IMPACT OF CLIMATE CHANGE ON GROUNDWATER RECHARGE IN A SEMI-ARID REGION OF NORTHERN INDIA

KAMBALE, J. B.[1*] – SINGH, D. K.[2] – SARANGI, A.[2]

[1]*Department of Agricultural Engineering, College of Agriculture, Bheemarayangudi, University of Agricultural Sciences, Raichur, India-585287*
(phone: +91-82-77-380340)

[2]*Water Technology Centre, Indian Agricultural Research Institute, New Delhi, India-110012*

**Corresponding author:*
e-mail: jbkambale@gmail.com

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Abstract. A study was undertaken to assess the impact of climate change on groundwater recharge under various climate change scenarios including the scenarios which influence the vadose zone processes and groundwater recharge for an agriculturally dominant semi-arid region. Climate change scenarios based on the predictions by Inter-Governmental Panel for Climate Change (IPCC), Indian Network for Climate Change Assessment (INCCA) and Auto Regressive Integrated Moving Average (ARIMA) model were used in this study. Ground water recharge under different scenarios was simulated using HYDRUS-1D and MODFLOW models. Results indicated that the average groundwater recharge during 2030s may increase by 0.03m compared to 2005 if simulations were based on ARIMA predicted average annual temperature, relative humidity, wind speed, and sunshine hours. It was observed that the cumulative groundwater recharge in the study area would increase if all the climatic parameters are considered for climate change impact assessment. This is in contrary to common perception that the groundwater recharge would decrease in semi-arid region as a result of climate change. Average groundwater recharge would decrease by 0.09 to 0.21 under IPCC and 0.11 m under INCCA projected temperature during 2100s and 2030s, respectively.
Keywords: *evapotranspiration, CROPWAT-8.0, Vadoze zone, HYDRUS-1D, MODFLOW*

Introduction

Groundwater is one of the major sources of irrigation in India and has played a significant role in increasing agricultural production and food security in the country. The contribution of groundwater in ultimate irrigation potential of India is about 48.19 % (CGWB, 2009). Importance of groundwater can be realized by the facts that about 61 % of the net irrigated area of the country is irrigated by ground water (CWC, 2010). However, large scale development and utilization of ground water in various parts of India has caused depletion of ground water resources. In several areas of Delhi, Punjab, Haryana, Rajasthan and Uttar Pradesh, the annual ground water pumping is more than the annual ground water recharge.With expected change in climate, it is anticipated that availability of ground water resources will further be affected in several regions.

Recharge from the rainfall is the major source of groundwater. Groundwater recharge primarily depends on rainfall and its intensity, evapotranspiration, infiltration, soil moisture storage in the vadose zone, hydraulic property of the aquifer and the depth of the water table. Vadose zone processes *viz.* the evapotranspiration, infiltration rate and soil moisture storage and depletion determine the availability of water for groundwater recharge. Evapotranspiration and soil moisture depletion depend on

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principal climatic parameters *viz.* temperature, relative humidity, wind speed and duration of sun shine hours. In the event of climate change, some of the climatic parameters are expected to increase, whereas a few are expected to decrease. Due to the compensating effect of different parameters, evapotranspiration and soil moisture depletion pattern may not be described solely by the rise in temperature, which is considered as the main parameter for describing the climate change. Therefore, for assessing the impact of climate change on groundwater recharge, it is essential to consider all important climatic parameters for estimating the evapotranspiration and soil moisture depletion pattern. A plethora of studies relating to ground water recharge under changing climate scenarios are available with consideration of only rise in temperature. However, limited studies have been reported to assess the impact of climate change on groundwater recharge by taking into consideration of vadose zone processes. It is reported that the strategic importance of ground water for global water and food security will probably intensify under climate change due to occurrence of more frequent and intense climate extremes (droughts and floods) besides, pronounced variability in precipitation, soil moisture and surface water (Taylor et al., 2012). It is also reported that there will be major change in rainfall pattern due to climate change. High intensity and short duration rainfall events will become more common in future (IPCC, 2007). Taylor et al. (2013) analysed 55-year record of groundwater level observations in an aquifer of central Tanzania and observed occurrence of episodic recharge resulting from high intense seasonal rainfall. They also observed that such episodic recharge would interrupt multiannual recessions in groundwater levels and would maintain the water security of the groundwater dependent communities in this region. Olago et al. (2009) studied the impact of climate change on ground water in the lake basins of Central Kenya Rift. They observed that the IPCC projected rainfall increase of 10–15% might not necessarily result in a proportional increase in groundwater recharge. Loáiciga et al. (2000) assessed the likely impacts of aquifer pumping on the water resources of the Edwards Balcones Fault Zone (EBFZ) aquifer, Texas in the United States and reported that the ground water resources appeared to be threatened under $2{\times}CO_2$ climate scenarios under predicted growth and water demand. They also reported that without proper consideration to variations in aquifer recharge and sound pumping strategies, the water resources of the EBFZ aquifer could be severely impacted under a warmer climate. Nyenja and Batelaan (2009) investigated the effects of climate change on groundwater recharge and base flow in the upper Ssezibwa catchment of Uganda and reported intensification in the hydrological cycle resulting in increase in groundwater recharge from 20 to 100% from the prevailing recharge of 245mm/year. Water resources would come under increasing pressure in Indian subcontinent due to the changing climate (Mall et al., 2007). Mizyed (2009) reported that the increase of temperature alone could reduce the natural recharge of groundwater aquifers by 7 to 21 % in the West Bank of Jordan Rift Valley. Ranjan et al. (2006) observed the reduction in fresh groundwater resources in Central America, the Mediterranean region, South Asia, and South Africa under both high and low emission scenarios. The trend in increasing temperatures may reduce the net recharge in the Southern Manitoba, Canada (Chen et al., 2004). Gokhale and Sohoni (2015) developed a quantitative groundwater assessment protocol to use the data available at different scales with government agencies in Maharashtra State to predict the groundwater level fluctuations under varying rainfall depths. It was reported that there existed an uncertainty in the prediction of groundwater table depth both within and across years

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and rainfall alone was a poor predictor of groundwater depths. It was suggested to consider the land use and irrigation requirement besides the hydro-climatic parameters while predicting the groundwater table fluctuations at regional scales.

As the ground water recharge depends upon its dynamics and pathways within the vadose zone, so variably saturated model such as HYDRUS-1D can be used to simulate the moisture movement in the vadose zone and recharge flux joining the water table. Ficklin et al. (2010) used HYDRUS-1D model to simulate the impact of climate change on vadose zone hydrologic processes and groundwater recharge for three different crops *viz.* Alfalfa, almonds and tomatoes in the San Joaquin watershed in California. They reported that the increase in the daily temperature by 1.1 and 6.4 ^{0}C would decrease the cumulative groundwater recharge due to reduced evapotranspiration and irrigation water use by crops. Leterme and Mallants (2011) evaluated the impact of climate and land use change on groundwater recharge in the Dessels region of North-Eastern Belgium. They used HYDRUS-1D for simulation of groundwater recharge under various climate change and land use scenarios and reported that the transition to a warmer climate may decrease the groundwater recharge. Groundwater flow model combined with the vadose zone model would provide a more realistic assessment of groundwater recharge. The recharge flux at the bottom of vadose zone obtained from HYDRUS-1D can be used to estimate the groundwater recharge using MODFLOW. Twarakavi et al. (2008) evaluated the performance of HYDRUS package developed for MODFLOW in the Las Cruces trench infiltration experiment. They reported that HYDRUS could simulate the vadose zone processes realistically. Anilkumar (2011) investigated the groundwater recharge processes in a semi-arid region using HYDRUS-1D and MODFLOW. The recharge flux upto the water table depth was simulated using HYDRUS-1D under various scenarios and subsequently the MODFLOW was used to simulate the groundwater recharge. MODFLOW was used by several researchers to simulate groundwater behavior and estimate the groundwater recharge (Ravi et al., 2001; Senthilkumar and Elango, 2001; Leslie et al., 2002; Boronina et al., 2003; Mali, 2004; Mane et al., 2007; Biswas et al., 2008; Anilkumar, 2011, Shahid, 2011 and Tesfagiorgis et al., 2011). In these studies, MODFLOW was used to estimate the groundwater recharge without considering the vadose zone processes. Use of HYDRUS-1D and MODFLOW not only facilitate the accounting of vadose zone processes, but also take into account the effect of climatic parameters in simulation of ground water recharge.

This study was undertaken to assess the impact of climate change on groundwater recharge considering all the climatic parameters which influence groundwater recharge for an agriculturally dominant semi-arid region under National Capital Territory (NCT) of Delhi, India. The main objective of the study was to evaluate the impact of vadose zone processes on groundwater recharge which depends on all climatic parameters and not only on the temperature. Crop evapotranspiration estimated from ARIMA forecasted climatic parameters were used in the variably saturated flow model to simulate the recharge flux at the water table. Recharge flux at water table was given as input to groundwater model MODFLOW for prediction of groundwater recharge. Groundwater recharge was also estimated from the IPCC and INCCA predicted rise in temperature data to highlight the importance of other climatic parameters in assessing the impact of climate change on groundwater recharge.

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Materials and Methods

Study area

The study was undertaken for an agriculturally dominant Najafgarh Block under South West District of National Capital Territory (NCT), Delhi, India. The area is enclosed between latitude 28° 30’ 10” N to 28° 39’ 30” N and longitude 76°51’ 45”E to 77° 6’ 15”E (*Fig.1*) and falls in semi-arid regions of Northern India. The study area is a part of National Capital Region (NCR) which comprises mainly of Haryana, Utter Pradesh, Rajasthan and entire NCT of Delhi. These surrounding States of the study region are the major food grain producers of the Country. Major crops grown in NCR are rice, wheat, barley, sorghum, pearl millet and maize. Groundwater is being used to irrigate about 90% of the cultivated area.

Major part of the study area falls in the Trans-Gangetic plain region of India under Agro Climatic Region (ACR) - VI. Average altitude is 214.5 m above mean sea level (amsl). The total geographical area is about 200.64 km^2. Out of this, 112.67 km^2 area was under cultivation (*Fig.1*).

