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IRRIGATION STRATEGIES FOR OPTIMAL USE OF SALINE WATER IN MEDITERRANEAN AGRICULTURE

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SUMMARY – In this paper management strategies optimizing irrigation, and also reducing the risk of secondary salinization, were explored for seven Sicilian soil profiles by using the SWAP model. Two viable options addressing constraints of limited water availability were simulated for the seven soil profiles. These options were (i) different irrigation scheduling, i.e. irrigation with a fixed amount of water but different number of irrigations, and (ii) cyclic strategies, i.e. alternating two irrigation waters having different salinity. Analysis of three different irrigation scheduling evidenced that making a limited number of irrigations (two in our case), using larger application volumes, determined a lower risk of salinization. With reference to the role of cracks in the process of salt-leaching, the simulations performed indicated that water stored in cracks promoted leaching of the accumulated solutes, and that neglecting the presence of cracks led to overestimating salinization. Cyclic strategy proved to be the best management option to be suggested to reduce the risk of salinization. Findings concerning the role of cracks in the process of salt-leaching suggested that, under field conditions, application of a leaching solution was more efficient if the soil presented a considerable degree of cracking.

Key words: Salinization, Cracking, Irrigation, Management scenarios

RESUME – *Dans ce papier on a exploré des différentes options de gestion de l'irrigation qui peuvent aider à réduire le risque de salinisation en appliquant le model SWAP à sept profiles de sol en Sicile. On a exploré (i) trois différentes calendrier d'irrigation et (ii) l'alternance de deux eaux d'irrigation ayant une différente salinité. Les résultants ont démontré que la meilleure gestion se peut réaliser en faisant deux irrigations seulement. En plus, les résultas ont démontré l'importance que les fissures du sol peuvent avoir dans la lixiviation des sals accumulés dans le sol, en indiquant qu'il faut tenir en compte les fissures dans la prévision de la salinisation du sol. L'alternance de deux eaux de différente salinité se démontre être la pratique la plus efficace pour prévenir la salinisation du sol. En plus, l'application d'une solution lixiviante se démontre plus efficace si la même est fait quand le sol présente une considérable percentage de fissures.*

Mots-clés: *Salinisation, Fissures, Irrigation, scénarios de gestion*

INTRODUCTION

In Mediterranean regions, irrigation with saline/sodic waters, often a consequence of intensive agricultural systems, is one of the main causes of secondary salinization, resulting in soil degradation. Although accurate worldwide data are not available, vast areas of irrigated land are increasingly threatened by salinization and/or sodication.

Sustainable land management practices are urgently needed to preserve the production potential of agricultural land while safeguarding environmental quality. According to one of the various definitions given by FAO (1993), sustainable land management combines " technologies, policies and activities aimed at integrating socio-economic principles with environmental concern so as to protect the potential of natural resources and prevent degradation of soil and water quality".

In Sicily, the increasing scarcity of good quality waters coupled with intensive use of soil under semi-arid to arid climatic conditions results in irrigation with saline waters. Salinization is closely associated with the process of desertification, defined as "land degradation in arid, semi-arid and dry sub-humid areas resulting from climatic variations and human activities", with the term "land" including soil, water resources, crops and natural vegetation (UNEP, 1991).

Without appropriate management, irrigated agriculture can be detrimental to the environment and endanger sustainability. Therefore, the goal of modern irrigation is to develop methods allowing to save water and to improve both the water and the salt distribution within the root zone, also preserving maintenance of good structural conditions. According to one of the various definitions given by FAO (1993), sustainable land management combines "technologies, policies and activities aimed at integrating socio-economic principles with environmental concern so as to protect the potential of natural resources and prevent degradation of soil and water quality".

van Dam et al. (1997) developed a model describing water and solute transport in the vadose zone, taking into account soil shrinkage and cracking. This model, named SWAP93, provides as output the water content (and matrix potential), as well as the concentration of the soil solution, C, from which the electrical conductivity of the saturated extract (EC_{sat}) can be also calculated (Rhoades, 1996).

Crescimanno and Garofalo (2005) tested the applicability of SWAP for prediction of water content (θ) and electrical conductivity of the saturated extract (EC_{sat}) in a Sicilian clay soil having a high shrink-swell potential and susceptibility to cracking. Using θ measurements collected from seven profiles located in a Sicilian vineyard, they found that using the parameter estimation method based on multi-step outflow experiments, and representing the soil hydraulic properties by the Brutsaert retention equation, coupled with the hydraulic conductivity model proposed by Gardner (*B-G* model), it was possible to obtain an accurate prediction of θ.

In this paper management strategies optimizing irrigation, and also reducing the risk of secondary salinization, will be explored for some Sicilian soil profiles by using the SWAP model. Options addressing constraints of limited water availability were simulated. These options were (i) different irrigation scheduling, i.e irrigation with a fixed amount of water but different number of irrigations, and (ii) cyclic strategies, i.e. alternating two irrigation waters having different salinity.

