Modelling of climate-induced groundwater recharge for assessing carbon emission from groundwater irrigation

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In this study impact of climate change on groundwater recharge is investigated and the carbon emission from groundwater irrigation is assessed under projected climate change scenarios for Karnal district of Haryana state in India. HYDRUS-1D and MODFLOW models were used to simulate the climate change impacts on groundwater recharge for different projected climate change scenarios. Simulation results showed that groundwater recharge would increase marginally by 2030 over the baseline year of 2008 under the scenario based on ARIMA predictions, which considered the effect of all climate parameters. However, under the scenarios, which considered only rise in temperature, groundwater recharge would decrease by 0.07–0.22 m. Rise in temperature by 3.5°C and 4.3°C along with 9% and 16% increase in rainfall over the base year would increase the recharge by 0.09 m and 0.14 m respectively. The study also revealed that the effect of climate change on cumulative recharge would be more in sugarcane fields than in rice fields. Carbon emission of groundwater irrigation under the scenarios based on rise in temperature only would increase by a minimum of 12 kg CO_2/ha in pearl millet crop by the year 2030 to a maximum of 3250 kg CO_2/ha for sugarcane crop by the end of this century. Estimated total carbon emission in 2030 would be 345,857 metric tonne from groundwater irrigation in Karnal district which is 87,474 metric tonne more than the baseline emission.

Keywords: Climate change, carbon emission, groundwater modelling, groundwater recharge, HYDRUS, MODFLOW.

GROUNDWATER is the backbone of irrigated agriculture and drinking water supply in India and has helped in achieving food and nutritional security. The share of groundwater in net irrigated area is about 60.7% (ref. 1). However, excessive extraction of groundwater for irrigation has resulted in water level decline in many areas within the country[2]. Due to this, centrifugal pumps mostly used by farmers are being replaced by submersible pumps[2,3]. Climate change has been identified as a major threat to surface and groundwater resources[4,5]. Studies are being conducted worldwide to assess the impact of climate change on groundwater recharge and water table fluctuations[6,7]. It has been reported that groundwater levels may decline further due to increased temperature and decreased precipitation under different projected scenarios of climate change[8]. However, the exact nature of the impact of climate change on groundwater resources is still unclear and may not necessarily be negative as some studies have suggested[9]. Climate change is expected to cause imbalances in the water cycle in the future due to variation in the hydro-meteorological parameters[10]. This would affect groundwater recharge and its availability particularly in arid and semi-arid regions[11].

Quantification of the impact of climate change on groundwater resources is difficult when compared to surface water resources mainly because of existing uncertainties present in climate predictions[12]. Groundwater recharge process is complex and influenced by several hydro-meteorological parameters[12]. Downscaled data at regional scale are usually combined with different hydrological models to evaluate the impact of climate change on the groundwater recharge process[13]. Several studies have reported on the impact of climate change on groundwater recharge using groundwater model MODFLOW and reported a decrease or increase in groundwater recharge under different scenarios of climate change[14,15]. Unsaturated zone modelling combined with groundwater flow models play an important role in evaluating the impact of climate change on groundwater recharge[16,17].

Increased energy consumption for groundwater abstraction is adding to another important global concern of greenhouse gas (GHG) emissions as it contributes to the emission of CO_2 (refs 18–20). Pumping of water from higher depths also demands more energy for irrigation and consequently would increase the carbon emission. According to the National Productivity Council (NPC) of India, the total energy consumed in agriculture sector was

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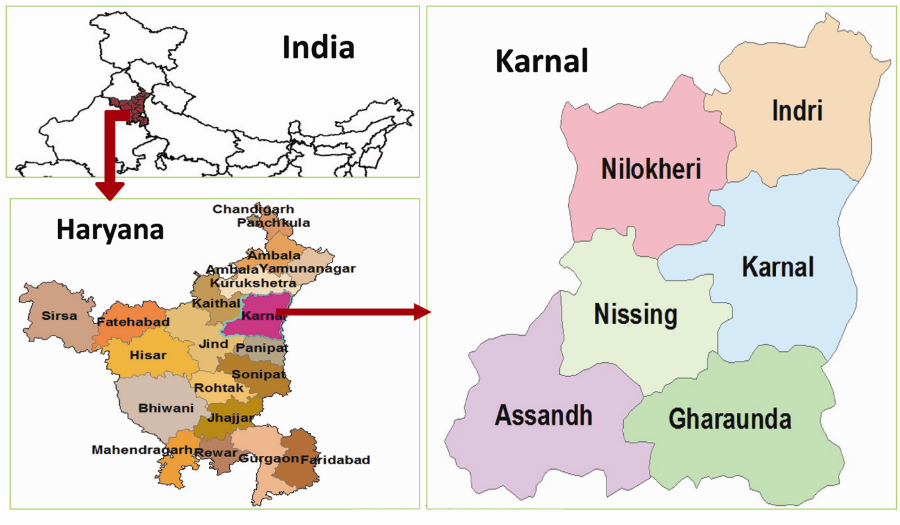

Figure 1. Study area.