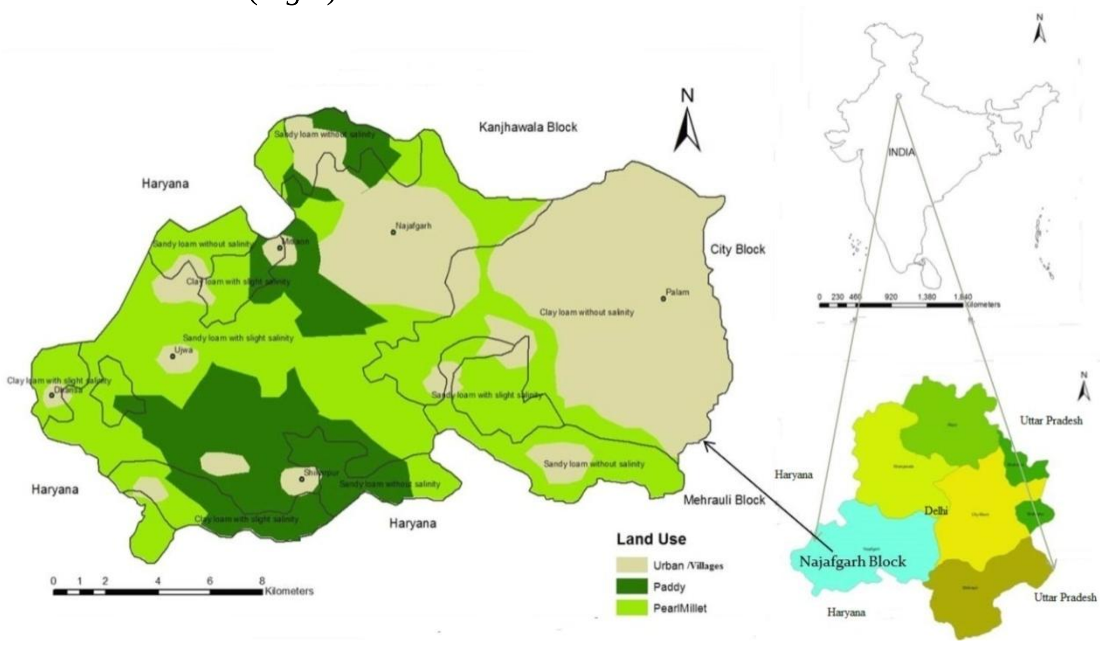

Figure 1. *Location and land use map of the study area*

The climate of the area is characterized by subtropical and semi-arid climate. Summers are very hot and dry with very cold winter season. The mean annual temperature is 24 ºC. May and June are the hottest months and the maximum temperature goes up to 47 ºC. The normal daily maximum and minimum temperatures of 30 years are 31ºC and 17 ºC, respectively. The minimum temperature dips to even 0 ºC and the mean annual rainfall observed in the study area is 730 mm. The major share of rainfall is received during monsoon season. The soil texture of the study region is of sandy loam and clay loam type with some patches having slight salinity (*Fig. 2*)

Climatic parameters of two weather stations *viz.* Palam and ICAR-Indian Agricultural Research Institute (IARI) located in South West District of NCT were collected from concerned agencies. The soil maps and related information were collected from Regional Station of National Bureau of Soil Survey and Land Use

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Planning (NBSS&LUP), New Delhi, India. Data pertaining to groundwater resources were acquired from Central Ground Water Board (CGWB), New Delhi. Data on land use and cropping pattern were collected from Department of Agriculture, NCT of Delhi, India.

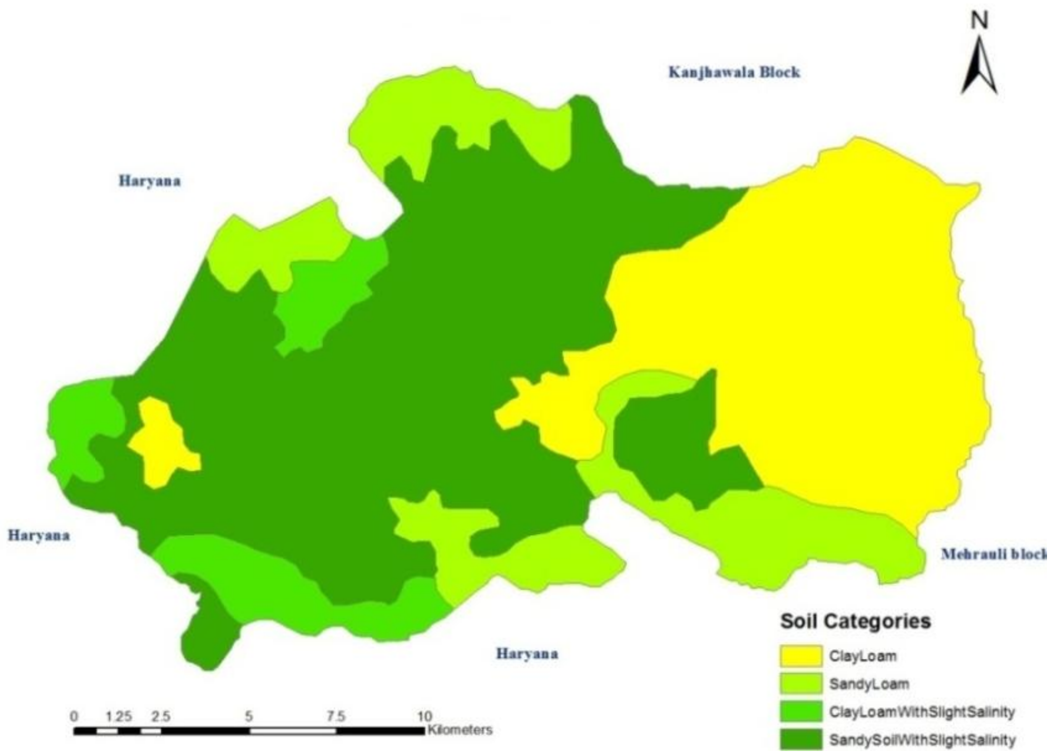

Figure 2. *Soil texture map of the study area*

Modelling of groundwater recharge

Variably saturated flow model, HYDRUS-1D was used to simulate the daily water flux at the bottom boundary of vadose zone (unsaturated zone) which coincided with the groundwater table (*i.e.* Upper most boundaries of the saturated zone). Water flux obtained as output from HYDRUS-1D was taken as the recharge rate at the water table surface. The net bottom flux was obtained by subtracting the pumping rate. The net bottom flux was given as recharge rates at the water table during simulation with MODLFOW for estimation of groundwater recharge. A conceptual representation of modelling of recharge flux and groundwater recharge using both HYDRUS-1D and MODFLOW models is shown in *Figs. 3* and *4*.

Description of models used for ground water recharge
HYDRUS-1D model

The vadose zone model HYDRUS-1D *ver.* 4.08 (Šimůnek et al., 2009) was used to simulate the vertical water movement, root water uptake, soil moisture storage, surface runoff and evaporation from the soil surface in one-dimensional variably-saturated media. The basic assumption of the model was that the air phase does not affect liquid flow processes and the water flow due to thermal gradients became negligible.

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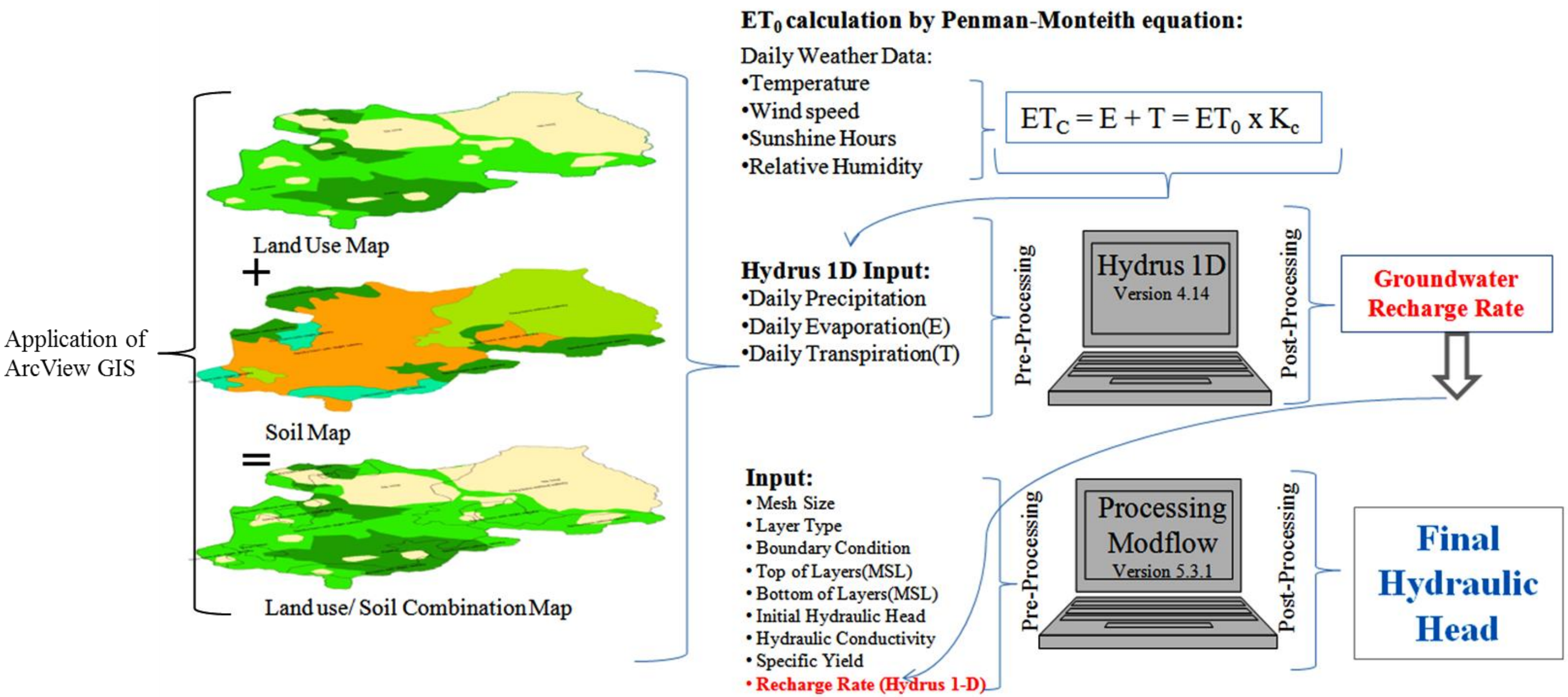

Figure 3. *Conceptual frameworks for simulation of groundwater recharge using HYDRUS-1D and MODFLOW models*

