RESEARCH
REPORT

86

Strategies for the Management of Conjunctive use of Surface Water and Groundwater Resources in Semi-arid Areas

A Case Study from Pakistan

Asad Sarwar Qureshi, Hugh Turral and Ilyas Masih

International
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Executive Summary

Agriculture is the single largest sector of Pakistan's economy. It contributes about 24 percent of the GDP, directly accounts for about 70 percent of the export earnings and employs more than 50 percent of its civilian force. Because of arid and semi-arid conditions prevailing in most parts of the country, the contribution of direct rainfall to the total crop water requirements is even less than 15 percent. Therefore, irrigated farming is considered as the most economical and remunerative form of agriculture.

This huge gap between water availability and water demand has consistently been met by the exploitation of groundwater. Over the last decade, number of private tubewells in Pakistan has taken a quantum jump mainly because of decreased surface water supplies and incidences of drought. The surface water availability in Pakistani Punjab has reduced by 46 percent from 1996-2001, whereas the number of private tubewells has increased by 59 percent over the same period. This clearly demonstrates the increasing role of groundwater in agriculture.

The on-demand availability of fresh groundwater helped farmers to cope with the vagaries of the surface supplies and achieve more secure and predictable yields. However, the use of poor quality groundwater for irrigation added huge amounts of salts in the root zone, which aggravated the salinity problems. As a result, large tracts of irrigated lands are already salinized and many others are under threat. The major reason of this land degradation is the lack of proper knowledge of farmers to manage different quality waters for irrigation. Therefore, there is every motivation to designate more efforts to formulate strategies for the optimal management of available surface and groundwater resources to ensure long-term sustainability of irrigated agriculture.

In Pakistan, groundwater for irrigation is used both in isolation and in conjunction with canal water. Conjunctive use of surface and groundwater is more common due to two main reasons: (1) to increase the supply of irrigation water and (2) to improve the groundwater quality through dilution. However, farmers are not fully aware of mixing ratios, resultant salinities and their long-term consequences on crops and soils. This stresses the need to develop innovative strategies for the management of available surface and groundwater resources with respect to quality and quantity in view of increasing demand, limited supplies, rising groundwater tables and increasing soil salinization.

This report presents the results of a modeling study carried out to evaluate the long-term effects of a different quality of irrigation water on root zone salinity. The simulations were performed for the Rechna Doab (subbasin of the Indus Basin), Punjab, Pakistan by using 15 years of actual rainfall and climatic data. Rechna Doab covers approximately 2.8 million hectares of cultivated land. Groundwater quality in Rechna Doab varies from north to south. In the upper part of the doab, groundwater is relatively fresh (EC = 1.0 dSm^{-1}), in the middle, there are several pockets where groundwater quality is marginal (EC = 1.5 - 2.7 dSm^{-1}) and in the lower part of the doab groundwater is highly saline (EC > 2.7 dSm^{-1}). In all these areas, groundwater is mixed with canal water in different ratios without knowing the consequences of any quality hazard. For model simulations, groundwater of these three qualities (i.e., 1.0 dSm^{-1}, 1.5 dSm^{-1}, and 3.0 dSm^{-1}) was mixed with canal water in four different ratios i.e., 0 percent, 25 percent, 50 percent and 75 percent. In total 12 different scenarios were generated. The resultant water quality of each scenario was used as input to the model to

study the long-term effects of this water quality on crop production and soil salinization.

The simulation results indicate that in fresh groundwater areas, farmers present irrigation practices i.e., mixing groundwater and canal water with a 1:1, which ratio provides sufficient leaching to push salts below the root zone, thereby minimizing the risk of reduction in crop production. The direct use of fresh groundwater for irrigation will accumulate salts at shallow depths in the root zone, therefore, the risk of an upward movement of salts due to capillary action during a dry year will be high. Under these conditions, occasional leaching with canal water will be necessary to maintain favorable salt balance in the root zone.

In marginal groundwater areas, direct use of groundwater for irrigation can reduce crop transpiration by 3 percent as compared to the scenario when 25 percent of marginal groundwater is mixed with 75 percent of canal water. The role of precipitation in marginal groundwater areas is much more critical than in fresh groundwater areas. The long-term simulations reveal that years with below average rainfall (relatively dry years) will enhance the soil salinization in the root zone, which will affect the water uptake by roots, and crop transpiration during these years could be further reduced by about 10 percent. Therefore, the farmers of these areas need to know the exact amount of crop water demands and leaching requirements in order to halt soil salinization and ensure long-term sustainability of irrigated agriculture.

The irrigations with saline groundwater directly or in conjunction with canal water by any ratio will be a complete disaster. The root zone salinity will start building and whole soil profile will be salinized with salinity levels reaching to 20 dSm^{-1}, making crop production almost impossible. The impact of these high salinity values on transpiration of wheat and cotton crops is relatively low as these crops are moderately to highly tolerant. For more salt sensitive crops, affects of higher root zone salinity can be of much greater magnitude. For the reclamation of these highly saline soils, availability of fresh water resources and installation of extensive drainage systems is a compulsory requirement. Leaching of salts by means of poor quality irrigation water will not be suitable and lands will go out of production even at a faster rate. Therefore, for these areas, other options like growing more salt tolerant crops, eucalyptus or phreophytes should be adapted.

The modeling results indicate that adoption of similar approach for conjunctive use of surface and groundwater resources in fresh, marginal and saline groundwater areas will not be a successful strategy for halting environmental degradation and fostering crop production. This necessitates the need to educate farmers about the long-term implications of conjunctive water use and to provide appropriate guidelines for the optimal management of surface and groundwater resources.

Strategies for the Management of Conjunctive use of Surface Water and Groundwater Resources in Semi-arid Areas: A Case Study from Pakistan

Asad Sarwar Qureshi, Hugh Turral, and Ilyas Masih

Introduction

Increasing demand and decreasing water quality has put enormous pressure on the agriculture sector to use its available water resources more efficiently. These pressures are a result of the increasing demand for food and inter-sectoral competition for water, particularly from the municipal and industrial sector. Therefore, in future, irrigation's contribution to food security will largely depend on the use of low-quality water in agriculture in addition to renewing efforts to achieve water conservation.

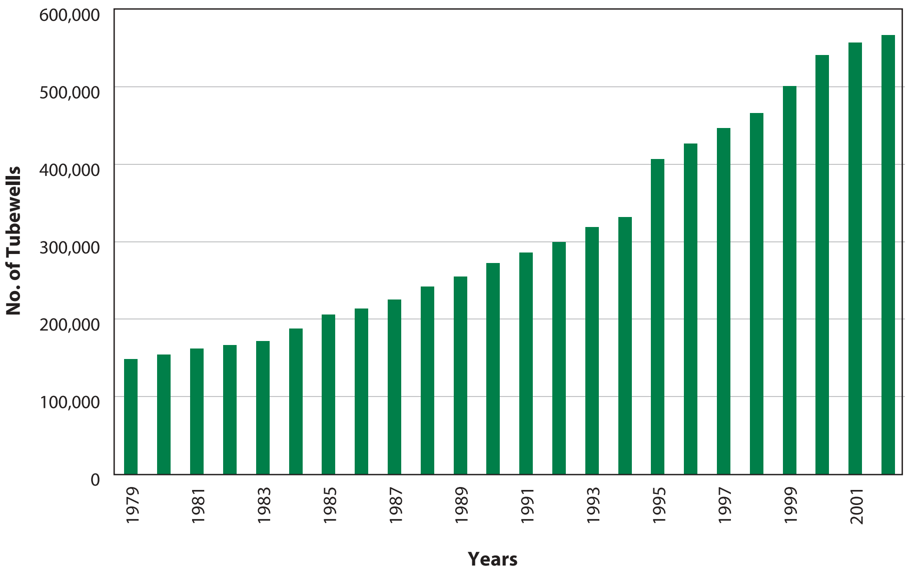
Irrigated agriculture in Pakistan is mainly confined to the Indus Plains where it has been developed by harnessing principal water resources available to the country. Without assured irrigation supplies, these arid and semiarid areas of Pakistan cannot support any agriculture, as the evapotranspiration demand is high and rainfall is either meager or unreliable. The contiguous Indus basin irrigation system irrigates an area of about 16 million ha. The total annual Indus water available to Pakistan is about 181 billion cubic meters (BCM). Of this available water, about 131 BCM are diverted to the 43 main irrigation canal systems, while of the reminder an estimated 11 BCM are lost in the river system and 39 BCM flow to the sea (Badruddin 1996).

