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Modeling Shallow Groundwater Behavior Using Hydrus-1D and MODFLOW Models: Its Impact on Groundwater Salinity

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Abstract

Shallow groundwater often plays an important role in soil salinization and crop production. A modeling study was conducted at experimental farm Nain, Panipat of ICAR-Central Soil Salinity Research Institute, Karnal, representing shallow saline groundwater region to simulate groundwater behavior and its impact on groundwater salinity in non-monsoon (winter and summer) and monsoon period using Hydrus-1D and MODFLOW analytical models. Result of the study indicate that net groundwater flow (inflow-outflow) in the study area was positive during the monsoon season while negative during winter and summer period. Continuous intrusion of ground water from outside farm area, seepage from pond and deep percolation from field resulted into rise in watertable depth and diluted saline groundwater at the end of monsoon period (July-Sep). However, a little spatial variation in hydraulic head (212.34-212.40 m) existed by the end of the monsoon season. The spatial variability maps of ground water salinity revealed that in monsoon period there was 13.19% reduction in the area of high to extreme salinity (8-20 dS m^{-1}), while 3.8% and 10.2% increase in moderate (4-8 dS m^{-1}) and non-saline (0-4 dS m^{-1}) area, respectively. Overall, study provides quantitative understanding of multiple behaviors of shallow groundwater system with seasonal changes of drying and wetting cycles and its impact on groundwater salinity. Outcome of the study can be used to prioritize the area for implementing the groundwater management plan in the salt-affected areas having shallow groundwater.

Key words: Groundwater modelling, Groundwater salinity, MODFLOW, Hydrus-1D

Introduction

In arid and semi-arid regions, shallow and saline groundwater plays a typical role in ecosystem functions. The shallow saline groundwater system is related to the processes of evaporation, groundwater recharge, runoff, water and salt movement and plays a critical role in crop production and salinization. Irrigation is one of the main components responsible for maintaining productivity of Indian agriculture, mainly in North Western Indo-Gangetic region (Mandal *et al.*, 2007). Though irrigation has brought prosperity, but there have been some isolated environmental impacts also. Excessive irrigation caused the shallow groundwater table to rise and the soil to become more saline (Singh *et al.*, 2012). Existence of shallow groundwater table is near the surface caused capillary rise of salts towards the surface and potentially leading to salinization of the topsoil (Northey *et al.*, 2006; Meena *et al.*, 2022). If the groundwater table rises above a certain critical depth, soil salinization may occur. Pedologists ascertained that 2–3 m is the "critical groundwater table depth" of soil salinization on the Songnen plain of northeast China (Zhang and Wang, 2001), while Guo and Liu, (2002) and Qiao and Yu, (2003) reported that 1.5–2.5 m is the "critical groundwater table depth" of soil salinization in arid and semi-arid regions of China. Kamra *et al*. (2019) reported that "critical groundwater depth" of soil salinization in arid and semi-arid regions of North West India is 1.5 m and area under water table depth of 1.5-3.0 m is potentially waterlogged.

The rising groundwater table usually leads through changes in soil salinity to accelerate soil deterioration (Mahmood *et al.*, 2001). However, limited attention has been paid to seasonal changes of drying and wetting cycles following these changes especially when the shallow groundwater table has risen above the critical and brought soil salinity. The knowledge of the specific characteristics of an area would allow us to identify the salinized areas, evaluate the salinization status, and especially, estimate the effect of seasonal changes of groundwater table depth on soil salinization.

Over the last decades, a number of integrated surface and subsurface hydrologic models (SWAT-MODFLOW- Baily *et al*., 2016; Hydrus-MODFLOW- Beegam *et al*., 2018; Aqua Crop-MODFLOW- Kumar *et al*., 2022) have been developed and used to simulate the groundwater behavior at regional scale. The main objective of such models is to visualize the hydrologic cycle in a wholesome way, particularly by integrating the surface and subsurface (unsaturated and saturated zones) hydrological processes. Such integration is particularly important in semi-arid regions where the watertable is shallow saline and close to the surface and greatly affected by seasonal changes.

Measurements on groundwater table depth and groundwater salinity are expensive, time consuming and require development of observation well and repetitive data measurement to identify the seasonal changes (Adhikary and Dash, 2017). The simulation model has been an effective tool to describe such complicated behaviors of shallow groundwater system which was affected by seasonal monsoonal changes and vadose zone transport processes. Keeping these facts in view, the present study was planned to (1) simulate groundwater flow behaviors in dry and wet season using loosely coupled vadose zone model (Hydrus-1D) and groundwater flow model (MODFLOW), and (2) analyze the spatial distribution and seasonal variability of groundwater salinity with respect to seasonal groundwater behavior. The results of this study provide a scientific basis for sustainable water management, regional environmental protection and increasing awareness on the local environmental consequences brought by shallow groundwater level variation due to seasonal and climate change.

Material and Methods

Study site

Study site was experimental farm of ICAR-Central Soil Salinity Research Institute, Karnal , situated in Nain village (Dist: Panipat, Haryana, India). The farm area is characterized by low-lying, having shallow and saline ground water conditions having a total area of 11 ha and geographically it extends from 29.31864 to 29·31944 N latitude and 76.79166 to 76.80 E longitude at an elevation of 212.99 to 213.67 m above mean see level. The area falls under semi-arid climate and hyperthermic soil temperature regimes with average annual rainfall of about 550-650 mm and about 1550 mm annual evaporation (Ustic soil moisture regimes) (Mandal *et al*., 2013; Narjary *et al*., 2021a). The north side of the farm is surrounded by road, in the western side a surface drain is passing about 3-4 m away from the farm boundary and in southern and eastern side of the farm boundary is surrounded by farmers' land. The farm is situated in low elevation location vis-a- vis to its surrounding fields for a prolonged period of time is the main reason for shallow saline groundwater table in the farm and also existence of saline parent material (Narjary *et al*., 2019). Since groundwater quality is not suitable for irrigation, good quality irrigation was available only through harvesting monsoon rainwater. In addition, available good quality runoff water in surface drain passing close to western boundary of farm, was also a potential irrigation source during the monsoon season.