MATERIALS AND METHODS

Soil shrinkage and hydraulic characteristics

Data collection was carried out in a 25 by 25 m field located in Sicily (37° 40' 55" N; 12° 38' 50" E) where irrigation with saline waters is performed on grapes by a sprinkler system, which allows high application rates at the soil surface. Irrigation water is taken from the Trinità artificial reservoir. The electrical conductivity of irrigation water, EC_w, is about 2.1 dS/m. However, when rainfall is particularly low, and water stored in this reservoir is not enough to cover irrigation needs, water from wells is used for irrigation, with EC_w values up to about 6.2 dS/m.

Seven soil profiles (Baglio1-Baglio7) were considered in this field. The soil shrinkage curve was determined by measuring vertical and horizontal shrinkage on undisturbed soil cores (diameter d=8.5 cm, height H=11.5 cm) (Crescimanno and Provenzano, 1999). The shrinkage characteristic was expressed by the model proposed by Kim (Crescimanno and Garofalo, 2005).Bulk density (ρ_b) was determined from the shrinkage curve and used to calculate the volumetric water content, θ, which therefore accounted for a variable soil volume. The coefficient of linear extensibility, *COLE* (Grossman et al., 1968), indicating the shrink-swell potential (Parker et al., 1977), was also calculated.

Parameter estimation was carried out according to Crescimanno and Garofalo (2005), representing the soil hydraulic functions by:

- the equation proposed by Brutsaert (B) (1966), for the water retention curve:

$$\frac{\theta-\theta_r}{\theta_s-\theta_r}=\Theta=\left[1+\left|\alpha' h\right|^{n'}\right]^{-1} \tag{1}$$

- coupled with the model proposed by Gardner (1958) (G) for the hydraulic conductivity function *k(h)*:

$$k(h)=\frac{k_{sat}}{1+\left|\beta h\right|^{\lambda}} \tag{2}$$

where *h* (cm) is the pressure head, θ_s is the volumetric water content at saturation, θ_r is the residual water content, *k* is the unsaturated hydraulic conductivity (cm/h), k_{sat} is the saturated hydraulic conductivity (cm/h), α', n', β and λ are empirical parameters.

The soil physical and chemical properties, together with the soil shrink-swell potential, were reported in *Table 1*. The soil hydraulic parameters were reported in *Table 2*.

Table 1. Classification, physical and chemical properties, COLE and shrink-swell potential of the considered soils.

	Classification †	Horizon	Depth	Clay	Silt	Sand	COLE ‡	Shrink-swell potential §	EC_{sat} ¶	ESP #
			cm	——	%	——	h=-333 cm to oven-dry		dS/m	%
Baglio1	Typic Chromoxerert	Ap	0-30	35	28	37	0.052	Medium	2.38	3.5
Baglio1	Typic Chromoxerert	A1	30-60	33	23	44	0.049	Medium	3.56	5.2
Baglio2	Typic Chromoxerert	Ap	0-30	36	24	40	0.065	High	1.83	3.8
Baglio2	Typic Chromoxerert	A1	30-60	30	24	46	0.069	High	2.52	5.0
Baglio3	Typic Chromoxerert	Ap	0-30	34	27	39	0.103	Very high	1.75	3.8
Baglio3	Typic Chromoxerert	A1	30-60	34	21	45	0.083	High	2.35	4.8
Baglio4	Typic Chromoxerert	Ap	0-30	32	28	40	0.054	Medium	1.80	3.4
Baglio4	Typic Chromoxerert	A1	30-60	33	23	44	0.062	High	2.47	5.1
Baglio 5	Typic Chromoxerert	Ap	0-30	35	28	37	0.132	Very high	2.17	3.5
Baglio 5	Typic Chromoxerert	A1	30-60	21	37	42	0.122	Very high	2.06	3.8
Baglio 6	Typic Chromoxerert	Ap	0-30	42	29	29	0.113	Very high	1.93	3.4
Baglio 6	Typic Chromoxerert	A1	30-60	44	23	33	0.101	Very high	2.59	3.5
Baglio 7	Typic Chromoxerert	Ap	0-30	44	27	29	0.080	High	2.22	3.0
Baglio 7	Typic Chromoxerert	A1	30-60	43	22	35	0.077	High	2.88	3.5

† Soil Survey Staff, 1992
‡ COLE= coefficient of linear extensibility
§ Parker et al., 1977
¶ EC_{sat} = Electrical Conductivity of saturated soil extract
# ESP = Exchangeable Sodium Percentage

Table 2. Hydraulic parameters determined according to the hydraulic conductivity equation proposed by Gardner coupled with the Brutsaert retention equation (*B-G* model).

