Modeling climate change impact on groundwater and adaptation strategies for its sustainable management in the Karnal district of Northwest India

Satyendra Kumar[1] · Bhaskar Narjary[1] · Vivekanand[1] · Adlul Islam[2] · R. K. Yadav[1] · S. K. Kamra[1]

Abstract

Extensive use of groundwater in the rice–wheat cropping system of northwest India has resulted in groundwater depletion at an alarming rate of 33–88 cm per year over the past 2–3 decades. Projected climate change is likely to affect crop water demand, groundwater withdrawal, and replenishment in future. A modeling study was undertaken to simulate the impact of climate change on groundwater resources under existing rice–wheat cropping system and with revised crop management strategies in the Karnal district of Northwest India. Different cop management strategies considered are marginal shift in sowing dates of rice and wheat, and fractional diversification of rice area to maize. MODFLOW software driven by the projected climate change scenarios under four representative concentration pathways (RCP2.6, RCP4.5, RCP6.0, and RCP8.5) were used for simulating groundwater behavior in the study area under business as usual and proposed crop management strategies. Simulation results indicated 4.3–61.5 m (28.9–291.2%) additional decline in groundwater levels in different zones of the study area under different RCPs by the end century (2070–2099) period in relation to the reference groundwater level of year 2015 under the existing sowing dates of 15 June for rice and 15 November for wheat. Maintaining rice sowing date at 15 June but advancing wheat sowing date by 10 days can reduce groundwater decline by 9.8–14.4%, 14.4–19.6%, and 18.1–25.8% under different RCPs by the end of early (2010–2039), mid (2040–2069), and end (2070–2099) century periods, respectively, vis-à-vis prevailing sowing dates. Replacing 20%, 30%, and 40% rice area with maize in rice–wheat system is likely to reduce groundwater decline by 7.1 (24.9%), 10.1 (35.3%), and 13.8 m (48.5%), respectively, in comparison to projected end century (2099) decline of 28.5 m under the prevailing sowing dates of rice–wheat. However, declining groundwater trend of rice–wheat would be reversed with the replacement of 80% rice area under maize crop. Simulation results suggest that specific crop management strategies can potentially moderate groundwater decline in the study area under the envisaged climate change.

Keywords Climate change · Groundwater · Sowing dates · Crop diversification

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Extended author information available on the last page of the article

1 Introduction

Groundwater plays an important role in fulfilling demand of water for irrigation, domestic, industrial, and recreation sectors. However, excessive use of groundwater in irrigated agriculture and industrial sectors has resulted in rapid decline of groundwater resources in many countries (Treidel et al. 2012). Groundwater use system in the northwestern India is heavily stressed, and there is substantial spatial and temporal heterogeneity in groundwater levels and its forcing mechanisms (Joshi et al. 2021). The groundwater depletion rate was estimated as 0.33 m year^{-1} in the northwestern Indian states of Haryana, Punjab, and Uttar Pradesh (Rodell et al. 2009). However, the rate of decline of groundwater in Haryana has increased to 0.88 m year^{-1} in the last decade (Narjary et al. 2014). In the northwestern states of the country, rice–wheat is the main cropping system that requires approximately 2100 mm groundwater withdrawal to meet crops water demand (Jalota et al. 2018). Recognizing the severity of groundwater depletion problem, Indian federal and state governments have undertaken certain policy initiatives to control groundwater decline. For example, to control the rapidly falling groundwater level, Punjab and Haryana governments enacted their respective state legislations in 2009. These legislations are enacted to preserve the subsoil water by prohibiting paddy nursery sowing and paddy transplanting before specific notified date so that groundwater is not used to irrigate fields in the hottest part of the year resulting in significant loss of water through evaporation (Singh 2009; Joshi et al. 2021; Rosencranz et al. 2021). Implementation of this Act reduced the long-term rate of decline in the groundwater level by about two-thirds, or 0.30 m year^{-1} and also resulted in saving in electricity consumption (Singh, 2009). Maize followed by wheat has higher system productivity than rice–wheat system due to early sowing of wheat crop escaping it from the terminal drought (Rakshit et al. 2021), and saving of water and energy (Meena et al. 2021). Haryana State government is making concerted efforts to substitute rice cultivation by less water requiring maize crop in dark zone (where over-exploitation of groundwater is acute, and withdrawal and usage of water exceed its recharge) blocks.

Climate change and variability are likely to aggravate the groundwater vulnerability in many complex and unprecedented ways (Treidel et al. 2012; Thomas and Famiglietti 2019), especially in relation to crop water requirement, groundwater recharge, and its availability in future (Niraula et al. 2017). Asoka et al., (2018) reported that the number of rainy days with low-intensity precipitation has decreased while the extreme precipitation events have increased which have implications for groundwater recharge in India. They also reported that the monsoon season groundwater recharge in the northwest and north-central India is linked with the low intensity precipitation, but in south India, high-intensity precipitation is a major driver of groundwater recharge in bedrock dominated aquifers. Hence, accurate estimation of spatio-temporal availability of groundwater under futuristic climate change scenarios and different land uses is essential for groundwater budgeting and developing sustainable groundwater management strategies for irrigated agricultural systems of semi-arid and arid regions (Lauffenburger et al. 2018). Groundwater draft for irrigation and irrigation induced recharge plays a major role in groundwater budget (Hanson et al. 2012). Predictions of irrigation requirement under climate change scenarios would require estimates of change in land use, technology, and climate and associated feedbacks (Scibek and Allen 2006). Crop simulation models such as Aquacrop, DSSAT, and Cropsim have the potential to estimate irrigation requirement and groundwater recharge under a variety of land use and climate change scenarios (Lauffenburger et al. 2018). A number of field and modeling studies have been carried out worldwide to estimate the use of groundwater

for different crops or cropping systems (Jalota et al. 2018; Kumar et al. 2019), though most were restricted to field scale water budgeting. Specific information on the effect of crop management strategies for judicious and efficient use of groundwater on regional scale is very scanty.

It is reported that pressure on groundwater resources will increase in the future because of the decreased groundwater recharge and intensive groundwater withdrawal to cope up with changed precipitation patterns and increased evapotranspiration (ET) under projected climate change scenarios (Treidel et al. 2012; Zaveri et al. 2016; Switzman et al. 2018). Studies suggest that groundwater depletion negatively impacts the yield, area, and production of all grain crops during the dry winter season when groundwater is the main source of irrigation (Bhattarai et al. 2021), which may further amplify the negative effects under changing climate scenarios. Further, climate change-induced precipitation increase in certain areas may not alleviate groundwater stress due to the expansion of irrigated areas (Zaveri et al. 2016). Though a few research studies have been conducted to evaluate the effect of climate change on groundwater recharge and withdrawal (Treidel et al. 2012; Niraula et al. 2017; Lauffenburger et al. 2018) including some for Indo-Gangetic Plain of South Asia (Kaur et al. 2015), still systematic spatio-temporal studies on the effect of crop management plans on groundwater behavior under climate change scenarios are lacking for dominant rice–wheat cropping system of northwest India. Considering the above facts, the present study was undertaken to assess the impact of future climate on groundwater behavior with existing land use pattern, and to develop suitable crop management plans to control the over-exploitation of groundwater. Effects of crop management plans, namely, shifting in sowing dates of prevailing rice–wheat cropping system and crop diversification with maize crop coupled with projected climate change scenario on groundwater behavior, were studied using crop growth model Aquacrop and groundwater simulation model MODFLOW. In the present study, practically feasible adoption strategies were tried considering the prevailing rice–wheat system and contemplating the difficulties in convincing the farmers to entirely abandon the cultivation of highly remunerative rice crop (Bhattarai et al. 2021). Similarly, effect of crop diversification, i.e., replacing rice by maize in different proportions, was also studied in view of the concerted efforts of the local state government to promote maize cultivation as a viable option for controlling declining groundwater level in the agriculturally dominant northwestern region of the country.

2 Materials and methods

2.1 Description of the study area

The study area Karnal, India, has 2520-km² total geographical area which extends from 29° 25′ 05″–29° 59′ 20″ N to 76° 27′ 40″–77° 13′ 08″ E (Fig. 1). About 85% of the area is under agriculture, and most of which is under rice–wheat cropping system. The study area falls in the semi-arid climatic region having an average (1981–2015) annual rainfall of 740 mm. The average elevation of the study area is 240 m above the mean sea level (AMSL), ranging from 256 m in the north to 245 m AMSL in the south with the general southwards slope. For assigning spatial scale model inputs, the study area was divided into 5 zones based on administrative block boundary, i.e., zone 1 (Asandh), zone 2 (Karnal), zone 3(Gharaunda), zone 4 (Nilukheri), and zone 5 (Indri).
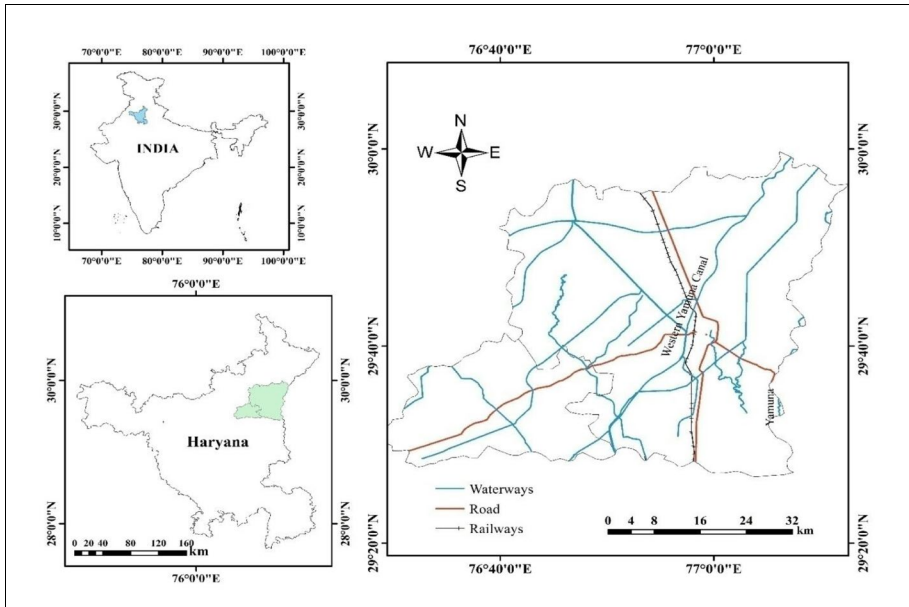
Fig. 1 Thematic map of the study area (Karnal, Haryana, India)

2.2 Data collection

Daily weather data (rainfall, maximum and minimum temperature, relative humidity, sunshine hours, and wind speed) for the period of 1980–2015 was collected from the observatory of ICAR-Central Soil Salinity Research Institute, Karnal. The data on groundwater table depth of 55 observation wells of the study region was collected from the District Hydrology Department, Karnal, Haryana, for the period of 2000–2015. Digital elevation model (DEM) of 90×90 m resolution was obtained from the Consortium for Spatial Information (CGIAR-CSI) website http://srtm.csi.cgiar.org/SELECTION/inputCoord. asp. Hydro-geological and lithological parameters of saturated zone of the study area were adopted from the report of Central Groundwater Board (CGWB, 2013). The data on cropping pattern was collected from the Statistical Abstract of Haryana (Statistical Abstract Haryana, 2000–2015), while the population information was derived from 2011 Census data (Census, 2011, https://census2011.co.in/census/district/213-karnal.html) for calculation of water consumption of the domestic sector.

