Modelling vadose zone processes for assessing groundwater recharge in semi-arid region

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Normally groundwater recharge is estimated using methods based on water balance, water table fluctuations, fixed factor of annual rainfall and tracer movement. In many of these methods water stored in the vadose zone and evapotranspiration are not accounted properly. These factors control groundwater recharge to a large extent, particularly in arid and semi-arid regions which are normally characterized by a deep water table, thick vadose zone and high evapotranspiration. In this study, HYDRUS-1D and MODFLOW models were used to assess the recharge flux and groundwater recharge in an area under a semi-arid region giving due consideration to important vadose zone processes. Cumulative recharge flux at water table in various sub-areas varied from 20.01 cm to 23.43 cm (29.26% to 34.26% of the monsoon rainfall). The average groundwater recharge was 22.2%. Total surface runoff in various sub-areas varied from 3.39 cm to 14.36 cm (5% to 21% of the monsoon rainfall). Evapotranspiration was found to be a major recharge controlling factor. Reference evapotranspiration varied from 37.19 cm to 45 cm (54% to 66% of the monsoon rainfall). Natural recharge under the prevailing pumping rate and pumping schedule was 23.3% of the monsoon rainfall. Simulation results revealed that if all the surface runoff is retained in the area, water table will rise by 1.46 m.

Keywords: Groundwater recharge modelling, HYDRUS and MODLFOW, semi-arid region, vadoze zone processes.

HIGH evapotranspiration, low to medium rainfall with poor distribution and thick unsaturated zone in groundwater irrigated areas are typical hydrological characteristics of semi-arid regions. Estimation of groundwater recharge is essential for assessing groundwater potential and for sustainable groundwater development and utilization. Rate with which the vertically downward moving water front joins the water table without any structural interventions is termed as natural groundwater recharge rate. Structural interventions are required to increase the recharge in areas where natural recharge is not adequate to compensate for the groundwater pumping. Groundwater recharge is the addition of water to an aquifer from overlying unsaturated zone or surface water body[1]. Estimation of natural groundwater recharge has been a major challenge to hydrologists since the 1930s[2–4]. Main source of water for groundwater recharge is rainfall. At surface, part of the rainfall infiltrates into the soil and the remaining is lost as evapotranspiration and surface runoff. Infiltrated water joins groundwater after travelling through unsaturated or vadose zone. Simultaneously, part of infiltrated water also flows away as sub-surface runoff and base flow. The important factors which control groundwater recharge are climate, soil and geology, vegetation and land use, topography and depth to water table[5].

A comprehensive review on the effect of various controls on diffuse recharge and its analysis on groundwater recharge was presented using unsaturated flow modelling[6]. Recharge estimation in arid and semi-arid regions is not an easy task because of temporal variation in precipitation and spatial variations in soil characteristics, topography, vegetation and land use[7]. Three basic factors which facilitate recharge are infiltration rate, permeability of unsaturated zone and saturated zone[4].

Rate of transfer of water between land surface and groundwater table is controlled by flow of water in the vadose zone. It has been reported that the recharge is greater in coarser soil than fine textured soils[8–10]. In Texas, recharge varied from 23% to 60% from arid to humid climate, vegetation reduced recharge by factors of 2 to 30 for humid to arid climate and soil textural variability reduced recharge by factors of 2–11 relative to recharge in bare sand[6].

Vadose zone processes play an important role in groundwater recharge in semi-arid regions where the water table is deep. A thick layer of unsaturated or vadose zone in such regions stores a substantial amount of infiltrated water which is lost by evapotranpiration and does not reach the water table. Rate of groundwater recharge in such regions depends on the amount of water stored and other flow processes in the vadose zone. Therefore, for accurate prediction of recharge rate, modelling of the unsaturated flow process is required, which is too

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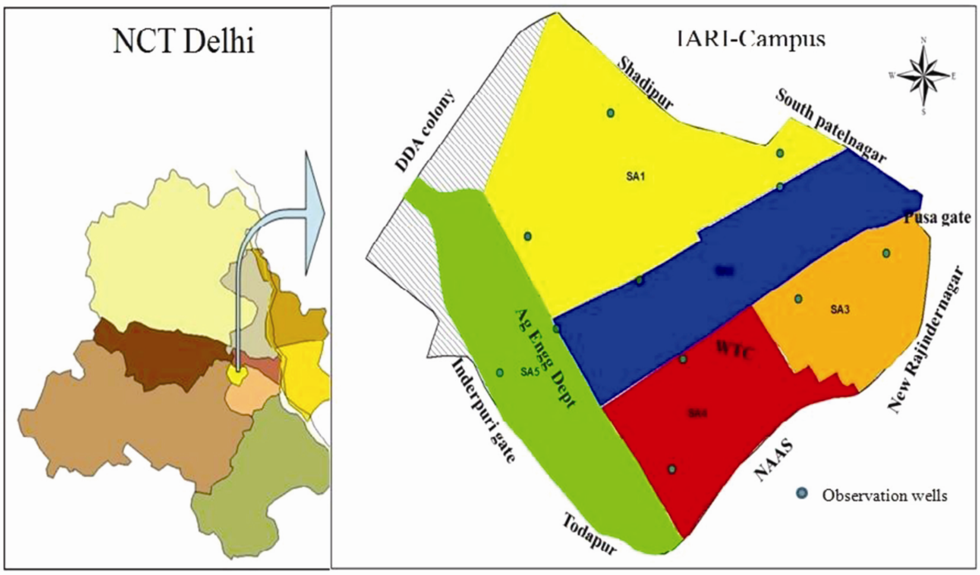

Figure 1. Locations and land marks in the IARI farm.

complex[11]. Despite several methods based on physical, chemical, mathematical and isotopic techniques, estimation of groundwater recharge is still considered the most difficult task[7,12,14]. Several methods have been used to estimate groundwater recharge with varying degrees of success[13–16].

