Sustainable Eco-Systems under Land Retirement

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Abstract: This study uses five years of field data from the Land Retirement Demonstration Project located in western Fresno County of California to develop a comprehensive theoretical and numerical modeling framework to evaluate the specific site conditions required for a sustainable land retirement ecosystem outcome based on natural drainage. Using field data, principles of mass balance in a control volume, the HYDRUS-1D Software Package for simulating one-dimensional movement of water, heat, and multiple solutes in variably-saturated media, and PEST, a model-independent parameter optimizer, the processes of soil water and solute movement in root zone and the deep vadose zone were investigated. The optimization of unsaturated soil hydraulic parameters and downward flux (natural drainage) from the control volume against observed vadose zone salinity levels and shallow groundwater levels yield difficult to obtain natural drainage rate as a function of water table height within the control volume. The results show that unsaturated soil hydraulic properties and the downward flux from the soil profile are the critical parameters. A 'natural drainage approach' to sustainable land management for drainage impaired land is proposed. With this approach it is feasible to design a sustainable land use regimen for drainage impaired lands in general and retired lands in particular.

Further analysis of data on the evolution of vadose zone salinity and perched water levels also show that effective unsaturated soil hydraulic property and the "natural drainage rate" change with average soil water salinity. The results show that at the same pressure head, soil water content is less with higher soil water salinity as compared to lower soil water salinity. It is thus concluded that the use of soil water salinity invariant soil water hydraulic parameters in numerical modeling can seriously compromise prediction, especially for a variable soil water salinity environment.

Introduction

Use of intensive irrigation in arid and semi-arid areas usually leads to gradual salination of the soil which is detrimental to crop-yields (Ayers and Westcot, 1985). It is estimated that about 20-25% of the world's irrigated land including 27% of irrigated land in the U.S. are affected by salination (Gates et al., 2002). One of the effective strategies for controlling the salinity of soil in the root zone is application of irrigation water, in excess of the evapotranspiration requirement, which leaches the excess salt load to the groundwater system. In many irrigated regions, the excessive recharge to the groundwater is greater than the natural downward or horizontal discharge from the groundwater system, which then commonly leads to a gradual rise in the water table. The efficacy of the leaching program is thus reduced, eventually making the land waterlogged and unfit for any productive economic activity for agriculture or ecosystem services. An effective drainage network is required to keep the water table and the salinity level from rising to detrimental levels, which may not always be feasible due to environmental or other factors. In such cases, either the lands overlying the saline shallow water table have to be abandoned or some alternative ways of disposing of the saline groundwater have to be devised. The San Joaquin Valley of California represents such a case, where a combination of lack of adequate out-of-basin drainage caused by topographic and environmental constraints, intensive irrigation practices, and the presence of a shallow underlying layer of low permeability soil has caused the root zone to become highly saline and the shallow water table to rise. Because the San Joaquin Valley of California is one of the major agricultural production regions of the state, the mitigation of its salinity-toxicity drainage problems has been a top priority of both federal and state agencies. The U. S. Department of Interior, Bureau of Reclamation (BR) through San Luis Drainage Feature Re-evaluation project decided to implement a combination of drainage reduction measures, drainage water reuse, evaporation ponds and land retirement in what it calls the In-Valley/Water Needs Land Retirement Alternative. The BR intends to retire up to a total of approximately 78,500 ha of land in the drainage area. Retired lands are assumed to be managed as dryland farming, grazing, or fallowing.

Land retirement is the intentional discontinuation of irrigation over specified areas and it is assumed that the depth to the shallow water table will increase and the total salt load in the drainage water will decline. The link between the land retirement and shallow water table decline has been established in the hydrologic model studies of Belitz and Philips (1992), and Purkey and Wallender (2001). On the other hand, based on a modeling study of water and salt transport in unsaturated soils in arid climates, the United States Department of Agriculture, US Salinity Laboratory presented a worst case scenario where the retired lands could become excessively salinized over time and would thus become unsuitable for sustained agriculture and even dry land farming and non-irrigated rangeland (Wallender et al., 2002). If in certain cases the possibility of worsening of the environmental conditions due to land retirement exists, it is important that these cases are identified before it is decided to retire a given area, especially considering the cost and time required to acquire land for retirement. It is thus important to evaluate the efficacy of the proposed land retirement in terms of various outcomes that are possible depending upon the field conditions and land uses. However there are limited conceptual or empirical frameworks available to evaluate the field condition likely to emerge as a result of land retirement. The lack of knowledge regarding the potential effects, positive and negative, of retirement of agricultural land on a large scale has long been identified as a cause of concern (Selmon et al., 2000). Because of these concerns, the U.S. Department of Interior through the Interagency Land Retirement Team implemented the Land Retirement Demonstration Project (LRDP) located in western Fresno County of California to provide site specific scientific data (Erysian et al., 2005).

There are two main criteria that can be used to evaluate the outcomes of the land retirement. First is the depth of the shallow water table. For a successful land retirement outcome it would be expected that the shallow water table should decline as a result of discontinuation of irrigation, achieving an average water table level which is deep enough to allow the root zone to be free from water logging. The second criterion is low salinity of the root zone in particular and vadose zone in general. Usually, when land is selected for retirement, a highly saline vadose zone is overlying highly saline shallow groundwater. After retirement it would be expected that the average salinity of the root zone and vadose zone would gradually decline to an extent that plant growth is possible with natural rainfall. Due to the discontinuation of irrigation, the amount and direction of water flux within the vadose zone is expected to change from the irrigated condition. The change in the amount and direction of water flux in the vadose zone affects the water table level and the salinity level in this zone. The understanding of these changes in the water and salt fluxes in the vadose zone could be used to guide the land retirement decisions. These land retirement decisions pertain to the selection of the land to be retired as well as its appropriate use for dryland farming, grazing or habitat restoration. The changes in vadose zone salinity and groundwater level affect the natural species of plants that can grow under the given soil and water condition and by extension relates to achieving native habitat restoration goals. While modeling studies and field studies provide some linkage between the shallow water table and the vadose zone salinity, a comprehensive theoretical, empirical and numerical modeling framework is needed to evaluate the specific site conditions required for a beneficial land retirement outcome.

Another issue of concern is the changes in soil hydraulic properties as a result of land retirement which can impact the management of a sustainable ecosystem. Soil hydraulic properties impact the process of water and salt movement in the vadose zone that play an important role in estimating infiltration, soil moisture storage, root zone salt balance, drainage disposal and drainage water reuse, recharge to the groundwater and scheduling and duration of irrigation events (Thayalakumaran et al., 2007). The numerical models used to simulate the water flow and solute transport process in the unsaturated zone rely on the Richard's equation for variably saturated flow, and the Fickian based convection-dispersion equation for solute transport (Simunek and Bradford, 2008). HYDRUS 1D with the UNSATCHEM module (Simunek et al., 2005) is widely used. The Richard's equation, most often implemented in these models to simulate the water movement, requires the characterization of the soil hydraulic properties in terms of functional relationships between (1) soil water pressure head h and volumetric water content θ ($\theta(h)$), and (2) soil hydraulic conductivity K and the pressure head or water content ($K(h)$ or $K(\theta)$). The unsaturated soil hydraulic properties are in general highly nonlinear functions of the pressure head.

The analytical models of Brooks and Corey (1964) and van Genuchten (1980) are commonly used as a predictive equation for the hydraulic conductivity in terms of soil water retention parameters. The van Genuchten model (1980), together with the capillary based unsaturated hydraulic conductivity prediction model (Mualem, 1976), uses five independent parameters: θ_r(residual soil water content), θ_s(saturated soil water content), α (soil water retention parameter), n (exponent in the soil water retention function), and K_s (saturated hydraulic conductivity). The unsaturated soil hydraulic functions are expressed as

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{\left(1 + |\alpha h|^n\right)^m} \text{ for } \theta_s \geq \theta \geq \theta_r \tag{1}$$

$$K(h) = K_s S_e^l \left[1 - \left(1 - S_e^{1/m}\right)^m\right]^2 \tag{2}$$

where,

$$S_e = \frac{\theta(h) - \theta_r}{\theta_s - \theta_r} \tag{3}$$

$$m = 1 - 1/n, \quad n > 1 \tag{4}$$

The pore connectivity parameter l in the hydraulic conductivity function was estimated (Mualem, 1976) to be about 0.5 as an average for many soils. The five soil hydraulic parameters of the van Genuchten equations are either estimated from direct or indirect methods. Direct methods, either field or laboratory, require up-scaling of parameters, which introduces error. Indirect methods include pore size distribution models, inverse methods and pedotransfer functions (Mualem, 1976; Kool et al., 1987; Simunek et al., 1999). The current methods used to estimate soil hydraulic parameters do not take into account the salinity levels of the soil water, although saturated hydraulic conductivity is known to be affected by the soil solution chemistry and the content and the nature of soil particles (Quirk and Schofield 1955; Mcneal and Coleman 1966; Scotter and Loveday 1966). The soil hydraulic properties are also affected by exchangeable sodium percentage (ESP) for normal plastic soils (McIntyre, 1979). Levy et al. (2005) conclude that salinity, sodicity and rate of wetting all have effects on saturated hydraulic conductivity and the effects are complex. While there have been number of studies on the effect of salinity levels on saturated hydraulic conductivity in laboratory conditions, there is only limited literature on the effect of soil water salinity on hydraulic conductivity and soil water retention parameters under variably saturated flow conditions. Chawla et al. (1983) evaluated the infiltration and water transmission capacity under such conditions by simulating salinization by using irrigation water of high salinity and high sodium absorption ratio (SAR) and subsequently leaching with good quality water. The steady state infiltration increased with salinization and the unsaturated hydraulic conductivity values were higher in the salinized soil. The effect of soil water salinity on crop yield has been long recognized and it has been understood that increasing soil solutions salinity decreases available water for plant use (Warrence et al., 2002).

