The Abdus Salam
International Centre for Theoretical Physics

United Nations
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International Atomic
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SMR.1674- 22

COLLEGE on SOIL PHYSICS

12 - 30 September 2005

Modeling and Evaluation of Salinization Risks

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MODELING AND EVALUATION OF SALINIZATION RISKS

Practical use of the Pla model to evaluate salinization risk in irrigated land of the Valencia region (Spain)

(Paz, J.M., F. Visconti, R. Zapata & J. Sánchez. 2004. Integration of two simple models in a geographical information system to evaluate salinization risk in irrigated land of the Valencian Community, Spain. Soil Use and Management 20:333-342.)

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Soil Use and Management (2004) **20**, 333–342 DOI: 10.1079/SUM2004265

Integration of two simple models in a geographical information system to evaluate salinization risk in irrigated land of the Valencian Community, Spain

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Abstract. Salt affected soil is one of the main problems decreasing the productivity of irrigated agriculture in the Mediterranean area. Simulation models in combination with geographical information systems (GISs) could be used to evaluate the risk of salinization at a regional scale. In this study, two logical models (Pla and Riverside) were combined in a GIS to evaluate the risk of soil salinity and sodicity in the irrigated agriculture of the Valencian Community, Spain. Simple models were chosen so that they could be used at a regional scale. Before running them in a GIS framework, a soil and irrigation water survey was conducted to validate the models with observed data. The Pla model fitted observed data better than Riverside guidelines, probably because parameters of water quality, soil and climate were considered by the Pla model. The resulting maps indicated that the soils most affected by salts are those located in the south of study area, owing to the arid climate, and those areas near the coast due to saline intrusion. Close to 42% of the irrigated area was predicted to be somewhat affected by salinization. The regional-scale soil salinity assessment presented here for the Valencian Community is the first to be made for this region and will be useful in targeting critical areas that may require special management.

Keywords: GIS, salinity model, risk evaluation, soil salinization, Spain

INTRODUCTION

The accumulation of salt in soil is a problem that affects irrigated agriculture. This process decreases crop yields, the quality of water resources, and in some cases reduces the quality of the crop. Szabolcs (1996) estimated that 50% of the world's irrigated areas are affected to some extent by salt. In Europe, 4 million hectares are threatened by salinization (Oldeman *et al.* 1991). In Spain, the Ebro river basin and the arid and semiarid areas of the Mediterranean coast have a high risk of salt accumulation (Szabolcs 1996). The progressive nature of salinization hinders its early detection.

The Valencian Community is a Mediterranean region flanking the Spanish coast, where soil salinization has become a problem. This region includes more than 380 000 hectares of irrigated agriculture (Consellería d'Agricultura Peixca i Alimentació 1999). In this region the scarcity and the poor quality of the irrigation water, restricted soil drainage and the arid to semiarid climate are the main factors causing soil salinization. The problem could be aggravated by global changes that foresee an increase in temperature and aridity in the region, which will lead to an increase in irrigated areas with poorer quality water.

There are several techniques to reclaim salt-affected soils, but they usually have a high economic cost. In some areas the lack of good quality water resources makes it difficult to reclaim the salinized land, and agriculture becomes ultimately abandoned.

Prevention of salt accumulation is more advisable than soil desalinization. Simulation models that predict the effect of irrigation and drainage management on soil salinization can help in deciding the most suitable management for each combination of climate, soil and water. A decision system is absolutely necessary where there is strong competition for good quality water. This is the case for several irrigated areas of the Valencian Community.

To extend the capabilities of salinity simulation models at a regional scale, it is convenient to couple them with geographical information systems (GISs). With this combined tool it is possible to make predictive maps of salinity risk, identify problem areas and determine their extent. Several authors have modelled the risk of salinization at a regional scale using GISs (Corwin *et al.* 1989, 1996, 1997; Vaughan *et al.* 1996; Bui 1997; Bui *et al.* 1999; MacMillan & Marciak 2000; Utset & Borroto 2001) with the main

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objective of identifying areas that have a high risk of salt accumulation.

The purpose of this study was to develop a GIS model to evaluate the soil salinization risk at a regional scale. Two simple models (Richards 1954; Pla 1996, 1997) were integrated in a GIS (Arcview 3.2) to elaborate soil salinity risk maps in the irrigation land of the Valencian Community.

MATERIAL AND METHODS

Description of study area

The study area occupies the total irrigated area of the Valencian Community (380 000 ha), which represent 45% of its agricultural land. Three provinces (Castellón, Valencia and Alicante) constitute this region in eastern Spain (Figure 1), which has a mainly arid to semiarid climate (51% of the total territory), with hot dry summers and wet autumns. The most frequent irrigated soils are calcareous Fluvisols (FAO-UNESCO 1988) formed in various loamy materials, overlying loamy to clayey textures. The main irrigated crops are citrus (10%), vegetables (3%), and fruits (1.6%). These crops are usually irrigated with basins and furrows (80%), although drip irrigation (19%) is now being introduced in permanent crops such as citrus as part of an irrigation update plan. The irrigation water comes from several sources (Table 1), and its quality is variable. Groundwater makes up 45% of the irrigation water, and in some areas near the coast, where the agriculture is more intensive, groundwater contains more salts due to sea water intrusion.

Modelling approach

Several models have been developed to simulate salt movement through the soil profile. Some of them such as UNSATCHEM (Simunek & Suarez 1994), SALTMED (Ragab 2002) and BUDGET (Raes *et al.* 2001) are complex, and their large data requirement makes it impossible to apply them to large areas. Simple models such as the evaluation criteria developed by Pla (1996, 1997) and the Riverside guidelines (Richards 1954) are more suitable for large areas because they require less data.

Table 1. Average electrical conductivity (EC) and percentage of area of the three main types of irrigation water used in the study.

Irrigation water source	EC ($dS\,m^{-1}$)	% surface
Surface	1.33 (0.88)[a]	42
Groundwater	1.80 (1.90)	45
Tajo–Segura transfer	1.07 (0.37)	11

[a] Standard deviation in parentheses.
Source: Data provided by Confederación Hidrografica del Júcar, Confederación Hidrográfica Segura, Instituto Geominero y Tecnológico de España, and Riegos de Levante irrigation community.

Pla classification

The classification criteria developed by Pla (1996, 1997), based on the experience and knowledge of salinity–sodicity processes in soils, can be considered as a logical model. It combines information about soil (drainage), climate (humidity index), and quality of irrigation water (electrical conductivity and anion/cation composition) (Figure 2). It assumes that changes in the concentration of salts in the soil solution could affect the salt composition because less soluble salts may precipitate (calcium and magnesium carbonate and calcium sulphate) increasing the concentration of soluble salts (sodium chloride and sulphate). In order to predict problems of salt or sodium accumulation using this model, we must know the salt concentration and composition of the irrigation water, the climate, and the hydraulic properties of the soil.

