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Assessment of different strategies for managing the water resources problems of irrigated agriculture

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ABSTRACT

The intensification of irrigated agriculture is required for attaining food security. It could result, however, in water resources problems of waterlogging and secondary salinization. To assess different management strategies in solving the problems, the current study used a simulation model SaltMod in a command area of north-west India which faced the problems of salinization and waterlogging. Following the thriving testing in the course of calibration and validation, it was used for studying various water management alternatives for the command area. The analysis of different scenarios shows that watertables in the command would persist to go up under the normal conditions. Thus, right management alternatives, for example, increased groundwater use, rice area reduction, and reduced canal water use are recommended. The ideal scenario revealed that small changes of 3–6% in input values would contain the problems of the study region.

1. Introduction

The water and soil resources are limited and they experience gradual degradation (Chitsaz and Azarnivand, 2017; Singh, 2018a, 2016a). Besides, farm production requires to be increased using these limited resources for feeding the burgeoning global population (Xie et al., 2018; Lomba et al., 2017; Li and Zhang, 2015; Singh, 2018b, 2014; Liu et al., 2016; Davijani et al., 2016). The intensification of irrigated agriculture is required for realizing food security (Das et al., 2015; Singh et al., 2016) in dry regions given that normal rainfall in these areas is highly unreliable (Herrmann et al., 2016; Adhikari et al., 2017; Postel, 1999). This intensification, however, could result in water resources problems of rising watertables and secondary salinization (Tilman et al., 2002; Houk et al., 2006; Singh, 2012, 2017a,b). Abbas et al. (2013) stated that soil salinization is growing globally at an average annual rate of over 2 million ha. In recent times, the Food and Agriculture Organization FAO reported that more than 19 percent of the total irrigated territory is suffered by salinization (FAO, 2016).

The simulation models can predict the possible impacts of a specific management option. In recent past, researchers across the world, i.e., Rezaeianzadeh et al. (2017), Kacimov et al. (2016), Mao et al. (2017), Droogers et al. (2000), Xu et al. (2011), Sedki and Ouazar (2011), Xie and Cui (2011), and Yazdi and Salehi Neyshabouri (2012) have used a large number of simulation models for studying various aspects of water resources problems. A physical-based 1-D simulation model SWASALT was used by Singh (2010) for mitigating the rising watertable and salinity problems in north-west India. The study reported that a poor quality water of 7.5 dS/m salinity can safely be used for crop production in most soils and climatic conditions in waterlogged areas. Later, Chandio et al. (2012) used a 3-D simulation model in an irrigated area of Pakistan. In all the earlier studies some groundwater withdrawal increase or recharge reduction measures are suggested to manage the salinization and waterlogging problems. Nevertheless, the majority of these models entail specific soil characteristics as inputs, i.e., osmotic and matric soil-water potential, soil moisture content of root-zone, and dispersivity and hydraulic conductivity, which measurement is difficult.

Having considered findings of the previous studies and the current need as discussed, the current study used a water and salt balance model SaltMod (Oosterbaan, 2008). The model needs inputs that are usually obtainable (Srinivasulu et al., 2004). The model was used in a command of north-west India which faces the hydrological problems of water resources, i.e., salinization and waterlogging (Groundwater Cell, 2014a). Previously the SaltMod was used by Vanegas Chacon (1993) in Leziria Grande Polder, Portugal. Later, it was applied in Nagarjuna Sagar Command of India by Srinivasulu et al. (2005), in Krishna district of India by Sarangi et al. (2006), and in the Plain of Konya-Cumra, Turkey by Bahceci et al. (2006) among others.

In almost all the preceding studies, the model SaltMod was used in areas which are equipped with the drainage system. There is no indication of model application for the long-term evaluation of water and salt balances in irrigated lands under different hydrological conditions. In this paper, an attempt has been made to analyse the long-term water and salt balances under various management strategies. The study is

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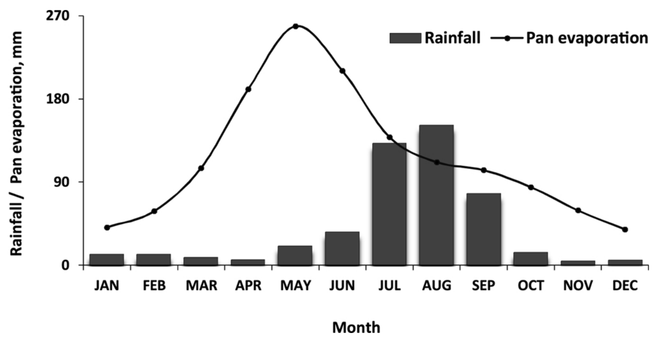

