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MODELING ROOT ZONE SALINITY DYNAMICS USING INTEGRATED EFFECT OF SOIL, WATER, CROP AND CLIMATE FOR SEMI-ARID REGION

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The soil salinization in Indus Basin of Pakistan is becoming an important ecological unit among current issues. The use of poor quality groundwater for irrigation has aggravated the main problem of secondary salinization of the soil. Ground water due to the presence of salts can be a source of root zone salinization through capillary pressure-induced upward water flow or through its direct application for irrigation. To identify the more hazardous condition which results in root zone salt concentrations, we have used a combination of the mass balance equations for water and salt transport, accounting with rainfall distribution, irrigation application and groundwater contribution. In this study, a stochastic modeling frame work has been developed to evaluate the behavior of sugarcane cropping system on soil salinity with different irrigation scenarios and water table conditions. The simulations were performed for a period of 34-years using actual climatic data for sugarcane crop. The results indicated that using PDF (Probability Density Functions) drawn value of groundwater salinity in simulations (i.e. 0.009 $mol_c.L^{-1}$), the mixing of canal water (having salinity value of 0.003 $mol_c.L^{-1}$) with saline groundwater in any ratio i.e. 0.003 $mol_c.L^{-1}$, 0.0048 $mol_c.L^{-1}$, 0.006 $mol_c.L^{-1}$, 0.0072 $mol_c.L^{-1}$ and 0.009 $mol_c.L^{-1}$ for S_1, S_2, S_3, S_4 and S_5 scenarios respectively, did not cause severe salinity problems under 300 cm, 600 cm and 1150 cm deep water table conditions and long-term root zone salt concentration remained below the crop threshold limit (i.e. 0.017 $mol_c.L^{-1}$ for sugarcane crop). The maximum simulated value estimated under 300 cm deep water table using S_5, was 0.0145 $mol_c.L^{-1}$. On other hand, using the highest mean value of groundwater salinity in simulations (i.e. 0.051 $mol_c.L^{-1}$), enhanced the root zone salinity level up to and more than crop threshold value, particularly under shallow water table conditions. The maximum simulated values for scenario S_5 (0.051 $mol_c.L^{-1}$ salinity) estimated under 300 cm, 600 cm and 1150 cm deep water tables, were 0.0485 $mol_c.L^{-1}$, 0.0283 $mol_c.L^{-1}$ and 0.0255 $mol_c.L^{-1}$ respectively. The results showed that there was a greater influence of capillary flux on root zone salt concentration than irrigation water, the shallow saline water table attributed greater root zone salinity due to more contribution through capillary upflow.

Keywords: Sugarcane, irrigation scenarios, rainfall, water table depth, numerical modeling, salt concentration, capillary flux, leaching flux, crop ET.

INTRODUCTION

Pakistan is located in arid to semi-arid region of the world, where precipitation is generally low and evaporation is high which causes the accumulation of soluble salts on the soil surface. The salinity of the soil is one of the largest abiotic stresses, causing great economic damage in agriculture. The cultivated land in Pakistan is about 22.16 Mha and agricultural practice is carried out throughout the year on irrigated land of about 15.35 Mha (Pakistan Economic Survey, 2018), where about 6.67 Mha of land is under salt affected region (Khan, 1998) which is 35-40% of irrigated land; out of this 8% is under intense salinity and 6% is moderately affected (Qureshi *et al.*, 2003). About 40, 000 ha of land are demolished every year due to salinization hazard (Qayyum and Malik, 1998).

Due to scarcity of surface water resources, the groundwater has become an essential entity to supplement the existing irrigation supplies. In Punjab province private tubewells have increased to reach 1.1 million (Pakistan Bureau of Statistics, 2015), out of 43 MAF balanced recharge the pumping rate has been exceeded. The unregulated and unmanaged use of groundwater has led a problem of aquifer over extraction and saltwater intrusion in most of the Indus Basin soils (Kijne and Kuper, 1995). The use of saline groundwater for irrigation has aggravated the main problem of secondary salinization, which is adding a large amount of salt to the root zone and increasing soil salinity.

Salts accumulation on the soil surface through pumped groundwater is primarily the recirculation of salts in groundwater and in the root zone. However, studying the localized cases where salt recycling from groundwater to root zone and soil to groundwater has degraded the soil up to a level that salt accumulation exceeded threshold limit, which negatively affected the agricultural productivity. Although in some cases, where mixing of saline groundwater with canal water has resulted the soil salinization through irrigation. The groundwater sustainability for irrigation requires maintaining salt balance in groundwater and canals.

Saline water irrigation can alter the physicochemical properties of the soil to cause salinization of the soil and reduce crop yields (Li *et al.*, 2015). The effects of salinization on hydraulic and physical soil properties are very complex systems that may be affected by many factors. The main salinity controlling factors are soil type (Quirk and Schofield, 1955; Felhendler *et al.*, 1974), soil structure (Goldberg *et al.*, 1991), the method of irrigation application, the initial content of salt, water and cations (Dehayr and Gordon, 2005) and organic content of matter.

In order to avoid the salt content in the soil, the salts must be drained through leaching. This concept was developed by Richards *et al.* (1954). This concept has been the subject of continuous studies in recent decades (Rhoades, 1974; Corwin *et al.*, 2007). Therefore, there is an urgent need to periodically remove these salts deposited in soil with proper water management from the root zone (Richards *et al.*, 1954; Schoups *et al.*, 2005, Slama *et al.*, 2019).

Groundwater either through its direct application to plants or through capillary upflow towards the root zone is of greater interest and is vulnerable to soil salinization (Bresler *et al.*, 1982; Ali *et al.*, 2019). Hence groundwater may be termed as a dominant factor with respect to plant development and vegetation patterning (Lamontagne *et al.*, 2005; Scott *et al.*, 2006). In past analysis, a framework of system (Rodriguez-Iturbe and Porporato, 2004) was developed for carrying out the modeling simulation of the water balance in soil, particularly for rain-fed ecosystems in semiarid region. Initially feedback of the ground water with the root zone soil and water dynamics was not considered in this framework. Later on, the interactions between root zone and groundwater were considered by Ridolfi *et al.* (2008), Vervoort and van der Zee (2008, 2009), Laio *et al.* (2009) and Tamea *et al.* (2009). In semi-arid regions, the estimations of the upward flow of groundwater through capillary action to the root zone is of concern because it accumulates salt in crop root zone which rises due to capillary flux, causing the risk of salinization in the root zone soil (Bresler *et al.*, 1982; Liang *et al.*, 2016).

The water balance for a vegetated soil was taken into consideration by Vervoort and van der Zee (2008, 2009), where the impact of drainage/ leaching was not considered on groundwater levels. This drainage/ leaching influence on groundwater levels was accounted for later on by Ridolfi *et al.* (2008), Tamea *et al.* (2009), Laio *et al.* (2009) and Ansari *et al.* (2017) for vegetated and unvegetated soil. Similarly Shah *et al*. (2011) considered a root zone which had a hydrological contact with groundwater and investigated the accumulation of salt as a function of root zone water dynamics, where it was presumed that the primary source of root zone salinity is through capillary upflow from groundwater in spite of irrigation water, in similar case of Suweis *et al.* (2010) and Liu *et al.* (2019).

In our study, it was presumed that the primary source of root zone salinity is from groundwater which is both through capillary upflow and irrigation application with the emphasis on such dynamics variation by atmospheric triggered functions. Similarly, the influence of climate driven elements such as rainfall intensity, frequency and pattern; and evaporative demand were investigated along with the impact of capillary upflow from the groundwater (Abbas *et al*., 2013; Yang *et al.*, 2019). A framework was followed to keep the emphasis on intensity of rainfall and precipitation timing as presented by Rodriguez-Iturbe and Porporato (2004).

In our analysis, the root zone was considered as a single layer without undertaking the dynamics of infiltration. A condition presented by Guswa *et al.* (2002, 2004) with appropriate assumption where it was examined that the ability of vegetation to compensate for heterogeneous soil moisture distributions, either through capillary uptake compensation or redistribution through hydraulic action, the spatially explicit models with single layer gave similar results which has been demonstrated in many ecosystems (Dawson, 1993; Green *et al.* 1997; Caldwell *et al.*, 1998; Oliveira *et al.*, 2005; Adhikary *et al.*, 2010; Domec *et al.*, 2010; Katul and Siqueira, 2010; Nadezhdina *et al.*, 2010; Adhikary *et al.*, 2012).