22%, of which groundwater pumping contributed 18.43% (ref. 21). The energy requirement for groundwater irrigation is also influenced by the quantity of water to be lifted, total head, pump set efficiency, friction losses, etc. Irrigation efficiency and pump set efficiency also play a major role in total energy consumption and emission of carbon from groundwater pumping. In view of increasing global groundwater withdrawal, the energy use and carbon foot print of water use in agriculture assumes greater importance[22].

In view of the above, an attempt has been made to simulate the impact of climate change on groundwater recharge and assess carbon emission from groundwater irrigation under projected climate change scenarios in the Karnal district (Haryana state in India).

Materials and method

Study area

The study area comprising the Karnal district is divided into six administrative blocks (Figure 1). Karnal district has an average area of 2520 sq. km and falls in the semi-arid region. The district is located between lat. 29°25′05″N and 29°59′20″N and long. 76°27′40″E and 77°13′08E. The elevation of the district ranges from 256 m in the north to 245 m in the south. The major drainage of the area is provided by Yamuna river, which flows by the side of the east boundary. The soil types are sandy loam and clay loams. Groundwater is a primary source for irrigating field crops and the district has about 70% of irrigated area using groundwater. Rice and wheat are the major crops grown in the district.

Daily meteorological parameters of 31 years (1981–2011) namely rainfall, temperature (minimum and maximum), relative humidity, wind speed and sunshine duration were collected from the Central Soil Salinity Research Institute (CSSRI), Karnal. Groundwater level data (1974–2010) were collected from Central Ground Water Board (CGWB), Chandigarh and Groundwater Cell, Karnal. Data related to crop area, cropping pattern, irrigation data, land use and land cover were collected from the agriculture and irrigation department, Chandigarh. Information about soil and crop cultural practices was obtained through field study. Soil maps were obtained from the office of the National Bureau of Soil Survey and Land Use Planning (NBSS and LUP, New Delhi).

Methodology

Modelling of climate-induced water level fluctuations included modelling of vadose zone processes for assessing recharge flux and modelling of aquifer processes for assessing groundwater recharge and water level fluctuations. Crop water requirement was estimated using FAO CROPWAT 8.0 program. Land use and soil cover maps were prepared using Arc GIS 9.3.1. ARIMA model was used for envisaging trends in climate parameters and forecasting of groundwater level fluctuation for 2030. Variably saturated model HYDRUS-1D and groundwater model MODFLOW were used to estimate the recharge flux at the water table and groundwater level fluctuations respectively.

Recharge flux estimation: HYDRUS-1D approach

HYDRUS-1D model (version 4.08)[23] was applied for simulation of vertical water movement, root water uptake, soil moisture storage, surface runoff and evaporation from the soil surface[23]. Complete information about the

Table 1. Area under various land units

Soil types	Land use	Land units	Area (ha)
Sandy loam (A)	Rice	A1	14,238
	Sugar cane	A2	2900
	Non agriculture	A3	2285
Clay loam with slight salinity (B)	Rice	B1	8006
	Sugar cane	B2	1494
	Non agriculture	B3	2636
	Pearl millet	B4	351
Clay loam with moderate saline and sodic (C)	Rice	C1	2460
	Non agriculture	C3	703
Clay loam with strong saline and sodic (D)	Rice	D1	4746
	Non agriculture	D3	791

model is given in the HYDRUS-1D manual[23]. HYDRUS-1D model is based on Richards equation[24] (eq. 1)

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left[K\left(\frac{\partial h}{\partial x} + \cos\alpha\right)\right] - S, \quad (1)$$

where h is the water pressure head (L), θ the volumetric water content ($L^3\ L^{-3}$), t the time (T), x the spatial coordinate (L), K the unsaturated hydraulic conductivity function (LT^{-1}), α the angle between flow direction and vertical axis (°) 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[25].

Simulation of groundwater fluctuations using MODFLOW

Groundwater model MODFLOW PMWIN (version 5.3.1) was used for simulating the water table fluctuations[26]. It uses the partial differential equation as represented by eq. (2)

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right) - W = S_s\frac{\partial h}{\partial t}, \quad (2)$$

where K_{xx}, K_{yy}, K_{zz} are the hydraulic conductivities along x, y and z directions (LT^{-1}); h the hydraulic head (L); W the volumetric flux of per unit volume of sources and sinks (T^{-1}); S_S the specific storage (L^{-1}) and t is the time (T)[26].