Fig. 1. Distribution of mean monthly rainfall and pan evaporation.

first of its kind in the selected canal command and it will give an impression of the progression dynamics that lead to a system disparity. The paper is prepared as: Section 1 provides a succinct overview of water resources problems and the implication of the study; Section 2 briefly describes the study system and data analysis. The model description is presented in Section 3. Section 4 presents the results and discussion. Finally, conclusions and some suggestions are provided in Section 5.

2. Study system and data

2.1. Location and hydrometeorology

The Ismaila Distributary is situated in Rohtak district of Haryana State in north-west India and lies between 28°42 to 28°51′N latitude and 76°39–76°27′E longitude. The command area covers about 4679 ha. The altitude of the command ranges between 214 m and 222 m from the mean sea level. The climatic conditions of the command are semiarid with normal annual rainfall of 483 mm. The values of pan evaporation surpass the matching rainfall for each month of a year excluding July and August as shown in Fig. 1.

2.2. Soil and cropping system

The soil in the command is largely of sandy loam with the specific yield values of 0.09-0.23. The hydraulic conductivity ranges between 4.7 m d^{-1} and 11.2 m d^{-1}. The year is normally divided into two major crop seasons, i.e., *winter* and *monsoon*. The *winter* season starts in November while the *monsoon* starts in July. Wheat and rice are the main crops grown in *winter* and *monsoon* seasons, respectively. Millets, sorghum, mustard, and gram are the other crops grown in the area. Besides, pulses, barley, vegetables, and fruits are grown in tiny areas (Table 1).

Table 1
Existing seasonalcropping pattern in the command area.

Crop	Area (ha)	
	Monsoon	Winter
Rice	1253	–
Millets	640	–
Sorghum	469	–
Pulses	52	–
Wheat	–	2758
Mustard	–	540
Gram	–	232
Barley	–	86
Vegetables, fruits etc.	26	79

2.3. Data collection

The data on aquifer, canals, crops, and climate were obtained from different State and Central Government departments such as Irrigation Department, Groundwater Cell, etc. The data analysis is briefly described as:

Irrigation system and groundwater

Ismaila Distributary supplies the canal water, to the command area, which is of high-quality. More than 800 shallow tubewells pump the groundwater; over 90% of which are operated via the diesel engines. In the command, the watertable varies from a depth of 4.85 m during the summer to 1.15 m in the monsoon.

Water requirement

The method suggested by Allen et al. (1998) was used to calculate the water requirement of each crop. The reference evapotranspiration (*ETo*; mm d^{-1}) was initially computed from the climate statistics using Hargreaves and Samani approach (1985) as:

$$ETo = 0.0023 \times (T_{avg} + 17.8) \times R_a \times \sqrt{T_{\max} - T_{\min}} \quad (1)$$

wherein T_{avg}, $T_{min,}$ and T_{max} are daily mean, minimum, and maximum air temperatures (°C) and R_a is the extraterrestrial solar radiation (mm d^{-1}).

From the Eq. (1), the potential evapotranspiration (ETc) of each crop was computed by the use of pertinent crop coefficients (*Kc*) as:

$$ETc = ETo \times K_c \quad (2)$$

The water requirements of crops were computed at 648, 413, 399, 301, 481, and 413 mm for rice, millets, gram, mustard, wheat, and sorghum, correspondingly.

The FAO method suggested by Dastane (1978) was employed to find out the effective rainfall (R_{eff}) of each season. The R_{eff} was computed from daily rainfall (*R*) data using the equations below:

$$R_{eff}\ (t) = 0.8\ R(t), \text{ for rice crop} \quad (3)$$

$$R_{eff}(t) = 0.7\ R(t), \text{ for other crops} \quad (4)$$

The net crop irrigation requirement (*NIR*) was computed using the equation (Eq. (5)) as:

$$NIR = ETc - Reff \quad (5)$$

Canal seepage

The seepage through canals was computed using Eq. (6) as:

$$R_c = WP_c \times L_c \times SF \times N_d \times 86{,}400 \quad (6)$$

wherein WP_c and L_c are wetted perimeter and canal length (m), N_d is the seasonal canal running days (d), SF is the seepage factor (-), and R_c is the seasonal canal seepage (m^3). For the command area, the SF was suggested at 2.5–3.0 and 0.62-0.75 m^3 per second per million m^2 of the wetted area for unlined and lined canals, correspondingly (Irrigation Department, 2015).