		Hydraulic parameters						
Soil	**Horizon**	**k_{sat} †**	**θ_s ‡**	**θ_r §**	**α' #**	**n' #**	**β#**	**λ' #**
		cm/h	cm^3/cm^3	cm^3/cm^3	cm^{-1}	cm^{-1}	-	-
Baglio 1	Ap	4,70	0,47	0,23	0,002	0,883	0,079	2,917
Baglio 1	A1	0,30	0,47	0,28	0,017	0,408	1,486	1,650
Baglio 2	Ap	1,49	0,50	0,27	0,038	0,463	2,049	2,270
Baglio 2	A1	0,05	0,48	0,28	0,025	0,322	0,333	3,081
Baglio 3	Ap	4,05	0,47	0,29	0,024	0,876	0,470	4,065
Baglio 3	A1	0,29	0,47	0,29	0,009	0,420	2,659	2,704
Baglio 4	Ap	2,67	0,50	0,25	0,040	0,520	0,068	4,209
Baglio 4	A1	0,11	0,48	0,25	0,032	0,265	1,174	1,321
Baglio 5	Ap	0,78	0,51	0,31	0,0031	0,826	0,130	3,275
Baglio 5	A1	0,03	0,49	0,31	0,0081	0,483	0,313	1,626
Baglio 6	Ap	0,24	0,51	0,31	0,0012	0,514	2,89	1,295
Baglio 6	A1	0,01	0,49	0,32	0,0118	0,500	1,13	1,045
Baglio 7	Ap	1,74	0,55	0,28	0,0174	0,386	1,03	1,98
Baglio 7	A1	0,02	0,53	0,30	0,0730	0,336	0,134	2,48

† k_{sat} = saturated hydraulic conductivity of the soil matrix, fixed at measured value
‡ θ_s = saturated volumetric water content at saturation, fixed at measured value
§ θ_r = residual water content
# parameters of *B-G* model

Management scenarios

Climatic data (rain intensity, maximum and minimum temperature, rainfall height) recorded daily from 08/07/1998 to 31/12/2000 by a rain gauge located in the field were used as input in SWAP. Annual rainfall in 1998, 1999 and 2000 was 390 mm in average and the annual reference evapotranspiration in 1998, 1999 and 2000 was 1450 mm in average. Although an annual amount of irrigation water equal to 120 mm is supplied under normal conditions, due to the constraints of limited water availability, the annual irrigation amount supplied from 1998 to 2000 was very low, and equal to 66 mm in 1998, to 48 mm in 1999, and to 24 mm in 2000. The irrigation season in this vineyard usually ranges from mid June to mid September. A root distribution characterized by 60% roots in the 30-70 cm layer, and by 20% both in the 0-30 cm and in the 70-100 cm layers, was assumed (Crescimanno and Garofalo, 2005). Simulations were performed by using a bottom boundary condition of freely draining profile, and the *B-G* hydraulic parameters were used to simulate water transport.

The following management scenarios were considered:

– *Scenario 1 Irrigation scheduling.* Irrigation with a fixed annual volume of 1120 m^3, and electrical conductivity of irrigation water equal to 6.2 dS m^{-1} (the most critical possible salinity value), but testing different options in terms of number of water applications, i.e.: 1a: eight water applications, which means weekly irrigation; 1b: four water applications, which means irrigation every two weeks; 1c: two water applications, which means a monthly water application. The 1c is the irrigation scheduling more often used in this irrigated area.

To explore how cracks may affect the process of salt-accumulation and/or leaching, scenario 1c was repeated under the hypothesis of no shrinkage, which means no cracking and bypass flow. This scenario was indicated with 1c'.

– *Scenario 2c – Cyclic strategy.* Irrigation with a fixed annual volume of 1120 m^3, but alternating two waters of different salinity. The saline irrigation water is the one used in Scenario1, the less saline water, with EC_w=2.1 dS m^{-1}, which is the value measured during the winter season, is used when the crop is more sensitive to salinity according to the crop physiology.

A performance indicator (Smets et al., 1997) was used to evaluate the impact of management scenarios on salinization:

$$\Delta S = S_f - S_i \tag{3}$$

where S_i and S_f (mg cm^{-2}) represent the quantity of salts accumulated in the soil profile at the starting date and to the end of simulation, respectively.

In order to compare the different scenarios in terms of crop transpiration, and of evaporation, the following ratios were calculated:

$$RT=T_{scen}/T_{1c} \tag{4}$$

$$RE=E_{scen}/E_{1c} \tag{5}$$

where T_{scen} (cm) and E_{scen} (cm) were the actual crop transpiration and evaporation of the considered scenario, and T_{1c} (cm) and E_{1c} (cm) represent transpiration and evaporation obtained by scenario 1c, which is the commonly applied irrigation scheduling in the irrigated area.

RESULTS AND DISCUSSION

Irrigation scheduling (Scenario 1)

Decreasing ΔS values were obtained for the seven profiles passing from scenario 1a to scenarios 1b and 1c (Fig. 1). This result can be explained by the fact that reducing the number of irrigations, and increasing the amount of water applied, determined a higher application intensity (I). Since in all the three scenarios irrigation was performed in summer (starting date June 15), when cracks were open and the hydraulic conductivity (*HC)* of the soil matrix was low, bypass flow of water was prevalent. According to the SWAP, at increasing I, an increasing amount of water, and of dissolved salts, bypasses the upper layers, rapidly reaching the bottom layers. This is the reason why, when irrigation was performed according to scenario 1c, a higher percentage of water and salts bypassed the surface layers compared with scenarios 1b and 1c.

