Modeling the Effects of Conjunctive Water Management on Secondary Salinization

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ABSTRACT

The shortage of good quality water for irrigation is becoming an important issue in the arid and semi-arid zones. For this reason, the availability of water resources of marginal quality such as saline groundwater has become an important consideration. Saline groundwater is used for irrigation both in isolation and in conjunction with good quality canal water. Due to lack of proper knowledge of management of different quality waters for irrigation, large tracts of irrigated lands are already salinized or under threat. To avoid the process of secondary salinization of soil, irrigation with saline water requires a comprehensive analysis to ensure long-term sustainability of irrigated agriculture. This paper presents the results of a modeling study carried out to evaluate the long-term effects of different quality irrigation water on root zone salinity.

Keywords: Groundwater quality, secondary salinization, modeling, irrigation water quality, conjunctive water use.

INTRODUCTION

In the Indus Basin, inadequacy and unreliability of surface irrigation supplies have turned the farmers more and more to the use of groundwater without the full awareness of the hazard represented by its quality. The massive development of groundwater from the Indus Basin aquifer started about 30 years ago. At present, total groundwater contribution is estimated as approximately 40-50 % of the total water available at the farm gate. This source is exploited by the use of 20,000 public and over 500,000 private tubewells. About 70 % of the private tubewells are located in the canal command areas where groundwater is used in conjunction with canal water, the rest provides irrigation based on groundwater alone. The quality of groundwater is highly variable ranging from fresh (EC $\leq$ 1.0 dS/m) to extremely saline (EC $\geq$ 3.0 dS/m) and is a main factor in the salinity development in the root zone.

The exploitation of groundwater provides an opportunity for the farmers of these areas to supplement their irrigation requirements and cope with the vagaries of the surface supplies. However, the uncontrolled and unregulated use of groundwater is replete with serious consequences as it is aggravating the problem of secondary salinization. As a result, salt affected soils have become an important ecological entity in the Indus Basin of Pakistan. It is estimated that nearly six million hectares area is already affected with this menace, of which about half is in irrigated areas (WAPDA, 1989). Out of this estimated area, about two million hectare are abandoned due to severe

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salinity (Wolter & Bhutta, 1997). The extent keeps on changing due to dynamic nature of the problem.

Over the past three decades, numerous efforts have been made to solve the problem of soil salinization and improve water use efficiency at farm level. In spite of huge investments, the success has been limited. The reasons are that the research conducted to advice farmers on appropriate practices of using different quality irrigation water was generally based on field scale experiments and was not tested for their long-term consequences on crop production and environmental degradation. The results were, therefore, regarded as local and short-term solutions and could not get the attention of the farming community. An integrated water management approach could be useful to manage available surface and subsurface water resources with respect to quantity and quality in view of crop production and soil salinization.

Dynamic simulation models that can calculate soil water and solute transport originating from all water resources in combination with crop growth, are best tools to provide a rapid, flexible and relatively inexpensive means of estimating the effects of various irrigation management practices on crop production under a variety of climatic and physical conditions (Bradford and Latey, 1992; Teixeira et al, 1995). The main objective of this study was to evaluate the long-term effects of different quality irrigation water on soil salinity for the conditions prevailing in the wheat-cotton agro-climatic zone of Rechna Doab, of Punjab, Pakistan. For this purpose, soil water flow model SWAP (Feddes et al, 1978; Belmans et al, 1983) calibrated by Sarwar et al. (2000) for Rechna Doab was used.