Tubewell draft

The Groundwater Cell (2014b) recommended the guidelines for the estimation of tubewell draft. Accordingly, the normal discharge of a tubewell in the command was taken at 0.006-0.010 $m^3\ s^{-1}$.

3. Model description

3.1. Principle

SaltMod is a computer program for the forecast and simulation of the salinity of soil moisture, drainage water and groundwater, the watertable depth, and leaching of salts and drain discharge in irrigated areas under various agro-geo-hydrological conditions, several crop rotations, and a range of water management scenarios (Oosterbaan, 2008). SaltMod is based on seasonal salt and water balances of cropped areas. The SaltMod program, description of principles, user's manual,

Table 2
Input parameters used in the model.

Input parameter	Parameter value /range[a]
1. Season duration (month)	
Season 1 (July-October)	4
Season 2 (November-June)	8
Area fraction of crops in season 1	0.33-0.51
Area fraction of crops in season 2	0.71-0.81
2. Properties of soil	
Fraction of irrigation water stored in root zone	0.60
Total porosity of root zone	0.42
Total porosity of transition zone	0.44
Total porosity of aquifer	0.44
Drainable porosity of root zone	0.17
Drainable porosity of transition zone	0.15
Drainable porosity of aquifer (calibrated)	0.18
Leaching efficiency of root zone	0.86
Leaching efficiency of transition zone	0.88
Leaching efficiency of aquifer (calibrated)	0.89
3. Components of water balance	
Irrigation in season 1 (m)	0.27-1.12
Irrigation in season 2 (m)	0.48-1.25
Rainfall in season 1 (m)	0.19-0.90
Rainfall in season 2 (m)	0.03-0.29
Evapotranspiration in season 1 (m)	0.39-0.71
Evapotranspiration in season 2 (m)	0.33-0.51
Incoming groundwater flow through aquifer in season 1 (m) (calibrated)	0.01-0.08
Incoming groundwater flow through aquifer in season 2 (m) (calibrated)	0.00-0.01
Outgoing groundwater flow through aquifer in season 1(m)	0.00
Outgoing groundwater flow through aquifer in season 2(m)	0.00
Surface runoff in season 1 (m)	0.02-0.12
Surface runoff in season 2 (m)	0.00-0.02
4. Initial and boundary conditions	
Depth of water table in the beginning of season 1 (m)	4.26
Initial salt concentration of the soil moisture in root zone (dS/m)	2.43
Initial salt concentration of the soil moisture in transition zone (dS/m)	2.59
Initial salt concentration of the soil moisture in aquifer zone (dS/m)	6.54
Average salt concentration of incoming irrigation water (dS/m)	0.95
Average salt concentration of incoming groundwater (dS/m)	3.88
Root zone thickness (m)	0.93
Transition zone thickness (m)	3.33
Thickness of aquifer (m)	30.50

[a] Range of input parameters during the study period (1991–2015).

examples of previous applications in various locations, and literature related to its uses are freely available at www.waterlog.info.

3.2. Calibration and validation

The model was calibrated for a 12-year period, i.e., from October 1991 to June 2003, which was followed by its validation with recorded system variables for a different 12-year period, i.e., from October 2003 to June 2015. The standard procedure reported by Sorooshian and Gupta (1995) was followed for the calibration. In the command area, the majority of the model input parameters were either estimated or measured. Values of some non-sensitive or less-sensitive model parameters were assumed rationally. For instance values of leaching efficiency of transition-zone and root-zone and total porosity of root-zone, transition-zone, and aquifer were assumed. The measurement of some factors such as leaching efficiency (Flq) and effective porosity (Peq) could not be done. These factors were established during the model calibration. The different inputs used in the model are given in Table 2.

3.3. Sensitivity analysis

The sensitivity analyses were carried out for effective porosity and leaching efficiency. A ± 50% change to the calibrated values were considered to evaluate the sensitivity.