Ground water level monitoring and sampling

Total 32 observation wells (Fig. 1) were installed in the entire study area for periodic monitoring of water level and salinity. Few of them were installed near to working tube well to observe influence of groundwater pumping on water level fluctuation. Eight observation wells were installed around the pond and 3 were installed in the area confined between pond and surface drain to observe the impact of water bodies on fluctuation of groundwater table. Water level recorder (OTT KL 010, OTT HydroMet) was used to measure water table depth. Groundwater salinity (EC_{gw}) of collected water samples from observation wells was determined by using a standard electrical conductivity meter (Eutech Con 700, Eutech Instruments Pvt Ltd, Singapore). The water table depth and salinity were monitored fortnightly in winter, summer and monsoon months of 2017.

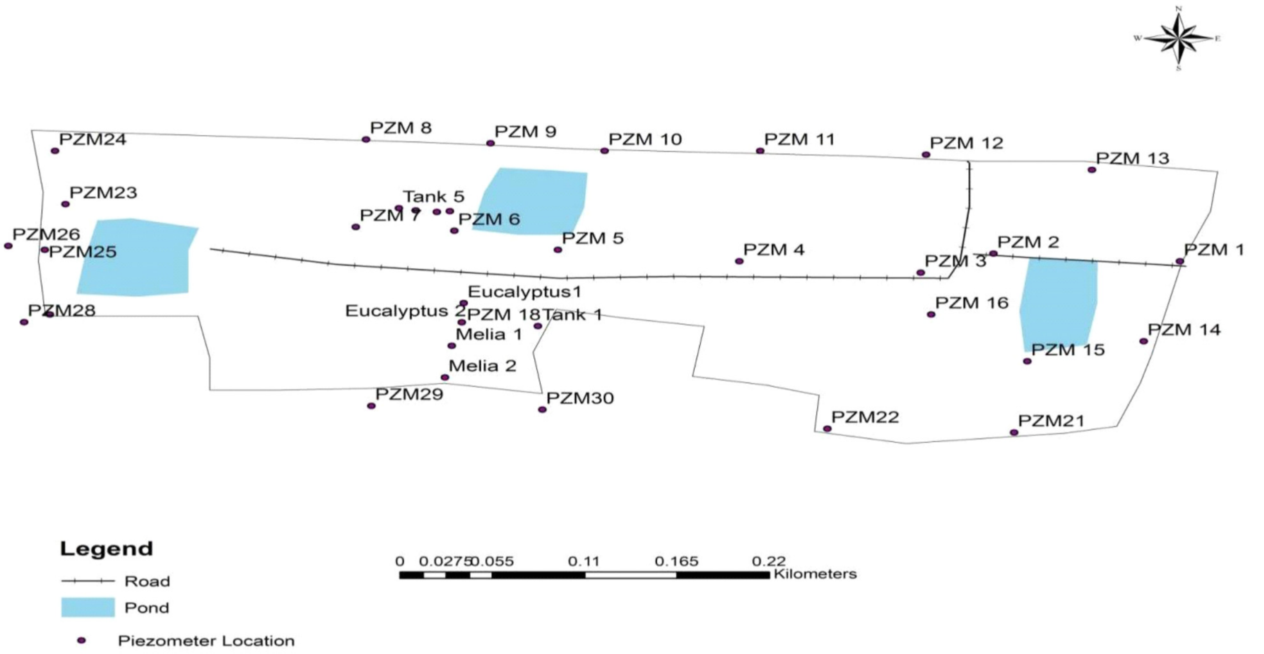


Fig . 1 Thematic view of study site with location of observation wells

Data collection

Rainfall and evaporation data of the year 2017 were collected from the weather station situated at the study area. Elevation map was prepared at 50 × 50m grid using dumpy level. Hydrogeological and lithological parameters of saturated zone are taken from district Central Groundwater Board Report, Panipat, Haryana (CGWB, 2013).

Estimation of groundwater draft and recharge

Different land uses such as cropped, barren land and water bodies were taken into consideration while calculating groundwater recharge and draft. The cropped land of the farm occupies about 75% of the total land. The procedures used to estimate recharge (return flow) and draft components for different land uses are described below:

Draft

The draft for cropped area was taken as groundwater applied as supplementary irrigation for crop production. For other land uses, draft was taken zero as there was no irrigation. The total irrigation depth was considered as groundwater draft.

Return flow

Hydrus-1D (Simunek *et al.*, 2005) was used to estimate return flow (deep percolation) from the cropped area using soil, crop, and climate data. This model estimates water balance components based on following relationship

$$Dr = (I + R) - ET_c + \Delta\theta + Sr \qquad \ldots(1)$$

Where, I is the irrigation applied (cm), R the precipitation (cm), ET_c the evapotranspiration (cm), Dr is deep percolation (return flow) in cm, $\Delta\theta$ is change in soil moisture (cm), and S_r is surface runoff (cm). It was hypothesized that the fraction of water (irrigation and precipitation) that passed beyond the root zone will eventually reach the aquifer since the water table was shallow. The calibrated and validated Hydrus1d model (Narjary *et al.*, 2021b) for the study area was adopted for estimation of return flow.