For assessing climate change impact on groundwater behaviour (draft, recharge, depth to water table), the Inter-Governmental Panel on Climate Change (IPCC) Fifth Assessment Report's climate change projections based on representative concentration pathways (RCPs) were used in this study. Bias-corrected and spatially disaggregated (BCSD) monthly projections of rainfall and temperature at $0.5 \times 0.5°$ resolution, from the World Climate Research Program's (WRCP's) Coupled Model Inter-comparison Project Phase 5 (CMIP5) multi-model dataset for the period 1950–2099, were obtained from ftp://gdo-dcp. ucllnl.org/pub/dcp/archive/cmip5/global_mon. The CMIP5 multi-model datasets have been used, as also considered in several climate change impact studies around the globe, due to their ability to produce reliable and robust results (Walton et al. 2015; Zhang et al. 2019; Abeysingha et al.2020; Doulabian et al. 2021). For generating climate change scenarios in

this study, we used rainfall and temperature projections of 33 general circulation models (GCMs) (Supplementary file-Table 1).
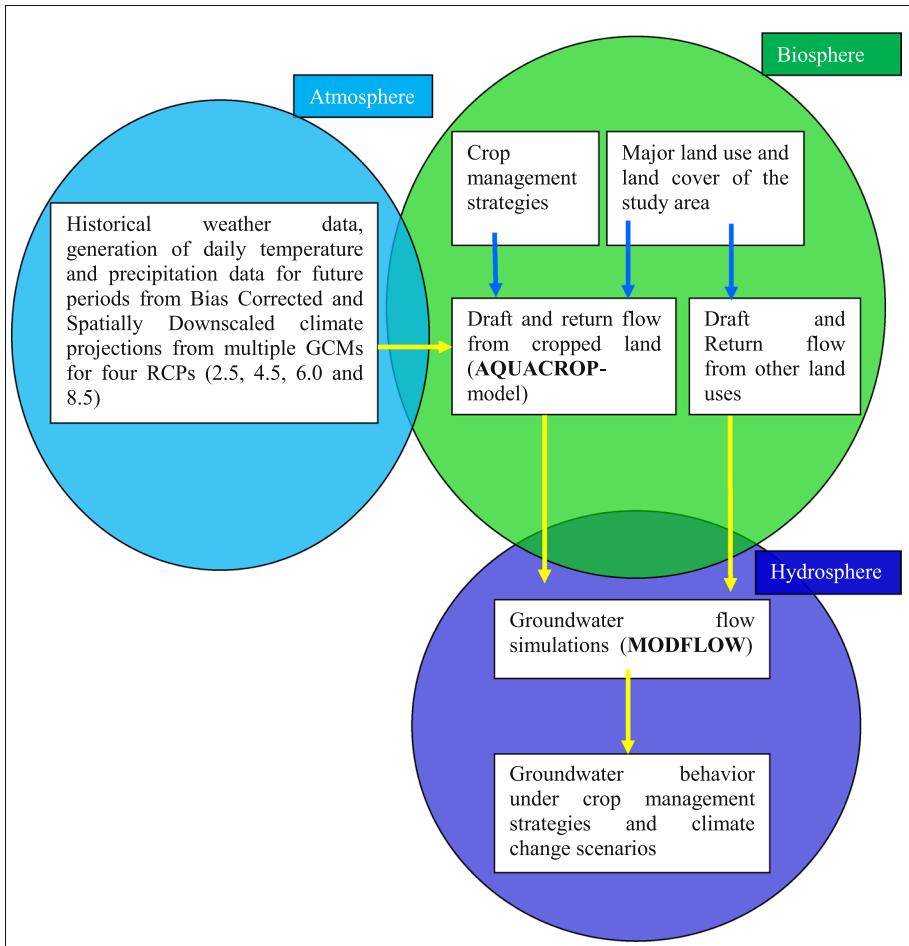
2.3 Software used

Different simulation models were used to explore the interactions between atmosphere, biosphere, and hydrosphere. The interaction between atmosphere and biosphere was built by Food and Agriculture Organization (FAO) process-based field scale crop growth simulation model Aquacrop (Raes et al. 2009) for cropped area and transport model Hydrus-1D (Šimůnek et al. 2012) for fallow land. The output of these models is used as input to groundwater flow model MODFLOW (McDonald and Harbaugh, 1988) to simulate groundwater behavior of the study area. The methodological process followed to accomplish the proposed goal is depicted in Fig. 2.

2.4 Generation of climate change scenarios

The hybrid-delta method (Islam et al. 2012a &b; Dickerson-Lange and Mitchell, 2014; Tohver et al. 2014) was used in this study for generating multi-model ensemble climate change scenarios from multiple GCM projections for four different RCPs. The hybrid delta method is similar to the delta change (change factor) method, but in case of the hybrid delta method, a different scaling factor is applied to each month of the historic time series based on where it falls in the probability distribution of monthly values (Dickerson-Lange and Mitchell, 2014). In this method, BCSD monthly GCM data (rainfall and temperature) were disaggregated into individual calendar months, and then, cumulative distribution functions (CDFs) for each of the month were developed for historical (1950–1999), future time periods of 2010–2039 (early century), 2040–2069 (mid century), and 2070–2099 (end century). The CDFs for the observed time series data (1981–2010) were also developed. For creating ensemble of multiple GCMs/runs, historical and future CDFs for each month were developed using data from multiple GCMs/runs. Quantile mapping (Wood et al. 2002) was applied to re-map the observations onto historical and future CDF for each month to obtain the historic and future GCM projected rainfall and temperature data corresponding to the non-exceedance probability of the observed data. The difference between the future and historical temperature values was then computed to get the change factor. In case of rainfall, the ratio of future and historical rainfall was computed to get the change factors. In this way, change factor corresponding to all the observed values for a given month is computed. This process is repeated for all the 12 months. The monthly change factor so obtained corresponding to all the observed values was applied to the daily observed time series data to obtain daily future projections. Step-by-step procedure for generating ensemble of multiple GCMs using the hybrid-delta method is described in Tohver et al. (2014). The hybrid delta ensemble method has been applied in several impact assessment studies (Dickerson-Lange and Mitchell, 2014; Lee et al. 2015; Abeysingha et al. 2020; Mali et al. 2021).

2.5 Estimation of groundwater draft and recharge

Different land uses such as cropped, forest and residential area, water bodies including canal network, and other land uses (barren, pasture, and waste land) were taken into consideration while calculating groundwater recharge and draft. The cropped land occupies

Fig. 2 Flow chart of adopted methodological approach depicting interaction of atmosphere, biosphere, and hydrosphere with standard methodology and software used for estimating fluxes for simulating groundwater behavior of the study area

about 85% of the total land uses. The procedures used to estimate recharge (return flow) and draft components for different land uses are described below:

2.5.1 Draft from different land uses

Aquacrop model (version 5) was used to estimate groundwater draft (irrigation) and recharge, i.e., return flow (deep drainage) from cropped area using soil, crop, and climate data. The total irrigation depth, calculated by crop model based on the soil, crop, weather conditions, and irrigation scheduling criteria, was considered as groundwater draft for modeling groundwater behavior (Xiang et al. 2020; Kumar et al. 2020). Draft for domestic sector was estimated considering per capita water requirement of 200 l day^{-1} (Shaban and Sharma, 2007) for the total population (www.census2011.co.in/district.php) of the study area. The groundwater draft from the forest land was calculated by taking into

consideration the water requirement of *Eucalyptus* plants since most forest area is covered by this plantation. The annual water requirement for high density *Eucalyptus* plantation was taken as 1500 mm year^{-1} (Minhas et al. 2015). For other land uses (barren and water body), groundwater draft was considered as nil in the simulation study. Keeping in view the canal network density in each study zone, estimated annual draft was varied to match the groundwater fluctuation in each observation well during calibration and validation of MODFLOW. The average of estimated groundwater draft for other land uses (forest, barren, etc.) for calibration and validation periods was used to simulate future groundwater behavior.

2.5.2 Return flow

Return flow from crop land was estimated using the water balance module of FAO Aquacrop model (Vanuytrecht et al. 2014). This model estimates water balance components based on the following relationship:

$$I + R = ET + Dr + Sm + Sr \tag{1}$$

where I is the irrigation applied (mm), R is the precipitation (mm), ET is the evapotranspiration (mm), Dr is deep drainage (return flow) in mm, S_m is change in soil moisture (mm), and S_r is surface runoff (mm). It was hypothesized that the fraction of irrigation and precipitation that passed beyond the root zone will eventually reach the aquifer. Return flow from the bare land was estimated using Hydrus 1-D under no crop conditions. The calibrated and validated Hydrus1-D model (Narjary et al. 2021) for the study area was adopted for estimation of return flow under the projected climate change scenarios. Return flow from the urban land was estimated by subtracting surface runoff from precipitation and assuming no evapotranspiration losses.

2.5.3 Seepage losses from canal network

Canal network design dimensions of length, bed width, full supply depth, slope, discharge, seepage rate, and number of canal operation days in a year were used for estimating seepage losses from the canal network by adopting standard methodology (GEC, 2009).

2.5.4 Calibration and validation of models

Aquacrop For calibration and validation of Aquacrop model, reference evapotranspiration was calculated using the FAO reference evapotranspiration (ET$_0$) calculator with the recorded weather data. Aquacrop model was calibrated for rice, wheat, and maize crops by comparing observed and simulated values of return flow and grain yield. The return flow was estimated by using the following relationship:

$$\mathrm{RF} = (I + R) - (\mathrm{ET}_c) - Ro - S + \theta_{smc} \tag{2}$$

where RF return flow (deep drainage) passed beyond the root zone in a specific period (mm), I and R are depth of irrigation (mm) and rainfall (mm), respectively, ET$_c$ and R_o are evapotranspiration (mm) and runoff (mm), respectively, while θ_{smc} is moisture storage in different soil layers (mm) in a period, and S is the lateral seepage (mm). In order to know the total amount of water passed beyond 0–1.5 m, weekly RF was summed up for

the month period and whole season. The detailed procedure for measurement of different components of return flow is described in Kumar et al. (2019).

The return flow and yield data for rice, wheat, and maize crops were generated from the field experimentation conducted during 2014 and 2015. Model was calibrated and validated using the field experimental data of 2014 and 2015, respectively. Calibration and validation of model for return flow was done using the monthly return flow data collected through field experimentation. Model performance was evaluated in terms of Nash Sutcliffe model efficiency (NSE), coefficient of determination (R^2), root mean square error (RMSE), mean absolute error (MAE), and mean error (ME).