Riverside guidelines

The Riverside guidelines (Richards 1954) are the most commonly used criteria to evaluate the adequacy of irrigation water for crops and are based on electrical conductivity (EC) and the sodium adsorption ratio (SAR) of the irrigation water to evaluate the risk of salinity and sodicity (Table 2). These simple guidelines are useful under conditions in which the climate or the soil parameters are not restrictive.

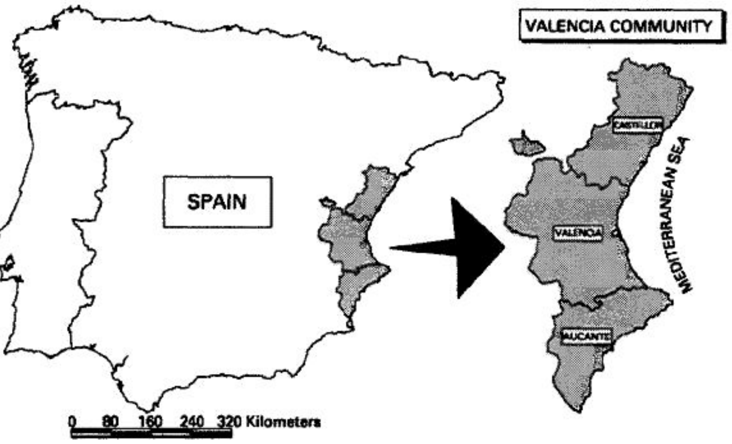

Figure 1. Location of the study area.

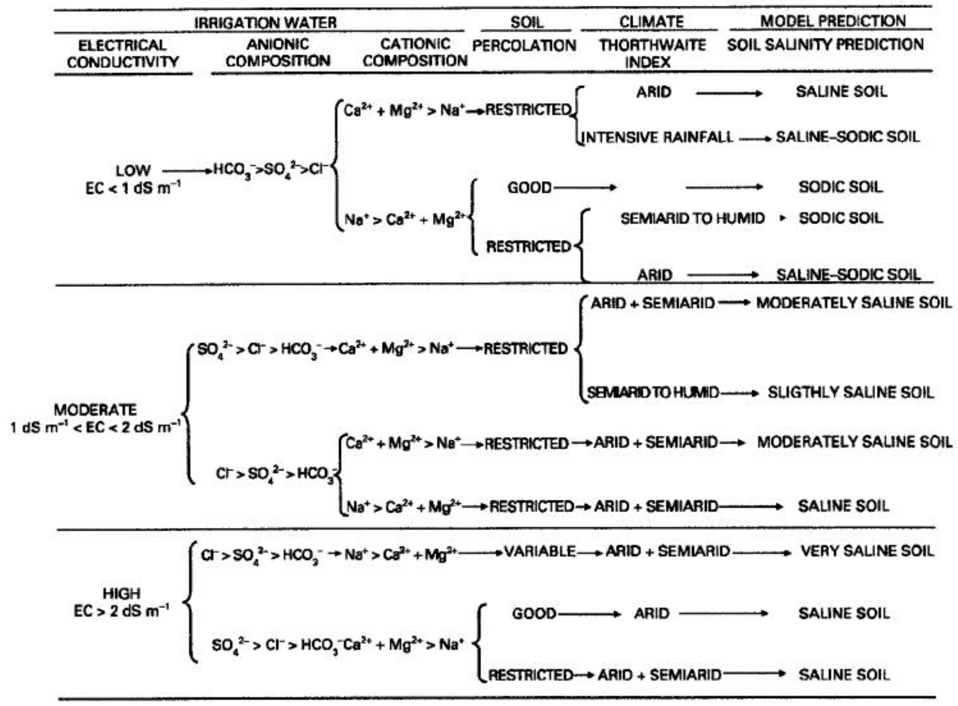

Figure 2. Evaluation criteria of salinity–sodicity. (Adapted from Pla 1996, 1997.)

Table 2. Classification of the salinity risk of irrigation water following Riverside guidelines (Richards 1954).

Riverside classification	Low risk C1	Moderate risk C2	High risk C3	Very high risk C4	Excessive risk C5
EC ($dS\,m^{-1}$)	<0.25	0.25–0.75	0.75–2.25	2.25–4	4–6
SAR[a]					
Low risk S1	<9	<7	<5	<3	<2
Moderate risk S2	9–16	7–13	5–10	3–8	2–6
High risk S3	16–24	13–20	10–16	8–13	6–11
Very high risk S4	>24	>20	>16	>13	>11

[a] Sodium adsorption ratio limits are the average of the range. EC = electrical conductivity.

Model input data

The data required for the Pla classification were obtained from several sources and organized in three layers related to the three base maps that were input to a GIS.

1. *Soil drainage.* The model requires the soil drainage to be classified in three ranges based on saturated conductivity of the most limiting soil layer: restricted ($<5\,mm\,h^{-1}$), moderate ($5–50\,mm\,h^{-1}$) or good ($>50\,mm\,h^{-1}$). Conductivities were classified according to soil texture and depth to water table.
2. *Climate.* The climate is classified using a humidity index and the period of time with water deficit. We used the Thorthwaite (1948) humidity index, which is based on a monthly water balance, to classify the climate as arid, semiarid, dry subhumid, subhumid, or humid.
3. *Irrigation water quality.* The model requires the EC, the anion (Cl^-, SO_4^{2-}, HCO_3^-) and the cation (Ca^{2+}, Mg^{2+}, Na^+) concentrations.

The Riverside model only requires data on irrigation water quality, viz. EC and the concentration of Na^+, Ca^{2+} and Mg^{2+}, to calculate the SAR index.

Model validation

Soil and irrigation water were sampled at 66 locations across the Valencian Community (Figure 3) to validate the model. In each location, four soil samples at 0–10, 10–30, 30–60, 60–90 cm depths were taken as well as irrigation water samples. Determinations were made of EC, cation and anion composition in the irrigation water and also soil texture, total carbonates, organic matter and EC in the saturated soil extract (EC_e). The maximum EC_e in the first 90 cm depth and the predictions of the two models were compared to validate the models (Table 3).

The Pla system predicted well the observed data from soils. Soils with EC $>8\,dS\,m^{-1}$ were classified as very saline, those $>4\,dS\,m^{-1}$ as saline, those $>2\,dS\,m^{-1}$ as moderate to slightly saline and those $<2\,dS\,m^{-1}$ as non-saline (Figure 4a). Only those cases where the soil EC_e was close to a threshold (4 or $2\,dS\,m^{-1}$) were not well predicted. We consider that our validation of Pla model was adequate to make a screening analysis of the salinity risk in the study area.