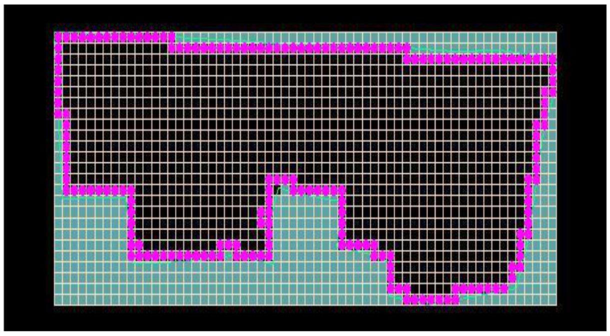
MODFLOW model

MODFLOW is a numerical model that represents the area specific groundwater system like real-physical aquifer system (McDonald, 1988). It is recognized as potential tool to solve the real-world groundwater problem worldwide. MODFLOW based on a partial differential equation (Bossinesq equation) solved by finite or discreet element method (Javandel and Witherspoon, 1968, 1969). Bossinesq equation is written as following:

$$\frac{\partial}{\partial a}\left(kd_{ax}\frac{\partial p}{\partial x}\right)+\frac{\partial}{\partial b}\left(kd_{by}\frac{\partial p}{\partial y}\right)+\frac{\partial}{\partial c}\left(kd_{cz}\frac{\partial p}{\partial z}\right)-V=S_a\frac{\partial p}{\partial \breve{T}} \qquad \ldots(2)$$

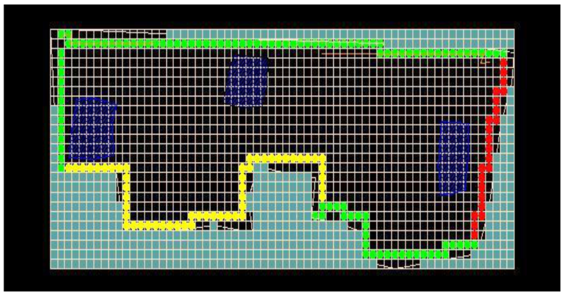
whereas, p is the hydraulic head (m) at a point, S_a is the aquifer storage term that change with type of aquifer system, in our case it is specific yield as aquifer is unconfined, kd_{ax}, k_{dy} and k_{dz} are the hydraulic conductivity in x, y and z-direction in (m day^{-1}), V is a volumetric flux, $\check{T}$ is time period in day.

Based on the hydro-geological information, graphical representation of the ground water flow system was developed for the study area. In first step, an unconfined aquifer zone was created using lithology data. In the study, only first aquifer (unconfined aquifer) was considered as majority of the pumping for irrigation was done form the same aquifer. In the second step, all the hydraulic parameters of aquifer such as Hydraulic conductivity (22 m day^{-1}) and Specific yield (0.12) were assigned in the model (CGWB, 2013). In the third step, boundary conditions were assigned. During the winter and summer season specified flux (Neumann boundary condition) has been assigned (Fig. 2). The specified flux is estimated by Darcy flow tool (Kumar *et al.*, 2020) which inbuilt in Arc GIS 9.3. As in monsoon season, drain water is continuous flowing, constant head boundary condition was taken (Fig. 3). In fourth step, the estimated groundwater recharge for different land uses was uniformly assigned in the model as downward flux. The observation wells having different co-ordinates were taken as points for assigning downward and upward flux in the conceptual model. In last step, the conceptual model was converted into numerical model. After success numerical model conversion, the model was auto calibrated by running PEST and trial and error method by tuning of specific yield and hydraulic conductivity. The model was calibrated and validated for non-monsoon (winter and summer) and monsoon season of 2017. The hydraulic head data of 32 observation wells was used for model calibration purpose. Three statistical indicators i.e., coefficient of determination (R^2), root mean square error (RMSE) and normalized RMS % were used for assessing the performance of model during calibration and validation process. These can be written as follows:



🟪 Specified flux boundary condition

Fig. 2 Boundary condition during winter and summer period (January-May) (Non monsoon period)



🟩 No flow boundary

🟥 Constant Head boundary condition (Drain)

🟨 Constant head boundary condition (outside field)

Fig. 3 Boundary condition during monsoon period (June - October) (Non monsoon period).

$$R^2=\frac{\sum(x_i-x_p)^2}{\sum(x_i-mean\,x_i)^2} \qquad \ldots(3)$$

$$RMSE=\sqrt{\frac{\sum_{i=1}^{N}(x_p-x_i)^2}{N}} \qquad \ldots(4)$$

$$Normalized\ RMSE\,\% = \left(\frac{RMSE}{\hat{O}}\right)\times 100 \qquad \ldots(5)$$

where, x_p is the predicted/simulated value, x_i is the observed value and mean x_i is the mean of observed values and Ô represents the average of observation value.

Spatial map of groundwater salinity

Ordinary kriging (OK) interpolation (Narjary *et al.*, 2017a) was used for determining spatial dependence of groundwater salinity recorded from 32 observation well points for summer, monsoon and post monsoon months of 2017 using Arc-GIS 9.3.

Results and Discussion

Draft and recharge

Different inflow and outflow components of groundwater of the study area were characterized to understand spatio-temporal dynamics of ground water table depth using Hydrus -1D. The net ground water recharge (return flow-draft) was found negative during winter and summer season (Table 1) due to higher groundwater withdrawals to meet out crop water requirement, higher atmospheric evaporative demand and outflow of the ground water from the study area. Rainfall (11.2 cm) and inflow of seepage water from adjoining drain during the month of February-March, probably resulted in positive groundwater recharge (1.37 cm). During summer seasons (March-June), due to greater water consumption (53.43 cm) by the crop and limited amount of rain (6.9 cm), the net ground water recharge was negative (34.56 cm) and groundwater table reached to 3.42 m from 2.45 m. During monsoon season, ground water recharge was positive (18.21 cm). In this monsoon period total rainfall received was 80.73 cm and total evapotranspiration loss was 62.99 cm. During monsoon season, study area received a mean net recharge of 35 cm, which resulted in an average groundwater table rose to 1.1 m. The deep percolation from crop field and seepage from water body (pond) contributed 52.5 and 8.4%, respectively towards groundwater recharge during monsoon season, that led to water level rise. Hence, 40% of groundwater recharge was received from outside farm area and nearby drains. That indicates that there was a continuous intrusion of ground water from outside farm area and contributed in rise in water level. Inflow and out flow of the ground water might have played a vital role in fluctuation in groundwater table depth and salinity (Narjary *et al*., 2017b).

