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Comparison of four steady-state models of increasing complexity for assessing the leaching requirement in agricultural salt-threatened soils

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Abstract

Irrigation scheduling in salt-threatened soils must include an estimation of the leaching requirement (LR). Many models have been developed over the last 40 years for assessing the LR, and they should be compared on common grounds to guide potential users. The LR for salts (LR_Y), chloride (LR_{Cl}) and SAR (LR_{SAR}) and therefore the eventual LR was assessed with simple equations and three steady-state computer models of increasing complexity, WATSUIT, SALSODIMAR and SALTIRSOIL. These models were assessed in 30 scenarios characterised by different crops and water qualities in the irrigated area of the *Vega Baja del Segura* (SE Spain). The simple equations, WATSUIT and SALTIRSOIL calculated quite similar eventual LRs, which were between < 0.01 and > 0.99 depending on crop species and water quality. The SALSODIMAR gave remarkably higher eventual LRs (between 0.31 and > 0.99). This occurred because SALSODIMAR uses the hypothesis that the saturation extract is more concentrated than the drainage water, contrary to what is assumed by the simple equations or calculated by WATSUIT and SALTIRSOIL. Rainfall, which is not taken into account by the simple equations and WATSUIT, and soil calcite weathering, which is not taken into account by SALSODIMAR, were revealed, respectively, as important and very important aspects to be included in steady-state models. Although the SALTIRSOIL appears to be the most complete model, the simple equations give acceptably similar irrigation doses for many of the situations considered in this study. Irrigation doses lower than presently used could be profitably applied in the *Vega Baja del Segura*.

Additional key words: irrigation scheduling; SALSODIMAR; SALTIRSOIL; Segura River Lowland; WATSUIT.

Resumen

Comparación de cuatro modelos de estado estacionario de complejidad creciente para el cálculo del requerimiento de lixiviación en suelos agrícolas con riesgo de salinizarse

La programación de riegos en suelos amenazados por sales debe incluir una estimación del requerimiento de lixiviación (RL). Durante los últimos 40 años se han desarrollado muchos modelos para calcular el RL, y es necesario compararlos sobre bases comunes para orientar a los potenciales usuarios. El RL para sales (RL_R), cloruro (RL_{Cl}) y RAS (RL_{RAS}), y en consecuencia el RL final fueron calculados con ecuaciones sencillas, y con tres modelos de estado estacionario de complejidad creciente, WATSUIT, SALSODIMAR y SALTIRSOIL. Estos modelos se evaluaron en 30 escenarios con diferentes cultivos y calidades de agua en la zona de regadío de la Vega Baja del Segura (SE de España). Las ecuaciones sencillas, WATSUIT y SALTIRSOIL calcularon RLs finales bastante similares (entre < 0,01 y > 0,99 en función de las plantas cultivadas y la calidad del agua); SALSODIMAR dio RLs finales notablemente más altos (entre 0,31 y > 0,99), debido a que en SALSODIMAR se supone que el extracto de saturación está más concentrado que el agua de drenaje, al contrario de lo que se asume en las ecuaciones sencillas o se calcula en WATSUIT y

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Abbreviations used: EC (Electrical Conductivity); ESP (Exchangeable Sodium Percentage); HC (Hydraulic Conductivity); LF (Leaching Fraction); LR (Leaching Requirement); SAR (Sodium Adsorption Ratio); SIAR (Sistema de Información Agroclimática para el Regadío).

SALTIRSOIL. La lluvia, que no es tenida en cuenta en las ecuaciones sencillas ni en WATSUIT, y la disolución de calcita del suelo, que no es tenida en cuenta por SALSODIMAR, se revelaron, respectivamente, como aspectos importantes y muy importantes a tener en cuenta en los modelos de estado estacionario. Aunque SALTIRSOIL resulta el modelo más completo, las ecuaciones sencillas dan riegos aceptablemente similares para muchas de las situaciones consideradas en este estudio. Riegos inferiores a los que se utilizan actualmente en la Vega Baja del Segura se podrían aplicar productivamente.

Palabras clave adicionales: programación de riegos; SALSODIMAR; SALTIRSOIL; Vega Baja del Segura; WATSUIT.

Introduction

In irrigated areas, the control of soil salt build-up is essential to guarantee sustainable agriculture. When changing to a safer water supply is not possible, the primary method used to control soil salinity is to leach the soil salts with an excess of percolating water. Achievement of this objective demands application of water in excess of that required by the crops and, more importantly, the installation and maintenance of drainage systems to collect and dispose of the excess percolating water. The provision of capable drainage systems is essential where one or both of the following situations exist: i) shallow water tables, and/or ii) surface irrigation systems. These two characteristics, in addition to the aggravating factor of clayey soils, are commonly present in alluvial flat bottom areas, such as the *Vega Baja del Segura* (SE Spain).

Over-irrigation and drainage have been performed in many agricultural areas, providing farmers control over soil salinity. However, uncontrolled over-irrigation is no longer possible because of the growing lack of water, difficulties for drainage disposal, losses of nitrogen from soils and concomitant pollution (Tanji & Kielen, 2002). It is necessary to know precisely how much water in excess of the crop requirement is needed to leach the soil salts while preserving the environment. This demands the calculation of the leaching requirement (LR).

The fraction of the infiltrating water (*i.e.,* rainfall (R) plus irrigation (I)) that passes through the root zone is known as the leaching fraction (LF) and is expressed as $LF = D / (I + R)$, where D is drainage. The LR is defined as the minimum LF required to keep the soil salinity below a critical value that would otherwise excessively reduce crop yield. Expressing water salinity in terms of electrical conductivity (EC) and ignoring rainfall, the LR is usually calculated with the following formula (Eq. [1], Rhoades, 1974), where EC_{iw} and $\overline{EC}_{\text{se}\,(Y)}$ stand, respectively, for the EC of the irrigation water, and the critical soil average saturation extract EC beyond which crop yield excessively declines, that is, crop yield falls below a limit (Y).

$$LR_Y = \frac{EC_{\text{iw}}}{5\overline{EC}_{\text{se}(Y)} - EC_{\text{iw}}} \qquad [1]$$

However, this equation is strictly valid provided several assumptions are met, which are, more or less matched depending on the particular characteristics of the irrigation project. The most important are the following: i) steady-state movement of water and salts through soil, ii) negligible amount of rainfall compared to irrigation, iii) neither precipitation of salts nor weathering of soil minerals, iv) total mixing of the infiltrating water with the soil solution, that is, no by-pass flow, and v) bijective and linear relationship between electrical conductivity and salinity.

Several models of increasing complexity appropriate for situations in which one or more of the previous assumptions fail have been developed from the mid-1960s onwards. Specifically, the steady-state assumption has been the most controversial, and this has led to the development of transient models (Corwin *et al.,* 2007; Letey *et al.,* 2011). These usually provide more precise predictions of soil salinity than steady-state models. However, transient models also require data that are difficult to obtain, which limits their applicability to research purposes. As a consequence, the traditional LR model is still used and recommended for irrigation management worldwide, largely supplementing crop water requirement models. The only practical alternatives are steady-state models that overcome one or more of the other four assumptions (ii to v) upon which the traditional LR model is based.

The following three computer models, WATSUIT (Rhoades & Merrill, 1976; Rhoades *et al*., 1992), SALSODIMAR (Pla, 1968, 1988, 1996) and SALTIRSOIL (Visconti, 2009; Visconti *et al*., 2011) have been developed to overcome some of the limitations of the traditional LR equation. They all are steady-state models, which data needs increase gradually starting from the traditional LR model in the sequence WATSUIT < SALSODIMAR < SALTIRSOIL, but without being onerous to fulfil.

The objectives of this investigation were i) to evaluate the adequacy of the traditional LR model for estimating the leaching requirement in comparison to the steady-state models WATSUIT, SALSODIMAR and SALTIRSOIL by searching for differences, measuring the magnitude of the differences, and understanding the reasons behind them, and ii) to discuss the implications these findings could have for developing irrigation recommendations for traditionally irrigated salt-threatened areas and particularly the *Vega Baja del Segura* (SE Spain).

