



## Impact assessment of climate change on the future conjunctive water use

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### ABSTRACT

The present study was carried out during rainy (*kharif*) and winter (*rabi*) seasons of 2019–20 and 2020–21 in the Puri main canal system's Phulnakhara distributary command, particularly in the coastal districts of Odisha, in eastern part of India. The study offers a new perspective involving the future climate data driven model resulting water requirement at RCP 4.5 in a canal command and after integrating it with the optimal cropping area, the optimal future irrigation water need for *kharif* and *rabi* seasons, have been found out. The impact of climate change was assessed by means of the irrigation water need in future both from the conjunctive use of water sources (surface and groundwater) in the study command area. Based on the prediction results it has been calculated that future irrigation water demand would be the highest in the year 2042–43 during *kharif* season and in the year 2044–45 during the *rabi* season, respectively. It was estimated that the decline in groundwater table in *kharif* would be 1.23–1.42 m below ground level (BGL) and the decline in groundwater table in *rabi* season would be 1.46 to 1.64 m BGL during the upcoming 30 years (2021–22 to 2050–51). So, the values of groundwater table declination would be the highest in 2042–43 and 2044–45 years for *kharif* and *rabi* seasons, respectively. Based on this study, integrating the optimal crop area with future irrigation water need, resulted the groundwater table fluctuation in the permissible limit.

**Keywords:** Climate change, Conjunctive use of water sources, Groundwater table, Irrigation water demand

The earth's climate has altered dramatically from the pre-industrial era, as per the Intergovernmental Panel on Climate Change (IPCC). Generally, three notable visual indicators of climate change have been noted, viz. rise in global average temperature, shifting of regional precipitation patterns and increase in frequency of extreme occurrences, i.e. regional hydrologic extremes of floods and droughts resulting altered groundwater recharge. As per IPCC, anthropogenic greenhouse gas emissions have led to substantial warming of the atmosphere, land, and oceans, with observable consequences such as rising global average temperatures, altered regional precipitation patterns, and an increased frequency of extreme hydrological events like floods and droughts (IPCC 2023). The average global surface temperature is predicted to rise by 1.1–2.9°C for low emission scenarios and 2.4–6.4°C at high emission scenarios during 2090–2099 compared to 1980–1999 (IPCC 2007). So, improved knowledge of the effects of climate change on water resources will aid in the formulation of plans for sustainable use and management of these resources. Integration of surface water and groundwater is governed by

climate, geology, surface topology, ecological quantity and quality of available water. Sahuquillo *et al.* (2022) suggested that the conjunctive use of canal water (surface water) and groundwater can mitigate the impact of climate change. Tabari (2020) reported that due to climate change, there is occurrence of extreme events, i.e. due to uneven distribution of rainfall, some months receive too much water whereas there are water shortages in the remaining months, which can be overcome by conjunctive water use. In addition to helping with water conservation (demand management), it is a beneficial addition for meeting water needs during dry spells and interruptions in the water supply. The aim is to bridge the research gap by analyzing the effect of climate change on future irrigation demand in the Phulnakhara canal command area under RCP 4.5 scenario, utilizing the outputs from one of the best performing GCMs. The anticipated variation in future irrigation water demand and water table declination hold substantial implications for policymakers, providing valuable insights for future irrigation planning and reservoir operation modeling within the command area. By addressing this gap in the literature, this study contributes to the broader understanding of climate change impacts on crop evapotranspiration, irrigation water demand at the command level.

Here, the climate change impact was assessed for future years from the perspectives of conjunctive water resources'

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uses in the command area, i.e. a gap analysis was done between the future seasonal crop water demand and the present supply of irrigation water in a canal system that is based on runoff from rivers (*Phulnakhara* distributary of *Puri* main canal) in eastern Odisha. Presently, plenty of groundwater resource is available in the study area, the deficit in irrigation supply from the canal system can be fulfilled through conjunctive use of groundwater. But for the future, the climate change impact will cause the decline in the groundwater table, resulting the diminished irrigation water supply from the conjunctive water resources.

This study offers a novel approach by integrating surface water and groundwater management through an optimization and a climate model tailored to the specific needs of the *Phulnakhara* canal command area. It comprehensively analyzed future water table fluctuations in both the cropping seasons, offering critical insights for future water management and policy formulation in the region. Additionally, the use of future climate data driven model in forecasting long-term sustainability under changing climatic conditions contributes to the originality of this approach.