Calibration and Validation of MODFLOW

The flux (draft-recharge) was calculated with the estimated draft and recharge values and utilized as an input in MODFLOW to simulate groundwater behavior of the study area. For modeling of groundwater behavior under shallow saline groundwater environment, MODFLOW was calibrated with the observed data of water table depth. Calibration of MODFLOW was done for non-monsoon period (Jan-May) and validation for monsoon (June-Oct). Auto-calibration (parameter estimation) model PEST was used for calibrating the model parameters, namely, hydraulic conductivity and specific yield. During the calibration period, the specific yield varied between 0.11-0.15, while the hydraulic

Table 1. Groundwater draft and recharge components of the study area

Season	Year (2017)	Irrigation (cm)	Rainfall (cm)	Water consumption (cm)	Soil water storage (cm)	Seepage from pond (cm)	Ground water recharge (cm)	Water table depth fluctuation (cm)
Winter	Jan-Feb	2.1	0.77	7.47	-1.15	0.77	-1.16	1.8
	Feb-March	0.93	11.92	11.05	1.22	0.67	1.37	-2.6
Summer	March-April	0	3.7	5.4	-0.88	0.22	-0.82	4.0
	April-May	1	1.3	24.75	-3.04	0.21	-17.11	6.9
	May-June	1.4	1.9	23.28	-1.15	0.04	-16.63	4.4
Total winter and Summer (Non-Monsoon)		5.43	19.59	71.75	-4.99	1.91	-34.35	14.6
Monsoon	June-July	1.5	43	32.81	5.82	0.67	8.61	-6.3
	July-August	1	1.8	8.93	-3.93	0.52	-2.08	-15.2
	August-Sep	1.4	29.13	9.43	8.86	0.81	12.71	-12.6
	Sep-Oct	1	6.8	11.82	-2.67	0.92	-1.03	-0.6
Total Monsoon		4.9	80.73	62.99	8.08	2.91	18.21	-34.7

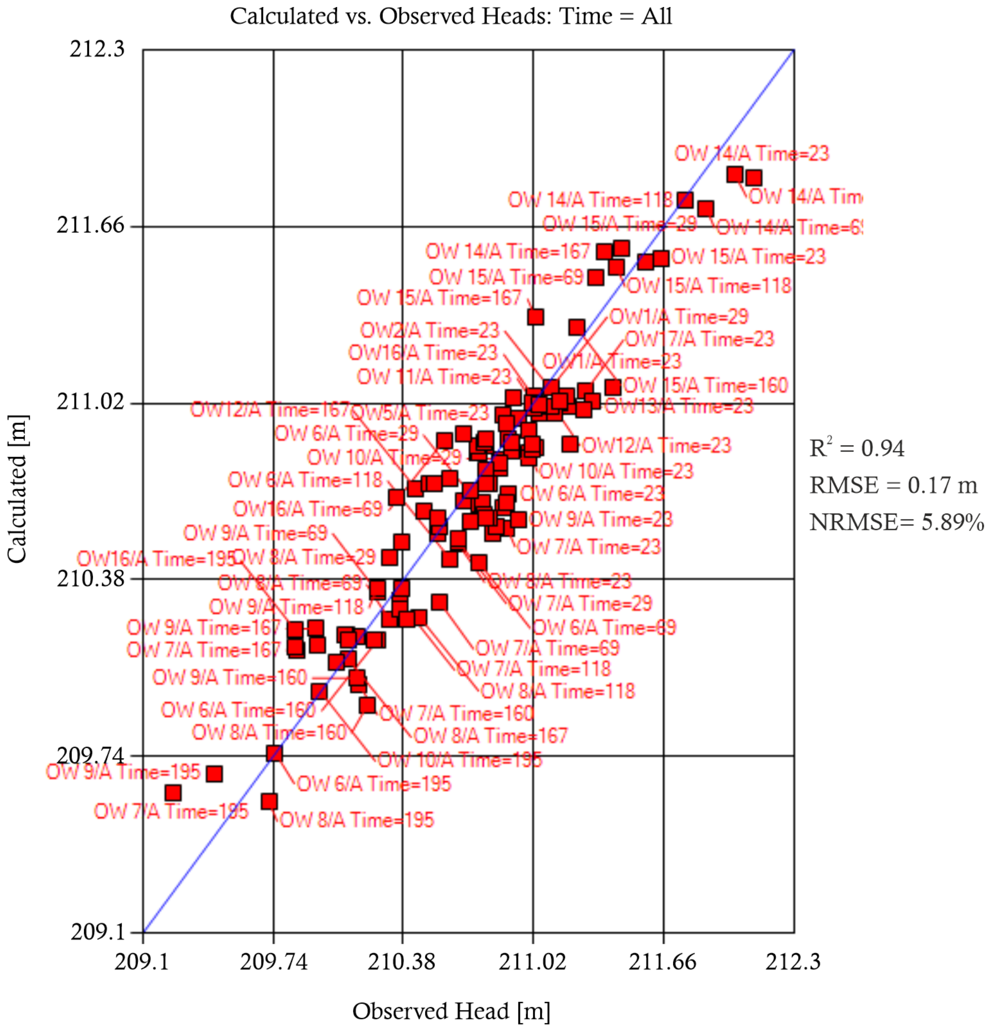


Fig. 4 Observed and simulated hydraulic head during calibration (non-monsoon, January-May) period (2017) of the study area

conductivity varied between 15-25 m day^{-1} in the study area. The sensitivity analysis of different parameters indicated that model results were more sensitive to specific yield than hydraulic conductivity. Very good agreement was found between observed and simulated hydraulic heads during the calibration period of non-monsoon period (January-May) with R^2, RMSE and NRMSE values of 0.94 and 0.17 m and 5.89%, respectively (Fig. 4). In monsoon (validation) period also, there was a good agreement between the observed and simulated head of groundwater table as indicated by the smaller RMSE and higher R^2 values (Fig. 5). The model accounted RMSE of 0.28 m and R^2 of 0.96 and NRMSE of 8.17% during the monsoon period. In general, the good agreement between the observed and simulated groundwater hydraulic head during the calibration and validation period showed that the MODFLOW model accurately captured the actual condition of groundwater variability (Xiao *et al.*, 2021).