The Riverside guidelines gave poor predictions, probably because important variations in soil and climate are not

Figure 3. Location of the soil samples used for the model validation.

included as part of the assessment of salinity risk. For example, the model considers a high risk of salt accumulation (classified as C3) when the soil maximum EC_e is close to $1\,dS\,m^{-1}$ (Table 3, Figure 4b), even though most crops can be grown under these conditions without a yield reduction. Because this validation was unsatisfactory we did not use this model to make the predictions at the regional scale.

The GIS approach

The Arcview v.3.2 GIS was employed to integrate the Pla model into the GIS and to organize the information required by the model in three base maps. This GIS was selected for two main reasons: (a) it has raster and vector capabilities; (b) it is possible to program some routines to automate the data flow between model and GIS; and (c) it is easy to implement a graphical user interface (GUI) using the avenue language program.

The information required by the model was organized in three map layers using the GIS.

1. *Drainage map* (Figure 5). This was derived from a lithology map (Martinez & Balaguer 1998) and piezometric map. Lithologic materials like sand and gravel were classified as good drainage conditions, while clayey and silty materials were considered as restricted drainage (Table 4) in agreement with Custodio & Llamas (1976), Freeze & Cherry (1979) for consolidated materials, and Rawls *et al.* (1982) for non-consolidated materials. In addition, the presence of a superficial water table at less than 2 m was classified as restricted drainage. The piezometric map was constructed using ordinary kriging to interpolate from 2500 piezometric measurements points provided by the ITGME (Spanish Technological Geomining Institute). The model that best fitted the semivariogram was the exponential ($\gamma_h = 388 + 3023\ \mathrm{exp}_{36560}\,h$) (Figure 6). Areas with a water table depth less than 2 m were combined with the lithology map to generate the map of soil drainage conditions.
2. *Climate classification map.* This map was constructed using data from 110 weather stations distributed in the Valencian Community (Perez 1994). Ordinary kriging was used to interpolate the Thorthwaite humidity index. The spatial model that best fitted the observed data was spherical ($\gamma_h = 256\ \mathrm{sph}_{96187}\,h$) (Figure 7).
   The output raster map of the kriging interpolation containing the Thornthwaite index was classified as: arid (-60 to -40), semiarid (-40 to -20), dry sub-humid (-20 to 0), subhumid (0 to 20), and humid (20 to 40) (Figure 8).
3. *Irrigation water quality map.* The map of the irrigated agriculture was provided by the national public institution dedicated to the control, planning and study of irrigation systems (General Secretary of the Agriculture Ministry for Rural Development). Each irrigated area was visited to take a water sample and to assess the EC, and cation and anion composition. This information, in addition to the data of groundwater quality provided by the ITGME database and Sanchis (1991), was used to elaborate the map of irrigation water quality (Figure 9). Data from 1210 control points for groundwater irrigation quality and 135 points for surface water were considered.

A spatial combination of these three maps was made to obtain the final map divided in homogeneous units according to soil, climate and irrigation water characteristics. This final map was used to run the simulation models and display the predictions.

GIS–model linkage

To link the model with the GIS, several strategies could be followed, from a loose coupling to full integration (Tim 1996; Corwin *et al.* 1997). Since the models used in this study are simple, full integration was selected and a GUI was developed to facilitate the use of the GIS–model

Table 3. Input data and comparison between the salinity predictions for the Pla model (1996) and Riverside guidelines, with the maximum electrical conductivity (EC_e) observed in the saturation extract of soils.