Simulation set-up

Karnal block (404.34 sq. km) was selected to simulate the impact of climate change on recharge flux and groundwater level fluctuations under various scenarios of climate change[25]. The total area was divided into eleven similar land units (A1, A2, A3, B1, B2, B3, B4, C1, C3, D1 and D3) considering land use pattern, type of crops, soil and extent of salinity and sodicity[25] and further delineated with ArcGIS9.3.1 (Table 1). Identified land use patterns in Karnal block were rice, sugarcane, pearl millet and non-agriculture. Similarly, the soil types were sandy loam (A), clay loam with slight salinity (B), clay loam with moderate saline and sodic (C) and clay loam with strong saline and sodic (D)[25]. HYDRUS-1D was applied in each land unit to simulate the recharge flux and other unsaturated zone processes. For modelling of groundwater level fluctuations, the whole area was discretized into 25 rows and 30 columns with a grid size of 937.5 m × 937.5 m having 460 active cells. Groundwater model MODFLOW was applied to simulate the hydraulic heads in each cell. A conceptual framework was constructed for simulating recharge flux and groundwater level fluctuations as shown in Figure 2. Recharge flux obtained from HYDRUS-1D simulations for each land unit was used as the recharge rate at the water table[25].

Initial and boundary conditions for HYDRUS-1D and MODFLOW model

An identical 3 m depth, vertical column of soil was used as flow domain for simulation of recharge flux on a daily basis[25]. Simulations were performed for 122 days starting from 1 July to 30 October 2008 and the flux found at the lowermost point of the 3 m vertical column of soil was considered as maximum probable recharge under prevailing field and climatic conditions. For HYDRUS-1D, initial and boundary conditions were selected. Initial conditions were taken as soil moisture content present in soil profile during the first day of simulation[25]. For sugarcane and pearl millet crop, the value of initial moisture content was fixed at field capacity whereas in the case of rice crop it was fixed at saturated moisture content[25]. Upper boundary

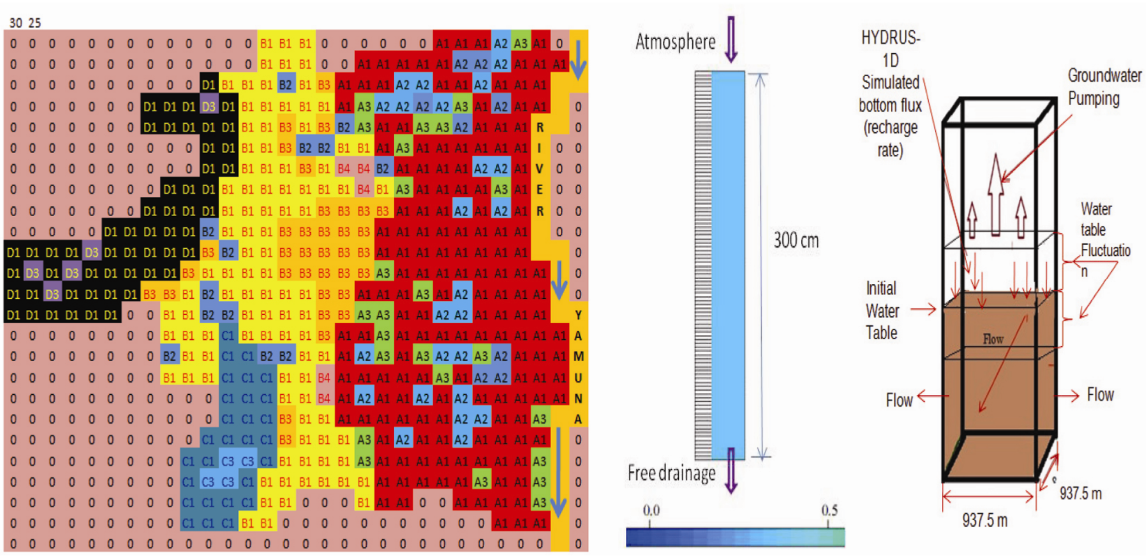

Figure 2. Conceptual framework for simulation with MODFLOW.

condition was fixed as atmospheric boundary with surface runoff, whereas free drainage was taken as bottom boundary since water table in the study area was much below the simulated domain. The amount of bottom water flux obtained on the last day of simulation was presumed equal to groundwater recharge[25]. Elevation of water table and bottom of the aquifer were considered as top and bottom boundaries of the flow domain for simulating water level fluctuations using MODFLOW. Time-dependent recharge flux m/day (obtained from the HYDRUS-1D) and average groundwater pumping rate (m/day) was specified at the top boundary. The eastern side of the study area is confined with river Yamuna. Therefore, constant head boundary was specified for the eastern borderline of the study area.

Input parameters for HYDRUS-1D and MODFLOW models

Input parameters required in HYDRUS-1D are residual water content (θ_r), saturated water content (θ_s^3), saturated hydraulic conductivity (K_s), inverse of air entry value (α), pore size distribution index (n) and pore connectivity parameter (l)[25]. These parameters were estimated from soil texture and bulk density using pedo-transfer function model Rosetta present in HYDRUS-1D[25]. Predicted values of the above parameters using model Rosetta were adjusted within the specified range with the saturated hydraulic conductivity of soil remaining unchanged. These calibrated values were assigned as input in HYDRUS-1D[25]. The value of pore connectivity parameter equal to 0.5 was used in the model[25]. The value of saturated hydraulic conductivity for saline soils (strong and moderate) was selected from the range of hydraulic conductivities (3.84–6.72 cm/day)[27,28]. Potential evapotranspiration (ET_c) was bifurcated into potential evaporation (E_p) and potential transpiration (T_p)[29].