#### MATERIALS AND METHODS

*Area of study:* The present study was carried out during rainy (*kharif*) and winter (*rabi*) seasons of 2019–20 and 2020–21 in the *Puri* main canal system's *Phulnakhara* distributary command (20°19'16"N to 20°14'56"N and 85°52'52"E to 86°0'0"E, and elevation ranging from 0–29 m amsl) particularly in the coastal districts of Odisha, in eastern part of India. The *Phulnakhara* distributary originates from the *Puri* main canal system's *Kakatpur* branch canal and spans 21.41 km. It has 4903.29 ha cultivable command area and a 6.03 cumec design discharge. The canal command has more than 60% area with 1% slope, 35% area having 2% slope and rest 5% area have a slope of 2–5%. Mostly, the distributary command area is hegemonized by clay and loam soil. The bulk density of the soil ranged from 1.42–1.64 g/cm<sup>3</sup>. In the research region, there is roughly 1530 mm of yearly rainfall on average. During the *kharif* season, more irrigation water is delivered to the *Phulnakhara* distributary command area, than the necessary amount. The canal flow during *rabi* season, was far less than the full supply level, making it impossible to meet the crops' irrigation needs. A sizeable portion of the command remained fallow since the canal water throughout *rabi* and summer is insufficient to meet the crop water demand (Mishra *et al.* 2008). This can be overcome by using the groundwater resources.

*Data requirement and processing:* Various climatic parameters like rainfall, minimum and maximum temperature, solar radiation on earth's surface on daily basis for future years, viz. 2022–2051 were obtained from the MarkSim Global Climate Model (GCM) at representative concentration pathway (RCP)-4.5, by the model Global Coupled Model-CM3, created at Geophysical Fluid Dynamics Laboratory (GFDL).

The sub-division office of the Water Resources Department, Pratapnagari, Govt. of Odisha, provided the

daily canal discharge data at the head regulator (HR) of the *Phulnakhara* distributary, which is used for comprehending the canal delivery schedule and comparing with the irrigation demand from the optimal cropped area.

The main crops planted in the command region are paddy, vegetables in more areas and maize, chilly, ginger in lesser areas in *kharif* season. Similarly, *rabi* season is used to cultivate summer paddy, wheat, maize, green gram, black gram, gram, field pea, groundnut, sugarcane, potato, other vegetables, mustard, sesamum, sunflower, onion, chilly and turmeric. The optimal area of the studied command is given in Table 1, which was obtained from the optimization model WinQSB by involving the area, yield, production, total water requirement, irrigation water requirement data, Minimum Support Price (MSP), and cost of cultivation data (Dalai *et al.* 2023).

The minimum and maximum area constraint in *kharif* season was decided by considering *kharif* paddy as base crop. So 50% area of the total command is considered as the minimum area for *kharif* paddy and rest 50% area of the command is considered as the maximum area constraint for *kharif* maize, *kharif* other vegetables, *kharif* chilly, and ginger. The minimum area constraint for these *kharif* crops are considered as the least area under respective crops grown in the last 10 years in the canal command. Similarly,

Table 1 Optimal area for different *kharif* and *rabi* crops in *Phulnakhara* canal command

<i>Kharif</i> Crops	Optimal area (ha)
Paddy	2,451
Maize	5
Other Vegetables	236
Chilly	18
Ginger	2,193
<i>Rabi</i> Crops	Optimal area (ha)
Paddy	49
Wheat	0
Maize	3
Greengram	728
Blackgram	403
Gram	3
Field Pea	4
Groundnut	50
Sesamum Til	6
Sunflower	1
Mustard	20
Potato	76
Onion	18
Other Vegetables	649
Chilly	48
Sugarcane	22
Turmeric	2,824

the maximum area constraint during *rabi* season was decided by taking greengram and *rabi* other vegetables as base crops. So, 100% area of the total command is considered as the maximum area for greengram and *rabi* vegetables. The actual minimum area for these two crops in last 10 years' period together was found to be about 28% of the total command area. Hence, 72% area of the command is considered as the maximum area constraints for rest of the *rabi* crops. The minimum area constraint for *rabi* crops are considered as the least area under respective crops grown in the last 10 years in the canal command (Dalai *et al.* 2023).