The aim of our study is to evaluate the accumulated long-term effects of capillary upflow and irrigation water having different qualities (development of various quality irrigation scenarios by mixing of low quality groundwater in different ratios with the good quality canal water or in pure form of canal and groundwater), on soil salinity for the conditions prevailing in the Sugarcane cropping system in study area. For this purpose, an analytical model was developed in ‘R’ environment by incorporating the empirical equations which is the modification in earlier soil water and solute transport model of salinity dynamics (Vervoort and Van der Zee, 2008; Shah *et al.*, 2011). *R* is an integrated set of software installations for data manipulation, calculation and graphical representation. This suit is very much a vehicle for newly developing methods of interactive data analysis.

MATERIALS AND METHODS

Model Development**:** Modeling is a most effective tool to investigate the fate and movement of solute and water in soil root zone and to analyze salinity accumulation in groundwater driven agro-ecosystems. To investigate these aspects, recently some fully numerical models such as HYDRUS (Simunek *et al.*, 1998; Somma *et al.*, 1998) and UNSATCHEM (Simunek *et al.*, 1996) have been developed. Using these tools, it becomes possible for detailed assessment of how solute transport along with various water fluxes, and root water uptake affect each other under a monotonic decline in soil health. The major constraint while using these models is their large computational demand than analytical and analytically inspired numerical models. Therefore, the both analytical and numerical modeling approaches are of greater importance to investigate the extent of soil salinization at various depths and its spatial and temporal variations and also different aspects of the transport phenomena.

In this study we considered a root zone having homogeneous soil with thickness *Dr* (cm), the water table depth *D* (cm) below the ground surface and porosity ∅, same as considered in ecohydrological model developed by Vervoort and Van der Zee (2008, 2009). In this model the main attempt was made to investigate for a root zone having a hydrological contact with groundwater, where the accumulation of salts in root zone is directly related to water dynamics, with the main focus on water dynamics variation due atmospheric forcing agents.

In modeling simulation, we considered that, the movement of various fluxes in and out of the root zone soil has a direct effect on the root zone water saturation caused by the rainfall, irrigation and evaporation occurs on soil surface, whereas groundwater contribution through capillary upflow to the root zone. The resultant random variation in root zone water saturation causes the variation in soil salinity due to the contribution of pertaining water fluxes. This water and salt balance in root zone caused by various fluxes, is the primary focus of this study. In this study simple mass balance approaches of water and solute movement were modeled in *R* environment to quantify the root zone salinity development. The water and salt balance equations were drawn in *R* to model the various scenarios and their future outcomes.

To calculate the water and salt balance, the following assumptions were made: (i) Root zone water storage is mainly affected by: Soil evaporation, crop transpiration, capillary upflow, drainage, pumped groundwater irrigation and rainfall; (ii) The soil water profile below the root zone was considered in steady state condition with respect to water saturation and related fluxes; (iii) For study area, the level of groundwater was considered constant at depth *D* below the soil surface, because it takes relatively more time in water table fluctuations to be occurred compared to the fluctuations in climate drivers (rainfall, solar radiation, evaporation); (iv) The soil is initially considered as saline with real on site salinity level.

In general, to investigate the behavior of soil and vegetation the simple water and salt balance techniques gives better results in terms of simulated time and input parameters under various soil type, water table depth, root zone depth, climate, and groundwater and soil salinity level. Groundwater through capillary upflow and irrigation application is the major source of soil salinization. In the drainage zones of the landscape, groundwater and dissolved salts are released from the soil surface. The hydraulic gradients, including soil evaporation and plant transpiration are the main driving element behind the upward water and salts movement. In case where water level is below the threshold depth, the salt accumulation becomes high (Li *et al.,* 2015; Shah *et al.,* 2011; So and Aylmore, 1993). However, this level of threshold may vary subject to the climatic conditions and the hydraulic properties of the soil. The consequence of saline irrigation or capillary flow of saline groundwater is that salts are concentrated in the root zone.

***Water Balance Equation*:** A root zone system can be resembled a container holding the water where fluctuation in water content may occur due to various internal and external actions taking place. Soil water content can be expressed in terms of root zone depletion due to adding and subtracting of gains and losses caused by various water fluxes and soil water budget. Addition of water to the root zone is mainly done by irrigation, rainfall and capillary upflow through groundwater towards root zone and rate of root zone depletion decreases, conversely crop transpiration, soil evaporation and percolation losses remove root zone water content rate of root zone depletion increases.

In our study the water balance equation (Equation 1) was developed for a root zone system to express the water flow mainly due to rainfall P_r, irrigation I_r, leaching L_e, capillary upflow C_u, evapotranspiration *ET* and Runoff R_o.

$$\emptyset D_r \partial s/\partial t = P + I - ET(s) + Cu(n) - Le(n) - Ro(n) \quad (1)$$

Where D_r is root zone thickness (cm) and ∅ is porosity, where *n* is the soil saturation which is less than one and greater than zero. Water balance equation carries all inflow and outflow water fluxes. In this equation the evapotranspiration and capillary upflow fluxes as well as drainage or leaching fluxes are the function of change in water saturation due to flow of water. Here the surface runoff (R_o) is the function of applied irrigation depth in combination with excess rainfall which cannot be stored immediately in root zone.

The soil hydraulic functions used in equation are modification of those used by Brooks and Corey (1966), Vervoort and van der Zee (2008) and Shah *et al.* (2011). Depending on applied irrigation and rainfall depth and thus the root zone water content reaches at full saturation. In our model the surface runoff (*R*) was calculated based on antecedent rainfall and resultant soil saturation, as all rain water cannot store immediately in the root zone. The evapotranspiration, capillary upflow and leaching flux or drainage fluxes are also function of soil water saturation. These combined fluxes *ET, U,* and *L* lead towards development of loss function as described by Vervoort and van der Zee (2008) and Shah *et al.* (2011). Here it implies that *U* is assumed as a steady state flux which is triggered by root zone water saturation, water table depth, and the hydraulic forcing functions. Teuling and Troch's (2005) equation was used to calculate maximum *ET*. The saturation-switches are the main functions to determine the reduction in *ET* with an indication that at which value of saturation (soil moisture wilting point and the dynamic field capacity), the *ET* was reduced to zero.

The fluxes pertaining to water balance equation causes a loss function in a hydrological contact with groundwater as reported by Vervoort and van der Zee (2008).

$$\delta = \begin{cases} \frac{(\eta - y)\,(n - n_{cr})}{(n^* - n_{cr})} & when;\ n_{cr} < n < n^* \quad (2a) \\ (\eta - w)\,\{(1 - e^{\gamma(n - n\mathrm{lim})}\} & when;\ n^* < n < n_{lim} \quad (2b) \\ (\eta + x)\,\{(e^{\gamma(n - n\mathrm{lim})} - 1\} & when;\ n_{lim} < n < 1 \quad (2c) \end{cases}$$

Where;

$$y = \frac{K_s F}{\emptyset D_r}$$

$$w = \frac{y}{\{1 - e^{\gamma(n* - n\mathrm{lim})}\}}$$

$$x = \frac{K_n}{\emptyset D_r \{e^{\gamma(1 - n\mathrm{lim})} - 1\}}$$

$$\mu = \frac{E_{max}}{\emptyset D_r}$$

In equation 2 the parameters ‘y’, ‘w’ and ‘x’ are constants, where maximum capillary flux is represented by y for specified water table depth and hydraulic function and w is normalized version of which represents the reduction in capillary flux with increase in saturation. The function γ represents thehydraulic shape parameter which is related to *b*, represented as the slope of the water retention curve. The parameter μ is a normalization of maximum evapotranspiration (E_{max}) with root zone depth, where the Teuling and Troch’s (2005) equation was used to estimate E_{max}.