Thus the main objective of this paper is to determine the required soil properties and the downward flux from shallow groundwater (defined as natural drainage rate) for a successful land retirement outcome by using the principle of mass balance across a fixed control volume, and the field data from the LRDP. The field data is used to set up a numerical modeling framework which, together with inverse modeling, allows determining the required soil properties and the natural drainage rate to achieve the reported salinity level and shallow water depths at the LRDP site. The study proposes a new numerical modeling approach to the evaluation of the natural drainage rate which is a challenge to evaluate. The mass balance formulation together with the calibrated numerical modeling framework identifies the necessary conditions required to yield favorable land retirement outcomes.

The field data from the LRDP in conjunction with the numerical simulation results is used to test the following two hypotheses:

(1) A specific combination of soil properties and natural drainage rate is required for land retirement to result in the decline of shallow water table level and a decrease in the average root zone salinity.

(2) A priori knowledge of the natural drainage rate of the site can be used to design a sustainable land use regimen.

Additionally the data set is also used to evaluate the nature and degree of changes in the soil water retention parameters and unsaturated hydraulic conductivity due to changes in soil water salinity. The field data from the LRDP in conjunction with the numerical simulation model and inverse modeling is used to obtain effective van Genuchten parameters for the system corresponding to different salinity levels which evolve with time. It is proposed that the changes in effective unsaturated soil hydraulic functions at various average salinity levels in the soil water at the same site could thus be used to demonstrate the effects of salinity on unsaturated soil hydraulic functions.

MATERIAL AND METHOD

Land Retirement Demonstration Project (LRDP)

In response to concerns about the lack of scientific data to identify potential benefits and impacts of retiring land from irrigated agriculture, the Land Retirement Program, an interagency Department of Interior initiative, completed a five-year, large scale Land Retirement Demonstration Project (LRDP) at two drainage–impaired sites on the west-side of the San-Joaquin Valley (Erysian et al., 2005). The drainage-impaired sites at Tranquillity in western Fresno County and Atwell Island in the Kings and Tulare Counties, respectively, were selected for monitoring the impacts of agricultural land retirement. The analysis of the five-year study, spanning the period 1999-2004, was completed at the Tranquillity site only.

Site Description

The Tranquillity site with an area of 845 ha is located in the trough of the San Joaquin valley (Fig. 1).

Figure.1 Location of Tranquility site (modified from http://esrp.csustan.edu/gis/maps/lrdp_loc.png)

The area south of Adams Avenue was under irrigated agriculture prior to land retirement in 1998 for the study (Fig 2).

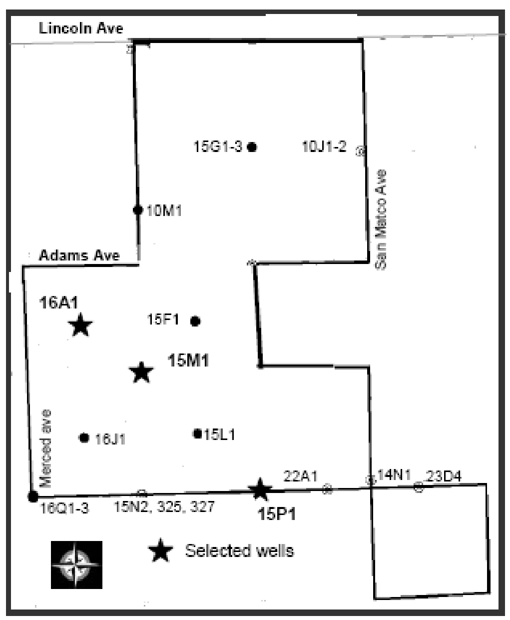

Figure 2 Location of selected groundwater observation wells (modified from http://esrp.csustan.edu/publications/pdf/lrdp/2003ar/LRDP81605CA.pdf)

During the study period, only a barley crop was planted to serve as a cover crop for weed and dust control. Approximately 7.6, 12.4, and 11.7 cm of water were applied to the barley during 1999, 2000, and 2001, respectively, using a hand moved sprinkler irrigation system. The site is underlain by flood basin deposits derived from overbank deposition from the San Joaquin River and Fresno Slough. The flood basin deposits consist of fine textured, moderately to densely compacted clays in thickness from 1.5 to 10.7 m (Belitz and Heimes 1990). Soils in the Tranquility Demonstration Project area primarily consist of clays, silty clays, and silty clay loams. The site has Mediterranean climate with an annual average precipitation of about 18 cm, but the site only received an average annual precipitation of about 14.4 cm. during the study period. The precipitation events mostly occur between the months of November through April. Hourly precipitation, temperature, wind, and relative humidity data for the Tranquillity site are available at the California Irrigation Management Information System (CIMIS) weather station No. 105, located 2.4 kilometers west of the demonstration project site. The nearby CIMIS station, operated by the California Department of Water Resources, is the best source of weather data for the study site. During the course of the project, data were collected on a) changes in groundwater levels, b) changes in groundwater quality, and c) changes in average soil salinity to a depth of 1.5 meters. These data together with climate data, crop data and irrigation data were used in this study to understand the process and mechanism of groundwater and soil salinity response to land retirement. The methods utilized for monitoring soil and groundwater levels are described in the land retirement demonstration project five-year report (Erysian et al., 2005). Baseline soil samples were collected during September and October 1999. The sites were re-sampled in November 2002 and August 2004. There are 50 monitoring wells and three drain sumps in the project vicinity that were used to measure groundwater levels on a quarterly basis. However, a complete set of water level data are available for only 20 monitoring wells for the entire period of record from October 1999 to October 2004. Furthermore, some of those wells are located on the edges of the demonstration site, where shallow ground water levels could have been affected by the irrigated agriculture in the adjacent land and some of the other wells are located in areas, which were already retired when measurements were started. In not all the 20 wells, the groundwater major ion chemistry had been analyzed, while some of the wells were meant only to record the changes in the regional water table. Thus after eliminating the wells lacking the range of data required for this study, three groundwater observation wells (15M1, 16A1 and 15P1) were selected for the analysis (Fig. 2).

The site is characterized by the presence of perched water table conditions, with a downward water flux from the saturated zone to the regional water aquifer through a partially saturated layer (Erysian et al., 2005). The shallow, perched groundwater is extremely saline but varies across the sampling wells. The well 15M1 had the most saline groundwater with an initial EC of 52.2 dS/m, whereas wells 16A1 and 15P1 had an initial EC of 35.5 and 26.0 dS/m, respectively. The salinity of the perched water table fluctuated in the five year period following the land retirement, with a slight increasing trend. This could be mainly due to the salt from vadose zone being flushed to the perched water table. In terms of major ion chemistry, the dominant cation in the perched groundwater is sodium, while sulfate is the dominant anion.

The perched water table was at 1.82, 1.85 and 2.95 meters below the surface for wells 15M1, 15P1 and 16A1, respectively, at the beginning of the LRDP. Following land retirement, all the three wells showed a similar decline of 2.29 meters, 2.26 meters and 2.07 meters for 15M1, 16A1, and 15P1, respectively, over a five year period (1999-2004). The final depth of the water table under land retirement was the initial values plus the sum of these declines. The rate of decline in the perched water table is highest immediately following land retirement and the rate decreases continuously with time (Fig. 3).

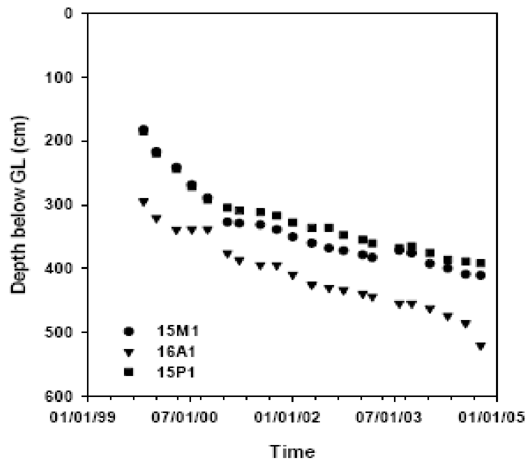

Figure 3 Decline in the perched water table following land retirement

The electrical conductivity of the soil saturation extract (EC_{se}) for each site is represented by the average value of EC_{se} for four sampled locations adjacent to each well. The EC_{se} measurements represent the depth-averaged value for three layers of the root zone, 0-30 cm (0-1 ft), 60-90 cm (2-3 ft) and 120-150 cm (4-5 ft) (Fig. 4).