Estimation of recharge is done effectively using vadose zone model and groundwater model[6]. Hydrodynamic process-based vadose zone models are preferred over methods that give areal average groundwater recharge and are becoming common tools for evaluating groundwater recharge and its spatial distribution[6,17,18]. To understand the impact of increased thickness of the unsaturated zone on groundwater recharge potential, soil water infiltration movement (SWIM) model was used in canal irrigated area of Punjab Agricultural University (PAU), Ludiana campus. It was reported that the deep water table may be due to large thickness of the vadose zone holding large amount of irrigation return flows[19].

Vadose zone properties affect groundwater recharge in several ways. It encompasses the unsaturated soil root zone and control the flux of water, matter and energy between the atmosphere, land surface and subsurface water bodies[20]. Due to the complexity and data requirements, vadose zone flow processes have rarely been included in hydrological models[6,14,21]. Models are effective tools used to assess and predict groundwater recharge. However, in most studies, flow processes in unsaturated zone were not given due importance or were oversimplified or neglected due to constraints on computation resources[9]. HYDRUS package[22] developed for MODLFOW-2000[23] was used to evaluate interactions between groundwater and vadose zone. It was reported that HYDRUS package provided many more efficient alternatives to variably saturated flow processes (VSF) for large scale groundwater problems. One-dimensional agro-hydrological model, soil–water–atmosphere–plant (SWAP), was used to estimate the groundwater recharge rate in Bethamangala watershed in Karnataka state of India, to predict the water table depth on a daily basis[24].

In India, groundwater recharge is estimated by following the recommendations of the Groundwater Estimation Committee[25,26]. Groundwater recharge is estimated using water table fluctuation method, if adequate data of pre-monsoon and post-monsoon water levels are available. Rainfall infiltration factor method is used where adequate water level data are not available. However, accuracy of this method is poor particularly when used in arid and semi-arid regions[27]. Water table fluctuation method gives better results but requires continuous monitoring of groundwater levels.

From the above it is evident that for realistic assessment of recharge, it is imperative to consider the water flow through vadose zone which has rarely been represented in hydrological models[6,14,21]. Conventional methods for estimation of recharge over simplify the effect of vadose zone flow processes. The present study was conducted to model the flow processes in the entire vadose zone for assessing groundwater recharge in semi-arid regions.

Materials and methods

Description of the study area

The study was carried out at the Indian Agricultural Research Institute (IARI) farm, New Delhi, India (Figure 1). IARI campus is spread over 473 ha which falls in the semi-arid region. This area was selected as the representative area of the semi-arid region, for modelling the

Table 1. Land use and soil type

Sub area	Area (ha)	Land use	Soil type
SA1	143.3829	Agriculture	Loam with some patches of sandy loam and clay loam
SA2	96.5456	Urban and high density urban	Loam
SA3	65.6925	Urban	Loam
SA4	65.1417	Mixed land use	Sandy loam and loam
SA5	101.9569	Urban and agricultural	Sandy loam with small patches of loam

groundwater recharge processes, because the required input data for calibration of the model were easily available. IARI campus is located between the latitudes of 28°38′23″N and 28°39′N and longitude of 77°09′27″E and 77°10′24″E at an average elevation of 230 m above mean sea level (m amsl). Out of 473 ha area, around 290 ha is for agricultural land use. The mean annual temperature is 24°C. May and June are the hottest months and the normal temperature during these months is above 40°C. The normal maximum and minimum temperatures of 30 years (1978–2008) were 31°C and 17°C respectively. January is the coldest month, when the minimum temperature dips to 0°C. The mean annual rainfall is 711 mm of which 75% is received during monsoon season (June–September).

A major portion of the farm is under sandy loam soil. In certain pockets, clay and sandy clay texture class are also found. There are some places where hard *kanker* calcium layer is found below 150 cm. Moisture content at field capacity varies from 20% to 25%. The campus has mixed land use consisting of experimental farms, residential complexes, office buildings, fallow lands, roads, and play grounds (Table 1). In general the surface elevation of the farm ranges from 217 m to 230 m above mean sea level and the surface is moderately rolling to tabletop. The subsurface deposit includes dominantly stratified clay minerals called glacial till, but has some stratified beds of silt, sand and gravel. Analysis of well logs showed the presence of sandy clay, pebbles with clay, boulders and pebbles and boulders with clay up to a depth of 18 m and sticky clay up to a depth of 18–24 m. Fine sand with clay, fine sand, boulder with pebbles, pebbles with clay, stone and pebbles with fine sand were encountered up to a depth of 27 m. To estimate the recharge flux and total recharge, IARI campus was divided into five sub-areas on the basis of major road networks, as they are the major sub-boundaries for surface flow (Figure 1). Simulation of vadose zone processes was done for each sub-area. The important properties of the sub-areas such as soil type, infiltration rates, hydraulic parameters of the soils and aquifers, and land use were either determined through field experiments or collected through various sources.

