15

Soil, Water and Crop Management for Agricultural Profitability and Natural Resources Protection in Salt-Threatened Irrigated Lands

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1. Introduction

In the world areas under arid, semi-arid or dry subhumid climate, i.e. where potential evapotranspiration (ETp) exceeds rainfall (R), water scarcity imposes limits on agricultural diversity and productivity. Nevertheless, soils of high potential productivity are also often found under such climates, usually associated to river lowlands where fresh water proximity has allowed irrigation development to produce crops of high nutritional and economic value. It has been estimated that one sixth of world cultivated area is irrigated (AQUASTAT, 2008). What is more important, one third of world agricultural production comes from irrigated lands, and this fraction is going to significantly increase in the upcoming years (Winpenny, 2003). The main restriction to meet all of the soil productive potential of areas where ETp exceeds R is, in addition to water scarcity, soil salinity.

Most of the water nowadays used for irrigation has first originated in rainfall (Fig. 1). The precipitation water on the continents can either infiltrate or run across the rocks and/or soil until it reaches a water body. The infiltrating water into the soils constitutes the soil moisture. It can percolate away from the rooting depth and eventually becomes groundwater. Throughout the soil and ground rocks, water reacts with minerals and as a consequence dissolves salts. Groundwater contributes a significant part of surface water and then, it adds the salts originated in soils and ground rocks. If groundwater does not spring, it continues its movement through the underground rocks usually increasing its load of salts. The salinization of the groundwater occurs due to a lengthy contact with ground minerals, and also because of other phenomena such as contact with saline strata, and seawater intrusion in coastal aquifers. Quite the opposite, the load of salts of surface waters is diluted by direct surface runoff. As a consequence, groundwaters are, in general, more saline than stream waters (Turekian, 1977). Whichever the case, when waters are applied to soils for irrigation, the salts in solution are also applied. Crops absorb water and exclude the major portion of salts, which are left behind in the soil. The absorbed water is transpired to the atmosphere and therefore salts concentrate in the soil solution. Nevertheless, when part of the irrigation water percolates through the bottom of the rooting depth, the salt build-up in soils does not increase indefinitely, it reaches an equilibrium point. This equilibrium point features a steady state, in which the mass of salts entering the soil equals the mass of salts leaving it. This equilibrium point is characterized by a constant medium-to-long-term-average soil salt content.

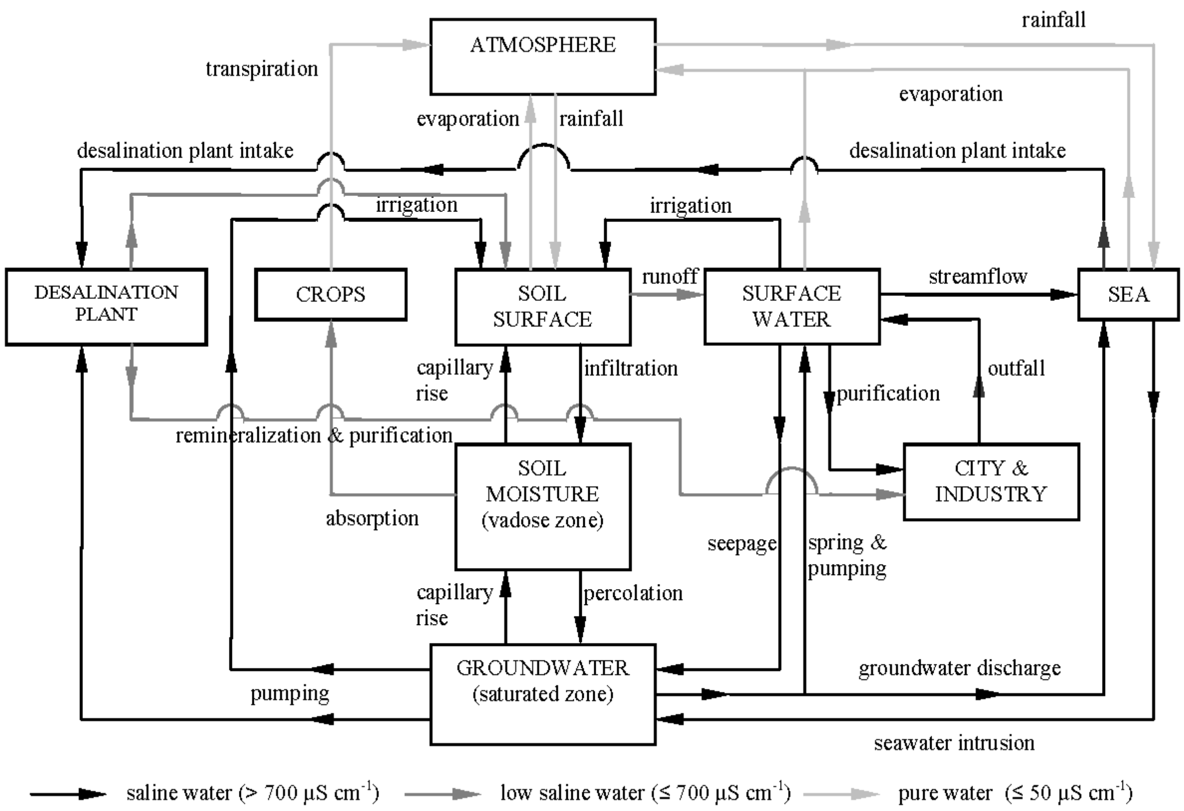

Fig. 1. Agrohydrological cycle

In arid, semi-arid and dry subhumid areas evapotranspiration exceeds precipitation and little water from rainfall percolates through the rooting depth. The more arid is climate the higher is the soil salinity featuring the equilibrium point. The excess of salts is defined with regards to plant tolerance. Plants absorb water from the soil solution, and therefore they respond to the salinity of the soil solution, rather than to the overall salinity of the soil. The salts dissolved in the soil solution decrease the potential of the soil water, which leads to a drought-like situation for plants. Given one plant species, as the soil solution salinity overcomes a plant-characteristic limit the crop suffers from drought and therefore yields decline. A good management of irrigation in arid to dry subhumid areas must provide the plants not only with the water they need to match the crop evapotranspiration, usually called the crop water requirement, but also with some excess water. This extra amount of water leaches, —in arid areas—, or helps to leach, —in semi-arid and dry subhumid areas—, part of the salts carried by the irrigation water itself. In addition to excess irrigation a good drainage must be assured to dispose of the percolating water. This way drainage complements irrigation to achieve a sustainable irrigation management.