**Extraction of climatic data from GCM model:** MarkSim GCM is one of the tools to produce daily climate data, which shows the resemblance of the future climatic parameters for any place on the earth. This web-based programme makes use of techniques for data production by downscaling with a user friendly interface in Google Earth (<https://gisweb.ciat.cgiar.org/MarkSimGCM/#>). The International Centre for Tropical Agriculture (CIAT) developed MarkSim, which is a spatially explicit daily weather generator, that was made available in 2004 (Mishra *et al.* 2018). MarkSim GCM tool and similar approach have been used to download the future climatic data of Rasulpur Jattan village, situated in Shahpur block of Muzaffarnagar district, Uttar Pradesh and the future climatic data was analyzed (Mishra *et al.* 2018). First, MarkSim computes the daily precipitation, from which it derives the weather variables like daily solar radiation, maximum and minimum temperature. By using the monthly means of these variables, it calculates the maximum and minimum daily air temperatures as well as the values of daily solar radiation (Jones and Thornton 2013). In MarkSim GCM, a total of 17 global climate models are accessible. The study now underway, chose to acquire future climate data using the GFDL-Global Coupled Model-CM3 for *Phulnakhara* distributary command, as amongst 17 Global Climate Models available in MarkSim GCM, GFDL is the most suitable model for the study, i.e. its advanced representation of aerosol-cloud interactions, atmospheric chemistry, and land-atmosphere coupling, making it suitable for studying climate change and decadal prediction.

The IPCC designated a trajectory for greenhouse gas concentrations known as RCP. The IPCC's 5<sup>th</sup> Assessment Report (AR5) from 2014 employed four pathways for climate research and modelling approaches. The RCPs—initially RCP 2.6, RCP 4.5, RCP 6, and RCP 8.5—are categorized after a feasible range of radiative force in the year 2100 (2.6, 4.5, 6 and 8.5 W/m<sup>2</sup>, respectively) (Moss and Elgizouli 2008, Weyant *et al.* 2009).

The Global Change Assessment Model (GCAM) team at the Joint Global Change Research Institute (JGCRI) in the United States developed Representative Concentration

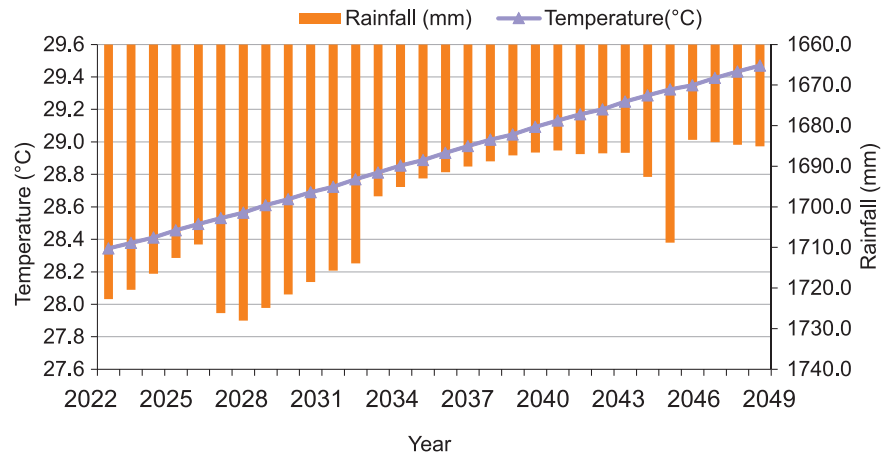


Fig. 1 Multi-year average rainfall and temperature of the study area.

Pathway (RCP)-4.5 and under RCP 4.5, the long-run radioactive forcing target level is not exceeded, and the total radiative forcing level stabilizes soon after 2100 (Wayne 2013). This is a scenario with medium emissions where, carbon dioxide emissions rise somewhat before beginning to drop about 2040, methane emissions are stabilized, and crop and grassland consumption declines as a result of rising yields and dietary changes. In this scenario, the temperature increases more quickly until the middle of the century and then decreases.

The analysis focuses on RCP 4.5 scenario, excluding lower emission pathways RCP 2.5 and higher emission pathways RCP 8.5, which could offer an optimistic outlook.