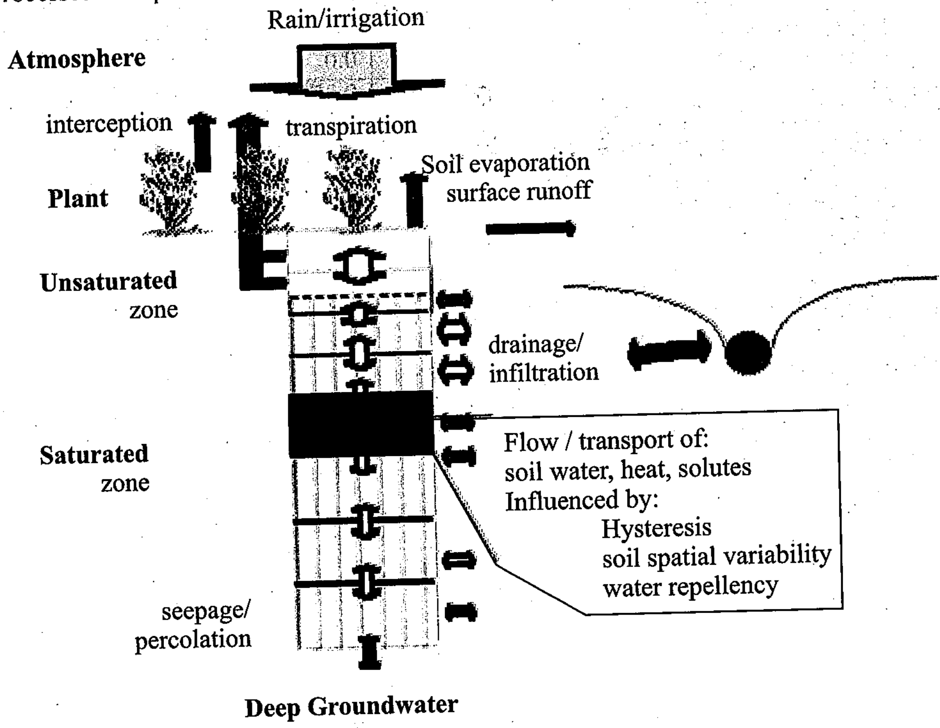
MODEL DESCRIPTION

SWAP (Soil, Water, Atmosphere and Plant) simulates vertical transport of water, solutes and heat in the unsaturated/saturated soils. The program is designed to simulate the transport processes at field scale level as well as during entire growing seasons (Van Dam and Feddes, 2000; Kroes et al., 1999). SWAP employs the Richards' equation for the soilwater movement in the soil matrix, subject to specified initial and boundary conditions and with known relations between soil water content, soilwater pressure head and unsaturated hydraulic conductivity. Rootwater extraction at various depths in the root zone is calculated from potential transpiration, root length density and possible reductions due to wet, dry, or saline conditions. Solute transport is simulated using governing equations of convection, diffusion, and dispersion, non-linear adsorption, first order decomposition and root uptakes of solutes. Different processes simulated by SWAP model are shown in Figure 1.

Crop growth is simulated by using a detailed model WOFOST, which explains crop growth on the basis of processes, such as rate of phenological development, interception of global radiation, CO_2 assimilation, biomass accumulation of leaves, stems, storage organs and roots, leaf decay and root extension. The assimilation rate is affected by water and/or salinity stress in the root zone. SWAP can use simple crop model, when sufficient data is not available or crop growth simulation is not needed. In this case, leaf area index, crop height and rooting depth as function of development stage are prescribed by the user. Basic daily meteorological data are used to calculate daily, potential evapotranspiration according to Penman-Monteith.

Irrigation applications (irrigation timing, depth and water quality) can be prescribed at fixed times or user may choose various timing and depth criteria in order to optimize irrigation application. The scheduling options allow the evaluation of impact of different irrigation scenarios on crop growth and salinity development. The SWAP model can also be used to evaluate drainage design and surface water systems.

Figure 1: Processes incorporated in the SWAP model



Model Calibration and Application

SWAP model was calibrated for the lower Rechna Doab. The area is part of an alluvial plain between the rivers Ravi and Chenab (31°N and 73°E). The climate is continental, sub-tropical and characterized as semi-arid with large seasonal fluctuations in temperature and rainfall. The average annual rainfall is about 350 mm and the class A Pan evaporation is about 2000 mm. The soils of the area are mainly loam to silt-loam underlain by highly conductive aquifer of loamy sand to sandy loam. The model was calibrated for the field conditions on the bases of actual soil, crop, climate and irrigation data (Sarwar, 2000). Wheat-cotton rotation was used for the simulations. Different soil and crop parameters used as input for SWAP calibration are given in Table 1 & 2. The validated model was used to simulate the scenarios to investigate the impact of different quality groundwater either alone or in conjunction with good quality canal water on soil salinity build up.

Table 1: Input parameters used in the SWAP model. The h_1 to h_4 values refer to the sink term theory of Feddes et al. (1978).

Input parameters	Wheat	Cotton
Boesten parameter, β ($cm^{1/2}$)	0.63	0.63
k_c-value for full crop cover	1.15	1.15
Maximum rooting depth (cm)	110	160
Limiting pressure heads (cm)	h_1= -0.1; h_2= -1.0; h_3= -500; h_3'= -900; h_4= -16000	h_1= -0.1; h_2= -1.0; h_3= -500; h_3'= -900; h_4= -16000

Table 2: Calibrated Van Genuchten-Mualem (VGM) parameters used to describe soil hydraulic properties in the SWAP model.