The salinity of water systems including soil solution is made up mainly of only eight inorganic ions: sodium (Na^+), chloride (Cl^-), calcium (Ca^{2+}), magnesium (Mg^{2+}), sulphate (SO_4^{2-}), bicarbonate (HCO_3^-), potassium (K^+), and often also nitrate (NO_3^-). As charge bearing particles these ions give the water where they are dissolved the property to conduct electricity. Therefore the electrical conductivity at 25º C (EC_{25}), usually in units of dS m^{-1} or µS cm^{-1}, is commonly used as a measure of the salinity of water systems including soil solutions and irrigation waters. The ions just indicated combine to form several salts that differ in their solubility from the low to moderate solubility of calcite ($CaCO_3$) and gypsum ($CaSO_4 \cdot 2H_2O$) to the high solubility of the sodium and chloride salts. Precipitation of calcite and gypsum prevents the salinity of the soil solution from attaining harmful values when calcium, bicarbonate and / or sulphate are concentrated enough in the irrigation water. In addition to this favourable effect on salinity, calcite and gypsum have also a favourable effect on the soil cation balance. The combination of low salinity with a relatively high concentration of sodium with respect to calcium and magnesium, which is traditionally accounted for by the sodium adsorption ratio ($SAR = [Na^+]/([Mg^{2+}] + [Ca^{2+}])^{1/2}$), harms soil structure with consequences on water infiltration and soil aeration. High SAR values have also harmful effects on plants independently of salinity, because of the nutritional imbalance caused by the excessive concentration of sodium with regard to calcium. The weathering of calcite and/or gypsum from soil materials increases the calcium and sometimes magnesium content of the soil solution counteracting, on the one hand, the damage low salinity and high SAR have on soil structure, and on the other hand, counteracting the damage caused on the plant by a sodium high soil solution.

According to the sensitivity analysis of the steady-state soil salinity model SALTIRSOIL the expected average soil solution salinity depends on three main factors: climate, irrigation water salinity and irrigation water amount in this order (Visconti et al., 2011a). Traditionally, farmers have acted on these three factors to gain control on soil solution salinity.

Control over precipitation is out of human reach, however, farmers have some control on soil's climate. All the water saving practices aimed at increasing water infiltration and decreasing water evaporation help decrease also soil salinity (Zribi et al., 2011). Soil infiltration is traditionally enhanced by tillage and mulching with coarse materials of organic and inorganic origin. Soil evaporation is diminished through suppression of weed growth, irrigating at night and mulching with the same materials as before in addition to plastic mulches.

Regarding water quality, farmers have little control on the salinity of a given water body. Surface water has been traditionally the first and usually only option for irrigation. However, other water supplies have been made available throughout history thanks to collective initiatives led by irrigators unions, governments and enterprises. Rainwater harvesting (Huang et al., 1997; Abdelkhaleq & Ahmed, 2007) and water diversions have been used in many instances as non-conventional water supplies well before the 20th century. Groundwater has been used for millennia to irrigate where surface water was absent. However, the intensive exploitation of groundwater resources for irrigation did not occur until the late 19th century when the powerful machinery necessary for drilling and pumping water from depths beneath 8 m was available (Narasimhan, 2009). Other non-conventional water resources have arisen during the 20th century such as waste and reclaimed waters of urban, industrial and mining origin and also desalinated waters. Each one of these water supplies is characterised by a different composition and therefore salinity and SAR. Traditionally farmers have not been aware of these differences until the effects on plants have revealed themselves. Nowadays measurement of, at least, surface water salinity is often routinely carried out by government authorities and irrigators unions. Although farmers cannot change the quality of a water body, modern irrigation methods have allowed them changing the quality of the water actually used for irrigation. This is usually done by fertigation, but also by blending waters from different sources in irrigation reservoirs. The same technology available for fertigation can be used for adding chemicals such as gypsum or mineral acids to decrease the soil solution SAR if necessary.

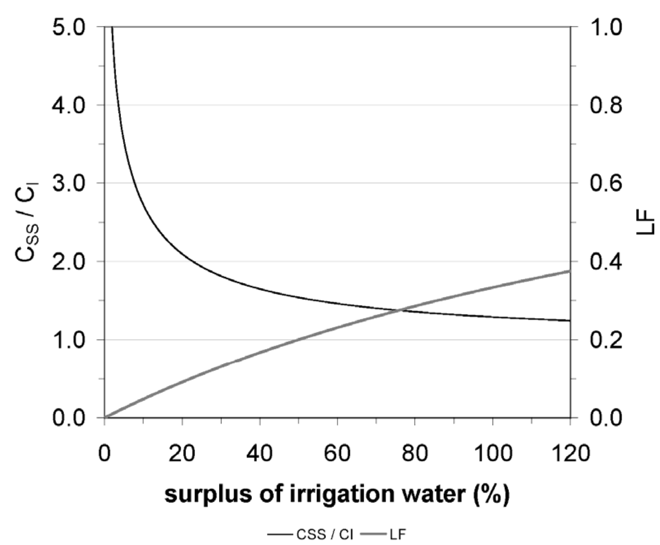

Fig. 2. Leaching fraction (LF) and relative salinity of the soil solution (C_{SS} / C_I) as function of the surplus of irrigation water following a 40:30:20:10 root water uptake pattern and a quotient R / ET_c of 0.5. Equations after Hoffman & Van Genuchten (1983)

The irrigation water amount is not as influential on soil salinity as climate and irrigation water quality. However, this factor has been traditionally considered as the one through which the farmer can exert more control over soil salinity. The idea that irrigation water leaches soil salts has established itself in many places as the popular belief that the more you irrigate the more salts you leach out of the soil. However, the relationship between soil salinity and irrigation water amount is far from being linear. The relationship is in fact a rational in which once the sum of rainfall and irrigation have matched the crop water requirement the soil solution salinity rapidly decreases with irrigation water surpluses of only 10 to 20% (Fig. 2). From 30% on, the soil solution salinity hardly decreases. It tends asymptotically to a limit which depends on climate, specifically the quotient rainfall to evapotranspiration, and irrigation water salinity.

Not only excess overirrigation constitutes a waste of water, which is on itself a severe problem in the present global scenario of scarcity and competition for safe water resources. As occurs with overfertilization it can be self-defeating. The amount of irrigation water must not surpass the limits imposed not only by the availability of water resources, but also by the capability of the drainage systems and the hydrology of the whole area where the crops are grown. In the medium to long term overriding the natural and man-made irrigation and drainage limits gives rise to serious on and off-farm problems of degradation of lands and water bodies (rivers, lakes and aquifers). Among these problems caused by overirrigation we find the rise of the water table underlying the crop fields, which impedes the soil leaching and leads to waterlogging and soil salinization. Furthermore, overirrigation increases the amount of drainage effluents, which are usually loaded with salts, nutrients and agrochemicals. This constitutes on the one hand a waste of farm investment, and on the other, a potential damage to the natural water bodies because of salinization, eutrophication and pollution.