Feddes model[30] was used to simulate the root water uptake. Root depth of 45 cm for rice, 150 cm for sugarcane and 90 cm for pearl millet crop was used during simulation. The values of Feddes parameters for rice, sugarcane and pearl millet were adopted from the literature[31–33]. Daily and seasonal crop water requirements (ET_c) for rice, sugarcane and pearl millet were estimated using CROPWAT. The ET_c of rice, sugarcane and pearl millet were 543.44, 560.98 and 301.89 mm respectively. Irrigation efficiency for rice was considered as 50%, and for sugarcane and pearl millet as 60%. Net irrigation requirement for rice, sugarcane and pearl millet was estimated to be 548.09, 500.96 and 54.15 mm respectively.

Groundwater is mostly pumped from unconfined aquifer for irrigation in Karnal district. The average depth of the unconfined aquifer was taken as 90 m below ground level (bgl). The specific yield, horizontal hydraulic conductivity and average transmissivity were taken as 0.12, 24 m/day and 2200 m^2/day respectively[34]. Groundwater pumping rate (m/day) was calculated from the data on a number of groundwater withdrawal structures and their unit draft for the study area. The total groundwater pumping during monsoon season was evenly distributed over the whole study area. The total amount of groundwater pumping per unit area for different uses during simulation was 0.26310 m. From this, the daily pumping rate was estimated at 0.0021390 m day^{-1} and was termed as the prevailing pumping rate. Observed pre-monsoon groundwater levels below the land surface in 2008 were converted into water table elevations using surface elevation maps, and were used as initial hydraulic heads. River package was used to simulate the seepage from the river using hydraulic conductance of the river bed ($L^2 T^{-1}$), head in the river stream (L) and bottom elevation of the river bed (L). Hydraulic conductance was calculated as 20862 m^2/day, the average depth of water in the river was 3.0 m and the river bottom elevation was 238.5 m. River flood level elevation was 241.5 m above mean sea level (msl). River bed thickness was worked out to be 4.0 m. Seepage from the canal was not considered, as the canals in the study area are lined. Simulations were performed with four stress periods and daily time steps. The time-dependent boundary condition was changed at the beginning of each stress period. During simulation, recharge flux was assigned as major input at the start of every stress period, whereas hydraulic conductivity and specific yield remained constant.

Development of climate change scenarios for simulations

For simulation of climate-induced groundwater recharge, seven climate change scenarios (1–7) were used in this study. Scenario 1 was based on the predictions of weather data for 2030s using ARIMA model. Climatic parameters were predicted for 2030s over the base year 2008. Average annual rise in temperature, relative humidity, and wind speed were 0.23°C, 2.44%, 5.2 km/day respectively and decrease in sunshine duration was by 0.26 h. Effect of increase or decrease in climatic parameters predicted by the ARIMA model was used to estimate crop evapotranspiration which was bifurcated into evaporation and transpiration as required in HYDRUS-1D.

Scenarios 2, 3 and 4 were based on the Indian Network for Climate Change Assessment (INCCA) predictions for 2030 for India using regional climate model PRECIS for A1B emission scenario of the IPCC[35]. Scenario 2 (2°C increase in temperature) is based on only temperature increase whereas scenario 3 (1.7°C increase in temperature and 3% increase in rainfall) and scenario 4 (2°C increase in temperature and 7% increase in rainfall) consider both increase in temperature and rainfall. Scenario 5 (5.4°C increase in temperature) is based on IPCC predictions for A2 (medium high emission) for 2100. Scenario 6 (3.5°C increase in temperature and 9% increase in rainfall) and scenario 7 (4.3°C increase in temperature and 16% increase in rainfall) were based on Kumar *et al.* predictions using IPCC-SRES A1B scenario for 2080 (ref. 36). For modelling of climate-induced groundwater recharge, the year 2008 was taken as the baseline year. In the case of INCCA, IPCC and Kumar *et al.*[36] prediction, 1970 was taken as the baseline year. Hence, increase in temperature over baseline year 1970 was converted into an increase in temperature over the year 2008 (ref. 25). According to predictions, the all-India average annual temperature increased at 0.21°C per decade during the post-1970 period (refs 25, 36). Using the above information, the annual increase in temperature was determined and was used to convert increase in temperature under these scenarios above base year 2008.