INPUT DATA									MODEL PREDICTION		OBSERVED DATA
Soil drainage	Aridity index	Irrigation water							Pla[a]	Riverside	Soil max. EC_e
		EC ($dS\ m^{-1}$)	Na^+	$Ca^{2+} + Mg^{2+}$ ($meq\ L^{-1}$)	HCO_3^-	Cl^-	SO_4^{2-}	SAR			
Restricted	Arid	5.74	37.28	32.63	6.77	37.40	36.07	7.56	Very saline	C5S2	16.87
Moderate	Semiarid	2.12	15.81	11.62	3.90	18.67	11.03	6.56	Very saline	C3S2	7.92
Restricted	Subhumid	3.92	45.54	14.83	3.28	32.72	3.81	16.72	Saline	C4S4	7.80
Restricted	Semiarid	2.80	15.46	22.75	2.13	15.80	11.04	4.58	Saline	C4S2	5.38
Restricted	Semiarid	3.99	15.66	17.59	3.96	27.93	6.12	6.29	Saline	C4S2	4.70
Restricted	Arid	4.22	19.54	25.99	6.73	22.22	25.35	5.42	Saline	C5S2	4.55
Restricted	Arid	4.53	26.01	32.47	5.97	23.90	20.16	6.46	Saline	C5S2	4.33
Good	Arid	4.92	29.45	33.96	4.97	27.53	30.93	7.15	Saline	C5S3	4.32
Restricted	Semiarid	2.36	4.66	22.83	4.58	8.85	14.73	1.38	Saline	C4S1	4.28
Restricted	Arid	2.07	9.87	15.47	3.57	8.22	12.44	3.55	Saline	C3S1	4.25
Restricted	Semiarid	2.36	4.66	22.83	4.58	8.85	14.73	1.38	Saline	C4S1	4.00
Restricted	Semiarid	1.08	3.41	9.76	3.06	3.09	5.97	1.54	Moderately saline	C3S1	3.95
Restricted	Semiarid	2.84	5.45	26.70	4.56	12.25	13.09	1.49	Saline	C4S1	3.94
Moderate	Semiarid	1.82	3.39	16.31	3.84	7.00	4.12	1.19	Moderately saline	C3S1	2.84
Restricted	Semiarid	2.00	5.52	15.75	4.21	9.99	3.75	1.97	Non-saline, non-sodic	C3S1	2.77
Restricted	Semiarid	1.76	3.58	15.04	4.25	5.47	8.11	1.31	Moderately saline	C3S1	2.56
Restricted	Semiarid	1.60	3.72	13.73	4.24	4.65	7.40	1.42	Moderately saline	C3S1	2.41
Moderate	Dry-subhumid	0.90	2.46	6.79	4.62	3.24	2.31	1.34	Non-saline, non-sodic	C3S1	2.14
Moderate	Dry-subhumid	1.97	4.02	20.98	4.20	4.29	17.29	1.24	Non-saline, non-sodic	C3S1	2.13
Moderate	Semiarid	0.81	1.10	6.77	3.23	1.36	4.91	0.60	Non-saline, non-sodic	C3S1	2.10
Restricted	Semiarid	1.76	3.63	14.92	5.04	5.47	9.79	1.33	Moderately saline	C3S1	2.07
Moderate	Subhumid	2.00	8.62	9.82	4.11	13.09	2.78	3.89	Non-saline, non-sodic	C3S1	2.07
Moderate	Semiarid	0.95	1.70	8.22	5.05	2.05	2.58	0.84	Non-saline, non-sodic	C3S1	2.03
Restricted	Semiarid	1.33	2.91	14.77	4.97	3.36	7.29	1.07	Non-saline, non-sodic	C3S1	2.00
Restricted	Semiarid	1.59	7.00	12.14	5.59	6.38	6.74	2.84	Moderately saline	C3S1	1.95
Good	Arid	1.32	4.31	11.83	3.11	4.43	6.81	1.77	Non-saline, non-sodic	C3S1	1.76
Good	Dry-subhumid	0.98	1.22	10.71	4.57	1.73	3.27	0.53	Non-saline, non-sodic	C3S1	1.66
Moderate	Dry-subhumid	0.98	3.22	6.86	5.38	3.28	2.43	1.74	Non-saline, non-sodic	C3S1	1.66
Moderate	Dry-subhumid	1.95	5.11	15.08	4.35	6.16	11.50	1.86	Non-saline, non-sodic	C3S1	1.59
Restricted	Semiarid	0.95	1.53	8.15	3.21	2.04	5.69	0.76	Non-saline, non-sodic	C3S1	1.53
Restricted	Semiarid	1.07	2.00	9.01	3.34	2.33	6.84	0.94	Non-saline, non-sodic	C3S1	1.41
Restricted	Semiarid	1.55	1.31	16.99	4.07	1.63	10.47	0.45	Non-saline, non-sodic	C3S1	1.39
Restricted	Arid	1.92	7.02	14.34	4.30	8.58	11.03	2.62	Moderately saline	C3S1	1.34
Restricted	Semiarid	1.33	2.91	14.77	4.97	3.36	7.29	1.07	Non-saline, non-sodic	C3S1	1.27
Restricted	Semiarid	0.99	2.35	10.25	3.48	2.28	5.67	1.04	Non-saline, non-sodic	C3S1	1.25
Good	Dry-subhumid	5.63	42.19	21.48	2.34	54.63	5.58	12.87	Non-saline, non-sodic	C5S4	1.25
Good	Dry-subhumid	1.42	5.52	12.49	2.95	6.04	7.38	2.21	Non-saline, non-sodic	C3S1	1.18
Good	Dry-subhumid	0.42	0.17	4.26	3.11	0.40	0.66	0.12	Non-saline, non-sodic	C2S1	1.18
Moderate	Semiarid	0.81	1.10	6.77	3.23	1.36	4.91	0.60	Non-saline, non-sodic	C3S1	1.17
Restricted	Semiarid	0.81	1.10	6.77	3.23	1.36	4.91	0.60	Non-saline, non-sodic	C3S1	1.17
Restricted	Semiarid	0.99	2.35	10.25	3.48	2.28	5.67	1.04	Non-saline, non-sodic	C3S1	1.16
Good	Semiarid	1.99	5.03	15.14	4.98	6.02	10.87	1.83	Non-saline, non-sodic	C3S1	1.16
Restricted	Dry-subhumid	0.94	4.18	5.22	3.89	3.37	2.34	2.59	Non-saline, non-sodic	C3S1	1.12
Good	Dry-subhumid	1.01	1.86	8.15	3.17	2.23	5.63	0.92	Non-saline, non-sodic	C3S1	1.11
Restricted	Semiarid	1.78	10.44	10.70	4.82	11.92	2.25	4.51	Non-saline, non-sodic	C3S1	1.10
Restricted	Dry-subhumid	1.04	1.97	9.53	3.91	3.10	4.94	0.90	Non-saline, non-sodic	C3S1	1.08
Moderate	Subhumid	0.36	0.22	3.41	3.01	0.50	0.83	0.17	Non-saline, non-sodic	C2S1	1.05
Good	Semiarid	0.39	0.18	3.77	2.94	0.54	1.01	0.13	Non-saline, non-sodic	C2S1	1.04
Good	Semiarid	1.82	3.39	16.31	3.84	7.00	4.12	1.19	Non-saline, non-sodic	C3S1	0.99
Moderate	Dry-subhumid	0.62	0.49	5.54	4.11	0.61	1.09	0.29	Non-saline, non-sodic	C2S1	0.98
Restricted	Semiarid	1.13	2.69	8.73	3.63	2.84	5.65	1.29	Non-saline, non-sodic	C3S1	0.97
Moderate	Semiarid	0.82	1.12	7.05	2.80	1.35	4.84	0.60	Non-saline, non-sodic	C3S1	0.96
Restricted	Semiarid	0.93	1.15	6.84	0.79	1.52	5.31	0.62	Non-saline, non-sodic	C3S1	0.93
Restricted	Dry-subhumid	0.93	2.09	10.86	3.36	2.42	5.17	0.90	Non-saline, non-sodic	C3S1	0.93
Restricted	Semiarid	1.03	2.38	8.31	3.41	2.60	5.48	1.17	Non-saline, non-sodic	C3S1	0.92
Good	Dry-subhumid	0.39	0.18	3.77	2.94	0.54	1.01	0.13	Non-saline, non-sodic	C2S1	0.86
Moderate	Subhumid	0.59	0.52	5.33	3.96	1.14	1.19	0.32	Non-saline, non-sodic	C2S1	0.86
Restricted	Semiarid	1.34	2.44	12.70	4.39	3.60	3.91	0.97	Non-saline, non-sodic	C3S1	0.84
Moderate	Dry-subhumid	0.55	0.28	4.91	3.71	0.47	0.90	0.18	Non-saline, non-sodic	C2S1	0.84
Restricted	Dry-subhumid	0.78	1.01	7.06	3.30	1.62	2.30	0.54	Non-saline, non-sodic	C3S1	0.78
Moderate	Dry-subhumid	0.49	0.59	4.45	2.75	0.81	1.19	0.40	Non-saline, non-sodic	C2S1	0.69
Moderate	Semiarid	1.00	2.53	7.92	2.59	2.60	5.32	1.27	Non-saline, non-sodic	C3S1	0.67
Restricted	Dry-subhumid	1.21	4.34	7.56	5.35	4.72	2.81	2.23	Non-saline, non-sodic	C3S1	0.63
Good	Dry-subhumid	0.52	0.26	4.33	4.89	0.47	0.58	0.18	Non-saline, non-sodic	C2S1	0.40

[a] Electrical conductivity (EC) categories: non-saline, non-sodic $< 2\ dS\ m^{-1}$; slightly to moderately saline 2–4 $dS\ m^{-1}$; saline $> 4\ dS\ m^{-1}$; very saline $> 8\ dS\ m^{-1}$. SAR = sodium adsorption ratio.