Provided excess overirrigation is far from being adequate either in terms of agricultural profitability or natural resources protection, the question is how much water in excess of the crop water requirement is necessary to keep soil salts below the limit from which yields will decline. This question has been traditionally answered performing the following calculation (Eq. 1), where IR, R and ET_c are for the irrigation requirement, rainfall and crop evapotranspiration respectively, all in units of L T^{-1}, usually mm yr^{-1}.

$$IR = \frac{ET_c}{1 - LR} - R \tag{1}$$

Providing the amount of water that percolates through the bottom of the root zone is the soil drainage (D), the fraction of the infiltrating water ($I + R$) which becomes the soil drainage is known as the leaching fraction ($LF = D / (I + R)$) where I is for the actual irrigation. In Eq. 1 LR stands for the leaching requirement, which is defined as the minimum leaching fraction necessary to leach the soil salts below a limit considered harmful for a given crop. In order to optimize the irrigation rates the calculation of the leaching requirement has been the objective of several simulation models during the last 50 years.

The irrigation scheduling based on the calculation of a leaching requirement assume at least that i) the steady-state hypothesis is valid enough for the irrigation project, and ii) that the farmer has enough control over the irrigation application to adjust the quantity of water delivered to the soil. The steady-state hypothesis has been criticized because soil salinity fluctuates heavily in the short term following mostly the soil water content. Nevertheless, the leaching requirement is not intended to be a parameter useful at little scale either in time or spatial terms. Rather the leaching requirement is useful for irrigation planning from months to years, and from plots to irrigation districts. Ideally, how the irrigation rates and scheduling should be applied would start from the knowledge of the maximum soil salinity tolerable by the crop or crops to be cultivated during the whole growing season. Next the annual leaching requirement would be assessed with a model such as the traditional LR model (Rhoades, 1974), the WATSUIT (Rhoades & Merrill, 1976) or another developed for the same purpose. Accurate enough predictions of soil salinity only demand i) annual averaged boundary conditions, ii) a coarse spatial discretization, and the simulation of iii) cation exchange and iv) gypsum dissolution–precipitation (Schoups et al., 2006). WATSUIT has the characteristics (i) and (ii) and simulates gypsum equilibrium chemistry. Therefore, despite the last version of WATSUIT is 20 years old, it continues to be a benchmark for developing irrigation guidelines for salt-threatened soils. Once the leaching requirement is known, the required amount of irrigation water can be calculated by means of Eq. 1. Nevertheless, as weather varies from year to year how this amount of water has to be applied demands knowledge about soil water content. This knowledge can be based on meteorological data and soil water content measurements. All these in addition to farmers' experience should guide the application of irrigation water.

The model SALTIRSOIL was originally developed for the simulation of the annual average soil salinity in irrigated well-drained lands (Visconti et al., 2011b). It has characteristics similar to WATSUIT. The input data to the model included i) climate data such as monthly values of reference evapotranspiration (ET_0) and amount and number of days of rainfall, ii) water quality data such as yearly average concentrations of the main ions, iii) irrigation scheduling data such as monthly values of irrigation amount, number of irrigation days and percentage of wetted soil, iv) crop data such as monthly or season basal crop coefficients, percentage of canopy ground cover and sowing and harvest dates for annual crops, and finally v) chemical and hydrophysical soil data. The SALTIRSOIL was intended to be a predictive model, however, it can be used for irrigation and soil management. The best irrigation scheduling for keeping soil salinity below some critical value can be found batch running the same simulation while changing the irrigation rates and schedule.

Following the methodology just described the SALTIRSOIL model is useful to search for the most adequate irrigation rates and scheduling in order not to surpass an average-annual limit of soil salinity. This is interesting but it could be improved without any loss of the original applicability of the model, i.e. optimum ratio of information to data requirements. This has been done adapting the SALTIRSOIL algorithms for the monthly average calculation of soil salinity.

In the following the new algorithms implemented in SALTIRSOIL for the calculation of the monthly average soil salinity in irrigated well-drained lands, and the use of this new SALTIRSOIL, from now on referred to as the SALTIRSOIL_M model, for the development of optimum guidelines for soil, water and crop management in irrigated salt-threatened areas will be shown. These guidelines will be discussed in the framework of the different productive and environmental challenges irrigation faces in a relevant place in SE Spain.

2. SALTIRSOIL_M: A new tool to assess monthly soil salinity and for irrigation management in salt-threatened soils

The SALTIRSOIL was developed as a deterministic, process-based and capacity-type model. The development of the SALTIRSOIL model started from the characteristics that made the steady-state models WATSUIT (Rhoades & Merrill, 1976) and that of Ayers & Westcot (1985) so useful for the leaching requirement calculation and for assessing the water quality for irrigation.

Steady-state models for soil salinity start from the hypothesis that soil water and salt content keep constant through time. These conditions could only be true if water would continuously flow through soil. This is never the case because irrigation and rainfall are discontinuous processes. Modern transient-state models take into account the time variable, which makes them able to give accurate values of soil water and salt content as has been shown by Goncalves et al. (2006) for the HYDRUS model. Despite these advantages, transient-state models are seldom used outside of research applications because they demand data not available or difficult to obtain. The time variable can be, however, implemented in soil salinity steady-state models while preserving their basic assumptions. This has been shown by Tanji & Kielen (2002), and on a daily basis by Isidoro & Grattan (2011).

The original SALTIRSOIL model has been adapted for the monthly calculation of soil salinity to give the SALTIRSOIL_M model. Therefore the new SALTIRSOIL_M performs a water and salt balance in monthly steps. In the simulations the soil is divided in a number of layers selected by the user. In each simulation the water balance is calculated first, and then the soil solution concentration factor of the soil solution regarding the irrigation water in each layer. An average soil solution concentration factor for each month is calculated afterwards. The composition of the irrigation water each month is multiplied by the corresponding monthly average concentration factor and the calculation of the composition of the soil solution at different soil water contents and allowing to equilibrate with soil CO_2, calcite and gypsum is carried out. Finally the electrical conductivity at 25 ºC is assessed. The SALTIRSOIL model concepts for the annual calculation of the soil salinity have been described in detail elsewhere (Visconti et al., 2011b). Here only the calculations implemented in SALTIRSOIL_M for the monthly balance of salts in the soil solution are shown.

2.1 Monthly mass balance of salts in the soil solution

Let the soil be split in a number n of layers, and let the shallowest soil layer be the layer 1. The mass of a conservative solute in the solution of the layer 1 in the month i ($m_{i,1}$) can be calculated from Eq. 2.

$$m_{i,1} = m_{i-1,1} + I_i C_{Ii} - D_{i,1} C_{i,1} \quad (2)$$

Where $m_{i-1,1}$ is the mass of the solute in layer 1 the previous month (i – 1), I_i and $C_{i,1}$ are, respectively, the amount of irrigation water and the concentration of the conservative solute the month i, and $D_{i,1}$ and $C_{i,1}$ are the drainage from the layer 1, and the concentration of the solute in the soil water in that layer.