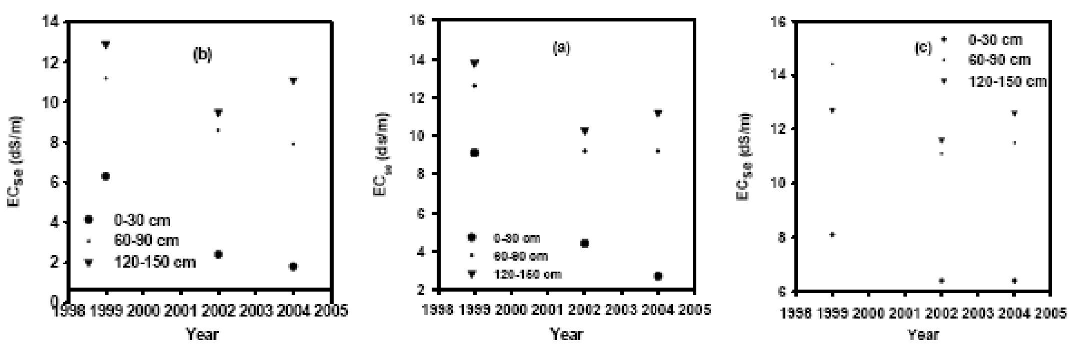

Figure 4 Changes in root zone salinity levels for sites a) 15M1, b) 16A1, and c) 15P1

Water mass balance

The interrelationship amongst precipitation, evapotranspiration, change in depth to the perched water table and the bottom flux of water through a confining layer can be explained with reference to a one dimensional fixed control volume (Fig. 5).

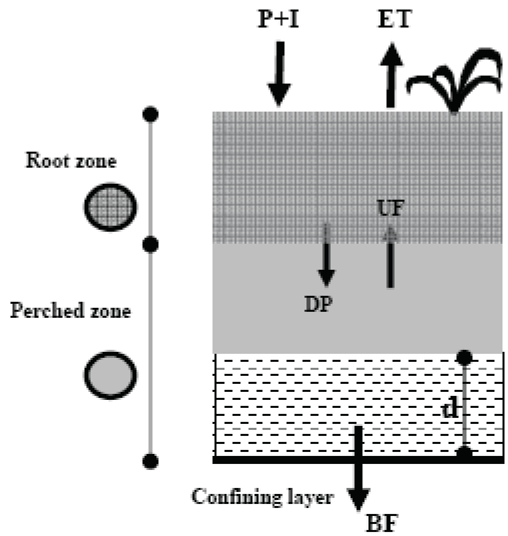

Figure 5 Control volume for mass balance

The upper and lower horizontal boundaries for the control volume are the ground surface and the confining layer below the shallow water table, respectively. The control volume can further be subdivided into two subsystems as the root zone and the perched zone. The perched zone also includes the deep vadose zone, below the root zone.

With the principle of mass conservation, the change in water storage in the control volume over an annual time period can be expressed as,

$$\sum (P+I) - \sum ET - \sum BF = \Delta W_{vz} + \Delta W_{sz} \qquad (5)$$

where $P =$ precipitation (L), $I =$ irrigation if any (L), $ET =$ evapotranspiration (L), $BF =$ bottom flux (natural drainage) out of the control volume (L), and ΔW_{vz}, ΔW_{sz} are the change in water storage (L) in vadose zone and the saturated zone, respectively. For the land retirement scenario under consideration, surface runoff is assumed to be negligible. This assumption is based on the monitoring of precipitation during the study period, where the monthly precipitation were never in excess of 5 cm and the precipitation threshold to cause runoff is well in excess of 5 cm. The shallow water table will rise, fall or remain the same depending upon whether $\sum (P+I)$ is greater than, less than, or equal to $(\sum ET + \sum BF)$. When the shallow water table is rising, commonly the case for an area deemed suitable for land retirement, $\sum (P+I)$ is greater than $(\sum ET + \sum BF)$, but with land retirement, irrigation is either ceased or greatly reduced with the expectation that on an annual cycle, $\sum (P+I)$ will be less than $(\sum ET + \sum BF)$. In such a scenario, it is possible for $\sum ET$ to be greater than $\sum (P+I)$ due to periodic upward flux of water from the saturated zone to the root zone and the soil surface, in the initial years after the land retirement. This scenario produces an increase in the salinity in the vadose zone after land retirement, even though shallow water level falls. If the root zone control volume is considered as a subsystem of the total control volume, the change in water storage in the subsystem over an annul cycle can be represented as,

$$\sum(P+I)-\sum ET-\sum DP+\sum UF=\Delta W_{vz1}. \qquad (6)$$

Here DP is the depth of water moving down from the root zone (L) and UF is the upward flux of water into the root zone (L), and ΔW_{vz1} is the change in water storage in the root zone. Assuming that on an annual cycle, change in water storage in the root zone is negligible and rearranging and substituting equation (6) into equation (5) gives

$$\sum DP-\sum UF-\sum BF=\Delta W_{vz2}+\Delta W_{sz} \qquad (7)$$

in which ΔW_{vz2} = the change in vadose zone water storage in the perched zone. For achieving a decline in the shallow water table level and maintaining a net downward flux of water out of the root zone so as to decrease the average root zone salinity levels, the following two relations must hold, respectively,

$$(\sum DP-\sum UF)<\sum BF \qquad (8)$$

$$\sum DP>\sum UF \qquad (9)$$

For a completely closed system, if BF is zero, then it is not possible to increase the depth to shallow water table level and decrease the root zone salinity simultaneously as it is not possible to meet both the constraints of Eqs.8 and 9.

HYDRUS-1D with UNSATCHEM module

In the present study, HYDRUS 1D with the UNSATCHEM module (Simunek et al., 2005), a one-dimensional numerical soil water flow and transport model was used to simulate the effect of land retirement on vadose zone salinity and perched water table level. The numerical model selected for the study simulates movement of water, heat and 7 major ions, coupled to equilibrium and kinetic chemistry routines in variably-saturated media. In the present study, heat transport as well as CO_2 production and its transport processes is excluded. Variably saturated flow is simulated with the Richards equation; the unsaturated soil hydraulic properties (the constitutive relationships) are described using van Genuchten (1980) parameters. Root water uptake is simulated as a function of depth and time. Root growth in HYDRUS-1D is simulated by means of a logistic growth function. The flow equation is solved numerically using a mass-lumped fully implicit Galerkin finite element method. Solute transport of each aqueous species is simulated with the Fickian-based advection-dispersion equation. The geochemical salinity models like HYDRUS-1D have been successfully tested with leaching experiments in lysimeters (Oster and Rhoades, 1975; Wierenga, 1977; Robbins et al., 1980) and small field plots (Dudley et al., 1981; Ali et al., 2000). It is assumed that the HYDRUS-1D model with daily boundary conditions is valid at the local scale for simulation of the short-term dynamics of soil salination (Schoups, 2004).

Simulation parameters and input data

The control volume used in the model is based on the site specific groundwater conditions at the Tranquillity site. The one dimensional vertical domain of the soil profile is fixed at 500 cm (15M1 and 15P1) or 600 cm (16A1), to insure that the control volume is always within the saturated zone during five year simulation period. The domain is discretized with 1 cm uniform nodal spacing to yield a total of 501 or 601 nodes. This level of spatial discretization is expected to capture the highly nonlinear flow dynamics in the root-zone (van Dam and Feddes, 2000) during simulation. Data for upper (top) boundary conditions of rainfall were obtained from CIMIS weather station No. 105; irrigation and crop details were used from Land Retirement Demonstration Project Five-Year Report (Erysian et al., 2005). Each year barley was grown as a cover crop to which approximately 12.4 and 11.7 cm of irrigation was applied during 2000 (March 29 to April 26), and 2001 (March 15 to April 30), respectively. The barley crops were not irrigated after 2001 (Erysian et al., 2005). The root zone for barley was set at 107 cm (Allen et al., 1998).

The upper (top) boundary conditions of rainfall, irrigation and potential evaporation and transpiration rates were specified on a daily basis. As the monthly precipitation was less than 5 cm and there was not evidence of runoff, all rainfall infiltrated.

The water flow lower boundary condition was specified as a constant flux but varied stepwise by period during the five years (solved by inverse modeling and hereafter described as variable flux). The top transport boundary condition was of the Cauchy type, with specified ion concentrations for rain water (Schoups, 2004). The lower transport boundary was specified as a Neumann condition for the variable flux case with zero gradients, for which no diffusion or dispersion occurs across the lower boundary.

Initial soil moisture content was assigned an average value for layers i.e. 0-45 cm, 46-105 cm and 106-165 cm and full saturation was specified below the perched water level. Soil samples were tested only for soil salinity and thus there is no record available of the ion specific chemistry for the soil water. Thus for specifying the initial soil solutions ion chemistry, the reported average soil water electrical conductivity of each soil layer for one part soil and five parts water extracts (EC5) was converted to saturation extract (EC_{se}) conductivity using the relationship between the saturation extract (EC_{se}) and 1:5 (EC5) extract conductivity levels (Uptain, et al., 2004). Extract Chem software (Suarez and Taber, 2007) was then used to recreate ion chemistry for the saturation extract making it consistent with the composition of the perched water table ion chemistry. The Extract Chem software was then again used to convert the saturation extract (EC_{se}) salinity and ion chemistry to the soil solution ion chemistry for the assigned soil water contents. Soil solution below the water table was assigned the measured ion chemistry of the shallow groundwater.