Material and methods

Models for irrigation recommendations in salt-threatened areas

WATSUIT was obtained from the US Salinity Laboratory website (http://www.ars.usda.gov/Services/docs.htm?docid=8968). SALSODIMAR was obtained from its author (ipla@macs.udl.es, Dept. Medi Ambient i Ciències del Sòl, Universitat de Lleida, Lleida, Spain). Finally, SALTIRSOIL was obtained from the website (http://www.uv.es/fervisre/saltirsoil.html).

Review of model concepts

Assessment of the maximum permissible salinity for a given crop

According to the three-piece linear (threshold-slope) function model, the yield (Y(%)) of most crops decreases from a threshold electrical conductivity value (EC_t) as a linear function of soil saturation extract electrical conductivity (Eq. [2]). The EC_t and the slope of the line (s) are characteristics of each crop (Maas & Hoffman, 1976).

$$\left\{\begin{array}{l} \text{If } EC_{se} < EC_t \rightarrow Y(\%) = 100 \\ \text{If } EC_{se} \in \left[EC_t, EC_t + \dfrac{100}{s}\right] \rightarrow Y(\%) = 100 - s(EC_{se} - EC_t) \\ \text{If } EC_{se} > EC_t + \dfrac{100}{s} \rightarrow Y(\%) = 0 \end{array}\right\} \quad [2]$$

With the selection of a minimum crop yield (Y(%)), the corresponding maximum permissible $EC_{se(Y)}$ can be calculated with the reciprocal form of Eq. [2]. The target $EC_{se(Y)}$ can be subsequently substituted in Eq. [1] for the calculation of the corresponding LR_Y.

The traditional LR model and extensions for chloride and SAR control

The traditional LR model starts from Eq. [3] where $EC_{dw(Y)}$ is the critical drainage water EC from which crop yield excessively declines.

$$LR_Y = EC_{iw} \, / \, EC_{dw(Y)} \quad [3]$$

According to the steady-state hypothesis, the salinity of the soil solution increases as depth increases, while the soil water content is constant. Under such conditions, the EC of the drainage water (EC_{dw}) in Eq. [3] represents the maximum soil solution EC (EC_{ss}) to which the plant roots are likely to be exposed. A more reasonable assumption is that the plant responds mainly to the average soil solution EC ($\overline{EC_{ss}}$). Therefore, EC_{dw} was related to $\overline{EC_{ss}}$ by Rhoades (1974), who proposed an empirical expression (Eq. [4]), where, for convenience, $\overline{EC_{ss}}$ was substituted by the average saturation extract critical EC beyond which crop yield falls below Y ($\overline{EC_{se}}_{(Y)}$).

$$EC_{dw(Y)} = 5\,\overline{EC_{se(Y)}} - \mathrm{EC}_{iw} \quad [4]$$

The substitution of Eq. [4] in Eq. [3] led to what has been called the traditional model for the LR calculation (Eq. [1]).

Apart from salt stress, crops are sensitive to particular ions and solutes such as chloride, sodium and boron. Toxicity to chloride has been studied particularly in the case of citrus, which can withstand, without experiencing leaf burn, no more than 10 to 25 mmol L^{-1} of chloride in the saturation extract ($[Cl^-]_{se}$) depending on species (Ayers & Westcot, 1985). Providing chloride is readily mobile in the soil under the influence of water, the traditional LR model (Eq. [1]) can be extended to calculate the LR for chloride (Eq. [5], Ayers & Westcot, 1985).

$$LR_{Cl} = \frac{[Cl^-]_{iw}}{5\overline{[Cl^-]}_{se} - [Cl^-]_{iw}} \quad [5]$$

Waters high in sodium with regard to calcium and magnesium increase the soil solution sodium adsorption ratio (SAR), defined as $SAR = [Na^+] \, / \, ([Mg^{2+}] + [Ca^{2+}])^{1/2}$.

Increments in the soil solution SAR can on the one hand, cause toxic effects on plants, and on the other hand, increase the soil exchangeable sodium percentage (ESP), which in turn can severely reduce the soil hydraulic conductivity (HC) depending on the soil solution overall salinity. Low HC is favoured by high SAR, in addition to low overall salinity of the soil solution. However, the SAR may also be controlled achieving a minimum LF, that is, a LR (Rhoades, 1968).

The traditional LR model was extended to calculate the LR for SAR control (LR_{SAR}) by combining the traditional LR model (Eq. [1]) with the calculation of the adjusted SAR according to Suarez (1981). The LR_{SAR} to achieve a target SAR in the saturation extract (SAR_{se}) is thus obtained by solving the following second order equation (Eq. [6]) for the plus sign where all concentrations in the irrigation water ($[Mg^{2+}]_{iw}$ and $[Na^{+}]_{iw}$) are expressed in mmol L^{-1} and SAR in (mmol L^{-1})$^{1/2}$.

$$[5\left([Mg^{2+}]_{iw} + 5[Ca^{2+}]_{eq}\right)SAR_{se}^2 - [Na^+]_{iw}^2]LR_{SAR}^2 - -\left(2[Na^+]_{iw}^2 - 5[Mg^{2+}]_{iw}SAR_{se}^2\right)LR_{SAR} - [Na^+]_{iw}^2 = 0 \quad [6]$$

In Eq. [6], $[Ca^{2+}]_{eq}$ is the calcium concentration at equilibrium with calcite and the carbon dioxide partial pressure in the saturated extract ($p\mathrm{CO_2}$). This calcium concentration is calculated with the following metamodel based on the work of Suarez (1981), where EC_{iw} is in dS m^{-1}, calcium ($[Ca^{2+}]_{iw}$) and alkalinity ($[Alk]_{iw}$) concentrations in the irrigation water are in mmol L^{-1} and meq L^{-1} respectively, and $p\mathrm{CO_2}$ is in atm (Eq. [7]).

$$[Ca^{2+}]_{eq} = \left(16.4 + 2.68EC_{iw} - 0.259EC_{iw}^2 + +0.0134EC_{iw}^3\right)\cdot\sqrt[3]{\left(\frac{[Ca^{2+}]_{iw}}{[Alk]_{iw}}\right)^2 p\mathrm{CO_2}} \quad [7]$$

WATSUIT

The calcite equilibrium in the soils where its existence or precipitation is feasible has a remarkable influence not only on the value of the SAR, but also on its overall salinity. In addition to calcite, gypsum is another mineral the precipitation or weathering of which can have a profound effect on soil salinity and SAR. WATSUIT extends the capabilities of the traditional LR model by taking into account the possibilities of calcite and gypsum precipitation and weathering.

Given a user-selected leaching fraction (LF), the WATSUIT model calculates the concentration factor of the soil solution at field capacity (f_d) for five different depths d or nodes, from the surface (d = 0) to the bottom (d = 4), according to a 40:30:20:10 plant water uptake pattern (Eq. [8]).

$$f_d = \frac{20}{(1-LF)d^2 + 9(LF-1)d + 20} \quad [8]$$

Next, the model multiplies the composition of the irrigation water (Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, alkalinity and SO_4^{2-} concentrations) by each concentration factor (f_0, f_1, etc). Provided built-in carbon dioxide partial pressures ($p\mathrm{CO_{2d}}$), WATSUIT solves for the composition at the chemical equilibrium at each depth by means of a semi-thermodynamic equilibrium module allowing for calcite and gypsum precipitation and, optionally, weathering. Next, it calculates the corresponding soil solution ECs at each depth d (EC_d) by means of the model by McNeal *et al*. (1970). Finally, the depth average values of EC, SAR and chloride concentration at field capacity (EC_{fc}, SAR_{fc} and $[Cl^-]_{fc}$, respectively) are calculated with Eq. [9], where P_{fc} stands for the property of interest.

$$P_{fc} = \frac{1}{8}\sum_{d=0}^{3}(P_d + P_{d+1}) \quad [9]$$

The average values for the saturation extract must be calculated separately. A proportionality factor of ½ is usually used in this regard (P_{sat} = ½ P_{fc}; Rhoades *et al*., 1992).

SALSODIMAR

Similarly to the WATSUIT model previously described, SALSODIMAR also considers the composition of the irrigation water and the possibility of calcite and gypsum precipitation, although not weathering, from the soil solids. Furthermore, it includes a factor for leaching efficiency.