Groundwater balance

Net groundwater flow (inflow-outflow) during the non-monsoon period was in the negative phase. During winter season, net groundwater recharge of -0.1426 and -0.125 m^3 was occurred in January and February months, respectively. During the summer season, -0.4922, -0. 875 and -0.694 m^3 net groundwater recharge was taken place in March, April and May months, respectively. The net groundwater flow (Inflow-outflow) was found positive during the monsoon season. It was found to be 0.18, 0.33, 0.43, 0.52 and 0.57 m^3 in June, July, August, September and October months, respectively (Fig. 6).

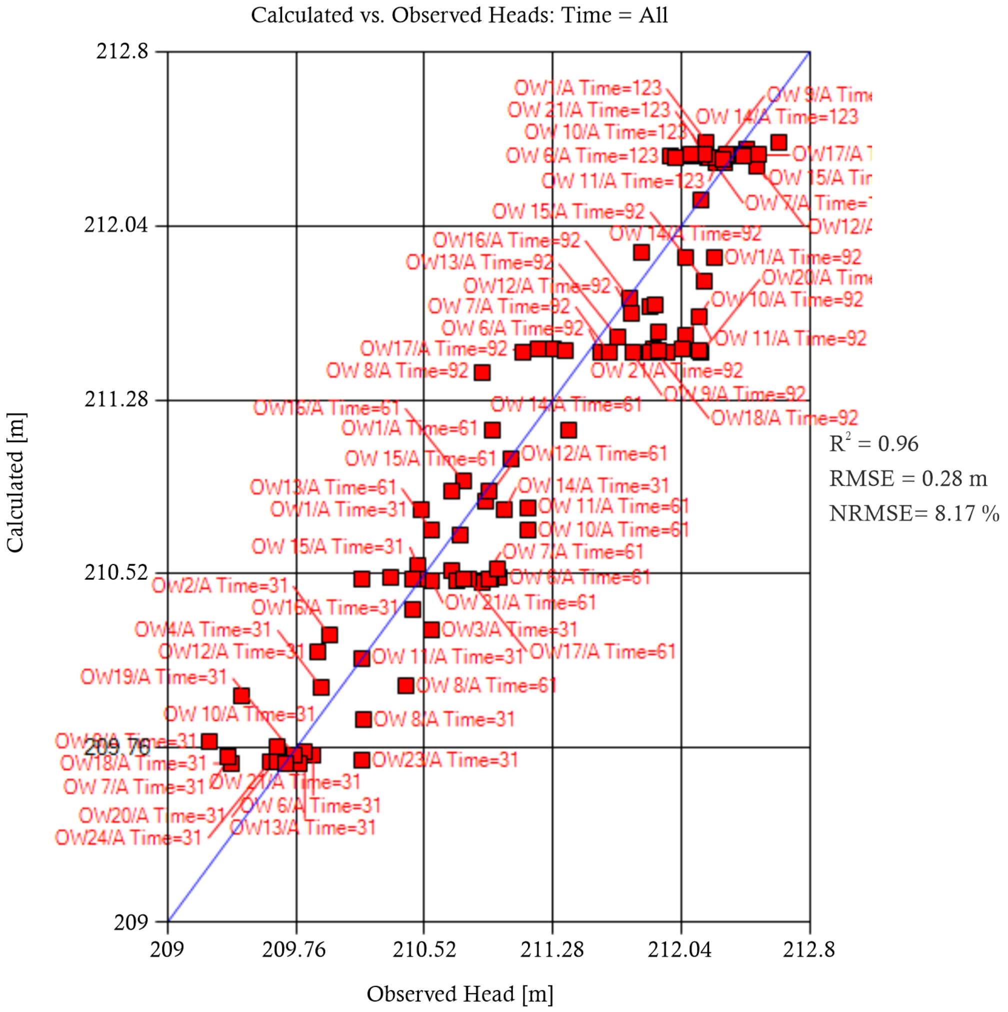


Fig. 5 Observed and simulated hydraulic head during validation (monsoon, June-Oct) period (2017) of the study area