An initial run of the model was made for well 16A1 by specifying the van Genuchten soil water retention parameters θ_s - saturated water content [-], θ_r - residual water content [-], α, n - empirical parameters [L^{-1}], [-], and K_s - saturated hydraulic conductivity [$L\ T^{-1}$] from the Rosetta data base of the US salinity laboratory for clay-loam soil type as specified in the HYDRUS-1D database. Solute transport parameters, longitudinal dispersivity [L] and molecular diffusion coefficient in free water [L^2T^{-1}] were set at the default value of the model. The water flux at the lower boundary was specified by adopting an iterative procedure so as to match the trend in the declining perched water level. With this approach while the simulated and observed perched water levels produced a good match, the simulated soil salinity levels did not match with the observed trend. The simulated soil salinity levels in the top 150 cm of the soil layer were found to be increasing over the years whereas the observed average salinity levels decreased after three years of land retirement. The same trend of rising salinity level with time in the root zone was observed when van genuchten soil water retention parameters for silty clay loam from Rosetta data base were used. These results were not sensitive to the transport parameters. This clearly indicated that soil water retention properties as given by Rosetta data base failed to characterize the soil water movement and transport properties of salinized soils. Thus model calibration or inverse modeling was required to derive the soil water retention and transport parameters along with the variable bottom flux such that model output matched the observed behavior of the retired lands with respect to salinity levels in the root zone and changes in the perched water levels.

PEST (Parameter Estimation) is a widely used calibration model, where parameter optimization is achieved using the Gauss-Marquardt-Levenberg method for which the discrepancies between model-generated numbers and corresponding field data is reduced to a minimum in the weighted least squares sense (Doherty et al., 2004). In the initial stages of the calibration process, five van Genuchten soil water retention parameters, two transport parameters and five time averaged, stepwise constant, flux rates were defined as the parameters to be optimized, which PEST was free to adjust. Six observed soil water electrical conductivity values corresponding to three different depths each in year three and year five of the simulation period and 18 observed perched water levels at specified times were set as "observations." Since the values for electrical conductivity and water levels were of vastly different magnitude, observation weights, as suggested in the PEST user manual, were assigned to each of the observations. The observation weights were assigned such that each weight was inversely proportional to the standard deviation of the observation with which it was associated. From initial runs of the PEST, optimized values for saturated water content (θ_s) and residual water content (θ_r) were estimated and the parameters values were fixed at 0.379 and 0.056, respectively, for subsequent optimization runs. This was done to reduce the number of parameters to be optimized in the final runs. For the same reason, only five stepwise constant bottom flux rates (BF_1-BF_5) were specified for the optimization purpose, although it is realized that in a general sense, bottom flux is a continuous time function of the bottom head. Permissible domains of the adjustable parameters were indicated by specifying upper and lower bounds. The problem of parameter nonuniqueness in inverse modeling of vadose zone water and solute transport has often been cited as the weakness of the inverse modeling process (Friedel, 2005) which results in large predictive uncertainty in the optimized parameter values. Using different types of observations such as water levels and electrical conductivity introduce uncorrelated information which improves the inversion process and permits a better identification of the parameters (Friedel, 2005).

The optimized parameter values for all three simulation models corresponding to three observation wells are given in Table 1.

Optimized parameter	Units	Sites		
		15M1	16A1	15P1
α (empirical parameter)	cm^{-1}	0.206	0.223	8.16E-02
η (empirical parameter)	-	2.79	2.39	1.70
K_s (Saturated hydraulic conductivity)	cm/day	7.9	3.0	3.0
D_L (Longitudinal dispersivity)	cm	25	3.8	4.7
D_W (Diffusion coefficient)	cm^2/day	111.7	45.34	7.39
BF_1(1-68 days)	cm/day	0.1781	0.1554	6.1E-02
BF_2 (69-448 days)	cm/day	8.4E-02	5.5E-02	4.41E-02
BF_3 (449-512 days)	cm/day	3.8E-02	2.4E-02	2.4E-02
BF_4 (513-1207 days)	cm/day	3.0E-02	2.5E-02	1.8E-02
BF_5 (1208-1827) days	cm/day	2.7E-02	2.2E-02	1.6E-02

Table 1 Optimized parameter values in the HYDRUS-1D models

The comparison of observed to simulated perched water level with the optimized parameter values is presented in Fig. 6. Figure 7 gives the observed and simulated value for the electrical conductivity of saturation extract soil water (EC_{se}) for all three sites.

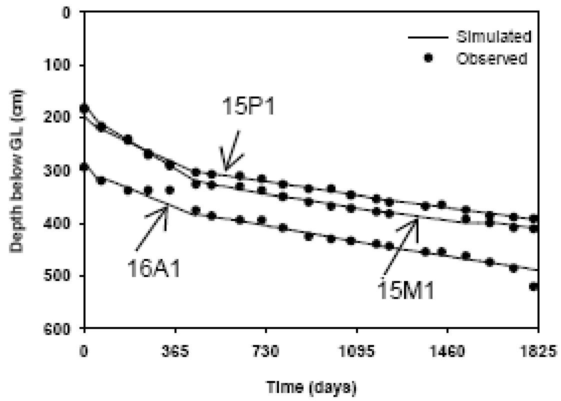

Figure 6 Observed and simulated perched water levels

Although the observed and simulated perched water levels match for all three sites (Fig. 6), the simulated EC_{se} for the top 150 cm depth of the soil profile deviate from the observed values for the same location and time (Fig. 7) but accurately

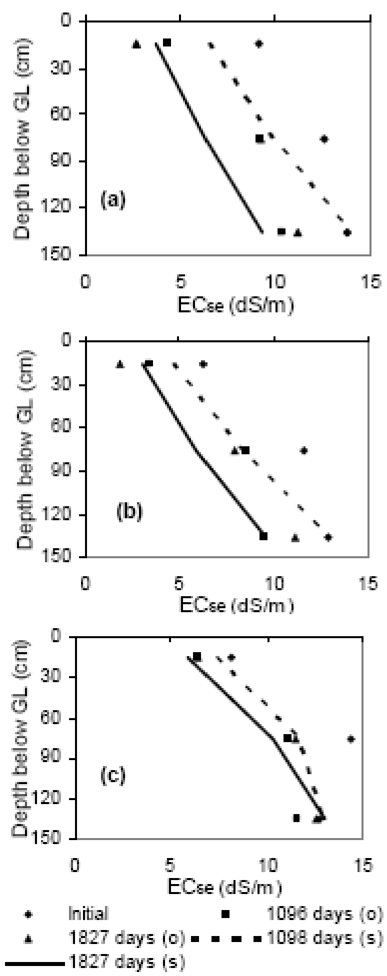

Figure 7 Observed (o) and simulated (s) EC_{se} (dS/m) for sites (a) 15M1, (b) 16A1, and (c) 15P1

reproduce the trend in the reduction of the EC_{se} with depth for each of the three sites.

The most prominent deviation in salinity occurred for the layer 60-90 cm. These differences in the observed and simulated EC_{se} could be due to the inherent heterogeneous properties of the soil, because in the one dimensional numerical modeling soil was treated as homogenous with depth. As a result of the heterogeneity, the soil water content can vary greatly especially between soils at the same high soil water tension (Harter and Zhang, 1999). The EC_{se} is dependent upon the water content and electrical conductivity of soil water (EC_{sw}), hence for two soils having the same EC_{sw}, EC_{se} could be different because of water content. It should be noted that the measured electrical conductivity at the LRDP site was depth averaged over the 30 cm samples (EC 1:5 extract). It is observed that simulated EC_{se} is in general higher than the observed EC_{se} at the end of year 3 (Yr3), while it is in general lower at the end of year 5 (Yr5) a shown in Table 2.

Soil layer	15M1		16A1		15P1	
	Yr3	Yr5	Yr3	Yr5	Yr3	Yr5
	(o-s)	(o-s)	(o-s)	(o-s)	(o-s)	(o-s)
0-30 cm	***-2.1***	***-1.0***	***-1.3***	**-1.2**	***-0.6-***	***0.7***
60-90 cm	***-0.7***	***2.9***	***0.3***	**2**	***-0.7***	***1.2***
120-150 cm	***-3.7***	***1.9***	***-3.4***	**1.5**	***-1.3***	***-0.5***

Table 2 Difference between simulated (s) and observed (o) depth averaged soil salinity (EC_{se}) using the 5-Year model

This observation forms the basis for our hypothesis that the effective unsaturated soil hydraulic properties is changing with the decreasing average soil water salinity levels in the vadose zone at the LRDP site. For this simulation a single set of effective hydraulic properties was used for the entire five year study period and designated as the 5-Year model.