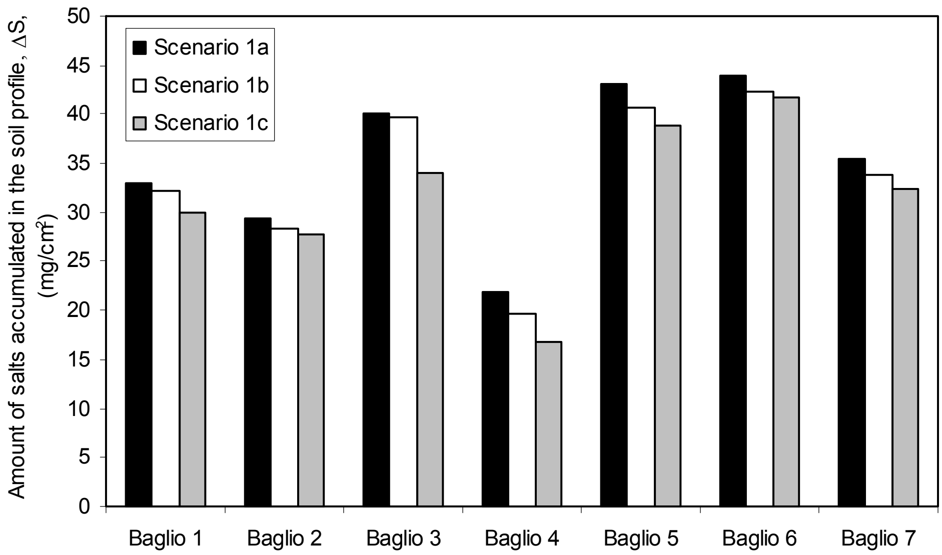

Fig. 1. Amount of solutes accumulated, ΔS (g/cm^2), in the seven soil profiles according to the three considered irrigation scheduling (Scenario 1)

Concerning relative transpiration, the highest *RT* values were associated with scenario 1c (*Table 3*). This was not only a consequence of the lower ΔS, but was also the consequence of water content distribution in the profile after irrigation (Fig. 2, Baglio1 profile). As can be seen in the figure, θ values higher than those obtained by the 1a and by the 1b scenarios were obtained by scenario 1c in the 5-60 cm layer, where the maximum percentage of roots was concentrated, one day after irrigation. This water distribution was the consequence of bypass flow, which promoted storage of water in the deepest layers. Consistently with this water distribution, the lowest evaporation was also obtained in scenario 1c, as demonstrated by the *RE* values (*Table 4*).

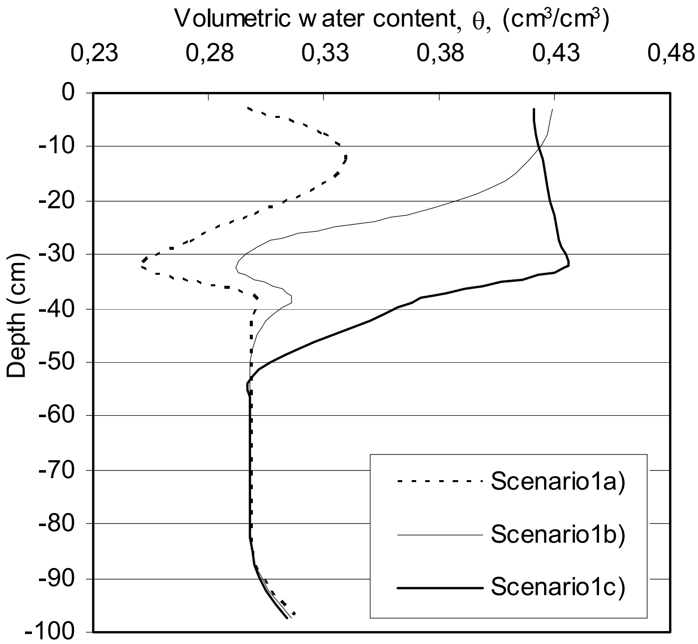

Fig. 2. Water distribution along the soil profile one day after irrigation (Baglio1 profile)

Table 3. Ratio (*RT*) between transpiration (*T*) obtained by scenarios 1a, 1b, 1c and 2c, and T obtained by scenario 1c.

	Scenario 1a	**Scenario 1b**	**Scenario 1c**	**Scenario 2c**	**Actual Transpiration (cm)**
Baglio 1	0,88	0,98	1,00	1,06	29,43
Baglio 2	0,75	0,90	1,00	1,04	44,51
Baglio 3	0,88	0,95	1,00	1,03	43,77
Baglio 4	0,87	0,98	1,00	1,02	43,62
Baglio 5	0,81	0,92	1,00	1,02	44,58
Baglio 6	0,81	0,89	1,00	1,02	28,85
Baglio 7	0,79	0,90	1,00	1,03	35,62

Table 4. Ratio (*RE*) between evaporation (*E*) obtained by scenarios 1a, 1b, 1c and 2c, and *E* obtained by scenario 1c.

