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Saline Ground Water and Irrigation Water on Root Zone Salinity

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ABSTRACT
Salinisation of land and rivers is a problem of national importance in India. Appropriate land management options to alleviate salinisation should be chosen with knowledge of the effects of land management on stream flow, stream salinity, stream salt load and land productivity. The Management of Catchment Salinisation (MCS) modelling approach has been described in earlier work. It links a one-dimensional soil water model with a groundwater model to investigate the effects of management options in study areas of approximately 50 km2. The one dimensional model is used to characterize the annual soil water balance as a function of underlying aquifer Vpotential for all required combinations of soil, vegetation and groundwater salinity. It includes the effect of salt accumulation on plant water use. A groundwater model is then used to estimate the depth to water table across the study area that reflects the topography, hydrogeology and the distribution of vegetation. The MCS model is used to investigate the potential effects of future land use scenarios on catchment salt and water balance. Land use scenarios that have been considered include: forest plantations, revegetation with native trees and shrubs, and development of small areas of crops (10 to 20 ha) irrigated with groundwater. This project focuses on the development of small crop areas irrigated with groundwater and investigates the sustainability of these schemes. It also compares the reduction of catchment salt load export under irrigation development with the reduction under afforestation
KEYWORDS: National Highway, Remote sensing, Alignment Using Gis, Shortest route

I. INTRODUCTION

1.1 Problem definition

Increased demands for water by municipal, industrial, agricultural and environmental consumers force conservation of high-quality water and incorporation of recycled or other marginal quality water in enterprises such as agriculture where lower-quality water can be utilized (Asano et al., 1996; Angelakis et al., 1999; Lazarova et al., 2001; Hamilton et al., 2007). A consequence of irrigation or capillary upflow from groundwater is that salts may concentrate in the root zone. Excess irrigation is required to periodically remove accumulated salts and maintains agro-ecosystems productivity.

Where drainage is inadequate, the excess irrigation results in waterlogging that accelerates salinization. Consequences of such practices are evident world-wide. The Food and Agricultural Organization (2002) estimates the productivity of approximately 20-30 million irrigated hectares has been significantly decreased by salinity and that salinization results in the loss of an additional 0.25-0.5 million hectares each year globally. In 1990, 1.4 million hectares of irrigated California land were assessed as having a water table within 1.5m of the surface and 1.7 million hectares were determined to be saline or sodic (Tanji, 1990).

The work by Schoups et al. (2005) involving regional scale hydro-salinity modeling questions the sustainability of irrigated agriculture in the San Joaquin Valley, California because of inevitable salinization of soil and groundwater. Approximately 8.8 million hectares in Western Australia are threatened by rising water tables and may be lost to production by 2050 (National Land and Water Resources Audit, 2001).

Despite installation of extensive drainage systems and groundwater management in recent years, some 25 percent (more than 5 million hectares) of the Indus River basin of Pakistan is still estimated to be affected by salinity, sodicity, and waterlogging (Tanji and Kielen, 2002). According to a report published by the FAO in 2000, the total global area of saltaffected soils including saline and sodic soils is 831 million hectares (Martinez-Beltran and Manzur, 2005), extending over all the continents including Africa, Asia, Australia, and the Americas.

The challenge for water management is to maximize productivity under market and environmental constraints including protection of soil and water resources. Meeting the challenge will require a quantitative understanding of not only the effects of water supply, but also the deleterious effects of salts and potentially toxic constituents (such as sodium) of marginal quality waters coming through irrigation or through capillary upflow from groundwater.

Deleterious effects of salinity on plant physiology result from reduced water availability due to decreased osmotic potential, specific ion toxicity, or investment in assimilates required to maintain plant activities under saline conditions (Bernstein, 1975; Munns, 2002), and by changes in soil solution matric and osmotic potential and soil hydraulic conductivity via feedback mechanisms (Bernstein, 1975).