A parameter *F* presented in equation 3, which describes the relationship of water table depth with the capillary flux and account for the hydraulic shape parameters α and *b*and bubbling pressure p_b, having the following equation. (Eagleson, 2002).

$$F = \alpha \left[\frac{p_b}{\{D - D_r\}}\right]^{2+\frac{3}{b}} \quad (3)$$

The loss function presented in equation 4 is a fundamental for this study which calculates net root zone water loss with incorporating the effect of capillary flux (a contribution to the root zone) using combined calculations of fluxes. The capillary upflow and leaching/drainage never occur at same time in upper function (Shah *et al.*, 2011; Vervoort and van der Zee, 2009). It contains a transition point n_{lim} between wetter and drier conditions in root zone depending upon groundwater depth, which defines a saturation level of root zone. Equation 4 represents the separate loss function, where capillary upflow *U* has been separately calculated (Vervoort and van der Zee, 2008). In this function the soil saturation with lower limit (excluding the η parameter) of equation 2 has been used to calculate the leaching flux.

$$L_{total} = \begin{cases} -\mathrm{y} & when;\ n_{cr} < n < n^* \quad (4a) \\ -\mathrm{w}\{1 - e^{\beta(n - n\mathrm{lim})}\} & when;\ n^* < n < n_{lim} \quad (4b) \end{cases}$$

Where;

$$y = \frac{K_s F}{\emptyset D_r}$$

$$w = \frac{y}{\{1 - e^{\gamma(n* - n\mathrm{lim})}\}}$$

Loss function defines three boundary conditions, the first boundary condition (n_{lim}) describes the transition line between wetter and drier conditions in root zone reflecting a saturation level of root zone where no leaching and capillary upflow (L_e=C_u=0) occurs as function of irrigation/rainfall and soil type. Second boundary condition (n_{cr}) is function of water table depth, which represents further drier conditions where moisture level in root zone is such that as C_u=*ET*. At this condition the resultant loss from soil storage is zero where capillary flux contributes to all evaporation demands. An important condition of soil saturation level is n^* where a limited transpiration occurs. This condition falls in between n_{lim} and n_{cr}. Whereas n_w represents the saturation level of soil at wilting point, which is used for calculation of n_{cr}.

Basically, n_{cr} is the minimum level of soil saturation which defines the particular groundwater level from root zone, the soil type and demand of *ET* (Shah *et al.* 2011). The moisture level below n_{cr} will reduce the potential capillary upflow up to a level where it matches the actual *ET*. Shah *et al.* (2011) also defined the impact of groundwater level on net loss in terms of *ET*, which is apparent in deep water table condition and non-apparent for shallow water table conditions due to balance of *ET* losses with capillary upflow. In case of shallow water table, the n_{cr} becomes equal to n^*, while for deep water tables, n_{cr} becomes equal to n_w.

Equation 2 is valid for the situations where groundwater is deep and allows a very small capillary flux to maintain a maximum level of evapotranspiration capacity (Shah *et al.*, 2011; Vervoort and van der Zee, 2008). In this situation, $w<\mu$, which means $n_{cr} < n^*$. In very shallow water table conditions, where $w>\mu$, and $n_{cr} < n^*$, the equation 2 can be used in two linear piecewise sections (see Vervoort and van der Zee, 2008, equation 11). This means that the soil water saturation remains higher than n^* and *CU* allows *ET* always to be at its maximum capacity.

***Salt Transport Equation*:** Water movement through various components of water balance (i.e. irrigation, rainfall, evapotranspiration, leaching and capillary upflow) and salts convection with the soil water are the main factors to govern the salts transport and distribution in the soil profile. The distribution of salts mainly depends upon the frequency, the method, and the applied irrigation depth, the evaporation amount from soil surface, the distribution and amount of capillary upflow from groundwater and leaching below root zone. On evaporation of water from soil surface, all the salts are left behind, whereas the plants also selectively take up water, virtually excluding the salts. The solute transport is mainly due to the convection with the soil water. Equation 1 gives us the analytical solution of water balance components as presented by Shah *et al.* (2011) and Vervoort and van der Zee (2008).

The salt accumulation through various fluxes (i.e., *Cu*, *Le* and *ET*) was calculated through numerical solution. Whereas, each water flux propagates salt transportation, some of the fluxes comparatively have high concentration of salts. Each water flux containing dissolved salts in it, causes its transportation and concentration towards moving direction and creates the salts balance in soil matrix. Irrigation water and capillary upflow with dissolved salts have the potential to accumulate the salts in the soil matrix which is of greater importance (Bresler *et al*., 1982; Runyan and D'Odorico, 2010; Isidoro and Grattan, 2011). So, for this study, the primary source of salt mass fluxes that we have considered is due to saline irrigation application, capillary flux from groundwater and the salts leaching toward downward into the groundwater that have accumulated in the root zone. In this study the following salt balance equation was defined to calculate the salt mass *M*:

$$\partial \mathrm{M}/\partial \mathrm{t} = \emptyset D_r \partial \mathrm{sC}/\partial \mathrm{t} = Cu(n)\, C_D - Le(n)\, C + IrC_i \quad (5)$$

Where the C_D is groundwater salt concentration in $\mathrm{mol_c\ L^{-1}}$ at depth *D*. C_i is salt concentration of irrigation water in $\mathrm{mol_c\ L^{-1}}$, *C* is salt concentration in the root zone in $\mathrm{mol_c.L^{-1}}$, M is salt mass in $\mathrm{mol_c\ m^{-2}}$ and *s* is soil saturation. In these fluxes the '$\mathrm{mol_c}$' is the abbreviation of mole-charge and 100 $\mathrm{mol_c.L^{-1}}$ salinity level corresponds to an equivalence of electrical conductivity of the solution heaving 1 dS/m or 1 mS/cm salinity level. In our study the both equations 5 and 6 were numerically solved to provide root zone saturation, salt concentration, and various salt and water fluxes contribution. In this study, we have combined the osmotic and matric potentials keeping in view the concept of chemical potential and a virtual saturation n_v using $n(h)$ was determined to control *ET*, *Cu* and *Le*. We have obtained the virtual saturation 'n_v' by the given equation (Bras and Seo, 1987):

$$n_v = n_s h(1)^{\,1/b}\left[h(1)\left(\frac{n}{n_s}\right)^{-b} + kC\right]^{-1/b} \quad (6)$$

Where, n_v is virtual soil saturation, n_s is actual soil saturation, *h(1)* is saturated soil matrix potential (MPa) , the element *b* is related to tortuosity and conductivity, *C* is salt concentration level in $\mathrm{mol_c.L^{-1}}$, *k* is coefficient incorporating the temperature effect. The virtual saturation is the level of soil saturation which is available to plants considering the both osmotic and matric effects. In this model, we assume that soil root zone may receive only the real part of rainfall which enters into the soil. If rainfall amount becomes greater than the soil current storage capacity, which is termed as *1 - s*, then at full saturation the excess rainfall starts to loss in form of runoff (Laio *et al.*, 2001).

Calculations**:** Initially, the soil and groundwater salinity PDFs were drawn to represent an average salinity value for soil and groundwater in study area. These average soil and groundwater salinity values were used in simulations. For this purpose, two datasets in point format (coordinate-wise) including groundwater and soil salinity were used. The data consisted upon 9,435 soil samples analysis and 18,250 groundwater samples analysis acquired from soil fertility labs situated in study area. Using sampling data, the soil and groundwater salinity PDFs were drawn which represented a single probable salinity value for study area. There is a huge difference among salinity level of sampling data, thus to represent the highest range of groundwater salinities, model simulations were also performed using a mean value among highest range.

Soil properties for dominant soil types in study area were used in model simulations. The particular soil type for selected district from soil directory was used for each simulation (Table 1).

Table 1. Soil Properties used in Simulations for various Soil types fall in Study Area

Soil Type	Porosity Φ	Sat. Hydraulic Conductivity ***Ks*** (cm $\mathrm{d^{-1}}$)	b	Soil Field Capacity S_{fc}
Loam	0.458	44.50	6.12	0.267
Sandy Loam	0.410	120.70	5.41	0.179

Source: From SPAW Hydrology software.

The determination of the water availability to crop (Assouline *et al.*, 2015) and irrigation amount to be applied to soil depends on the soil water level at field capacity as well as permanent wilting point (Stofberg *et al.*, 2017). The field capacity indicates how much water retained by the soil after a certain time of soil saturation by irrigation. The modeling study was carried out on sugarcane crop. In Punjab, planting season of sugarcane is from February to March and harvesting date is from December to January (Malik, 2004). Calibrated vegetation properties for sugarcane crop used in model simulations are shown in table 2.