The major source of water supply at IARI farm is rainfall and groundwater. Groundwater has been playing an important role in meeting the irrigation and domestic requirements. However, a declining water table has posed a big challenge in ensuring continuous water supply for irrigation. Groundwater recharge could be a solution to reduce the rate of water table decline in the campus.

Modelling of recharge flux and groundwater recharge

Variably saturated flow model, HYDRUS-1D was used to estimate water flux on a daily basis at the bottom boundary of the unsaturated zone (vadose zone) which coincided with the upper most boundaries (water table) of the saturated zone. Water flux estimated by HYDRUS-1D was taken as the recharge rate at water table. The daily bottom flux obtained from HYDRUS-1D simulations (recharge rate) was converted into daily net bottom flux by subtracting the daily pumping. The net bottom flux was given as recharge rates at water table during simulation with MODLFOW for estimation of groundwater recharge. A conceptual representation of modelling of recharge flux and groundwater recharge with HYDRUS-1D and MODFLOW is shown in Figure 2.

HYDRUS-1D is a finite element model which solves Richards's equation for saturated-unsaturated water flow using numerical techniques to analyse water and solute movement in unsaturated, partially saturated, or fully saturated porous media. One-dimensional uniform water movement in a partially saturated rigid porous medium is described by a modified form of Richard's equation (eq. (1)) using the assumptions that the air phase plays an insignificant role in the liquid flow process and that water flow due to thermal gradients can be neglected.

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z} - 1\right)\right] - S, \tag{1}$$

where h is the water pressure head [L], θ the volumetric water content [$L^3 L^{-3}$], t the time [T], z the vertical coordinate [L] (positive upward), S the sink term [$L^3 L^{-3} T^{-1}$] and K is the unsaturated hydraulic conductivity function [LT^{-1}] given by

$$K(h,z) = K_s(z)K_r(h,z), \tag{2}$$

where K_r is the relative hydraulic conductivity (dimensionless) and K_s is the saturated hydraulic conductivity [LT^{-1}].

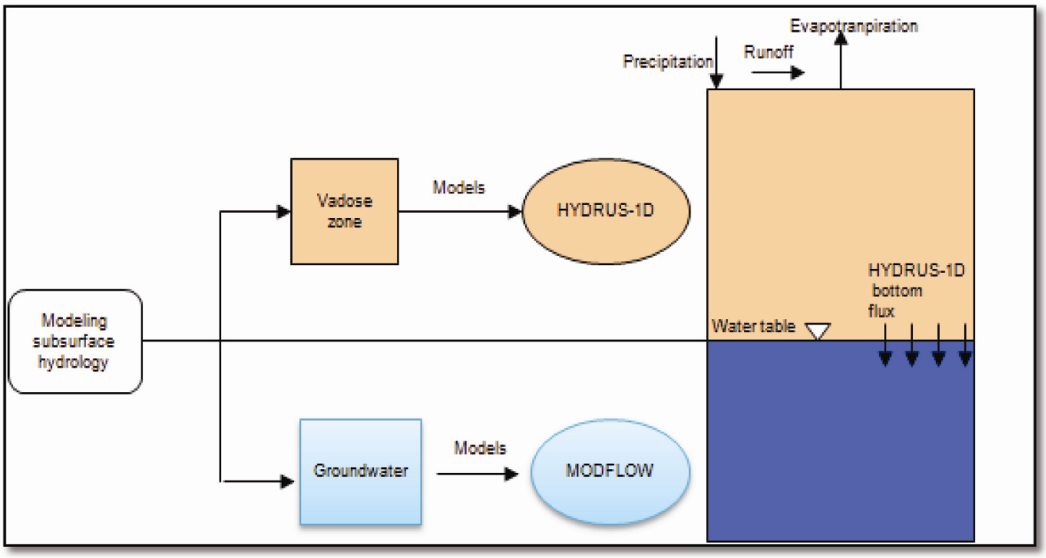

Figure 2. Conceptual representation of modelling of recharge flux and groundwater recharge with HYDRUS-1D and MODFLOW.

HYDRUS uses the soil-hydraulic functions[28] with the statistical pore-size distribution mode[29] to obtain a predictive equation for the unsaturated hydraulic conductivity function in terms of soil water retention parameters. The expressions are given by

$$\theta(h)=\begin{cases}\theta_r+\dfrac{\theta_s-\theta_r}{[l+|\alpha h|^n]^m} & h<0\\ \theta_s & h\geq 0,\end{cases} \tag{3}$$

$$K(h)=K_s S_e^l[1-(1-S_e^{l/m})^m]^2, \tag{4}$$

where

$$m=1-\frac{1}{n},\ n>1, \tag{5}$$

and

$$S_e=\frac{\theta-\theta_r}{\theta_s-\theta_r}, \tag{6}$$

where α is the inverse of air-entry value (or bubbling pressure), n the pore-size distribution index, and l the pore-connectivity parameter, S_e the effective saturation, θ_r and θ_s are residual and saturated water contents. The parameters α, n and l in HYDRUS are empirical coefficients affecting the shape of the hydraulic functions. The details of modelling procedures with HYDRUS-1D are described in the manual[30].