The calculation of the LR for salts starts from Eq. [3] but it considers the main soluble cations instead of EC as the measure of salinity as expressed by Eq. [10], where TS_{iw} and TS_{dw} are the sum of Na^+, Ca^{2+} and Mg^{2+} concentrations in meq L^{-1} in the irrigation and drainage water, respectively.

$$LR_Y = TS_{iw} / TS_{dw(Y)} \quad [10]$$

Next, the main assumption of SALSODIMAR is that the sum of cations in the saturation extract (TS_{se}) is related to that of the drainage water (TS_{dw}) by Eq. [11], where F is labelled as a parameter of leaching efficiency bounded between 0 and 1 ($0 < F \leq 1$). Its specific value depends mainly on soil texture and irrigation method: medium to coarse soils have F values between 0.6 and 1, and medium to fine soils lower than 0.6 (Van Hoorn & Van Alphen, 1994; Pla, 1996). Regardless of the texture, F decreases with surface irrigation and increases with drip and sprinkler irrigation (Van Hoorn & Van Alphen, 1994).

$$TS_{dw} = F\ TS_{se} \qquad [11]$$

The likely precipitation of calcite, gypsum and also magnesian calcite is taken into account by subtracting adequate quantities (Table 1) from TS_{iw} and TS_{se} respectively, giving the general expression upon which the SALSODIMAR leaching requirement calculation for soil salinity is based (Eq. [12]):

$$LR_Y = \frac{TS_{iw} - k}{F(TS_{se(Y)} - w)} \qquad [12]$$

$$LR_{Cl} = \frac{[Cl^-]_{iw}}{F \cdot [Cl^-]_{se}} \qquad [13]$$

Similarly to the LR_Y, the LR for chloride toxicity is calculated by SALSODIMAR with Eq. [13] regardless of precipitation.

The LR for SAR (LR_{SAR}) is calculated by SALSODIMAR starting from the following equation: $LR_{SAR} = SAR^2_{iw} / SAR^2_{se}$, which is the one specifically used when no mineral precipitates (case a, Table 1). When precipitations occur (cases b, c, d, e, Table 1), the SAR of the irrigation water (SAR_{iw}) and the target SAR of the saturated extract (SAR_{se}) are corrected similarly to what has been previously shown (Eq. [12] and Table 1). This gives a particular formula for the LR_{SAR} calculation for each precipitation case (Pla, 1988).

SALTIRSOIL

SALTIRSOIL shares the foundations of the WATSUIT but extends its calculation capabilities. SALTIRSOIL carries out a monthly multilayer soil water balance from climate, soil, crop and irrigation management data. From this balance, SALTIRSOIL calculates an average soil solution concentration factor at field capacity (f_{fc}) by means of Eq. [14], where I and R are the irrigation and rainfall in mm yr^{-1}, ET_j is the actual evapotranspiration from the soil layer j also in mm yr^{-1} and n is the number of soil layers or nodes in which the soil is conceptually split.

$$f_{fc} = \frac{I}{n} \sum_{i=1}^{n} \frac{1}{I + R - \sum_{j=1}^{i} ET_j} \qquad [14]$$

From f_{fc} and the soil water contents at field capacity and at saturation, SALTIRSOIL calculates the soil solution concentration factor at saturation (f_{sat}). The irrigation water composition (Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, NO_3^-, SO_4^{2-} and alkalinity) is multiplied by f_{sat} to obtain a soil solution away from equilibrium. These data are the inputs to a semi-thermodynamic equilibrium module that calculates the saturation extract composition

Table 1. Values of the k and w parameters of the SALSODIMAR model (Eq. [12])

Precipitation case	Relations among ions in the irrigation water[1, 2]	Mineral precipitations	k	w
a	$[HCO_3^-] \leq 2([Ca^{2+}] + [Mg^{2+}])$	No precipitations	0	0
b	$[HCO_3^-]\ TS_{se} / TS_{iw} > 10$; $[CaS]\ TS_{se} / TS_{iw} \leq 30$	Calcite	$[HCO_3^-]$	10
c	$[HCO_3^-]\ TS_{se} / TS_{iw} > 10$; $[CaS]\ TS_{se} / TS_{iw} > 30$	Calcite and gypsum	If $[Ca^{2+}] > [SO_4^{2-}] + 0.5\ [HCO_3^-] \rightarrow 2[SO_4^{2-}] + [HCO_3^-]$ If $[Ca^{2+}] \leq [SO_4^{2-}] + 0.5\ [HCO_3^-] \rightarrow 2[Ca^{2+}]$	40
d	$[HCO_3^-]\ TS_{se} / TS_{iw} \leq 10$; $[CaS]\ TS_{se} / TS_{iw} > 30$	Gypsum	If $[Ca^{2+}] > [SO_4^{2-}] + 0.5\ [HCO_3^-] \rightarrow 2[SO_4^{2-}]$ If $[Ca^{2+}] \leq [SO_4^{2-}] + 0.5\ [HCO_3^-]$	30
e	$[HCO_3^-] > 2([Ca^{2+}] + [Mg^{2+}])$	Magnesian calcite	$2([Ca^{2+}] + [Mg^{2+}])$	$2([Ca^{2+}] + [Mg^{2+}])$

[1] All ion concentrations are in mmol L^{-1}. [2] If $[Ca^{2+}] > [SO_4^{2-}] + 0.5\ [HCO_3^-]$ then $[CaS] = 2[SO_4^{2-}]$, if $[Ca^{2+}] \leq [SO_4^{2-}] + 0.5\ [HCO_3^-]$ then $[CaS] = 2[Ca^{2+}] - [HCO_3^-]$.

at equilibrium with the mean soil pCO_2 and allows for calcite and gypsum precipitation and weathering. Finally, the EC is calculated with the equation developed by Visconti *et al*. (2010).

Simulations

Simulation area

The *Vega Baja del Segura* (SE Spain) is a very important agricultural area where approximately 80% of the irrigated soils are salt-affected (de Paz *et al*., 2011). The main crops (Visconti, 2009) that cover 61% of the irrigated area are citrus such as orange, mandarin and Verna lemon grafted onto various different rootstocks. The moderately salt-tolerant Sour Orange and especially Cleopatra mandarin are used as rootstocks for more than 60% of citrus. Vegetables (including tubers) cover 16% of the area. These are globe artichoke, lettuce, melon, broccoli, and potato. Non-citrus fruit trees cover 12% of the area, specifically almond, pomegranate and date palm. All crops grown in the area, but especially date palm, pomegranate and globe artichoke, are more or less tolerant to salinity (Table 2).

The average Penman-Monteith reference evapotranspiration and precipitation in the period of 2007-2009 were 1215 and 385 mm yr^{-1}, respectively. The main irrigation water supply in the area is the Segura River. Since the early 1980s, water from the Tajo-Segura transfer has also been available for some farmers. Beginning in 2011, up to 40 hm^3 yr^{-1} of desalinated water will be available for irrigation by the *Sindicato Central de Regantes del Acueducto Tajo-Segura* (Tajo-Segura Aqueduct Irrigators Union) (MMA, 2006). Although new irrigation projects use drip systems, at least 50% of the area is still irrigated by surface (Visconti, 2009).