Parameters	Layer 1	Layer 2	Layer 3
Depth of Layer (cm)	0-30	30-280	>280
Soil Texture	loam	Silt loam	loamy sand
Residual moisture content θ_{res}	0.0	0.0	0.028
Sat. moisture content θ_{sat}	0.384	0.509	0.40
Sat. hyd. cond. K_{sat} (cm d^{-1})	60	40	72
Shape parameter α (cm^{-1})	0.0085	0.0090	0.014
Shape parameter n (-)	1.35	1.45	2.663
Shape parameter λ (-)	1.0	1.0	0.5

SCENARIOS STUDIED

In Rechna Doab area, groundwater quality varies from North to South (Figure1). In the upper part of the Doab, groundwater is relatively fresh (EC < 1.0 dS/m) and it keeps on deteriorating as we go to the downstream end of Rechna Doab. In middle, there are several pockets where groundwater quality is marginal (EC = 1.5 – 2.7 dS/m) and in lower part of the Doab groundwater is highly saline (EC > 2.7 dS/m). This ranking of groundwater quality is based on the criteria developed by WAPDA (Latif and Lone, 1992) (Table 3).

Figure 1: Groundwater quality in Rechna Doab.

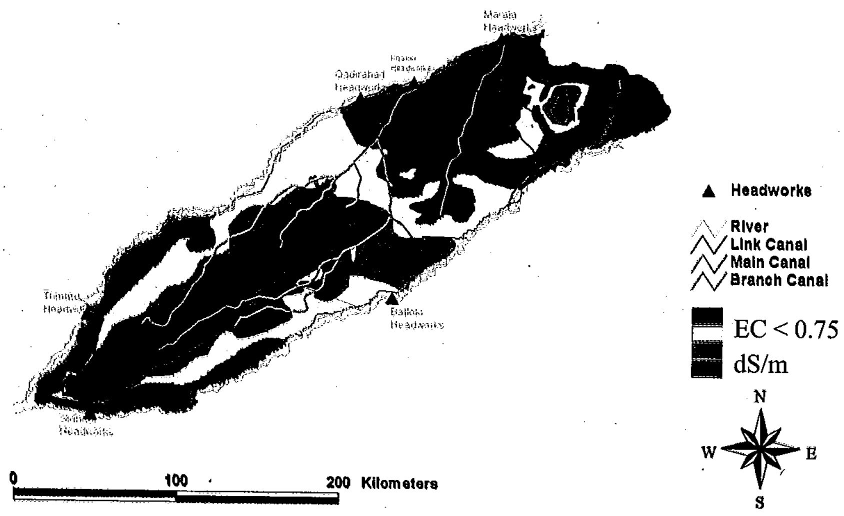


Table 3: Water quality standard for irrigation based on electrical conductivity.

Category	EC (dS/m)
Fresh	< 1.5
Marginal	1.5 – 2.7
Hazardous	> 2.7

In order to develop conjunctive water use strategies for the Rechna Doab, 12 different scenarios considering three groundwater qualities and 3 mixing ratios of surface water (EC = 0.3 dS/m) and groundwater were examined (Table 4).

The effect of these water management scenarios was evaluated on salinity development in the root zone.

Table 4: Scenarios studied using different quality groundwater with combinations of canal water.

Groundwater Quality	Combination 1			Combination 2			Combination 3			Combination 4		
	GW (%)	CW (%)	EC (dS/m)	GW (%)	CW (%)	EC (dS/m)	GW (%)	CW (%)	EC (dS/m)	GW (%)	CW (%)	EC (dS/m)
Fresh	100	0	1.0	80	20	0.86	50	50	0.65	20	80	0.44
Marginal	100	0	1.5	80	20	1.26	50	50	0.90	20	80	0.54
Saline	100	0	3.0	80	20	2.46	50	50	1.65	20	80	0.84

RESULTS AND DISCUSSIONS

Figure 2 shows the salinity development in the root zone when fresh groundwater is used for irrigation in different ratios with canal water. The EC_e values represent the average root zone salinity calculated at 1.0 m deep root zone at the end of each simulation year. Irrigation with fresh groundwater alone does not guarantee the long-term sustainability as the year with below average precipitation enhances soil salinization in the root zone immediately, which also affects the water uptake by the roots (less crop transpiration). However, mixing fresh groundwater with 20 % canal water will keep the root zone salinity below the threshold value of 4 dS/m, although a slightly increasing trend may be witnessed. The value of 4.0 dS/m is usually considered for non-saline soils in Pakistan (Mulk, 1993).