1.2 Objectives of the thesis

In order to quantify the soil salinity and sodicity development, we have modeled the simple mass balance approaches of water, salt, and cations. The cation exchange between soil solution and exchange complex is modelled by using the Gapon equation used in salinity research. The interrelation between salinity and sodicity is translated into reduction in saturated hydraulic conductivity by using the analytical expressions developed by *McNeal* (1968). The feedback effects of reduction in saturated hydraulic conductivity on the root zone fluxes, salinity, and sodicity are analysed for the range of climates, groundwater depths. In the second theme of thesis, we have used the analytical model developed by *Shani et al.* (2007) to optimize the irrigation water for the sequential farms along the river basin. To overcome the problems and challenges as discussed above, the objectives of the study can therefore be divided into the following specific themes:

- To develop a relatively simple model that emphasizes some dependencies only, to assess as transparent as possible, to what degree periodic salinity may cause soil sodicity under different climates, groundwater depths, and soil types.
- To determine the analytical approximations of long term average fluxes, salt concentrations and soil sodicity (quantified by *ESP)* under different climates, root zone thicknesses, and groundwater depths.
- To quantify the effect of reduction in saturated hydraulic conductivity on root zone fluxes under saline and sodic conditions for different groundwater depths under seasonal and non-seasonal rainfall.
- To determine optimal water management strategies for water use chains using an explicit agro-physical model for yield reductions caused by salt stress. Therefore, this thesis aims to investigate theoretically how the different input parameters such as rainfall/irrigation, capillary flux, groundwater salinity, and groundwater SAR (sodium adsorption ratio) affect soil saturated hydraulic conductivity. The presented analysis can be applied ranging from point scale to regional scale due to the relative simplicity.

1.3 Thesis outline

Presents the modeling results of soil sodicity development due to capillary upflow from groundwater in a stochastic ecohydrological framework. The sodicity model developed in this chapter is based on the salinity model developed in Chapter 3. Based on the sodicity model, we have quantified the soil salinity and sodicity development under different climates, groundwater depths, soil, and root zone thicknesses. In heavy clay soil, the long term calcium fraction in soil solution (*f*) becomes almost same as the groundwater calcium fraction (*fz*).

On the basis of these results, we can approximate long term fluxes (similar as *Laio et al., (2001)*), to derive analytically the long term salinity, and soil *ESP* under different climates, groundwater depths, and root zone thickness. In an integrated model based on the salinity and sodicity model is presented. We have considered the feedback effects of saturated hydraulic conductivity due to salinity and sodicity on root zone fluxes, salinity, and sodicity.

This model helps to find the conditions like weather seasonality, non-seasonality, groundwater depth, and degree of wetness of climate where feedback and no feedback effects are significant. In, we have developed a sequential model of irrigation that predicts crop yields and tracks the water flow and level of salinity along a river dependent on irrigation management decision. The model incorporates the agro-physical model of plant response to environmental conditions including feedbacks. For a system with limited water resources, we have compared the efficiency of outcomes when access rights to water are unregulated, water is not priced, and water loss occurs due to inefficient application with the outcomes of an optimally managed system. Finally summarizes the findings of this thesis and provides some recommendations for future research.

II. SOIL SODICITY AS A RESULT OF PERIODICAL DROUGHT

Soil sodicity development is a process that depends nonlinearly on both salt concentration and composition of soil water. In particular in hot climates, soil water composition is subject to temporal variation due to dry-wet cycles. To investigate the effect of such cycles on soil salinity and sodicity, a simple root zone model is developed that accounts for annual salt accumulation and leaching periods. Cation exchange is simplified to considering only *Ca/Na* exchange, using the Gapon exchange equation.

The resulting salt and *Ca/Na*-balances are solved for a series of dry/wet cycles with a standard numerical approach. Due to the nonlinearities in the Gapon equation, the fluctuations of soil salinity that may be induced, e.g. by fluctuating soil water content, affect sodicity development. Even for the case that salinity is in a periodic steady state, where salt concentrations do not increase on the long term, sodicity may still grow as a function of time from year to year.