Set up of simulations

Ten crops, namely i) globe artichoke, ii) cantaloupe melon and broccoli rotation, iii) cantaloupe melon and potato rotation, iv) date palm, v) orange, vi) Verna lemon grafted onto sour orange, vii) Verna lemon grafted onto Cleopatra mandarin, and viii) Verna lemon grafted onto *Citrus macrophylla*, ix) non-grafted Verna lemon, and x) pomegranate, were combined with three different water supplies, the Segura River, Tajo-Segura transfer and desalinated water, to simulate 30 scenarios. These crops and crop rotations exhibit different salt tolerances and were selected to be representative of at least 75% of the irrigated area. The LR_Y values were calculated for 90% potential yield (Table 2). The water quality data (Table 3) for the Segura River and Tajo-Segura transfer are average values for the river and transfer, respectively, in the area for the years 2007-2009 (*Confederación Hidrográfica del Segura*). The desalinated water characteristics are from a reverse osmosis desalination plant with treatment for boron removal located on the Mediterranean coast of Spain (Hernández-Suárez, 2010). The soil data (Table 4)

Table 2. Threshold-slope values and saturation extract electrical conductivity for 90% yield

Common name	Botanical name	EC_t / dS m^{-1}	s / (dS m^{-1})$^{-1}$	EC_{90} / dS m^{-1}	Reference
Globe artichoke	*Cynara scolymus* L.	4.9	10.7	5.83	Shannon & Grieve (1999)
Cantaloupe melon	*Cucumis melo cantalupensis*	2.2	7.4	3.55	Turini (2011)
Broccoli	*Brassica oleracea,* Botrytis group	2.8	9.2	3.89	Shannon & Grieve (1999)
Potato	*Solanum tuberosum*	1.7	12.0	2.53	Maas & Hofmann (1977)
Date palm	*Phoenix dactylifera*	4.0	3.6	6.80	Maas & Hofmann (1977)
Sweet orange tree	*Citrus sinensis*	1.7	16.0	2.33	Maas & Hofmann (1977)
Verna lemon tree on sour orange	*Citrus limon* (L) Burm f. × *Citrus aurantium* L.	1.5	10.4	2.48	Cerdá *et al*. (1990)
Verna lemon tree on Mandarin cleopatra	*Citrus limon* (L) Burm f. × *Citrus reshni* Hort. ex Tan.	2.1	13.7	2.81	Cerdá *et al*. (1990)
Verna lemon tree on *Citrus macrophylla*	*Citrus limon* (L) Burm f. × *Citrus macrophylla* (Wester)	1.0	14.2	1.72	Cerdá *et al*. (1990)
Verna lemon tree	*Citrus limon* (L) Burm f.	1.6	18.1	2.19	Cerdá *et al*. (1990)
Pomegranate	*Punica granatum* L.	3.0	7.7	4.30	Maas (1993)

Table 3. Characteristics of the irrigation water supplies

Water	pH	Alkalinity / meq L^{-1}	Na^+ / mmol L^{-1}	K^+ / mmol L^{-1}	Ca^{2+} / mmol L^{-1}	Mg^{2+} / mmol L^{-1}	Cl^- / mmol L^{-1}	NO_3^- / mmol L^{-1}	SO_4^{2-} / mmol L^{-1}	SAR / mmol L^{-1}	EC_{25} / dS m^{-1}
Segura River	7.72	5.44	22.85	0.52	6.50	6.53	21.48	0.51	10.69	6.33	4.32
Transfer	8.24	2.53	3.36	0.11	2.68	2.25	3.26	0.04	3.59	1.51	1.24
Desalinated	8.60	0.02	4.15	0.11	0.02	0.07	4.76	< 0.01	0.05	13.29	0.62

used in the simulations correspond to a *Vega Baja* typical clay loam soil sampled in 2006. The 2007-2009 climate data were taken from the records of three agricultural weather stations in the area, Almoradí, Catral and Orihuela - La Murada managed by the SIAR (*Sistema de Información Agroclimática para el Regadío*). A leaching efficiency (F) equal to 0.6 was selected for the SALSODIMAR simulations according to the soil texture and the predominant surface irrigation.

Calculation of leaching requirements and irrigation doses

As management oriented models, both the traditional LR model with extensions and SALSODIMAR calculate the LR as their key output. Moreover, SALSODIMAR calculates the irrigation and drainage volumes required to fulfil the LR provided that the crop evapotranspiration and rainfall are known. As more predictive oriented models, WATSUIT and particularly SALTIRSOIL, do not calculate the LR *per se*.

In the case of WATSUIT, the user calculates the soil solution EC caused by different leaching fractions (LFs). Then, the LR is taken equal to the LF that produces the target value of soil solution EC. Next, the irrigation doses have to be assessed separately, which include the crop evapotranspiration calculations.

The use of SALTIRSOIL to calculate the LR is similar to WATSUIT, except that the LF is a model output jointly with the soil solution salinity. In this case, the user tests some irrigation volumes instead of some LFs. When, instead of EC, the SAR or chloride are the parameters of interest, the procedure is the same but then logically searching for a target SAR or [Cl$^-$] respectively. In SALTIRSOIL, the irrigation doses are calculated with the dual crop coefficient paradigm (Allen *et al*., 1998) using appropriate monthly basal crop coefficients (Table 5). For the vegetable crops, these were assessed on basis usual planting and harvest dates in the area: artichoke from October 1st until July 8th, melon from April 1st until August 19th, broccoli from September 14th until January 27th and potato from September 14th until January 22nd.

Results

Traditional LR model extended for chloride and SAR control

The LR_Y values for the Segura river water were between 0.17 and 0.52 for vegetable crops and between 0.15 and > 0.99 for tree crops (Table 6). The lower limit in each group corresponded to the most tolerant crop, that is, artichoke and date palm with EC_{90} equal to 5.8 and 6.8 dS m^{-1}, respectively. The higher limit corresponds to the most sensitive crops, that is, potato and lemon tree grafted onto *C. macrophylla* with EC_{90} equal to 2.5 and 1.7 dS m^{-1}, respectively. Citrus are known to be sensitive to soil salinity. However, the differences among rootstocks are reflected in the LR_Y values,

Table 4. Soil characteristics of a typical calcaric fluvisol in the *Vega Baja del Segura*

Layer cm^{-1}	Sand (%)	Clay (%)	θg_{sat} [1] (%)	θv_{fc} [2] (%)	θv_{wp} [3] (%)	ρ_b (g cm^{-3})	Stones (%)	CCE[4] (%)	SOM[5] (%)	Gypsum (%)
0-10	27	35	45	39	19	1.22	0	40	2.7	0.1
10-30	23	38	48	39	21	1.27	0	40	1.8	0.1
30-65	15	41	52	40	23	1.33	0	44	1.2	0.0
65-95	10	45	56	41	24	1.31	0	45	1.0	0.1

[1] Gravimetric soil water content at saturation. [2] Volumetric at field capacity. [3] Volumetric at wilting point. [4] Calcium carbonate equivalent. [5] Soil organic matter.

Table 5. Monthly basal crop coefficients used for SALTIRSOIL evapotranspiration assessment

Crop	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Artichoke[1]	0.84	0.98	0.98	0.98	0.98	0.55	0.11	0.00	0.00	0.35	0.35	0.49
Melon[1]-Broccoli[1]	0.77	0.00	0.00	0.15	0.58	0.87	0.97	0.49	0.09	0.32	0.55	0.92
Melon[1]-Potato[1]	0.59	0.00	0.00	0.15	0.58	0.87	0.97	0.49	0.09	0.50	0.99	1.03
Date palm[2]	0.80	0.80	0.80	0.90	1.00	1.00	1.00	1.00	1.00	0.80	0.80	0.80
Orange[3]	0.63	0.62	0.63	0.59	0.52	0.59	0.65	0.75	0.70	0.80	0.69	0.60
Lemon[1]	0.50	0.50	0.55	0.55	0.55	0.60	0.60	0.60	0.60	0.60	0.55	0.55
Pomegranate[4]	0.00	0.00	0.27	0.42	0.65	0.76	0.76	0.76	0.76	0.65	0.34	0.00

[1]Allen *et al*. (1998). [2] Liebenberg & Zaid (2002). [3] Castel (2001). [4] Intrigliolo *et al*. (2011).

for example, the lower LR_Y was 0.44 and corresponded to lemon grafted onto Cleopatra mandarin, which exhibited an EC_{90} of 2.8 dS m^{-1}. The maximum chloride concentrations in mmol L^{-1} for the citrus trees are 10 for orange, 15 for lemon grafted onto sour orange and also non-grafted lemon tree, and 25 for lemon grafted onto Cleopatra mandarin (Ayers and Westcot, 1985). These differences gave rise to remarkable differences in LR_{Cl}, which ranged from 0.83 for the most sensitive to 0.22 for the least. A SAR up to 10 (mmol L^{-1})$^{1/2}$ may be permissible at whatever the expected soil solution EC attainable with the Segura water. This produced a LR_{SAR} equal to 0.14.

As expected, when the Tajo-Segura transfer was the water supply, all LRs were lower. The LR_Y was between 0.04 and 0.11 for vegetable crops and between 0.04 and 0.17 for tree crops. For citrus, the LR_{Cl} was always below LR_Y and, although the maximum permissible SAR with this water was 7 (mmol L^{-1})$^{1/2}$, the LR_{SAR} was even lower than before (0.02).

