SALTIRSOIL: A simple integrated simulation model for the prediction of soil salinisation in agricultural irrigated well-drained lands

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Abstract
SALTIRSOIL (SALTs in Irrigation SOILs) is a soil salinisation model able to make accurate predictions of soil salinity, sodicity and alkalinity at soil water saturation using no more information than that obtained during most regular land surveys. It is a deterministic, static and functional (capacity-type) process-based model composed in turn of two main modules. The first one calculates the soil water balance through the year, and hence the soil solution concentration factor with regard to the irrigation water. Next, the irrigation water major ion composition is multiplied by this factor and then, the second module, called SALSOLCHEM, calculates the major inorganic ion composition of the soil solution at equilibrium with soil calcite and gypsum at the soil CO_2 partial pressure. The SALTIRSOIL algorithms were verified by simulating two horticultural crop developments in a fine to medium texture heavily calcareous soil under a semi-arid Mediterranean climate. The quotients of electrical conductivity at saturation to electrical conductivity in the irrigation water were 1.68 and 1.60 respectively. These quotients of EC_{25} are very close to the value of 1.5 used in the development of FAO guidelines for irrigation water assessment.

Key Words
Soil salinisation, agricultural modelling, irrigation, SALTIRSOIL model.

Introduction
When waters are applied to soils for irrigation, the salts they carry 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. However, 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 naturally 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. With the water table under control or deep enough, the salt concentration in the equilibrium point depends on the irrigation water salinity as well as on climate (evapotranspiration and rainfall) and irrigation water amounts, being independent from groundwater depth and salinity.
The guidelines for water quality classification for irrigation purposes are often specified as 2D-plots where the salinization and sodication risks are jointly evaluated graphing the electrical conductivity at 25ºC (EC_{25}) and the sodium adsorption ratio (SAR) on the the *x* and *y* axes respectively. The guidelines are the summary of models able to predict the salinization and sodication of soils assumming average climate and conditions of use. Ayers and Westcott (1985) based the FAO guidelines on a model which gave as a result that the saturation extract concentrates 1.5 times regarding the irrigation water. This condition is expressed by equation 1 where $\overline{C_{\mathrm{SE}}}$ is the average salt concentration of the soil water at saturation and C_{I} is the salt concentration of the irrigation water.

$$f_{\mathrm{SE}} = \frac{\overline{C_{\mathrm{SE}}}}{C_{\mathrm{I}}} = 1.5 \qquad (1)$$

However, wherever climate, soil and management conditions significantly different from those under which the guidelines were derived are met, they should be changed.
The aims of this work are to outline the model conceptualization, development and verification of algorithms, and computer implementation of a new easy-to-use low-data-demanding model called SALTIRSOIL designed to predict the average electrical conductivity and composition of salts in the mid to long term in the soil solution of irrigated well-drained lands.

Model development

Model conceptualization of SALTIRSOIL

SALTIRSOIL (Visconti *et al* 2006; Visconti 2009) is a deterministic, static and functional (capacity-type) process-based model which calculates the major inorganic ion composition and electrical conductivity at 25ºC in the soil solution at water saturation. Specifically, SALTIRSOIL is composed of two primary modules (Figure 1).

Module A calculates the soil water balance and as a consequence the relative concentration of the soil solution at field capacity with regard to the irrigation water. This variable, called the concentration factor at field capacity (f_{FC}), is an average value calculated from the soil surface to the specific soil depth chosen by the user. Provided the soil water content at field capacity and at saturation are known, the concentration factor at saturation is calculated (f_{SE}). The concentrations of the major inorganic ions in the irrigation water are multiplied by the concentration factor at saturation. The concentrations obtained from this calculation are used to feed a chemical equilibrium module called SALSOLCHEM (SALine SOLution CHEMistry). SALSOLCHEM calculates the major inorganic ion concentrations at equilibrium in the soil solution. Finally, the electrical conductivity at 25 ºC is calculated from this composition using the equation developed by Visconti (2009).