MODFLOW model MODFLOW (Visual MODFLOW Flex, Waterloo Hydrogeologic, Canada) was used to simulate three-dimensional transient groundwater flow for unconfined aquifer conditions. The model is based on the following partial differential equation (McDonald and Harbaugh, 1988) and solves the equation with different possible properties, boundary conditions, and initial conditions.

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right) - W = S_s\frac{\partial h}{\partial t} \tag{3}$$

where h is the hydraulic head (m) at a point, S_s is the storage coefficient of permeable material (m^{-1}), K_{xx} is the hydraulic conductivity in x direction (m day^{-1}), K_{yy} is the hydraulic conductivity in y direction (m day^{-1}), K_{zz} is the hydraulic conductivity in z direction (m day^{-1}), W is a volumetric flux per unit volume representing sources and/or sinks of water, with $W > 0.0$ for flow in and $W < 0.0$ for flow out of the groundwater system, and t is time in day. Based on the hydro-geological information, graphical representation of the groundwater flow system was developed for the study area. The first aquifer region of the study area was unconfined, occurred at 90–180-m depth, with average storativity and hydraulic conductivity values of 0.12 and 22.0 m day^{-1}, respectively (CGWB, 2013). Specified flux and head dependent (river boundary condition) boundary conditions were assigned for developing conceptual model (Supplementary file-Fig. 1). Specified flux boundary condition was applied on north, south, and western sides of the study area which actually had no physical boundary. The specified flux was estimated using the Darcy flow tool-based methodology (Kumar et al. 2020). Yamuna River passes through the eastern side boundary of the study area, and hence, Cauchy boundary condition was considered in this side. The measured depth to water level of pre-monsoon season of the year 2000 was interpolated using the inverse distance interpolation method, and initial generated hydraulic head map was assigned as initial head boundary.

Based on total geographic spread of the study region (2520 km^2), aquifer was discretized into 4333 cells of approximately 1 km × 1 km grid size. By adjusting aquifer parameters, boundary conditions, and stresses (groundwater recharge and draft) within reasonable ranges, simulated hydraulic heads were matched with the recorded hydraulic heads of the study area for the same period to calibrate the model. The hydraulic head data of 55 observation wells, spread over the entire study area, was used for model calibration purpose (Supplementary file-Fig. 1). Calibration and validation of MODFLOW was done using the hydraulic head data for 2001–2010 and 2011–2015 periods, respectively. Five statistical indicators, i.e., Nash Sutcliffe model efficiency (NSE), coefficient of determination (R^2), root mean square error (RMSE), mean absolute error (MAE), and mean error

(ME) were used for assessing the performance of model during calibration and validation periods. These can be written as follows:

$$NSE = 1 - \frac{\sum_{i=1}^{n} (x_i - x_p)^2}{\sum_{i=1}^{n} (x_i - \text{mean} x_i)^2} \tag{4}$$

$$R^2 = \frac{\sum (x_i - x_p)^2}{\sum (x_i - \text{mean} x_i)^2} \tag{5}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N} (x_p - x_i)^2}{N}} \tag{6}$$

$$MAE = \frac{1}{N} \sum \sum_{i=1}^{N} \left| x_p - x_i \right| \tag{7}$$

$$ME = \frac{1}{N} \sum \sum_{i=1}^{N} (x_p - x_i) \tag{8}$$

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

2.5.5 Groundwater flow modeling under climate change scenarios

Daily projected precipitation and minimum and maximum temperatures, generated using the methodology described in Sect. 2.3.4, were used as input to the Aquacrop model for upward flux (draft) and downward flux (return flow) estimation for cropped land, and the estimated values were imported into the MODFLOW for simulating groundwater behavior for the period of 2016–2099.

2.5.6 Crop management plans

Different crop management plans were tested to assess the effectiveness of different options for minimizing groundwater draft and arrest declining water table under different climate change scenarios. Shifting of sowing dates of rice and wheat crops, from the existing sowing dates, was considered as a management plan to reduce the evapotranspiration (ET) and groundwater withdrawal. The hypothesis was to find out the best set of sowing dates for rice and wheat crop which would have potential to minimize rate of decline of groundwater under changing climate scenarios. Five combination of sowing dates of rice–wheat viz. 15 June–5 Nov, 15 June–15 Nov, 25 June–15 Nov, 25 June–25 Nov, and 5 July–5 Dec were tested to identify the best combination of sowing dates resulting in minimum use of groundwater. Local government is also promoting maize to replace prevailing rice crop for controlling depletion of groundwater resources. Therefore, less water requiring maize crop was taken as crop diversification option in this simulation study. In *kharif* season (June–October), maize and rice in different proportions (maize + rice–wheat cropping system) in the groundwater irrigated area was also evaluated as another crop management

option for reduction of groundwater use under climate change scenarios. The treatments involved replacement of 20%, 30%, 40%, 80%, and 100% of the groundwater irrigated area of rice by maize. The effect of other two scenarios, i.e., rice–wheat and maize-wheat cropping system when entire water requirement is met from groundwater resource only, was also simulated. The crop diversification scenarios considered for the simulation study are listed in Table 1.

3 Results and discussion

3.1 Projected change in temperature and precipitation

The projected change in mean minimum and maximum temperature and precipitation was assessed with reference to historical weather data of 1981–2010 as the base period. The minimum temperature (T_{min}) is projected to increase in the range of 1.4–1.7 °C, 2.0–3.3 °C, and 2.0–5.3 °C under different RCPs during early, mid, and end century periods, respectively, as compared to the baseline period (Supplementary file-Table 2). Similarly, the maximum temperature (T_{max}) is projected to increase in the range of 1.0–1.3 °C, 1.7–2.8 °C, and 1.8–4.7 °C under different RCPs during early, mid, and end century periods, respectively. The higher rise in minimum and maximum temperature is projected under RCP8.5 in all the three future time periods. Interestingly, the minimum temperature is projected to increase more than the maximum temperature. Other studies have reported 0.5, 2.2, and 3.4 °C increase in maximum temperature and 0.8, 2.6, and 3.8 °C increase in minimum temperature during early, mid, and end century, respectively, in the Central India (Bal et al. 2016 and Kundu et al. 2017).

The rainfall is projected to increase under all RCPs in the range of 10.0–11.1%, 11.1–14%, and 10.6–21.0% during early, mid, and end century (Supplementary file-Table 2). However, higher increase in rainfall is projected under RCP8.5, particularly

Table 1 Different crop diversification scenarios considered for groundwater resources management

Crop diversification option	Description
CD-1	Entire cropped area under rice during *Kharif* followed by wheat using existing water supply (80% area irrigated using groundwater, 20% area irrigated using canal water supply)
CD-2	20 and 80% cropped area under maize and rice, respectively, during *Kharif*, followed by wheat using existing water supply
CD-3	30 and 70% cropped area under maize and rice, respectively, during *Kharif*, followed by wheat using existing water supply
CD-4	40 and 60% cropped area under maize and rice, respectively, during *Kharif*, followed by wheat using existing water supply
CD-5	80 and 20% cropped area under maize and rice, respectively, during *Kharif*, followed by wheat using existing water supply
CD-6	Entire cropped area under maize during *Kharif*, followed by wheat using existing water supply
CD-7	Entire cropped area under maize-wheat cropping using groundwater supply only
CD-8	Entire cropped area under rice–wheat cropping using groundwater supply only

CD crop diversification plan, *CD2–CD5* introduced maize in groundwater irrigated rice area

during mid and end century. Other researchers across the globe have also projected higher increase in annual precipitation under RCP8.5 (Polade et al. 2014; Konapala et al. 2020). It was noticed that there is increase in evapotranspiration due to rise in temperature under climate change scenarios. Though there is increase in rainfall in the future for all climate scenarios, magnitude of crop ET increase is comparatively higher due to a considerable increase in temperature. The rainfall is projected to increase in the range of 51.4–60.5 mm, 61.9–82.9 mm, and 33.1–94.1 mm under different RCPs during the early, mid, and end century periods, respectively, in comparison to the reference period (1981–2010) rainfall of 640.8 mm (Supplementary file-Table 3). Whereas evapotranspiration is likely to increase in the range of 178.7–186.9 mm, 199.0–217.0 mm, and 211.9–261.0 mm under different RCPs during the early, mid, and end century periods, respectively, in comparison to the base period crop ET of 844.0 mm. This would result in a notable water deficit despite the increase in rainfall. Hence, irrigation demand could not be completely met out by increased rainfall under projected climate change scenarios. Greve and Seneviratne (2015) also reported increased average annual evaporation due to increase in temperature under futuristic scenario of climate change. Similarly, Zaveri et al. (2016) reported increase in water requirement to meet out the ET demand of agricultural sector, as a larger chunk of the study area is under cultivation, and there by posing further pressure on groundwater resources in future.

3.2 Calibration and validation of models

3.2.1 Calibration and validation of Aquacrop model

Aquacrop model was calibrated by adjusting soil and crop parameters till satisfactory match was achieved between simulated and field measured values of grain yield and return flow for rice, maize, and wheat crop. The model simulated rice yield of 3.54 Mg ha^{-1} (Megagram per hectare) compared well against the observed yield of 3.36 Mg ha^{-1} from the field studies of the year 2014, i.e., only 5% variation between the observed and simulated results. The difference between simulated and observed yield of wheat and maize was 4.6% and 8.75%, respectively. Good agreement was also observed between the measured and simulated return flow from rice and maize field (Supplementary file-Fig. 2a and 2c) for the calibration period (2014), but recorded return flow for wheat was zero. The NSE, R^2, ME, MAE, and RMSE were found to be 0.95, 0.98, − 15 mm, 16.90 mm, and 22.30 mm, respectively, in case of rice (Supplementary file-Fig. 2a), and 0.93, 0.98, − 8.45 mm, − 8.50 mm, and 10.0 mm in case of maize (Supplementary file-Fig. 2c).

Very good agreement was recorded between observed and simulated grain yield for validation period with yield variation of 3.74%, 5.32%, and 5.24% for rice, wheat, and maize, respectively. While the NSE, R^2, ME, MAE, and RMSE for return flows were computed as 0.94, 0.96, − 16.95 mm, 24.60 mm, and 31.08 mm, respectively, from rice field (Supplementary file-Fig. 2b) and 0.85, 0.93, − 3.7 mm, 5.2 mm, and 6.34 mm, respectively, from maize field during the validation period (Supplementary file-Fig. 2d).

In summary, the variation in simulated and observed yield of rice, wheat, and maize remained within 10% during calibration and validation periods. Similarly very good agreement between observed and simulated return flow from rice and maize were found with NSE > 0.85 during calibration and validation periods. These results clearly indicated that the Aquacrop can be used effectively for simulation of water balance and yield for future predictions in the study area.