Processing MODFLOW for Windows (PMWIN) was used to estimate the rise in water table during the pre- and post-monsoon period for assessing groundwater recharge from rainfall in different sub areas. PMWIN is a simulation system for modelling groundwater flow and transport processes with the modular three-dimensional finite-difference groundwater model MODFLOW of the USGS[31]. PMWIN is a total integrated simulation system for modelling groundwater flow and transport processes. MODFLOW uses mass conservation equation and Darcy's law to describe the groundwater flow behaviour. MODFLOW can efficiently simulate the response of various hydrological system stresses such as groundwater pumping, recharge and extreme exchanges. The governing flow equations in MODFLOW is given by

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W=Ss\frac{\partial h}{\partial t}, \tag{7}$$

where K_{xx}, K_{yy} and K_{zz} are hydraulic conductivities along x, y and z direction (L/T), h the total head (L), W the volumetric flux of per unit volume of sources and sinks (T^{-1}), Ss the specific storage (L^{-1}) and t is time (T).

The detailed descriptions governing flow equations and solution techniques have been given in the MODFLOW manual[31].

Calibration of hydrus-1D and Modflow

Recharge flux obtained from HYDRUS-1D simulations was used to predict the rise in groundwater level due to recharge from rainfall during pre- and post-monsoon period. Predicted water table rise was compared with the observed water table. Mean absolute error (MAE), mean

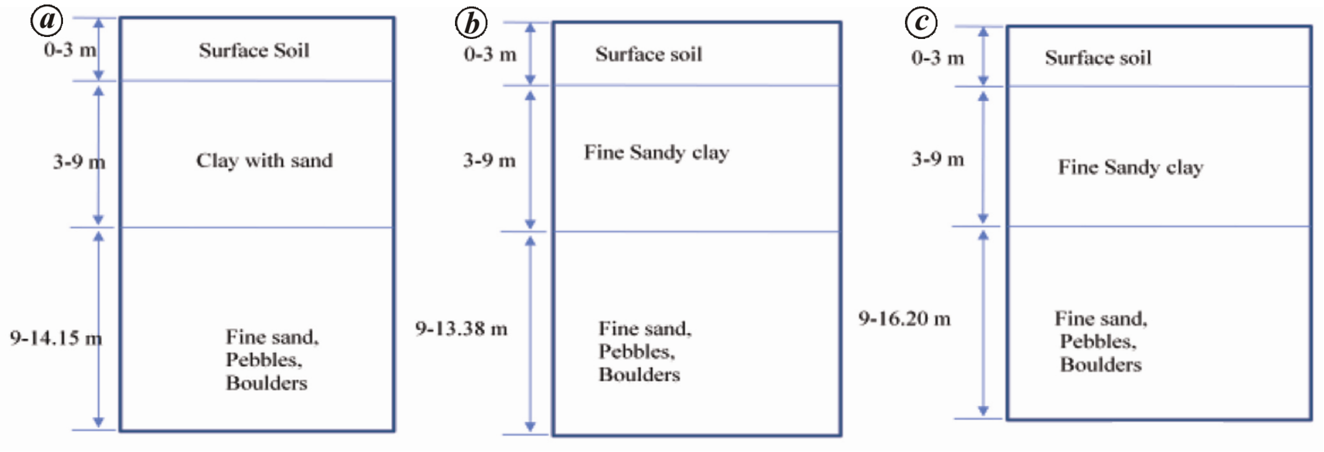

Figure 3. Soil layers in vadose zone. Composition of soil profile: ***a***, Sub-areas SA1 and SA5; ***b***, sub-areas SA2 and SA3; ***c***, sub-area SA4.

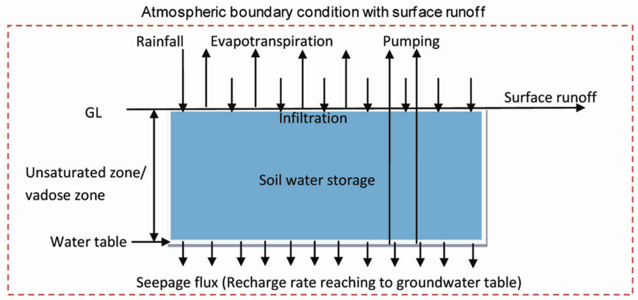

Figure 4. Vadose zone processes and boundary conditions for modelling recharge flux with HYDRUS-1D.

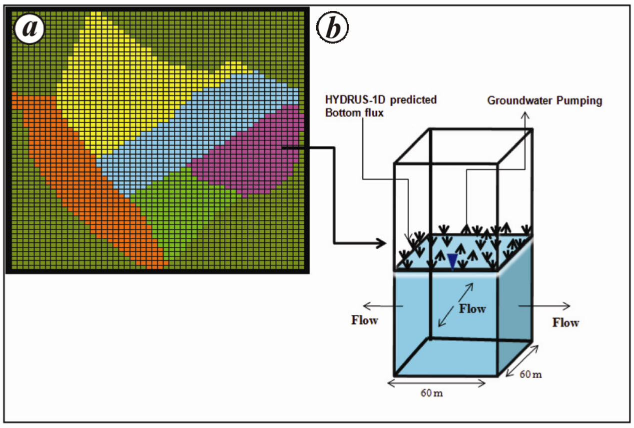

Figure 5. ***a***, Descritization of simulated area. ***b***, Conceptual representation of flow processes in a cell.

absolute percentage error (MAPE) and root mean square error (RMSE) were estimated to describe the closeness of predicted values with the observed values.