The operation of the Indus basin irrigation system is based on a continuous water supply and is not related to actual crop water requirements. Irrigation canals are usually not allocated more than their design capacity, of which a typical value is about 2 mm d^{-1}. Despite significant increase in storage capacities, it is essentially a supply-based system. Hence, it cannot adequately accommodate changing water demands during the crop season. The system was originally designed for an annual cropping intensity (i.e., yearly cropped area) of about 75 percent with the intention to spread the irrigation water over as large an area as possible to expand the settlement opportunities. The major objective of irrigation development at that time was to prevent crop failure and avoid famine (Jurriens and Mollinga 1996). Increasing demand for food to cope with the ever-increasing population has caused the annual cropping intensities to rise to about 150 percent. Due to age and poor maintenance, the delivery efficiency of the irrigation system is low, ranging from 35 to 40 percent from canal head to the crop root zone (Tarar 1995). Moreover, many canals can even no longer convey their official design capacity, due to siltation and erosion of banks. From the scarcity by design and the intensified farmer practices, over time canal water availability per unit of irrigated land has become even more limited.

The surface water resources of Pakistan are finite and potential for increasing water supplies is limited, and there is a likelihood of further reduction in surface supplies through capacity losses in the reservoirs, which is due to siltation and drought. Due to the inadequacy, variability and unreliability of the surface irrigation supplies, the farmers have turned more and more to the use of groundwater to meet their crop water requirements. Therefore, groundwater has gradually acquired a vital role in the development of agricultural and rural economy of Pakistan (Qureshi et al. 2002).

The Indus Basin is underlain by an extensive groundwater aquifer covering about 16 million ha, of which 6 million ha are fresh and the remaining 10 million ha are saline (Haider et al. 1999). The use of groundwater for irrigated agriculture in Pakistan has a long history. However, the large-scale "pumpage" of groundwater for irrigation started during 1960s with the launching of Salinity Control and Reclamation Projects (SCARPs). Under this program more than 20,000 large capacity public tubewells were installed to lower the groundwater table and to supplement irrigation supplies. This demonstration led to a proliferation of private tubewells with a capacity of 0.028 m^3/sec and smaller capacity by farmers in 1970s and 1980s. Subsidized power supply and introduction of country made diesel engines also provided an impetus for dramatic increase in the number of private tubewells. At present, about 600,000 private tubewells are in operation in the Pakistani Punjab (figure 1).

FIGURE 1.
Trends in tubewell development in the Punjab Province of Pakistan.

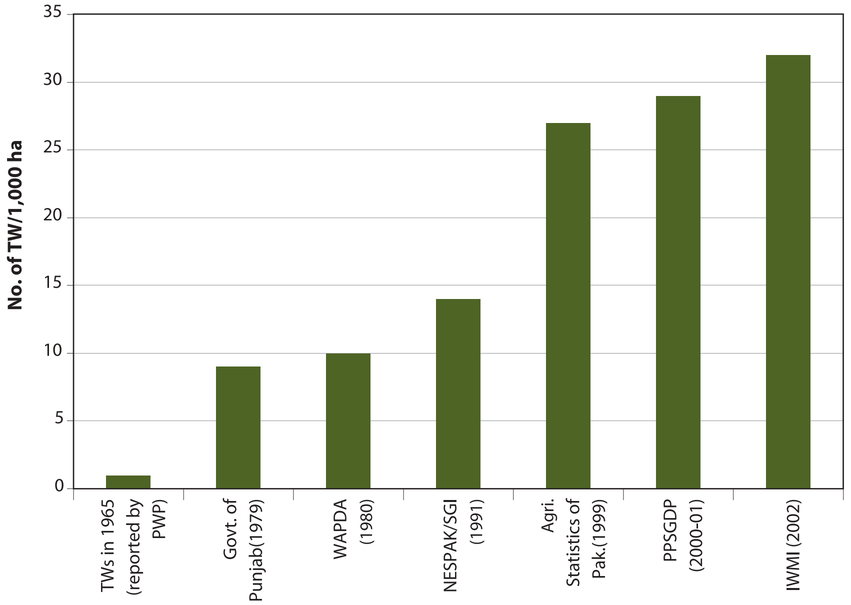


Source: Qureshi and Mujeeb (2003)

These private tubewells are responsible for the abstraction of more than 80 percent of the total groundwater pumped in Punjab and contributes 40-50 percent of the total water available at the farm gate (Haider et al. 1999). About 70 percent of the private tubewells are located in the canal command areas where groundwater is used in conjunction with canal water, whereas the rest provides irrigation using only groundwater. The extent of groundwater use can be gauged by the fact that private tubewell density (number of private tubewells/1,000 ha) in Punjab has increased to 32 in 2002 as compared to only 1 in 1960 (figure 2) (Qureshi and Akhtar 2003). The dramatic increase of almost 100 percent in the private tubewell density during the last 10 years clearly illustrates the increasing dependence of agriculture on groundwater.

The exploitation of usable groundwater provided an opportunity to the farmers of these areas for supplementing their irrigation requirements and cope with the vagaries of the surface supplies. The availability of

FIGURE 2.
Increase in the density of private tubewells in the Punjab Province of Pakistan.

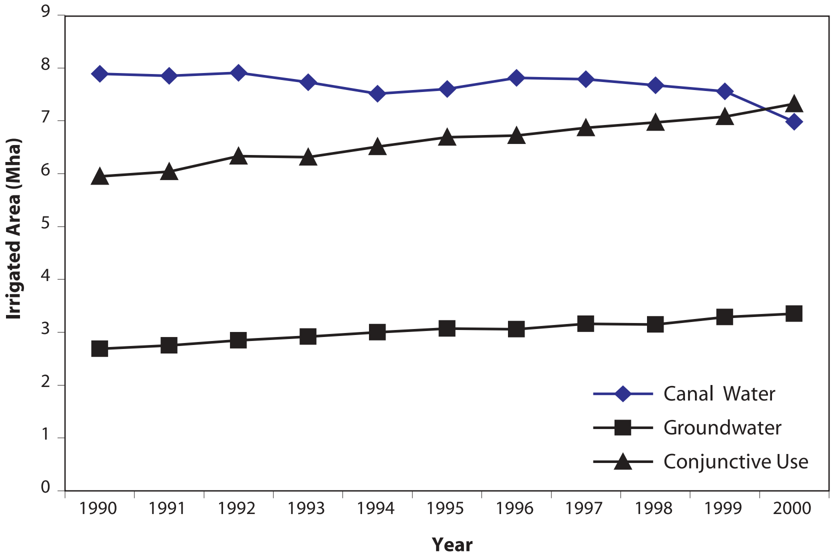


groundwater for irrigation has transformed the concept of low and uncertain crop yields to more secure and predictable form of crop production. However, the present uncontrolled and unregulated use of groundwater is replete with serious consequences as it is depleting the fresh groundwater. The farmers are using groundwater for irrigation without full awareness of the possible hazards due to its quality, which 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 an area of nearly six million hectares is already affected with this menace, of which about half is in irrigated areas (WAPDA 1989). Out of this estimated affected area, about two million hectares are abandoned due to severe salinity (Wolters and Bhutta 1997). The extent of salt-affected area keeps on changing due to dynamic nature of the salinity problem.

In Pakistan, generally two approaches are used for applying irrigation water from two different sources i.e., canal and groundwater. In the first approach, canal and groundwater are used separately in a cyclic mode and, in the second approach, these waters are used simultaneously in a blending mode. Cyclic use is adopted to accommodate significant fluctuations in the canal supplies due to the rotational system. This approach is also used as a strategy to maintain a favorable salt balance in the root zone.

Simultaneous use or blending strategy is mainly used because canal supplies are usually inadequate, and mixing of groundwater with the canal water is necessary to get required flow rate for proper irrigation. By mixing tubewell water with good quality canal water, farmers tend to decrease the salinity of the irrigation water in order to reduce the risk of soil salinization. Although evidences exist that blending of saline and non-saline irrigation water is less effective in keeping soil salinity levels lower than applying cyclic irrigations (Hussain et al. 1990; Shalhevet 1994; Kumar 1995), this strategy is widely practiced in Pakistan. Figure 3 shows the increasing trends in the groundwater use over time. In Punjab, over the last 10 years, the area subject to the conjunctive mode of irrigation has increased by about one million hectares. The way in which water from different sources is combined is

FIGURE 3.
Increasing trend in the conjunctive use of surface water and groundwater resources for irrigation in the Punjab Province of Pakistan.



Source: Qureshi et al. (2002)

also of critical importance to sustain long-term crop production. In Pakistan, farmers mix tubewell water with canal water in different proportions without consideration of the resultant quality and its consequences on crops and lands. As a result, large tracts of irrigated lands are already salinized and many are under threat. Therefore, there is a strong need to make a thorough investigation of the minimum amounts of canal water supplies that are needed to mix with the groundwater to mitigate the adverse effects of poor quality groundwater on soil salinization. This information needs to be generated separately for fresh, marginal and saline groundwater zones. This may provide an opportunity to divert surplus canal water supplies to the areas where groundwater is of poorer quality and the need for fresh water resources is more pressing.