**Future climate parameters:** A graph showing multi-year average future rainfall and temperature is provided in Fig. 1. From the graph, it is confirmed that the temperature presents an increasing trend, whereas the rainfall presents an increasing trend until 2034; then, there is a decreasing rainfall until 2051, barring 2047.

**Future climate parameter analysis:** The reference evapotranspiration was calculated by the Hargreaves equation involving the future projected temperature and solar radiation data (Michael 2007), expressed as follows:

$$ET_0 = 0.0023 (T_{\text{mean}} + 17.8) (T_{\text{max}} - T_{\text{min}})^{0.5} R_a \quad (1)$$

Where  $ET_0$ , Reference evapotranspiration (mm/day);  $T_{\text{max}}$ , Maximum air temperature for a given day (°C);  $T_{\text{min}}$ , Minimum air temperature for a given day (°C);  $T_{\text{mean}}$ , Mean air temperature for a given day (°C);  $R_a$ , Extraterrestrial solar radiation (mm/d). The unit of  $R_a$  in equation (1) is changed from MJ/m<sup>2</sup>/day to mm/day by multiplying a conversion factor 0.408.

The data on solar radiation observed on earth's surface, derived from the MarkSim model, must be transformed into extraterrestrial radiation by the following relationship:

$$R_s = K (T_{\text{max}} - T_{\text{min}})^{0.5} R_a \quad (2)$$

Where  $R_s$ , Solar radiation on earth surface (MJ/m/day);  $R_a$ , Extraterrestrial solar radiation (MJ/m<sup>2</sup>/day);  $K$ , Adjustment coefficient (taken as 0.16 for interior regions where land mass is predominant and air masses are not

significantly influenced by large water bodies).

*Crop evapotranspiration:* Crop evapotranspiration ( $ET_c$ ) is determined by the product of reference crop evapotranspiration ( $ET_0$ ) and the crop coefficient ( $K_c$ ) (Allen *et al.* 2004).

$$ET_c = K_c \times ET_0 \tag{3}$$

Where  $ET_c$ , Crop evapotranspiration (mm/d);  $K_c$ , Stage-wise coefficient of crop; and  $ET_0$ , Reference crop evapotranspiration (mm/d).

The parameters, viz. crop coefficient for the various growth phases, length of each stage, planting or sowing date, and the harvesting date for the *kharif* and *rabi* crops (ICAR 2011, Chadha 2003) are used for calculation of demand for irrigation water at the head regulator (HR) (Dalai *et al.* 2022).

*Future irrigation water need for major crops:* The effects of climate change will cause the agriculture sector's water demand to change in the upcoming years. So, this industry needs to use water resources efficiently. The estimated  $ET_0$  of future years and the  $K_c$  values of the corresponding crops were used to calculate the irrigation water requirements for the key crops cultivated in the *Phulnakhara* distributary command region. After taking the effective rainfall value and crop water requirement into account, the irrigation water requirement was found out. U.S. Department of Agriculture's Soil Conservation Service (USDA SCS) method was used to calculate effective rainfall (Dastane 1978). The crop water demand at the distributary HR was computed by taking the conveyance efficiency (70%) and application efficiency (60%) into consideration (Brouwer *et al.* 1989). The quantity of irrigation water supply for the month and the season was calculated using the daily canal flow release at the HR of the study distributary. Then comparison was done between demand for crop water and supply of irrigation water.

Reduction in precipitation and increase in the evapotranspiration, cause reduction in recharge and probably enhance groundwater withdrawal rates. Groundwater recharge depends on the distribution, quantity and timing of precipitation as well as evapotranspiration losses. The climate change impact on water resource availability and conjunctive use, especially in canal command is found out. The irrigation water need for the optimal cropping pattern is determined. Considering the surface water availability for these years as the average of the historical years under consideration, the groundwater draft for the future years is determined.

## RESULTS AND DISCUSSION

Research has been undertaken on the effects of climate change for coming 30 years by considering RCP 4.5 scenario. This scenario is considered, as it is the medium emission scenario (650 ppm of carbon dioxide-equivalent emissions). In RCP 4.5 scenario, the demand for irrigation water was calculated for various crops and the average existing irrigation water supply details are given below.