In study area the main source of groundwater is tubewell which in pure form or alternatively used with canal water to

Table 2. Vegetation Properties for Sugarcane crop used in Simulation.

Crop	Root zone depth D_r (cm)	Max Evapotra-nspiration E_{max} (cm $\mathrm{d^{-1}}$)	Evapotranspiration at wilting point E_w (cm $\mathrm{d^{-1}}$)	Matric Potential at n^* (MPa)	Matric Potential at n_w (MPa)	Leaf Area Index *LIA*	Rainfall interception depth (cm)
Sugarcane	175	0.438	0.89	-0.11	-2.1	6.21	0.22

Source: FAO irrigation and Drainage Paper No. 24 (1977), Porporato *et al.* (2001), FAO Paper 56 (2002), Asner *et al.* (2003), Whitehead and Beadle (2004), Malik (2008), Baez-Gonzalez *et al.* (2017), Ali *et al.* (2019).

irrigate the crops. This alternative practice is called conjunctive irrigation. In order to identify the effect of pure canal and groundwater and their conjunctive use strategies on sugarcane cropping system, five different irrigation scenarios were developed. To develop these scenarios the groundwater was mixed with the canal water (EC = 0.003 $mol_c.L^{-1}$) in five different ratios as given in table 3. The resultant water qualities (salinity level) acquired after each mixing of canal and ground water, were used in the model to predict the long-term effects of various fluxes on salt built-up in the root zone through irrigation and capillary upflow from groundwater.

Table 3. Irrigation Scenarios used in Simulation

Scenarios	Description	Ratio
S1	Pure Canal Water	100% CW and 0% GW
S2	Canal Water + Ground Water	70% CW and 30% GW
S3	Canal Water + Ground Water	50% CW and 50% GW
S4	Canal Water + Ground Water	30% CW and 70% GW
S5	Pure Ground Water	0% CW and 100% GW

In model simulations the real rainfall data were used as an input. The 34-years rainfall data were obtained from Punjab Meteorological Department (PMD). In modeling process, we assumed that only the part of the rainfall equal to storage capacity may enter into the root zone for determining the soil saturation (following Laio *et al.*, 2001; Aguilar *et al.*, 2009). The amount of rainfall greater than current soil storage capacity, which is represented by *1-n* in model, is lost in form of runoff. So due to a limited capacity of infiltration rate, the surface runoff is also considered as part of water-balance equation in this model (Appels *et al.*, 2011).

***Model Calibration and Validation*:** Model calibration was performed on a range of input values for given parameters and sensitivity analysis was performed to choose a suitable value for the area as given in table 2. Thereafter model validation was carried out for sugarcane cropping system under three different water table conditions (300 cm, 600 cm and 1150 cm), included 19 to 26 locations selected with a previous (4 to 10 years) data about irrigation, rainfall, groundwater and soil salinity. The R^2 values obtained under 300 cm, 600 cm and 1150 cm water table conditions are 0.78, 0.81and 0.80 respectively. The coefficient of variations (*CV*) for observed salt concentration under 300 cm, 600 cm and 1150 cm deep water table conditions are 0.85, 0.89 and 0.87 respectively. Similarly, the *CV* for simulated salt concentration under 300

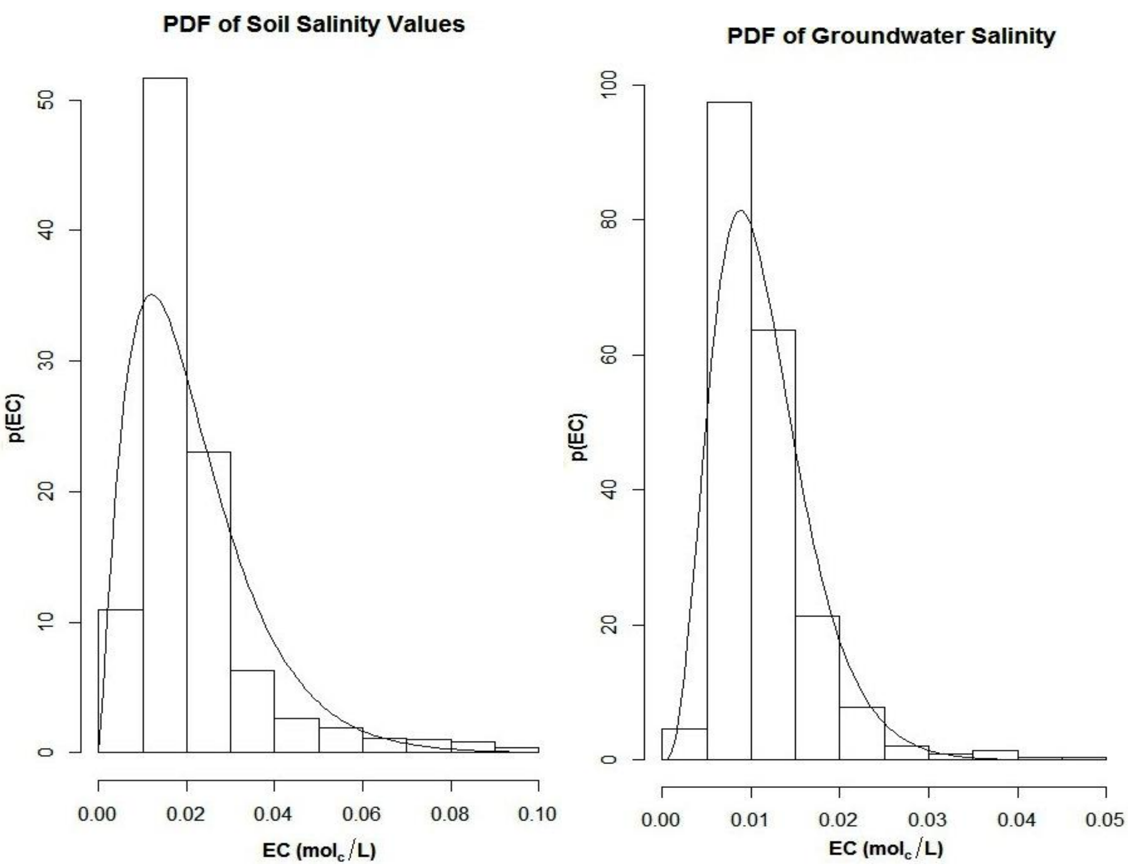

Figure 1. Probability Density Functions (PDFs) of soil and groundwater salinity values