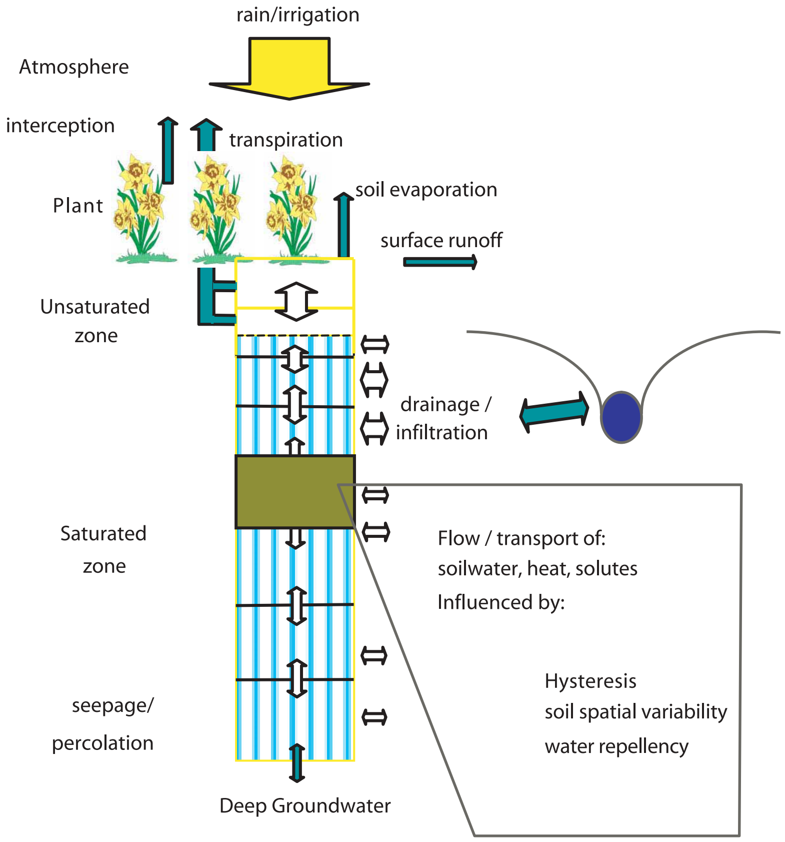
Over the past three decades, numerous efforts have been made to solve the problems of secondary salinization and improve water use efficiency at the farm level. In spite of huge investments, the success has been limited. The reasons are that the research conducted to advice farmers on appropriate practices of using different quality irrigation water is generally based on field scale experiments and is 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.

The application of a particular irrigation strategy depends on the local conditions, such as climate, soil, plants, water availability and traditional irrigation management. 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 Letey 1992; Teixeira et al. 1995). The main objective of this study was to evaluate the long-term effects of different quality irrigation water (obtained through mixing of low-quality groundwater in different ratios with the good quality canal water) on soil salinity for the conditions prevailing in the wheat-cotton agro-climatic zone of Central Punjab, Pakistan. For this purpose, soil water flow model SWAP (Feddes et al. 1978; Belmans et al. 1983) calibrated and validated by Sarwar et al. (2000) 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 the entire growing seasons (Van Dam et al. 1997; Kroes et al. 1999). SWAP employs the Richards' equation for the soil-water movement in the soil matrix, subject to specified initial and boundary conditions and with known relations between soil-water content, soil-water pressure head and unsaturated hydraulic conductivity. Root-water 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 4.

FIGURE 4.
Processes incorporated in the SWAP model.

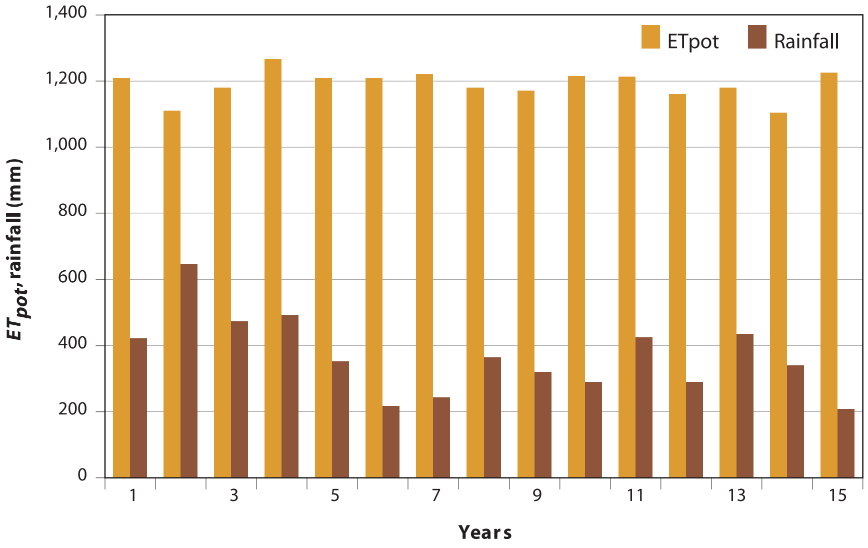


Source: Sarwar, 2000

Crop growth is simulated by using a detailed model called WOFOST, which explains crop growth on the basis of processes, such as the 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. The SWAP can use a simple crop model, when sufficient data is not available or crop growth simulation is not needed. In this case, the user prescribes the leaf area index, crop height and rooting depth as a function of development stage. Basic daily meteorological data are used to calculate 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 the 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 5.
Comparison of annual potential evapotranspiration (ET_{pot}) and rainfall for a period of 15 years (1980-1994).



Source: Sarwar et al. (2000)

Model Calibration

Description of the study area

The data for model calibration was taken from wheat-cotton agro-climatic zone of the Rechna Doab of Pakistan. This area is located in the center of doab and has a longitude of 73°E and latitude of 31°N. The area is subtropical, continental lowland, characterized as semi-arid with large seasonal fluctuations in temperature and rainfall. Summers are long and hot, lasting from April to September, with maximum daytime temperature varying between 27 °C and 43 °C, while in winter, it varies between 4°C and 24°C. The average annual rainfall is about 360 mm. The monsoon, or rainy season, occurs from July to September and accounts for about two-third of the total annual rainfall. One-third falls in winter from January to March as low-intensity frontal rains. A comparison of rainfall and annual potential evapotranspiration, calculated with the Priestley-Taylor (1972) method, for a period of 15 years (1980-1994) is shown in figure 5.

The study area consists of a vast stretch of alluvial deposits, mainly unconsolidated sand and silt with major amounts of clay and gravels. The soils are mainly loam to silt-loam underlain by highly conductive aquifer of loamy sand to sandy loam. These soil types are well representative of the whole Rechna Doab soils. Soil salinity is highly variable. This is mainly due to inequity and uneven distribution of canal water supplies, and use of poor quality groundwater for irrigation.

The average farm size in the area is about 3.75 ha compared to the national average of 5 ha and a decrease in farm sizes is still continuing (Bhatti and Kijne 1992). More than 80 percent of the farms are either owner-operated or owner-cum-tenant operated. The crops are selected, to a small degree, to serve the farmers own household consumptions and for livestock. The crop yields in the area are generally below the national average yields in Pakistan. Wheat, cotton, sugarcane and fodder are principal crops in the area. Next in importance are maize and vegetables.

The irrigation water in the area is transported to the farmer fields through an extensive system of unlined canals and small watercourses. The delivery of water in the tertiary unit is based on a 7-day fixed rotational system called *warabandi*. Each farmer is allowed to take the entire flow of the watercourse once in 7 days. The time of water allocation for each farmer is proportional to his landholding. Mostly farmers use the basin-flooding method to spread water over the fields. The timing and quantity of water applied to each field depends on the wish of the farmer. This system is based on a continuous (but not necessarily constant) supply, which is not related to crop water requirements. Due to limited canal water supplies, farmers are prompted to use more and more groundwater to supplement their crop water requirements.

Input data for model calibration

For the calibration of the SWAP model, a farmer field of 0.2 ha was selected and extensively monitored for 17 months (December 95 to April 97). Soil-water Pressure heads, soil moisture contents, electrical conductivity of soil saturation paste (EC_e), irrigation depths, meteorological data and other related soil and crop parameters were measured.

Daily climatic data (rainfall, sunshine hours, wind speed, maximum and minimum temperatures) for this period were taken from the meteorological station situated in the study area. These data were used to calculate reference evapotranspiration (RET) by Priestley and Taylor (PT) method (Priestley and Taylor 1972). Potential evapotranspiration (PET) was obtained by multiplying reference evapotranspiration (RET) with the crop factor (Kc). The PT method was preferred because it has been recommended for conditions that are similar to Pakistan, where the differences in surface and air temperatures are minimal i.e., where sensible heat flux is low and latent heat flux is high (Paw U and Gao 1988; Kumar and Bastiaanssen, 1993). The depths of all irrigations applied to the monitoring field were recorded and used as input for model calibration.