### 3.2.2 Calibration and validation of MODFLOW

Calibration of MODFLOW under transient conditions was done for a 10-year period (2001–2010) by comparing observed and simulated hydraulic heads, i.e., depth to water table. Auto-calibration (parameter estimation) model PEST was used for calibrating the model parameters, namely, hydraulic conductivity and specific yield. During the calibration period, the specific yield varied between 0.12 and 0.15, while the hydraulic conductivity varied between 15 and 110 m day^{-1} in different geographical zones of the study area (Supplementary file-Fig. 3). The sensitivity analysis of different parameters indicated that model results were more sensitive to hydraulic conductivity than specific yield. Very good agreement was found between observed and simulated hydraulic heads during the calibration period (2001–2010) with NSE, R^2, RMSE, ME, and MAE values of 0.97, 0.97, 2.36 m, -0.37 m, and 1.62 m, respectively (Supplementary file–Fig. 4a). Similarly, very good agreement also noticed between observed and simulated hydraulic head for the validation period (2011–2015) with NSE, R^2, RMSE, ME, and MAE of 0.93, 0.93, 1.85 m, -0.025 m, and 1.85 m, respectively (Supplementary file-Fig. 4b). These results clearly indicate that the calibrated and validated MODFLOW model with prescribed boundary conditions and computed parameters can be successfully applied for assessing climate change impact on groundwater behavior in the study region.

3.3 Estimated groundwater draft and recharge under projected climate change scenarios
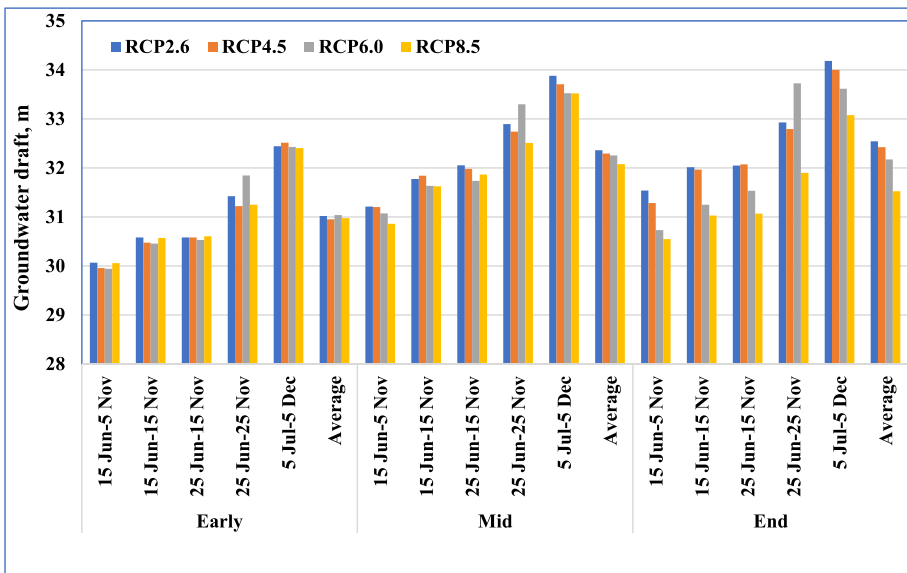
3.3.1 Groundwater draft

Irrespective of climate change projections (RCPs) and time period (early, mid, and end of century), groundwater draft varied in all five zones depending upon the proportion of groundwater and surface water used for irrigation (supplementary file-Table 4). Irrespective of RCPs, the maximum groundwater draft was estimated in the zone 5, and the least in the zone 1 under prevailing sowing dates of rice (15 Jun) and wheat (15 Nov) (Fig. 3). The projected groundwater draft varied in the range of 32.5–34.1 m in zone 5 and 28.7–30.2 m in zone 1 for different RCPs and time periods under prevailing sowing dates of rice and wheat (Supplementary file-Table 4). On an average, the groundwater draft in the study area was projected in the range of 30.5–30.6 m, 31.6–31.8 m, and 31.0–32.0 m during early, mid, and end century, respectively (Supplementary file-Table 4).

For better understanding of the effect of crop management options and climate change on groundwater draft, average annual draft of the study area (mean of all zones) is presented in Fig. 4. As shown in Fig. 4 under the prevailing sowing dates of rice and wheat (15 June and 15 Nov), the groundwater draft was estimated to be lower under RCP8.5 during mid and end century as compared to other RCPs. Under the prevailing sowing dates, the groundwater draft was estimated to be varied between 31.0 and 32.0 m under different RCPs during end century. Similarly during mid century, the groundwater draft was estimated in the range of 31.6–31.8 m for different RCPs with the prevailing sowing dates. In fact, lower average groundwater draft (mean of all pairs of sowing dates) was projected during the mid and end century in all proposed sowing dates under RCP8.5 (Fig. 4), mainly due to greater increase in rainfall (supplementary file-Table 2). Though the projected mean temperature was higher during the end century period, the anticipated higher amount of rainfall perhaps offsets the effect of rising temperature on groundwater draft. Our finding
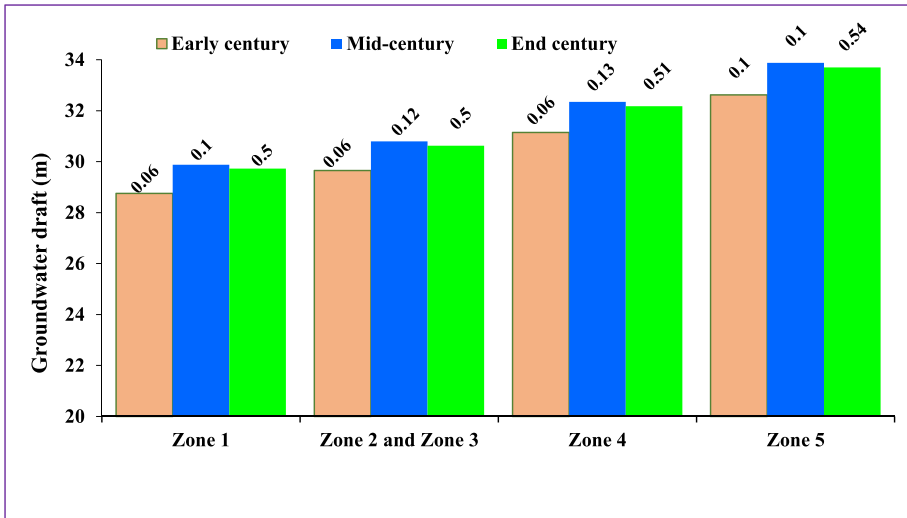
Fig. 3 Groundwater draft in different zones of the study area during simulation period (bar represents average of groundwater draft under different RCPs, and values above the bar indicates standard deviation)


Fig. 4 Effect of crop management options with delaying of rice and wheat sowing dates from the prevailing date of 15 June (rice) and 15 November (wheat) on groundwater draft under different climate change scenario

confirms the observation that change in rainfall characteristics influences annual water demand and management (Mishra et al. 2010).

Similarly, this study revealed that groundwater draft increases with the delay in transplanting/sowing dates of rice–wheat from the prevailing dates of 15 June and 15 November

(Fig. 4). The projected groundwater draft was found to be the highest under delayed (5 July) transplanting/sowing dates of rice and (5 December) of wheat. The combination of 10 days advanced wheat sowing (i.e., 5 Nov) from the existing date (15 Nov) and prevailing sowing date (15 June) of rice resulted in the lowest groundwater draft. Dubey et al. (2020) reported that under prevailing sowing dates, wheat yield would decrease by 11.1% at 2050 scenario due to terminal heat stress resulting in the early maturity of the crop. Additionally, the 10-day advancement in sowing of wheat is likely to reach crop grain filling stage during relatively cooler temperature. The expected cooler temperature regime during grain filling stage associated with delayed initiation of senescence consequently tend to improve grain filling and final grain yield. Lobell et al. (2012) reported that wheat grain filling and grain yield are affected by the onset of senescence. They further estimated that 2 °C rise in temperature during wheat grain filling can cause yield loss up to 50%. Nevertheless, this sowing schedule may require relatively shorter duration rice varieties to suitably fit in the available period for rice growing.

The effect of crop diversification (substitution of rice by maize in rice–wheat cropping system) on groundwater draft under all RCPs is presented in Fig. 5 and Supplementary file-Table 5. Under the existing scenario (CD-1), the mean simulated groundwater draft (average of all RCP values) varied in the range of 29.6–30.8 m during different time periods (Fig. 5). But, in CD-8 (complete dependency of rice–wheat system on groundwater), mean draft varied in the range of 34.0–35.4 m during different time periods, which is higher than the projected draft of CD-1. This is because in CD-1,
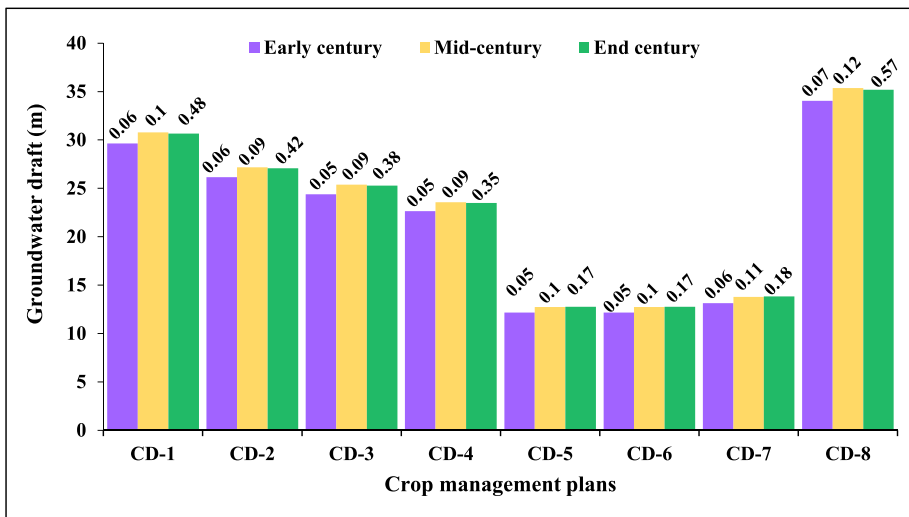
Fig. 5 Effect of crop diversification (CD) in *Kharif* season followed by wheat on average groundwater draft during the simulation period. Bar represents mean value of groundwater draft of different RCPs; values given above the bars depict standard deviation (CD-1 = entire (100%) cropped area under rice (R)-wheat (W) cropping system with existing water supply (EWS) (80 and 20% area irrigated with groundwater (GW) and canal water (CW), respectively); CD-2 = 20% in maize (M) + 80% in rice (R) of cropped area with EWS; CD-3 = 30% (M) + 70% (R) of cropped area with EWS; CD-4 = 40% (M) + 60% (R) of cropped area with EWS; CD-5 = 80% (M) and 20% (R) of cropped area with EWS; CD-6 = entire cropped area under M-W with EWS; CD-7 = entire cropped area under M-W with GW only; CD-8: entire cropped area under R-W with GW only)

20% of the area of rice was irrigated by canal water. However, when entire rice area was replaced with maize using groundwater irrigation (CD-7), mean groundwater draft varied in the range of 13.1–13.8 m, which is significantly lower than that of CD-8 and CD-1 (Fig. 5). Hence, replacement of rice with *kharif* maize resulted in decrease in groundwater draft in all the RCPs and future time periods. Scenario CD-5 resulted in the lowest mean groundwater draft (12.2–12.8 m) depending upon different RCPs and time periods. Interestingly, CD-6 resulted in exactly similar groundwater draft as that of CD-5 because contribution to draft from groundwater irrigated maize field (80% of cultivated land) was similar in both the scenarios, while the draft from the remaining 20% area covered by rice/maize was zero due to canal irrigation. These results clearly indicated that low irrigation demanding maize crop could be helpful in minimizing groundwater withdrawal. However, despite the concern of fast declining groundwater table, convincing farmers for complete replacement of highly remunerative rice crop with low water consuming maize crop is the major constraint in this region.