Assessment of carbon emission of groundwater irrigation

Carbon emission from groundwater irrigation was assessed using a developed procedure[37]. Estimation of carbon emission included the quantity of groundwater pumped and used for irrigation and energy consumed in lifting water[37]. Subsequently energy (kWh) used during groundwater pumping was multiplied by a suitable emission factor for assessment of carbon emission from groundwater irrigation[37]. Simulated pre-monsoon and post-monsoon groundwater levels under various scenarios were used to assess carbon emission of groundwater irrigation. Karnal district has nearly 70% of groundwater irrigated area. Hence, for assessment of carbon emission, only 70% of the total irrigation requirement was considered as the amount of water pumped from the aquifer[37]. Carbon emission for irrigating one hectare of each crop under unit head was estimated. Then the area under different crops and total head was multiplied to obtain the total carbon emission. The carbon emission from groundwater irrigation under various climate change scenarios was assessed by considering the projected groundwater levels under various climate change scenarios. The baseline scenarios were assessed for the irrigation requirement and total dynamic head that prevailed in 2008 (ref. 37). Initially carbon emission in kg CO_2/ha/m was calculated for Karnal block of the district and accordingly carbon emission was estimated for the whole district based on information on average water table depth and groundwater irrigated area under different crops in the district.

The amount of irrigation water pumped depends on irrigation efficiency. Irrigation efficiency for groundwater irrigated rice and other crops was considered as 50% and 60% respectively[37]. Energy required for pumping groundwater for irrigation mainly depends on the mass of water to be pumped (m), lift or total dynamic head (H) and pumping system efficiency (η_p)[37]. It was estimated by eq. (3)

$$\text{Energy (kWh)} = \frac{9.8\ \text{m/s}^2 \times \text{lift(m)} \times \text{mass (kg)}}{3.62 \times 10^6 \times \eta_p(\%)}. \quad (3)$$

Total dynamic head (TDH) was obtained by adding the values of average initial water level, drawdown, delivery head and head losses. Average initial water level was calculated from the average of the pre- and post-monsoon groundwater levels[37]. Average drawdown for Karnal was about 12 m as reported by CGWB. Frictional losses in the pipe was considered as 4.17 m per 100 m length[37]. Average operating efficiency of irrigation pumps in Haryana is

34.7% and the same was used to calculate energy after a detailed review of literature[38]. Grid emission factor of 0.94 kg CO_2/kWh as reported by the Central Electricity Authority of India (CEA) for 2013 was used to estimate the carbon emission[37].

Results and discussion

The model was calibrated and validated by comparing the observed and predicted post-monsoon water tables. Results of model calibration and validation are presented in Figure 3. Figure 3 *a* presents the comparison between observed and predicted average water table elevations (hydraulic heads) in different cells whereas, Figure 3 *b* compares water table elevations in different land units located in the study area. These figures revealed that the observed and predicted water tables are in close agreement.

Further the model performance was checked by the Nash-Sutcliffe efficiency (NSE), coefficient of determination (R^2), root mean square error (RMSE), and RMSE observation standard deviation ratio (RSR). The values of RMSE, RSR, NSE and R^2 for the land unit and cell comparison of observed and predicted average hydraulic heads were 0.655, 0.249, 0.938 and 0.94 and 0.94, 0.299, 0.911 and 0.90 respectively. It can be observed that all these parameters are within acceptable limits. Therefore, the combination of HYDRUS-1D and MODFLOW can be used for modelling groundwater fluctuation.

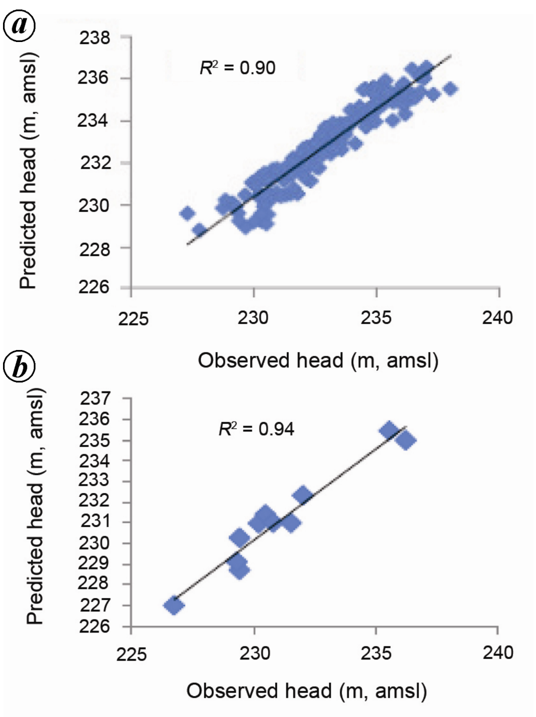

Figure 3 ***a***, ***b***. Comparison of observed and predicted hydraulic heads in the study area.