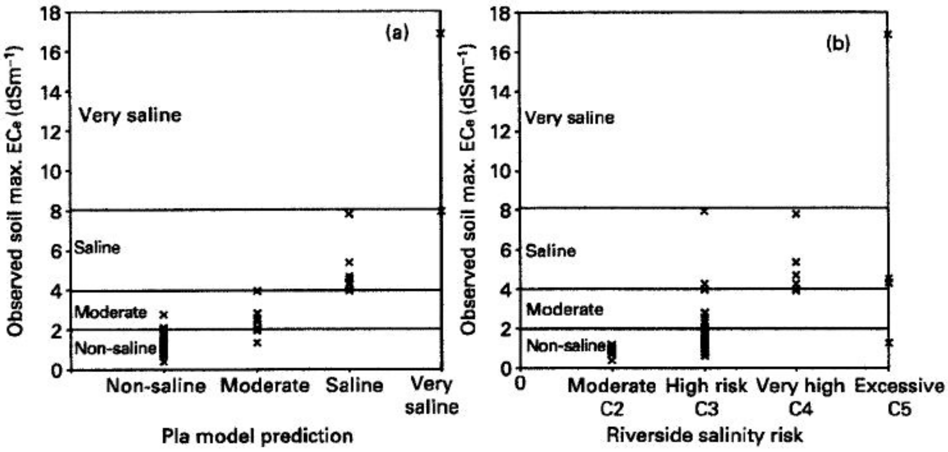

Figure 4. Comparison of the observed maximum EC_e measured in the first 90 cm depth with (a) Pla model predictions and (b) Riverside salinity risk.

system for non-expert users. Several avenue routines and menus were programmed in the GIS to allow the simulation processes (input data, run model and display result maps) and the implementation of the GUI. The coupling scheme is shown in Figure 10. After the simulation, Arcview GIS was used to display the results as thematic maps.

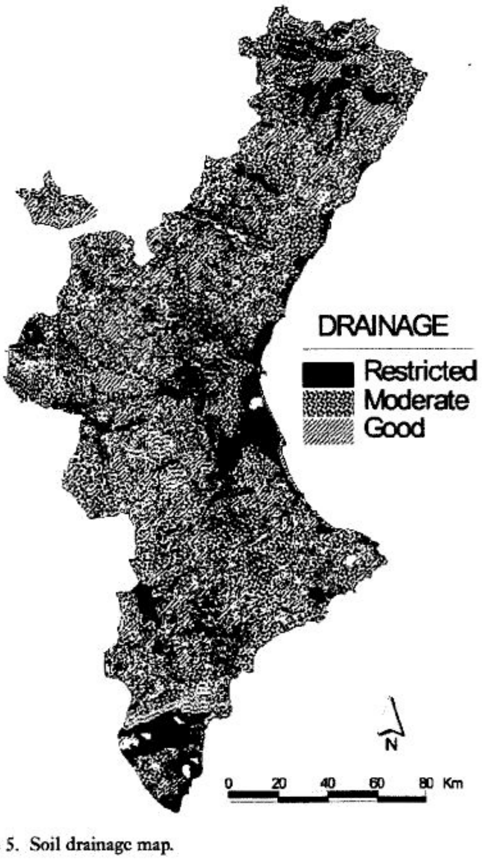

Figure 5. Soil drainage map.

RESULTS AND DISCUSSION

Figure 11 shows the soil salinity maps resulting from Pla evaluation criteria. Eighty-four per cent of the total irrigated area in the Valencian Community was evaluated, and only areas where data for irrigation water were not available were excluded.

Following the Pla criteria, 21% of the irrigated land is at high risk of developing saline or very saline soil; another

Table 4. Relation between the lithology and the drainage condition adapted from Custodio & Llamas (1976), Freeze & Cherry (1979) and Tauber (1997) for consolidated material, and Rawls *et al.* (1982) and Custodio & Llamas (1976) for unconsolidated material.

Lithology	Drainage
Sandstone	Good
Limestone	Moderate
Marl	Moderate
Clay	Restricted
Silt	Restricted
Sand	Good
Gravel	Good
Gravel + sand + clay	Moderate

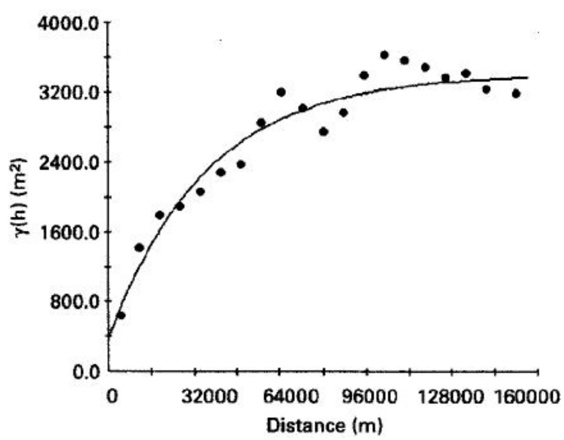

Figure 6. Exponential variogram modelled for piezometric levels.

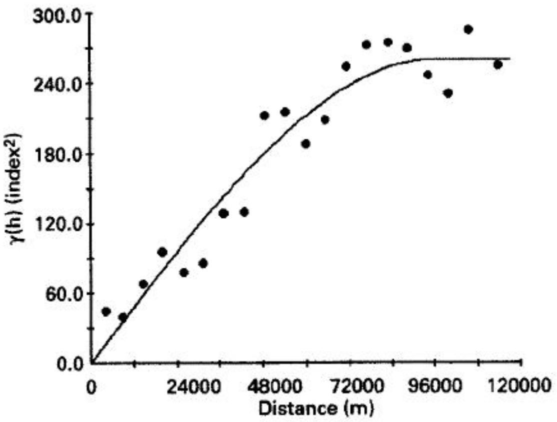

Figure 7. Spherical variogram modelled for Thorthwaite humidity index.