System geometry

Pre-monsoon water table in different sub-areas varied from 13.38 m to 16.20 m. Therefore, the thickness of the unsaturated zone/vadose zone varied from 13.38 m to 16.20 m in various sub-areas. Composition of vadose zone in various sub-areas is shown in Figure 3. The various vadose zone processes and boundary conditions included in the modelling are shown in Figure 4.

The study area was descritized into 58 rows and 52 columns with square grids of 60 m × 60 m (Figure 5 *a* and *b*). The conceptual diagram of a single cell for employing governing equations of MODFLOW for simulating water table behaviour is shown in Figure 5 *b*. The simulation period coincided with active period of the monsoon in the National Capital Territory of Delhi. Total simulation period was 121 days starting from 1 June 2008 to 30 September 2008. This was divided into 121 stress periods with a time step of one day. A solution was obtained at each time step. Boundary conditions were changed at the beginning of stress periods. The main input at the beginning of each stress period was the net recharge rate. Other inputs such as hydraulic conductivity, transmissivity and specific yield were given in each cell. Initial and final time steps selected for simulation were 0.1 and 0.001 days and the maximum time steps were 5 days.

Initial and boundary conditions

Initial water content in various soil layers of vadose zone was given as the initial condition. This varied from 0.034 to 0.3 from surface to water table. The conceptual representation of boundary conditions is presented in Figure 4. The upper boundary condition in HYDRUS-1D represented the atmospheric boundary with surface runoff. The bottom boundary was taken as seepage face. Time variable boundary conditions included daily rainfall and reference evapotranspiration, which were given at the top of the boundary. In case of simulation with MODFLOW, initial water table (pre-monsoon groundwater level) was considered as a top boundary and bottom of the aquifer was

Table 2. Input for HYDRUS-1D

Sub area	θ_r (cm^3/cm^3)	θ_s (cm^3/cm^3)	α (cm^{-1})	n	K_s (cm/day)	l
SA1	0.020	0.368	0.0132	1.30	7.64	0.5
	0.012	0.418	0.0003	1.33	9.00	0.5
	0.100	0.391	0.0363	3.20	290.00	0.5
SA2	0.010	0.360	0.0291	1.37	5.04	0.5
	0.012	0.418	0.0003	1.33	9.00	0.5
	0.090	0.390	0.0363	3.20	290.00	0.5
SA3	0.010	0.360	0.0330	1.34	5.04	0.5
	0.012	0.418	0.0003	1.33	9.00	0.5
	0.090	0.390	0.0363	3.20	290.00	0.5
SA4	0.011	0.338	0.0333	1.34	12.60	0.5
	0.012	0.418	0.0003	1.33	9.00	0.5
	0.080	0.390	0.0363	3.20	290.00	0.5
SA5	0.020	0.368	0.0135	1.30	7.70	0.5
	0.012	0.418	0.0003	1.33	9.00	0.5
	0.100	0.391	0.0363	3.20	290.00	0.5

Table 3. Inputs for MODFLOW

Parameter	SA1	SA2	SA3	SA4	SA5
Top elevation (surface elevation; m)	218.90	224.02	231.13	228.34	221.32
Bed rock (bottom elevation; m)	142.17	152.47	162.84	156.06	148.98
Average elevation of initial water level or head (m)	205.70	211.20	215.00	211.80	210.10
Aquifer hydraulic conductivity (m/day)	2.24	2.13	2.30	1.19	2.17
Transmissivity (m^2/day)	172.08	149.20	156.60	158.43	157.25
Specific yield	0.16	0.16	0.16	0.16	0.16
Thickness of aquifer (m)	76.72	71.55	68.29	72.27	73.33

considered as a bottom boundary. The top boundary was considered as a time-dependent flow boundary. The net daily recharge rates were given as input at water table along with other parameters. Side boundaries of the sub areas were considered as flow boundaries. All the elevations were above mean sea level.

Input parameters

The various input parameters required in HYDRUS-1D such as residual moisture content (θ_r), saturated moisture content (θ_s), inverse of the air-entry value (α) (or bubbling pressure), pore-size distribution index (n), pore-connectivity parameter (l) and saturated hydraulic conductivity were taken from published literature[32–35] (Table 2). The parameters α, n and l are empirical coefficients that determine the shape of the hydraulic functions. The pore connectivity parameter l in the hydraulic conductivity function was taken as 0.5 as suggested[29] for several soils. The time-dependent boundary conditions used for simulation of recharge were daily rainfall and reference evapotranspiration. These values were given in the model on a daily basis for the entire simulation period. The simulations were done to estimate the recharge rate at water table from each sub-area. Input parameters for MODFLOW are given in Table 3. The total groundwater pumping for various uses in IARI was 1,633,255 m^3/year. This was uniformly distributed over the entire farm area, and the average daily pumping rate was estimated. Groundwater pumping rate in monsoon months was taken as half of the average daily pumping rate as considerable part of the water requirement was met through rainfall. This was termed as prevailing pumping rate and was estimated to be 0.000946 m/day. It was also assumed that pumping was not done on those days when surface runoff was produced. Net daily recharge flux was estimated by subtracting the daily pumping rate from daily recharge flux obtained from HYDRUS-1D.

Results and discussion

Calibration results of HYDRUS-1D and MODFLOW

Calibration was done by comparing the observed water table and water table predicted by MODFLOW. The result is shown in Figure 6. The MAE, the MAPE and the RMSE between the observed and predicted values were 0.05, 0.023 and 0.22 respectively. This showed close agreement between observed and predicted water tables.