Table 2 Existing irrigation water supply for *kharif* and *rabi* season

Year	<i>Kharif</i> irrigation supply at HR (Mm <sup>3</sup> )	<i>Rabi</i> irrigation supply at HR (Mm <sup>3</sup> )
2011–12	32.36	26.38
2012–13	37.67	0.62
2013–14	39.99	0.00
2014–15	38.02	1.04
2015–16	40.25	0.00
2016–17	29.83	0.00
2017–18	34.86	0.00
2018–19	43.40	1.23
2019–20	39.48	0.00
2020–21	38.00	0.00
10 Yrs Avg	37.39	2.93

HR, Head regulator.

*Average existing supply of irrigation water during kharif and rabi season:* The existing irrigation water supply for 10 years during *kharif* and *rabi* season is presented in Table 2.

*Determination of irrigation water demand for kharif crops:* The highest anticipated demand for irrigation water at the HR of the study distributary was predicted in October (1.33 Mm<sup>3</sup>) followed by November (0.89 Mm<sup>3</sup>) and July (0.23 Mm<sup>3</sup>) (Table 3). The highest irrigation demand is primarily due to the critical growth period (maturity to harvesting stage) of paddy, other vegetables and ginger in October. The amount of water required for irrigation is found to be relatively low in August and June due to heavy rainfall in these two months. When the rain stopped by the end of September, there was a significant need for water in October and November (Dalai 2023). The least amount of water needed for irrigation (almost 0.00 Mm<sup>3</sup>) was found in August.

*Comparison of average existing irrigation water supply with future demand for crop water during kharif season:* The maximum average monthly *kharif* demand for irrigation water calculating 1.33 Mm<sup>3</sup>, was recorded in October, and the lowest was in August (Table 3); in contrast, the HR's

Table 3 Gap between future average irrigation water demand and existing average irrigation water supply on monthly basis for *kharif* season

Months	Future Irrigation Water Demand at HR (Mm <sup>3</sup> )	Irrigation Supply at HR (Mm <sup>3</sup> )	Difference (Mm <sup>3</sup> )
June	0.02	0.04	0.03
July	0.23	0.79	0.56
August	0.00	10.47	10.47
September	0.21	8.50	8.29
October	1.33	11.93	10.61
November	0.89	5.65	4.76
Total	2.67	37.39	34.71

HR, Head regulator.

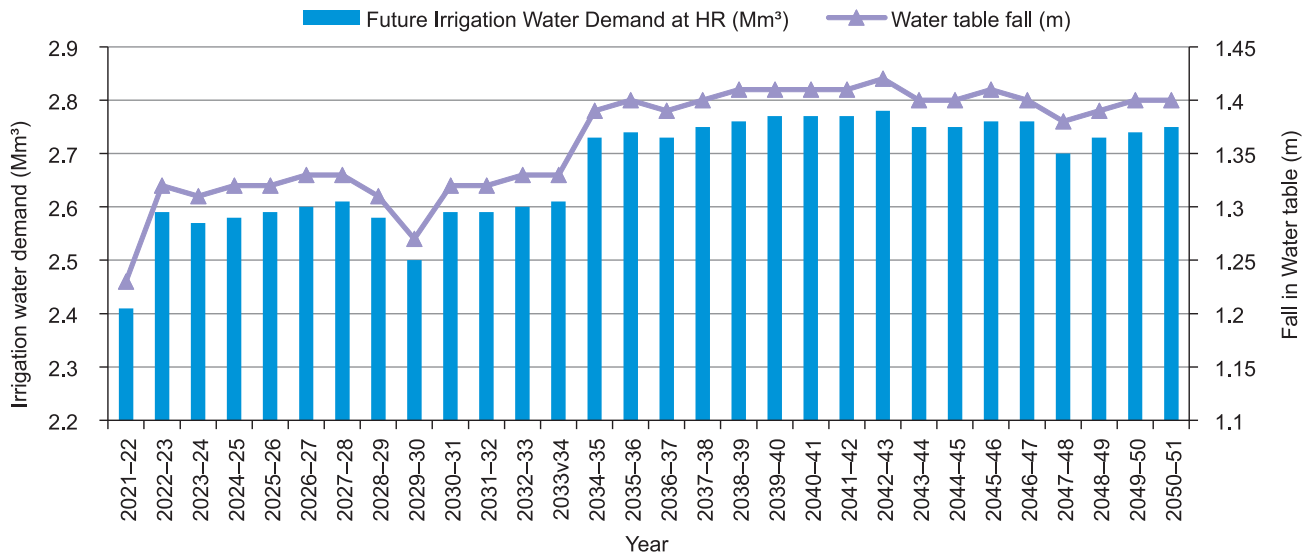


Fig. 2 Future irrigation water demand and average existing irrigation supply gap for *kharif*. HR, Head regulator.