3.4. Statistical evaluation

Statistical evaluation computes the variations in the modeled and recorded watertable depth and groundwater salinity values. Root mean square error (RMSE), model efficiency (EF), and mean error (ME) were used to test the model performance in this study.

$$ME = \frac{1}{N}\sum_{i=1}^{N}(O_i - P_i) \tag{7}$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(O_i - P_i)^2} \tag{8}$$

$$EF = \frac{\sum_{i=1}^{N}(O_i - O)^2 - \sum_{i=1}^{N}(O_i - P_i)^2}{\sum_{i=1}^{N}(O_i - O)^2} \tag{9}$$

wherein O_i and P_i are recorded and predicted state variable of the i[th] observation, O is the mean of the recorded state variables (i = 1 to N), and N is the number of the observations.

3.5. Simulation of water management strategies

Following the successful simulation during the calibration and validation periods, the model was used for studying various water management alternatives for the command area. In the prediction mode, the model parameters fixed through the calibration process were used to forecast the system response under a specific set of conditions. Prognostic simulations were carried out to analyse the long-term (16 years, from 2015 to 2031) effect of various strategies on the watertable depth and groundwater salinity. The extended simulations include different hydrological conditions and various combination of tubewell/canal water use for irrigation. The study examines five different water management scenarios which descriptions follow:

Scenario 1: existing situations

The water and salt balances of the command in the next 16 years (in 2031) is shown under this scenario, if the existing situations about cropping, agro-hydrological settings, and discharge/recharge would prevail.

Scenario 2: dry situations

This scenario discloses the salt and water balances of the command in the coming 16 years if some dry years take place in a row.

Scenario 3: wet situations

This scenario presents the situation of water and salt balances in the command in the next 16 years if wet years happen sequentially.

Scenario 4: increased groundwater use

The rising groundwater level in the command can be moderated by raising the total pumping volume. This can be done by increasing the pumping volumes from the currently installed wells. This scenario shows the impacts of raising the pumping volume by four percent over the current level.

Scenario 5: optimal conditions

The eventual aim of a management study is to sustain the groundwater depth at a level which is neither very deep nor very shallow. It facilitates to circumvent the undesirable effects of overexploitation of groundwater and also it would not lead to waterlogging and secondary salinization of root-zone. In this scenario, a number of permutations are analysed to find out optimal input values, for example decreased/

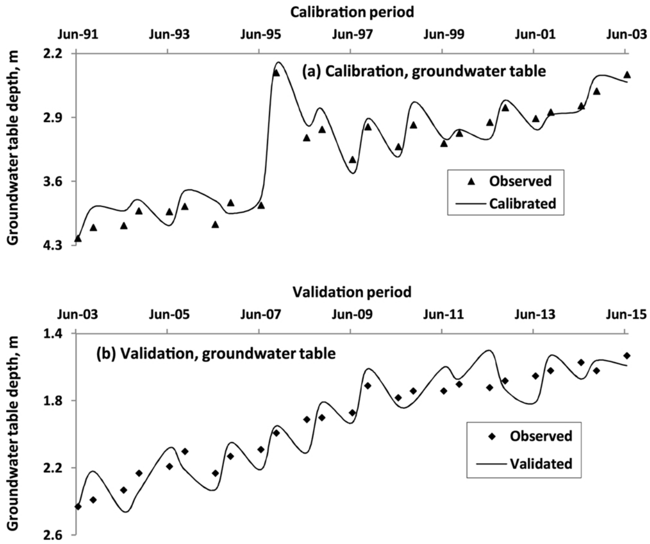

Fig. 2. Simulated versus observed groundwater tables during (a) calibration and (b) validation period.

increased tubewell/canal water and/or increased/decreased crop area, in order that the groundwater level could be stabilized at a safe depth throughout the simulation.

4. Results and discussion

4.1. Calibration and validation

The results with recorded groundwater levels during the SaltMod calibration and validation are shown in Fig. 2. The predicted values convincingly fit with the recorded values throughout the simulation. Fig. 3 shows more or less similar results with the groundwater salinities values throughout the simulation runs. The statistical analysis of data acquired during the simulation was done. The RMSE and ME are reasonably low during the simulation as given in Table 3. The error relative to the normal deviation of the recorded values is judged through the EF which ranges between - ∞ and 1.00. Values of EF above 0.50 are good enough. The EF values were computed at 0.81 and 0.87 during