Figure 3 further explains the process of profile salinity built up in the root zone. Irrigation with fresh groundwater alone accumulates salts in shallow depths (i.e., 90 – 150 cm). During the dry years leaching of salts due to monsoon rains become low. Increased soil temperatures forced the salts to move in the upper layers due to capillary action. This phenomenon is much more strong in the areas where watertables are shallow. Mixing fresh groundwater with canal water will keep the salts well below the root zone making it almost impossible to come at the surface even in dry seasons.

Figure 2: Long-term impact of irrigation with fresh groundwater (EC = 1.0 dS/m) on soil salinity

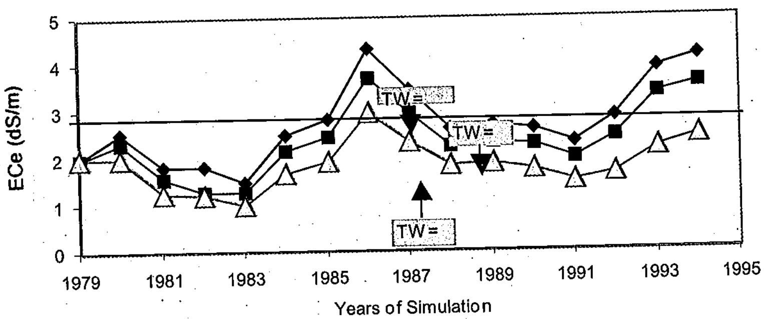
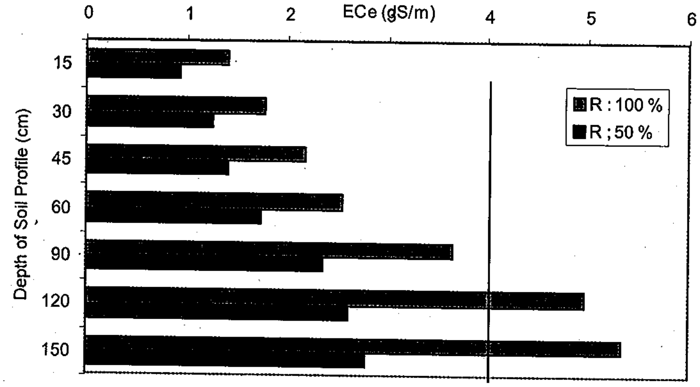


Figure 3: Soil profile salinity with depth after 15 years of simulations, with fresh groundwater irrigation



In the marginal groundwater areas, long-term sustainability can only be achieved by equitable mixing of canal water (Figure 4). By applying marginal groundwater for irrigation alone, the root zone salinity increases sharply in the first 5-6 years and crosses the threshold value of 4 dS/m (Figure 4). Then this salinization process reaches to certain equilibrium with small variation in the salt storage over the years, which can be ascribed to difference in annual precipitation. Figure 5 shows the distribution of salts in the root zone when marginal quality groundwater is used for irrigation alone or in different proportions with canal water. The graph shows that ideally more canal water should be mixed to keep the salts well below the root zone depth. However under water shortage environment 1:1 mixing ratio will at least be required for keeping root zone free of undesirable salt accumulation.

Figure 4: Long-term impact of irrigation with marginal quality groundwater (EC = 1.5 dS/m) on soil salinity

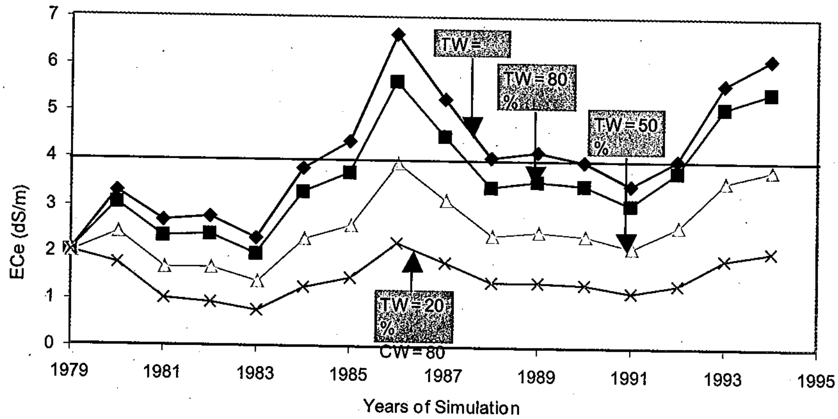
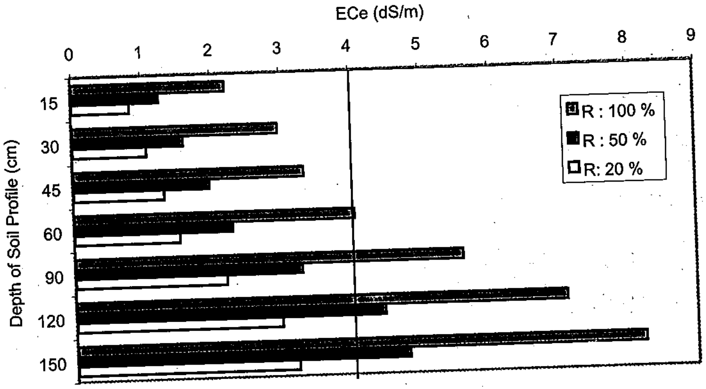