To test the hypothesis that unsaturated soil hydraulic functions change with the average soil water salinity levels, the five year simulation period was divided into two time periods for each of the three sites. Each of the original models, designated as 5-Year model covering the time period of 0-1827 days, is replaced by two models, one covering the time period of 0-1096 days (the first three years), designated 3-Year model and the second model for the same site covering the time period of 1097-1827 days (the last two years), designated as 2-Year model. The 3-Year model, is labeled with superscript ‘A’ and uses the same initial and top boundary conditions as that for the 5-Year model but the period of calibration and simulation is over the first 1096 days. The 2-Year model for each of the sites, is labeled with superscript ‘B’ and uses initial conditions in soil water content, soil water salinity, and perched water table depth from the final results of the first model ‘A’. The variable daily top boundary conditions are the same as in the 5-Year model for the period starting at day 1097 (year three). The parameters selected for optimization are the same as in the original model, except that four time averaged bottom water fluxes for the first model and two time averaged bottom fluxes for the second model are used. The increase to six from five time averaged bottom fluxes specified from the original model is solely due to breaking the calibration and simulation into two periods. The specified parameters for each of the two models, covering the same site but for different time period, are optimized with PEST against the observed salinity levels in the vadose zone at the end of year three for the first model and at the end of year five for the second model, and the perched water table levels during the simulation period.

The depth and time averaged soil salinity for the top 150 cm of the soil profile at each of the three sites corresponding to 5 year, 3 year and 2 year model is presented in Table 3.

Site	Model set-up	Depth averaged soil salinity (dS/m)	% change between 3-Year and 2-Year model	% change between 5-Year and 3 -Year model	% change between 5-Year and 2-Year model
15M1	5-year model (15M1)	9.2	20	8.8	13.3
	3-year model ($15M1^A$)	10.0			
	2 year model ($15M1^B$)	8.0			
16A1	5-year model (16A1)	8.0	18.6	8.0	12.0
	3-year model ($16A1^A$)	8.6			
	2-year model($16A1^B$)	7.0			
15P1	5-year model (15P1)	10.6	7.3	3.2	4.8
	3-year model ($15P1^A$)	10.9			
	2-year model ($15P1^B$)	10.0			

Table 3 Depth averaged soil salinity (EC_{se}) by site and time period.

As can be expected, for sites with gradually declining soil salinity levels, the depth averaged soil salinity for the 3-Year model set up is higher by about 7-20 percent than the 2-Year model. The average soil salinity for the 5-Year period model lies between the 3-Year model and 2-Year model.

RESULT AND DISCUSSION

The analysis of modeled daily and cumulative water and salt flux in the control provides a unique opportunity to understand the water and solute transport processes in the root zone, the perched zone and the groundwater that led to a gradual decline in the perched water table and the root zone salinity. The daily fluxes at the top and bottom boundaries of the control volume for the first three years are given in Fig. 8. Only the results for sites 15M1 and 15P1 are being presented here, since the behavior of the model representing site 16A1 is similar to site 15M1.

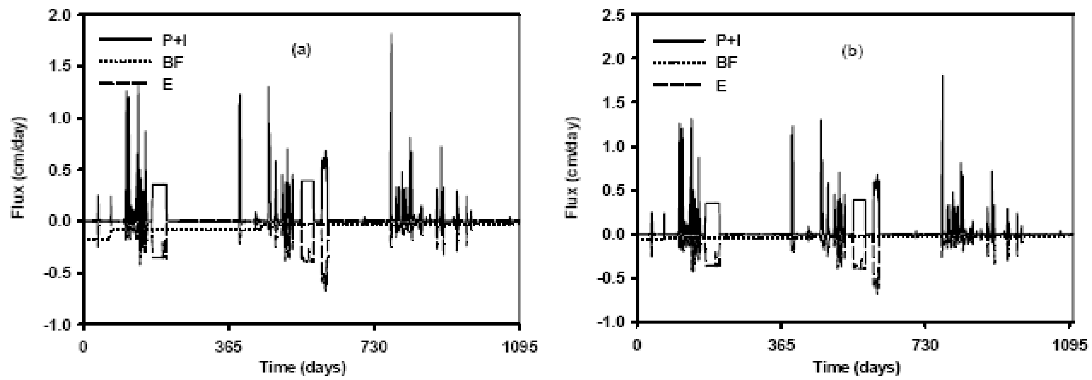

Figure 8 Daily fluxes at top and bottom boundaries for sites (a) 15M1 and (b) 15P1 starting October 1999

Natural precipitation and irrigation (P+I) were the input values and represented the external impetus to change soil water in the profile. The values of bottom flux (BF) and evaporation (E) were model generated. While BF was a function of the perched water table level, E was a function of both atmospheric conditions and the depth to the perched water table. Calculated daily transpiration for the barley crops was small compared to other fluxes; it was not plotted on the figure. Cumulative fluxes (Fig. 9) are different for the two sites.

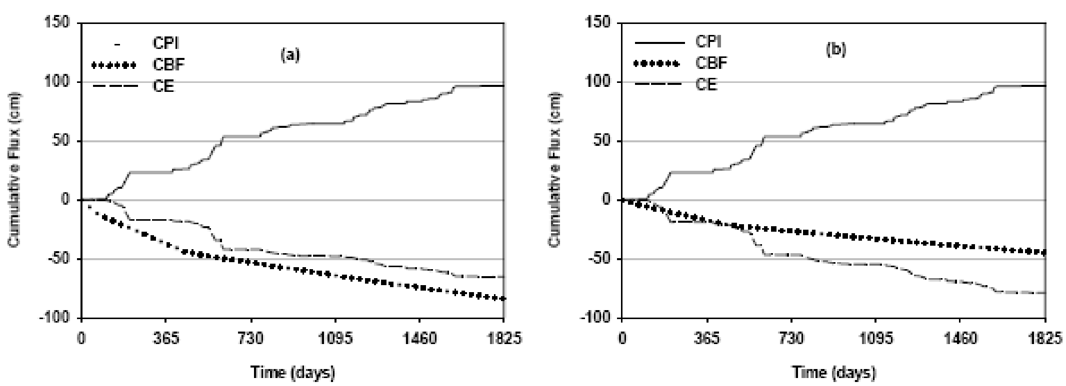

Figure 9 Cumulative fluxes at top and bottom boundaries for sites (a) 15M1 and (b) 15P1 starting in October 1999

After five years cumulative evaporation (CE) for site 15P1 is about 20 percent larger than for site 15M1, while cumulative bottom flux (CBF) is 50 percent smaller than for site 15M1. Evaporation accounts for about 65 and 82 percent of precipitation and irrigation amount for sites 15M1 and 15P1, respectively. The smaller percentage of evaporation water returned to the atmosphere results in a higher leaching fraction for 15M1, and this is reflected in the larger drop in the salinity level in the root zone at 15M1 compared to 15P1 (Fig. 4).

Water content profiles (Fig. 10) over the five year period show the decline in the water storage in the control volume as the water table declines (Fig. 3).

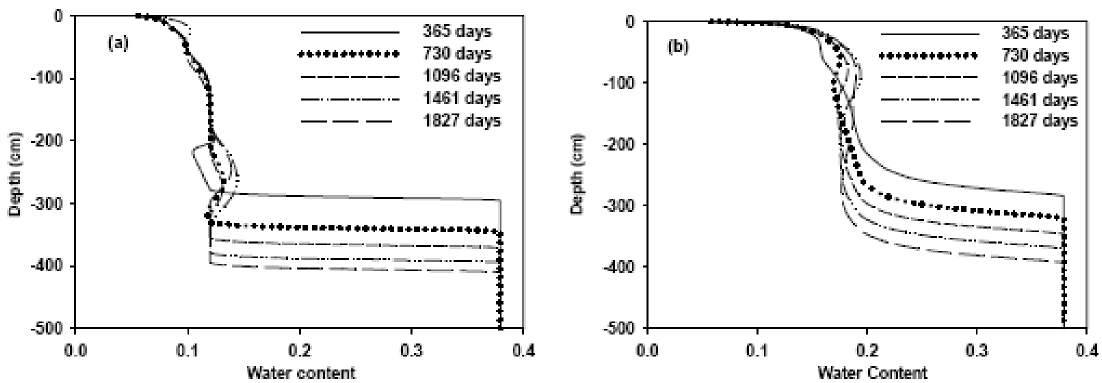

Figure 10 Water content profile at sites (a) 15M1 and (b) 15P1 for October of each year

There is less change in the water content profile nearer the surface in the root zone from year to year than there is within the year. The profiles at site 15P1 (Fig. 10b) retain more water than those for 15M1 (Fig. 10a). This is consistent with the observation that site 15P1 has higher evaporation rates compared to the site 15M1. The difference in water retention characteristics is also evident near the water table. Site 15M1 represents a case where there is an abrupt change from very low water content to saturation (more sand like behavior), whereas in well 15P1, a more gradual change is observed (more clay like behavior).

Soil water EC for sites 15M1 and 15P1 decline over the simulation period but differently (Fig. 11). At site 15M1, which has less cumulative evaporation flux and more bottom flux compared to site 15P1 (Fig. 9), soil water EC decreases more. A higher percentage of precipitation and irrigation flux passes through the control volume and leached site 15M1 more than site 15P1.