3.3.2 Return flow

A very little difference in simulated return flow was observed for different sowing dates of rice–wheat under different RCPs (Supplementary file-Table 6a). The return flow in rice–wheat cropping system is projected to vary in the range of 25.8–27.0 m, 26.0–28.5 m, and 25.9–28.9 m during early, mid, and end century, respectively, with different pairs of sowing dates. Irrespective of RCPs and sowing dates, in general, the lowest simulated return flow was found during the early century and the highest during the end century period (Supplementary file-Table 6a). While comparing the return flows during different sowing dates, simulation results indicated greater return flow in 15 June (rice)–15 November (wheat) sowing dates under different RCPs and future periods.

Simulated return flow from rice + maize-wheat cropping system under different RCPs with prevailing dates of sowing indicates that replacing rice with maize reduces return flow due to decrease in irrigation amount (Fig. 6 and Supplementary file-Table 5). The average return flow for four RCPs varied in the range of 8.2–27.0 m, 9.0–28.4 m, and 9.4–28.6 m during early, mid, and end century, respectively, under different crop diversification (CD) scenarios. Maize requires 2–3 irrigation only as compared to 20–25 irrigation in rice (Kumar et al. 2019), and about 75–80% of the total water percolates as return flow (Dari et al. 2017). This was the reason that replacement of rice area with maize resulted in decreased return flow. The return flow from different crops under RCP8.5 is presented in Supplementary file-Table 6b. Simulation results indicated that rice field contributes major portion (88–89%) towards return flow in rice–wheat cropping system irrespective of RCPs and time periods. The return flow from wheat field was negligible as irrigation was scheduled to meet crop water demand only and very little rain expected during the crop growing season. It was observed that water deficit (ET-Rainfall) in wheat was not lesser than the rice despite of considerably higher irrigation water requirement in rice. Jalota et al. (2018) and Bhattarai et al. (2021) also reported that decline in groundwater table is more in winter or wheat crop than rice due to greater water deficit in winter season. Hence, any pair of sowing dates which results in higher return flow with lower groundwater draft would be the best option for sustained management of depleting groundwater resources. Further, any crop management plan or agronomic practices owing to the reduced irrigation amount could be much more effective in controlling declining water table in the study area.
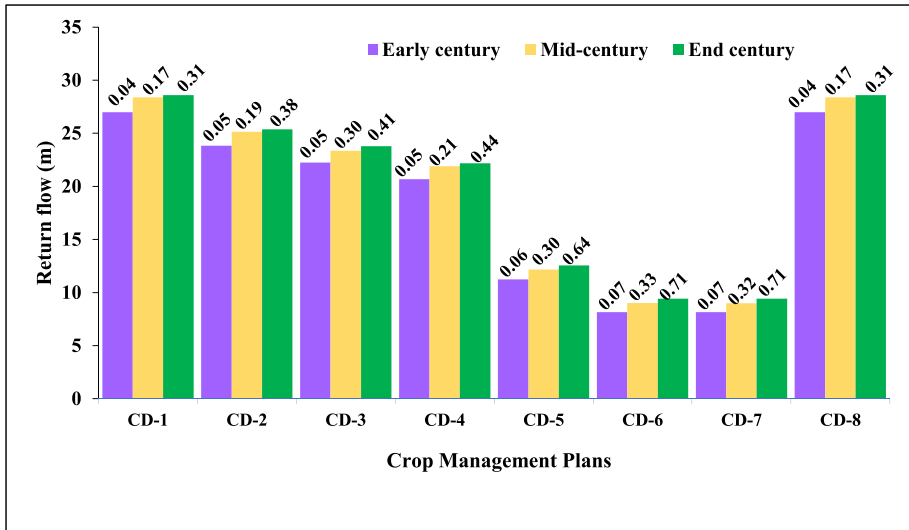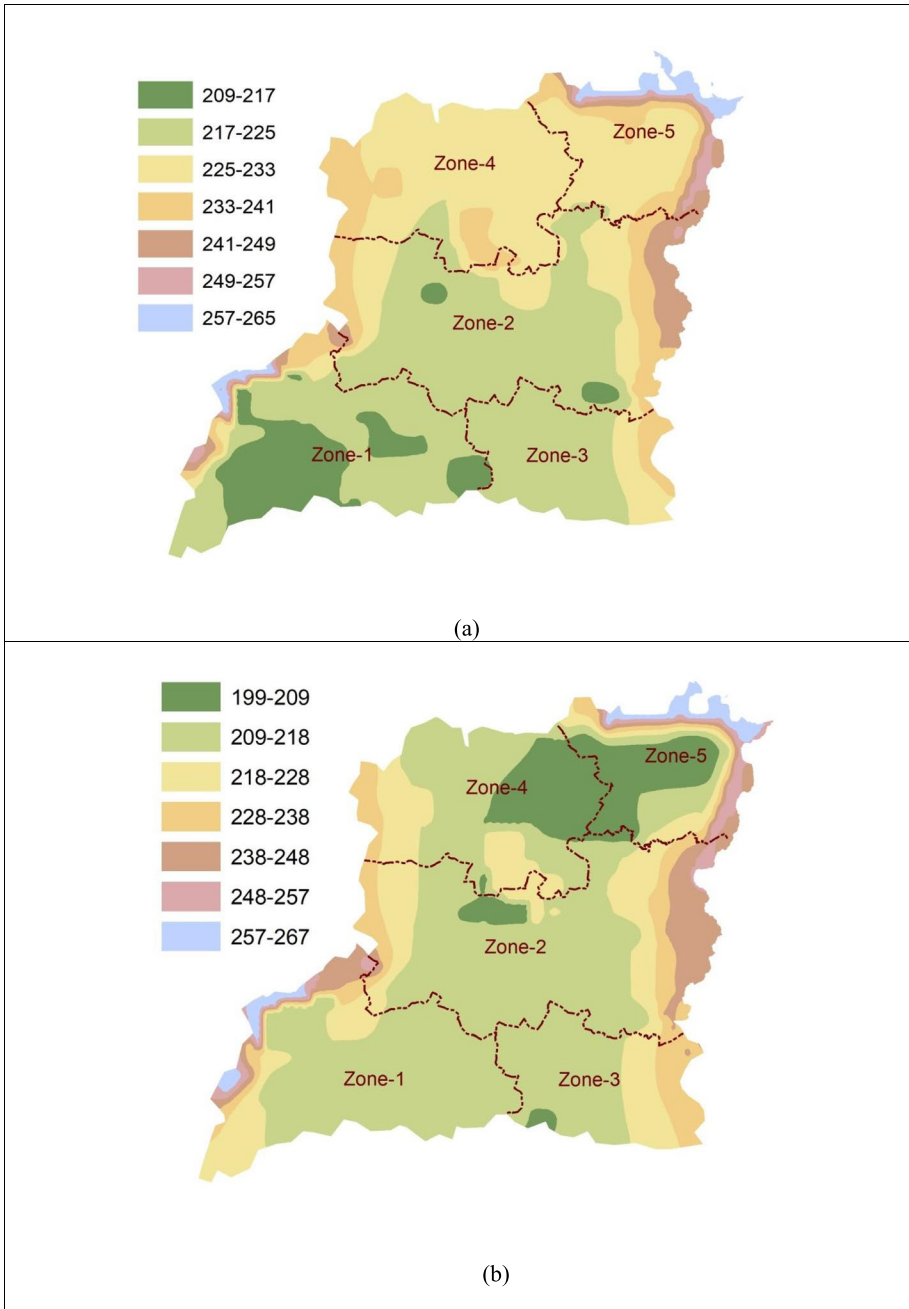
Fig. 6 Return flow during the simulation period under different crop diversification (CD) scenarios in *Kharif* season followed by wheat. Bar represents mean value of return flow simulated for different RCPs, and values given above the bars reflect standard deviation (CD-1 = entire (100%) cropped area under rice (R)-wheat (W) cropping system with existing water supply (EWS) (80 and 20% area irrigated with groundwater (GW) and canal water (CW), respectively); CD-2 = 20% in maize (M) + 80% in rice (R) of cropped area with EWS; CD-3 = 30% (M) + 70% (R) of cropped area with EWS; CD-4 = 40% (M) + 60% (R) of cropped area with EWS; CD-5 = 80% (M) and 20% (R) of cropped area with EWS; CD-6 = entire cropped area under M-W with EWS; CD-7 = entire cropped area under M-W with GW only; CD-8: Entire cropped area under R-W with GW only)

3.4 Spatio-temporal changes in groundwater table depth

To understand the effect of climate change scenarios on spatio-temporal behavior of groundwater table of the study region, under existing rice–wheat cropping pattern and sowing dates (15 June–15 November), variation in groundwater table depth of 5 zones of the study area with reference to the year 2015 is presented in Fig. 7 and Supplementary file-Fig. 5. Results indicated the minimum annual groundwater table decline rate (0.05–0.27 m year^{-1}) in zone 1 and the maximum (0.48–0. 74 m year^{-1}) in zone 5 under different climate change scenarios for the simulation period. This variation in groundwater decline rates may be attributed to the variation in changes of rainfall and temperature under different RCPs, different hydro-geological characteristics and dependency on groundwater for crop production in 5 zones of the study area.