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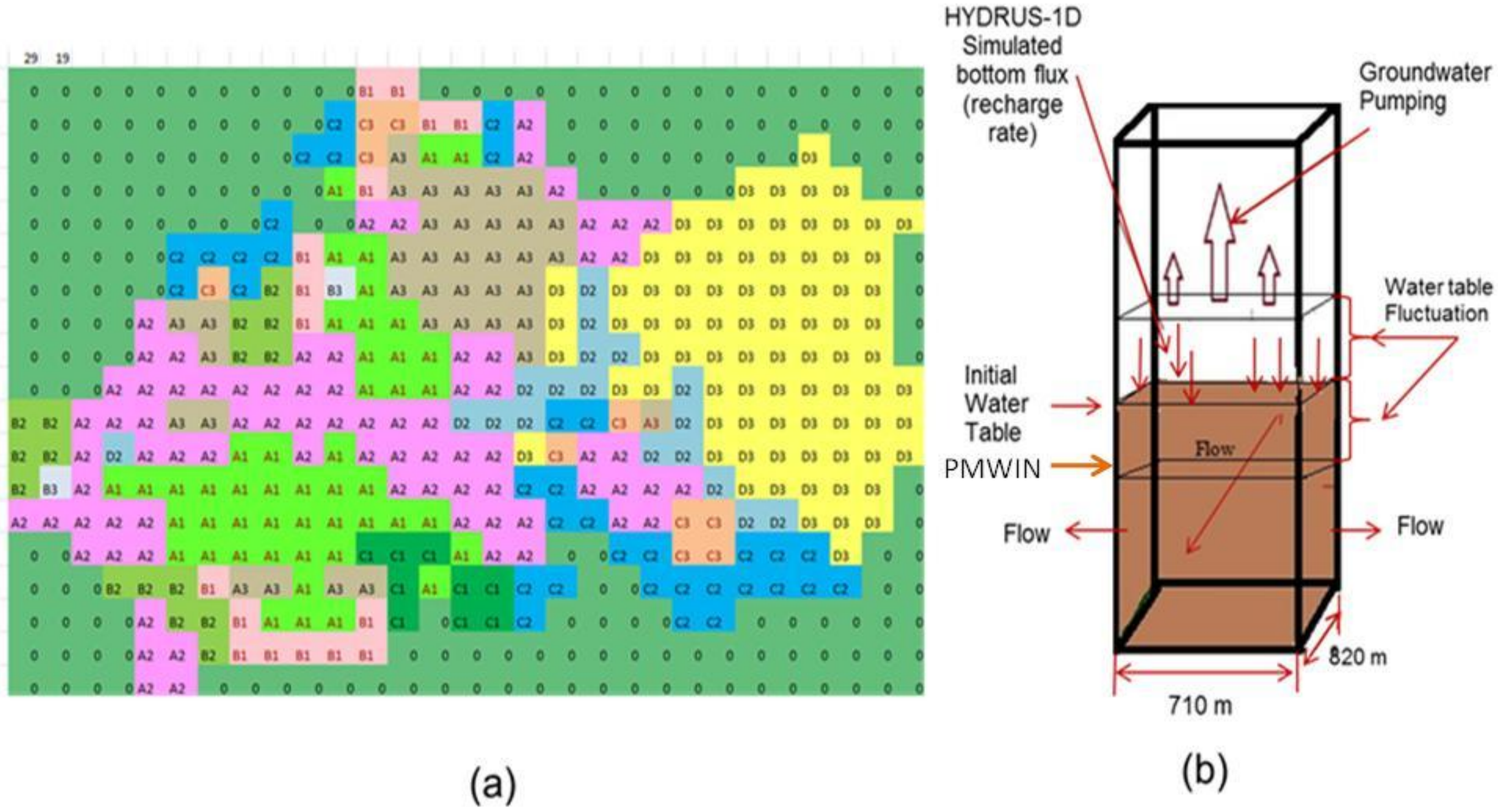

Figure 4. *Conceptual framework for simulation with MODFLOW and gridded map with cell values of the study region*

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HYDRUS-1D is a finite element model which simulates these processes in vadoze zone by solving the Richards equation (Richards, 1931). The governing equation for water flow in porous medium and root water uptake used in HYDRUS-1D is:

$$\frac{\partial \theta(h)}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z} - 1\right)\right] - S(h) \qquad \text{(Eq.1)}$$

Where h is the water pressure head (L), θ is the volumetric water content ($L^3 L^{-3}$), t is the time (T), z is the spatial coordinate (L), K is the unsaturated hydraulic conductivity function (LT^{-1}), and S is the sink term in the flow equation ($L^3 L^{-3} T^{-1}$) which is the volume of water removed from a unit volume of soil per unit time due to plant water uptake.

Saturated and unsaturated hydraulic conductivity are related by

$$K(h,z) = K_s(z)K_r(h,z) \qquad \text{(Eq.2)}$$

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

Soil-hydraulic functions of van Genuchten (1980) with the statistical pore-size distribution model of Mualem (1976) are used in HYDRUS-1D to obtain a predictive equation for the unsaturated hydraulic conductivity in terms of soil water retention parameters (equations 3, 4, 5, 6)

$$\theta(h) = \begin{cases} \theta_r + \frac{\theta_s - \theta_r}{[1 + |\alpha h|^n]^m} & h < \\ \theta_s & h \geq \end{cases} \qquad \text{(Eq.3)}$$

$$K(h) = K_s S_e^l \left[1 - \left(1 - S_e^{l/m}\right)^m\right]^2 \qquad \text{(Eq.4)}$$

Where

$$m = 1 - \frac{1}{n}, n : \qquad \text{(Eq.5)}$$

and

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \qquad \text{(Eq.6)}$$

Where α is inverse of the air-entry value (or bubbling pressure), n is pore-size distribution index, and *l* is pore-connectivity parameter, *n* is a pore-size distribution index, Se is effective saturation, θr and θs 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 modeling procedures with HYDRUS-1D are described in HYDRUS manual (Simunek et al., 2008).

Processing MODFLOW for Windows (PMWIN)

Processing MODFLOW for Windows (PMWIN) was used to estimate the groundwater recharge in terms of rise of the water table in different land parcel units.

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PMWIN *ver.* 5.3.1 (Processing MODFLOW for Windows) is widely used for modelling groundwater flow and transport processes with the modular three-dimensional finite-difference groundwater model MODFLOW (McDonald and Harbaugh, 1988). Effects of well, river, drains, head dependent boundaries, recharge and evapotranspiration on groundwater behaviour under steady and unsteady flow conditions can be simulated efficiently using PMWIN. The principle of conservation of mass and Darcy's law are the basic concepts used in the model to describe the groundwater flow behaviour. The three-dimensional partial differential equation used to describe the groundwater flow in the unconfined aquifer under specified initial and boundary conditions is given by:

$$\frac{\partial}{\partial x}\left(Kxh\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(Kyh\frac{\partial h}{\partial y}\right)=-Sy\frac{\partial h}{\partial t}-R \qquad \text{(Eq.7)}$$

Where Kx, Ky = Directional components of hydraulic conductivity (L T^{-1})
h = Total head (L)
Sy= Specific yield
R= General sink/source term
t = Time (T)

The detailed description of governing flow equations and solution techniques has been given in MODFLOW manual (McDonald and Harbauch, 1988).

Simulation of recharge flux using HYDRUS-1D

The major source of groundwater recharge in the study area was due to the monsoon rainfall and return flow from irrigation. Normal non-monsoon rainfall amounting 179.5 mm was distributed in 8 months from November to June. Therefore, the possibility of recharge from rainfall in non-monsoon months was assumed to be negligible. This assumption doesn't deviate from reality as the area falls in the semi-arid region. The major factors which control the groundwater recharge in the study area are infiltration, hydraulic conductivity, soil moisture storage, evapotranspiration, surface runoff and depth of the water table below ground surface. The HYDRUS-1D model was used to simulate the recharge flux in the vadose zone and the MODFLOW was used to simulate the ground water recharge in terms of rise in the water table. The conceptual framework for simulation under varying climatic conditions is shown in *Fig. 3*.

The study area was divided into 11 land parcel units (LPUs) based on land use, soil type and salinity levels using ArcGIS 9.3.1. The delineated areas of LPUs are presented in *Table 1*. HYDRUS-1D was used to simulate the recharge flux from each LPU. Soil profile of 3 m depth in each LPU was considered for the simulation of recharge flux. The flux estimated at the bottom of 3 m soil profile was considered as maximum possible recharge under given field and climatic situations. Simulations were carried out on a daily basis for one crop growing season starting from 1st July of the year 2005, which was the date of onset of monsoon in the study region. The total simulation period was 122 days. This was considered to match the duration of crops grown in the study area. The simulation period also coincided with the normal duration of monsoon in this region.

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Table 1. *Area under different land parcel units (LPUs)*

Soil types	Land use/ crops	LPUs	Area (ha)
Sandy loam with low salinity (A)	Paddy	A1	2736
	Pearl millet	A2	4446
	Urban	A3	2109
Clay loam with low salinity (B)	Paddy	B1	912
	Pearl millet	B2	912
	Urban	B3	114
Sandy loam (C)	Paddy	C1	513
	Pearl millet	C2	1995
	Urban	C3	571
Clay loam (D)	Pearl millet	D2	1026
	Urban	D3	4731

Input parameters

Evaporation and transpiration

The HYDRUS-1D model requires evaporation and transpiration as separate input parameters in each time step for simulating the influence of soil water on root water uptake. Reference evapotranspiration (ET_o) and crop evapotranspiration (ET_c) were estimated from CROPWAT 8.0 (FAO, 2009) using climatic, crop, and soil parameters besides the crop coefficients for local conditions. Reference evapotranspiration is the potential evapotranspiration from reference crop under adequate moisture conditions, whereas the crop evapotranspiration is the potential evapotranspiration from the crops considered in the study *viz.* Rice and pearl millet. Reference evapotranspiration was converted to crop evapotranspiration by multiplying it with the crop coefficients of respective crops. As required by HYDRUS-1D, crop evapotranspiration was bifurcated into evaporation from soil (E) and transpiration from plants (Tp) using equation given by Belmans et al. (1983):

$$E = ET_c \times e^{-K_{gr} \times} \quad \text{(Eq.8)}$$

Where

K_{gr}: Extension coefficient for global solar radiation {0.3 for rice (Phogat et al., 2010) and 0.56 for pearl millet (Oosterom et al., 2001)}.

LAI: Leaf Area Index {for rice: 0.24, 1.25, 3.86, 0.45 (Tyagi et al., 2000) and for pearl millet: 0.5, 2.5, 2.8, 1.0 (Oosterom et al., 2001). Leaf area index depends on the area of leaf at different growth stages. Rice and pearl millet have different growth pattern and the area of leaves are different at different growth stages.