The concentration of the conservative solute in the soil solution of the layer 1 is obtained through Eq. 3 where the mass of the solute given by Eq. 2 has been divided by the average water content of that layer the month i ($V_{i,1}$).

$$C_{i,1} = C'_{i-1,1} + \frac{I_i C_{Ii}}{V_{i,1}} - \frac{D_{i,1} C_{i,1}}{V_{i,1}} \quad (3)$$

Equation 3 can be reorganized to isolate the concentration of the solute as a function of the rest of variables (Eq. 4).

$$C_{i,1} = \frac{C'_{i-1,1} V_{i,1} + I_i C_{Ii}}{V_{i,1} + D_i} \quad (4)$$

In Eq. 3 and Eq. 4 $C'_{i-1,1}$ is the mass of solute the previous month divided by the volume of soil water in that layer the present month i. This variable can be expressed in terms of the concentration of the solute in the layer 1 the previous month considering the quotient of the soil water the previous month and the present month (Eq. 5).

$$C'_{i-1,1} = C_{i-1,1} \frac{V_{i-1,1}}{V_{i,1}} \quad (5)$$

Eq. 5 is substituted in Eq. 4 and after dividing by C_{Ii} Eq. 6 is obtained for the calculation of the concentration factor of the soil solution in layer 1 the month i at average field water content ($f_{i,1} = C_{i,1} / C_{Ii}$).

$$f_{i,1} = \frac{f_{i-1,1} V_{i-1,1} \frac{C_{Ii-1}}{C_{Ii}} + I_i}{V_{i,1} + D_{i,1}} \quad (6)$$

Similarly to Eq. 2 the mass of a conservative solute in the soil water of a layer j ($j \neq 1$) is calculated with the following equation (Eq. 7).

$$m_{i,j} = m_{i-1,j} + D_{i,j-1} C_{i,j-1} - D_{i,j} C_{i,j} \quad (7)$$

Where $D_{i,j}$ and $D_{i,j-1}$ are respectively the drainage water the present month i from the layer j and from its overlying layer (j – 1), and $C_{i,j}$ and $C_{i,j-1}$ are the solute concentration the present month i in the layer j and in its overlying layer j - 1. Following similar steps to those heading to Eq. 6 we get to Eq. 8 for the calculation of the concentration factor of a conservative solute in the soil water of a layer j in the month i.

$$f_{i,j} = \frac{V_{i-1,j} f_{i-1,j} \frac{C_{Ii-1}}{C_{Ii}} + D_{i,j-1} f_{i,j-1}}{V_{i,j} + D_{i,j}} \quad (8)$$

2.2 Development of irrigation recommendations: A case study for several crops in the traditional irrigated area of *Vega Baja del Segura* (SE Spain)

The SALTIRSOIL_M model has been used to develop irrigation recommendations in the relevant traditional irrigated district of *Vega Baja del Segura* (SE Spain).

The *Segura* River and *Baix Vinalopó* lowlands together represent one of the most important agricultural areas in Spain. More than 90% of the land is irrigated and approximately 80% of it is salt-affected (de Paz et al., 2011). The main crops that cover 61% of the irrigated area are citrus such as orange, mandarin and Verna lemon (*Citrus sinensis*, *Citrus reticulata* and *Citrus limon* (L) Burm f.) grafted onto various different rootstocks. The moderately salt-tolerant Sour Orange (*Citrus aurantium* L.) and especially Cleopatra mandarin (*Citrus reshni Hort. ex Tan.*) are used as rootstocks for more than 60% of citrus. Vegetables (including tubers) cover 16% of the area. These are globe artichoke (*Cynara scolymus* L.), lettuce (*Lactuca sativa* L.), melon (*Cucumis mello* L.), broccoli (*Brassica oleracea*, Botrytis group), and potato (*Solanum tuberosum* L.). Non-citrus fruit trees cover 12% of the area, specifically almond (*Prunus dulcis*), pomegranate (*Punica granatum* L.) and date palm (*Phoenix dactylifera* L.).

The *Segura* River and *Baix Vinalopó* lowlands comprise several irrigation districts, each one of them featured by different irrigation systems, crops and water supplies. The traditional irrigation district of *Vega Baja del Segura* (Fig. 3) is one of the most important because of the use of water resources, which has been estimated between 80 and 120 hm^3 yr^{-1} (Ramos, 2000), number of farmers, productivity, history and the large stretch of land, which amounts up to approximately 20000 ha from which 15000 ha are actually irrigated each year (MMA, 1997). The average Penman-Monteith reference evapotranspiration and precipitation are 1215 and 385 mm yr^{-1}, respectively. In this irrigation district the distribution of horticultural and tree crops is 70-30% (MMA, 1997). The main irrigation water supply in the irrigation district is the *Segura* River itself. Although new irrigation projects use drip systems, at least 50% of the area is still irrigated by surface.