	Scenario 1a	**Scenario 1b**	**Scenario 1c**	**Scenario 2c**	**Actual Evaporation (cm)**
Baglio 1	1,04	1,01	1,00	1,00	86,05
Baglio 2	1,19	1,08	1,00	0,99	57,55
Baglio 3	1,11	1,06	1,00	0,99	60,32
Baglio 4	1,08	1,05	1,00	0,99	65,23
Baglio 5	1,15	1,02	1,00	1,00	61,41
Baglio 6	1,07	1,04	1,00	0,99	84,07
Baglio 7	1,10	1,05	1,00	0,99	70,24

These results showed that under our conditions, reducing the number of irrigations, and increasing the irrigation amount at each application, proved to be the best strategy to prevent salinization, also enhancing crop transpiration.

Cyclic strategies (Scenario 2c)

With reference to alternating two waters of different salinity, expressed as EC_w, (first water with lower salinity, then water with higher salinity) (Scenario 2c), the ΔS values obtained by Scenario 2c (Fig. 3) were significantly lower that those provided by Scenario 1c for all seven profiles. This indicated that, as expected, this strategy effectively prevented salinization (Rhoades, 1989; Crescimanno et al., 2002).

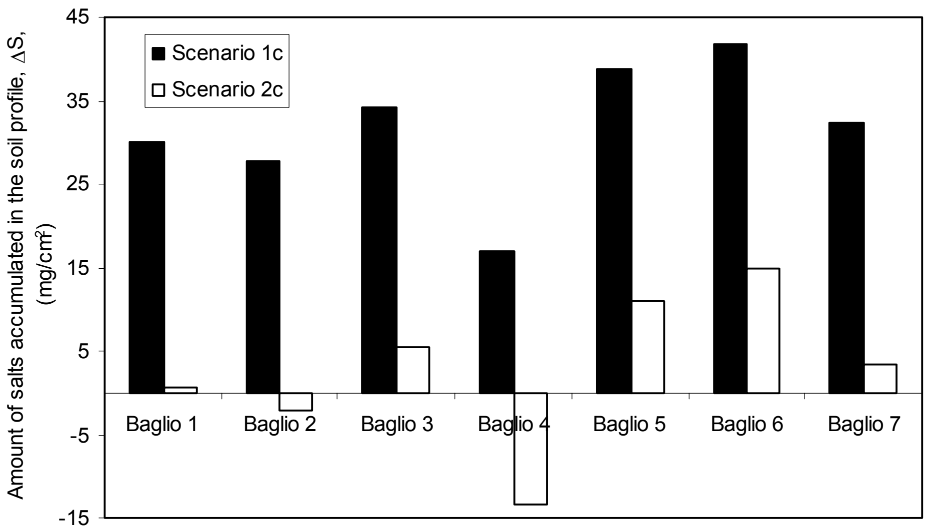

Fig. 3. Amount of solutes accumulated in the soil profiles, *ΔS* (g/cm^2), according to scenarios 1c and 2c.

However, considerable differences were found between the different profiles in terms of *ΔS* (Fig. 3). Negative *ΔS* values, indicating salt-leaching, were obtained only for Baglio4 and Baglio2; negligible *ΔS* values, indicating no solute accumulation, for Baglio1; and positive and increasingly higher *ΔS*, indicating salt-accumulation, for Baglio7, Baglio3, Baglio5 and Baglio6 (in order of increasing *ΔS*).

The negative ΔS values found for Baglio4 and Baglio2 were certainly due to the highest *CWQ*s (Fig. 4); the difference ($diff2 = \Delta S_{1c} - \Delta S_{2c}$) between the ΔS values obtained with scenarios 1c and 2c decreased from 30.40 mg cm^{-2} (Baglio4) to 26.90 mg cm^{-2} (Baglio 6), following the same order in which *CWQ* decreased.

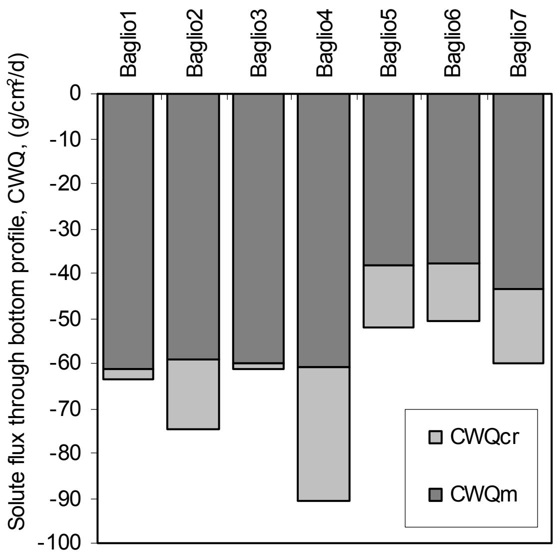

Fig. 4. Overall flux of solutes, *CWQ* (g/cm^2), from the soil profiles in the 2c scenario