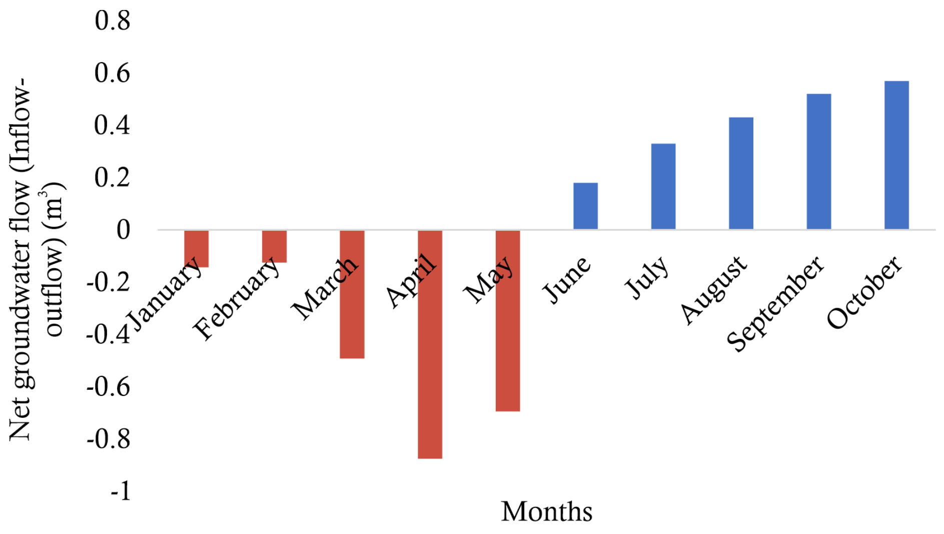
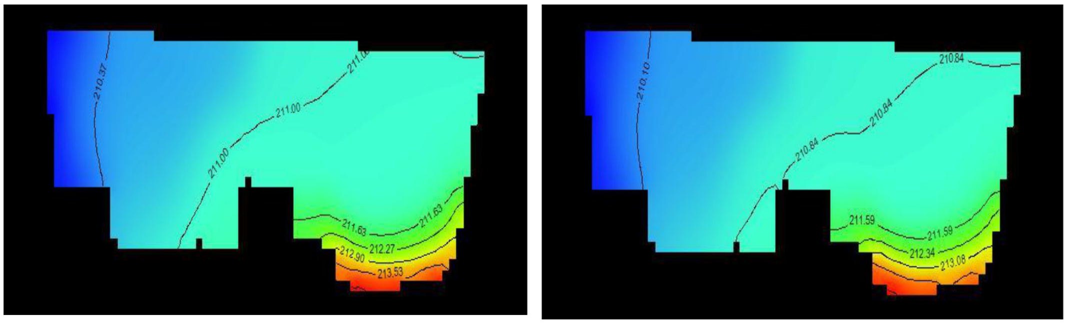


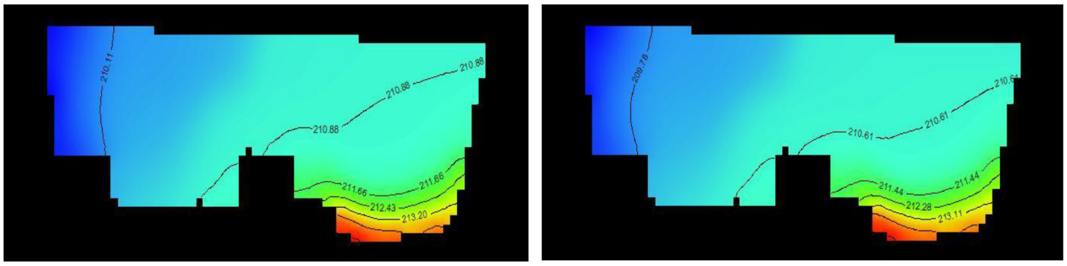
Fig. 6 Groundwater water balance (Net groundwater flow = Inflow-outflow) during the non-monsoon (January-May) and monsoon periods (June-October) (2017) of the study area

Spatio-temporal behavior of groundwater level

During non-monsoonal period (January-May), hydraulic head was least in the eastern side corner of the farm (210.37 m) and highest (213.53 m) in south western side of the farm (Fig.7). However, in monsoon season (July–October), hydraulic head was more in southwest corner of the farm i.e. along the drain side of the farm (Fig. 8). During June –July period, average hydraulic head of the farm ranged between 208.84 to 210.78 m. A little spatial variation in groundwater hydraulic head (212.34-2.12.40 m) was recorded by the end of monsoon season (Fig. 8). The lower hydraulic head during non-monsoon period indicates

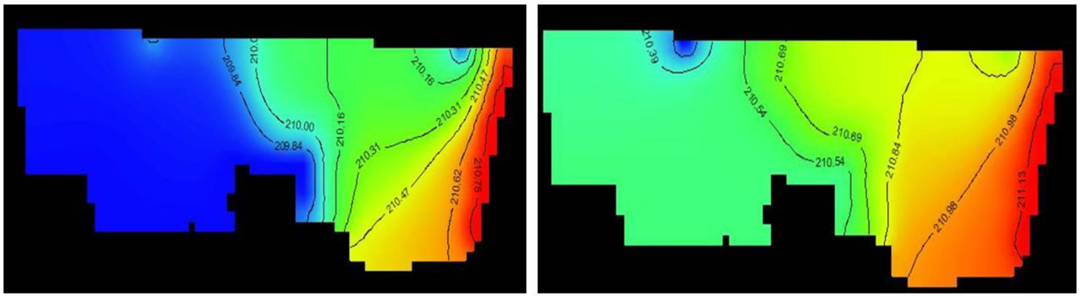


January - February February - March

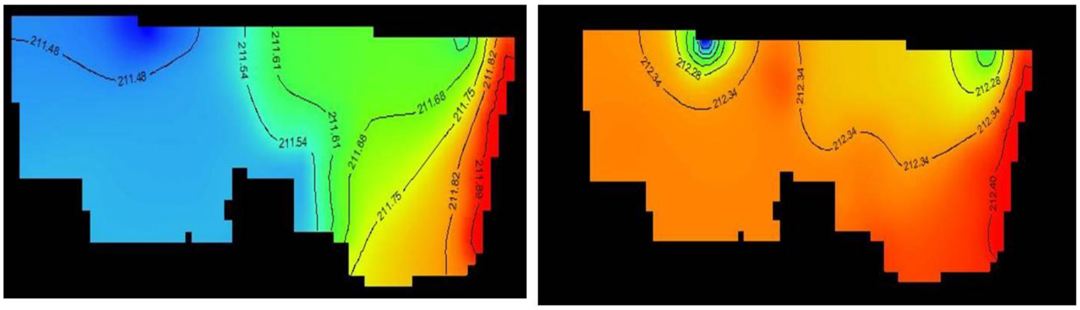


March - April April - May

Fig. 7 Groundwater behavior of the study area in non-monsoon season (January-May) of 2017



June - July June - August



August - September September - October

Fig. 8 Groundwater behavior of the study area in monsoon season (June-October) of 2017 decline in groundwater level. This was probably due to continuous groundwater withdrawal to meet irrigation requirement under heavy evaporative demand.