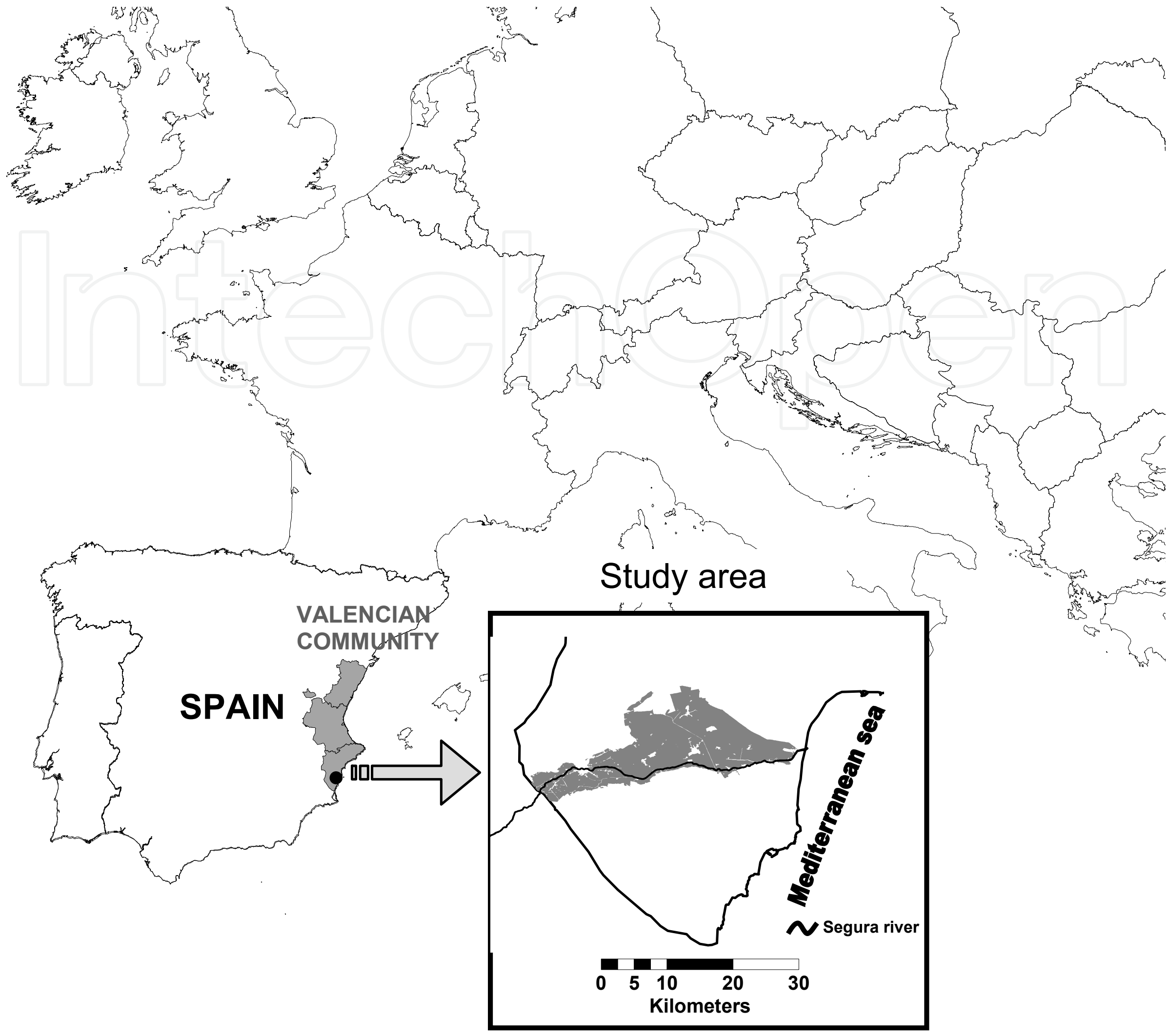

Fig. 3. Location of the Traditional Irrigation Area of the *Vega Baja del Segura*

Month	pH	Alk.	Na^+	K^+	Ca^{2+}	Mg^{2+}	Cl^-	NO_3^-	SO_4^{2-}	EC_{25}
Jan	7.75	5.75	20.84	0.52	6.24	5.87	17.22	0.59	9.62	3.91
Feb	7.77	5.85	21.84	0.50	7.22	6.93	19.53	0.52	11.33	4.19
Mar	8.10	5.42	20.76	0.57	7.34	7.09	21.81	0.66	12.41	4.41
Apr	7.85	5.81	24.67	0.63	7.49	7.47	24.14	0.51	12.03	4.92
May	7.80	5.78	22.13	0.45	6.60	6.77	20.27	0.34	9.77	4.49
Jun	7.48	5.03	16.94	0.44	5.80	5.74	16.87	0.22	9.56	3.51
Jul	7.50	5.93	39.71	0.68	7.13	8.21	39.83	0.38	12.42	6.39
Aug	7.63	5.16	30.42	0.48	5.81	6.23	28.10	0.38	10.92	4.89
Sep	7.78	4.69	16.65	0.40	5.03	5.16	15.25	0.24	7.90	3.38
Oct	7.60	5.37	27.15	0.60	6.82	6.68	23.77	0.65	11.52	4.46
Nov	7.88	4.96	19.86	0.52	5.88	5.88	17.49	0.65	10.19	3.87
Dec	7.64	5.02	20.58	0.52	6.54	6.54	18.80	0.64	11.15	4.09
Avg.	7.73	5.40	23.46	0.53	6.49	6.55	21.92	0.48	10.73	4.37

Table 1. Monthly characteristics of the Segura River water during the three year period 2007-2009. All ion concentrations in mmol L^{-1}, EC_{25} in dS m^{-1} and alkalinity (Alk.) in $mmol_C$ L^{-1}

The *Segura* River goes through the traditional irrigated district of *Vega Baja del Segura*, and there exhibits annual averages of electrical conductivity at 25 ºC (EC_{25}) and SAR of 4.3 dS m^{-1} and 6.3 (mmol $L^{-1})^{1/2}$, respectively. However, the EC_{25} and SAR remarkably fluctuate through the year (Table 1) following the cycle of water releases from upstream dams (Ibáñez & Namesny, 1992). From late autumn till mid spring water is slowly released from dams to maintain environmental flow, which includes winter irrigation. Important water releases start in spring, and along with them the EC_{25} slightly increases because the low EC_{25} water (≈ 1.2 dS m^{-1}) of the upstream dams helps sweep the outfalls from the sewage treatment plants and irrigation returns through a river that otherwise presents a constant but low base-flow. The next months, the EC_{25} decreases until it reaches a minimum in June. During July the EC_{25} increases again because the irrigation returns from upstream lands increase the river flow and because water releases stop during this month. In late July and early August the important water releases resume and the EC_{25} decreases again until it reaches another minimum in September. Then the important water releases stop until the next year and the EC_{25} attains a maximum during October because of the autumn rainfalls. This is the most important rainfall season in the area and it effectively leaches the salts from the lands as the increase in the EC_{25} of the river shows. Because of the correlation between electrical conductivity and sodium adsorption ratio in the *Segura* River the SAR follows a parallel fluctuation to the EC_{25}.

2.2.1 Set up of simulations

The soil saturation extract composition of the soils of the *Vega Baja del Segura* was simulated with SALTIRSOIL_M under ten different crops. These were three horticultural crops and seven tree crops. The horticultural crops were globe artichoke, grown from October 1st until July 8th, and rotation of melon and broccoli, from September 14th until January 27th, and melon also from April 1st until August 19th and potato from September 14th until January 22nd. The tree crops were date palm, sweet orange, lemon grafted onto sour orange, lemon grafted onto Mandarin Cleopatra, lemon grafted onto *Cytrus Macrophylla*, Verna lemon and pomegranate. These ten crops are representative of at least 75% of the agriculture of the *Vega Baja del Segura* and according to their threshold-slope functions of yield against electrical conductivity of the saturation extract (EC_{se}) they exhibit different tolerances to soil salinity (Figure 4). Except for date palm and globe artichoke which are from moderately tolerant to tolerant, the rest of crops are moderately sensitive to soil salinity. Pomegranate is between moderately sensitive to moderately tolerant defining in fact the limit between both categories. The data on soil, climate, threshold-slope functions and basal crop coefficients used in the simulations can be found in Visconti et al. (2012).