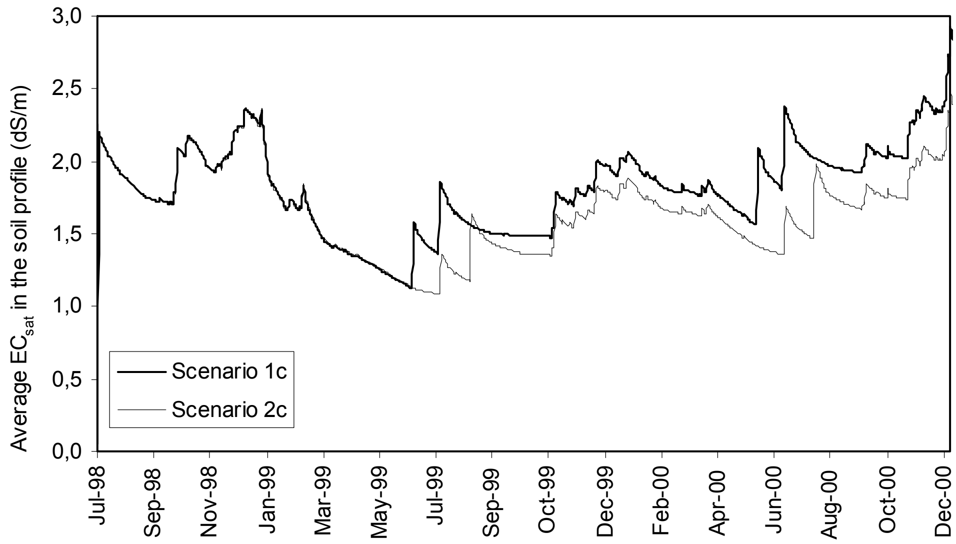

Fig. 5. Average electrical conductivity of the saturated extract, EC_{sat} (dS/m), vs time (Baglio1 profile).

Higher *RT* values corresponded to scenario 2c compared with those obtained by scenario 1c (*Table 3*). This result can be explained by the lower average values of EC_{sat} in the soil profile (Fig. 5), which . determined a higher root water flux, S_a. The same *RE* values (*Table 4*) were found in scenarios 1c and 2c. The reasons for this are that *RE* was not influenced by salinity, and that scenarios 1c and 2c determined the same water distribution along the profile.

Cracking, salinization and salt-leaching (Scenario 1c')

To evaluate the influence of cracks on salinization, and to check the consequences of neglecting shrinkage and cracking on selection of irrigation strategies preventing salinization, scenario 1a was repeated with the assumption of no shrinkage and cracking, i.e. rigid soil (scenario 1c').

The ΔS values obtained by scenario 1c' (Fig. 6) were always higher than those obtained by scenario 1c, in which cracks were taken into account. Since the only difference between scenarios 1c and 1c' was that in this latter scenario the soil was considered as non shrinking, with no cracks, the lower ΔS obtained by scenario 1c certainly depended on the fact that the cumulative water flow from the cracks into the matrix, *CWF* (cm) (Fig. 7), was taken into account. Significantly different *CWF*s were found for the different profiles, with the lowest value for Baglio3, and increasingly higher values for Baglio1, Baglio6, Baglio5; Baglio2 and Baglio7 (in the order of increasing *CWF)*. A significantly higher *CWF* was found for Baglio4. It is interesting to notice that cracks differently affected the difference in ΔS between scenarios 1c and 1c'. For Baglio1 and Baglio3 this difference ($diff1=\Delta S_{1c}-\Delta S_{1c'}$) was negligible; for the other profiles, the effect of the cracks was more pronounced, especially for Baglio2 (*diff1*= 8.0 mg cm^{-2}), Baglio7 (*diff1* = 8.2 mg cm^{-2}) and Baglio4 (*diff1*=16.6 mg cm^{-2}). The increasing order of *diff1* corresponded to a decreasing order of *CWF* (Fig. 7).