Spatial distribution of groundwater salinity

The spatial distribution of groundwater salinity during non-monsoon (January-May) and monsoon (June-November) seasons is presented in Fig. 9 and 10. The percentage of area falls under different salinity ranges is also presented in Table 2. In non-monsoon season, groundwater salinity in most part of the study area was ranged between 2-22 dS m^{-1}, while in monsoon season, it varied between 0.5- 16 dS m^{-1}, indicating dilution effect of recharged rainwater from cropped area, surface water harvesting structures (pond) and inflow from passing drain and near by farmers field situated at higher elevation. During summer period (April-May) of non-monsoon season, hydraulic head reached its minimum (209.78 to 213.11 m) level and the highest range of groundwater salinity (2-22 dS m^{-1}) was observed. Rong *et al*. (2009) also reported that there is a close relationship between groundwater depth and groundwater salinity. In our case study, it was observed that in summer period (April-May) less than 9% of the farm area having non to slight saline (0-2 and 2-4 dS m^{-1}) category. While groundwater salinity in larger part of the study area was found moderate (42%). Highly-saline (8-16 dS m^{-1}) and extreme saline (> 16 dS m^{-1}) categories were found in 44% and 6% part of the study area. Extreme groundwater saline area was predominantly situated in the western part of the study area.

In September-October months of the monsoon season, 22% of the farm having non to slight saline (0-2 and 2-4 dS m^{-1}) groundwater category, 46% area having moderate saline(4-8

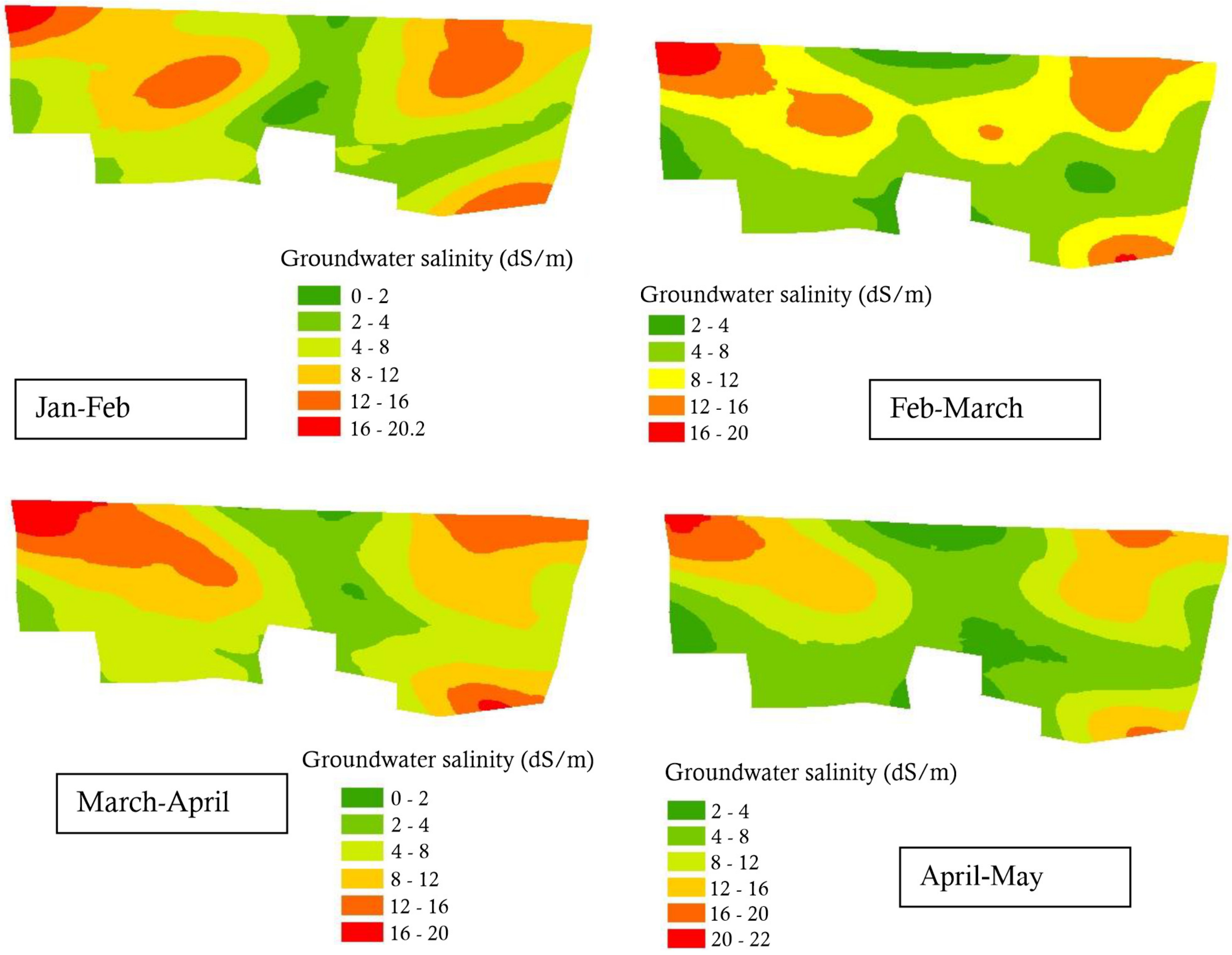


Fig. 9 Spatial map of groundwater salinity of the study area in the non-monsoon (January-May) season, 2017