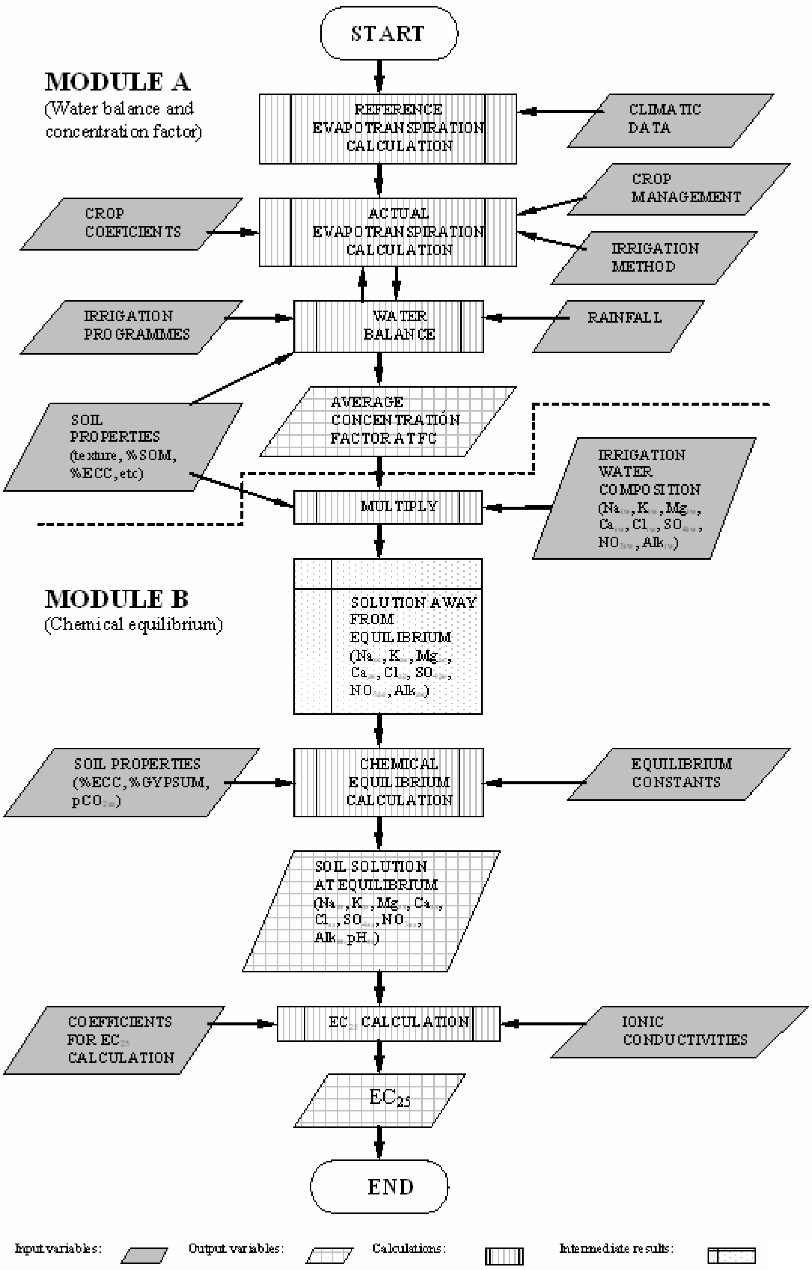

Figure 1. Flowchart of SALTIRSOIL.

Soil solution concentration factor and electrical conductivity

The average relative concentration of a conservative solute with regard to the irrigation water at field capacity (f_{FC}) can be calculated by means of equation 2, and at saturation by means of equation 2 and 3. Equation 2, where I and R stand for the annual irrigation and rainfall amounts, ET_j for the evapotranspiration from layer j, and n for the number of layers, has been obtained taking the approach that the concentration factor of each soil layer is equal to the concentration factor of the drainage water from that layer, and then calculating the mean concentration factor of the n soil layers in which the soil has been formally split. As the number of soil layers increases, this assumption is more reasonable. In equation 3 θ_{gFC} and θ_{gSE} stand for the gravimetric water content at field capacity and saturation respectively.

$$f_{FC} = \frac{\overline{C_{FC}}}{C_I} = \frac{I}{n}\sum_{i=1}^{n}\frac{1}{I+R-\sum_{j=1}^{i}ET_j} \quad (2) \qquad f_{SE} = \frac{\theta_{gFC}}{\theta_{gSE}} f_{FC} \quad (3)$$

The electrical conductivity of the soil solution in SALTIRSOIL is calculated from the major inorganic ion concentrations according to equation 4 (Visconti 2009).

$$EC_{25} / \mathrm{dS\,m^{-1}} = \left[0.21 + 0.681\left(\sum_{i=1}^{n}|z_i|\lambda_i^0[i]\right)\right] \pm 0.28 \qquad (4)$$

Where $|z_i|$ is the charge of ion i in absolute value in units of $mmol_C$/mmol, $[i]$ is the free ion concentration of ion i in units of mmol /L, and λ_i^0 is the ionic conductivity at the limit of infinite dilution of ion i in units of S $cm^2/mmol_C$.