Simulation results also indicated groundwater table decline from the reference groundwater table of 2015 in the range of 1.6–18.3 m, 6.5–40.3 m, and 4.3–61.5 m by the end of early, mid, and end century in different zones and RCPs. Hence, a change of 10.8–285% is projected under different RCPs in various zones. However, groundwater table decline was projected to be the lowest in zone 1, i.e., in the range of 1.6–3.1 m (10.8–20.9%), 6.5–11.2 m (43.7–75.4%), and 4.3–22.2 m (28.9–149.4%) during early, mid, and end century periods, respectively. While the maximum groundwater table decline was projected in zone 5 and varied in the range of 16.3–18.3 m (77.2–86.6%), 34.3–40.3 m (162.4–190.8%), and 40.2 to 61.5 m (190.3–291.2%), respectively, during early, mid, and end century

Fig. 7 Hydraulic head in the study area under different climate change scenario during the simulation period. (**a**) reference year 2015, (**b**) end of early century period under RCP2.6, (**c**) end of mid century period under RCP2.6, (**d**) end of end century period under RCP2.6, (**e**) end of early century period under RCP8.5, (**f**) end of mid century period under RCP8.5, and (**g**) end of end century period under RCP8.5. The presented spatio-temporal groundwater table (hydraulic head) is under existing rice–wheat cropping system with 15 June (rice)–15 November (wheat) sowing dates
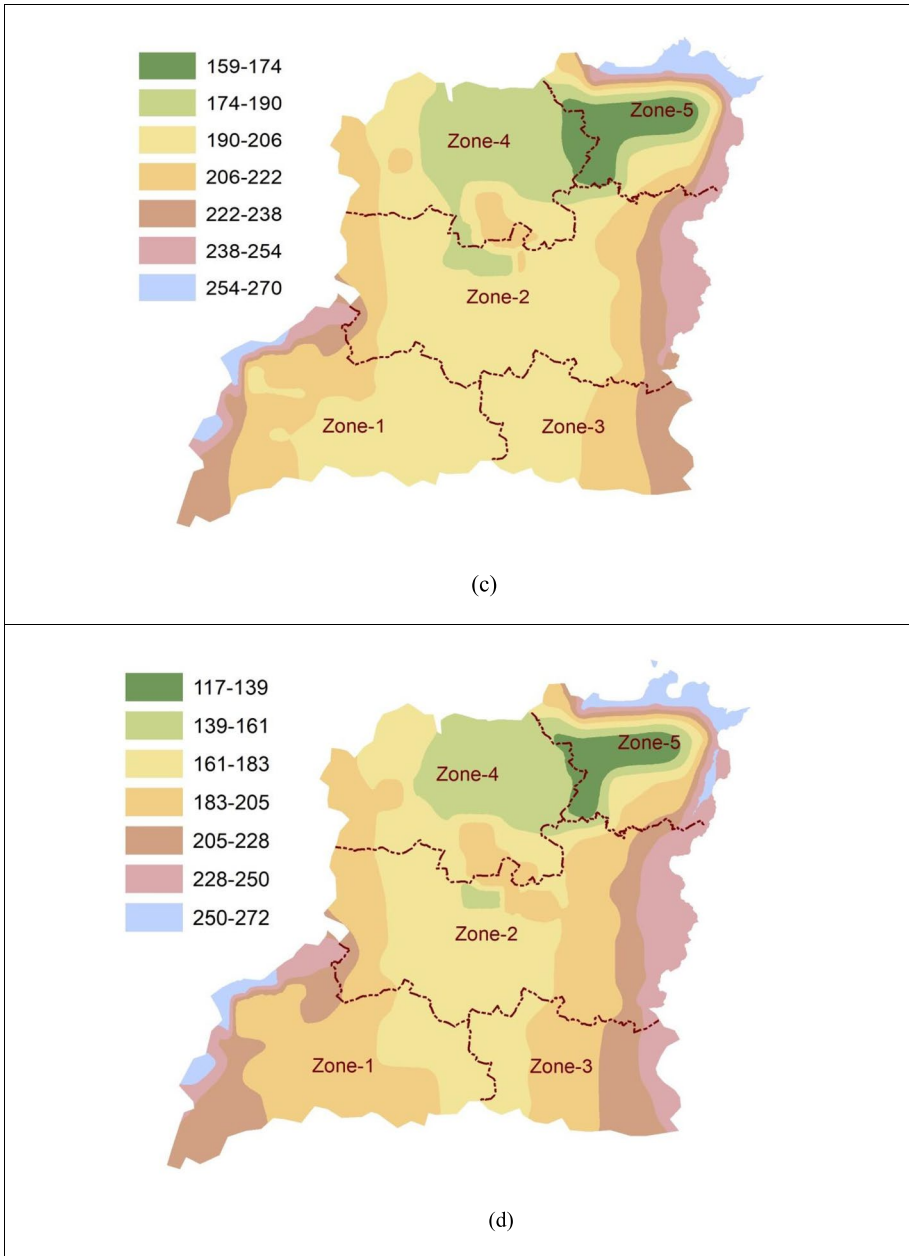
Fig. 7 (continued)

periods under different RCPs. As mentioned earlier, the lower groundwater decline in zone 1 may be attributed to the limited use of marginal quality groundwater for crop production under limited canal water supply, while the highest depletion in zone 5 may be attributed to mainly groundwater dependent rice–wheat cultivation.
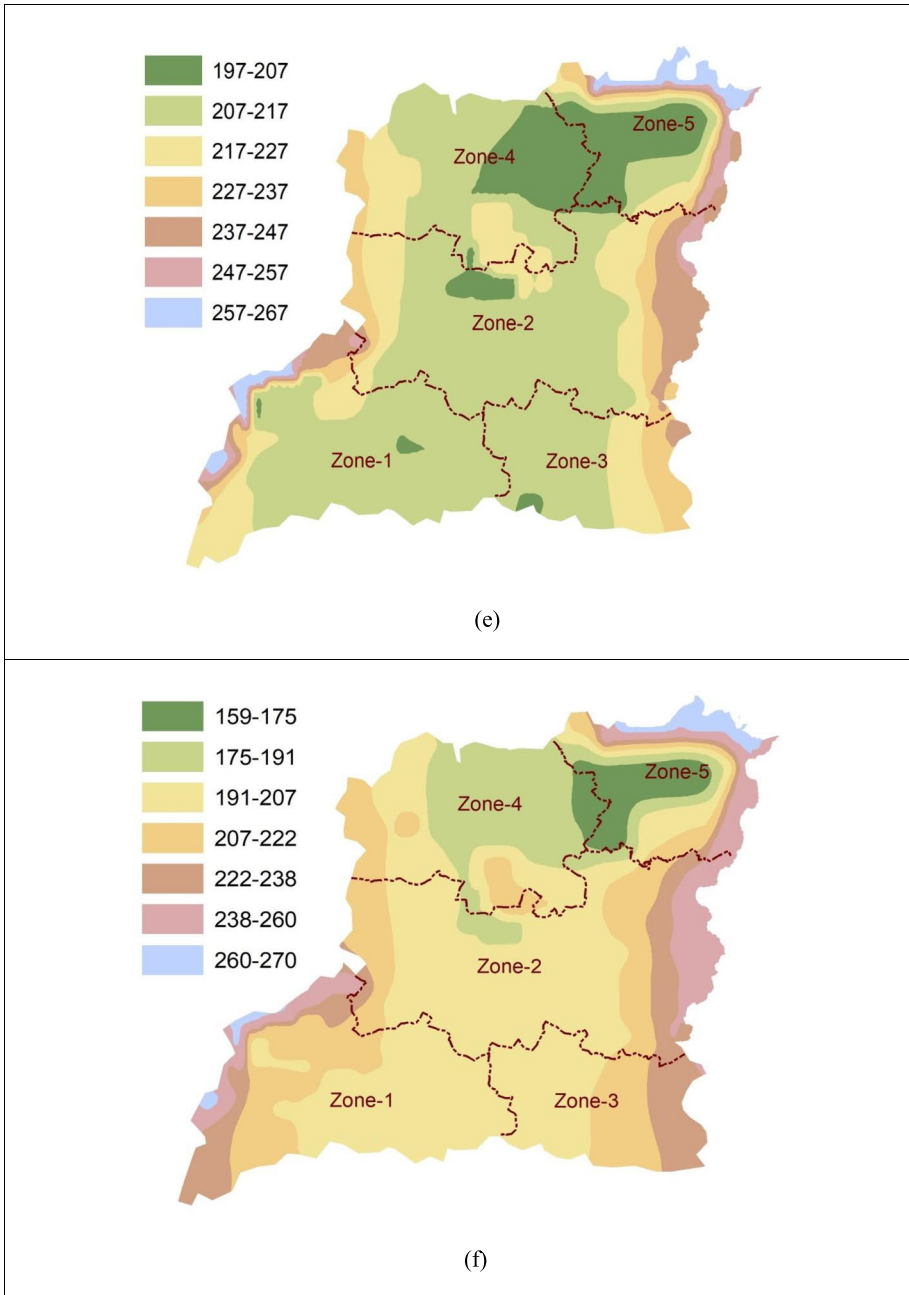
(e)

(f)

Fig. 7 (continued)

The simulation results also revealed that groundwater table decline was minimum under RCP8.5 and maximum under RCP2.6 irrespective of different study zones (Fig. 7). By the end of simulation period (2099), the change in groundwater table from the reference year
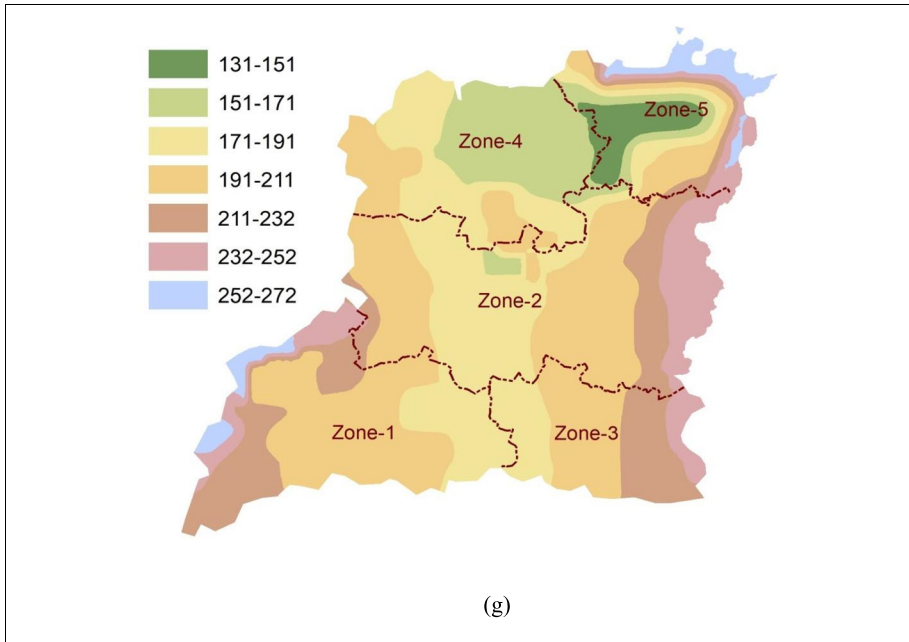
(g)

Fig. 7 (continued)

was 231.8% and 126.9% under RCP 2.6 and 8.5, respectively. The higher groundwater fluctuation in RCP 2.6 than the other RCPs could be attributed to the relatively low rainfall and higher groundwater withdrawal for irrigation due to anticipated higher evapotranspiration with projected higher rise in temperature. Despite higher temperature rise, lower groundwater depletion under RCP 8.5 may be attributed to projected higher precipitation. Therefore, it can be concluded that the increased crop water demand, with higher temperature rise in RCP8.5, is compensated by higher increase in projected rainfall as compared to other RCPs.