As expected, when irrigating with desalinated water, all LR_Y values decreased compared to the Tajo-Segura. However, the LR_{Cl} increased because the desalinated water is higher in chloride than the Tajo-Segura (Table 3). Furthermore, the maximum permissible SAR of 7 (mmol L^{-1})$^{1/2}$ and the high SAR of the desalinated water (Table 3) produced a LR_{SAR} equal to 0.08, which was higher than the previous value. This increment was expected because of the high SAR of the desalinated water (Table 3).

WATSUIT

The LR_Y values for the Segura water were between 0.13 and 0.79 for vegetables and between 0.09 and > 0.99 for trees (Table 6). When the target EC (EC_{90}) was higher than 4.8 dS m^{-1}, WATSUIT gave lower LR_Y values than the traditional model, whereas the opposite occurred when the target EC was lower than 4.8 dS m^{-1} (Fig. 1a). The LR_{Cl} values for citrus were between 0.27 and > 0.99, all higher than those calculated with the traditional model. Similarly to the LR_Y calculation, WATSUIT gave higher LR_{Cl} values than the extended traditional model when the target $[Cl^-]_{se}$ was under 38 mmol L^{-1}, which is common for all citrus (Fig. 1g). The LR_{SAR} was 0.08, lower than the LR_{SAR} calculated with the extended traditional model.

For the Tajo-Segura water, the LR_Y values were between < 0.01 and 0.04 for vegetables and between < 0.01 and 0.11 for trees. These values are lower than those calculated with the traditional model. For the Tajo-Segura water, WATSUIT gives lower LR_Y values than the traditional model when the target EC is higher than 1.2 dS m^{-1} (Fig. 1b). The LR_{Cl} values were between 0.01 and 0.05. In contrast to what occurred with the Segura water, the LR_{Cl} values were lower than those calculated with the traditional model. This is because for a target $[Cl^-]_{se}$ over 7 mmol L^{-1}, which is surpassed by all citrus, the LR_{Cl} calculated with WATSUIT is lower than the LR_{Cl} calculated with the traditional model (Fig. 1h). The LR_{SAR} was lower than 0.01 and, therefore, lower than the LR_{SAR} calculated with the extended traditional model.

For the desalinated water, the LR_Y values were between < 0.01 and 0.02 for vegetables and between < 0.01 and 0.03 for trees. They were again lower than those calculated with the traditional model. Over a target EC of 1.2 dS m^{-1}, WATSUIT gave lower LR_Y values than the traditional model with this water (Fig. 1c). The LR_{Cl} values were between 0.02 and 0.08 and were lower than those calculated by the traditional model. The LR_{SAR} was equal to 0.06, again lower than the value calculated with the traditional model. For a target SAR over 5 (mmol L^{-1})$^{1/2}$, the WATSUIT model calculated lower LR_{SAR} than the extended traditional model (Fig. 1f).

SALSODIMAR

The LR_Y values for the Segura water were all over 0.99 (Table 6), that is, according to SALSODIMAR, profitable irrigation with this water would not be possible. Only artichoke and date palm would, although only with leaching efficiencies higher than 0.9. The LR_{Cl} values were all over 0.99, while the LR_{SAR} for a target SAR of 10 (mmol $L^{-1})^{1/2}$ was equal to 0.67, which was remarkably higher than the values obtained with the extended traditional model (0.14) and WATSUIT (0.08) respectively.

For the Tajo-Segura water, the LR_Y was between 0.37 and 0.88 for vegetables and between 0.31 and >0.99 for trees, all remarkably higher than the corresponding values obtained with the preceding models. The LR_{Cl} values were between 0.22 and 0.55, while the LR_{SAR} for a target SAR of 7 (mmol $L^{-1})^{1/2}$ was 0.11, which was again higher than the LR_{Cl} and LR_{SAR} values calculated with the preceding models.

For the desalinated water, the LR_Y values were between 0.12 and 0.29 for vegetables and between 0.11 and 0.35 for trees. These values were higher than the LR_Y values calculated with the preceding models. The LR_{Cl} values were between 0.32 and 0.79, which were again higher than the values previously calculated. The LR_{SAR} for a target SAR of 7 (mmol $L^{-1})^{1/2}$ was over 0.99, that is, according to SALSODIMAR, irrigation with desalinated water would unavoidably lead to high SAR values.

Table 6. Leaching requirements calculated with all four models

Crop[1]	Water supply	Traditional LR			WATSUIT			SALSODIMAR			SALTIRSOIL[2]			
		LR_Y	LR_{Cl}	LR_{SAR}	LR_Y	LR_{Cl}	LR_{SAR}	LR_Y	LR_{Cl}	LR_{SAR}	LR_Y	LR_{Cl}	LR_{SAR}	LF_{CWR}
Artichoke	Segura River	0.17	—	0.14	0.13	—	0.08	>0.99	—	0.67	0.10	—	< 0.01	0.06
Melon-Broccoli	Segura River	0.32	—	0.14	0.42	—	0.08	>0.99	—	0.67	0.67	—	0.04	0.08
Melon-Potato	Segura River	0.52	—	0.14	0.79	—	0.08	>0.99	—	0.67	>0.99	—	0.04	0.08
Date palm	Segura River	0.15	—	0.14	0.09	—	0.08	>0.99	—	0.67	0.09	—	0.04	0.01
Orange	Segura River	0.59	0.83	0.14	0.92	>0.99	0.08	>0.99	>0.99	0.67	>0.99	>0.99	0.05	0.03
Lemon × SO	Segura River	0.53	0.43	0.14	0.82	0.64	0.08	>0.99	>0.99	0.67	>0.99	0.48	<0.01	0.08
Lemon × MC	Segura River	0.44	0.22	0.14	0.65	0.27	0.08	>0.99	>0.99	0.67	>0.99	0.10	<0.01	0.08
Lemon × CM	Segura River	>0.99	—	0.14	>0.99	—	0.08	>0.99	—	0.67	>0.99	—	<0.01	0.08
Lemon	Segura River	0.65	0.43	0.14	>0.99	0.64	0.08	>0.99	>0.99	0.67	>0.99	0.48	<0.01	0.08
Pomegranate	Segura River	0.25	—	0.14	0.27	—	0.08	>0.99	—	0.67	0.25	—	<0.01	0.10
Artichoke	Transfer	0.04	—	0.02	<0.01	—	<0.01	0.37	—	0.11	<0.01	—	<0.01	0.06
Melon-Broccoli	Transfer	0.08	—	0.02	0.02	—	<0.01	0.62	—	0.11	0.04	—	<0.01	0.08
Melon-Potato	Transfer	0.11	—	0.02	0.04	—	<0.01	0.88	—	0.11	0.10	—	<0.01	0.08
Date palm	Transfer	0.04	—	0.02	<0.01	—	<0.01	0.31	—	0.11	<0.01	—	<0.01	0.01
Orange	Transfer	0.12	0.07	0.02	0.06	0.05	<0.01	0.95	0.55	0.11	0.12	0.04	<0.01	0.03
Lemon × SO	Transfer	0.11	0.05	0.02	0.05	0.03	<0.01	0.89	0.37	0.11	0.04	<0.01	<0.01	0.08
Lemon × MC	Transfer	0.10	0.03	0.02	0.03	0.01	<0.01	0.79	0.22	0.11	<0.01	<0.01	<0.01	0.08
Lemon × CM	Transfer	0.17	—	0.02	0.11	—	<0.01	>0.99	—	0.11	0.50	—	<0.01	0.08
Lemon	Transfer	0.13	0.05	0.02	0.07	0.03	<0.01	>0.99	0.37	0.11	0.07	<0.01	<0.01	0.08
Pomegranate	Transfer	0.06	—	0.02	0.01	—	<0.01	0.52	—	0.11	<0.01	—	<0.01	0.10
Artichoke	Desalinated	0.02	—	0.08	<0.01	—	0.06	0.12	—	>0.99	<0.01	—	0.01	0.06
Melon-Broccoli	Desalinated	0.04	—	0.08	0.01	—	0.06	0.20	—	>0.99	<0.01	—	0.01	0.08
Melon-Potato	Desalinated	0.05	—	0.08	0.02	—	0.06	0.29	—	>0.99	0.04	—	0.02	0.08
Date palm	Desalinated	0.02	—	0.08	<0.01	—	0.06	0.11	—	>0.99	<0.01	—	0.01	0.01
Orange	Desalinated	0.06	0.11	0.08	0.02	0.08	0.06	0.31	0.79	>0.99	0.05	0.07	0.02	0.03
Lemon × SO	Desalinated	0.05	0.07	0.08	0.02	0.03	0.06	0.29	0.53	>0.99	<0.01	<0.01	<0.01	0.08
Lemon × MC	Desalinated	0.05	0.04	0.08	0.02	0.02	0.06	0.26	0.32	>0.99	<0.01	<0.01	<0.01	0.08
Lemon × CM	Desalinated	0.08	—	0.08	0.03	—	0.06	0.35	—	>0.99	0.08	—	<0.01	0.08
Lemon	Desalinated	0.06	0.07	0.08	0.03	0.03	0.06	0.33	0.53	>0.99	<0.01	< 0.01	<0.01	0.08
Pomegranate	Desalinated	0.03	—	0.08	<0.01	—	0.06	0.17	—	>0.99	<0.01	—	<0.01	0.10