Computer implementation

SALTIRSOIL has been written in Visual Basic 6.0© in a modular way. The climatic, irrigation, crop and soil data are stored in several sheets within a Microsoft Excel© workbook with a predetermined structure, which can be read by SALTIRSOIL. The reference evapotranspiration is calculated first, then the crop evapotranspiration and then the water balance, which is used to calculate the actual crop evapotranspiration afresh. This calculation is repeated until convergence is reached. Once the terms of the water balance are known, the average concentration factor at field capacity is calculated by means of equation 2. Knowing the soil water content at field capacity and at saturation, the concentration factor at this water content is also calculated with equation 3. The major ion concentrations in the irrigation water are multiplied by the concentration factor of interest, and the major ion concentrations at equilibrium with calcite, gypsum and CO_2 are calculated with the chemical equilibrium module SALSOLCHEM. SALTIRSOIL reads the values of the thermodynamic equilibrium constants from a sheet within the same Microsoft Excel© workbook. Finally the electrical conductivity at 25 ºC is also calculated by means of equation 4 using the apropriate data stored in another sheet within the Excel© workbook.

In SALTIRSOIL, an easy-to-use graphical user interface (GUI) has been designed with which the user controls the running of the simulations.

Results and discussion

Water balance and calculation of the soil solution concentration factor

SALTIRSOIL was applied to the calculation of the water balance and soil solution concentration factor at field capacity and at saturation. Two simulations were carried out with. Simulation 1 is the growing of a sweet melon crop, and simulation 2 is the consecutive growing of two crops: sweet melon and potato. A fine to medium texture heavily calcareous soil under a semi-arid Mediterranean climate was used. In both simulations the soil was split in 64 discrete layers.

The concentration factor of salts in the soil solution at field capacity (f_{FC}) in simulation 1 is equal to 3.10, which is higher than in simulation 2, in which is 2.83 (Table 1). This fact is shown on the concentration factor at saturation, which is 1.85 in the simulation 1 and 1.69 in simulation 2 (Table 1). The soil solution concentration factor at field capacity provided by a leaching fraction of 0.15-0.20 can be assumed to be equal to 3 according to Ayers and Westcot (1985). This value is bracketed by those found in our simulations. Nevertheless, the resulting concentration factors at saturation (in the saturation extract) in our simulations though similar, are significantly higher than the value given by Ayers and Westcot (1985), which is 1.5.

Major ion composition and electrical conductivity

Simulations 1 and 2 were finished including the irrigation water quality to calculate the major ion composition and electrical conductivity of the saturation extract (Table 2). The equilibrium constants and other data are given in Visconti (2009). An apparent CO_2 partial pressure equal to $10^{-3.07}$ atm for the saturated paste was also used.

Table 1. Summary of simulations 1and 2.

variable	Simulation 1	Simulation 2
Rainfall / mm /year	255	255
Irrigation / mm /year	400	520
ET_a / mm /year	558	631
Drainage / mm /year	98	144
ET_a / ET_c	0,82	0,88
$D/(R + P)$	0,15	0,19
f_{FC}	3,10	2,83
f_{SE}	1,85	1,69

Table 2. Average soil solution composition* in the saturation extract except the pH, for which the value in the saturated paste was calculated.

Simulation	Na	K	Ca	Mg	Cl	NO_3	SO_4	Alk	pH_{sp}	EC_{25}	EC_{se}/EC_{iw}
1	27,0	0,7	17,6	9,3	24,4	0,4	21,8	1,04	7,78	5,43	1,68
2	24,6	0,7	17,4	8,5	22,3	0,4	21,3	1,02	7,77	5,16	1,60

*All ion concentrations in mmol /L, Alk in $mmol_C$ /L and EC_{25} in dS /m.

The average electrical conductivity of the saturation extract in simulation 1 was 5.4 dS /m, whereas in simulation 2 was 5.2 dS /m. The quotient of electrical conductivity of the saturation extract to the irrigation water (EC_{se}/EC_{iw}) is equal to 1.68 in simulation 1 and 1.60 in simulation 2. Both values are lower than the respective salt concentration factors (Table 1, bottom row). The quotients EC_{se}/EC_{iw} are closer than the concentration factors to the value of 1.5 used by Ayers and Westcot (1985) to develop the FAO guidelines.

Conclusions

Two horticultural crop developments in a fine-to-medium texture heavily calcareous soil, under a semi-arid Mediterranean climate were simulated with SALTIRSOIL. Both simulations gave similar soil solution concentration factors at saturation with regard to the irrigation water. The quotients of electrical conductivity at saturation to electrical conductivity in the irrigation water were somewhat higher but very similar to the value of 1.5 used in the development of FAO guidelines for irrigation water assessment.

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