Cumulative recharge flux

Simulated cumulative recharge flux obtained from different land units with different scenarios of climate change and baseline scenario is shown in Table 2. The simulation carried out for the prevailing conditions in 2008 was referred to as baseline scenario. The cumulative recharge fluxes from land units A1, B1, C1 and D1 (under rice) for the baseline scenario were 69.2, 37.2, 32.4 and 29.8 cm respectively. In case of land units (A2 and B2) under sugarcane, cumulative recharge fluxes for the baseline scenario were 12.5 and 0.01 cm. As expected, recharge flux was higher from the rice field. Cumulative recharge flux from land unit A1 (rice in sandy loam soil without salinity) under different scenarios of climate change varied from 63.9 (scenario 5) to 74.4 cm (scenario 1). Here, the variation was not more owing to nearly the same percolation rates in all the scenarios. The small variation in cumulative recharge flux may be due to increased crop evapotranspiration. In case of sugarcane crop field, there was a large difference in cumulative recharge flux under different scenarios of climate change. This was mainly because of increased crop water requirement in some scenarios and no ponding condition in a sugarcane field. Soil texture, level of salinity and sodicity also affected the cumulative recharge obtained from different land units. Cumulative recharge from the sugarcane field varied from 0.0 to 17.1 cm and in case of pearl millet, it varied from 0 to 0.01 cm under various scenarios of climate change. Cumulative recharge from non-agricultural area (land units A3, B3, C3 and D3) was negligible. This was because of high surface run-off and evaporative loss due to impermeable surfaces. Highest cumulative recharge flux was obtained from rice fields. In case of ARIMA predicted scenario, cumulative recharge flux increased by 7.4%, over the baseline scenario for the rice field (land unit A1, sandy loam). This may be due to significant reduction in crop water requirement under scenario 1. In the case of sugarcane, recharge flux increased by 37.4%, 4.3%, 9.2%, 10.5% and 27.4% under scenarios 1, 3, 4, 6 and 7 over baseline scenarios. However, cumulative recharge flux decreased with rise in temperature (scenario 5) in A2 land units. In the case of land units B2, no change in cumulative recharge flux was observed, except for scenario 1 where recharge increased. Similarly, no change in cumulative recharge flux was observed for land units B4 under pearl millet crop. Results also revealed that cumulative recharge would increase in Karnal district considering all the climatic parameters for estimation of climate change impact. This is contrary to the general opinion that groundwater recharge decreases in semi-arid regions because of climate change[39–41]. This is due to falling trend in a few long-term meteorological parameters especially wind speed and sunshine duration and rising trend in relative humidity. Nevertheless, groundwater

Table 2. Cumulative recharge flux from the different land units under various climate change scenarios

	Scenarios							
Land units	Ref	1	2	3	4	5	6	7
A1	69.2	74.4	67.7	69.4	70.8	63.9	70.0	71.9
A2	12.5	17.1	11.0	13.0	13.6	7.3	13.8	15.9
A3	0	0	0	0	0	0	0	0
B1	37.2	39.8	36.1	37.1	38.4	33.7	38.8	39.9
B2	0.01	0.24	0.01	0.01	0.01	0.01	0.01	0.01
B3	0	0	0	0	0	0	0	0
B4	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
C1	32.4	35.4	31.8	32.6	33.3	29.3	34.4	35.0
C3	0	0	0	0	0	0	0	0
D1	29.8	34.3	29.0	30.0	30.2	27.1	31.8	31.7
D3	0	0	0	0	0	0	0	0

Table 3. Water table fluctuation during pre- and post-monsoon season under climate change scenarios

Scenarios	Pre-monsoon water table elevation (m, amsl)	Post-monsoon water table elevation (m, amsl)	Water table fluctuation between pre- and post-monsoon water table (m)	Water table fluctuation between pre- and post-monsoon season with respect to baseline scenario (m)
Reference	230.60	230.91	0.31	0.0
Scenario 1	230.60	231.16	0.56	0.25
Scenario 2	230.60	230.84	0.24	–0.07
Scenario 3	230.60	230.90	0.30	–0.01
Scenario 4	230.60	230.95	0.35	0.04
Scenario 5	230.60	230.69	0.09	–0.22
Scenario 6	230.60	231.00	0.40	0.09
Scenario 7	230.60	231.05	0.45	0.14

recharge may decrease because of increased rainfall intensity.

Findings of the study also showed that considering only rise in temperature, recharge flux would reduce as observed for scenarios 2 and 5. However, altogether combining increase in temperature and increase in rainfall (scenario 3, 4, 6 and 7), cumulative recharge would increase. This may be because the effect of increase in temperature on recharge flux is compensated with increased rainfall.

Climate induced water level fluctuations

Change in hydraulic heads and water table fluctuations between pre-monsoon and post-monsoon period under various scenarios of climate change compared to the baseline scenario are shown in Table 3. The water table in the post-monsoon period increased (varying from 0.09 to 0.56 m) under scenarios 1–7. This shows that there is a positive net effect of monsoon rainfall on post-monsoon level under all scenarios.