Figure 5: Soil profile salinity with depth, after 15 years of simulations, with marginal groundwater irrigation



The combined analysis of Figures 6 & 7 shows that irrigations with saline water will be a complete disaster. The only scenario, which is slightly sustainable, is that of 80% of canal water mixed with the saline groundwater. Mixing canal water with ratios less than that will not help and lands will go out of production due to salinity in 2-3 years time. Therefore for these areas, other options like growing more salt tolerant crops, eucalyptus or phreophyles should be adopted.

Figure 6: Long Term Impact of Irrigation with Saline Groundwater (EC = 3.0 dS/m) on Soil Salinity

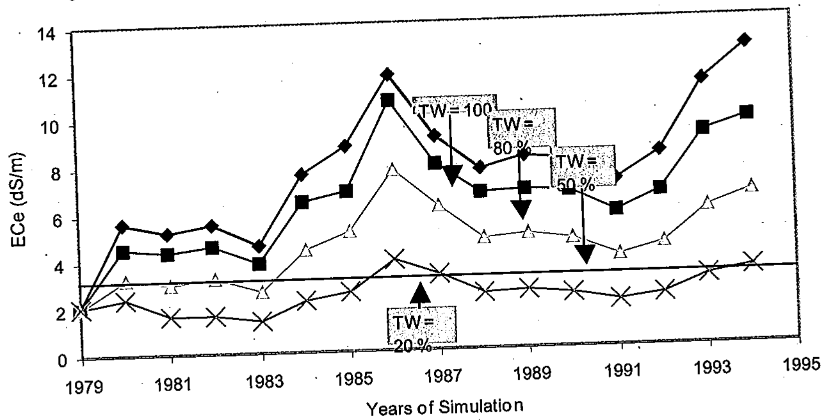
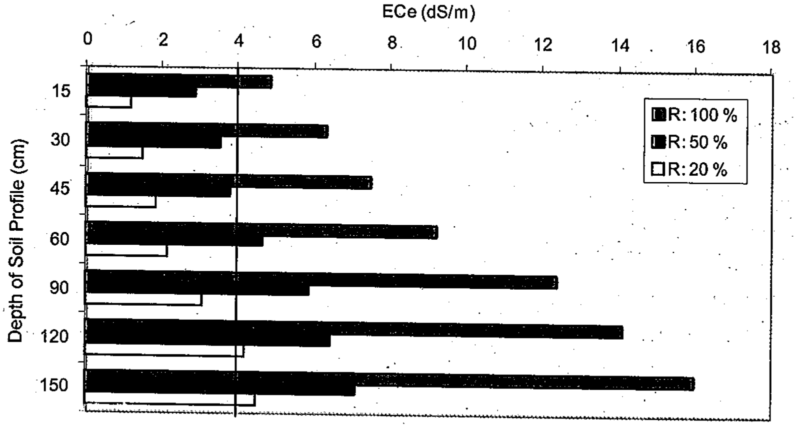


Figure 7: Soil profile salinity status with depth after 15 years of simulations, with saline groundwater irrigation



CONCLUSION

Simulation models such as SWAP are efficient and strong tools to understand and analyze the dynamics of soil salinity in the long run, as influenced by conjunctive use of groundwater with canal water. The following specific conclusions can be drawn:

- In fresh groundwater areas (EC = 1.0 dS/m), the use of groundwater alone for irrigation will build up salinity in the root zone. Occasional leaching will be required for long-term sustainability.
- In marginal groundwater areas (EC = 1.5 dS/m), mixing groundwater and canal water in 1:1 ratio will keep the soil salinity within acceptable limits, however, special leaching would be needed in relatively dry years.
- Irrigation with saline groundwater (EC = 3.0 uS/cm) will be a complete disaster. Mixing this groundwater with canal water will not help in reducing the danger of soil salinization.
- Farmers' present irrigation practices of applying more frequent irrigations with saline water do not help in getting away salts from root zone and this management scenario is not sustainable.

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