Soil hydraulic parameters

Different hydraulic parameter used in HYDRUS-1D are saturated water content (θ_s; L^3L^{-3}), residual water content (θ_r: L^3L^{-3}), saturated hydraulic conductivity (Ks; LT^{-1}), the inverse of the air entry value (α), pore size distribution index (n) and pore connectivity parameter (l). These hydraulic parameters were estimated based on sand,

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silt and clay content and bulk density of soils of the study region using pedo transfer function model *Rosetta Lite V 1.1* available as a module in HYDRUS-1D.Values of these parameters for the study area are presented in *Table 2*. Hydraulic conductivity of LPUs under residential land uses (*i.e.* Urban/villages/building) was reduced to 10 % to account for the lower infiltration rate and higher surface runoff. The pore connectivity parameter l was taken as 0.5 as suggested by Mualem (1976) for major soils.

Table 2. *Soil hydraulic parameters of different soil textures in the study area*

Sub area	Soil Type	θ_r(cm^{3}cm^{-3})	θ_s(cm^{3}cm^{-3})	α (cm^{-1})	n	K_s (cm day^{-1})
A	Sandy Loam with low salinity	0.0551	0.3836	0.0301	1.4549	33.642
B	Clay Loam with low salinity	0.0753	0.4113	0.0193	1.3079	8.487
C	Sandy Loam	0.0551	0.3836	0.0301	1.4549	37.38
D	Clay Loam	0.0753	0.4113	0.0193	1.3079	9.43

Root water uptake

Estimation of root water uptake was undertaken by HYDRUS-1D in which the method proposed by Feddes et al. (1974) was used. Root penetration depth for rice and pearl millet was taken as 45 cm and 90 cm, respectively. The function proposed by Feddes et al. (1978) and Homaee et al. (2002) were used to parameterize the inherent water stress reduction coefficient. The values of Feddes parameters were adopted from Phogat et al. (2010) and Wesseling (1991) and presented in *Table 3*.

Table 3. *Feddes parameters for root water uptake used in HYDRUS-1D*

Feddes Parameter	Crops	
	Pearl Millet	Rice
PO	-15	55
POpt	-30	100
P2H	-325	-160
P2L	-600	-250
P3	-8000	-15000
r2H	0.5	0.5
r2L	0.1	0.1

Initial and boundary conditions

Initial and boundary conditions were assigned for the partitioned soil profile depth of 3 m for each LPU. There were 11 such simulated flow domains having one in each LPU. Initial conditions were defined in terms of moisture content in the soil profile on the starting day of simulation. In the study area, rice is transplanted and grown under puddled method of rice cultivation. Therefore, initial moisture content in the soil profile for rice was taken equal to saturated moisture content. In case of pearl millet, initial

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moisture content varied uniformly from 10 % in the top layer to 30 % in the bottom layer. Upper boundary was defined as an atmospheric boundary condition with surface runoff. Bottom boundary was set to free drainage boundary as water table in each case was under the simulated domain (Ŝimunek, 2009). The bottom boundary flux was considered as the recharge rate. Rainfall, evaporation and transpiration were specified on the surface of upper boundary on a daily basis for the entire simulation period. In case of rice, daily percolation rate of 4 mm day^{-1} was specified to account for the return flow from irrigation (Khepar et al., 1999; Dash et al., 2015). For pearl millet, the irrigation amount of 0.09 m was accounted by specifying this at the surface as per the irrigation schedule.

Simulation of groundwater recharge using PMWIN

Groundwater recharge in each land parcel unit was estimated using MODFLOW. A conceptual framework for simulation of groundwater recharge with Processing Modflow for Windows (PMWIN) is shown in *Fig. 4 (a, b)*. The study area was discretized into 19 rows and 29 columns with square grids of 710 m x 820 m size (*Fig 4a*). The conceptual diagram indicating governing equations to simulate the water table behavior in a cell is shown in *Fig. 4b*. The net recharge flux obtained as the output of HYDRUS-1D simulations for each land parcel unit were given as an input recharge rate at the water table for simulation with MODFLOW.

Initial and boundary conditions

Initial hydraulic heads (*i.e.* pre-monsoon water table above mean sea level, AMSL) in the study area were used as initial conditions. The observed water table below ground surface in the pre-monsoon season and corresponding surface elevation values were used as input to generate water table contours with respect to mean sea level. Further, the water table contours were used to select the elevations of initial hydraulic heads in different cells. The pre-monsoon water table in different land parcel units (initial hydraulic head) was considered as the top boundary of the saturated zone, which coincided with the bottom boundary of the vadose zone, whereas the aquifer bottom was considered as the bottom boundary. The top boundary was set to time dependent flow boundary condition to account for the variable net recharge flux obtained from HYDRUS-1D. Elevations of the top and bottom boundaries, and initial water table depths are shown in *Figs. 5a, b,* and *c*, respectively.

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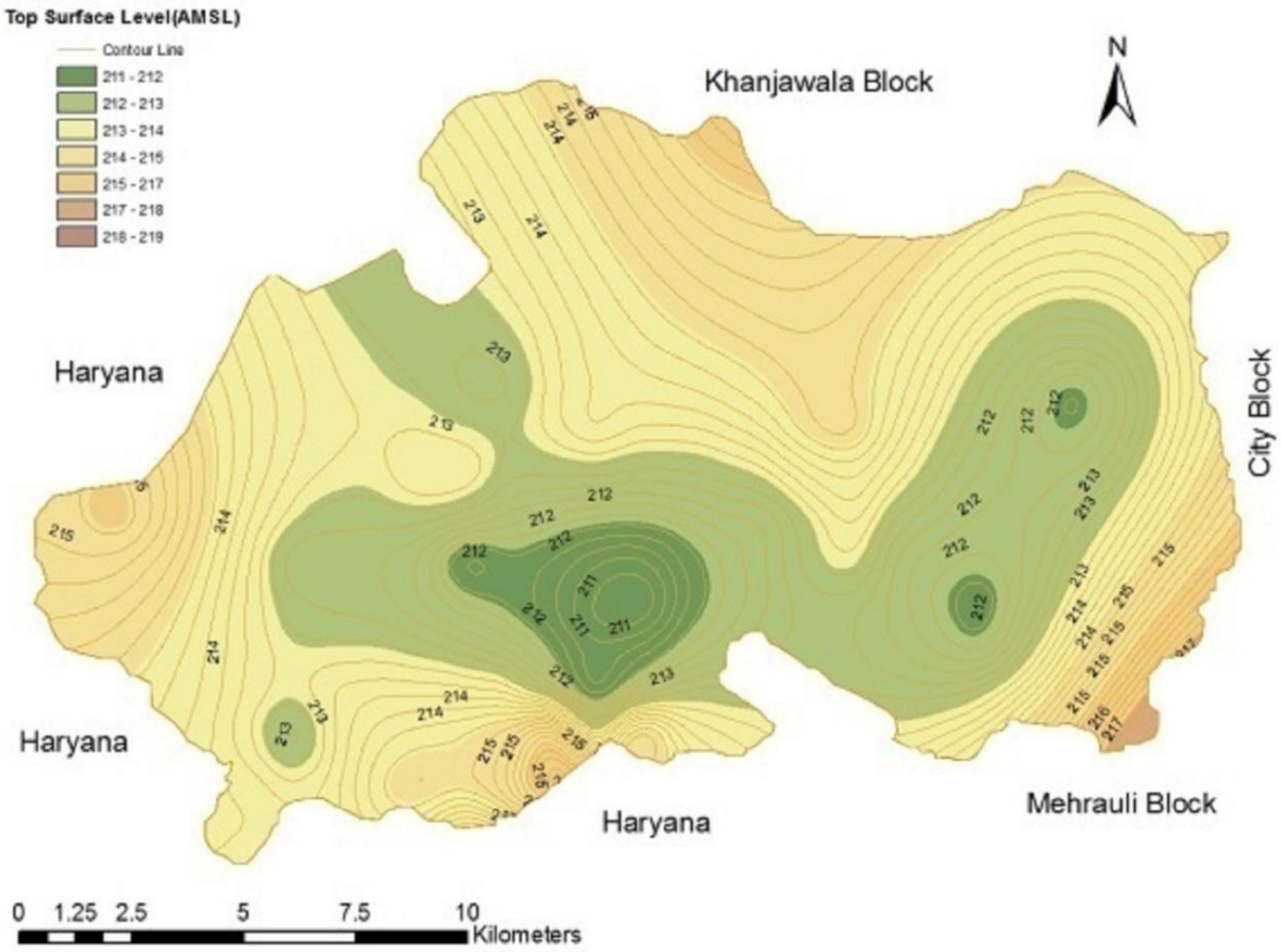

Figure 5a. *Surface elevations of all land parcel units (LPUs) above mean sea level (amsl)*

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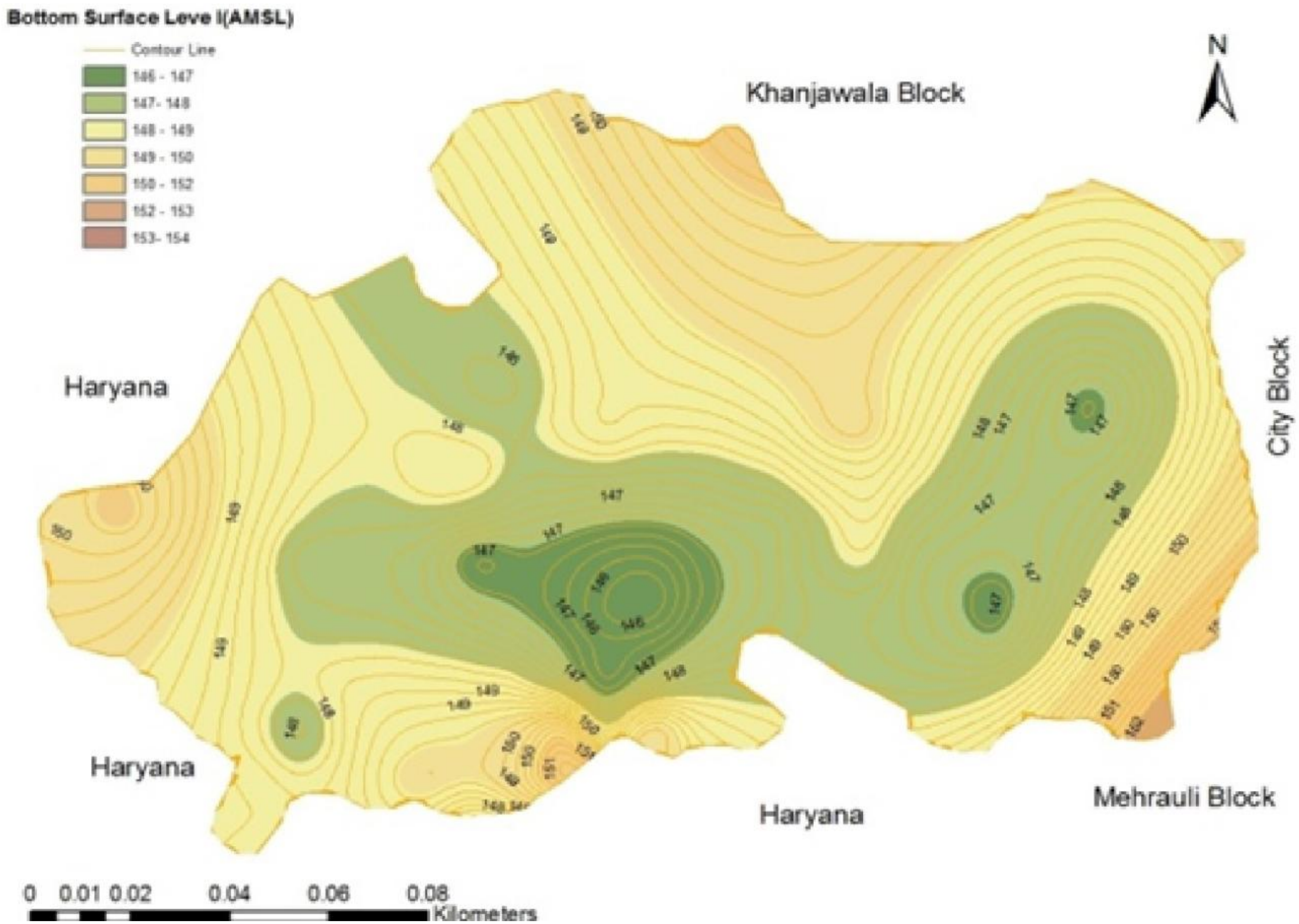