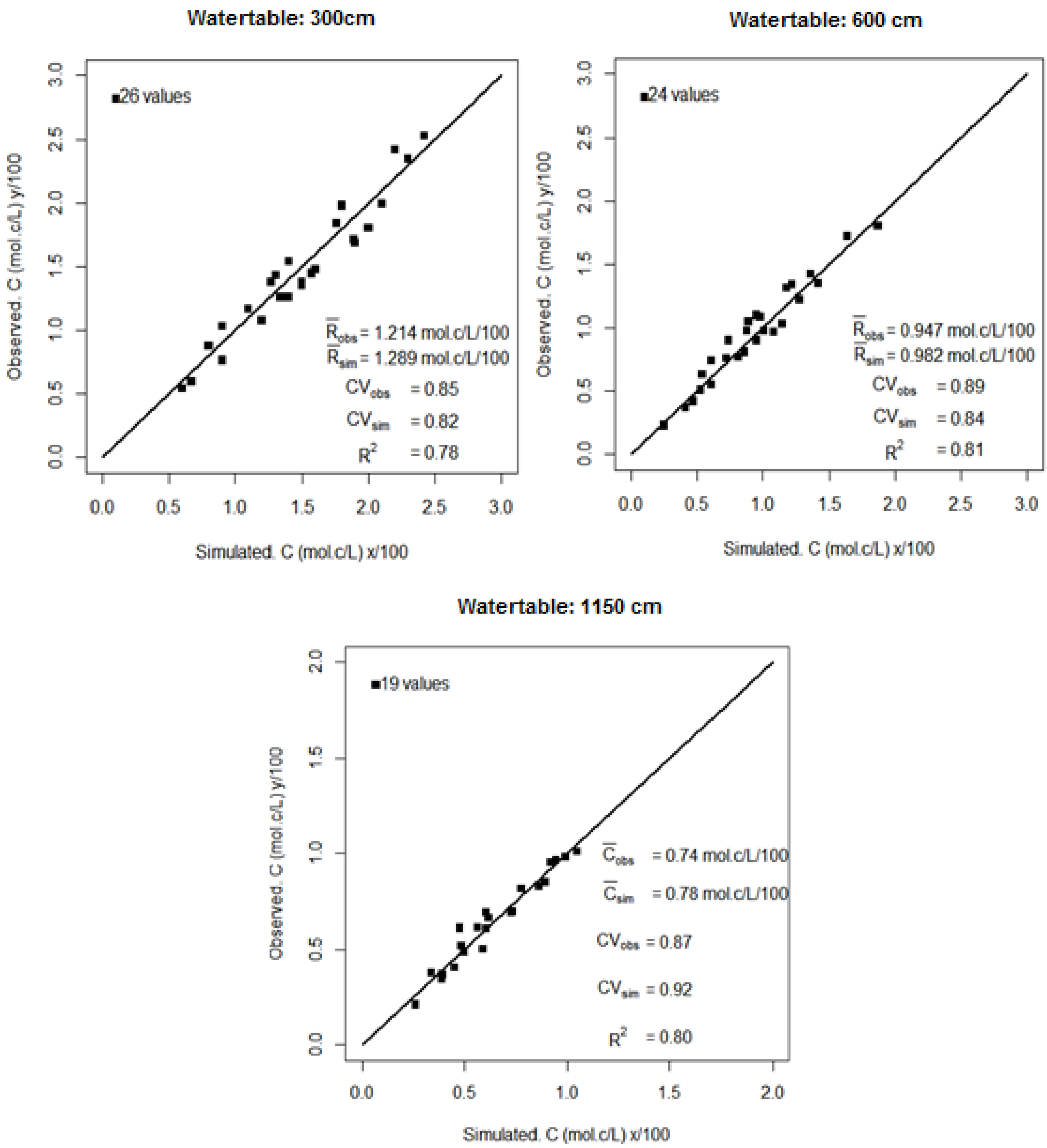

Figure 2. Model validation under various groundwater and soil salinities with three different water table conditions in sugarcane cropping system.

cm, 600 cm and 1150 cm deep water table conditions are 0.82, 0.84 and 0.78 respectively (Fig. 2).

RESULTS AND DISCUSSION

Salt Concentration and related Water Fluxes: The root zone salt built-up pattern and related water fluxes during entire growing season of sugarcane crop are shown in Fig. 3. Here it can be seen that the magnitude and pattern of rainfall and irrigation made a direct impact on various water fluxes and root zone salt concentration. The crop was grown under flood irrigation system physically practiced by the grower. If we compare the crop growing period from first to seventh irrigation intervals, the simulated crop *ET* gradually increased from minimum to its maximum level, whereas the capillary flux remained at its maximum level with no leaching due to the partial soil saturation. During this period root zone salt concentration monotonically increased as a function of soil saturation. At this stage the soil was fully saturated and simulated *ET* reached at its maximum level. Beyond this

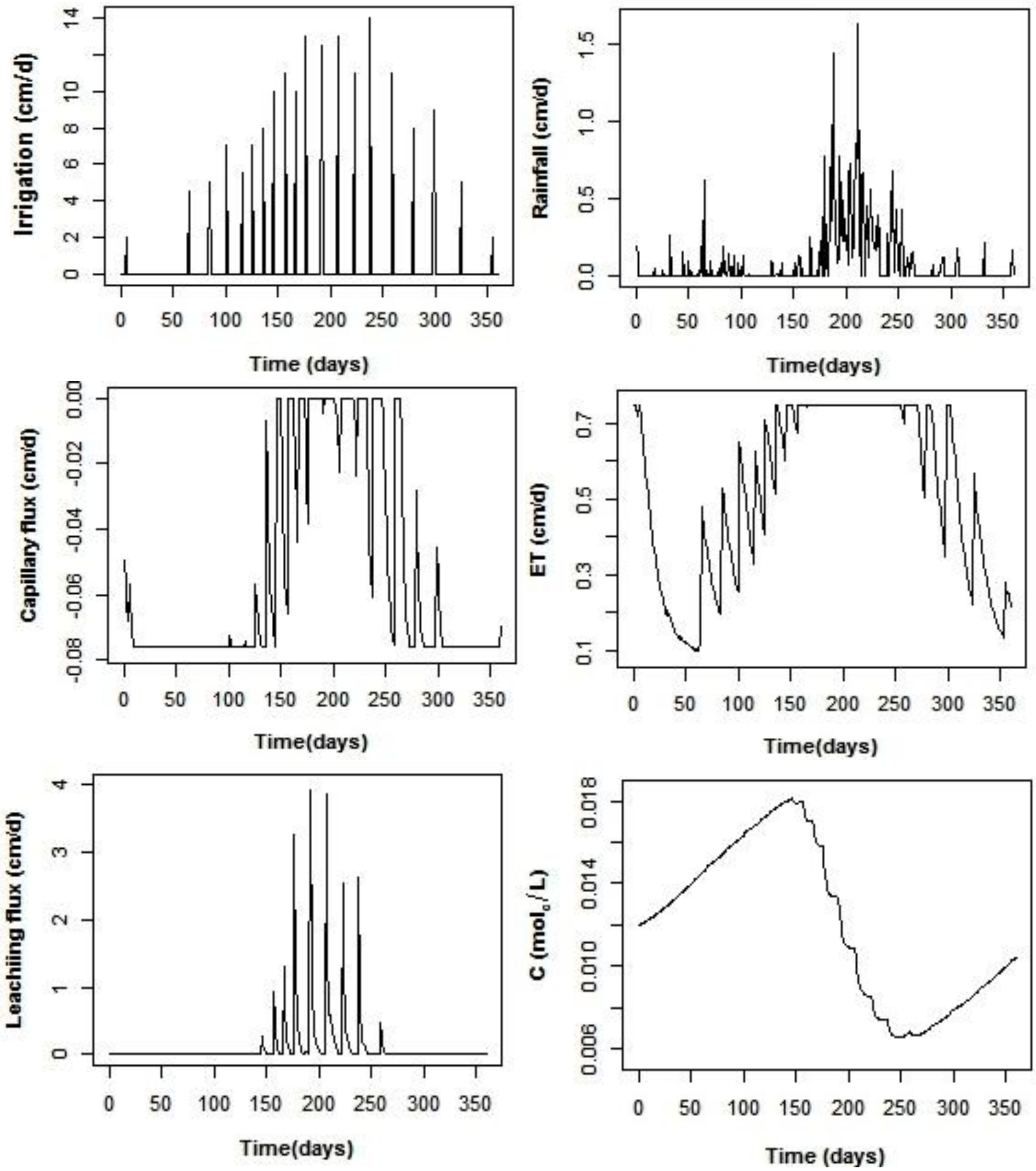

Figure 3. **Salt built-up pattern and related water fluxes in sugarcane cropping system under 300 cm deep water table having groundwater salinity 0.009 $mol_c.L^{-1}$ and initial soil salinity 0.012 $mol_c.L^{-1}$.**

stage, if we compare the crop period from seventh to fourteenth irrigation intervals, the crop *ET* remained at maximum level due to fully saturated soil root zone with higher level of leaching flux and lower range of capillary flux. During this period as the leaching starts, the salt concentration tends to reduce and adopts the decreasing trend upto a minimum range until the fourteenth irrigation. Beyond this stage again a reversal condition can be seen. Similar pattern was found in case of Shah *et al.* (2011).

The salt built-up pattern during the entire growing season of crop with respect to various water fluxes reveals that, the precipitation level and increasing magnitude of irrigation at each interval caused a monotonic increase in salt concentration as well as enhancement in crop *ET* and conversely a reduction in capillary flux until a fully saturation condition attained. At full saturation the leaching spell caused a gradual decrease in salt concentration upto three-fold lower position.