For the longer term, sodicity, as quantified by Exchangeable Sodium Percentage (*ESP*), approaches a maximum value that depends on drought and inflowing water quality, but not on soil cation exchange capacity. Analytical approaches for the salinity and sodicity developing under such fluctuating regimes appear to be in good agreement with numerical approximations and are very useful for checking numerical results and anticipating changes in practical situations.

2.1 Model development

The proposed model considers a homogeneous root zone, similar to the ecohydrological models considered by *Vervoort and van der Zee* (*2008, 2009*). The water balance of this root zone is simplified to cycles that consist of a period in which leaching of water is zero, followed by a period where leaching occurs. Only two cations are explicitly modeled, i.e., *Na* and *Ca*, where we make the common assumption that often present *K* behaves similar to *Na* and that *Mg* behaves similar to *Ca*. The type of anion is left out of consideration, which implies that chemical precipitation is ignored. Changes in salt concentration and distribution of *Ca* and *Na* are due to variations in time of incoming water (such as capillary rise/upflow, rainfall, irrigation), of drainage (leaching) and of evapotranspiration.

III. STOCHASTIC MODELING OF SALT ACCUMULATION IN THE ROOT ZONE DUE TO CAPILLARY FLUX FROM BRACKISH GROUNDWATER

Groundwater can be a source of both water and salts in semi-arid areas, and therefore capillary pressure induced upward water flow may cause root zone salinization. To identify which conditions result in hazardous salt concentrations in the root zone, we combined the mass balance equations for salt and water, further assuming a Poissondistributed daily rainfall and brackish groundwater quality. For the water fluxes (leaching, capillary upflow, and evapotranspiration), we account for osmotic effects of the dissolved salt mass using Van‘t Hoff’s law.

Root zone salinity depends on salt transport via capillary flux and on evapotranspiration, which concentrates salt in the root zone. Both a wet climate and shallow groundwater lead to wetter root zone conditions, which in combination with periodic rainfall enhances salt removal by leaching. For wet climates, root zone salinity (concentrations) increases as groundwater is more shallow (larger groundwater influence).

For dry climates, salinity increases as groundwater is deeper due to a drier root zone and less leaching. For intermediate climates, opposing effects can push the salt balance in either way. Root zone salinity increases almost linearly with groundwater salinity. With a simple analytical approximation, maximum concentrations can be related with the mean capillary flow rate, leaching rate, water saturation and groundwater salinity, for different soils, climates and groundwater depths.

3.1General

The scope of this paper is to assess, for a root zone in hydrological contact with groundwater, how salt accumulation is related to root-zone water dynamics, with the emphasis on the variability of these dynamics caused by atmospheric forcing. We are interested in the impact of climate drivers such as rainfall intensity, precipitation frequency, and evaporative demand, along with the influence of capillary upflow from the water table. In this work, we presume that the primary source of salt is from groundwater rather than irrigation water, as in the case of *Suweis et al.* (2010).

To keep the emphasis on precipitation timing and intensity, we follow the framework presented in *Rodriguez-Iturbe and Porporato* (2004) and consider the root zone as a single layer without resolving the dynamics of infiltration. *Guswa et al.* (2002; 2004) examined conditions where such a simplification is appropriate; they found that when vegetation has the ability to compensate for heterogeneous distributions of soil moisture, either through hydraulic redistribution, or compensatory uptake, the single layer and spatially explicit models gave similar results.

Such compensation ability has been demonstrated for plants in many different ecosystems (*Caldwell et al., 1998; Dawson, 1993; Domec et al., 2010; Green et al., 1997; Katul and Siqueira, 2010; Nadezhdina et al., 2010; Oliveira et al., 2005*). To understand the development of salinity of the root zone, we consider a conceptual model of a homogeneous root zone with thickness *Zr* (cm), porosity and groundwater *Z* (cm) below the soil surface: Figure 4.1.