The upper boundary condition of the soil profile was described on a daily basis by potential evapotranspiration rate (PET), actual rainfall and irrigation. The daily groundwater table depth was measured with the help of piezometers and was used as a bottom boundary condition. The maximum rooting depth for wheat and cotton was taken as 110 cm and 160 cm, respectively (PARC 1982). Root length density distribution was considered to decline linearly with depth. The Boesten model (Boesten and Stroosnijder 1986) was used for the reduction of the potential soil evaporation rate into actual soil evaporation rate. The values of limiting pressure heads for regulating root water uptake were taken from Taylor and Ashcroft (1972). The different input parameters used in the SWAP model are given in table 1.

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= -16,000	h_1= -0.1; h_2= -1.0; h_3= -500; h_3' = -900; h_4= -16,000

Source: Sarwar, 2000

On the basis of change in physical properties, soil profile of 480 cm was divided into three layers. The first layer is from 0-30 cm, second from 30-280 cm and third beyond 280 cm. The soil hydraulic properties of all three layers were described by the six Van Genuchten-Mualem (VGM) parameters (Van Genuchten 1980; Mualem 1976). These parameters are saturated soil moisture content (θ_s), residual soil moisture content (θ_r), empirical shape parameters (α, n, λ) and saturated hydraulic conductivity (K_s). The four VGM parameters (θ_s, θ_r, α and n) for the first two layers were derived from the field measurements of pressure heads and soil moisture content whereas the two parameters (λ and K_s) were optimized during the calibration process. The parameters for the third layers were taken from Beekma (1993) as they could not be measured in the field due to the presence of high water table conditions. The calibrated VGM parameters for the three layers are given in table 2.

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

Layers	Depth (cm)	Soil texture	VGM parameters					
			θ_s	θ_r	α(cm^{-1})	n(-)	λ(-)	K_s(cm d^{-1})
1	0-30	Loam	0.384	0.0	0.0085	1.35	1.0	60
2	30-280	Silt Loam	0.509	0.0	0.0090	1.45	1.0	40
3	> 280	Loamy sand	0.40	0.028	0.014	2.663	0.5	72

Source: Sarwar, 2000

Measured pressure head values at different depths were used as initial conditions for water balance calculations, whereas, measured EC_e values at different depths were used for salt balance calculations.

The salinity parameters in the classical convection-dispersion equation that describe salt transport are the dispersivity, L_{dis} (cm), and the diffusion, D_{dif} (cm^2 d^{-1}). Under field conditions with irrigation, solute spreading due to dispersion is much more pronounced than solute spreading due to diffusion. The value of L_{dis} typically ranges from 0.5 cm, or less, for laboratory scale experiments involving disturbed soils, to about 10 cm or more for field scale experiments (Nielsen et al. 1986). The values for L_{dis} and D_{dif} that gave best results of simulated profiles $EC_e(z)$ were 15 cm and 0.48 cm^2 d^{-1}, respectively.

Results of Model Calibration

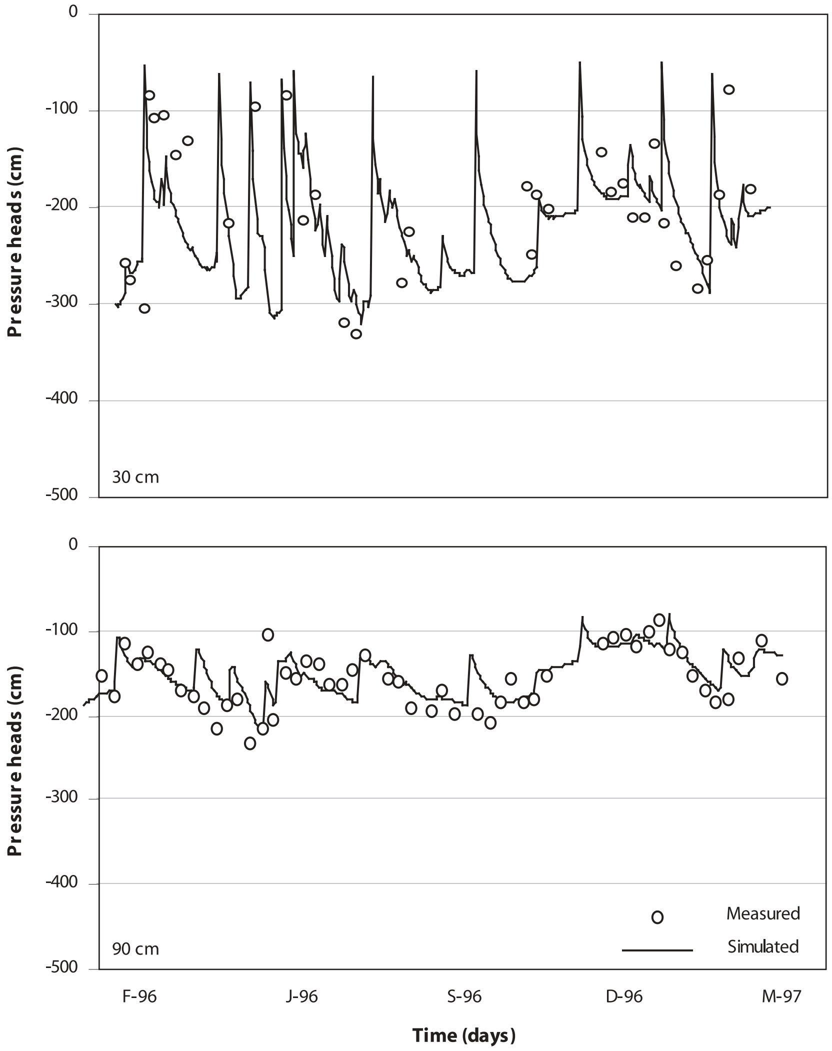
The measured pressure heads, soil moisture content and EC_e values were compared with the simulated results for model calibration (Sarwar et al. 2000). Pressure heads were measured in the field by means of tensiometers, installed at eight different depths (15, 30, 45, 60, 90, 120, 150 and 200 cm) and were read weekly. For the determination of soil moisture content, Time Domain Reflectometery (TDR) tubes (Topp et al. 1980) were installed at the same depths as that of tensiometers and were also read weekly. Salinity measurements for monitoring the field were taken at the beginning and end of each growing season by electromagnetic induction with EM38 equipment (McNeill 1986). Measurements were taken at 40 different locations for each sample field. EM38 measures apparent electrical conductivity (EC_a) in the first one meter of the soil profile. These EC_a values were then converted into EC_e values using equations developed by Beekma (1994) for this area. The measured EC_e values from the monitoring field were available for a limited number of days. Therefore, a comparison could only be accomplished for these days. The Root Mean Square Error (RMSE) was calculated to quantify the agreements between simulated and measured values. The RMSE represents how much the simulation overestimated or underestimated the actual field measurements.

$$RMSE = \left[\frac{\sum_{i=1}^{n} (M_i - S_i)^2}{n} \right]^{1/2}$$

Where M_i and S_i are the measured and simulated values at the end of day i and n is the number of days of observation.

Figure 6 shows the comparison of measured and simulated pressure heads at 30 cm and 90 cm depths. The results indicate that the measured trends of pressure heads at both depths are in good agreement with the model-simulated values. The RMSE for all depths was 29 cm (n = 88).

FIGURE 6.
Comparison of measured and simulated pressure heads at 30 cm and 90 cm depths.

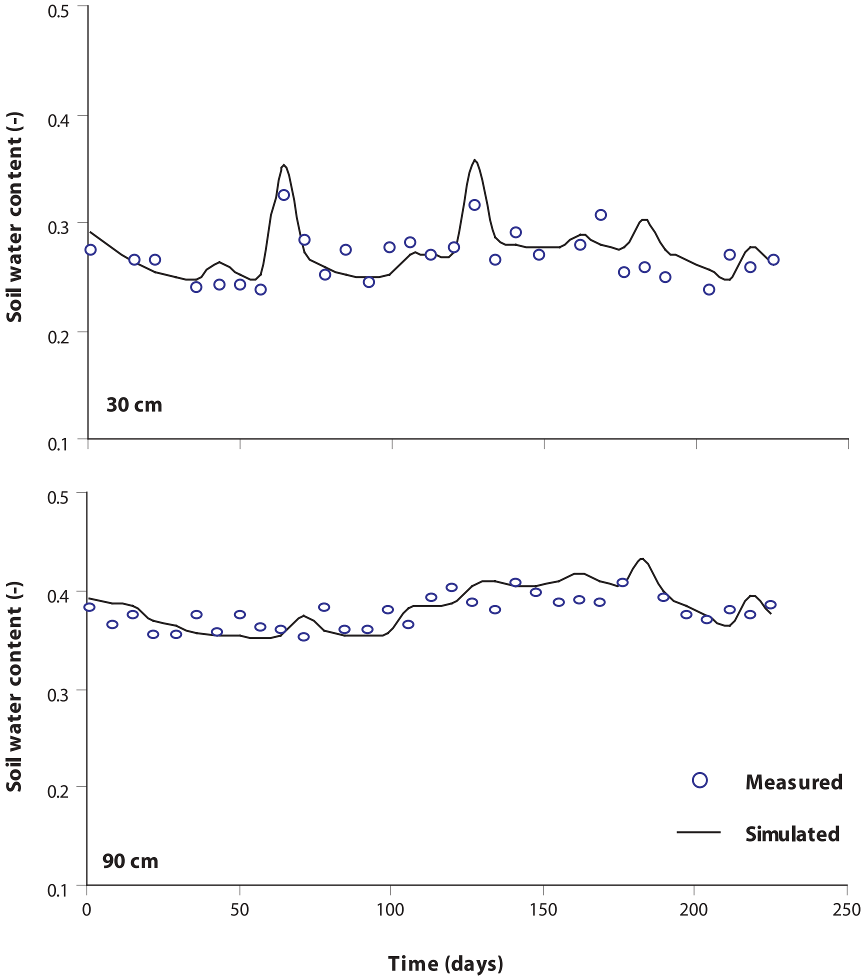


Source: Sarwar et al. (2000)

Figure 7 shows a typical example of measured and simulated soil water contents at 30 cm and 90 cm depths. The results indicate that the simulated soil water contents match quite well with the measured soil water contents at both depths. The RMSE for the volumetric soil water contents for all depths was 0.020 cm^3cm^{-3} (n = 170). This close match between measured and simulated values gives confidence on calibrated model parameters for the water balance component.