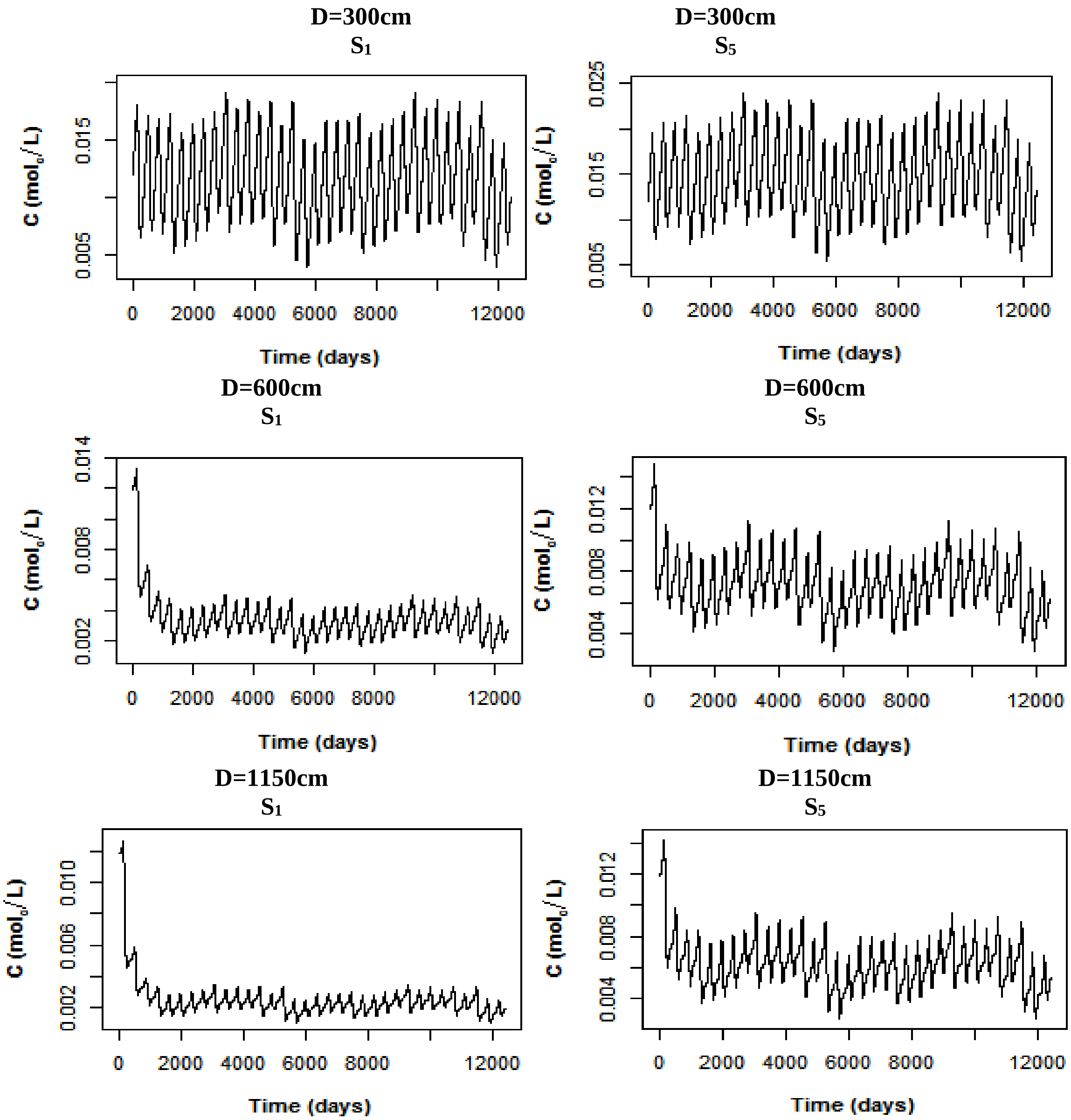

Figure 4. 34-year's salt concentration as a function of S_1 and S_5 with three different groundwater depths (300 cm, 600 cm and 1150 cm) under groundwater salinity 0.009 $mol_c.L^{-1}$.

***Effect of irrigation Scenarios and Varying Water table Conditions on Salt Concentration*:** Long-term salt concentration for the period of 34-years in sugarcane cropping system under varied groundwater depths and irrigation scenarios (S_1 and S_5) is presented in Fig. 4 and 5. Figure 4 represents long-term salt built-up pattern with underneath groundwater salinity 0.009 $mol_c.L^{-1}$. The root zone salt concentration in the soil irrigated with fresh canal water (S_1) having 0.003 $mol_c.L^{-1}$ salinity and under laid by shallow groundwater (300 cm depth), attained an average value of 0.0114 $mol_c.L^{-1}$ which was 73.25% and 81.5% greater than the salt concentration for soils under laid by 600 cm and 1150 cm deep water tables respectively. This means that there is a greater influence of capillary flux on root zone salt concentration than irrigation water (Subramani and Chandrasekaran, 2014; Shah *et al.*, 2011; Suweis *et al.*, 2010). The root zone salt concentration with shallow groundwater (300 cm depth) irrigated with pure saline groundwater (S_5) having 0.009 $mol_c.L^{-1}$ salinity attained an average value of 0.0145 $mol_c.L^{-1}$ with 52.71% and 59.32% lower concentrations for soils underlying 600 cm and 1150 cm deep water tables, respectively.

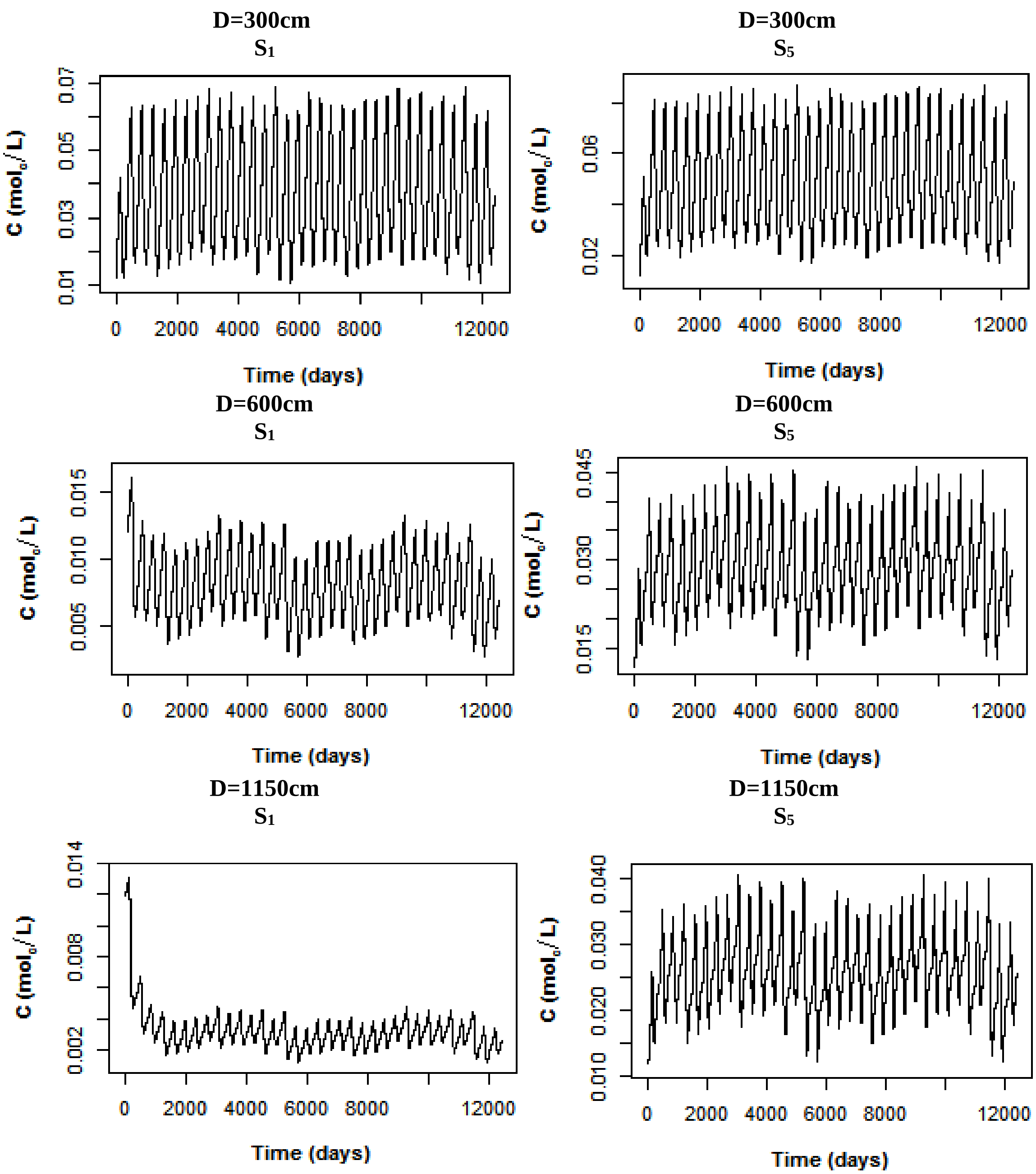

Figure 5. 34-year's salt concentration as a function of S_1 and S_5 with three different groundwater depths (300cm, 600 cm and 1150 cm) under groundwater salinity 0.051 $mol_c.L^{-1}$.