The root zone water balance is studied in the probabilistic framework of *Vervoort and Van der Zee* (2008) in view of the random character of rainfall. The random fluctuations of root zone water saturation affect the fluctuations of salinity through the contribution of the various fluxes into and out of the root zone, and this balance is the primary scope of this article.

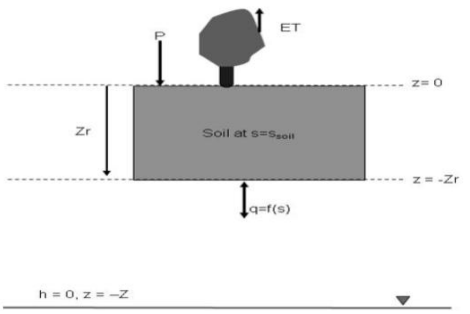

Figure 3.1. Conceptual model for groundwater uptake by vegetation in a semi-arid system.

3.2 Background theory

Our point of departure is the ecohydrological model including capillary upflow described by *Vervoort and van der Zee* (2008). Evaporation and rainfall occur at the soil surface and affect mainly the water storage in the root zone. No hysteresis occurs and the soil water profile below the root zone has a steady state. We assume that the groundwater level is constant, which means that the fluctuations in the groundwater level occur at a much larger time scale than the fluctuations in climate drivers (i.e., years versus days and weeks). We further assume that the soil is initially free from salts and that all salt originates from the groundwater, in what commonly is called primary salinization (*Szabolcs, 1989; Varrallyay, 1989*).

3.3 Salt mass and the related pdf

For a sandy clay loam soil type (*SCL*) and a root zone thickness (*Zr*) of 100 cm, the evolution of the salt mass and the related pdfs are shown in Figure 3.4. The temporal development of salt mass is shown for three climates (dry ($\alpha\lambda/Emax$ = 0.89), semi-arid ($\alpha\lambda/Emax$ = 1.35), and wet climate ($\alpha\lambda/Emax$ = 1.89)) and three groundwater depths (*Z*= 150 cm, *Z*= 200 cm, *Z*=250 cm). The primary results of numerical calculations are the patterns of salt mass as a function of time, but it is easier to observe the differences between different groundwater levels and climate from the pdfs of salt mass. These are 56 shown for six groundwater depths (*Z*= 150-400 cm in 50 cm increments). The dynamics of the salt mass lead to three major observations: (i) a wetter climate leads to a smaller salt mass in the root zone, (ii) the salt mass is larger for a shallow groundwater level than for a deeper groundwater level, (iii) in relative terms, the variability between groundwater depths is greater for the wet climate; however, in absolute terms the opposite is true: the means differ by 5 molc/m2 in the dry case, but only 3 molc/m2 for the wet case.

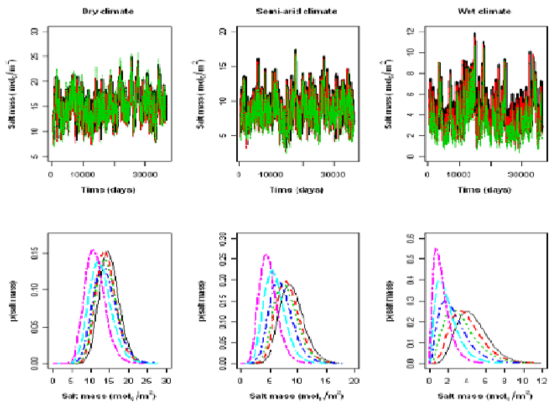

Figure 4.3. Development of the salt mass during 99 years for 3 different groundwater depths (*Z* = 150 cm (black color), *Z* = 200 cm (red color), *Z* = 250 cm (green color)) below soil surface. The pdfs of salt mass are shown for six groundwater depths (*Z* = 150 cm (black color), *Z* = 200 cm (red color), *Z* = 250 cm (green color), *Z* = 300 cm (blue color), *Z* = 350 cm (turquoise color), *Z* = 400 cm (pink color)). Both salt mass and related pdfs are plotted for three different climates (dry climate ($\alpha\lambda/$ *Emax* = 0.89), semi-arid climate ($\alpha\lambda/$ *Emax* = 1.35), wet climate ($\alpha\lambda/$ *Emax* = 1.89)).