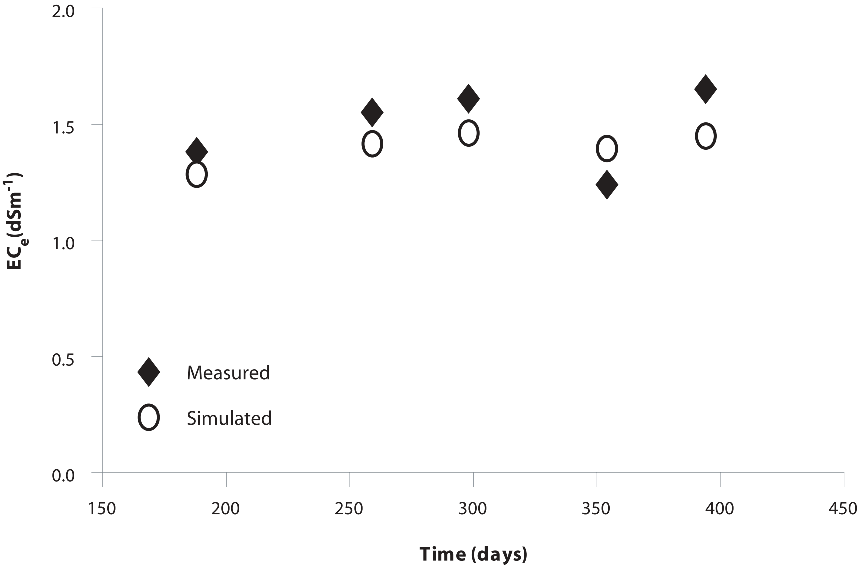
Figure 8 shows a comparison of measured and simulated EC_e values averaged over first one meter of the soil profile. The results indicate a close proximity between measured and simulated EC_e values. The root mean square error for EC_e was 0.15 dSm^{-1}, which satisfy the parameter values used for the calibration of solute transport.

FIGURE 7. Comparison of measured and simulated soil water content at 30 cm and 90 cm depths.



Source: Sarwar et al.(2000)

FIGURE 8. Comparison of measured and simulated ECe values (0-100 cm depth).



Source: Sarwar et al. (2000)

Model Application for Scenario Calculations

Simulations were performed for a period of 15 years using actual rainfall and climatic data from 1980 to 1994. Model simulations were performed for wheat-cotton crop rotation, which is the largest crop rotation system in the Indus Basin comprising over 4.5 million hectares (Mulk 1993).

The irrigation schedules in the Rechna Doab vary a lot. Farmers having access to groundwater in addition to canal water tend to apply more water compared to those who are fully dependent on canal water. The studies carried out by Vlotman et al. (1994) and Raza and Choudhary (1998) have shown that the number of irrigations to wheat crop varies from two to six and to cotton from four to six. In such a heterogeneous cropped and irrigation environment of the Rechna Doab, it was difficult to translate the behavior of individual farmers into an average condition. Therefore, in this study, altogether twelve irrigations for two crop seasons in a year are assumed. A total of five irrigations to wheat and five to cotton crop apart from two pre-sowing irrigations, one each for wheat and cotton are considered. This is similar to the recommended irrigation schedule by the Punjab Agricultural Department for the wheat-cotton cropping zone and is usually followed by the farmers.

The depth of each irrigation application has been a subject of many research studies (Willardson 1992; Vehmeyer 1992; Vlotman and Latif 1993; Raza and Choudhary 1998). These studies have found that average depth of water applied per irrigation ranged from 60 to 70 mm. Therefore, for this study, the depth of each irrigation was taken as equal to an average irrigation of an upland crop in Pakistan i.e., 65 mm (OFWM 1980). The amount and number of irrigations were kept constant for the years of simulations.

The groundwater table depths are generally shallow (3 to 5 m), however, it varies considerably before and after the monsoon season. The groundwater quality in the area is also variable. Therefore, groundwater table depth for this study was taken at 5 m below the soil surface.

In Rechna Doab area, groundwater quality varies from north to south (figure 9). In the upper part of the doab, groundwater is relatively fresh (EC < 1.0 dS/m) and it keeps on deteriorating towards the downstream end of the Rechna Doab. In the middle of the doab, 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 classification of groundwater quality is based on the criteria developed by WAPDA (Latif and Lone 1992 — table 3). Because of its poor quality, groundwater is usually applied in conjunction with the canal water.

Salinity surveys conducted in the Rechna Doab between 1990-1996, show that average salinity of soil profile up to a depth of 2.0 m varies between 1.5 and 2.6 dS/m with an average value of about 2.0 dS/m (Raza and Choudhary 1998). As depth-wise salinity data were not available, this average value was used as an initial condition for the salt balance simulations. For salinity stress the response functions of Mass and Hoffman (1977) were used.

FIGURE 9.
Variation in groundwater quality in the Rechna Doab of Punjab, Pakistan.

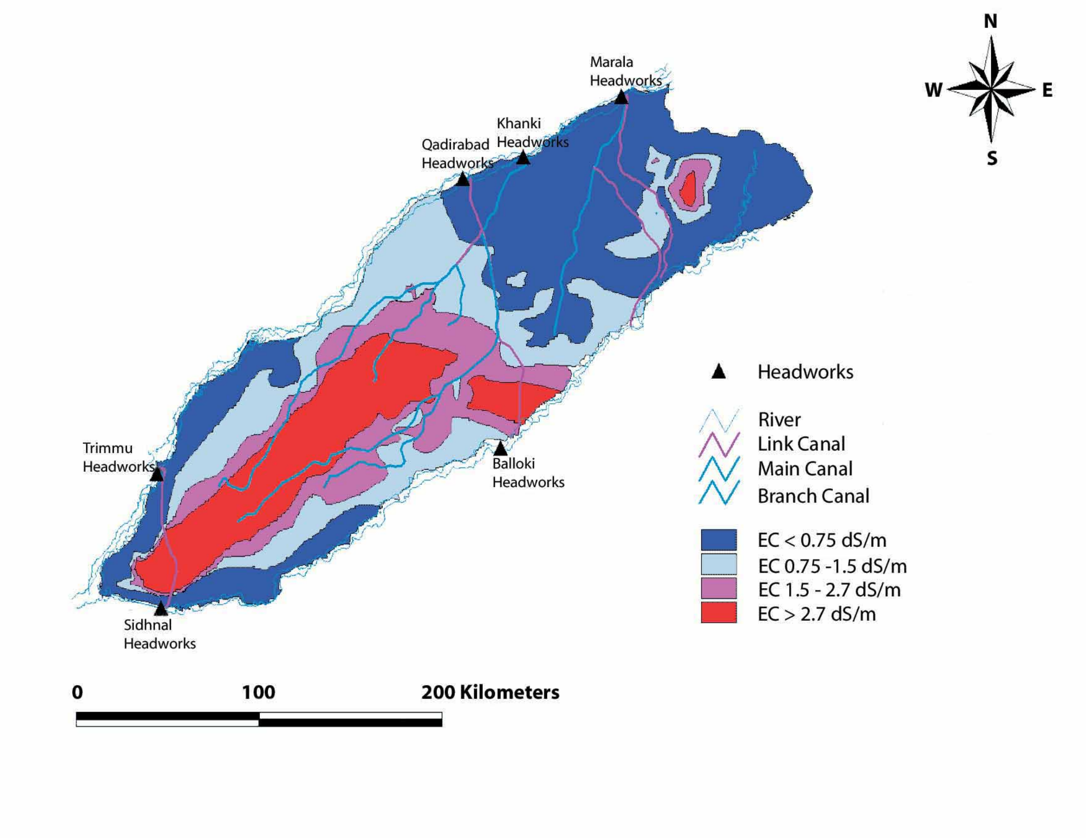


Table 3: Water quality standard for irrigation based on electrical conductivity.