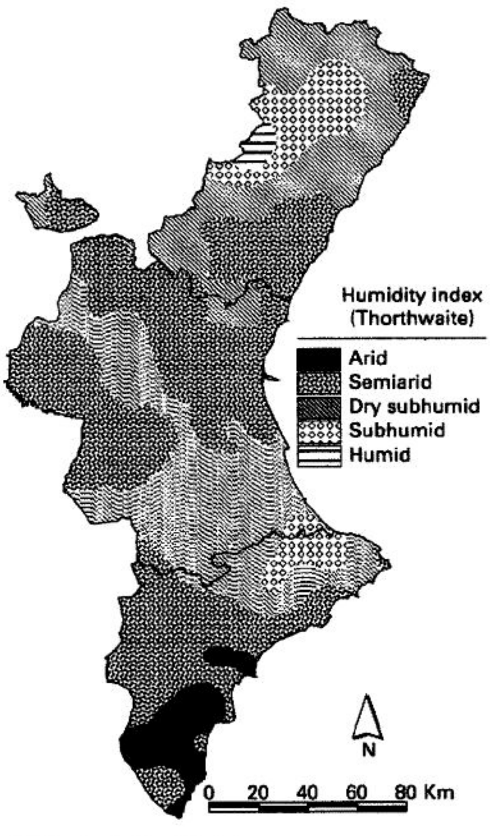

Figure 8. Thorthwaite humidity index map.

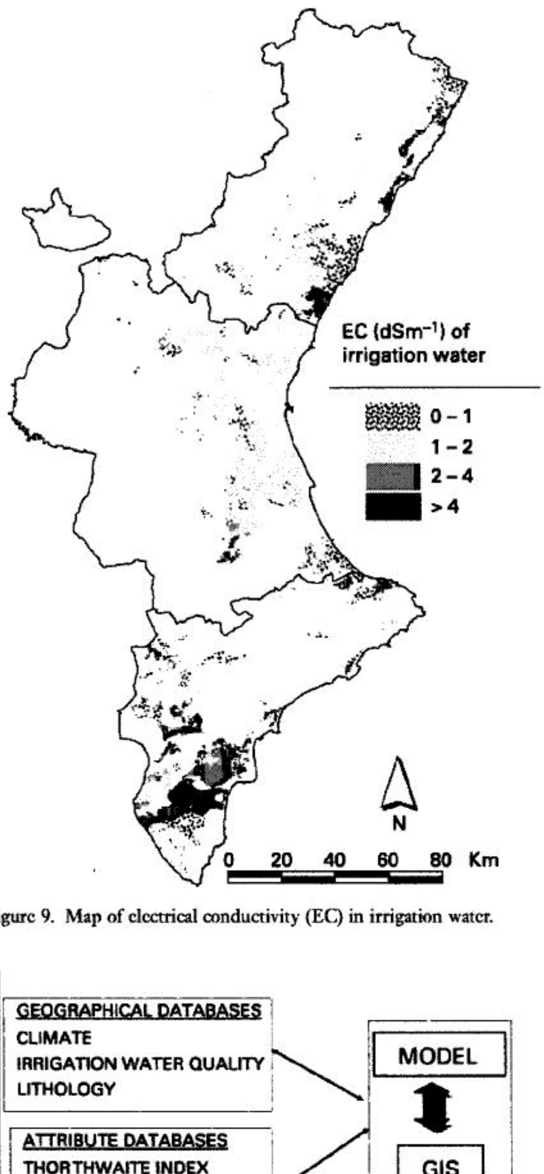

Figure 9. Map of electrical conductivity (EC) in irrigation water.

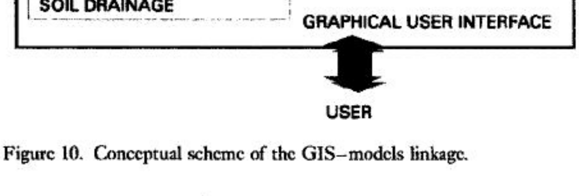

Figure 10. Conceptual scheme of the GIS–models linkage.

21% has a moderate-to-slight risk of developing salinity. This means that 42% of the total area evaluated has some risk of becoming saline soil ($EC_e > 2\,dS\,m^{-1}$). Most of the vegetable and fruit crops (early potatoes, onions, cauliflowers, watermelons, melons, etc.) and the citrus (oranges, lemons and mandarins) grown in the Valencian Community have a low tolerance to salinity (FAO 1985), and even slight-to-moderate soil salinity ($EC_e > 2\,dS\,m^{-1}$) affects crop yield. So, special strategies should be considered to reduce the risk of salinization.

Although the northern area (Castellón province) has, in general, good quality water, unrestricted soil drainage and a non-arid climate (Figure 12), in some of the coastal groundwaters there is a high content of chloride due to

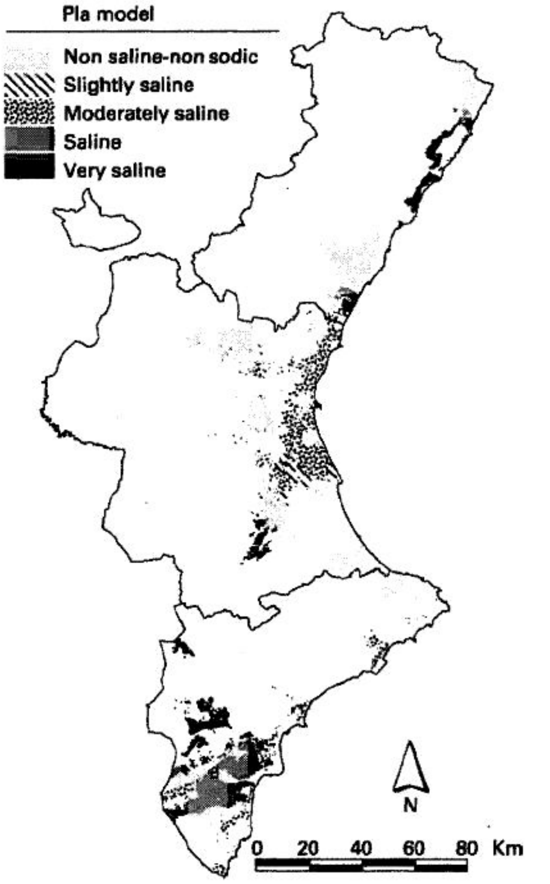

Figure 11. Map of the salinity predictions obtained by applying the Pla model.