[1] SO: Sour orange, MC: Mandarin cleopatra, CM: *Cytrus macrophylla*. [2] LF_{CWR}: Leaching fraction produced by no water stress conditions according to SALTIRSOIL.

SALTIRSOIL

The LR_Y values with the Segura water were between 0.10 and > 0.99 for vegetables and between 0.09 and > 0.99 for trees (Table 6). Only artichoke, melon and broccoli rotation, date palm and pomegranate presented LR_Y values under 0.99. The LR_Y values corresponding to artichoke (0.10), date palm (0.09) and pomegranate (0.25) were slightly lower than those calculated with WATSUIT, which were 0.13, 0.09 and 0.27, respectively. On basis the SALSODIMAR simulations, the LR_Y values were all over 0.99. The LR_Y values calculated with SALTIRSOIL led to irrigation doses of 368, 746 and 593 mm yr^{-1}, respectively (Table 7), which are reasonable values. The LR_Y values calculated with SALTIRSOIL for the other crops were higher than 0.99, that is, the same as those calculated with SALSODIMAR. The LR_{Cl} values were between 0.10 and > 0.99, this latter corresponding to the least tolerant orange. These LR_Y were, with the exception of orange, well under the corresponding values calculated with WATSUIT. The LR_{SAR} for a target SAR of 10 (mmol L^{-1})$^{1/2}$ was between < 0.01 and 0.05, that is, lower than the values calculated with WATSUIT (0.08) and remarkably lower than those calculated with SALSODIMAR (0.67).

For the Tajo-Segura water, the LR_Y values were between < 0.01 and 0.10 for vegetables and between < 0.01 and 0.50 for trees. The LR_Y values obtained for artichoke, melon and broccoli, date palm, pomegranate, non-grafted lemon and lemon grafted onto Sour Orange and Cleopatra mandarin are very similar to the LR_Y values obtained with WATSUIT, with differences less than 0.03. The LR_Y values obtained for melon and potato and orange tree were more similar to the values obtained with the traditional

Table 7. Irrigation doses (I mm^{-1} yr^{-1}) calculated with all four models

Crop[1]	Water supply	Traditional LR	WATSUIT	SALSODIMAR	SALTIRSOIL
Artichoke	Segura River	504	462	>47,708	368
Melon-Broccoli	Segura River	669	843	>44,787	1,823
Melon-Potato	Segura River	1,075	2,987	>45,421	—
Date palm	Segura River	941	864	>76,238	746
Orange	Segura River	4,255	9,566	>42,316	—
Lemon × SO	Segura River	1,111	3,471	>37,136	—
Lemon × MC	Segura River	869	1,621	>37,136	—
Lemon × CM	Segura River	>69,334	>69,334	>37,136	—
Lemon	Segura River	1,616	>69,334	>37,136	—
Pomegranate	Segura River	534	562	>43,368	593
Artichoke	Transfer	383	<356	760	339
Melon-Broccoli	Transfer	388	344	1192	407
Melon-Potato	Transfer	404	345	3667	444
Date palm	Transfer	793	<759	1105	658
Orange	Transfer	503	444	8700	528
Lemon × SO	Transfer	400	346	3497	343
Lemon × MC	Transfer	387	337	1759	343
Lemon × CM	Transfer	453	400	>37,136	957
Lemon	Transfer	415	364	>37,136	343
Pomegranate	Transfer	348	313	895	433
Artichoke	Desalinated	411	392	>47,708	340
Melon-Broccoli	Desalinated	390	372	>44,787	407
Melon-Potato	Desalinated	377	359	>45,421	424
Date palm	Desalinated	843	814	>76,238	660
Orange	Desalinated	489	461	>42,316	476
Lemon × SO	Desalinated	371	353	>37,136	344
Lemon × MC	Desalinated	371	353	>37,136	344
Lemon × CM	Desalinated	372	353	>37,136	347
Lemon	Desalinated	371	353	>37,136	344
Pomegranate	Desalinated	360	343	>43,368	430

[1] SO: Sour orange, MC: Mandarin cleopatra, CM: *Cytrus macrophylla.*

model, with differences of less than 0.01. The LR_Y values obtained with the SALTIRSOIL and SALSODIMAR models are very far apart from each other, with differences ranging from 0.31 to > 0.92. The LR_{Cl} values were between 0.04 and < 0.01, which are no more than 0.02 lower than the corresponding values calculated with WATSUIT. The LR_{Cl} values obtained with SALTIRSOIL and SALSODIMAR were again very different, ranging from 0.22 to 0.51. The LR_{SAR} for a target SAR of 7 (mmol $L^{-1})^{1/2}$ was less than 0.01 which matches the LR_{SAR} obtained with WATSUIT and was remarkably lower than the value calculated with SALSODIMAR (0.11).

For the desalinated water, the LR_Y was between < 0.01 and 0.04 for vegetables and between < 0.01 and 0.08 for trees. Again, the LR_Y values obtained for seven crops (artichoke, melon and broccoli, date palm, pomegranate, non-grafted lemon and lemon grafted onto Sour Orange and Cleopatra mandarin were very similar to the LR_Y values obtained with WATSUIT, with differences less than 0.03. The LR_Y for the other three crops were more similar to the LR_Y obtained with the traditional model, with differences of less than 0.02. The corresponding differences with the LR_Y values obtained with the SALSODIMAR were within 0.11 and 0.33. The LR_{Cl} values were between < 0.01 and 0.07, which were between 0.03 and 0.01 lower than those obtained with WATSUIT and between 0.32 and 0.72 lower than those obtained with SALSODIMAR. The LR_{SAR} for a target SAR_{se} of 7 (mmol $L^{-1})^{1/2}$ was between < 0.01 and 0.02, which was somewhat lower than the LR_{SAR} calculated with WATSUIT and the extended traditional model. These values were very far from the SALSODIMAR result (> 0.99).

Discussion

Generally, the saturation extract electrical conductivity simulated by the four models decreases with the LF, at first steeply and then more softly before becoming almost flat (Fig. 1a,b,c). From a point that depends on the salinity of the irrigation water, progressive increments of the LF hardly decrease the soil salinity. Although this general trend is followed by every model, there are differences among them concerning the specific magnitudes involved. The SALSODIMAR model gives remarkably higher LFs than the other three models for any water quality and EC. Therefore, the differences between the LR values calculated with SALSODIMAR and the other three models decrease as function of the EC of the irrigation water.