Simulated crop	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Tot**
Artichoke	1	25	32	70	89	81	31	7	0	0	4	0	339
Mel.-Broccoli	0	0	0	34	65	110	122	68	0	0	8	2	410
Melon-Potato	0	0	0	34	65	109	121	68	0	0	20	6	423
Date palm	2	23	27	73	97	135	139	122	22	0	18	3	660
Sweet orange	0	15	14	50	65	90	98	93	1	0	13	0	440
Lemon trees	0	9	4	39	51	81	84	72	0	0	7	0	347
Pomegranate	0	0	0	44	66	102	106	92	2	0	2	0	415

Table 2. Crop water requirements in mm calculated with SALTIRSOIL

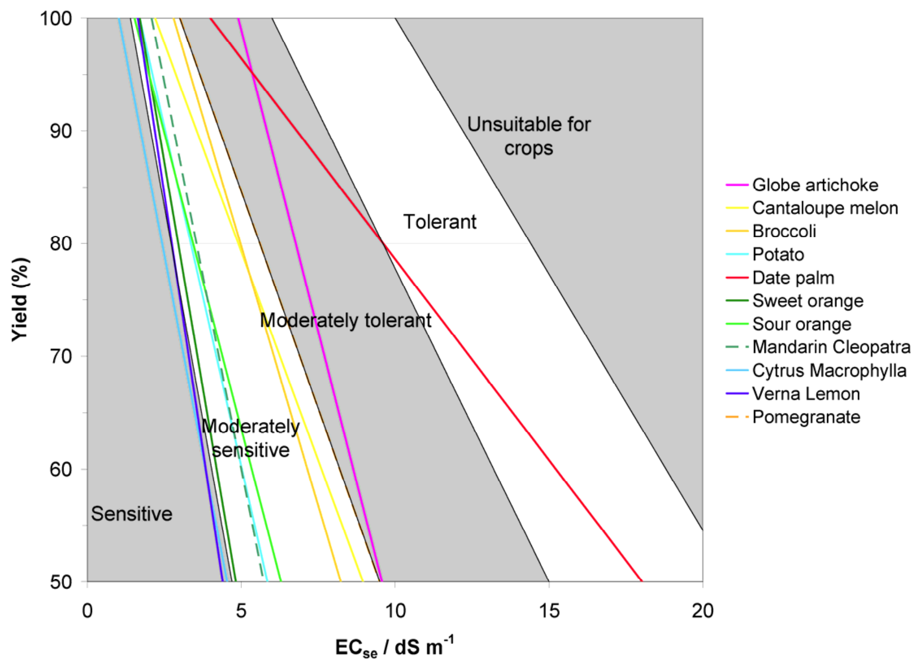

Fig. 4. Threshold-slope functions of yield versus electrical conductivity of the soil saturation extract (EC_{se}) for the crops simulated with SALTIRSOIL_M in the *Vega Baja del Segura.* Categories after Maas & Hoffman (1977)

For each one of the crops the annual leaching requirement was assessed in the following way. The crop water requirement, i.e. the crop evapotranspiration, was first calculated with the SALTIRSOIL (Table 2). Then starting with the simulation in which the irrigation dose was set equal to between – 50 to – 30% of the crop water requirement, several simulations were carried out gradually increasing the annual irrigation water amount in 5% steps. Once the batch of simulations was finished the monthly values of EC_{25} in each simulation were averaged to obtain the corresponding annual EC_{25}. As the annual LF is also calculated by the SALTIRSOIL_M, this allowed us to have the graph of annual EC_{se} against LF. The electrical conductivity for 90% yield, which is called EC_{90}, was then calculated from the corresponding threshold-slope functions (Fig. 4). For the horticultural crop rotations the EC_{90} was calculated for both crops, and the value for the most sensitive was used, i.e. the lower EC_{90}. These were melon and potato for the melon-broccoli and melon-potato rotations respectively. The values of EC_{90} (Table 3, second column) were then interpolated in their corresponding graphs of annual EC_{se} against LF to obtain the annual leaching fraction for 90% yield (LF_{90}). This value was taken as the leaching requirement, i.e. LR = LF_{90}.

2.2.2 Results of the simulations

The leaching requirements calculated with the SALTIRSOIL_M were between 0.08 and more than 0.99 (Table 3, last column). The moderately tolerant to tolerant globe artichoke and date palm presented leaching requirements of 0.08 and 0.09 respectively. The moderately sensitive to tolerant pomegranate presented a leaching requirement of 0.19. The melon-potato, sweet orange, lemon grafted onto sour orange and onto *Cytrus Macrophyla*, and Verna lemon presented values higher than 0.99. This means that a yield of at least 90% can not be achieved for these crops in the area when irrigating with *Segura* River water. With a leaching requirement of 0.75 the only citrus that could be grown for at least 90% yield with *Segura* River water would be those grafted onto the Mandarin Cleopatra rootstock. With a leaching requirement of 0.50 the succession of melon and broccoli could also be grown for at least 90% yield.

The results of the SALTIRSOIL_M model for the annual leaching requirement were compared with previously calculated leaching requirements with the WATSUIT and the SALTIRSOIL models (Visconti et al., 2012). The SALTIRSOIL_M calculates lower leaching requirements than the SALTIRSOIL as is shown in Table 3. The leaching requirements calculated with SALTIRSOIL_M are also lower than the corresponding values calculated with WATSUIT when dealing with the moderately sensitive to tolerant crops. When dealing with moderately sensitive crops the leaching requirements calculated with SALTIRSOIL_M are higher than the values calculated with WATSUIT.

Simulated crop	EC_{90} / dS m^{-1}	WATSUIT	SALTIRSOIL	SALTIRSOIL_M	
			Surface	Surface	Drip
Globe artichoke	5.83	0.13	0.10	0.08	0.07
Melon-broccoli	3.55	0.42	0.67	0.50	0.47
Melon-potato	2.53	0.79	> 0.99	> 0.99	> 0.99
Date palm	6.80	0.09	0.09	0.09	0.08
Sweet orange	2.33	0.92	> 0.99	> 0.99	> 0.99
Lemon onto SO	2.48	0.82	> 0.99	> 0.99	> 0.99
Lemon onto MC	2.81	0.65	> 0.99	0.75	0.73
Lemon onto CM	1.72	> 0.99	> 0.99	> 0.99	> 0.99
Verna Lemon	2.19	> 0.99	> 0.99	> 0.99	> 0.99
Pomegranate	4.30	0.27	0.25	0.19	0.17

Table 3. Electrical conductivities for 90% yields (EC_{90}) and corresponding leaching requirements calculated with the WATSUIT, SALTIRSOIL and SALTIRSOIL_M models