The comparison showed that post-monsoon water table would increase by 0.25 m in scenario 1 compared to the baseline scenario. This may be due to more cumulative recharge flux under scenario 1. This indicates that, if all climatic parameters are considered for assessment of cumulative recharge flux, there would be positive impact of climate change on groundwater recharge in Karnal district contrary to general perception. It is worth mentioning that scenario 1 represents predictions of climate change for 2030 using long-term local weather data. Groundwater elevations in the post-monsoon period (hydraulic heads) under scenario 2 (based on INCCA predictions considering only the temperature rise) are lower than the reference scenario by 0.07 m. In case of scenario 3 (based on INCCA with 1.7°C increase in temperature and 3% rainfall), groundwater elevations in the post-monsoon period will marginally decrease (by 0.01 m) whereas under scenario 4 (with 2.0°C increase in temperature and 7% increase in rainfall) it would increase by 0.04 m. This may be due to the fact that under scenario 3, the 3% rise in rainfall is not enough to compensate the effect of the 1.7°C rise in temperature. Whereas, in scenario 4, the 7% increase in rainfall can compensate the effect of a 2°C rise in temperature. In the case of scenario 5 (based on IPCC predictions of temperature rise), groundwater elevations in the post-monsoon period were lower than the baseline scenario by 0.22 m respectively. This suggests that groundwater recharge would reduce when climate change is defined only with increase in temperature. Scenarios 6 and 7 were based on Kumar

Table 4. CO_2 emission from groundwater pumping for irrigating major crops grown in the study area under various scenarios of climate change

		CO_2 emission													
		Rice		Pearl millet		Maize		Pigeon pea		Wheat		Mustard		Sugarcane	
Scenarios	TDH	(kg/ha)	(kg/ha/m)	(kg/ha)	(kg/ha/m)	(kg/ha)	(kg/ha/m)	(kg/ha)	(kg/ha/m)	(kg/ha)	(kg/ha/m)	(kg/ha)	(kg/ha/m)	(kg/ha)	(kg/ha/m)
Baseline	29.2	1178	40.4	117	4.0	504	17.3	394	13.5	809	27.7	764	26.2	2720	93.2
Scenario 1	28.9	953	334.0	12	0.4	378	13.1	278	9.6	744	25.7	702	24.3	2396	82.9
Scenario 2	29.2	1262	43.2	154	5.3	557	19.1	442	15.1	847	29.0	799	27.4	2871	98.3
Scenario 3	29.2	1229	42.1	135	4.6	534	18.3	414	14.2	837	28.7	790	27.1	2834	97.0
Scenario 4	29.1	1230	42.3	130	4.5	531	18.3	417	14.3	843	29.0	796	27.4	2859	98.3
Scenario 5	29.4	1472	50.1	250	8.5	690	23.5	565	19.2	940	32.0	887	30.2	3250	110.6
Scenario 6	29.1	1307	44.9	164	5.6	580	19.9	462	15.9	879	30.2	830	28.5	3011	103.5
Scenario 7	29	1323	45.6	160	5.5	584	20.2	464	16.0	901	31.1	851	29.	3101	106.9

et al.[36] prediction. Results also showed that the rise in temperature by 3.5°C and 4.3°C along with 9% and 16% increase in rainfall would increase groundwater elevations in post-monsoon period by 0.09 and 0.14 m compared to the baseline scenario. This indicates that if global warming is with significant rise in rainfall as predicted by Kumar *et al.*[36], there would be a positive impact of climate change on groundwater table fluctuation.

Carbon emission from groundwater irrigation

Carbon emission from groundwater irrigation under different scenarios of climate change is summarized in Table 4. The difference between simulated water level fluctuations under different scenarios of climate change and baseline scenario was added to the average water level during the baseline year to determine the total dynamic head. Table 4 reveals that carbon emission was highest in sugarcane (2396 kg/ha) followed by rice (953 kg/ha), wheat (744 kg/ha), mustard (702 kg/ha), maize (378 kg/ha), pigeon pea (278 kg/ha) and pearl millet (12 kg/ha) for ARIMA predicted scenario 1. The same pattern was observed for other climate change scenarios. Within the climate change scenarios (scenarios 1–7), the highest carbon emission was under scenario 5 which was based on IPCC predictions for 2100 (for medium high emission scenario–A2). Under this scenario, CO_2 emission was highest in sugarcane (3250 kg/ha) followed by rice (1472 kg/ha), wheat (940 kg/ha), mustard (887 kg/ha), maize (690 kg/ha), pigeon pea (565 kg/ha) and pearl millet (250 kg/ha). In the scenarios based on INCCA predictions (scenarios 2–4), lowest CO_2 emission was under scenario 4 (varied from 130 kg/ha for pearl millet to 2859 kg/ha for sugarcane). It may be mentioned that under scenario 4, temperatures and rainfall are predicted to rise by 2°C and 7% respectively.