Figure 5b. *Bottom elevation of all LPUs above mean sea level (amsl)*

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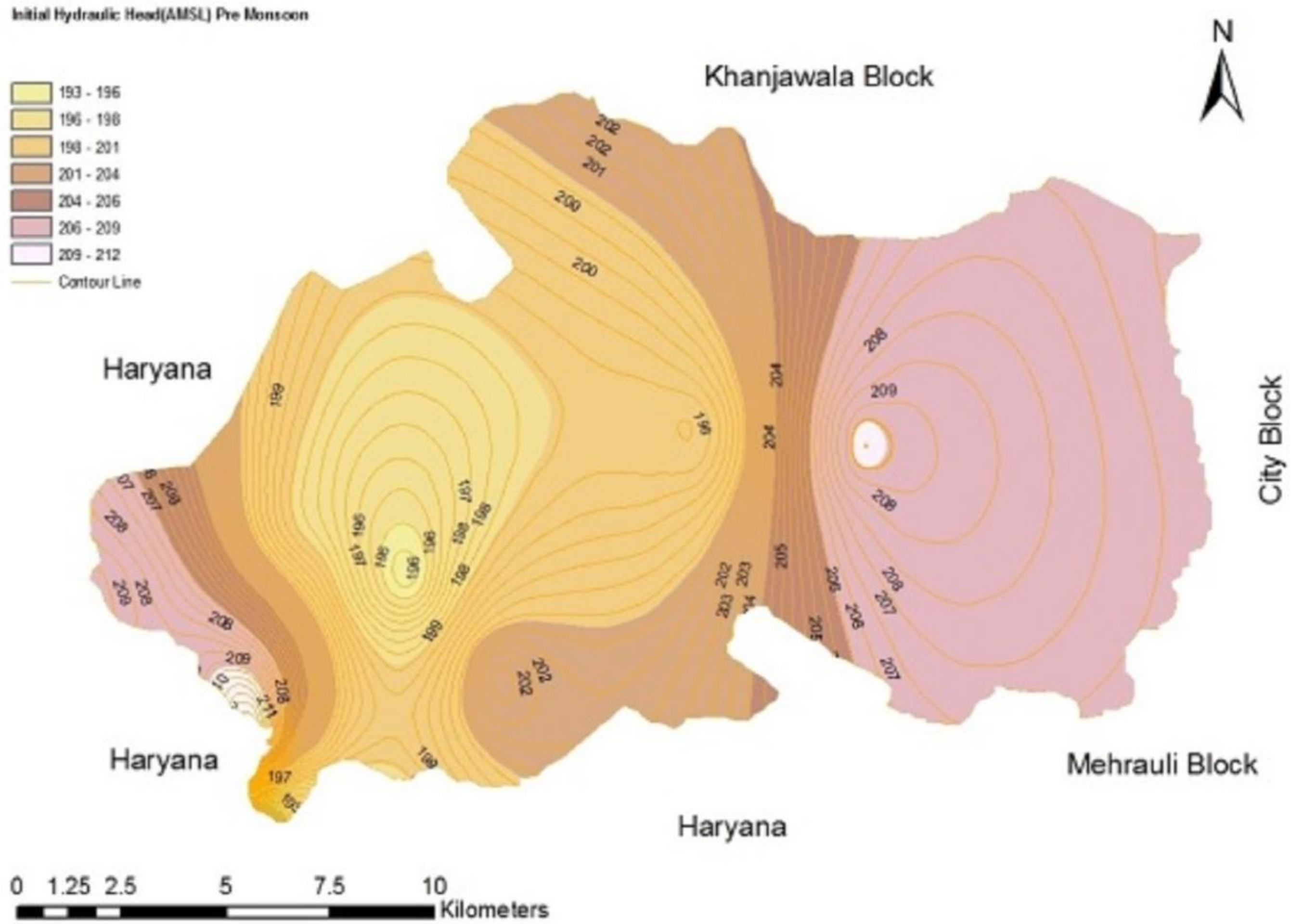

Figure 5c. *Initial hydraulic heads for all LPUs above mean sea level (amsl)*

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Calibration and validation of models

The calibration of MODFLOW was undertaken by comparing the observed and predicted water table rise during pre and post monsoon seasons. Nash-Sutcliffe Efficiency (NSE), Coefficient of determination (R^2) and Root Mean Square Error (RMSE) prediction error statistics were used to describe the model performance. Simulation was done for the monsoon period of the year 2005. The total simulation period was 122 days (*i.e.* From 1st July 2005 to 31st October, 2005). Four stress periods with time step of one day were considered for the simulation of water table fluctuations. The time dependent boundary condition was imposed at the beginning of each stress period. The input at the beginning of each stress period was the net recharge flux and the hydraulic conductivity and specific yield were kept constant during the simulation period. A similar procedure was adopted for estimation of net recharge flux for other climate change scenarios.

The groundwater pumping in the study area was from the unconfined aquifer. The depth of the aquifer was 65 m below ground level in the unconsolidated alluvium zone. The specific yield was taken as 0.16 (CGWB, 2009). Total groundwater pumping in the year was uniformly distributed over the entire study area. The total groundwater pumping per unit area for various uses was 0.4946 m y^{-1}. The daily pumping rate was estimated from the total pumping value which was termed as prevailing pumping rate. This was estimated to be 0.001355 m day^{-1}. The net daily recharge flux was estimated by subtracting the pumping rate from daily recharge flux obtained from the HYDRUS-1D simulated output.

Climate change scenarios considered for simulations

Calibrated and validated models were used to predict the groundwater recharge in terms of water table fluctuations under various climate change and groundwater pumping scenarios. Climate change scenarios considered for estimation of groundwater recharge were adopted from predictions by the Intergovernmental Panel for Climate Change (IPCC), Indian Network for Climate Change Assessment (INCCA), and Auto Regressive Integrated Moving Average (ARIMA) model. ARIMA model is one of the most popular models for analysis of time series data. It contains autoregressive (AR), integrated (I) and moving average (MA) estimation components which are expressed as ARIMA (p, d, q). Where, p is autoregressive component, d is integrated component and q is moving average component. ARIMA model was used for forecasting the variation in climatic parameters using the data for 35 years (1975 to 2010). The time series data were used to forecast the variation during the same period and co-relate it with the observed data. Thereafter, it was used to forecast the climatic parameters up to 2030s. The climatic data obtained from IARI, New Delhi for the period from 1975 to 2010 was used to forecast the changes in climatic parameters *viz.* Average temperature, relative humidity, wind speed and sunshine hours. ARIMA forecast for average temperature, wind speed, annual rainfall, sunshine hours and relative humidity are presented in *Fig. 6 (a-e)*. The performance of ARIMA forecast was determined through the coefficient of determination between observed and predicted values during the period of 1975-2010. Higher coefficient of determination between observed and predicted values indicated that the ARIMA forecast were realistic and can be used for forecasting the future scenarios (*Table 4*). The average changes in climatic parameters in the 2030s, with respect to the 1995 are presented in *Table 4*. The values of the climatic parameters

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forecasted by ARIMA for 2030s are given in *Table 5* as the climate change scenario 1. In case of IPCC predictions, two climate change scenarios (Scenarios 2 and 3) under low and high emission of CO_2 leading to increase average daily temperature of 1.1 ^{0}C and 6.4^{0}C, respectively, by the year 2100 were considered (Ficklin *et al.*, 2010) (*Table 5*). Indian Network for Climate Change Assessment (INCCA) had generated climate change scenarios for major climate sensitive regions of India using regional climate change model Providing Regional Climates for Impacts Studies PRECIS (INCCA, 2010). PRECIS simulations indicated an all-round warming over the Indian subcontinent. It is reported that the annual mean surface air temperature would rise by 1.7 ^{0}C and 2 ^{0}C (Scenarios 3 and 4) in 2030s. In case of scenarios based on IPCC and INCCA predictions, only rise in temperature was considered for assessing the impact of climate change on groundwater recharge whereas in case of ARIMA based forecast, all climatic parameters were considered. The climate change scenarios presented in *Table 5* were used to estimate crop evapotranspiration and was given as input in HYDRUS-1D after separating it into evaporation and transpiration for simulating the recharge flux under various climate change scenarios.