IV. MODELING OF SOIL SODICITY DEVELOPMENT DUE TO CAPILLARY UPFLOW FROM GROUNDWATER: AN ECOHYDROLOGICAL APPROACH

Soil salinity and sodicity development in groundwater driven agro-ecosystems play a major role in soil structure degradation. To identify which conditions lead to soil sodicity, we have modeled the coupled water, salt, and cation balances. The root zone salinity *C* and sodicity *ESP* gradually change to their long term average values. These long term average values are independent of the cation exchange capacity *CEC*.

The rate of change depends inversely on the size of the root zone reservoir, i.e., on root zone thickness for *C*, and additionally on *CEC*, for *ESP*. Soil type can have a large effect on both the rate of approach of the long term steady state salinity and sodicity, and on the long term levels, as it affects the incoming and out-going water and chemical fluxes. Considering two possible sources of salts, i.e., groundwater and irrigation water (here represented by rainfall), the long term salt concentration *C* of the root zone corresponds well with a flux weighted average of infiltrating and upflowing salt mass divided by the average water drainage. In full analogy, the long term *ESP* can be approximated very well for different groundwater depths and climates. A more refined analytical approximation, based on the analytical

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solution of the water balance of *Vervoort and Van der Zee* (2008), leads to a quite good approximation of long term salinity and sodicity, for different soils, groundwater depths, and climates.

4.1 General

The main aims of our current paper are (i) to quantify and understand how soil salinity and sodicity develop under different soil type, soil *CEC*, root zone thickness (*Zr*), climate, and groundwater depths (*Z*), (ii) to determine the long term and short term behavior of soil ESP for different groundwater depths, climates, and soil saturated hydraulic conductivity, (iii) to determine the analytical approximations of long term average fluxes, salt concentrations and soil ESP under different climates, root zone thicknesses, and groundwater depths.

4.2 Temporal changes of salt concentration and soil *ESP* for sandy clay loam soil and heavy clay soil

As the soil *CEC* increases, the amount of sodium in the soil solution required to exchange with calcium in the exchange complex increases. To identify the times where soil *ESP* reaches steady state, we have simulated the process for different groundwater depths, a range of climates and root zone thicknesses. Steady state is defined as the state where soil *ESP* is in dynamic equilibrium with respect to temporal exchange of cations between soil solution and exchange complex.

We use the term dynamic equilibrium for saturation, rootzone salt concentration, and *ESP* when these vary dynamically in time around a constant mean value. The equilibrium is reached because the loss of Na from the root zone equals the supply of Na to the root zone averaged over a longer period. Figure demonstrates how the soil *ESP* and salt concentration vary dynamically in response to rainfall for a 25 cm root zone thickness for sandy clay loam soil and heavy clay soil.

Although soil *ESP* for different values of *CEC* reaches a dynamic equilibrium, the magnitude of soil *ESP* (for a given groundwater depth, root zone thickness, and climate) decreases slightly with increasing soil *CEC* (Figure 4.2A). The rate of change towards the new dynamic equilibrium is slower if *CEC* is larger, as the quantity of calcium (*Ca*) that needs to exchange with sodium (Na) in the root zone increases with increasing *CEC*.

Hence, the amount of sodium (*Na*) that needs to be transported from the irrigation/groundwater to reach a specific *ESP* becomes greater. As the long term *ESP* is independent of *CEC*, according to the Gapon equation, the values of *ESP* depend only on *CEC* (and root zone thickness) if that limiting state has not yet been attained. The final *ESP* of sandy clay loam soil (SCL) for different *CEC* shows relatively smaller dependence of *ESP* on *CEC* compared to heavy clay soil (HC).