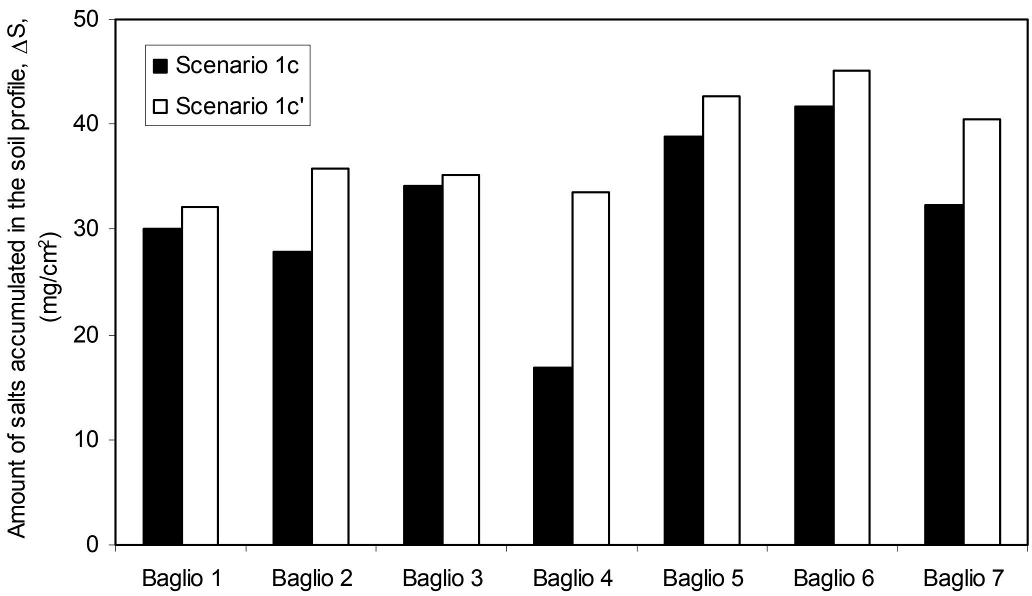

Fig. 6. Amount of solutes accumulated in the soil profiles, ΔS (g/cm^2), in scenarios 1c and 1c'

Comparing results of scenarios 1c and 1c' on the different soil profiles suggested that if cracks and water storage in cracks were not taken into account, the risk of salinization was overestimated. The magnitude of this overestimation depended on the soil shrinkage behaviour, being greater at increasing shrinkage and cracking. For soils showing a considerable susceptibility to shrinkage and cracking, management strategies optimizing irrigation should therefore be obtained by physically-based models taking into account a variable soil volume.

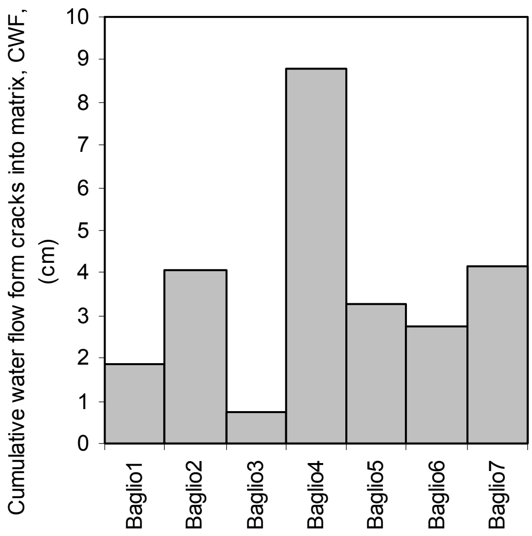

Fig. 7. Cumulative water flow from the cracks into the matrix, *CWF* (cm), obtained for the different profiles

CONCLUSIONS

Analysis of three different irrigation scheduling evidenced that the best scheduling was to make a limited number of irrigations (two in our case), using larger application volumes. This result was found to depend on the water distribution in the soil profile, which in turn depended on bypass flow of water, determined by the higher water application intensity involved in this scenario. As a consequence in our case, bypass flow was a mechanism determining a favorable water distribution. However, this result can be considered valid only for crops developing a deep root distribution. The best irrigation scheduling is therefore a function of soil type and crop characteristics, and the best option is to be found by simulations taking specific site conditions into account.

Cyclic strategy proved to be the best management option to be suggested to reduce the risk of salinization (scenario 2c).With reference to the role of cracks in the process of salt-leaching (Scenario 1c'), the simulations performed indicated that water stored in cracks promoted leaching of the accumulated solutes, and that neglecting the presence of cracks led to overestimating salinization. This overestimation was significant for the soils having a considerable susceptibility to shrinkage and cracking. When irrigation is performed in cracking soils, simulation models taking into account cracks should therefore used to explore sustainable irrigation strategies.

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REFERENCES

Bouma, J. (1991). *Influence of soil macro porosity on environmental quality*. Advances in Agronomy, 46: 1-37.
Bronswijk, J.J.B. (1988). *Modelling of water balance, cracking and subsidence on clay soils*. J. Hydrol., 97:199-212.
Brutsaert, W. (1966). *Probability laws for pore-size distributions*. Soil Science, Vol. 101, No. 2: 85-92.
Crescimanno, G., and G. Provenzano. 1999. Soil shrinkage characteristic curve in clay soils: measurement and prediction. Soil Sci. Soc. Am. J., 63: 25-32, 1999.