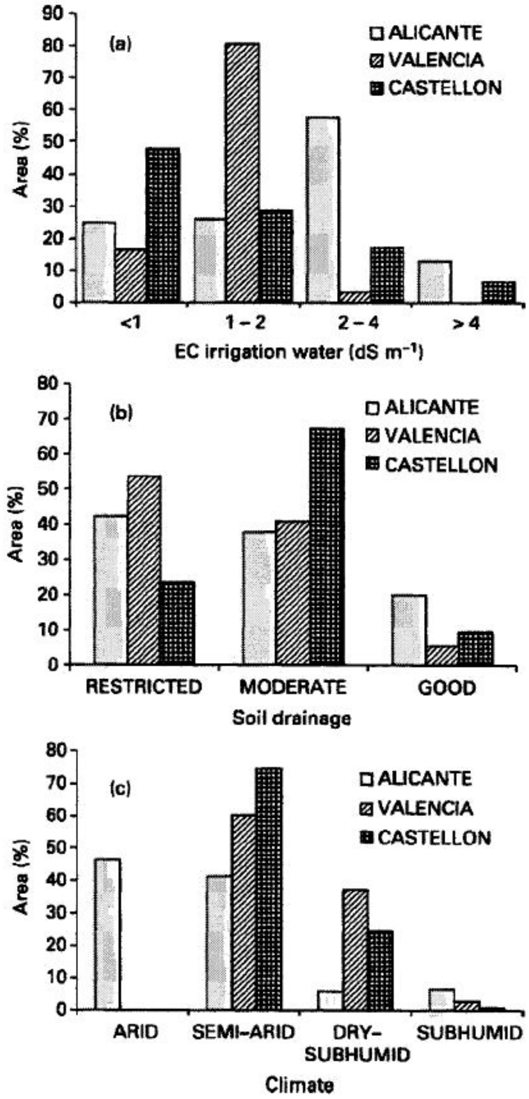

Figure 12. Area distribution of (a) electrical conductivity (EC) in irrigation water, (b) soil drainage and (c) climate for the irrigated area of the three provinces of the Valencian Community.

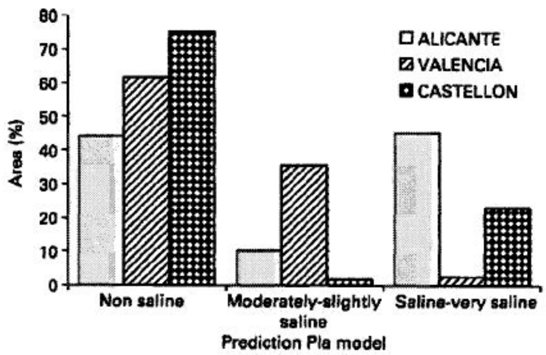

Figure 13. Predictions of the Pla model for the three provinces of the Valencian Community.

the influence of sea water. For these areas, the Pla model predicts a saline to very saline soil, but the most common vegetable crop, the artichoke, is more tolerant to salinity than other vegetables (Francois *et al.* 1991; Shannon & Grieve 1999). The inland areas irrigated with groundwater have more balanced salt compositions with a predominance of sulphates and bicarbonates and lower EC values.

In Valencia province (in the middle belt of the study area) the main factor that causes soil salinization is poor soil drainage, with more than 50% of the irrigated soils in this category (Figure 12). The restricted drainage in combination with a semiarid climate and an EC in irrigation water between 1 and $2\,dS\,m^{-1}$ (Figure 12) will lead to slightly to moderately saline soils in more than 35% of the area (Figure 13).

The Pla model predicted that 45% of the irrigated lands of Alicante province (located at the southeast of the study area) will develop saline or very saline soils (Figure 13). An arid to semiarid climate (more than 87% of the irrigated area) with a high evapotranspiration rate ($1200\,mm\,yr^{-1}$), scarcity of good quality irrigation water and more than 40% of the soils with poor drainage (Figure 12), are the main factors that promote soil salinization in this area. Irrigation is very important in Alicante because it ensures citrus and vegetables can be harvested out of season ensuring high value exports. Soil salinity is curtailing the economy of this province. The quality of the water varies from very poor (mainly groundwater), moderate quality from the Segura river, to good quality from the Tajo–Segura transfer, which determines the crop distribution. In areas irrigated with highly saline water, saline-tolerant crops such as date palm (*Phoenix dactylifera*), pomegranate (*Punica granatum*) and fig (*Ficus carica*) are grown. In contrast, citrus (mainly lemon) occupy areas where water quality is better (EC 1–2 $dS\,m^{-1}$). The area irrigated from the Segura river is also salinized due to the poor water quality (EC 2–2.6 $dS\,m^{-1}$). The solution for these areas is either conversion to saline-tolerant crops or a costly water desalinization plan.

The salinity maps inform land and water managers as to which areas are most affected by salinity. These areas require the highest standard of management of irrigation water. Although areas at high risk should be treated with most caution, areas with a moderate risk should not be ignored in any planning decision. With the model results it is easy to design strategies for soil protection against salinization. More complex models like SALSODIMAR (Pla 1996), UNSATCHEM (Simunek & Suarez 1994), SALTMED (Ragab 2002), BUDGET (Raes *et al.* 2001) and IMAGE (Al-Ajmi *et al.* 2002), which are more focused on the irrigation management and the assessment of the leaching fraction to maintain soil salts in a range that allows crops to grow without yield reduction, should be used in those areas with a higher salinization risk.

CONCLUSIONS

The GIS–model system developed here is a useful tool to evaluate soil salinization processes in the irrigated agriculture of the Valencian Community. Simple models are useful to evaluate the salinization processes at a regional scale, where the lack of data does not allow the use of more complex models. The Riverside guidelines were discarded in the validation analysis because of a poor fit with observed data. The use of the simple Pla model in combination with a GIS allows the screening for areas at high risk of salinization.

ACKNOWLEDGEMENTS

We thank the Spanish International Cooperation Agency (AECI), the Universitat de València and the Spanish Education Ministry for funding the stay of Dr Raúl Zapata in the 'Centro de Investigaciones sobre Desertificación-CIDE' during the course 2001–2002. The Consellería de Medi Ambient of the Valencian Community provided the financial support for this research in the framework of the Restoration and Protection of Natural Resources Program (14.04.442.40) line T3133000. We also thank to the 'Dirección General de Desarrollo Rural' for providing information about irrigation areas of the Valencian Community. The help in language editing by Adela Robles (San Francisco University, USA) is gratefully acknowledged.

REFERENCES

Al-Ajmi A Nortcliff S & Simmonds LP 2002. IMAGE: a physically-based one dimensional irrigation management model for soil salinity control. Soil Use and Management 18, 184–190.

Bui E 1997. Assessing the regional risk of salinisation over the Dalrymple Shire. Technical report 26/97, CSIRO Land and Water, PO Box 1666, Canberra, ACT 2601, Australia. Available: www.clw.csiro.au/publications/technical/tr26-97.pdf [2004, 20 May].

Bui E Keith RJ Moran CJ & Williams J 1996. Use of a soil survey information to assess regional salinisation risk using Geographical Information Systems. Journal Environmental Quality 25, 433–439.