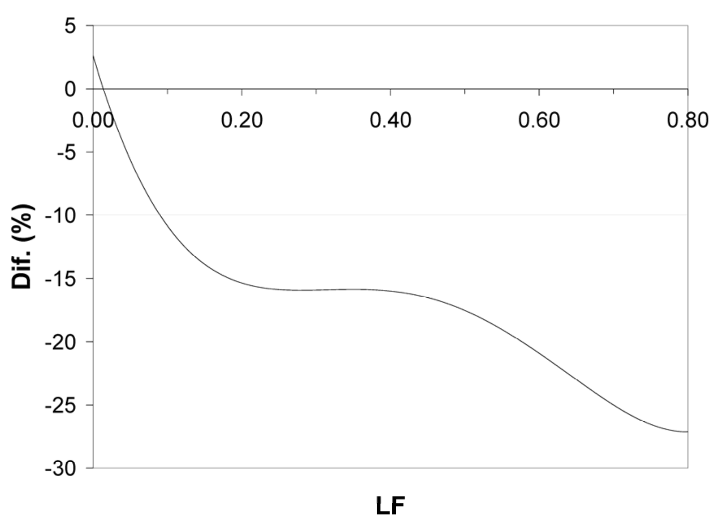

Fig. 5. Average percentage difference (Dif. (%)) between the EC_{se} calculated with SALTIRSOIL and SALTIRSOIL_M as a function of the leaching fraction (LF)

The SALTIRSOIL_M calculates average annual soil salinities between 10 and 30% lower than the SALTIRSOIL as is shown in Fig. 5. Transient-state models calculate lower soil salinities than steady-state models (Corwin et al., 2007). This fact makes the leaching requirements calculated with transient-state models to be lower than the leaching requirements calculated with steady-state models (Corwin et al, 2007; Letey et al., 2011). The implementation of the time variable as simple monthly steps in the SALTIRSOIL_M model has suffice to have soil salinities very similar to those calculated with other more complex and data-demanding transient-state models.

2.2.3 Proposal of irrigation recommendations

The irrigation requirements for the crops for which the 90% yield is achievable are between the 357 mm yr^{-1} of the moderately tolerant artichoke and the 2345 mm yr^{-1} of the moderately sensitive lemon grafted onto the Mandarin Cleopatra rootstock (Table 4). According to the *Segura* Valley Authority (MMA, 1997) and Ramos (2000) the average availability of water for irrigation from the *Segura* River in the traditional irrigated area of *Vega Baja del Segura* can be estimated between 530 and 800 mm yr^{-1}. Assuming that the maximum availability of irrigation water from the *Segura* River is never going to be higher than 800 mm yr^{-1}, the resulting soil salinity (EC_{se}) would be between the EC_{90} of the tolerant date palm (6.8 dS m^{-1}) and the 3.2 dS m^{-1} of the lemon trees (Table 4). The surface weighted average soil salinity would result to be 4.4 dS m^{-1}, with a monthly maximum of 7.3 dS m^{-1} for date palm orchards and a minimum of 2.8 dS m^{-1} for lemon trees orchards. Given this availability of water for irrigation the surface weighted average yield would be 82% with a minimum of 63% for sweet orange orchards. These yields would be achieved with an average 683 mm yr^{-1} of water, i.e., 102 hm^3 yr^{-1} for the whole irrigation district.

In the traditional irrigated area of *Vega Baja del Segura* almost all of the land is equipped with underground pipelines to collect of the waters that percolate through the rooting depth. The drainage waters are disposed by means of a hierarchical system of canals. The major canals are called *azarbes* and they go through the *Vega Baja* more or less parallel to the *Segura* River bed until they pour into the river mouth itself. According to the SALTIRSOIL_M calculations the drainage effluents from the traditional irrigated area of the *Vega Baja del Segura* would be between 61 and 513 mm yr^{-1}, with a surface weighted average of 338 mm yr^{-1}. This would amount to 51 hm^3 yr^{-1} of drainage effluents from the whole district. These drainage effluents would present a salinity (EC_{dw}) between 7 and 24 dS m^{-1}, while the sodicity (SAR_{dw}) would be between 9 and 24 (mmol L^{-1})$^{1/2}$ with weighted averages of 8.3 dS m^{-1} and 10.4 (mmol L^{-1})$^{1/2}$, respectively. These drainage effluents are, thus, high in EC and SAR and become an environmental concern. In spite of their salinity and sodicity, along their way through the district the irrigation returns from upstream lands are usually used again for irrigation (Abadía et al., 1999). Accordingly, on the one hand the district's irrigation water requirement would be less as an important part of the drainage water is reused, and on the other hand, the irrigation application in the moderately tolerant to tolerant crops in the area, i.e. artichoke, date palm and pomegranate, should increase a bit in order to have drainage effluents lower in salts and sodium. It is reasonable to think that both facts would compensate each other and the appropriate irrigation requirement for the whole area should not be less than 102 hm^3 yr^{-1}. Regarding the citrus trees the moderately sensitive sweet and *Cytrus Macrophyla* oranges and Verna lemon should be grafted onto more tolerant rootstocks such as Mandarin Cleopatra, sour orange and other similar to these. With these rootstocks citrus yields of 80-85% would be achievable with just 800 mm yr^{-1} of Segura River water. These little decrements in citrus yields are usually reflected in decreased average fruit size, however, they are also accompanied by higher juice sugar and acid contents (Grieve et al., 2007). Increments in fruit quality with slight salinity stress have been described for other fruits including melon (Bustan et al., 2005).

The traditional irrigated area of *Vega Baja del Segura* has been irrigated by surface for centuries. Nevertheless, since the early nineties localized irrigation systems are slowly replacing them. Localized irrigation systems are characterized by i) more frequent irrigations, ii) less water application in each irrigation, and iii) less wetted area. The effect of these three variables can be simulated with SALTIRSOIL and SALTIRSOIL_M.

Drip irrigation was simulated in SALTIRSOIL_M decreasing the wetted soil area from 40% to 3% and multiplying the number of irrigation days a year by 6. The irrigation amount was kept constant.

Simulated crop	IR_{90}	I_{rec}	ET_a	D	EC_{se}	EC_{se}min	EC_{se}max	Y(%)	EC_{dw}	SAR_{dw}
Globe artichoke	357	357	681	61	5.83	5.17	6.64	90	17.7	18.0
Melon-broccoli	1066	800	731	453	3.92	3.37	4.57	87	7.48	9.79
Melon-potato	—	800	748	437	3.97	3.36	4.61	73	7.68	9.93
Date palm	744	744	1032	97	6.80	6.55	7.26	90	23.9	24.3
Sweet orange	—	800	801	383	4.04	3.45	4.60	63	8.84	10.9
Lemon onto SO	—	800	672	513	3.22	2.75	3.82	82	7.27	9.41
Lemon onto MC	2345	800	674	510	3.22	2.75	3.82	84	7.27	9.41
Lemon onto CM	—	800	672	513	3.22	2.75	3.82	69	7.27	9.41
Verna Lemon	—	800	672	513	3.22	2.75	3.82	71	7.27	9.41
Pomegranate	528	528	736	177	4.30	3.55	5.04	90	11.5	13.1
AVERAGES	—	[a]683	[a]729	[a]338	[a]4.40	—	—	[a]82	[b]8.3	[b]10.4