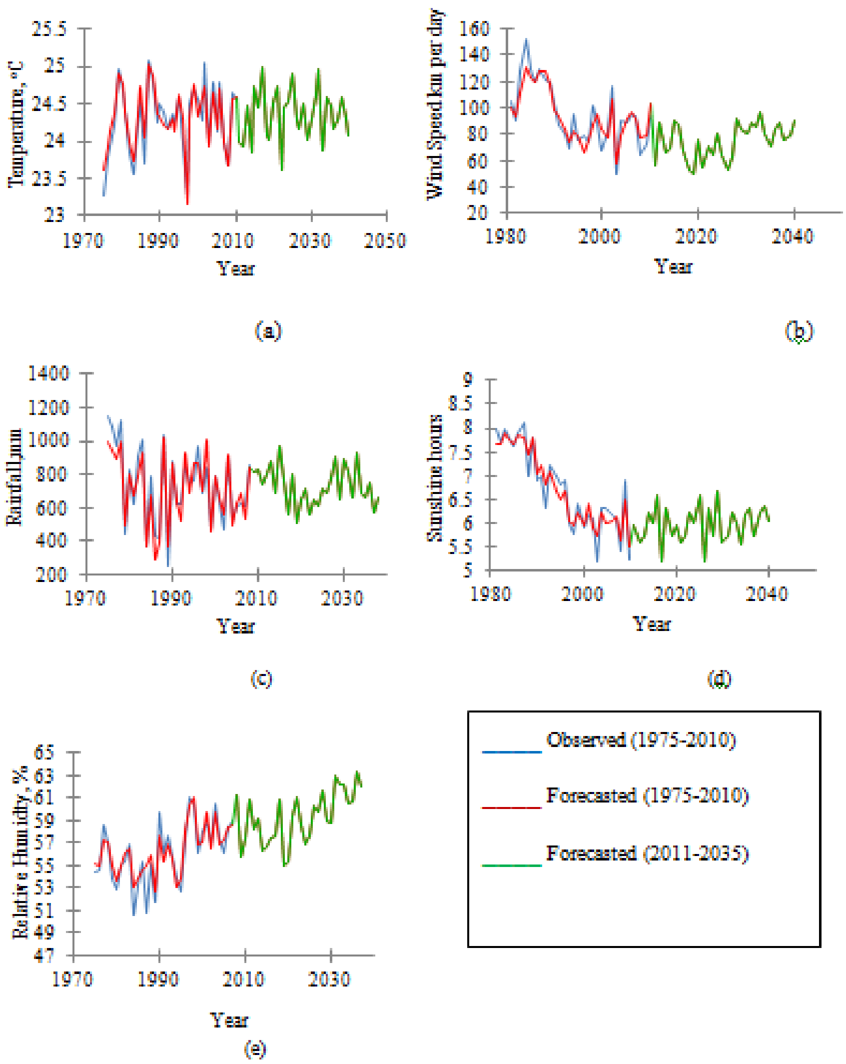

Figure 6. *ARIMA forecasted (a) average annual temperature (b) wind speed (c) total rainfall (d) sunshine hours and (e) relative humidity.*

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Table 4. *Performance indicator of ARIMA model and climate forecast for 2030s*

Meteorological Parameters	Coefficient of determination (R^2) between observed and forecasted values during 1975-2010	Forecasted variation in climatic parameters for 2030s with respect to 1995
Total rainfall (mm)	0.86	+0.50
Sunshine hours (hour)	0.89	-0.26
Relative humidity (%)	0.77	+4.00
Average wind speed (km day^{-1})	0.78	-5.15
Average temperature (^{0}C)	0.84	+0.26

Table 5. *Climate change scenarios considered for model simulations*

Scenarios	Average temperature (^{0}C)	Relative humidity (%)	Wind speed (km day-^{1}	Sunshine hours	Rainfall (mm)	Number of rainy days
Predictions for 2030s with local weather data using ARIMA						
Scenario 1	+0.26	+4	-5.15	-0.26	+0.5	-
IPCC Predictions for 2100s						
Scenario 2	+1.1	-	-	-	-	-
Scenario 3	+6.4	-	-	-	-	-
INCCA Predictions for 2030s						
Scenario 4	+1.7	-	-	-	-	-
Scenario 5	+2.0	-	-	-	-	-

Results and Discussions

Results of calibration are presented in *Fig 7 (a, b).* The *Fig. 7a* shows the comparison between observed and predicted average water table elevations (hydraulic heads) in different land parcel units. The *Fig. 7b* compares the water table elevations in different cells located in the study area. These figures showed that the observed and predicted water tables are in close agreement with each other. Predictability of models was also evaluated in terms of performance indicators such as Nash-Sutcliffe Efficiency (NSE), Coefficient of determination (R^2), Root Mean Square Error (RMSE) and are presented in *Table 6.* It can be observed from *Table. 6* that R^2 and NSE approaching one and RMSE approaching zero corroborated that the observed and model predicted values were in line with each other. Therefore, integrated use of the HYDRUS-1D model for the vadose zone moisture movement and MODFLOW for ground water flow could predict the groundwater recharge with acceptable accuracy in any region.

Cumulative recharge flux

Simulations were undertaken to predict the bottom flux, cumulative bottom flux, cumulative evaporation, cumulative root water uptake, actual root water uptake, soil water storage, cumulative surface runoff and surface runoff under different climate change scenarios from 11 land parcel units (*Table 5*). The simulations were carried out under the prevailing conditions during 2005, which is referred as the reference scenario.

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The moisture migration (boundary fluxes) simulated by HYDRUS-1D for land parcel, unit A1 is presented in *Fig.8 (a to f).* Similar output was also obtained from other land parcel units delineated in the study area. It was observed from *Fig. 8* that the cumulative recharge flux from rice cultivated area (A1) having sandy loam soil and low salinity was 71.6 cm. Besides this, the cumulative root water uptake, cumulative evaporation and cumulative surface runoff for A1 were 24.7 cm, 29.2 cm and 0.1 cm, respectively. Cumulative recharge flux from rice, pearl millet and urban land use under the various scenarios is shown in *Fig. 9, Fig. 10,* and *Fig. 11*, respectively. Comparison of cumulative recharge flux, cumulative root water uptake, cumulative evaporation and cumulative surface runoff from various LPUs for a baseline and other climate change scenarios are presented in *Table 7*. In case of baseline scenario, minimum and maximum cumulative recharge flux of 0.2 cm and 72.5 cm, respectively, were obtained from B3 (clay loam with low salinity) and C1 (sandy loam) LPUs, respectively. The cumulative recharge flux from LPUs *viz.* A1 (sandy loam with low salinity), B1 (clay loam with low salinity) and C1 (sandy loam) under rice crop varied from 42.6 cm to 72.5 cm. The cumulative recharge flux from different land parcel units under pearl millet *viz.* A2 (sandy loam with low salinity), B2 (clay loam with low salinity), C2 (sandy loam) and D2 (clay loam) varied from 1.2 cm to 8.6 cm. The cumulative recharge flux from A3 (sandy loam with low salinity), B3 (clay loam with low salinity), C3 (sandy loam) and D3 (clay loam) LPUs under urban land use varied from 0.2 cm to 1.3 cm. The variances in the cumulative recharge flux from these land parcel units (LPUs) were primarily due to differences in soil type and salinity levels. Simulation results showed that the maximum cumulative recharge flux was from rice fields. The cumulative root water uptake from cultivated land, cumulative evaporation, and cumulative surface runoff from various land units ranged from 18.1 to 24.7 cm, 13.72 to 29.45 cm and 0.01 to 24.15 cm, respectively. The highest and lowest cumulative root water uptakes were 24.7 cm (from A1, B1, and C1) and 18.15 (from D2) (*Table 6*). Average recharge (*i.e.* Average cumulative recharge flux) from rice fields was 38.4 % and from the pearl millet field was 8.3 % of total rainfall depth during the crop growth period. Average recharge from other land units was 1.3 % and total rainfall depth during the period of simulation was 504 mm.

Table 6. *Model performance indicators in prediction of average hydraulic head in different LPUs and gridded cells of the study region*

Observed and predicted head of average hydraulic head	RMSE	NSE	R^2
Land Units	0.653	0.89	0.83
Cells	0.826	0.95	0.94
Acceptable limits*	≥0	0.75 to 1	0.5 to 1

*Moriasi et al. (2007)

Cumulative recharge under various climate change scenarios from rice fields varied from a minimum of 36.6 cm to a maximum of 75.9 cm. The highest and lowest cumulative recharge under various scenarios were 66.6 cm to 75.9 cm and 36.6 cm to 45.6 cm from LPUs C1 (Sandy loam) and B1 (clay loam with low salinity), respectively

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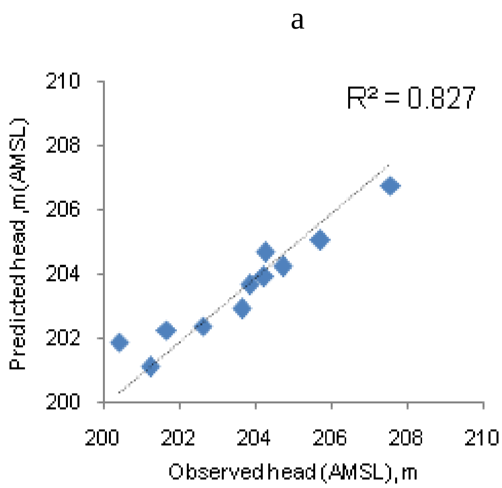
in rice fields. Differences in cumulative recharge can be attributable to different soil types and saline conditions of the study region. Cumulative recharge under various climate change scenarios from pearl millet fields varied from a minimum of 1.2 cm to a maximum of 10.8 cm. Highest and lowest cumulative recharge from the pearl millet field were 7.4 cm to 10.8 cm and 1.2 cm in LPUs B2 (clay loam with low salinity) and C2 (sandy loam) respectively. From the land parcel units under urban and village land uses, the cumulative recharge varied from 0.2 cm to 1.3 cm under various climate change scenarios. The highest and lowest cumulative recharge was observed to be 1.3 cm and 0.2 cm in C3 (sandy loam) and B3 (Clay loam with low salinity) and D3 (Clay loam) LPUs, respectively. The comparison of cumulative recharge flux, cumulative root water uptake and cumulative evaporation from various land units obtained under different climate change scenarios are presented in *Table 7*. Moreover, for rice, the cumulative recharge flux under all climate change scenarios decreased with the rise in temperature in all land parcel units except the scenario 1. Cumulative groundwater recharge from land parcel units under pearl millet except B2 and D2 scenarios increased in all climate change scenarios except scenario 3. There was no change in cumulative recharge flux in land units B2 and D2 under pearl millet. Effect of climate change in cumulative recharge flux was not observed in another six LPUs *viz.* A3, B2, B3, C3, D2 and D3. Results obtained from scenario 1 suggested that the cumulative groundwater recharge increased in all land parcel units compared to baseline scenario and varied from 0.2 cm to 75.9 cm. This indicates that the cumulative groundwater recharge would increase if all the climatic parameters are considered for assessment of the impact of climate change. This is in contrary to common perception that groundwater recharge would decrease in semi - arid regions as a result of climate change. This can be attributable to the decreasing trend of certain climatic parameters such as wind speed and sunshine hours and increasing trend of relative humidity as observed in the study region under semi-arid environment.