Conselleria d'Agricultura, Peixca i Alimentació 1999. Actuaciones en el regadío de la Comunidad Valenciana, años 1995–1999. Generalitat Valenciana, Conselleria d'Agricultura Peixca i Alimentació, Valencia Spain.

Corwin DL Sorensen M & Rhoades JD 1989. Field-testing of models which identify soils susceptible to salinity development. Geoderma 45, 31–64.

Corwin DL Rhoades JD & Vaughan PJ 1996. GIS applications to the basin-scale assessment of soil salinity and salt-loading to the groundwater. In: Applications of GIS to the modeling of non-point source pollutants in the vadose zone, eds DL Corwin & K Loague. SSSA Special Publication No. 48. Soil Science Society of America Madison WI Ch 18 pp 295–313.

Corwin DL Vaughan PJ & Loague K 1997. Modeling nonpoint source pollutants in the vadose zone with GIS. Environmental Science and Technology 31, 2157–2175.

Curtodia E & Lalams MR (eds) 1976. Hidrología subterránea, vol II. Omega España pp 1454–1497.

FAO 1985. Water quality for agriculture. FAO irrigation and drainage paper 29, eds RS Ayers & DW Westcot, Food and Agriculture Organization, Via delle Terme di Caracalla, 00100 Rome, Italy. Available: www.fao.org/DOCREP/003/T0234E/T0234E00.htm [2004, 20 May].

FAO-UNESCO 1988. FAO/UNESCO soil map of the world, revised Legend. World soil resources reports 60, FAO Rome.

Francois LE Donovan TJ & Maas EV 1991. Calcium deficiency of artichoke buds in relation to salinity. Hortscience 26, 549–553.

Freeze RA & Cherry JA, (eds) 1979. Groundwater. Prentice-Hall Englewood Cliffs NJ.

MacMillan RA & Marciak LC 2000. Modeling potential salinity hazard (PSH): predicting potential salinity hazard for a range and diverse test region in Alberta, Canada. In: Proceedings of 4th International Conference on Integrating GIS and Environmental Modeling (GIS/EM4), Banff, Canada. Available: www.colorado.edu/Research/cires/banff/organization/subview3.cgi.html [Accesssion date?].

Martinez L & Balaguer J 1998. Litologia, aprovechamientos de rocas industriales y riesgo de deslizamiento en la Comunidad Valenciana. Serie cartográfica nº5. Generalitat Valenciana, Conselleria d'obres Publiques, Urbanisme i Transports Avda. Blasco Ibáñez 50, 46010 Valencia Spain.

Oldeman LR Hakkeling RTA & Sombroek WG 1991. World map of the status of human-induced soil degradation: an explanatory note. Global assessment of soil degradation-GLASOD. Wageningen and Nairobi: International Soil Reference and Information Centre (ISRIC) PO box 353, 6700 AJ Wageningen Netherlands and United Nations Environmental Programme (UNEP).

Perez AJ 1994. Atlas climático de la Comunidad Valenciana, Generalitat Valenciana, Conselleria d'Obres Públiques, Urbanisme i Transports Avda. Blasco Ibáñez 50, 46010 Valencia Spain.

Pla I 1996. Soil salinisation and land desertification. In: Soil degradation and desertification in mediterranean environments, eds JL Rubio & A Calvo, Geoforma Logr oño Spain pp 105–129.

Pla I 1997. Evaluación de los procesos de salinización de suelos bajo riego. Edafología. Revista de la Sociedad Española de la Ciencia del Suelo. Edición especial 50 Aniversario. SECS, Dpto. Edafologia y química agrícola, Facultad de Ciencias, Univ. Granada Spain pp 241–267.

Raes DB Van Goidsenhoven K Goris B Samain E De Pauw M El Baba K Tubail IJ & De Nys E 2001. Budget, a management tool for assessing salt accumulation in the root zone under irrigation. Fourth inter regional conference on environment-water, ICID (ABID), Ministerio Do Meio Ambiente, Dos Recursos Hidricos E Da Amazonia Legal, Secretaria de

Recursos Hidricos, SCLR/N 712 Bloco 'C' Loja 18, 70760 Brasilia DF Brazil pp 244–252.
Ragab R 2002. An integrated modelling approach for irrigation water management using saline and non-saline water: the SALTMED model. Proceedings of the international symposium on techniques to control salination for horticultural productivity. Acta Horticulturae 573, 129–138.
Rawls WJ Brakensiek DL & Saxton KE 1982. Estimation of soil water properties. Transactions of the American Society of Agricultural Engineers 25, 305–316.
Richards LA, (ed) 1954. Diagnosis and improvement of saline and alkali soils. USDA Handbook 60, Washington DC.
Sanchis EJ 1991. Estudio de la contaminación por nitratos de las aguas subterráneas de la provincia de Valencia: Origen, balance, evolución espacial y temporal. PhD Thesis University of Barcelona Spain.
Shannon MC & Grieve CM 1999. Tolerance of vegetables crops to salinity. Scientia Horticulturae 78, 5–38.
Simunek JD & Suarez L 1994. Two-dimensional transport model for variably saturated porous media with major ion chemistry. Water Resources Research 30, 1115–1133.
Szabolcs I 1996. An overview on soil salinity and alkalinity in Europe. In: Soil salinisation and alkalinization in Europe, eds N Misopolinos & I Szabolcs, European Society for Soil Conservation, special publication. Giahudis-Giapulis Editions 15 K. Melenikou str. 546 35 Thessaloniki Greece pp 1–12.
Tauber FA 1997. A numerical and practical test of ternary diagrams for grain-size data classifications. In: Proceedings of International Association for Mathematical Geology, ed V Pawlowsky-Glahn, pp 186–191.
Thorthwaite CW 1948. An approach toward a rational classification on climate. Geographical Review 8, 55–94.
Tim US 1996. Coupling vadose zone models with GIS: Emerging trends and potential bottlenecks. Journal Environmental Quality 25, 535–544.
Ustet A & Borroto M 2001. A modeling-GIS approach for assessing irrigation effects on soil salinisation under global warming conditions. Agricultural Water Management 50, 53–63.
Vaughan PJ Simunek J Suarez DL Corwin DL & Rhoades JD 1996. Unsatchemgeo: Modeling water flow and multicomponent solute transport in a GIS context. In: Applications of GIS to the modeling of non-point source pollutants in the vadose zone, eds DL Corwin & K Loague. SSSA Special Publication No. 48. Soil Science Society of America Madison WI Ch 14 pp 235–246.

Received February 2004, accepted after revision June 2004.