[a]Surface weighted average (70% horticultural, 30% trees), [b]Surface and drainage weighted average

Table 4. Irrigation requirement for 90% yield (IR_{90}), recommended irrigation (I_{rec}), actual evapotranspiration (ET_a), and drainage (D) all in mm yr^{-1}, EC (dS m^{-1}) and SAR ((mmol $L^{-1})^{1/2}$) of the saturation extract and of the drainage water calculated for surface irrigation

The leaching requirement for drip irrigation slightly decreases regarding surface irrigation as is shown in Table 3. This occurs because drip irrigation minimizes the evaporation of water from the soil. Therefore, the actual evapotranspiration would drop from 729 to 683 mm yr^{-1} (Table 4 and Table 5), thus increasing the drainage from 338 to 369 mm yr^{-1}. If the whole irrigation district used drip irrigation systems the irrigation water demand would drop to 667 mm yr^{-1}, i.e., 100 hm^3 yr^{-1}. The soil salinity would also drop to 4.3 dS m^{-1}, with a maximum of 7.5 dS m^{-1} and a minimum of 2.6 dS m^{-1}. Furthermore the yields for citrus would rise and the overall average relative yields would keep or increase. On the other hand the amount of drainage effluents would rise to 55 hm^3 yr^{-1} with average electrical conductivity and sodium adsorption ratio of 8.4 dS m^{-1} and 10.8 (mmol $L^{-1})^{1/2}$, i.e., with salinity and sodicity slightly higher than when using surface irrigation systems.

Simulated crop	IR_{90}	I_{rec}	ET_a	D	EC_{se}	EC_{se}min	EC_{se}max	Y(%)	EC_{dw}	SAR_{dw}
Globe artichoke	317	317	649	52	5.83	5.09	6.71	90	19.30	19.2
Melon-broccoli	820	800	677	508	3.67	3.03	4.35	89	6.99	9.35
Melon-potato	—	800	694	491	3.72	2.99	4.40	76	7.14	9.46
Date palm	688	688	986	87	6.80	6.47	7.51	90	24.52	24.9
Sweet orange	—	800	730	454	3.70	3.04	4.33	68	7.85	9.73
Lemon onto SO	—	800	632	553	3.12	2.60	3.73	83	6.93	9.12
Lemon onto MC	2024	800	631	554	3.12	2.60	3.73	86	6.93	9.12
Lemon onto CM	—	800	632	553	3.12	2.60	3.73	70	6.93	9.12
Verna Lemon	—	800	632	553	3.12	2.60	3.73	73	6.93	9.12
Pomegranate	435	435	683	136	4.30	3.52	5.29	90	12.21	13.9
AVERAGES	—	[a]667	[a]683	[a]369	[a]4.26	—	—	[a]83	8.4	10.8

[a]Surface weighted average (70% horticultural, 30% trees), [b]Surface and drainage weighted average

Table 5. Irrigation requirement for 90% yield (IR_{90}), recommended irrigation (I_{rec}), actual evapotranspiration (ET_a), and drainage (D) all in mm yr^{-1}, EC (dS m^{-1}) and SAR ((mmol $L^{-1})^{1/2}$) of the saturation extract and of the drainage water calculated for drip irrigation

3. Conclusion

Modern irrigation faces a problem of optimization to attain maximum agricultural profitability with minimum damage to natural resources. This demands a precise use of water in the fields, which can be carried out combining i) modelling with ii) monitoring of soil water and salinity, and with iii) irrigation manager or advisor experience. Validated soil salinity models can assist on the development of optimum guidelines for the use of water in salt-threatened areas. The SALTIRSOIL_M model has been developed from the SALTIRSOIL model for the calculation of soil solution major ion composition, pH and electrical conductivity in monthly steps. The time variable has been included in the SALTIRSOIL_M preserving the original capabilities of the SALTIRSOIL model, i.e. maximum reliability-to-data-requirements. In fact no additional data is needed to run SALTIRSOIL_M regarding the original SALTIRSOIL. Just as occurred with the SALTIRSOIL more accurate results can be obtained if detail data on soil layers and monthly water composition is provided to the model. With such simple extension the SALTIRSOIL_M model provides lower leaching requirements. Therefore, similar leaching requirements, and hence, irrigation requirements, to those calculated with more complex transient-state soil salinity models.

The SALTIRSOIL_M model can be used to help develop irrigation guidelines. As such it was used for the important traditional irrigation district of *Vega Baja del Segura* (SE Spain). This is located in the lower basin of the Segura River, which lower reaches are featured by high salinity. This is therefore a salt-threatened area. According to the simulations carried out with some of the most important irrigated crops in the district, irrigation could be indefinitely go on without loss of agricultural profitability and preserving natural water quality and amount providing the following recommendations are observed: i) use of 100 hm^3 yr^{-1} of Segura River water to irrigate the 15000 ha of land in the district, i.e, an average of 670 mm yr^{-1}, ii) use of tolerant rootstocks for citrus growth, iii) replacement of surface by localized irrigation systems, iv) maintenance of the system of canals to dispose of the drainage effluents.

The data from soil water and salinity probes along with the irrigation manager or advisor experience should then be used to precisely adapt such guidelines to the plot and plant scales. Soil salinity models are, therefore, the key factor in the development of decision support systems for the sustainable use of water in irrigated areas.

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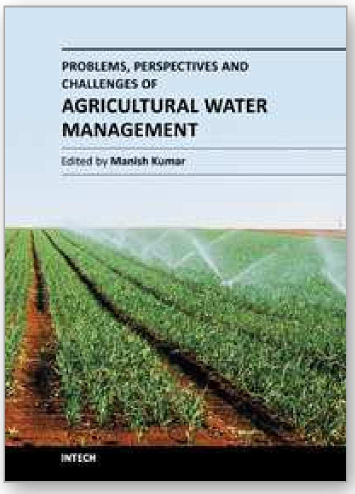

Problems, Perspectives and Challenges of Agricultural Water Management
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Food security emerged as an issue in the first decade of the 21st Century, questioning the sustainability of the human race, which is inevitably related directly to the agricultural water management that has multifaceted dimensions and requires interdisciplinary expertise in order to be dealt with. The purpose of this book is to bring together and integrate the subject matter that deals with the equity, profitability and irrigation water pricing; modelling, monitoring and assessment techniques; sustainable irrigation development and management, and strategies for irrigation water supply and conservation in a single text. The book is divided into four sections and is intended to be a comprehensive reference for students, professionals and researchers working on various aspects of agricultural water management. The book seeks its impact from the diverse nature of content revealing situations from different continents (Australia, USA, Asia, Europe and Africa). Various case studies have been discussed in the chapters to present a general scenario of the problem, perspective and challenges of irrigation water use.