3.5 Effect of dates of sowing on groundwater table depth under changing climate

The change in groundwater table of the study area with different sowing dates of rice–wheat under different RCPs is depicted in Fig. 8. For better explanation, mean groundwater table of the study area is compared with mean groundwater table (18.5 m) of year 2015. With prevailing rice–wheat sowing dates (15 June–15 Nov), the groundwater level was found to vary in the range of 26.5–28.2 m, 37.1–42.4 m, and 38.4–58.1 m below ground level (bgl) by the end of early, mid, and end century, respectively, under different RCPs. Delaying rice–wheat sowing dates, by 20 days from the prevailing 15 Jun–15 Nov, resulted in additional decline of groundwater table, in the range of 10.9–12.3 m (38.7–46.4%), 23.5–25.8 m (55.4–68.6%), and 32.2–37.9 m (55.4–97.7%) by the end of early, mid, and end century, respectively, in comparison to the existing pair of sowing dates for different RCPs. However, advancing the wheat sowing dates by 10 days with existing rice sowing date (i.e., 15 Jun–5 Nov) resulted in reduction in groundwater table decline by 10.9–12.3 m (38.7–46.4%), 23.5–25.8 m (55.4–68.6%), and 32.2–37.9 m (55.4–97.7%)
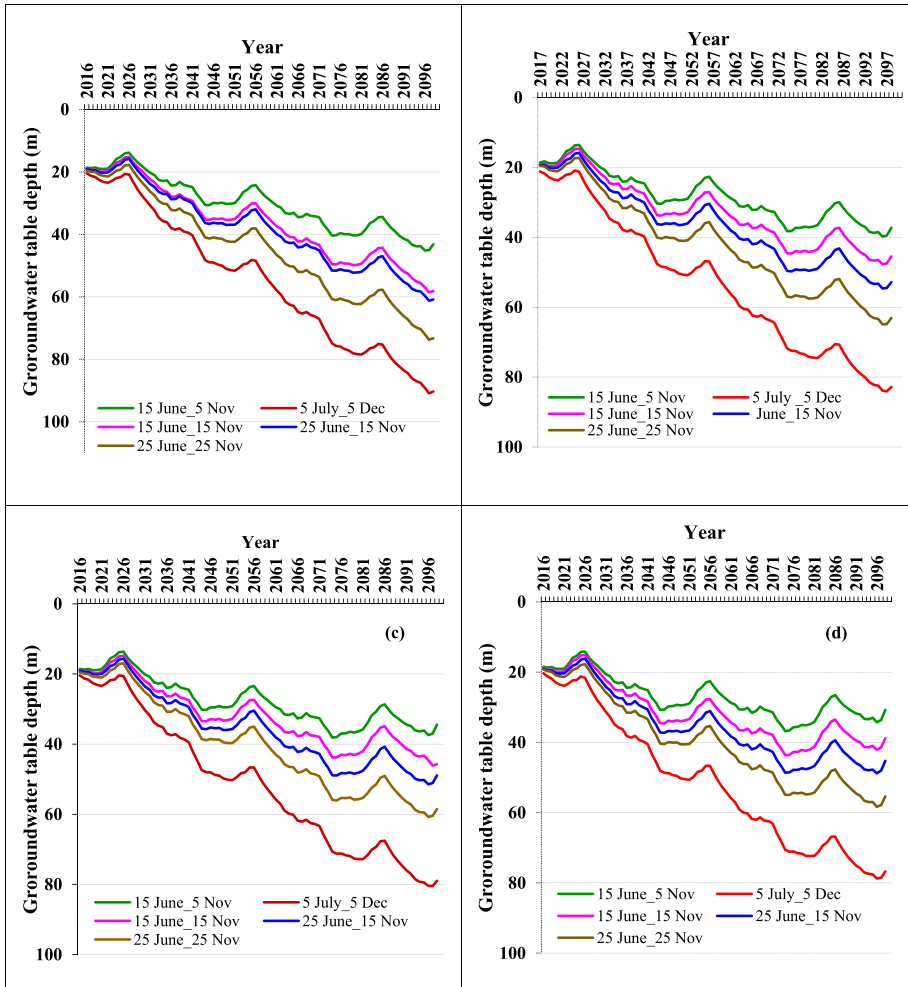
Fig. 8 Groundwater table depth (distance in m below ground level) for different pair of sowing dates of rice–wheat cropping system under (**a**) RCP2.6, (**b**) RCP4.5, (**c**) RCP6.0, and (**d**) RCP8.5

to the prevailing rice–wheat sowing dates (15 Jun–15 Nov) under different RCPs (Fig. 8). This lower groundwater table decline with advancement of wheat sowing dates by 10 days is attributed to the reduced groundwater draft for irrigation with advancement of wheat sowing date due to relatively less warm climate that resulted in lower evapotranspiration demand. This observation confirms the previous findings that appropriate sowing date reduces evapotranspiration demand and saves irrigation of wheat which plays a major role in groundwater table decline in rice–wheat cropping system (Jalota et al. 2018; Kaushika et al. 2019). Singh et al. (2015) also reported that delay in wheat sowing pushes growing season into period of high evaporative demand which leads to more irrigation in northwest India.

Since groundwater fluctuation in the study region is directly associated with irrigation demand, any effort to reduce irrigation amount will definitely help in moderating the

rate of groundwater table decline. In the study region, the onset of monsoon occurs by the end of summer month (June) and withdrawal begins in second week of September. Hence, manipulating rice growing season with the aim to utilize maximum rainfall may reduce dependency on groundwater irrigation. Further, use of short duration rice varieties and selecting sowing/transplanting date in such a way that maximum growing period of rice falls within the monsoon (rainy) period may also reduce groundwater draft. Though short duration rice varieties are being adopted by few farmers in the region for rice-potato cropping system, there is urgent need to promote those rice varieties for rice–wheat cropping system as well so that early sowing of wheat can also be adopted. Thus, short duration rice varieties with suitable sowing date coupled with early wheat sowing can be an effective option for sustainable management of groundwater resources of the study area under changing climatic threats.

3.6 Effect of crop diversification on groundwater table depth under changing climate

The effect of crop diversification, i.e., replacement of rice area with maize in different proportions followed by wheat with prevailing dates of sowing of rice–wheat cropping system (15 June–15 Nov) and maize (15 June), on groundwater behavior under different RCPs, is depicted in Fig. 9. Simulation results indicated that groundwater table decline rate will be reduced with the increase in proportion of maize area as compared to rice–wheat cropping system (Fig. 9). However, if the entire rice area (100%) is replaced by maize (CD-6), surprisingly higher decline in groundwater level is observed as compared to rice–wheat cropping system (CD-1). This could be attributed to relatively lower return flow from maize fields as compared to rice fields, which offsets the benefit of groundwater augmentation with available canal water supply. This was the reason that difference between recharge and draft (groundwater system loss) was more negative in CD-6 in comparison to CD-1 in all climate change scenarios. For example, under RCP2.6, groundwater system loss was estimated as 2.68 and − 4.04 m in CD-1 and CD-6, respectively, during early century period (Supplementary file-Table 5). Higher irrigation demand of rice significantly contributes towards return flow and thus helps in reducing recharge and draft gap as compared to CD-6 for maize-wheat cropping system. Hence, 100% replacement of rice with maize (CD-6) rebuffs the benefit of return flow under existing water supply scenario. It also shows the contribution of surface water supplies in sustained groundwater management of the study area.

The greater change in groundwater level is projected under RCP2.6 for the simulation period of 2016–2099, whereas it was found to be the least under RCP8.5 for all crop diversification scenarios (Fig. 9). For the simulation period (2016–2099), a reduction in annual groundwater table decline of about 26.1%, 33.3%, 40.2%, and 82% is projected in CD-2, CD-3, CD-4, and CD-5, respectively, under RCP2.6 as compared to the decline rate of 0.48 m of CD-1. Under RCP 8.5, reduction in groundwater decline rate is projected as 27.9%, 42.7%, and 57.6% in CD-2, CD-3, and CD-4, respectively, as compared to CD-1 (0.24 m year^{-1}). Interestingly, groundwater table will rise with an annual rate of 0.11 m year^{-1} in CD-5 under RCP8.5. Simulation results also indicated that the declining rate would further increase in CD-7 and CD-8. It is projected to be 64.2% and 117.6% higher in CD-7 and CD-8, respectively, than CD-1, under RCP2.6 for the respective diversification options. However, under RCP8.5 with the same crop management plans (CD-7 and CD-8), the decline rate was projected to be increased by 147.4% and 287.6%
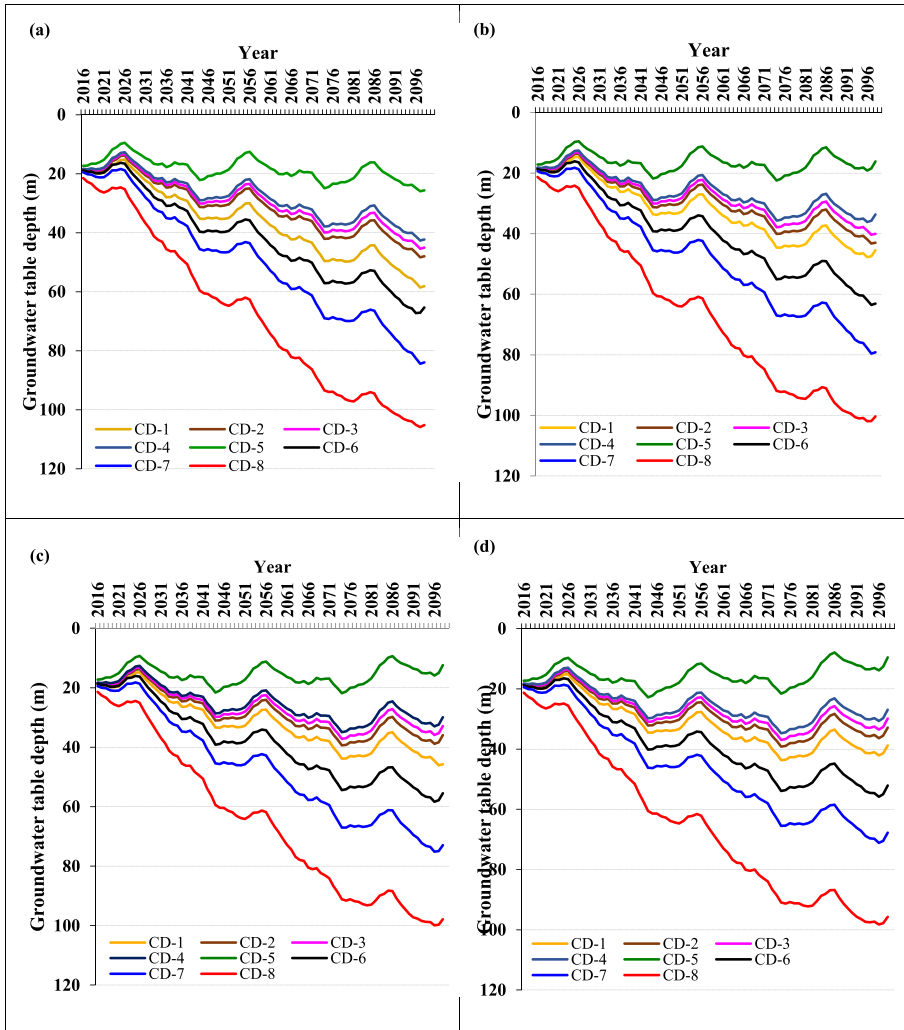
Fig. 9 Simulated groundwater table depth (distance in m below ground level) under different crop diversification scenarios (CDs) for (**a**) RCP 2.6, (**b**) RCP 4.5, (**c**) RCP 6.0, and (**d**) RCP 8

in comparison of CD-1 (0.24 m year^{-1}). Hence, results indicate that if groundwater is the sole source of irrigation, CD-7 had advantage over CD-8 in terms of better groundwater management.