Category	EC (dS/m)
Fresh	1.0 - 1.5
Marginal	1.5 - 2.7
Hazardous	> 2.7

Source: Latif and Lone (1992)

In order to develop conjunctive water use strategies for the Rechna Doab, 12 different scenarios were developed. Three groundwater qualities mentioned in table 3 were mixed in four different ratios (25%, 50%, 75% and 100%) with the canal water (EC = 0.3 dSm^{-1}). The resultant water quality (EC) after each mixing was used in the model to evaluate the long-term effects of these waters on salinity build up in the root zone. Table 4 gives an overview of the 12 scenarios used in this study.

Table 4. Description of different scenarios evaluated in this study.

Scenarios	Description	Resultant EC (dSm^{-1})
Fresh Groundwater (FGW) (EC = 1.0 dSm^{-1})		
FGW100	100% FGW and 0% CW	1.00
FGW75	75% FGW and 25% CW	0.83
FGW50	50% FGW and 50% CW	0.65
FGW25	25% FGW and 75% CW	0.50
Marginal Groundwater (MGW) (EC = 1.5 dSm^{-1})		
MGW100	100% MGW and 0% CW	1.50
MGW75	75% MGW and 25% CW	1.20
MGW50	50% MGW and 50% CW	0.90
MGW25	25% MGW and 75% CW	0.60
Saline Groundwater (SGW) (EC = 3.0 dSm^{-1})		
SGW100	100% SGW and 0% CW	3.00
SGW75	75% SGW and 25% CW	2.30
SGW50	50% SGW and 50% CW	1.65
SGW25	25% SGW and 75% CW	0.98

Results and Discussions

Conjunctive water management in fresh groundwater areas

Figure 10 shows the salinity development in the root zone when fresh groundwater is used for irrigation in different ratios with canal water. The simulations for a continuous period of 15 years show that there is a clear effect of different irrigation water qualities on salinity build up in the soil profile. The EC_e values represent the average root zone salinity for 100 cm depth at the end of each simulation year. Irrigation with fresh groundwater alone (EC = 1.0 dSm^{-1}) does not guarantee the long-term sustainability as in the years of below average precipitation (years 6 to 10) it enhances soil salinization in the root zone immediately, which might affect the water uptake by the roots and reduce crop transpiration. However, in all other combinations of mixing fresh groundwater with canal water will keep the root zone salinity below the threshold value of 4.0 dSm^{-1}, although a slightly increasing trend may be witnessed in the years of deficit rainfall. The value of 4.0 dSm^{-1} is usually considered for non-saline soils for most of the crops in Pakistan (Mulk 1993).

FIGURE 10. Temporal development of average root zone salinity as influenced by the conjunctive use of fresh groundwater (EC = 1.0 dSm-1) and canal water in four different ratios.

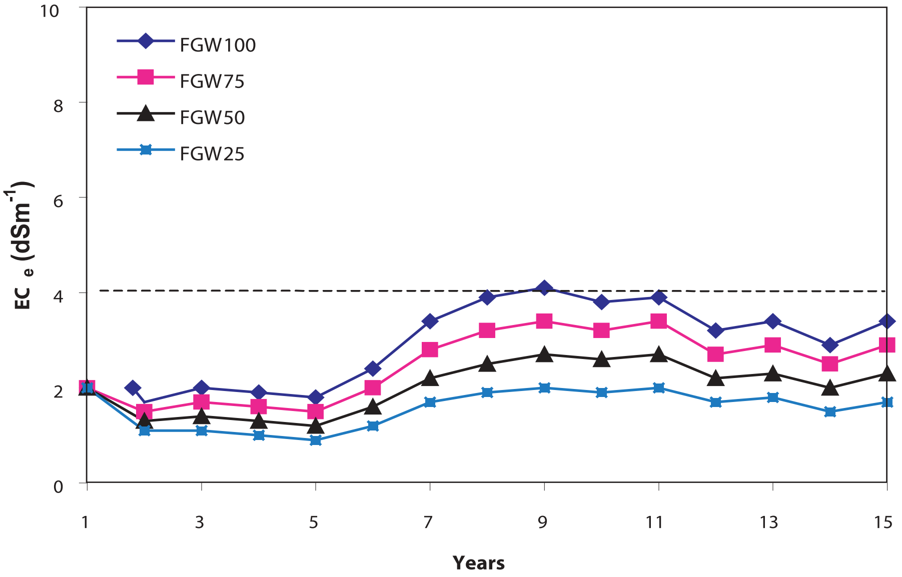
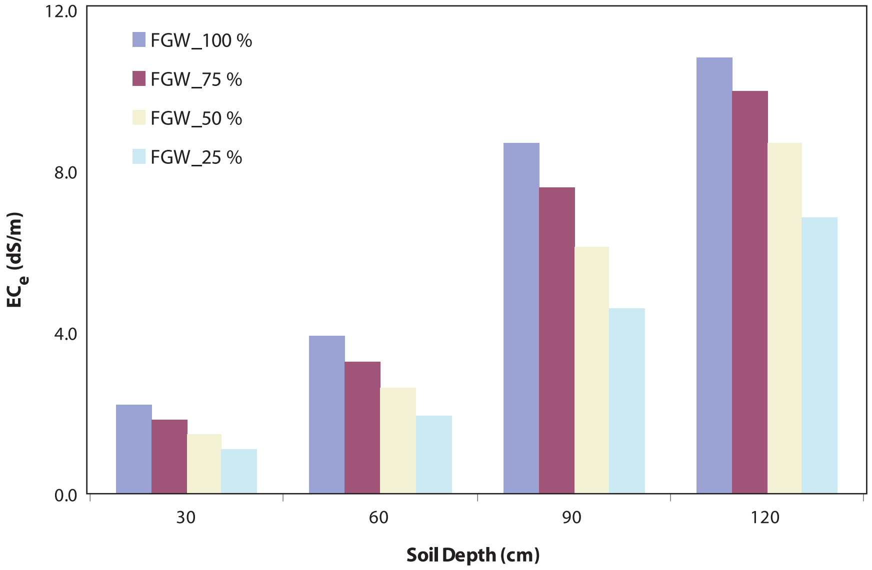


Figure 11 presents the salt build up at different depths of the root zone as influenced by different irrigation water qualities at the end of the simulation period of 15 years. Irrigation with fresh groundwater alone accumulates salts in deeper depths (90-120 cm) of the root zone**.** The salinity development is shown only up to 120 cm depth because the presence of excess salts at this depth is mainly responsible for reducing crop transpiration by limiting root water uptake. During dry years when soil temperatures are high and leaching of salts is low due to less rainfall, these salts may move to upper layers of the root zone due to capillary action. This phenomenon could be much stronger in the areas where groundwater tables are shallow. Mixing groundwater with canal water in 1:1 ratio provides sufficient leaching to push the salts below 1.0 m of the soil profile and thereby reducing the chances of movement of salts to the upper layers of the soil profile during the dry and hot years.

FIGURE 11. Development of salinity at different depths in the root zone as influenced by the conjunctive use of fresh groundwater and canal water in four different ratios.



The impact of different quality irrigation water on crop transpiration and salinity build up in the root zone is summarized in table 5. SSC referred to as Salt Storage Change, which is defined as $\Delta C/C_{initial}$. Where ΔC is the change in salt storage over a certain period and $C_{initial}$ is the salt storage at the beginning of the time period considered. Ideally, SSC should be zero, whereas negative or positive SSC values indicate reduction or build up in salt accumulation, respectively. However, in view of saline groundwater conditions, a small build up of salts is tolerable.

TR referred to as relative transpiration (T_a/T_p= actual transpiration/potential transpiration), which is considered equivalent to crop yields. It is certain that the crop yield is affected not only by this factor, but inclusion of other factors (crop variety, fertilizers, disease and pest management) is beyond the scope of this study. Therefore, these non-water factors are considered to be optimal for all scenarios.

Table 5: Simulated 15-year average annual water and salt balances for four different scenarios using fresh groundwater.

Scenario	Rainfall (mm)	Irrigation (mm)	T_a (mm)	T_p (mm)	TR (-)	SSC (-)
FGW_{100}	375	780	867	903	0.96	-0.18
FGW_{75}	375	780	875	903	0.97	-0.32
FGW_{50}	375	780	882	903	0.98	-0.47
FGW_{25}	375	780	893	903	0.99	-0.75

The data presented in table 5 shows that with the farmers present irrigation practices, maximum relative transpiration for both wheat and cotton crops can be obtained irrespective of the ratio with which fresh groundwater is mixed with the canal water. This shows that 780 mm depth of water applied by farmers not only fully meets the crop water requirements but also provides sufficient leaching of salts to maintain root zone salinity below threshold values of wheat and cotton crops. The negative SSC values given in table 5 further strengthen this argument.