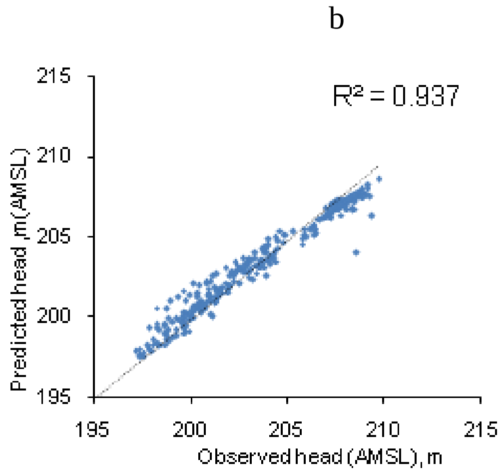


Figure 7. ***(a)*** *Observed and predicted average hydraulic heads in different land parcel units,* ***(b)*** *observed and predicted hydraulic heads in all grided cells*

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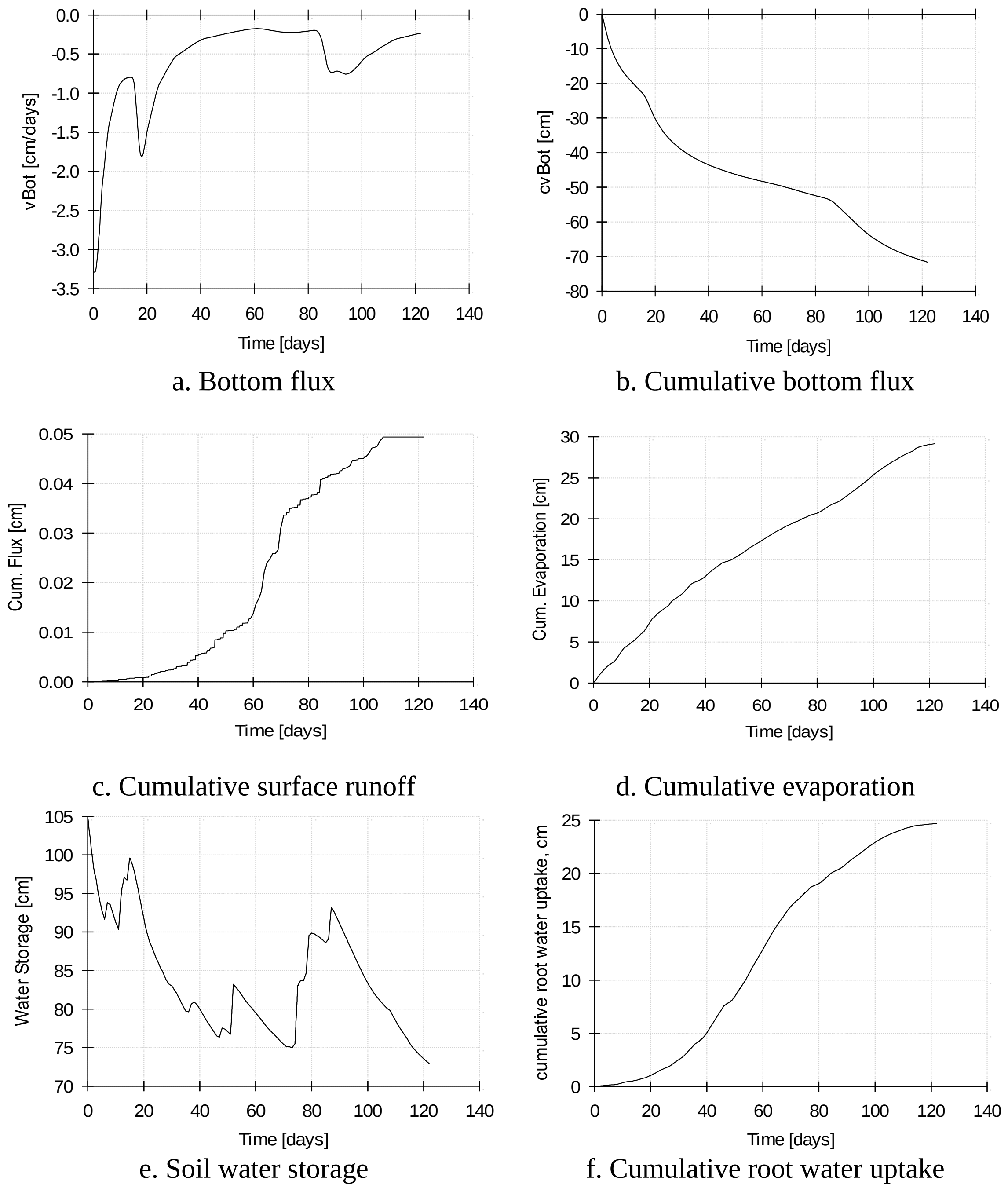

Figure 8. (a to f) *Simulated boundary fluxes and heads in land parcel unit A1 under rice crop for the year 2005*

Results presented in this study indicated that the effect of climate change on cumulative groundwater recharge was more pronounced in permeable soils with higher hydraulic conductivity. It was also observed that evaporation and transpiration rates during the growing period of rice increased with the rise in temperature compared to reference scenarios resulting in lower cumulative recharge under various climate change scenarios. However, in case of pearl millet, the transpiration rate increased marginally and evaporation decreased considerably in case of scenario 2, 4 and 5 as compared to

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the reference scenario. Such variation can be attributed to the increase of net cumulative groundwater recharge during the growing period of pearl millet.

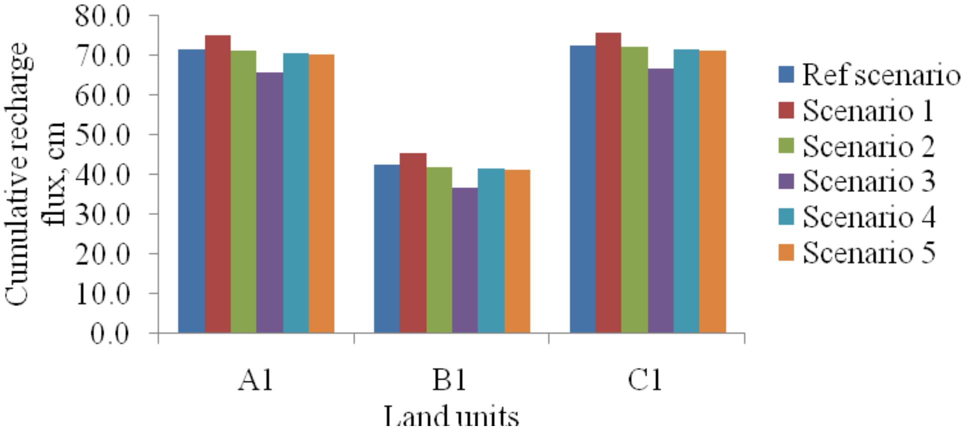

Figure 9. *Comparison of cumulative groundwater recharge fluxes from land parcel units under rice*

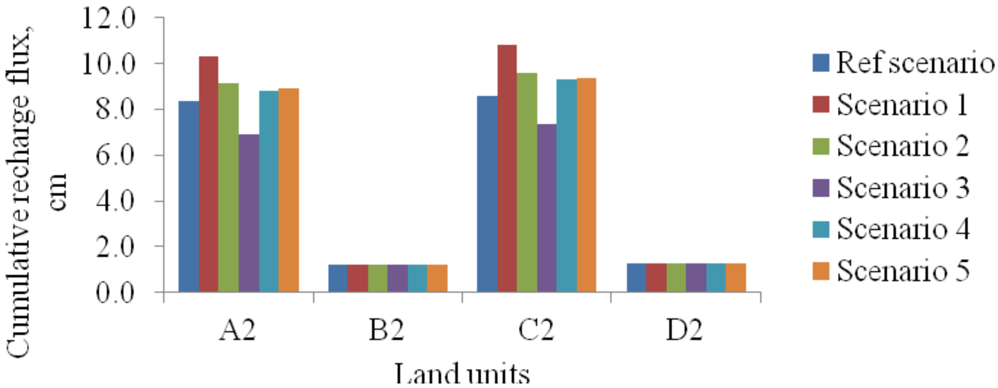

Figure 10. *Comparison of cumulative groundwater recharge fluxes from land parcel units under pearl millet*

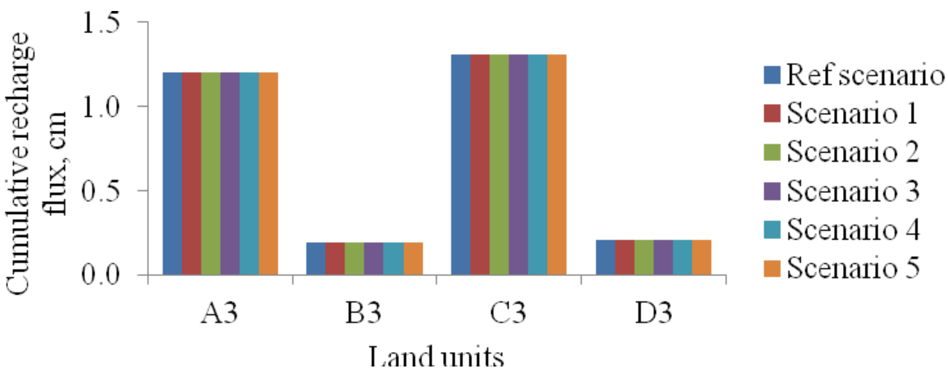

Figure 11. *Comparison of cumulative groundwater recharge fluxes from land parcel units under urban land use*

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Table 7. *Cumulative recharge flux, cumulative root water uptake, cumulative evaporation and cumulative surface runoff from various land units under different climate change scenarios.*