The reason is that the magnitude of fluxes (capillary and leaching) in sandy clay loam soil is relatively greater than the heavy clay soil. These greater magnitude fluxes in sandy clay loam soil cause the final soil ESP to deviate 2%-4% from ultimate value, whereas the final *ESP* for heavy clay soil under different *CEC* shows independence. As the temporal variations of salt concentration are in dynamic equilibrium, therefore, the corresponding pdfs of salt concentration for both soil types show the steady state pdfs. Also the corresponding pdfs of soil ESP for sandy clay loam soil approach the dynamic equilibrium relatively faster than heavy clays due to greater magnitude of fluxes.

4.3FEEDBACK EFFECTS OF SATURATED HYDRAULIC CONDUCTIVITY ON ROOT ZONE FLUXES, SALINITY, AND SODICITY

Soil sodicity may lead to soil structure deterioration for certain swelling soils, and if soil water salinity varies. However, this feedback is seldomly taken into account in modelling soil water and salinity dynamics. We have modelled the feedback effects of salt concentration and ESP on saturated hydraulic conductivity *(Ks(C,ESP))* for different groundwater depths and climates. The dependency of *Ks* on salinity (*C*) and *ESP* followed the procedure developed by *McNeal* (1968). Whether or not the *Ks*-value decreases at large *ESP* due to decreasing salinity may have a significant effect on salt concentrations and soil *ESP* that develops. Another important factor is the seasonality of rainfall. Ignoring such seasonality leads to under or over estimation of root zone fluxes (evapotranspiration, runoff, leaching flux and capillary flux), salt concentration and soil ESP. Since the decreasing *Ks*-value leads to smaller water fluxes through the root zone, the feedback implied is a sealing of this zone against further deterioration.

V. Numerical calculations

For the numerical simulations, light clay soil with *Ks* =3.5 cm/day is used. The other soil hydraulic parameters values were Ø (soil porosity) = 0.42, *b* (pore size distribution index) = 16, *s* □ (average soil matric potential at saturation)= -1.5E-3 MPa, *s,sh* □ (soil matric potential at hygroscopic point) = -10 MPa, (based on standard Australian soils in "Neurotheta", *Minansy and McBratney*, 2002). We use *slim* (shifting field capacity) in this paper as used in *Vervoort and van der Zee* (2008) and *Shah et al*. (2011) instead of the field capacity, which is more common.

The vegetation parameters values for a grass *Zr*= 40 cm**,** □ = 0.1 cm, *w E* (soil evaporation at wilting point) = 0.013 cm/day, *s,s** □ (matric potential at

which stomatal closure begins) = -0.09 MPa, and *s,sw* (matric potential at which stomatal closure completes) = -4.5 MPa were based on *Fernandez-Illescas et al.*
(2001).

Maximum evapotranspiration (max *E* = 0.43 cm/day) is calculated byusing the *Teuling and Troch* (2005) equation 3 and the leaf area index for grass (ξ = 5) is adopted from *Asner et al.* (2003). In order to compare the effect of seasonality and non-seasonality (Poisson distributed rainfall) on root zone fluxes, salt concentration, and soil *ESP*, we have selected the rainfall data for two locations with distinct seasonality, i.e., Oenpelli, and Tennant Creek Airport located in North Territory of Australia. Figure shows the monthly average rainfall of these locations.