Figure 10 shows slightly increasing trends of salinity build up for scenarios FGW_{100} and $FGW_{75,}$ but the overall salinity hazard for crops remains in control. Farmers applying irrigation water less than this amount might have a higher risk of soil salinization, particularly under the FGW_{100} scenario. This can be true for the farmers located at the tail end of the canals where surface water supplies are almost negligible and the availability of groundwater is out of reach for them, either due to the price or the quality of it.

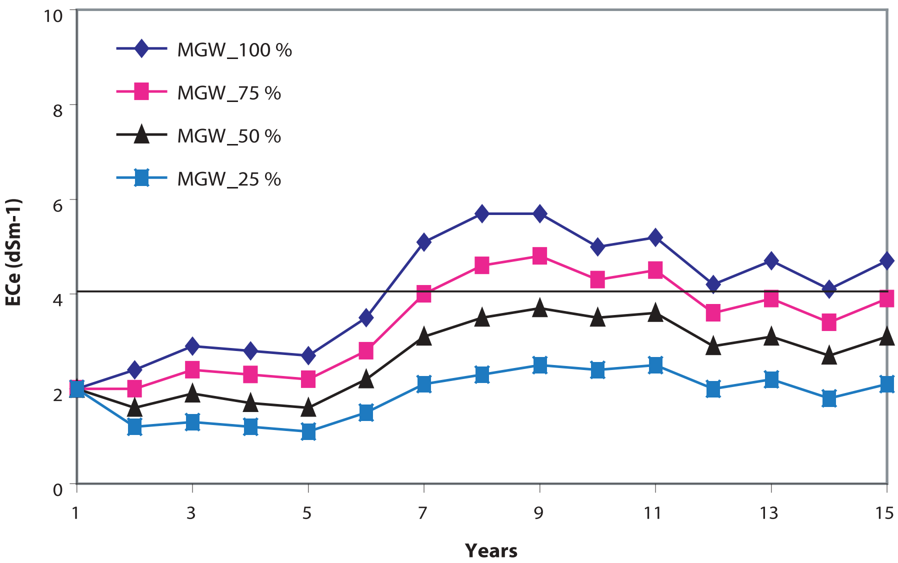
The detailed analysis of the 15 years of transpiration data reveals that in dry years, relative transpiration can be reduced substantially i.e., relative transpiration for year 6 reduced to 0.86, which is 11 percent lower than a normal year. This reduction can be attributed to increased salinity in the root zone (figure 10) owing to insufficient leaching and higher crop water demands due to relatively higher temperatures. This means that farmers need to adjust their irrigation applications according to the changing climatic conditions.

Conjunctive water management in marginal groundwater areas

Figure 12 shows that the direct application of marginal groundwater for irrigation (without mixing with the canal water) or mixing it with 25 percent of canal water, the root zone salinity for the first 5 years remains within safe limits and reduction in crop transpiration is not very likely due to salt stress. However, after this period, salinity increases sharply and crosses the threshold value of 4 dSm^{-1}. Then this salinization process reaches a certain equilibrium with more or less of a constant salt storage. The small variations in the salt storage over the subsequent years can be ascribed to differences in average annual precipitations (figure 5). Figure 12 also reveals that in the years of below average precipitation (years 6 to 10) soil salinization enhances in the root zone, which might affect the water uptake by roots. Mixing of marginal groundwater with canal water in 1:1 ratio seems more practical from sustainability point of view, as this may keep the root zone salinity below threshold levels.

Figure 13 shows the distribution of salts in the root zone when marginal quality groundwater is used for irrigation directly or in different proportions with canal water. The

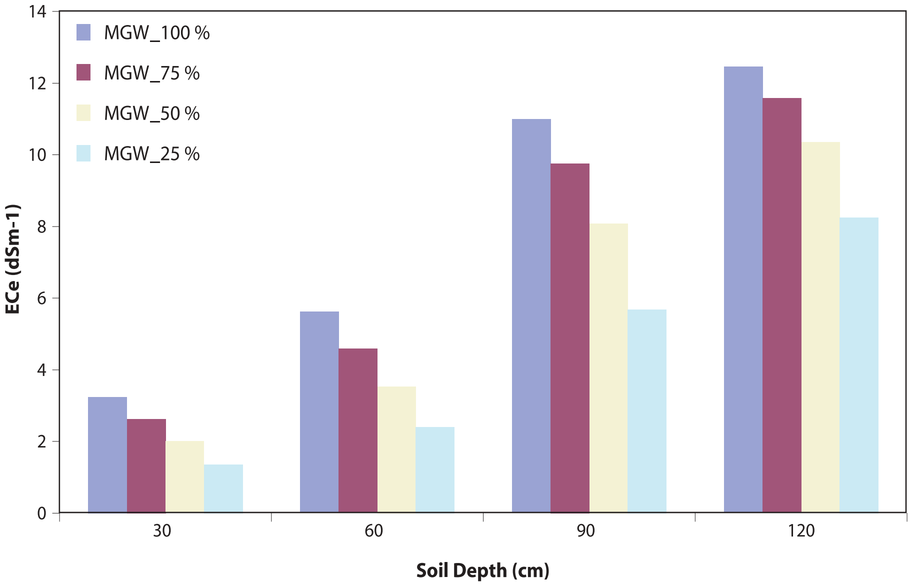
FIGURE 12.
Temporal development of average root zone salinity as influenced by the conjunctive use of marginal groundwater and canal water in four different ratios.



highest salinity build up can be observed at the depths of 90 and 120 cm regardless of mixing ratios. It is evident from the graph that in marginal groundwater areas, present irrigation practices of farmers can only help in pushing the salts to a depth of 90 cm. Therefore, occasional additional leaching with fresh water will be necessary to keep these salts well below the root zone in order to reduce the risk of salts movement in the upper layers due to capillary rise. While applying saline water for additional leaching, one has to be careful, particularly in shallow groundwater table areas.

The studies conducted by Sarwar and Bastiaanssen (2001) under similar conditions have shown that for saline water irrigations, the effect of shallow groundwater table is very pronounced. As plants are constrained in their capacity to extract water under highly saline conditions, the groundwater moves up due to percolation of applied water. This phenomenon not only increases the root zone salinity but also create waterlogging conditions. This is one of the major reasons for the rising groundwater table in the Indus Basin of Pakistan.

FIGURE 13. Development of salinity at different depths in the root zone as influenced by the conjunctive use of marginal groundwater and canal water in four different ratios.



Although salinity developments under scenarios MGW_{100} and MGW_{75} showed an increasing trend and surpassed the threshold value of 4.0 dSm^{-1}, they remained below the salinity tolerance level of wheat and cotton crops. This is evident from the positive SSC values for the MGW_{100} scenario (table 6). This slight increase in salt storage reduced the relative transpiration by almost 3 percent as compared tothe MGW_{25} scenario. The long-term simulations reveal that decrease in relative transpiration for dry years under MGW_{100} is about 10 percent. This clearly demonstrates that in marginal groundwater areas, a slight decrease in irrigation amounts can have serious consequences on the root zone salinity and ultimately on the crop yields. Considering these fragile equilibriums between leaching, root water uptake and groundwater interactions in semi-arid climates and saline soils, the farmers of marginal groundwater areas need to precisely know irrigation and leaching requirements in order to halt environmental degradation and foster crop production.

Table 6: Simulated 15-year average annual water and salt balances for four different scenarios using marginal groundwater.

Scenario	Rainfall (mm)	Irrigation (mm)	T_a (mm)	T_p (mm)	TR(-)	SSC(-)
MGW_{100}	375	780	840	903	0.93	+0.25
MGW_{75}	375	780	848	903	0.94	-0.01
MGW_{50}	375	780	854	903	0.95	-0.26
MGW_{25}	375	780	868	903	0.96	-0.52

Conjunctive water management in saline groundwater areas

The combined analysis of figures 14 and 15 shows that irrigations with saline groundwater directly or in conjunction with the canal water by any ratio will be a complete disaster. The root zone salinity will start shooting up above the threshold value just after 2-3 years and by the end of 15 years, it will reach up to 10 dSm^{-1}. Figure 15 illustrates that the whole soil profile will be highly salinized and the EC_e values at depths of 60 to 120 cm will reach to the 20dSm^{-1} level making any crop production almost impossible.

FIGURE 14.
Temporal development of average root zone salinity as influenced by the conjunctive use of saline groundwater and canal water in four different ratios.