	Cumulative recharge flux (cm)						Cumulative root water uptake (cm)						Cumulative evaporation (cm)						Cumulative surface runoff (cm)					
	Scenarios						Scenarios						Scenarios						Scenarios					
LPUs	**Ref**	**1**	**2**	**3**	**4**	**5**	**Ref**	**1**	**2**	**3**	**4**	**5**	**Ref**	**1**	**2**	**3**	**4**	**5**	**Ref**	**1**	**2**	**3**	**4**	**5**
A1	71.6	75.0	71.3	65.9	70.6	70.3	24.7	23.5	24.8	28.0	25.2	25.3	29.2	28.0	29.4	32.6	29.7	29.9	0.0	0.0	0.1	0.0	0.1	0.0
A2	8.3	10.3	9.1	6.9	8.8	8.9	21.6	20.4	21.6	24.3	21.9	22.0	13.8	12.2	12.5	13.1	12.6	12.8	0.0	0.1	0.1	0.1	0.1	0.0
A3	1.2	1.2	1.2	1.2	1.2	1.2	0.0	0.0	0.0	0.0	0.0	0.0	25.0	25.1	25.1	26.1	25.2	25.3	8.5	9.0	8.5	8.1	8.4	8.4
B1	42.6	45.6	41.8	36.6	41.5	41.3	24.7	23.5	24.8	28.0	25.2	25.3	29.5	28.3	29.7	32.9	30.0	30.2	0.9	1.0	1.0	0.9	0.9	1.0
B2	1.2	1.2	1.2	1.2	1.2	1.2	20.6	19.5	20.7	23.4	21.0	21.1	13.9	12.6	12.9	13.5	12.9	13.0	0.5	0.6	0.5	0.5	0.6	0.6
B3	0.2	0.2	0.2	0.2	0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0	21.7	20.0	21.0	21.8	20.8	20.8	24.1	23.8	24.4	23.9	24.1	24.2
C1	72.5	75.9	72.1	66.7	71.5	71.2	24.7	23.5	24.8	28.0	25.2	25.3	29.2	28.0	29.4	32.6	29.7	29.9	0.0	0.0	0.1	0.0	0.1	0.0
C2	8.6	10.8	9.6	7.4	9.3	9.4	21.6	20.4	21.6	24.3	21.9	22.1	13.7	12.3	12.6	13.2	12.7	12.8	0.1	0.1	0.1	0.1	0.1	0.0
C3	1.3	1.3	1.3	1.3	1.3	1.3	0.0	0.0	0.0	0.0	0.0	0.0	25.2	25.3	25.3	26.3	25.4	25.5	7.0	7.4	7.0	6.7	7.0	6.9
D2	1.3	1.3	1.3	1.3	1.3	1.3	18.1	19.6	20.7	19.9	21.0	21.2	12.3	11.6	13.4	17.1	13.5	13.5	1.1	1.3	1.1	1.6	1.1	1.1
D3	0.2	0.2	0.2	0.2	0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0	21.2	21.5	22.0	21.9	21.1	21.2	23.9	25.1	24.0	23.5	23.7	24.9

A1, B1, C1: Land units under rice **A2, B2, C2, D2**: Land units under pearl millet **A3, B3, C3, D3**: Land units under urban/villages **Ref:** Reference scenario (Data of year 2005)

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Therefore, further investigation is required to evaluate the effect of evaporation and transpiration separately on groundwater recharge under different cropping systems. Moreover, in general, the higher surface runoff in various land parcel units resulted in lesser cumulative groundwater recharge under different climate change scenarios (*Table 7*).

Water table fluctuations under different climate change scenarios

Water table fluctuations under different climate change and pumping scenarios were simulated using PMWIN. Simulation results are presented in *Fig.12* and *13*. Average hydraulic heads (water table elevations in the post monsoon period) above mean sea level (amsl) for different scenarios are presented on Y-axis (*Fig. 12*). The comparison of water table fluctuation under different climate change scenarios revealed that the post monsoon water table depth increased marginally (*i.e.* By 0.03 m) in scenario 1 compared to the reference scenario. This may be due to the higher cumulative recharge flux under scenario 1. Moreover, the impact of climate change on groundwater recharge investigations can be more realistic with consideration of all principal climatic parameters instead of considering only the temperature for estimation of cumulative recharge flux and groundwater recharge in any study region. It is worth mentioning that scenario 1 represented the prediction of climate change for 2030s using long climatic data collected from the study area. Groundwater elevations in the post monsoon period (hydraulic heads) under scenario 2 and 3 (*i.e.* Based on IPCC predictions) and scenario 4 and 5 (*i.e.* based on INCCA predictions) were lower than that of the reference scenario. This suggested that the groundwater recharge would decrease if climate change is described only in terms of rise in temperature. It may be mentioned that scenarios 2, 3, 4 and 5 represented the effect of climate change on groundwater recharge by considering the temperature rise only.

Water table fluctuations between pre and post monsoon period and change in hydraulic heads under different climate change with respect to reference scenario are presented in *Table 8*. It was observed from *Table 8* that the water table in the post monsoon period increased from 0.02 m to 0.15 m in scenarios 1, 2, 4, 5 and it decreased by 0.08 m under scenarios 3. The decrease in the post monsoon water level in various scenarios was mainly due to increase in temperature and increase in groundwater pumping in the study region. Change in groundwater levels under climate change scenarios with respect to reference scenario is shown in *Fig. 13*. It was observed that the annual groundwater recharge would decrease by 0.09 m to 0.21 m under scenarios 2 to 5 under IPCC temperature predictions as compared to the reference scenario. Moreover, under scenario 1, the annual groundwater recharge would increase by 0.03 m compared to the reference scenario.

Table 8. *Water table fluctuations under different scenarios*

Scenarios	Pre-monsoon water table elevation (AMSL, m)	Post-monsoon water table elevations (AMSL, m)	Water table fluctuations between pre and post monsoon (m)
Reference	203.53	203.65	0.12
Scenario 1	203.53	203.68	0.15
Scenario 2	203.53	203.56	0.03
Scenario 3	203.53	203.45	-0.08
Scenario 4	203.53	203.55	0.02
Scenario 5	203.53	203.55	0.02

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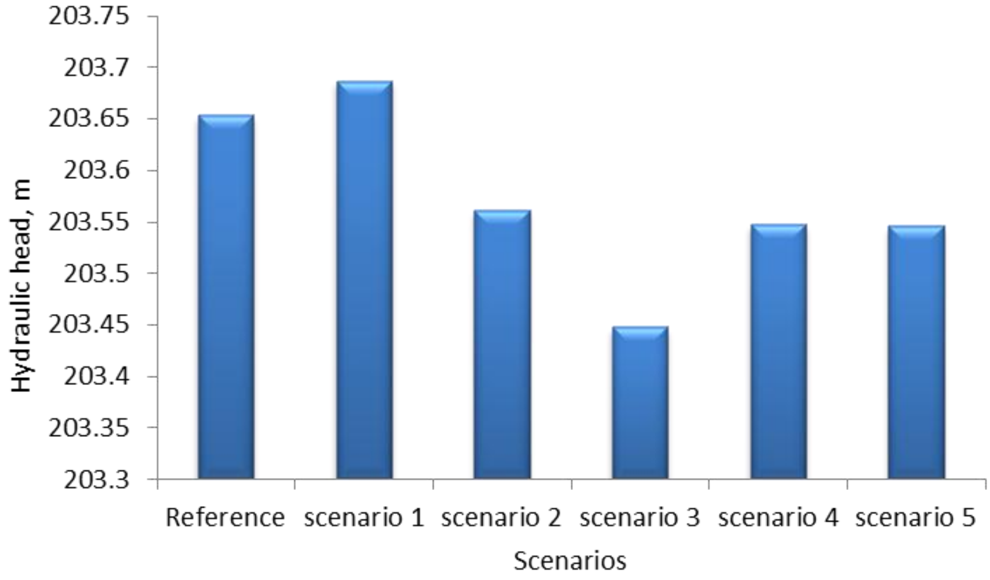

Figure 12. *Simulated groundwater elevations (hydraulic heads) under different climate change scenarios during post monsoon period*

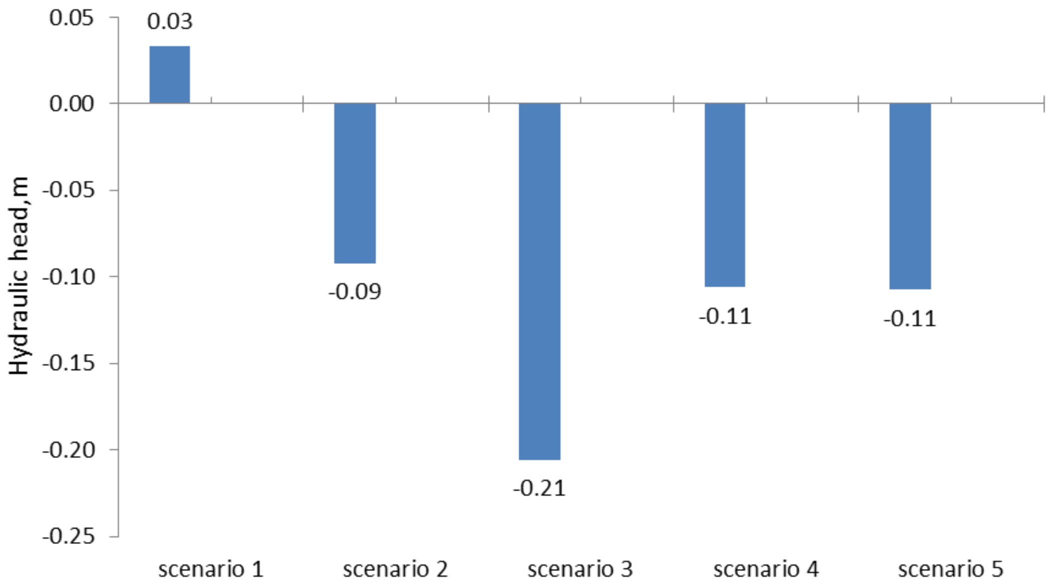

Figure 13. *Change in groundwater levels with respect to the reference scenario*

Conclusions

Assessment of impact of various climate change scenarios on groundwater recharge indicated that the groundwater recharge in the study area will not change much by the 2030s as compared to the reference year 2005, if it is estimated using all principal weather parameters. However, using the rise in temperature based on the IPCC and INCCA predictions, the groundwater recharge would decrease by 0.09 m to 0.21 m and 0.11 m, respectively, during 2030 and 2100 as compared to the reference year 2005 for the study area. Therefore, the difference in the estimated ground water recharge depth in

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the study region using all climatic parameters and only the temperature data revealed that for realistic assessment of the impact of climate change on groundwater recharge, the effect of changes in all important climate parameters should be considered rather than considering only the effect of temperature. It was also observed that the effect of climate change on groundwater recharge was more pronounced in permeable soils with higher hydraulic conductivity. Moreover, the effect of temperature rise on groundwater recharge was not observed in less permeable soils with low salinity. In the scenarios based on IPCC and INCCA predictions, evaporation and transpiration during the growing period, particularly for rice increased considerably with rise in temperature resulting in lower cumulative ground water recharge. An integrated modelling protocol using HYDRUS and PMWIN models was conceptualized and validated in this study for simulating the moisture dynamics in the vadose zone and its subsequent movement to ground water under different climate change scenarios. Nonetheless, this study revealed that for accurate estimation of ground water recharge at regional scales, all climatic parameters should be considered besides the cropping system of the region.

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