In the scenarios based on Kumar *et al.*[36] predictions (scenarios 6 and 7), lowest CO_2 emission was under scenario 6 (varied from 164 kg/ha for pearl millet to 3011 kg/ha for sugarcane). It may be mentioned that under scenario 6, temperatures and rainfall are predicted to rise by 3.5°C and 9% respectively. The results reveal that CO_2 emission from groundwater irrigation under the scenarios which were based on rise in temperature only (scenarios 2 and 5) would increase by minimum of 12 $kgCO_2$/ha in pearl millet crop (scenario 1) by the year 2030 to a maximum of 3250 kg CO_2/ha for sugarcane crop (scenario 5) by the end of this century. Scenarios 2–7 were mainly based on IPCC, INCCA and Kumar *et al.*[36] predictions which considered either only increase in temperature or both increase in temperature and rainfall.

To assess the impact of declining water table on CO_2 emission from groundwater irrigation, groundwater levels forecast by ARIMA model for 2030 were used. The best identified ARIMA model (0, 1, 2) was used for time series modelling and forecasting of average pre- and post-monsoon groundwater levels in Karnal district[42]. Table 5 shows the comparison between carbon emissions from groundwater irrigation of Karnal district for the base year 2008 and in 2030. The crops cultivated in the district are rice, wheat, pearl millet, sugarcane, pigeon pea and mustard. It was assumed that the area under the crops, the area irrigated by groundwater and the source of power for pumping groundwater for irrigation in 2030 would remain the same as base year 2008. Baseline estimate of irrigation requirement, energy consumption (kWh), and CO_2 emission (kg/ha/m) from groundwater pumping for irrigation are also presented in Table 5. Energy requirement for irrigating these crops in 2008 were 1255, 861, 124, 2894, 419 and 813 kWh/ha respectively. Results show that the CO_2 emissions for irrigating rice, wheat, pearl millet, sugarcane, pigeon pea and mustard in the year 2008 were 140,656, 98,153, 230, 18,416, 389 and 539 metric tonne and it will increase to 188,274, 131,383, 308, 24,651, 521 and 721 metric tonne respectively, in 2030. Higher CO_2 emission from rice and wheat crop is due to more irrigated area under these crops. Estimated total carbon emission from groundwater irrigation in Karnal district for 2008 was 258,383 metric tonne, whereas, it would be 345,858 metric tonne in 2030 which

Table 5. Carbon emission from groundwater irrigation in Karnal district for base year 2008 and in 2030

Crops	Irrigation depth (mm)	Irrigation volume (m^3)	Energy (kWh/ha)	Area (ha)	Area irrigated by groundwater (ha)	CO_2 emission (kg/ha/m)	Total CO_2 emission (metric tonne)	Total CO_2 emission (metric tone, 2030s)
Rice	548	5481	1255	169,100	118,370	40.4	140,656	188,274
Wheat	376	3760	861	172,000	120,400	27.7	98,153	131,383
Pearl millet	542	5415	124	2800	1960	4.0	230	308
Sugarcane	1264	12,639	2894	9600	6720	93.2	18,416	24,651
Pigeon pea	183	1831	419	1400	980	13.5	389	521
Mustard	355	3549	813	1000	700	26.2	539	721
Total				355,900	249,130		258,383	345,858

is 87,474 metric tonne more than the baseline emission. This is mainly due to the decline in average water level by 9.4 m between 2008 and 2030 (ref. 42).

Conclusion

Modelling of groundwater level fluctuations under different scenarios of climate change was carried out to assess the climate change impact on groundwater recharge from sandy loam and clay loam soils under rice, sugarcane and pearl millet cultivation. There was not much effect of climate change on groundwater recharge from irrigated rice fields. However, the effect was much more noticeable in sugarcane because of increased evapotranspiration in some climate change scenarios which affected the water balance in the root zone and recharge flux. Under the scenario based on ARIMA predictions (which considered all climatic parameters for modelling of water level fluctuations) groundwater recharge would increase marginally over the baseline scenario. However, in case of scenarios which considered only rise in temperature, water level would decline with respect to the baseline scenario. If an increase in rainfall is not enough to compensate the effect of increase in temperature on groundwater recharge as in the case of one of the INCCA based predictions (1.7°C increase in temperature and 3% increase in rainfall), groundwater level will go down with respect to the baseline scenario. Based on these observations, it was concluded that the cumulative recharge would decrease under the climate change scenarios based on the increase in temperature only. However, it would increase under scenarios in which increase in temperature is associated with a significant increase in rainfall and relative humidity and decrease in duration of sunshine hours. Energy required for pumping groundwater for irrigating sugarcane and associated CO_2 emission under baseline scenario were 2894 kWh/ha and 2720 kg/ha respectively. This was mainly due to the longer growing period of sugarcane. After sugarcane, rice was found to be a more energy-intensive crop. For reducing energy consumption and carbon emission, pearl millet and pigeon can be alternate crops to rice during *kharif* and mustard can be a substitute to wheat in *rabi*. CO_2 emission would increase under the scenarios which considered only increase in temperature. It was concluded that CO_2 emission from groundwater irrigation would increase in future if IPCC, INCCA and Kumar *et al.* predictions become a reality.

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