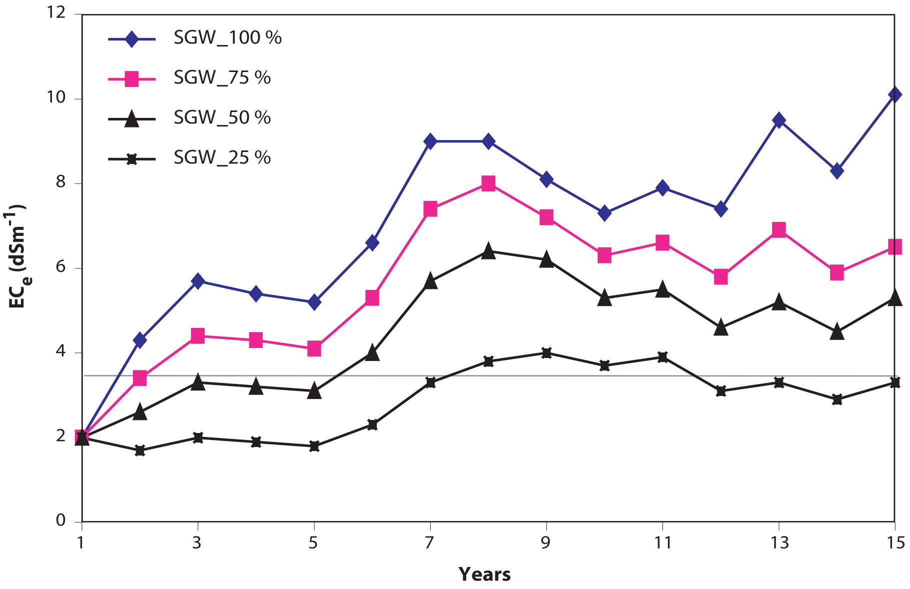


FIGURE 15.
Development of salinity at different depths in the root zone as influenced by the conjunctive use of marginal groundwater and canal water in four different ratios.

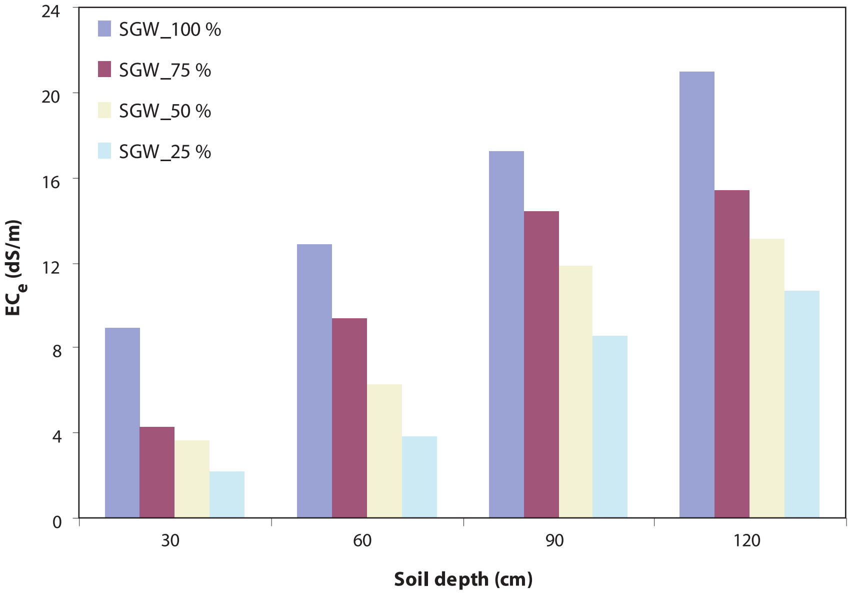


Table 7: Simulated 15-year average annual water and salt balances for four different scenarios using saline groundwater.

Scenario	Rainfall (mm)	Irrigation (mm)	T_a (mm)	T_p (mm)	TR (-)	SSC (-)
SGW_{100}	375	780	802	903	0.88	+6.08
SGW_{75}	375	780	812	903	0.90	+1.89
SGW_{50}	375	780	828	903	0.92	+0.46
SGW_{25}	375	780	839	903	0.93	-0.19

The positive SSC values for SGW_{100}, SGW_{75} and SGW_{50} demonstrate the accumulation of salts during the simulation period when saline groundwater is used for irrigation. Table 7 shows that direct application of saline groundwater for irrigation depressed the crop transpiration by about 6 percent when compared to the SGW_{25} scenario. The analysis of 15 years of simulation data on crop transpiration reveals that in dry years the relative transpiration for the SGW_{100} scenario will be further reduced by about 12 percent. Considering the substantial increase in soil salinity, the reduction in average annual crop transpiration is relatively small. This is due to the fact that both wheat and cotton are moderate to high salt tolerant crops. For salt sensitive crops, the reduction in transpiration would have been much higher. Sarwar and Bastiaanssen (2001) have shown that for the reclamation of these highly saline soils, an extensive drainage system and availability of fresh water are compulsory requirements. Based on their modeling study, they have also illustrated that leaching of salts by means of poor quality irrigation water will not be suitable and lands will go out of production even at a faster rate. Therefore, for these areas, other options like growing more salt-tolerant crops, eucalyptus or phreophytes should be adapted.

A closer look on the data presented in tables 5-7 shows that adopting the same strategy for conjunctive use of surface water and groundwater of different qualities could have serious consequences on soil degradation and crop production. The direct use of saline groundwater for irrigation can result in a 10 percent lower crop transpiration as compared to the direct use of fresh groundwater for irrigation. The common conjunctive use practice applied in Pakistan is, mixing canal water and groundwater with a 1:1 ratio regardless of the groundwater quality. The simulated results indicate that applying this strategy in fresh groundwater areas will result in a 8 percent higher crop transpiration as compared to saline groundwater areas. In addition, the pace of soil salinization in saline groundwater areas will be much faster (SSC = +0.46) as compared to fresh groundwater areas (SSC = -0.47). This stresses the need to educate farmers about the complexities of conjunctive water use and to provide guidelines for the optimal management of surface and groundwater resources with respect to quantity and quality in view of the rapidly diminishing land and water resources.

Conclusions

The premise of this study was that farmers' present irrigation strategies for conjunctive management of surface water and groundwater resources are unsustainable and exacerbate secondary salinization. The reasons are:

- Farmers do not have sufficient knowledge on the appropriate use of irrigation water of different qualities. As a result, they usually end up with sub-optimal use of their land and water resources.
- The research conducted to advise farmers on appropriate use of irrigation waters of different qualities was generally based on short-term field scale experiments and was not tested for their long-term consequences on crop production and land degradation.

The results were, therefore, regarded as short-term solutions and could not get the attention of the farming community for large-scale adoption.

In this study, 12 combinations of surface water and groundwater mixed in different ratios were evaluated for their long-term effects on crop transpiration and soil salinization. For this purpose, soil water flow and solute transport model SWAP was used. The simulations were performed for 15 years for wheat-cotton cropping rotation using actual rainfall and climatic data. Before scenario calculations, the model was calibrated and validated using field data from an experimental station located at the wheat-cotton agro-climatic zone of the Central Punjab.

From the simulation results, the following conclusions can be drawn:

In fresh groundwater areas (EC = 1.0 dSm^{1}), the farmers' present irrigation practices (i.e., using 780 mm of irrigation water in a year) provide sufficient leaching to push the salts below root zone, regardless of the ratio with which it is mixed with canal water. However, the FGW$_{100}$ and FGW$_{75}$ scenarios showed an increasing trend in root zone salinity, which may affect crop transpiration in below average rainfall years. Therefore, farmers need to adjust their irrigation requirements according to the changes in climatic conditions.

In marginal groundwater areas (EC = 1.5 dSm^{-1}), the risk of secondary salinization will be much higher than fresh groundwater areas. The results of long-term simulations reveal that irrigation applications according to MGW_{100} and MGW_{75} scenarios will take 4-5 years to build up root zone salinity to the level where it will start affecting crop transpiration. The reductions in crop transpirations during relatively dry years will be much more severe in marginal groundwater areas. These reductions can go up to 10 percent when the FGW_{100} scenario is taken as reference. In marginal groundwater areas, present irrigation practices of farmers will accumulate most of the salts to a depth of 90 cm. Therefore, additional leaching with fresh water will be necessary to push these salts below the root zone and reduce the risk of salts movement in the upper layers due to capillary rise.

The modeling results demonstrate that using saline groundwater ($EC > 2.7\ dSm^{-1}$) for irrigation either in isolation or in conjunction with the canal water (by any ratio) will be a complete disaster and that lands will become salinized in just 2-3 years. Sustainable crop production in these areas is linked with the installation of efficient drainage systems and periodical flushing of salts from the root zone. In the absence of drainage systems, leaching of salts with saline water will only accelerate the process of soil salinization and lands will go out of production even at a faster rate. Under such conditions, adaptation of more salt-tolerant crops such as eucalyptus or phreophytes could be a better option.

The temporal variations in crop transpiration and root zone salinity revealed that in (semi-) arid areas, the deviations in annual precipitations from an average year are very critical to maintain a fragile equilibrium between different water and salt components, particularly when poor quality groundwater is used for irrigation. Ideally, water allocations and applications should be based on the exact calculations of crop evapotranspiration, precipitation and salinity build up and reviewed yearly. However, for the present fixed rotational irrigation system of Pakistan, this will remain a constraint. Therefore, much will depend on the farmer’s proper understanding of on-farm water management practices.

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