Table 4. Bottom fluxes in different sub areas

	Bottom flux for simulation period (cm)		Cumulative surface runoff (cm)		Cumulative reference evapotranspiration (cm)	
Sub area	Cumulative	Monsoon rainfall (%)	Cumulative	Monsoon rainfall (%)	Cumulative	Monsoon rainfall (%)
SA1	20.01	29.26	7.72	11.0	42.03	61.0
SA2	21.77	31.83	3.39	5.0	37.19	54.0
SA3	21.74	31.79	14.36	21.0	45.00	66.0
SA4	23.43	34.26	7.00	10.0	41.64	61.0
SA5	20.01	29.26	7.72	11.0	42.03	61.0

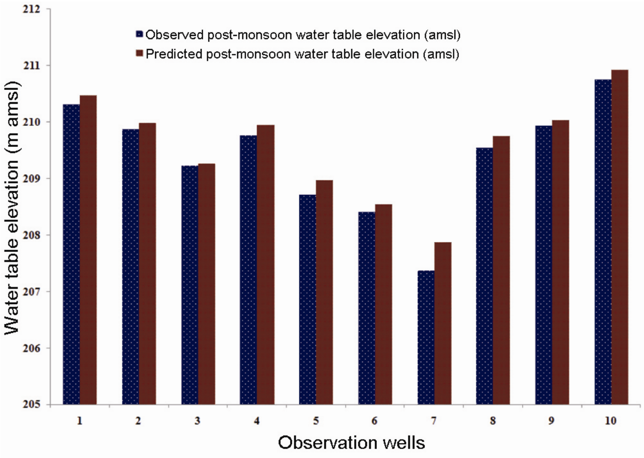

Figure 6. Comparison of observed and predicted post monsoon water tables.

Simulation of vadose zone processes

Predicted daily recharge flux and soil moisture storages for various sub-areas are shown in Figures 7 and 8 respectively. The variation of recharge flux with respect to time showed that it was not constant during the simulation period. This may be due to the fact that the infiltrated water took some time to reach the water table as the thickness of vadose zone was between 13.38 m and 16.20 m. Trend of recharge flux with respect to time may also be linked to the rainy day, continuous rainy day, dry day and amount of rainfall on a particular day, as these control various vadose zone processes such as evapotranspiration, percolation and change in soil moisture storage. Summary of cumulative fluxes is presented in Table 4. Among all the sub-areas, SA4 has the highest cumulative bottom flux of 23.43 cm followed by SA2 (21.77 cm) and SA3 (21.74 cm). The least cumulative bottom flux was observed for SA1 and SA5 sub-area (20.01 cm). The average bottom flux in the IARI campus for the year monsoon 2008 was 21.39 cm. Cumulative recharge flux as a percentage of total monsoon rainfall of 684 mm is given in Table 4. Cumulative surface runoff was highest for the SA3 (14.36 cm, 21% of the monsoon rainfall). Highest runoff from SA3 may be due the fact that this sub-area is partly under urban land use. Average surface runoff from the campus was 12% of the total monsoon rainfall for 2008. Reference evapotranspiration from IARI campus was 41.58 cm (about 61% of the monsoon rainfall). The results suggest that evapotranspiration is a major component in semi-arid regions.

Simulation of groundwater recharge in terms of water table rise

Pre-monsoon water table elevations in 2008 varied from 206.26 m to 211.66 m above mean sea level (13.38 m to 16.20 m below ground level). Average of pre-monsoon groundwater level in the IARI farm during 2008 was 14.63 m below ground surface. Post-monsoon water table elevations varied from 207.26 m to 212.06 m above mean sea level. The average post monsoon water level was 13.60 m below ground level. There was an average rise of 1.03 m during the monsoon season as a result of rainfall recharge.

Analysis of scenario

After calibration, models were used to predict the rise in water table under various scenarios which included natural recharge and artificial recharge with prevailing, increased and zero pumping. Summary of the predicted groundwater recharge for various scenarios is presented in Table 5.

Scenario-1: Natural recharge under prevailing pumping rate and pumping schedule: Predicted water table elevations under this scenario in 2008 varied from 207.26 m to 212.06 m. Average predicted water table rise between pre- and post-monsoon period was 0.99 m, which was nearly the same as the observed water table rise of 1.03 m during the same period. Groundwater recharge under this scenario was 23.2% of the monsoon rainfall.

Scenario-2: Artificial recharge-I under prevailing pumping rate and pumping schedule: Under this scenario, it was assumed that all the surface runoff predicted by HYDRUS-1D is used for recharge. Average runoff predicted by HYDRUS-1D was 8.04 cm. Predicted water