Fig. 5 represents the comparison of long-term salt concentration between shallow (300 cm depth) and deep (1150 cm depth) groundwater with salinity value 0.051 $mol_{c.}L^{-1}$. The root zone salt concentration in the soil irrigated with fresh canal water (S_1) having 0.003 $mol_{c.}L^{-1}$ salinity and under laid by shallow groundwater (300 cm depth) , attains an average value of 0.0373 $mol_{c.}L^{-1}$ which was 79.06% and 92.32% greater than the soils concentration under laid by 600 cm and 1150 cm deep water tables, respectively. This means that there is a greater influence of capillary flux on root zone salt concentration than irrigation water. The root zone salt concentration with shallow groundwater (300 cm depth) irrigated with pure saline groundwater (S_5) attained an average value of 0.0485 of $mol_{c.}L^{-1}$ which was 41.65% and 47.36% greater than the soils concentration having 600 cm and 1150 cm deep water tables, respectively. This means that the level of salt concentration in soil with deep groundwater (600 cm and 1150 cm) remained under lower position even

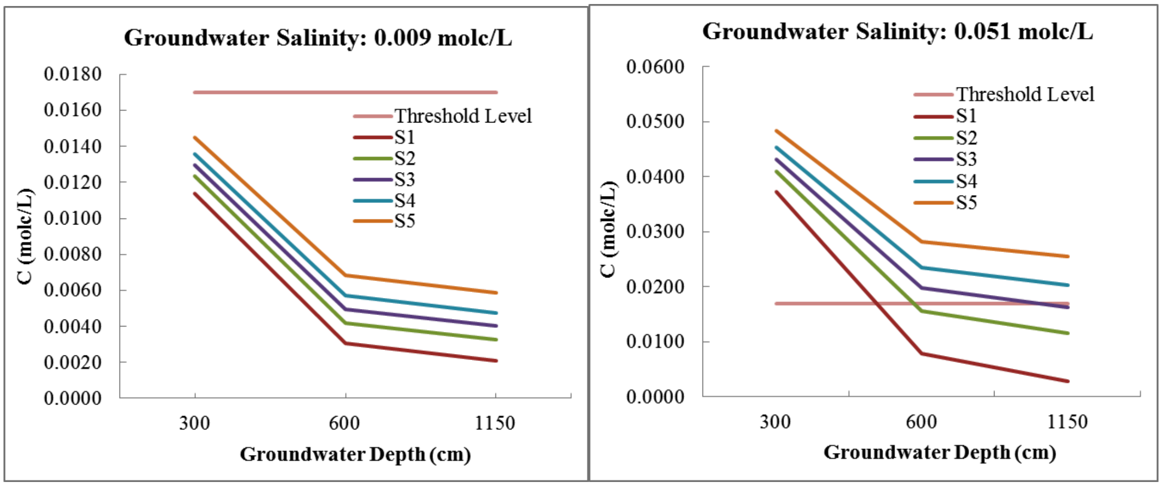

Figure 6. Long-term average salt concentration as a function of three different groundwater depths (300 cm, 600 cm and 1150 cm) under given irrigation scenarios (S_1, S_2, S_3, S_4 and S_5) for two groundwater salinities (0.009 $mol_c.L^{-1}$ and 0.051 $mol_c.L^{-1}$).

irrigated with pure saline groundwater as demonstrated by various researchers (Qureshi and Masih, 2009; Ehlers *et al.*, 2007).

It is apparent that with groundwater salinity 0.051 $mol_c.L^{-1}$, under 300 cm deep water table condition using fresh canal water for irrigation (S_1), the long-term average salt concentration in the soil root zone was 54.45% greater than crop threshold level, whereas using pure groundwater for irrigation (S_5) the average root zone salt concentration was 64.95% greater than crop threshold level (Fig. 5). For 600 cm deep water table condition using fresh canal water for irrigation (S_1), the simulated average salt concentration in the soil root zone was below crop threshold limit, whereas using pure groundwater for irrigation (S_5) the average root zone salt concentration was estimated as 39.91% greater than crop threshold level. On other hand, under 1150 cm deep water table condition using fresh canal water for irrigation the average salt concentration remained under safe limit, whereas using pure groundwater for irrigation average salt concentration was 33.38% greater than crop threshold level.

Mapping Root zone Salt Concentration as a Function of Various Irrigation scenarios and Water table Depths: Groundwater depth and salinity under various irrigation qualities have a direct impact on root zone salt concentration (Fig. 6). It is apparent that the simulated long-term average salt concentration in soil root zone under laid by groundwater with 0.009 $mol_c.L^{-1}$ salinity, under various water table conditions (300 cm, 600 cm and 1150 cm) using various quality waters for irrigation (S_1, S_2, S_3, S_4 and S_5), remained below crop threshold limit. On other hand, the simulated long-term average salt concentration in soil root zone under laid by groundwater with 0.051 $mol_c.L^{-1}$ salinity, under 300 cm deep water table, exceeded the crop threshold limit by 54.45%, 58.50%, 60.68%, 62.55% and 64.94% using various quality waters for irrigation respectively (S_1, S_2, S_3, S_4 and S_5). Whereas, under 600 cm deep water table the salt

Table 4. Long-Term average values of Simulated Root zone Salt Concentration, Evapotranspiration, Capillary Flux, Leaching Flux, Runoff, Irrigation and Rainfall under 300 cm Groundwater depth, 0.012 mol_c L^{-1} Soil salinity and Loamy soil for Sugarcane cropping system.

Irrigation Scenario	Groundwater Salinity (mol_c L^{-1})	IrrigationSalinity (mol_c L^{-1})	Salt Concentration (mol_c L^{-1})	ET (cm d^{-1})	Capillary Flux (cm d^{-1})	Leaching Flux (cm d^{-1})	Runoff (cm d^{-1})	Irrigation (cm d^{-1})	Rainfall (cm d^{-1})	Numerical Error (cm d^{-1})
S_1	0.009	0.0030	0.0114	0.5050	-0.0530	0.1057	0.0023	0.4605	0.0994	$1.45x10^{-5}$
S_2	0.009	0.0048	0.0123	0.5043	-0.0529	0.1063	0.0023	0.4605	0. 0994	$1.61x10^{-5}$
S_3	0.009	0.0060	0.0130	0.5037	-0.0528	0.1067	0.0023	0.4605	0. 0994	$1.70x10^{-5}$
S_4	0.009	0.0072	0.0136	0.5032	-0.0527	0.1072	0.0023	0.4605	0. 0994	$1.80x10^{-5}$
S_5	0.009	0.0090	0.0145	0.5022	-0.0526	0.1080	0.0023	0.4605	0. 0994	$1.94x10^{-5}$
S_1	0.051	0.0030	0.0373	0.4585	-0.0481	0.1468	0.00268	0.4605	0. 0994	$3.43x10^{-5}$
S_2	0.051	0.0174	0.0410	0.4514	-0.0474	0.1531	0.00274	0.4605	0. 0994	$4.31x10^{-5}$
S_3	0.051	0.0270	0.0432	0.4468	-0.0469	0.1572	0.00277	0.4605	0. 0994	$4.92x10^{-5}$
S_4	0.051	0.0366	0.0454	0.4424	-0.0464	0.1611	0.00280	0.4605	0. 0994	$5.51x10^{-5}$
S_5	0.051	0.0510	0.0485	0.4360	-0.0457	0.1668	0.00284	0.4605	0. 0994	$6.41x10^{-5}$

Table 5. Long-Term average values of Simulated Root zone Salt Concentration, Evapotranspiration, Capillary Flux, Leaching Flux, Runoff, Irrigation and Rainfall under 600 cm Groundwater depth, 0.012 mol_c L^{-1} Soil salinity and Loamy soil for Sugarcane cropping system.