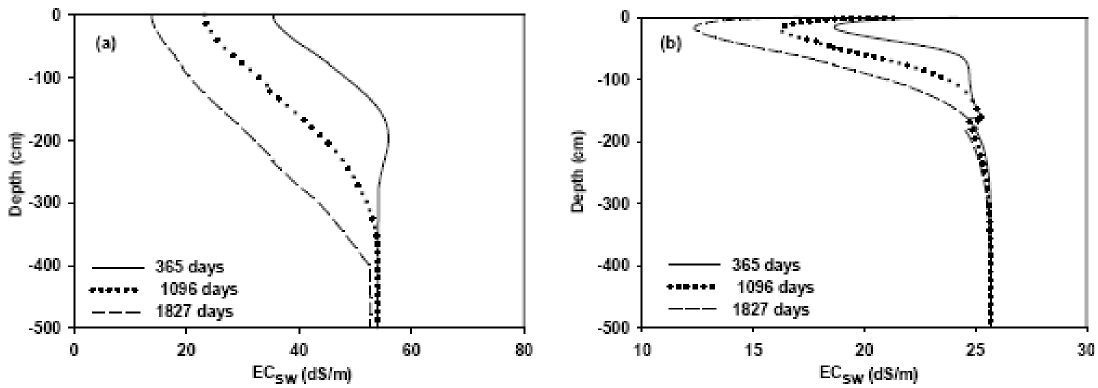

Figure 11 Soil water EC profile at sites (a) 15M1 and (b) 15P1 for October of each year

Because annual salinity levels are decreasing in the root zone for both the sites, it is expected that the annual upward flux (UF) to the root zone should be less than the deep percolation (DP) from the root zone for both of the sites. This is confirmed in Figure 12 in which the annual negative (UF-DP) shows a net downward flow of water from the root zone.

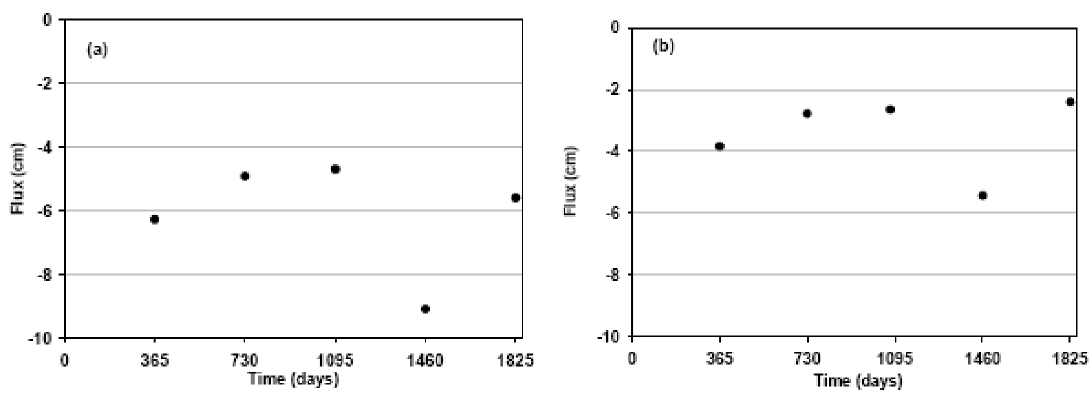

Figure 12 Annual net deep percolation flux (UF-DP) for sites (a) 15M1 and (b) 15P1

As could be expected, the annual net deep percolation varies from year to year with highest corresponding to the largest rainfall year and within the year it depends on the atmospheric demands, precipitation and irrigation, crop, and soil hydraulic properties. In summer and fall there is a net upward movement of water to the root zone, while during winter and spring (rainy period) there is a large net downward flux (Fig. 13).

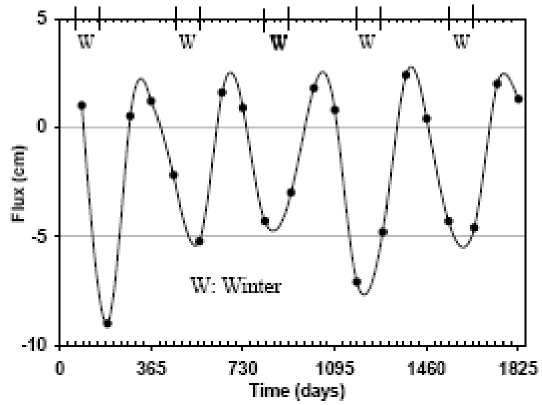

Figure 13 Quarterly net deep percolation flux at 15M1

Since the downward flux during the winter is larger than the upward flux during summer and winter, the net result is that on an annual basis there is a net downward flux, explaining the declining trend in the annual root zone salinity.

From a water budget perspective the increased depth to the perched water table is caused by greater cumulative bottom flux (natural drainage) compared to net deep percolation flux. Recall that net deep percolations flux is defined as $\sum DP - \sum UF$ (Eq 6). The bottom fluxes for the three sites have been derived from the inverse modeling technique using PEST. Bottom flux is highly correlated with the head at 500 cm depth for sites 15M1 and 15P1 (Fig. 14).

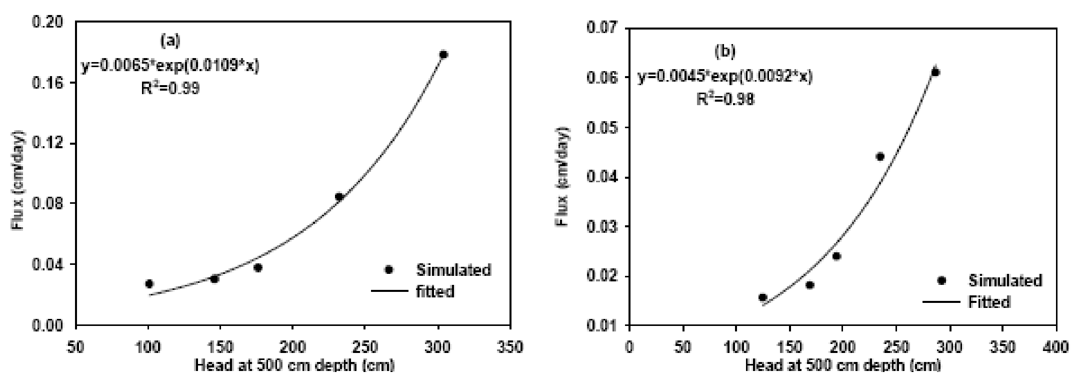

Figure 14 Bottom flux as a function of hydrostatic head at sites (a) 15M1 and (b) 15P1

Nonlinearity may be related to soil layering in these alluvial soils. When the data from the simulations for all the three sites are plotted together, the correlation coefficient declines, but the nonlinearity persists (Fig. 15).

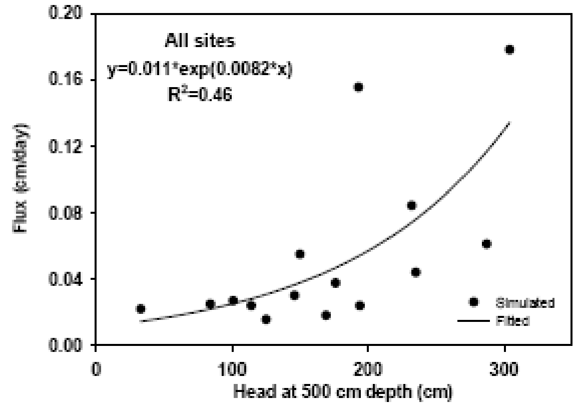

Figure 15 Combined bottom flux as a function of hydrostatic head

The decline in the site specific correlation coefficients and the combined coefficient indicates site specific differences in parameters such as soil water retention properties and salinity of the perched groundwater. This can be explained by the fact that apart from the head, the bottom flux is also a function of the saturated hydraulic conductivity of the perched water layer. The soil type and the salinity levels of the perched groundwater affect the saturated hydraulic conductivity.

The data and the simulation clearly show the management pathways to the reduction in the salinity levels in the root zone and the reduction in the perched water table height. The pathway to reducing the salinity levels in the root zone is to maintain a condition where the annual downward flux from the root zone exceeds the annual upward flux from the root zone. In the context of irrigated agriculture, enough irrigation water is applied to prevent salination. But the problem with this approach, as experienced in the places like the western San Joaquin Valley, is that in the absence of drainage options, the water table encroaches upon the root zone. With the decrease in the shallow water table depth, upward flux increases which in turn causes the salinity in the root zone to increase. To manage the increased salinity, still greater leaching is required which in turn exacerbates the rise of shallow water table and root zone salinity level. To understand and escape this cycle, the simulation results show that one has to quantify the natural drainage rate of the site. If the crop and irrigation is managed for salt balance such that leaching is constrained to match the natural drainage rate, the danger of rising water table is avoided. Thus the critical components in the management of drainage impaired land selected for land retirement is the knowledge of the natural drainage rate and the unsaturated soil hydraulic parameters. A new 'natural drainage approach' using the natural drainage rate of the site in designing a land and water use regimen for drainage impaired lands in general and retired lands in particular is presented here.

Natural drainage approach

In the 'natural drainage approach,' the search for land use management starts from the determination of the natural drainage rate of the site (bottom flux) for a given site. The relation between the bottom flux and the groundwater head (Fig. 14) is the tool that allows one to estimate the natural drainage rate for the given site. Based on a proposed land use (crop and root zone depth) and the soil type, a trial desired depth to groundwater table is then selected. This desired depth to groundwater table should be kept as high as possible, without impacting the root zone such that the greatest possible bottom flux is achieved. The trial depth to groundwater table is then used to estimate the bottom flux for the given site. This estimated maximum possible bottom flux is then used as a bottom boundary condition in a HYDRUS 1-D model to simulate the water table response for a given scenario of precipitation, irrigation, crop, and water management. If the results of the simulation show a rising water table, it implies an un-sustainable situation requiring a change in the land use and water application. On the other hand if the results show a declining water table, it implies that the site may be able to accept greater water application while avoiding waterlogging and salination. The second output of concern from the simulation is the net downward flux which must always be negative to ensure that the root zone salinity is balanced. The land use and water application practices are two of the main variables which can be changed to insure that water table level never rises above a predetermined level and the root zone salinity levels are maintained within a permissible level. To achieve these two objectives, the following options may be pursued during the simulation exercise, a) change in the land use, crop type, b) growing crops in only a part of the area each year, and c) intersperse dry land farming with other farming activities (this assumes adequate lateral flow which is the subject of ongoing research).