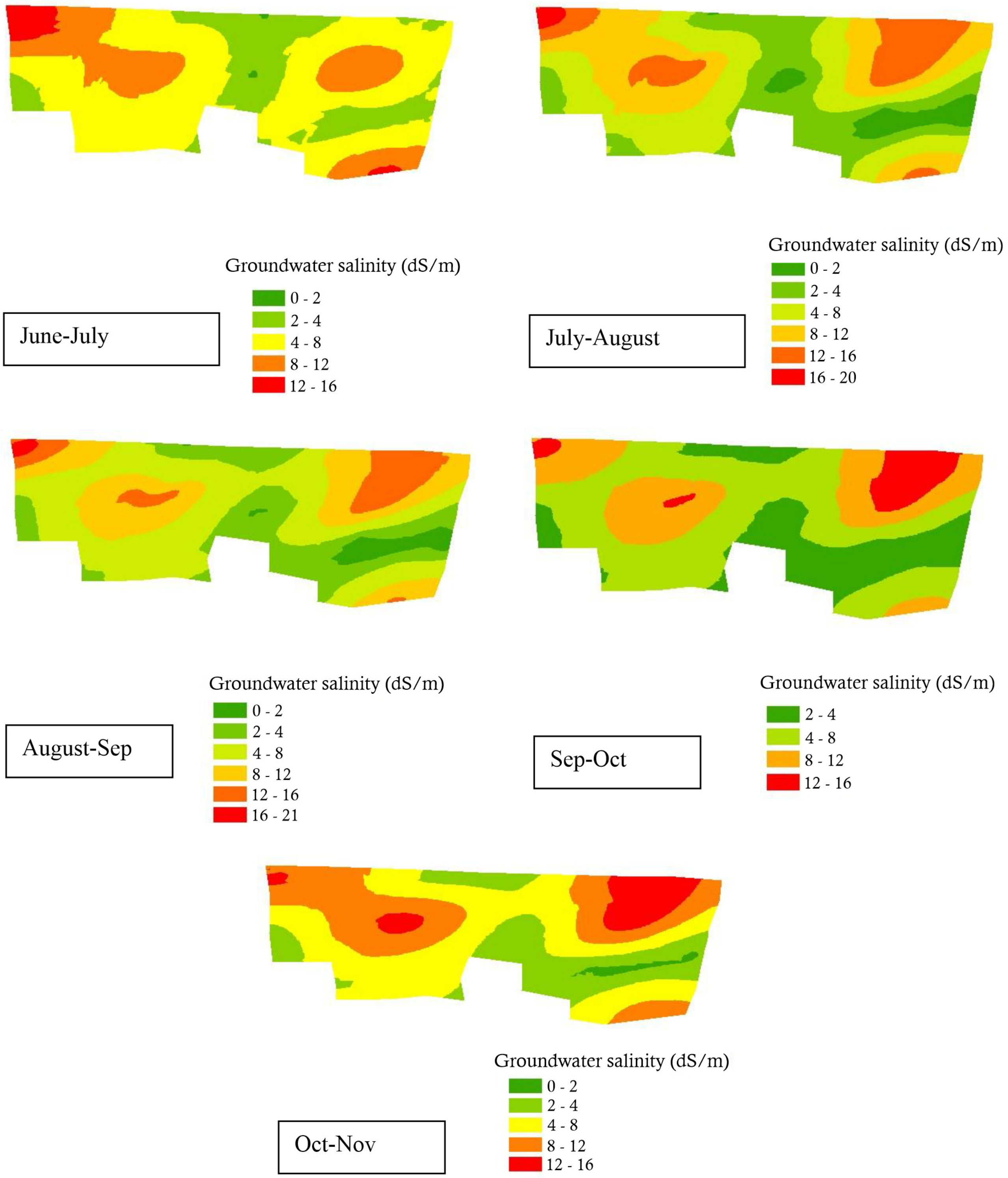


Fig. 10 Spatial map of groundwater salinity of the study area in the monsoon (June-November) season, 2017

dS m^{-1}) and 32% area was highly saline category (8-16 dS m^{-1}). In total, spatial variability maps of ground water salinity revealed that in monsoon period there was 13.19% reduction in area having salinity range between 8-20 dS m^{-1}, 3.8% increase in area having moderate salinity (4-8 dS m^{-1}) and 10.2% increase in non-saline area (0-4 dS m^{-1}). During the monsoon season (June-October), apart from the deep percolation and pond seepage, probably intrusion of good quality water took place from surface drain and nearby farmer's field. The good quality water recharge and intrusion

Table 2. Percent area under different groundwater salinity (EC_w- dS m^{-1}) levels during non-monsoon and monsoon seasons

Salinity (dS m^{-1}) class	Non-monsoon period					Monsoon period				
	Jan-Feb	Feb-March	March-April	April-May	May-June	June-July	July-August	August-Sep	Sep-Oct	Oct-Nov
0-2	2	—	1	—	—	—	6	4		1
2-4	20	7	17	9	18.1	21	24	22	22	22
4-8	35	42	37	42	39.2	55	32	41	46	40
8-12	28	33	26	23	28.0	21	25	23	25	28
12-16	14	16	16	21	12.1	3	13	9	7	9
16-20	1	2	3	5	2.1	—	1	1	—	—
>20	—	—	—	1	0.5	—	—	—	—	—

might have diluted the saline groundwater and resulted into reduced salinity level.

Conclusions

The groundwater behavior was modeled through vadose zone transport model (Hydrus-1D) and groundwater flow model (MODFLOW). Based on the observed data, a detailed loosely couple vadose zone transport model hydrus-1D and ground water flow MODFLOW was established for shallow saline groundwater region and was sufficient to characterize local groundwater behaviors for dry (non-monsoon) and wetting (monsoon) period. The following main inferences were drawn from this study:

(1) Net groundwater flow (inflow-outflow) during the non-monsoon period was negative while it was positive during the monsoon season.

(2) Return flow from crop field and water body (pond) contributed 52.5 and 8.4%, respectively towards ground water recharge, while remaining 40% of groundwater recharge took place as intrusion from outside farm area and nearby drain.

(3) Increase in area of shallow ground water level and reduction in groundwater salinity during monsoon season reveled a considerable amount of good quality water recharged/ intrude to groundwater system which reduced salinity level.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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