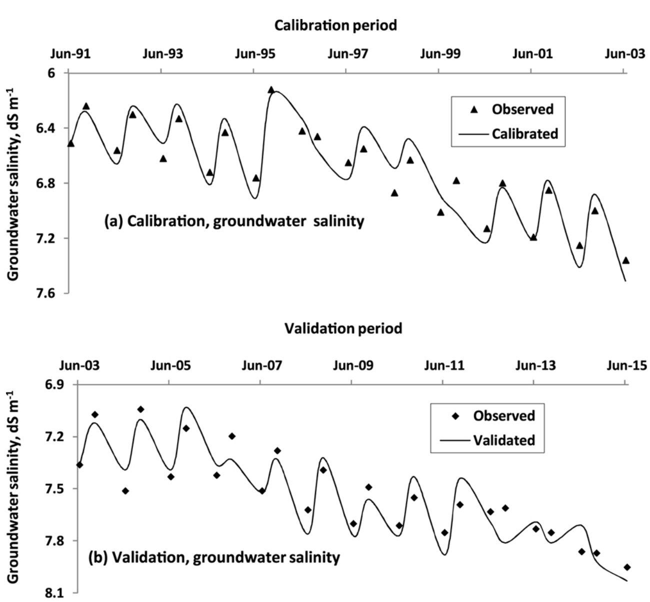

Fig. 3. Simulated versus observed groundwater salinities during (a) calibration and (b) validation period.

Table 3
Results of statistical analysis.

	Calibration period				Validation period			
	R^2	ME	RMSE	EF	R^2	ME	RMSE	EF
GWL[a]	0.916	0.07	0.21	0.81	0.837	0.05	0.16	0.89
GWS[b]	0.869	0.05	0.17	0.87	0.881	0.06	0.12	0.80

[a] GWL: Groundwater level data.
[b] GWS: Groundwater salinity data.

Table 4
Results of sensitivity analysis.

Parameter	Calibrated range	Findings
Effective porosity (Peq)	0.09–0.23	This parameter is sensitive to groundwater levels and salinities, both. An increase in Peq values results in lower groundwater salinities and deeper groundwater levels.
Leaching efficiency (Flq)	0.50–0.67	The leaching efficiency of the soil is sensitive only to the groundwater salinities. Thus, has no impact on groundwater levels.

calibration with the groundwater levels and salinities data, in that order (Table 3). The corresponding values were 0.89 and 0.80 during the validation period. Thus, from Figs. 2 and 3 and Table 3 it could be judged that the model SaltMod did well in forecasting watertable depths and groundwater salinities during the simulation periods.

4.2. Sensitivity analysis

Sensitivity analysis results for groundwater levels and salinities data are summarized in quantitative and qualitative terms in Table 4. It is observed that the Flq is sensitive to groundwater salinities only. While the Peq is sensitive to groundwater levels as well. The deeper watertable depths and lower salinities were observed with an increase in Peq values.

4.3. Assessment of simulated scenarios

Scenario 1: existing conditions

A steady and continuous groundwater table rise were obtained in this scenario during the study period 2015–2031(Fig. 4). This could be observed from the figure that groundwater table will rise 0.054 m annually to touch a level of 0.67 m bgsl (below the ground surface level) against the current 1.53 m. So it would register a total watertable rise of 0.86 m in the next 16-year simulation period. Furthermore, under

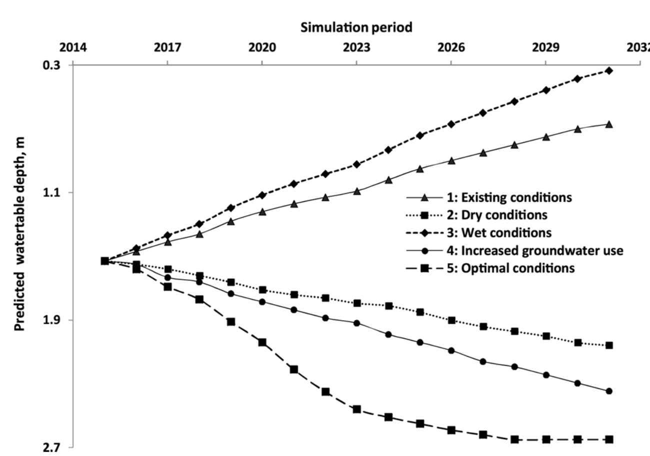

Fig. 4. Predicted watertable depths under different scenarios.

existing conditions, the watertable will arrive at the root-zone during the tenth year of the prediction period. Hence it could be wrapped up that if the current set of conditions persists for the coming 16 years there may not be feasible to cultivate any field crops under shallow watertable and poor groundwater conditions since the salinity of groundwater would rise to 8.81 dS m^{-1} against the current level of 7.95 dS m^{-1}. Because groundwater table has been going up in the study region for the last few decades (Singh, 2016b), the ongoing rise in the groundwater table, as predicted, is worrisome and necessitates urgent intervention for long-term sustainability in farm production.