General applicability of the approach

The key to the natural drainage approach is a priori knowledge of the relationship between the bottom flux (natural drainage rate) and the depth to the water table from ground surface. Although such a relationship is very useful, a practical approach required to evaluate it is missing. The paper presents a numerical modeling approach to discover such a relationship based on long term measurements of soil salinity and changes in the groundwater level. Water table elevation by itself is not enough to properly constrain the optimal set of parameters. By adding an independent set of salinity observations, new information is introduced in the inversion problem that allows the calibration algorithm to constrain the solution. In the present study, the lateral flow was not an issue, so HYDRUS 1-D was used as a modeling platform. For the larger problem where lateral flows that can affect the groundwater levels, the proposed approach may be extended with HYDRUS 2-D model.

Effect of soil water salinity on unsaturated soil hydraulic functions

The optimization process of splitting the total simulation period in two parts resulted in a significantly improved match in the values of simulated and observed depth averaged average soil salinity (EC_{se}) (Figure 16 compared to Figure 7).

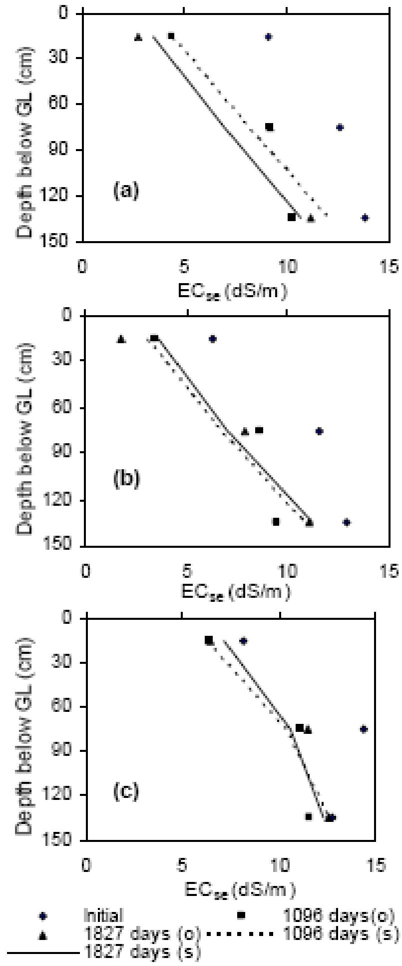

Figure 16 Observed (o) and simulated (s) EC_{se} (dS/m) for sites (a) 15M1, (b) 16A1, and (c) 15P1 with 3-year and 2-year models

The improvement in the simulated results with the two-period set up is quantified using root mean square deviation (RMSD). The RMSD is a measure of the difference between the simulated and observed values of the depth averaged soil salinity (EC_{se}), and is calculated as

$$RMSD(EC_{se}(o), EC_{se}(s)) = \sqrt{\frac{1}{3}\sum_{1}^{3}(EC_{se}(o) - EC_{se}(s))^2}$$

where $EC_{se}(o)$ and $EC_{se}(s)$ are the observed and simulated depth averaged soil salinity, respectively. The RMSD for the simulations using two periods showed a reduction ranging from 32 percent to 77 percent (Table 4).

	15M1		16A1		15P1	
	Yr3	Yr5	Yr3	Yr5	Yr3	Yr5

RMSD	Single period model	6.2	4.3	4.5	2.6	0.8	0.73
	Two-period models	1.4	1.9	2.0	1.3	0.5	0.5
% decrease		77.5	55.8	55.6	50.0	37.5	32.0

Table 4 Changes in the RMSD of observed and simulated depth averaged soil salinity (EC_{se}).

It is clear that a significant improvement in the (EC_{se}) simulation is achieved using three and then a two year rather than the entire five year period. It is expected that there would be an improvement in the simulation results with the two-model set up as PEST is optimizing depth averaged soil salinity (EC_{se}) at the end of each simulation period while in the single-model set up PEST is optimizing on two depth averaged soil salinities (EC_{se}) simultaneously. The reason for the improved simulations results is evident in the differences between optimized hydraulic function as well bottom flux values (BF_1, BF_2, BF_3, BF_4, BF_5, BF_6) between the two cases, shown in Table 5.

There is a consistent difference in the parameters α and n between the 3-year model and the 2-year model for each of the three sites. At each sites, α and n are lower for the later 2-year model set up (1097-1827 days) than the 3-year model set up (0-1827 days). The same parameters, when optimized with the 5-Year model, are generally between the values of the optimized parameters for the 3-year and 5-year model (Table 1). The exceptions are optimized α for the site 15M1 and optimized n for the site 15P1. The decrease may be related to a change in soil hydraulic behavior from that of a clayey to a sandy soil as generally α and n are lower for clayey soils compared to the sandy soils (Brooks and Corey, 1976; van Genuchten, 1980). A lower n signifies a gradual decrease of water content with an increase in negative pressure head.

Optimized parameter	Units	Site and model					
		$15M1^A$	$15M1^B$	$16A1^A$	$16A1^B$	$15P1^A$	$15P1^B$
α	cm^{-1}	0.30	0.13	0.28	0.17	0.15	0.089
η	-	3.22	3.08	2.53	1.85	1.80	1.35
K_s	cm/day	6.12	3.53	4.43	3.69	3.15	6.68
BF_1 (1-68 days)	cm/day	-0.19		-0.17		-7.9E-02	
BF_2 (69-448 days)	cm/day	-8.8E-02		-6.0E-02		-5.5E-02	
BF_3(449-512 days)	cm/day	-3.8E-02		-2.7E-02		-1.8E-02	
BF_4(513-1096 days)	cm/day	-3.2E-		-2.7E-		-1.8E-	

		02		02		02	
BF_5(1096-1207 days	cm/day		-1.7E-02		-1.5E-02		-4.5E-03
BF_6 (1208-1827 days)	cm/day		-1.7E-02		-1.5E-02		-4.5E-03

Table 5 Optimized parameter values and bottom fluxes for the two period models

Changes in Unsaturated Soil Hydraulic Properties

Optimized parameters are used in Equations 1 through 4 and the results are plotted to illustrate the changes in effective unsaturated soil hydraulic properties θ (*h*) and *K* (*h*) for each site varying by model. The θ(*h*) curve for all the three sites are similar (Fig 17) and at each site the θ(*h*) curve for the 5-Year model lies between the curves for the 3-Year and 2-Year model.

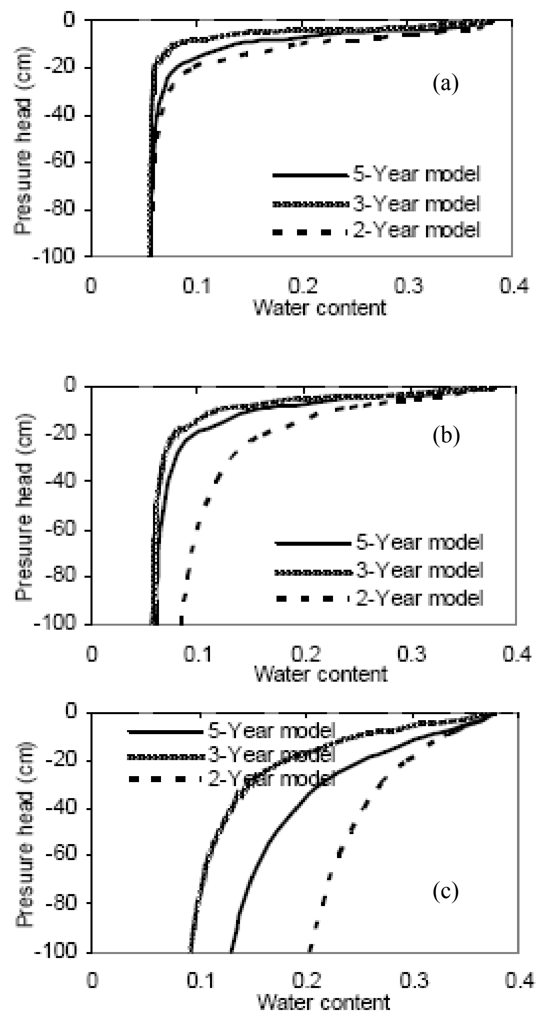

Figure 17 Water content as a function of pressure head for 5-Year, 3-Year and 2-Year models for sites (a) 15M1, (b) 16A1, and (c) 15P1