According to the SALSODIMAR model, the relationship between the drainage water and saturation extract salinities is given by a parameter labelled as leaching efficiency F (Eq. [11]). Because this parameter is a positive value never higher than 1, the drainage water is, by definition, less saline than the saturation in SALSODIMAR. In the other three models, this relationship is provided empirically (traditional LR; Eq. [4]) or by calculation (WATSUIT and SALTIRSOIL). Whatever the particular method, and contrary to SALSODIMAR, the drainage water is always more saline than the saturation extract in the three other models, that is, the quotient EC_{dw} / EC_{se} is variable and never less than one. Specifically, this quotient is never less than 4.3, 4.7 and 1.7 for the Tajo-Segura transfer water according to the traditional LR, WATSUIT and SALTIRSOIL models, respectively (Table 8). Similar values for

Table 8. Electrical conductivity of the drainage water (EC_{dw}) and quotient EC_{dw}/EC_{se} for the Tajo-Segura transfer water

Crop[1]	$EC_{se(Y)}$ / dS m^{-1}	Traditional LR		WATSUIT		SALSODIMAR		SALTIRSOIL[2]		
		EC_{dw} / dS m^{-1}	EC_{dw} / $EC_{se(Y)}$	EC_{dw} / dS m^{-1}	EC_{dw} / $EC_{se(Y)}$	EC_{dw} / dS m^{-1}	EC_{dw} / $EC_{se(Y)}$	$EC_{se(S)}$ / dS m^{-1}	EC_{dw} / dS m^{-1}	EC_{dw} / $EC_{se(S)}$
Artichoke	5.8	27.9	4.8	>52.2	>8.9	3.5	0.6	2.5	6.4	2.5
Melon-Broccoli	3.6	16.5	4.7	29.1	8.2	2.1	0.6	2.7	5.5	2.1
Melon-Potato	2.5	11.4	4.5	16.7	6.6	1.5	0.6	2.5	5.1	2.0
Date palm	6.8	32.8	4.8	>52.2	>7.7	4.1	0.6	4.1	24.9	6.1
Orange	2.3	10.4	4.5	13.2	5.7	1.4	0.6	2.3	4.8	2.1
Lemon × SO	2.5	11.2	4.5	13.9	5.6	1.5	0.6	2.1	5.2	2.5
Lemon × MC	2.8	12.8	4.6	20.9	7.4	1.7	0.6	2.1	5.2	2.5
Lemon × CM	1.7	7.4	4.3	8.1	4.7	—	—	1.7	2.9	1.7
Lemon	2.2	9.7	4.4	11.9	5.4	—	—	2.1	5.2	2.5
Pomegranate	4.3	20.3	4.7	41.5	9.7	2.6	0.6	2.2	5.0	2.2

[1] SO: Sour orange, MC: Mandarin cleopatra, CM: *Cytrus macrophylla*. [2] $EC_{se(S)}$: Electrical conductivity resulting from simultaneous no water and no salinity stress conditions according to SALTIRSOIL.

the quotient EC_{dw} / EC_{se} [Supplementary Table 1 (pdf)] are obtained with the Segura and desalinated waters.

In Figure 1 (d to f), we observe similar graphs, although SAR is the variable on the ordinate axis rather than EC. As for EC, the SAR decreases steeply at low LFs and then progressively flattens as LF approaches one. Again from a point, SAR hardly decreases with the LF. All four models follow similar trends. The corresponding lines for the traditional LR, WATSUIT and SALTIRSOIL remain very close and cross each other. However, the SALSODIMAR line is very far apart, that is, it gives remarkably higher LR_{SAR} for any water quality and target SAR. As previously indicated, in SALSODIMAR, the saturation extract is more saline than the drainage water by definition, which explains part of this behaviour. However, with SAR, higher differences between SALSODIMAR and the other models are found when considering desalinated water, and not the more saline Segura river water.

The desalinated water is characterised by very low calcium and relatively high sodium, which results in a high SAR. It is also undersaturated regarding calcium carbonate and, consequently, tends to dissolve calcite from soil solids (Hernández-Suarez, 2010). The soils from the *Vega Baja del Segura* are very high in the calcium carbonate equivalent (Table 4), and the weathering of some little calcite compensates for the initial lack of calcium in the desalinated water. The extended traditional LR, WATSUIT and SALTIRSOIL models include the weathering of calcite, and therefore, they calculate low LRs for SAR control in soils irrigated with desalinated water. However, SALSODIMAR only takes account of calcite precipitation, not weathering, giving rise to very high, and in fact unattainable, LRs for SAR control using desalinated water.

The traditional LR, WATSUIT and SALTIRSOIL models are very similar. However, for SALTIRSOIL, both EC and SAR change faster with LF at low LFs and slower at medium and high LFs, that is, the SALTIRSOIL line is the steepest. Following SALTIRSOIL, there is WATSUIT and finally the traditional LR, which gives softer transitions from low to high LFs. As a consequence, SALTIRSOIL gives the lowest LR_Y values for target ECs higher than approximately 1.5 times the irrigation water EC and the highest for much lower target ECs. The LR_Y values calculated on the basis of transient-state models are usually lower than those calculated on the basis of steady-state models (Letey *et al*., 2011). The refinements introduced in SALTIRSOIL have been sufficient to have lower LR values than those usually calculated with other steady-state models and, specifically, the traditional LR model.

SALTIRSOIL takes into account the rainfall, whereas the traditional LR and WATSUIT do not. Under Mediterranean climate conditions, rainfall is seldom negligible when compared to irrigation, so it should be included in the LR assessment. This is shown by using the following two equations (Eq. [15] and Eq. [16]), together with the traditional LR model:

$$D = ET_c \frac{LR_Y}{1 - LR_Y} \quad [15]$$

$$I = D + ET - R \quad [16]$$

If the non-linear system of three equations, [1], [15] and [16], is solved for every scenario, between 34 and 63% lower LR_Y values than those obtained with the traditional LR model alone are obtained. These differences are similar to those produced by the inclusion of soil calcite and gypsum precipitation and weathering into steady-state models (Corwin *et al*., 2007).

As we observe in the graphs of chloride against LF (Figs. 1g,h,i), SALTIRSOIL gives somewhat lower LR_{Cl} at high $[Cl^-]_{se}$ than WATSUIT, which follows the behaviour of LR_Y and LR_{SAR}. However, the differences between both models almost disappear as LF increases. At low LF, the magnitude of the irrigation water is similar to that of the rainfall and, therefore, the inclusion of this variable in SALTIRSOIL and not WATSUIT makes a difference between these models when compared with the traditional LR model. Nevertheless, as LF increases, the irrigation increases and for medium to high LFs, the LR_{Cl} calculated with both models is almost the same. The calculation methods for the average concentration factor at field capacity in WATSUIT and SALTIRSOIL (Eqs. [8], [9] and [14]) are therefore very similar, and thus the different results for LR_Y and LR_{SAR} (Fig. 1a to 1f) could only be explained by either the different way in which the calcite and gypsum equilibria are included in the models or by the different conversion of concentrations at field capacity to saturation.

In WATSUIT, the carbon dioxide partial pressures (log pCO$_2$) at the five different depths from top to bottom are –2.99, –2.20, –1.74, –1.54 and –1.39 atm, with a mean of –1.97, which is lower than the log pCO$_2$ used in SALTIRSOIL that is equal to –2.43 atm. This elevated pCO$_2$ along with the higher calcite solubility products (pKs) used in WATSUIT (from top to bottom 8.12, 8.22,