Crescimanno, G., and A. De Santis. (2004). *Bypass flow, salinization and sodication in a cracking clay soil*. Geoderma, 121, 307-321.
Crescimanno, G., and P. Garofalo. (2005). *Application and evaluation of the SWAP model for simulating water and solute transport in a cracking clay soil*. Soil Sci. Soc. Am. J. 69:1943-1954 (2005).
Crescimanno, G., M. Iovino and G. Provenzano. (1995). *Influence of salinity and sodicity on soil structural and hydraulic characteristics*. Soil Sci. Soc. Am. J. 59: 1701-1708.
Crescimanno, G., G. Provenzano and H.W.G. Booltink. (2002). *The effect of alternating different water qualities on accumulation and leaching of solutes in a Mediterranean cracking soil*. Hydrological Processes Vol. 16 Issue 3 pp. 717-730.
Crescimanno G, M. Lane, P.N. Owens, B. Rydell, O.H. Jacobsen, O. Düwel, H. Holger Böken, J. Berényi-Üveges, V. Castillo and A. Imeson. (2004). *Reports of the technical working groups established under the thematic strategy for soil protection*. Edited by Lieve Van-Camp, Benilde Bujarrabal, Anna Rita Gentile, Robert J A Jones, Luca Montanarella, Claudia Olazabal, Senthil-Kumar Selvaradjou (2004) EUR 21319 EN/2.
FAO (1990). Food and Agriculture Organization of the United Nations. *Soil map of the World. Revised Legend with corrections*. FAO, Rome.
FAO. (1993). *FESLM. An international framework for evaluating sustainable land management*. World Soil Resources Reports, 73, Rome.
Feigin, A., Ravina, I., Shalhevet, J., (1991). *Irrigation with treated sewage effluent*. Management for environmental protection. Springer-Verlag. Berlin
Gardner, W.R. (1958). *Some steady state solutions of the unsaturated moisture flow equation with application to evaporation from a water table*. Soil Sci. 85, pp. 228-232.
Grattan, S.T., and J.D. Rhoades. (1990). *Irrigation with saline ground water and drainage water*. p. 432–449. In K.K. Tanji (ed.) Agricultural salinity assessment and management. Manual and Rep. on Eng. Practice 71. Am. Soc. of Civil Eng., Reston, VA.
Grossman, R.B., B.R. Brasher, D.P. Franzmeier and J.L. Walker. (1968). *Linear extensibility as calculated from natural-clod bulk density measurements*. Soil Sci. Soc. Am. Proc., 32: 570-573.
Maas, E.V., and G.J. Hoffman. (1977). *Crop salt tolerance-current assessment*. J. Irrig. And Drainage Div., ASCE 103, pp. 115-134
Murray, R.S., and J.P. Quirk. (1980). *Clay-water interactions and the mechanism of soil swelling*. Colloids and Surfaces. 1:17-32.
Parker, J.C., D.F. Amos and D.L. Kaster. (1977). *An evaluation of several methods of estimating soil volume change*. Soil Sci. Soc. Am. J., 41: 1060-1064.
Rhoades, J. D. (1996). *Salinity: Electrical conductivity and total dissolved salts*. In Methods of Soil Analysis, Part 3, Chemical Methods, Soil Sci. Soc. Am. Book Series 5, Amer. Soc. of Agron. Inc., Madison, Wisconsin, pp. 417-435.
Rhoades, J.D. (1989). *Intercepting, isolating and reusing drainage waters for irrigation to conserve water and protect water quality*. Agric. Water Manage. 6:37–52.
Shalhevet, J. (1984). *Management of irrigation with brackish water. In: Soil Salinity under Irrigation*. I Shainberg and J. Shalhevet (eds.) Springer Verlag, New York. Pp. 298-318
Smets, S.M.P., M. Kuper, J.C. Van Dam and R.A. Feddes. (1997). *Salinization and crop transpiration of irrigated fields in Pakistan's Punjab*. Agricultural Water Management, 35, pp. 43-60.
Soil Survey Staff (1992). *Keys to soil taxonomy 8th edition*. SMSS technical monograph n.19, Blacksburg, Virginia. Pochaontas Press Inc., 556 pp.
Szabolcs, I. (1994). *Prospects of soil salinity for the 21st century*. 15th International Congress of Soil Science, Acapulco, Mexico
Tanton, TW, Rycroft, D.W. and F.M. Wilkinson, (1988). *The leaching of salts from saline heavy clay soils: factors affecting the leaching process*. Soil Use and Management, Vol. 4, n. 4
UNEP, (1991). *Status of desertification and implementation of the United Nations plan of action to combat desertification*. UNEP, Nairobi.
van Dam, J. C., J. Huygen, J. G. Wesseling, R. A. Feddes, P. Kabat, P. E. V. van Walsum, P. Groenendijk and C. A. van Diepen. (1997). Theory of SWAP version 2.0. DLO Winand Staring Centre, Wageningen, 1997.
Yaalon, D.H., Kalmar, D. (1978). *Dynamics of cracking and swelling of clay soils: Displacement of skeletal grains, optimum depth of slickensides, and rate of intra-pedonic turbation*. Earth Surf. Proc., 3: 31-42.