Scenario 2: dry conditions

In this scenario, a steady and continuous decline in groundwater table is noticed as shown in Fig. 4. This can be seen that groundwater table would decline by −0.53 m at the rate of −0.033 m per annum. The groundwater table would arrive at 2.06 m bgsl finally from 1.53 m in the beginning. The salinity of groundwater in this scenario would decline from 7.95 dS m^{-1} in the beginning to 7.21 dS m^{-1} towards the end. The decline in watertable in this scenario is clear for the reason of low net groundwater recharges throughout the successive dry years. The groundwater level decline signifies the overdraft condition and would entail some limitations on the groundwater use.

Scenario 3: wet conditions

Under this scenario, the groundwater table shows a rising trend (Fig. 4). It rises by 1.2 m in the 16-year simulation period to touch a level of 0.33 m bgsl against the current 1.53 m. The average annual rate of rise would be 0.075 m, though, it would be higher in the initial years. This rise would be higher by 0.021 m over and above the existing conditions. Moreover, the groundwater table will arrive at the root-zone during the seventh year of the prediction. The salinity of groundwater may rise to 8.33 dS m^{-1} against the current 7.95 dS m^{-1} in the wet conditions. The excess rainfall condition would generate more groundwater recharge which causes groundwater table rise in the command area.

Scenario 4: increased groundwater use

The results obtained for this scenario show a steady and continuous groundwater table decline throughout the study period 2015–2031 (Fig. 4). This could be observed from the results that groundwater table would decline at −0.051 m by year to touch a level of 2.35 m bgsl against the current 1.53 m. Thus, an increase in groundwater use might bring down the groundwater table of the command area by −0.82 m. The salinity of groundwater could decline to 7.05 dS m^{-1} against the current level of 7.95 dS m^{-1}. Also, in this situation, the groundwater table would never arrive at the root-zone of crops during the simulation period. Thus, this is recommended that groundwater use should be increased to sustain the groundwater level at a safe depth as it is a need for achieving the long-term sustainability in farm production.

Scenario 5: optimal conditions

The watertable in the command is already at 1.53 m bgsl which would negatively affect the crop productivity due to root-zone salinization. Different combinations are, therefore, tested to determine optimal input values, i.e., tubewell/canal water and/or increased/decreased crop area, in order that the groundwater level could be stabilized at a safe depth. The results of this scenario are depicted in Fig. 4. This can be seen that groundwater table would lower to more than 2 m bgsl in the fifth year of the simulation and it could be stabilized at 2.65 m in the twelfth year where it remains until the end. The salinity of groundwater in this scenario would vary between 6.93 and 7.14 dS m^{-1} starting the eleventh year. This rather favorable conditions of water and salt balances may possibly be realized by altering the tubewell draft by +5%, canal supply by −16%, and rice area by -7%, for the first five years of the simulation, after that tubewell draft by +3%, canal water supply by −6%, and rice area by −4%. Therefore it is concluded that little changes in different input parameters could keep the command from more salinization and waterlogging.

5. Conclusions

It is clear from evaluating the results that SaltMod appears to be a helpful model for the simulation of watertable depths and salinities in agricultural areas. It is capable of appraising the upcoming water and salt balances through a range of interventions. The watertables in the command area would persist to go up in the coming years in the existing conditions. Therefore, assured crop cultivation in the study region could not be continued under the present cropping pattern, discharge/recharge, and agro-hydro-meteorological settings. Under the optimal conditions, a decreased rice area against non-rice crops is recommended, since it could trim down percolation significantly. Apart from rice area reduction, enlarged use of groundwater and reduced canal water use are also recommended. Groundwater withdrawals can be augmented by putting in additional tubewells at fresh sites and encouraging stakeholders/farmers to utilize poor quality groundwater in conjunction with limited higher-quality canal water for irrigation purposes. The optimal scenario revealed that small changes of 3–6% in input values would contain the hydrological problems of the study region. The discussed management alternatives, if put into practice, will help significantly to lessen the groundwater table rise and secondary salinization of agricultural lands.

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