Irrigation Scenario	Groundwater Salinity (mol_c L^{-1})	IrrigationSalinity (mol_c L^{-1})	Salt Concentration (mol_c L^{-1})	ET ($cm\ d^{-1}$)	Capillary Flux ($cm\ d^{-1}$)	Leaching Flux ($cm\ d^{-1}$)	Runoff ($cm\ d^{-1}$)	Irrigation ($cm\ d^{-1}$)	Rainfall ($cm\ d^{-1}$)	Numerical Error ($cm\ d^{-1}$)
S_1	0.009	0.0030	0.0031	0.4645	-0.0052	0.0986	0.0021	0.4605	0.0994	$1.75x10^{-6}$
S_2	0.009	0.0048	0.0042	0.4641	-0.0052	0.0989	0.0021	0.4605	0. 0994	$2.88x10^{-6}$
S_3	0.009	0.0060	0.0050	0.4639	-0.0052	0.0992	0.0021	0.4605	0. 0994	$3.77x10^{-6}$
S_4	0.009	0.0072	0.0057	0.4636	-0.0052	0.0995	0.0021	0.4605	0. 0994	$4.52x10^{-6}$
S_5	0.009	0.0090	0.0068	0.4631	-0.0052	0.0999	0.0021	0.4605	0. 0994	$5.70x10^{-6}$
S_1	0.051	0.0030	0.0078	0.4624	-0.0052	0.1006	0.00205	0.4605	0. 0994	$5.10x10^{-6}$
S_2	0.051	0.0174	0.0157	0.4563	-0.0050	0.1066	0.00208	0.4605	0. 0994	$1.39x10^{-5}$
S_3	0.051	0.0270	0.0199	0.4495	-0.0049	0.1132	0.00217	0.4605	0. 0994	$1.88x10^{-5}$
S_4	0.051	0.0366	0.0235	0.4425	-0.0048	0.1201	0.00225	0.4605	0. 0994	$2.34x10^{-5}$
S_5	0.051	0.0510	0.0283	0.4323	-0.0047	0.1301	0.00237	0.4605	0. 0994	$3.02x10^{-5}$

Table 6. Long-Term average values of Simulated Root zone Salt Concentration, Evapotranspiration, Capillary Flux, Leaching Flux, Runoff, Irrigation and Rainfall under 1150 cm Groundwater depth, 0.012 mol_c L^{-1} Soil salinity and Loamy soil for Sugarcane cropping system.

Irrigation Scenario	Groundwater Salinity (mol_c L^{-1})	Irrigation Salinity (mol_c L^{-1})	Salt Concentration (mol_c L^{-1})	ET ($cm\ d^{-1}$)	Capillary Flux ($cm\ d^{-1}$)	Leaching Flux ($cm\ d^{-1}$)	Runoff ($cm\ d^{-1}$)	Irrigation ($cm\ d^{-1}$)	Rainfall ($cm\ d^{-1}$)	Numerical Error ($cm\ d^{-1}$)
S_1	0.009	0.0030	0.0021	0.4595	-0.0008	0.0993	0.0020	0.4605	0.0994	$4.03x10^{-7}$
S_2	0.009	0.0048	0.0033	0.4591	-0.0008	0.0996	0.0020	0.4605	0. 0994	$1.47x10^{-6}$
S_3	0.009	0.0060	0.0040	0.4588	-0.0008	0.0999	0.0020s	0.4605	0. 0994	$2.20x10^{-6}$
S_4	0.009	0.0072	0.0048	0.4586	-0.0008	0.1001	0.0020	0.4605	0. 0994	$2.91x10^{-6}$
S_5	0.009	0.0090	0.0059	0.4582	-0.0008	0.1005	0.0020	0.4605	0. 0994	$4.11x10^{-6}$
S_1	0.051	0.0030	0.0029	0.4592	-0.00079	0.0995	0.00200	0.4605	0. 0994	$8.48x10^{-7}$
S_2	0.051	0.0174	0.0115	0.4553	-0.00077	0.1034	0.00201	0.4605	0. 0994	$9.70x10^{-5}$
S_3	0.051	0.0270	0.0164	0.4503	-0.00076	0.1084	0.00205	0.4605	0. 0994	$1.51x10^{-4}$
S_4	0.051	0.0366	0.0204	0.4433	-0.00075	0.1152	0.00215	0.4605	0. 0994	$1.97x10^{-4}$
S_5	0.051	0.0510	0.0255	0.4327	-0.00073	0.1257	0.00226	0.4605	0. 0994	$2.60x10^{-4}$

concentration for S_1 and S_2 remained below crop threshold limit while for S_3, S_4 and S_5 it exceeded the crop threshold limit by 14.55%, 27.74% and 39.91% respectively. Similarly, under 1150 cm deep water table, the salt concentration for S_1, S_2 and S_3 remained below crop threshold limit, while for S_4 and S_5 it exceeded the crop threshold limit by 16.70% and 33.39% respectively.

***Salt Concentration and related Water Fluxes under Varying Groundwater and Irrigation Conditions*:** Tables 4 to 6 represent the salt concentration and related water fluxes for 300 cm, 600 cm and 1150 cm deep water tables under different irrigation and underneath groundwater qualities. If we compare the simulated salt concentration for all given water table conditions under same irrigation scenarios and groundwater qualities, then it reveals that the salt accumulation through capillary flux played major contribution to root zone salt built-up pattern than its direct application. It can well be understood by analyzing the salt accumulation under three water tables (300 cm, 600 cm and 1150 cm) condition with same irrigation scenarios. The salt concentration under 300 cm deep water table condition having groundwater salinity 0.009 $mol_{c.}L^{-1}$ using pure groundwater for irrigation (S_5) was found 0.0145 $mol_{c.}L^{-1}$ which is 21.49% greater than the salt accumulation using pure canal water for irrigation (S_1) under same water table condition (300 cm). Whereas, this simulated value (0.0145 $mol_{c.}L^{-1}$) under 300 cm deep water table was found 52.72% and 59.23% greater than the simulated salt concentration for 600 cm and 1150 cm water table conditions respectively under same parameters. This means that there is a greater influence of water table depth on root zone salt accumulation through capillary flux than irrigation application.

***Conclusions*:** Model simulations were made to identify the effect of long-term water table depth and conjunctive water use strategies on root zone salt accumulation in sugarcane cropping system. Five different irrigation scenarios (S_1, S_2, S_3, S_4 and S_5) were developed by mixing the groundwater with the canal water with specified ratios. The development of long-term root zone salt built-up under shallow water table was greatly influenced by the groundwater depth and quality through capillary flux. Shallow the water table depth the greater the root zone salt concentration, whereas deeper the water table depth the lesser the root zone salt concentration.

The soils underlying shallow and deep water table condition (300 cm to 1150 cm depth) using the PDFs value of groundwater salinity for irrigation in simulations, are suitable for sugarcane crop cultivation even irrigating with pure groundwater water. The soils underlying shallow water table condition (300 cm depth) using the highest mean values of groundwater salinity in simulations, are not suitable for sugarcane crop cultivation even irrigating with pure canal water. In determining the simulated crop *ET*, it was concluded that shallow water table attributed to greater crop *ET* with maximum value for 300 cm depth having least groundwater salinity. Conversely a shallow water table with higher groundwater salinity led to a lower crop *ET* than deep water table. This means that there was a greater influence of capillary flux on root zone salt concentration than irrigation water. The study revealed that the shallow water table attributed greater capillary flux with maximum value for 300 cm deep water table under lower groundwater salinity (0.009 $mol_{c.}L^{-1}$).

***Recommendations*:** This study reveals that 0.051 $mol_{c.}L^{-1}$ saline groundwater under shallow water table condition is a complete disaster and lands will become salinized in just 3-4 years. In these areas the sustainable crop production is connected with effective drainage systems installation and flushing of salts periodically from the root zone. In the absence of drainage systems, salts leaching with saline water will promote the salinization process of soil and lands will go out of production in quick manner. To avoid such conditions, cultivation of more salt tolerant crops could be a better option. In addition, the state needs to increase the existing canal water allowance for these critical areas.

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