Total rainfall for the Oenpelli and its equivalent Poisson rainfall is kept same by deriving the Poisson parameters (α and λ) of the Oenpelli climate using the procedure developed by *Rodriguez- Iturbe* (1984). The Poisson parameters for the Oenpelli climate are α = 1.5 cm/event, and λ = 0.4 cm/event. The average rainfall for these Poisson parameters is 0.41 cm/day, which is close to the real (seasonal) average rainfall for the Oenpelli climate of 0.39 cm/day. We disregard this small difference. Similarly, we have also selected the rainfall data of the location Tennant Creek Airport. The climate in Tennant Creek Airport is quite dryer than Oenpelli climate as shown in Figure 5.3. The Poisson parameters for the Tennant Creek Airport climate are α = 0.93 cm/event, and λ = 0.16 cm/event. The average Poisson rainfall for these Poisson parameters is 0.12 cm/day, which is also close to the real (seasonal) average rainfall for the Tennant Creek Airport of 0.13 cm/day.

VI. MANAGEMENT OF IRRIGATION WITH SALINE WATER: ACCOUNTING FOR EXTERNALITIES BY CONSIDERING SOIL-WATER-PLANT FEEDBACK MECHANISMS

In arid and semi-arid regions, irrigation water is scarce and often saline. To reduce negative effects on crop yields, the irrigated amounts must include water for leaching and therefore exceed evapotranspiration. The leachate (drainage) water returns to water sources such as rivers or groundwater aquifers and increases their level of salinity and the leaching requirement for irrigation water of any sequential user. We develop a sequential (upstream-downstream) model of irrigation that predicts crop yields and water consumption and tracks the water flow and level of salinity along a river dependent on irrigation management decisions.

The model incorporates a agro-physical model of plant response to environmental conditions including feedbacks. For a system with limited water resources, the model examines the impacts of water scarcity, salinity and technically inefficient application on yields for specific crop, soil, and climate conditions. As a general pattern we find that, as salinity level and inefficiency increase, the system benefits when upstream farms use less water and downstream farms are subsequently provided with more and better quality water. We compute the marginal value of water, i.e. the price water would command on a market, for different levels of water scarcity, salinity and levels of water loss.

6.1 A chain model of water use for irrigation

As we assume a single water source, and water quantity declines due to transpiration and surface evaporation losses, we can stipulate and such that water availability (*q*) declines and salinity (*s*) increases from upstream to downstream. Water is used for irrigation and we assume that all users (farms/regions) have to deal with equal ambient conditions (climate, soil type, crop in production, etc.) except for water availability and quality.

This assumption is necessary to postulate that the yield function dependency of production factors is everywhere the same, and that e.g. the potential yield is determined only by the amount of water used for transpiration (*Ben- Gal and Shani, 2003; Ben-Gal et al., 2003; De Jong van Lier et al., 2008; De Wit, 1958; Shani et al., 2007; Shani-et al., 2009; Shani and Dudley, 2001*), and not by e.g. soil nutrient status or other management or environmental factors. Hence, irrigation water is productive if it increases transpiration for situations that otherwise would be constrained by water availability.

However, we additionally assume that water productivity is reduced if its salinity is higher. This is an obvious assumption, in view of the adverse effects of salts on water availability caused, notably, by osmotic (*Homaee et al., 2002*), but also some salt specific toxic effects (*Marschner, 1995*). Enhanced salinities lead to additional constraints on the transpiration water that is available for primary production, and therefore yields diminish when salt stress increases.

It is reasonable that the initial river water quantity and salinity are input parameters, dictated by other factors than those of primary concern here. However, we assume that these factors are constant over time. Quantities and salinities for farms downstream of the first farm depend on management and crop response decisions of each previous farm and are dependent on the amount of available water, amount of water applied, and amount water leached at each previous stage. Water use at each farm *I* affects availability and quality of water downstream as Farm *i* removes some portion of the river water and applies it as irrigation. Of that water, some, depending on *i Y* is consumed (transpires) and the remainder leaches out of the root zone and returns to the river. Water is consumed by crops but salts are not. Therefore, salinity increases downstream as concentrated return flows are added to the original water source.

VII. CONCLUSION

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 largescale 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 dSm1), 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 FGW100 and FGW75 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 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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