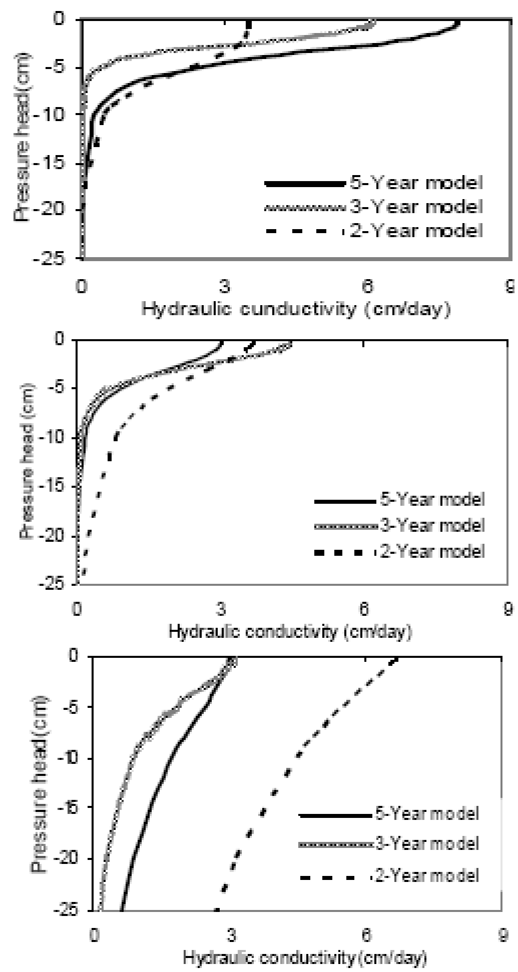

Figure 18 Hydraulic conductivity as a function of pressure head for 5-Year, 3-Year and 2-Year models for sites (a) 15M1, (b) 16A1, and (c) 15P1

Thus at the same pressure head, the 3-Year model (with the highest depth and time averaged salinity) has the lowest water content, the 2-Year model (with the lowest depth and time averaged salinity) has the highest water content and water content for the 5-year model (with the depth and time averaged salinity) falls between the two.

The K is lowest for the 3-Year model (with the highest depth and time averaged salinity). So the unsaturated hydraulic conductivity appears to be influenced by the averaged soil water salinity. It is not surprising as the 2-Year model (with the lowest depth averaged salinity) has the higher water content at the same pressure head (Fig 18). This is consistent with the understanding that unsaturated hydraulic conductivity is lower for lower water content because water in the pores becomes less connected.

The reason for the influence of soil water salinity levels on the hydraulic conductivity and soil water content can be found in the nature of the adsorbed water layer surrounding the soil particles (Singh and Wallender, 2008). Water in the soil pores is be said to be distributed between two phases, phase ‘a’ containing the so called free water, which is free to flow under a hydraulic gradient and a phase ‘b’, which is in general made up of about three layers of water molecules and is directly affected by the particle surface forces (Fripiat et al., 1982; Zhu and Granick, 2001). The phase 'b' water is thus bound to the particle like an elastic skin. The thickness of this solid-like water layer is not fixed but is a function of the electrochemical environment (Mitchell and Soga, 2005). Soil mineral surfaces, particularly clays are negatively charged and thus attract water molecules. It is reported that the thickness of the adsorbed water layer is inversely proportional to the electrolyte concentration of the free water. Similarly cation valence also influences the thickness of adsorbed water layer. At higher soil water salinity levels, the thickness of the water attached to the soil surface (adsorbed water) is less, leading to a lower conducting soil water content.

The dependence of soil water content on the soil water salinity levels can have profound implications on the available water content (AWC) of the soil. The AWC is defined as the difference between the water content at field capacity (θ_w) and wilting point (θ_{wp}). Pressure head at field capacity is generally given as -100 to -300 cm. At -100 cm of pressure head, the water content in the 2-Year model is 45-120% higher than the 5-Year model at the sites 16A1 and 15P1, while at site 15M1, the differences in water content is visible only below the -100 cm pressure head. These results support the previous studies where it was reported that increasing soil solutions salinity decreases available water for plant use (Warrence et al., 2002).

The dependence of the unsaturated soil hydraulic functions on the soil water salinity also affects the leaching efficiency of the applied water. At a higher soil water salinity level, the water applied to the soil is not retained by the soil and leaches through and past the root zone. Thus at higher soil water salinity the available water for the plant is less and a greater proportion of water leaches downward, and hence a larger amount of salt will be leached out from the root zone. This suggests that at each site, during the first three years, when the soil water salinity level was high; the rate of decrease in the soil water salinity is higher compared to the rate of decrease of soil water salinity levels in the last two years (Fig 4). The behavior of the rate of decrease in the soil water salinity supports the observation that as the soil water salinity levels decreased, the soil water retention increased, thereby decreasing the amount of water available for leaching. This in turn reduced the rate of decrease of soil water salinity levels. Thus there is a complex relationship between the soil water salinity level and the rate of decrease in the soil water salinity for a given application of water.

The differences in PEST optimized time averaged bottom flux is also consistent with the above findings. Bottom flux for 3-Year model is higher than the 5-Year model for the first three years whereas bottom flux for 2-Year model is lower than the 5-Year model results for the last two years. Recall once again that the depth averaged soil salinity is higher for the 3-Year model and lower for the 2-Year model both compared to the 5-Year model (Table 3). The reason for the differences in bottom flux can be attributed to the fact that at higher salinity levels (3-Year model), soil surfaces are able to retain less applied water, which results in an increase in the bottom flux. The opposite is the case for lower salinity level (2-Year model), where soil surfaces hold more applied water, which naturally results in a decrease in the bottom flux.

SUMMARY AND CONCLUSIONS

Data spanning a period of five years from the LRDP was used to calibrate a HYDRUS 1-D model for simulating the movement of water and solutes in a variably saturated soil. Model boundary conditions and initial conditions were obtained from CIMIS and data collected at the Tranquillity site. The model was calibrated using PEST to obtain van Genuchten soil water-retention parameters, transport parameters and bottom flux. Data for three sites at the Tranquillity site was assembled and calibrated separately. The calibrated parameter values were used to simulate the movement of water and solutes over the five year period to yield information on evaporation and transpiration as well as water content and EC_{sw} profiles. The total control volume was divided into the root zone and the perched water zone. Movement of soil water across the boundary between the two zones yielded the time averaged net deep percolation flux (from the root zone to the perched water zone) as well as bottom flux within and below the perched zone. The study presents a new and practical inverse modeling approach to the determination of relationships between the natural drainage rate of the site and the depth to the groundwater table.

The calibrated model was used to quantify the flow from the root zone control volume to perched water. Cumulative net downward flux of water from the root zone to the perched water zone was directly affected by the site specific unsaturated soil hydraulic properties.

The second finding was that, for salinity levels in the root zone to decline on an annual basis, there was cumulative net downward flux from the root zone (Eq. 9; Fig 12). Before steady state between the cumulative net downward root zone flux and the cumulative bottom groundwater flux is reached, it is possible for salinity level in the root zone to increase even though the perched water table is declining. Conversely it is also possible that salinity level is decreasing while the perched water table is rising.

The natural drainage rate (bottom flux) of the system constrains the capacity of the soil profile to accept water input. The formulation of land management options in drainage impaired areas without a priori taking into account the natural drainage rate of the site may not always lead to a more efficient and sustainable solution.

The knowledge of natural drainage rate of the site can be used to formulate a ‘natural drainage approach,’ where simulation using HYDRUS 1-D model can be used to arrive at a sustainable land use. It is thus possible to use the HYDRUS 1-D model as a management tool to design sustainable land use for the retired areas.

This study also quantifies the effect of soil water salinity on the unsaturated soil hydraulic functions by optimizing the van Genuchten soil water-retention parameters using PEST and HYDRUS-1D models. This study develops a methodology of analyzing the effect of soil water salinity on the unsaturated hydraulic functions using the PEST optimization. The original 5-year model time period is divided into two separate models with of time periods of the first three years and then the last two years. The two resulting models each were optimized for unsaturated soil hydraulic functions against the observed soil water salinity and perched water levels from the each of three sites. The depth and time averaged soil water salinity levels for each of the additional two models and the original five year model are different from each other thus allowing for the comparison of the optimized unsaturated soil hydraulic functions. The optimized unsaturated soil hydraulic functions for each of the three models are substantially different from each other and show a consistent correspondence with the underlying average salinity levels of the soil profile. The results from the optimization process clearly establish the link between soil water salinity level and unsaturated soil hydraulic functions.

A clear connection between the soil water salinity level and soil water content is observed. At the same pressure head, soil water content is less with higher soil water salinity as compared to lower soil water salinity. Because of this observed link between soil water salinity level and the soil water content, other important soil properties that are important from the irrigation management perspective are also affected by the soil water salinity level. Available water content in the root zone is less for higher soil water salinity level, while the movement of water through the unsaturated soil profile is more rapid. This results in a greater portion of the applied water moving downward resulting in a greater reduction in the soil water salinity level. The bottom flux from the perched water table is also affected, with higher salinity level again resulting in a higher bottom flux.

The current methods of evaluating unsaturated soil water hydraulic function do not take into account the effect of soil water salinity. The use of soil water salinity invariant soil water hydraulic functions in numerical modeling exercise can seriously compromise the results for a high soil water salinity environment. The effect of large changes in the soil water salinity as a result of land retirement and or annual leaching may be significant. The changing nature of the soil water content with soil water salinity has significant implications for irrigation and land management.

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