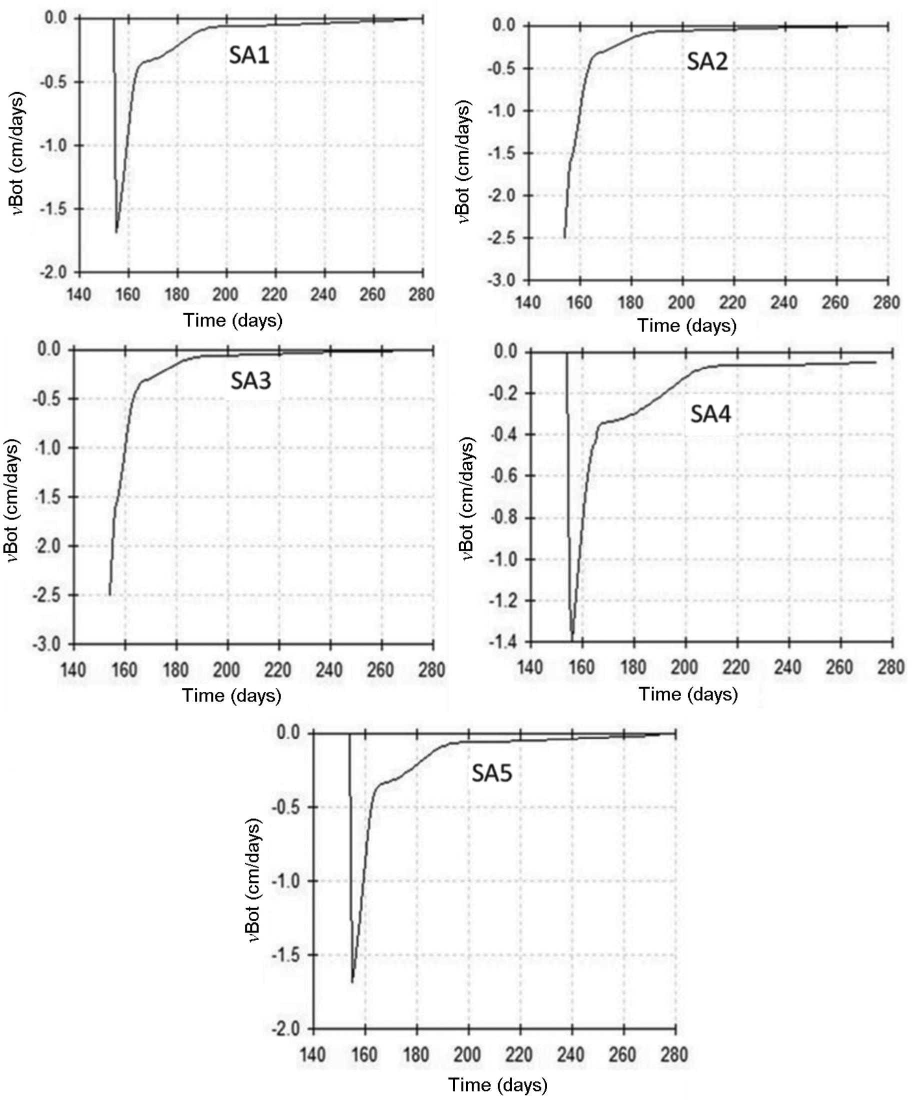

Figure 7. Predicted recharge flux for various sub areas.

Table 5. Groundwater recharge under various scenarios

Scenario	Particulars of the scenarios	Average rise in water table (m)	Monsoon rainfall (%)
1	Natural recharge under prevailing pumping rate and pumping schedule	0.99	23.20
2	Artificial recharge-I under prevailing pumping rate and pumping schedule	1.46	34.20
3	Natural recharge with no pumping	1.31	30.60
4	Natural recharge under 10% increase in daily pumping rate with prevailing pumping schedule	0.96	22.50

table elevation under this scenario varied from 207.89 m to 218.84 m. Rise in water level at the end of simulation (post monsoon) varied from 1.0 m to 1.80 m. Average water table rise was 1.46 m (34.2% of the monsoon rainfall) which was more than scenario-I. Additional rise of 0.43 m was mainly due to the fact that all the surface runoff was used as additional input in the model. In reality this may not be possible.

Scenario-3: Natural recharge with no pumping: This scenario was similar to scenario-1 except that in this case groundwater pumping was taken as zero. Predicted water table elevations varied from 207.56 m to 212.39 m. Rise in water table varied from 0.90 m to 1.70 m bgl. The average rise between pre- and post-monsoon period was 1.31 m which is about 30.6% of monsoon rainfall. This indicated that if there was no pumping, there would have