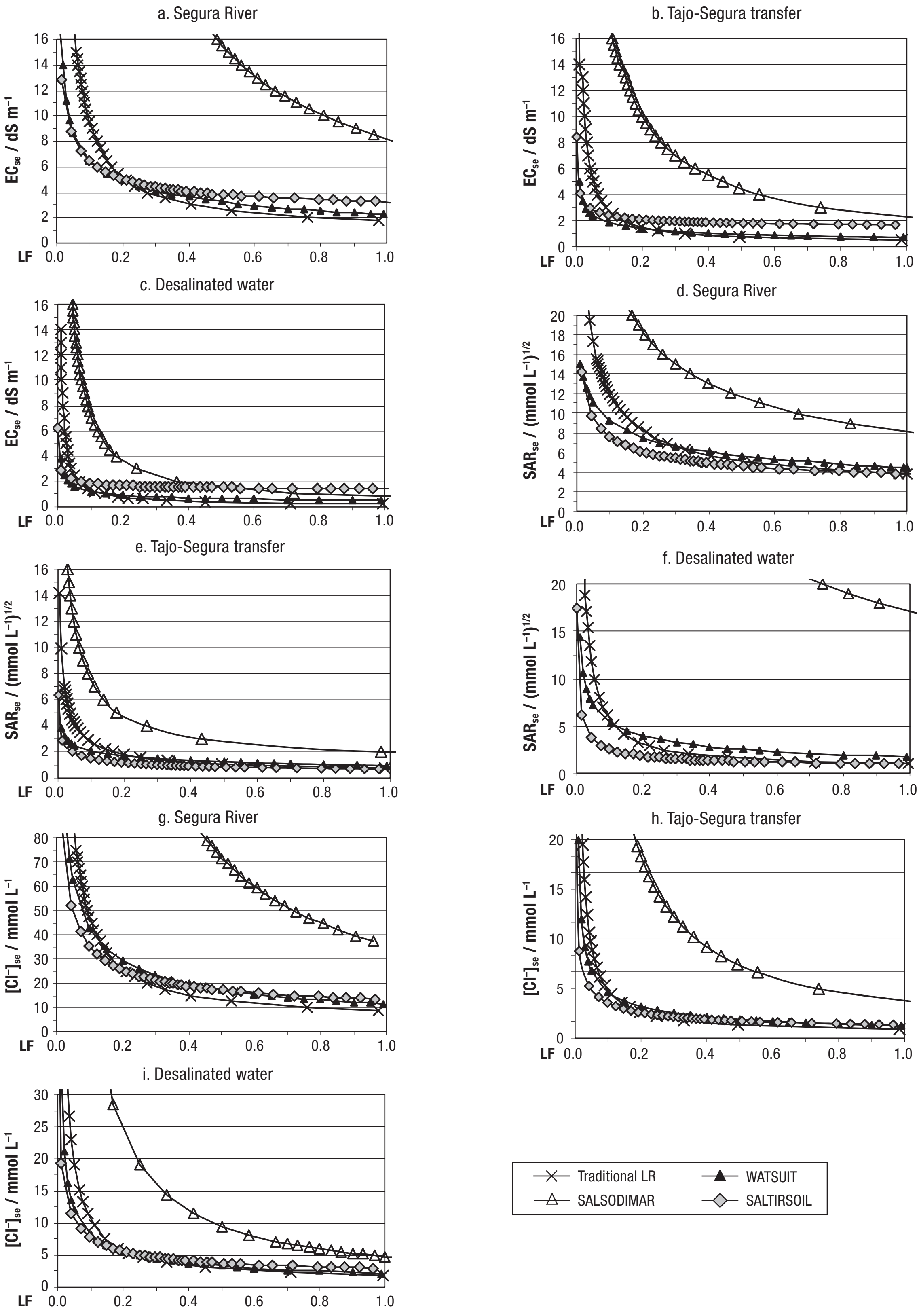

Figure 1. Graphs of electrical conductivity (a, b, c), sodium adsorption ratio (d, e, f) and chloride concentration (g, h, i) of the saturation extract against leaching fraction for Segura river, Tajo-Segura transfer and desalinated waters.

8.26, 8.29 and 8.33) compared to the SALTIRSOIL (8.29) should provide both higher EC and lower SAR than SALTIRSOIL as *LF* increases. Nevertheless, the opposite is observed. This is because in WATSUIT, the calcite equilibrium is assessed for the field capacity water content, whereas in SALTIRSOIL, it is assessed for the saturation extract. A factor of ½ is usually recommended to convert values at field capacity to saturation (Rhoades *et al.*, 1992). This conversion has little effect on ions not controlled by any equilibrium but it has a profound effect on ions such as calcium, the concentration of which is strongly dependent on calcite equilibrium. As we observe in Table 9, this makes the calcium concentration to have half the value it has at equilibrium. Thus, its concentration is underestimated, and the SAR is concomitantly overestimated. Similar reasons apply for the underestimation of the EC.

The eventual LR recommendation is given by the maximum value among LR_Y, LR_{Cl} and LR_{SAR}. However, SALTIRSOIL also calculates a LF caused by the crop water requirement (LF_{CWR}). This accounts for the minimum water loss produced by irrigation avoiding water stress. Therefore, the irrigation scheduling for each scenario has to be calculated based on the maximum value among LR_Y, LR_{Cl}, LR_{SAR} and LF_{CWR}. Taking 90% as the minimum profitable yield, the irrigation water demand in *Vega Baja del Segura* is between 368 and 1823 mm yr^{-1} for the Segura River, between 343 and 957 mm yr^{-1} for the Tajo-Segura transfer and between 340 and 660 mm yr^{-1} for desalinated waters (Table 7, last column). If the availability of irrigation water does not surpass 800 mm yr^{-1} (MMA, 1997), acceptable yields could have been obtained using Segura River water for the melon and broccoli, melon and potato, lemon grafted onto Sour Orange and Cleopatra mandarin with 86, 70, 79 and 80% yields, respectively. The irrigation doses calculated with the traditional LR model are, with the exception of salt-sensitive crops, within –22 and 31% of those calculated with SALTIRSOIL (Table 7).The irrigation doses actually applied to citrus and pomegranate in the *Vega Baja del Segura* have been estimated to be approximately 1600 and 750 mm yr^{-1}, respectively (MAPA, 2004). Using rootstocks moderately tolerant to salinity, no more than 800 mm yr^{-1} would be necessary to have citrus yields of at least 80%, even with the salty Segura River water. The water requirements for citrus would further decrease to 500 mm yr^{-1} or less if using Tajo-Segura transfer or desalinated waters. For pomegranate, no more than 600 mm yr^{-1} would be necessary with Segura water and less than 450 mm yr^{-1} with Tajo-Segura and desalinated waters.

Conclusions

For the simulations performed in the *Vega Baja del Segura* the SALSODIMAR model gave eventual LRs higher than 0.99 with both the Segura River and the desalinated water and between 0.31 and > 0.99 for the Tajo-Segura transfer, which are remarkably higher than the eventual LRs calculated with the rest of models. Specifically, SALTIRSOIL gave eventual LRs between 0.09 and > 0.99 for the Segura water, between 0.01 and 0.50 for the Tajo-Segura transfer, and between 0.01 and 0.10 for the desalinated water. These differences occur mainly because, in SALSODIMAR, the saturation extract is more concentrated than the drainage water by definition, whereas in the other models, the opposite is either assumed (traditional LR) or calculated (WATSUIT and SALTIRSOIL). Furthermore, SALSODIMAR does not take into account the weathering of soil calcite, which remarkably decreases the SAR of infiltrating desalinated waters as revealed by the other three models. The traditional LR, WATSUIT and SALTIRSOIL models gave similar LRs. The differences were because of i) the rainfall variable, absent in the traditional LR and WATSUIT, and present in SALTIRSOIL, and ii) because WATSUIT calculates the calcite equilibrium for the soil solution at field capacity whereas SALTIRSOIL so does at saturation. Therefore, after using WATSUIT,

Table 9. Characteristics of soil solutions obtained with LF = 0.5 and the Segura river water as calculated by WATSUIT at field capacity (A), and then converted to saturation (B), and SALTIRSOIL directly at saturation (C)*

Soil solution	pH	Alkalinity / meq L^{-1}	Na^+ / mmol L^{-1}	K^+ / mmol L^{-1}	Ca^{2+} / mmol L^{-1}	Mg^{2+} / mmol L^{-1}	Cl^- / mmol L^{-1}	NO_3^- / mmol L^{-1}	SO_4^{2-} / mmol L^{-1}	SAR / mmol L^{-1}	EC_{25} / dS m^{-1}
A	7.39	6.9	35.0	0.8	8.9	10.0	34.7	—	16.3	8.0	3.25
B	—	3.5	17.5	0.4	4.5	5.0	17.3	—	8.2	5.7	1.62
C	7.52	2.4	18.2	0.4	10.4	5.2	17.1	0.4	14.7	4.6	3.81

the conversion of ion concentrations from field capacity to saturation underestimates the electrical conductivity and also calcium, which in turn overestimates the SAR.

SALTIRSOIL seems to be the most complete model. Therefore, an irrigation dose was finally calculated for each scenario with SALTIRSOIL and compared to the traditional LR model. Despite the differences between the models, the irrigation doses were very similar except when salt- and chloride-sensitive crops are irrigated with waters of EC higher than 1.24 dS m^{-1} and high in chloride, respectively. The irrigation doses calculated with SALTIRSOIL were significantly lower than the actual irrigation doses presently used in the *Vega Baja del Segura*.

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