_{eS} and higher leaching fraction than sprinkler irrigation though it also led to higher ET deficit in the lower TAW soil; (ii) The winter concentrated rainfall series produced lower EC_{eS} than the series where rainfall was distributed more or less evenly throughout the year; and (iii) The higher TAW soil resulted in higher $EC_{eS,}$ except for sprinkler irrigation combined with winter rain. These results indicate the importance of the irrigation method, rainfall distribution (particularly disproportional distributions) and soil water holding characteristics for determining the EC_{eS}. Considering these site specific (meteorological, soil and irrigation management) features could help improve the estimation of the leaching requirements and the allowable salinity of the irrigation water for the protection of crop production.

The EC_{eS} could be predicted from the hydrologic year rainfall (P_{HY}) and leaching fraction (LF_{HY}) by regression; but not from the seasonal leaching fraction (LF_S) as assumed by the traditional FAO approach. Also, these regressions were different for each scenario; showing again the need to account for rainfall distribution, soil properties and type of irrigation to determine soil salinity. The EC_{eS} predicted by the model was lower than the EC_{eS} estimated by the traditional FAO approach, except for surface irrigation with year-through rainfall on the higher TAW soil. This suggests that the widely used FAO steady-state rules for soil salinity and leaching requirement estimation could be improved, particularly if knowledge of

site-specific conditions exists. The traditional FAO assumptions led to higher salinity than that predicted by the model particularly when rainfall occurs primarily in winter months, emphasizing the importance of winter leaching as an important factor to be considered in the determination of the EC_{eS}. If the model results were validated, the use of site specific information would result in lower leaching requirements or higher allowable irrigation water salinity; thus allowing for reducing the amount of water needed for irrigation or for the use of more saline waters for irrigation.

Acknowledgements

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