For a better explanation of impact of proposed crop diversification scenarios, the groundwater level decline was analyzed with reference to the existing cropping system (CD-1) for the respective periods. The decline in groundwater level in CD-1, from the reference level (18.5 m), is projected in the range of 9.6 to 39.6 m (51.9–214.1%), 8.0 to 26.9 (43.2–145.4%), 8.0 to 27.2 (43.2–147%), and 8.7 to 20.3 m (47–109.7%) under RCP2.6, RCP4.5, RCP6.0, and RCP8.5, respectively (Fig. 9). Results indicated that substitution of rice area by maize will help in controlling the decline in groundwater to some extent as CD-2, CD-3, CD-4, and CD-5 recorded about 19.3, 24.8, 30.0, and 62.0% less groundwater

table decline as compared to CD-1 by the end of early century period under RCP 2.6. For the same RCP, groundwater level decline was projected to be reduced by 38.3, 49.0, 59.6, and 123.4% by the end of mid century, and 55.1, 70.6, 85.6, and 175.6% by the end of end century in CD-2, CD-3, CD-4, and CD-5, respectively, as compared to CD-1. It was simulated that groundwater table depth would reach to 28.2, 42.3, and 58.2 m at the end of early, mid, and end century, respectively, in CD-1 under RCP2.6. It was noticed that by the end of simulation period (2099), groundwater table depth will be 16.2, 12.4, and 9.5 m under RCP4.5, RCP6.0, and RCP8.5, respectively, in CD-5. Hence, groundwater table depth would rise by 12.4%, 33.0%, and 48.1% in CD-5 from the reference groundwater table (18.5 m) under RCP4.5, RCP6.0, and RCP8.5, respectively. It indicates that replacement of 80% rice area with maize (CD-5) would likely help to control the declining of groundwater level. This means that replacement of 80% of existing rice area by maize would likely to reverse declining rate of groundwater level of CD-1. Instead of explaining groundwater simulation results of each climate change scenario for CD-6, CD-7, and CD-8, the mean value of all RCPs is discussed here. In CD-6, CD-7, and CD-8, additional groundwater table decline of 4.2 (48.8%), 9.0 (105%), and 21.1 (245.3%) m is projected during the end of early century, 8.7 (43.1%), 19.4 (96.2%), and 44.0 (218.8%) m during end of mid-century, and 12.0 (42%), 28.9 (101.4%), and 52.7 (304.2%) m during the end of end century period, respectively, as compared to the anticipated average decline of 8.6, 20.1, and 28.5 m in CD-1 from the reference groundwater level. The low return flow from the maize fields in CD-6 and CD-7 is responsible for higher groundwater table decline than the existing practices (CD-1); while in CD-8, the higher decline is projected due to more water withdrawal than the others because the entire area is irrigated by groundwater only. Hence, it is clear that total dependability on groundwater for irrigation would have adverse effect on groundwater resources in both the cropping systems (CD-7 and CD-8). But, maize-wheat (CD-7) system would be better option than rice–wheat cropping system (CD-8) in the absence of canal water supply. These results are confirmation of the earlier findings that maize-wheat cropping pattern can be better option for arresting declining groundwater level of northwest India (Jalota and Arora, 2002).

Simulation results clearly indicate that irrespective of RCPs and time period, maize + rice–wheat cropping system has clear advantage over the existing rice–wheat system for minimizing/arresting the groundwater-level declining rate. The results are on similar note that switching to less water-intensive cereals could be one way to reduce pressure on existing groundwater reserves of India (Davis et al. 2018). Minhas et al. (2010) also advocated shifting from traditional rice–wheat cropping system to other low water requiring cropping system like maize-wheat to arrest alarming rate of groundwater table decline in this region of India. The state governments are trying hard to increase crop diversification by promoting maize in the existing rice–wheat system (Siwach, 2019). However, due to the most stable and remunerative rice–wheat sequence owing to well established marketing system, convincing farmers for maize-wheat system is a challenging task. Nonetheless, the prevalent rice–wheat system has been perceived to be ecologically and economically unsustainable due to fast degradation of soil and depleting groundwater resources in Indo-Gangetic Plains. At the same time, substitution of rice by maize is reported to improve the system productivity and profitability by ~ 12 and 45%, respectively, with saving of ~ 70% irrigation water (Jat et al., 2021). Here, it is also pertinent to mention that monitory incentives for adoption of less water requiring crop, provision of enabling policies, and infrastructure for assured procurement and higher income through processing and value addition to maize can attract farmers for its adoption. How much area can be replaced could be a debatable issue, but simulation study indicated that replacement of 80% rice area with

maize in prevalent rice–wheat system can be a good option from the groundwater sustainability point of view.

4 Summary and conclusions

The groundwater resources in agriculturally important rice–wheat cropping system dominant northwestern India have depleted at an alarming rate during the past few decades, and the situation is likely to further aggravate with anticipated climate change and variability. Since northwest India is an agriculturally dominant region, devising suitable crop management strategies is essential for sustainable management of groundwater resources. Results of the present modeling study are based on crop growth simulation model "Aquacrop," transport model "Hydrus-1D," and groundwater flow model "MODFLOW." Effects of existing cropping system (*business as usual*) and management options like shifting rice–wheat sowing dates and fractional diversification of rice area to maize were simulated using MODFLOW model to study the groundwater behavior under projected climate change scenarios. Aquacrop model was found to satisfactorily simulate the yield and return flow from rice and maize field both during calibration and validation periods. Similarly, MODFLOW was found to explicitly simulate the hydraulic heads both during calibration and validation period with NSE, R^2, RMSE, ME, and MAE values of 0.97, 0.97, 2.36 m, -0.37 m, and 1.62 m, respectively, during calibration period and 0.93, 0.93, 1.85 m, -0.025 m, and 1.85 m, respectively, during validation period.

Based on the simulations, the study proposes for futuristic strategies for better management of depleting groundwater resources in Karnal district of Haryana, India. Comprehensive modeling results of our study can be synthesized into following salient conclusions:

1. The *business as usual* scenario (rice–wheat cropping system with sowing dates of 15 June for rice and 15 November for wheat) would lead to groundwater decline in the range of 26.5–28.4 m, 37.1–42.4 m, and 38.8–58.2 m in early, mid, and end century periods, respectively, under different RCPs. The groundwater decline (with reference to the year 2015) would vary considerably in the range of 4.3–61.5 m in different zones of the study area by the end century under above RCPs.
2. Delay in sowing dates of rice–wheat tended to increase groundwater draft under different RCPs vis-à-vis prevailing sowing dates. But advancing only wheat sowing date by 10 days from the existing 15 November (keeping same rice sowing date of 15 June) has potential to reduce groundwater decline by 9.8–14.4%, 14.4–19.6%, and 18.1–25.8% by early, mid, and end century periods, respectively.
3. Diversification of rice by maize during *Kharif* and keeping wheat during post monsoon *Rabi* season has clear advantage in terms of lesser groundwater decline over the prevailing rice–wheat cropping system. Replacing 20%, 30%, and 40% rice area by maize in rice–wheat system can reduce mean (average of RCPs) groundwater decline by 7.1 (24.9%), 10.1 (35.3%), and 13.8 (48.5%) m, respectively, in comparison to the projected end century (2099) decline of 28.50 m under prevailing sowing dates of rice–wheat. Further, replacement of 80% rice area by maize crop could reverse declining groundwater trend of rice–wheat in the study region. Such replacement would help to raise groundwater table depth by 2.4, 6.20, and 9.0 m under RCP4.5, RCP6.0, and RCP8.5, respectively, by the end century (2099) over that of reference groundwater level of 18.5 m in the prevailing rice–wheat system.

4. For desired groundwater resource equilibrium (draft equals replenishment) under the changing climate scenarios, different strategies such as introduction of supplementary approaches for diversification to less water consuming crops, short duration rice varieties, improved surface water supplies to reduce groundwater withdrawal and artificial enhancement of groundwater recharge would be helpful in arresting declining water table in the region.

5. Appropriate policy framework, based on efficient procurement and marketing infrastructure, incentives for cultivation of maize and other low water requiring crops, processing industries and emphasis on measures for improvement of water productivity, and farmer's income rather than just crop yields, will have to be devised and implemented for groundwater sustainability in similar ecologies in northwest India.

Results presented in this study will be helpful to prepare suitable strategies for sustainable management of groundwater resources in the study region. However, simulated groundwater draft and recharge are subjected to uncertainty due to model parameter uncertainty, soil heterogeneity, irrigation practices and groundwater pumping, other management practices, as well as future climate change projections (Dangar et al. 2021). Further, we have used CMIP5 climate change projections, which projects consistent increase in rainfall in the study area under all the RCPs. However, most of the global climate models lack skills to simulate summer monsoon variability (Kitoh et al. 2013; Ashfaq et al. 2017) . Further, daily rainfall is used to drive the model and changes in rainfall pattern (intensity and duration) were not considered in the study. As the changes in rainfall intensity influences the monsoon season groundwater recharge (Asoka et al. 2018), consideration of rainfall duration and intensity will reduce the uncertainty in simulation of groundwater draft and recharge. The estimated fluxes for different sources were loosely coupled with the visual MODFLOW flex in groundwater simulation of the study area. However, recently developed version, i.e., MODFLOW-NWT, provides opportunity of extracting and adding information of different independent sources to the same numerical solution, in addition to accounting water flow in dry cell and stream flow-aquifer interaction. The better handling of dry cell can improve accuracy and reliability of the model results (Hunt and Fienstin, 2012), and thus, its use in future studies may improve groundwater representation further.

Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare no competing interests.

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Authors and Affiliations

Satyendra Kumar[1] · Bhaskar Narjary[1] · Vivekanand[1] · Adlul Islam[2] · R. K. Yadav[1] · S. K. Kamra[1]

✉ Satyendra Kumar
s.kumar2@icar.gov.in

✉ Bhaskar Narjary
bhaskar.narjary@icar.gov.in

[1] ICAR-Central Soil Salinity Research Institute, Karnal 132001, India

[2] Natural Resource Management Division, Indian Council of Agricultural Research, New Delhi 110012, India