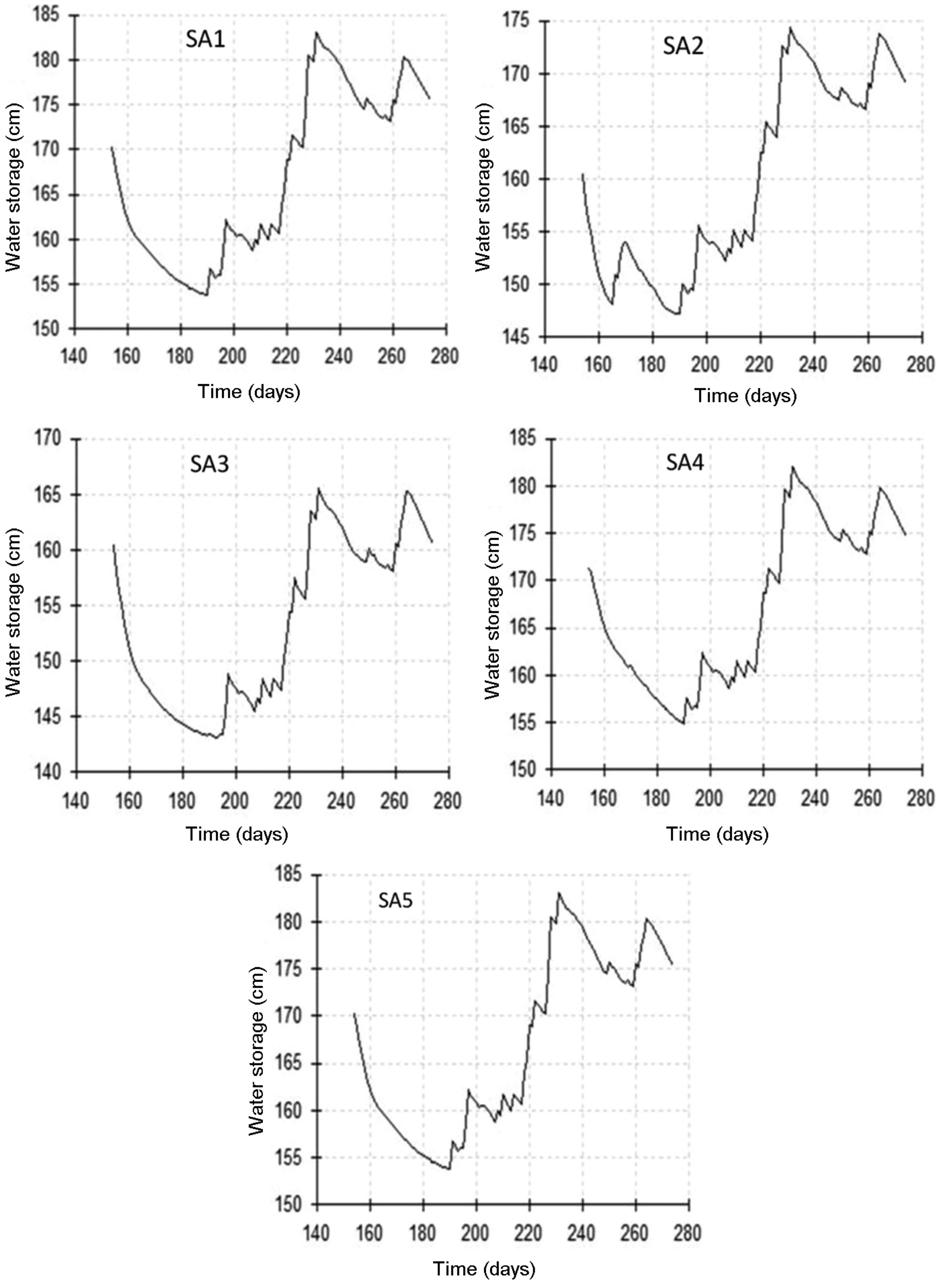

Figure 8. Predicted soil water storage for various sub areas.

been an additional rise of 0.32 m when compared to scenario-1.

Scenario-4: Natural recharge under 10% increase in daily pumping rate with prevailing pumping schedule: In this scenario, daily pumping rate was increased by 10% anticipating increase in water demand and subsequent increase in groundwater pumping rate. Predicted water table elevations varied from 207.23 m to 212.03 m. Predicted rise in post-monsoon water table varied from 0.50 m to 1.32 m whereas the average water table rise between pre- and post-monsoon was 0.96 m which is 22.5% of the monsoon rainfall. This indicates that 10% increase in daily pumping rate reduced the water table by 0.03 m when compared to scenario-1.

In the present study the estimated groundwater recharge under various scenarios varied from 22.50% to 34.20% of monsoon rainfall. The results are comparable to other studies conducted in semi-arid region. Groundwater recharge estimated using tracers in Western Rajasthan and Gujarat region was found to be 3–10% of annual rainfall whereas in Uttar Pradesh, Punjab and Haryana, it was in the range 12–20% of annual rainfall[36]. The lower recharge predicted may be due to the fact that the major part of Rajasthan and Gujarat receives rainfall lower than Delhi[36]. Natural recharge in semi-arid regions of North, South, South-East, West and Central India was 4–20% of the local average seasonal precipitation[37]. Another study reported a groundwater recharge of 14.5% of annual rainfall under the semi-arid region of Dulapally watershed near Hyderabad[38]. Recharge estimated for Vedavati river basin region of Karnataka and Andhra Pradesh varied from 13% to 20% of annual rainfall[39]. Recharge in semi-arid region of Rajasthan was 10–16% of the precipitation[40]. Estimated average groundwater recharge in Bethamangala sub-watersheds situated in Bangarpet taluk of Kolar district in India was 17% of average annual rainfall[24]. Contribution of storms to groundwater recharge in the semi-arid region of Bagepalli taluk, Karnataka was 19.5% to 27.5% (ref. 41) from 600 mm rainfall.

Conclusion

Vadose zone processes were simulated using HYDRUS-1D to demonstrate their importance in groundwater recharge. Based on simulation results it was concluded that variable saturated zone flow model HYDRUS-1D along with groundwater model MODFLOW can be used to simulate vadose zone flow processes, recharge flux and groundwater recharge in semi-arid regions. Results suggested that the evapotranspiration is a major recharge control parameter in semi-arid regions. About 61% of the rainfall goes as evapotranspiration (ET). A considerable portion of soil moisture stored in vadose zone is lost as ET. Average cumulative recharge flux was 31.28% of the monsoon rainfall. Under prevailing pumping conditions, net groundwater recharge was 23.20% of the monsoon rainfall. Excessive groundwater pumping is the major reason for water table decline. In the absence of groundwater pumping, the average groundwater recharge would have been 30.60% of the monsoon rainfall which is close to an average cumulative flux of 31.28%.

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