mean monthly *kharif* irrigation supply was at its peak, i.e. 11.93 Mm<sup>3</sup> in October and 0.04 Mm<sup>3</sup> as lowest in June. At the HR, the supply was above the demand for irrigation water during June to November. There was a range of 0.03 Mm<sup>3</sup> in June to 10.61 Mm<sup>3</sup> in October for the difference between irrigation water delivered and future mean monthly *kharif* irrigation water demand.

The gap between future irrigation water demand and average existing irrigation water supply for 30 years during *kharif* season is presented in Supplementary Table 1 and Fig. 2. The highest and the lowest irrigation water demand in *kharif* season was predicted as 2.78 (2042–43) and 2.41 Mm<sup>3</sup> (2021–22), respectively and the groundwater table declination ranged from 1.23–1.42 m.

The future irrigation water demand is based on the optimal cropping pattern. Though the irrigation water demand is marginally lower for future *kharif* periods than the existing 10-year average supply, actually the canal water in the tail reach of the canal command is problematic, farmers used to irrigate their crops by groundwater in *kharif* also along with *rabi* season, as the conveyance cost of water to the farmers' field from the canal is a major issue, these may be the reasons for fall in the water table in above estimate (Dalai 2023).

**Calculation of *rabi* irrigation water demand:** The monthly irrigation water demand throughout the *rabi* season was computed and displayed in Supplementary Table 2. The maximum water demand for irrigation (0.72 Mm<sup>3</sup>) was found to be in March followed by April (0.60 Mm<sup>3</sup>) and January (0.57 Mm<sup>3</sup>). The month of May had the lowest demand for irrigation water (0.32 Mm<sup>3</sup>). As, most of the crops except sugarcane and turmeric have been planted prior to May, so the lowest irrigation water demand has been observed in May.

**Comparison of average existing irrigation water supply with future demand of water for crop throughout *rabi* season:** It is obvious from Supplementary Table 2,

that throughout *rabi* season, the demand in two months (December and January) is more than the supply barring four months (February to May). There is practically little variation in crop water demand and irrigation supply during these four months. The decadal average difference is -0.23 Mm<sup>3</sup>. Therefore, in addition to surface water, groundwater should be tapped as an additional irrigation water source to fulfil the crop water demands. There was a gap ranged from -0.55–0.30 Mm<sup>3</sup> between the irrigation water delivered and mean monthly *rabi* irrigation water demand. Dalai (2023) reported a similar outcome, i.e. during the dry season more irrigation water was needed than could be obtained from the canal in the case of the current continuous canal delivery schedule (Mishra *et al.* 2008). Even though the monthly average of irrigation water supply comes 2.93 Mm<sup>3</sup>, but most of the years have no irrigation water supply, so *rabi* irrigation water demand will be mostly depending on groundwater. The gap between future irrigation water demand and average existing irrigation water supply for 30 years during *rabi* season is presented in Supplementary Table 3 and Fig. 3. The highest and the lowest irrigation water demand in *rabi* season was predicted as 3.20 (2044–45) and 2.87 Mm<sup>3</sup> (2021–22), respectively and the groundwater table fluctuation ranged from 1.46–1.64 m.

It is observed from Supplementary Table 3 that, there is a little gap between future irrigation water demand and average existing irrigation water supply for 30 years during *rabi* season due to the involvement of optimal cropping pattern, which leads to higher water productivity (Dalai 2023). For the (Shared Socio-economic Pathways-1) SSP1-4.5 scenario, a decrease in irrigation water supply is anticipated (-26.8%), primarily due to a decrease in groundwater supplies, which is thought to be restricted to SSP1's natural aquifer recharge (Eekhout *et al.* 2024). Practically, in every research site, surface water irrigation supply contributes more than groundwater during both wheat and rice phases, with the exception of Haryana (*rabi*

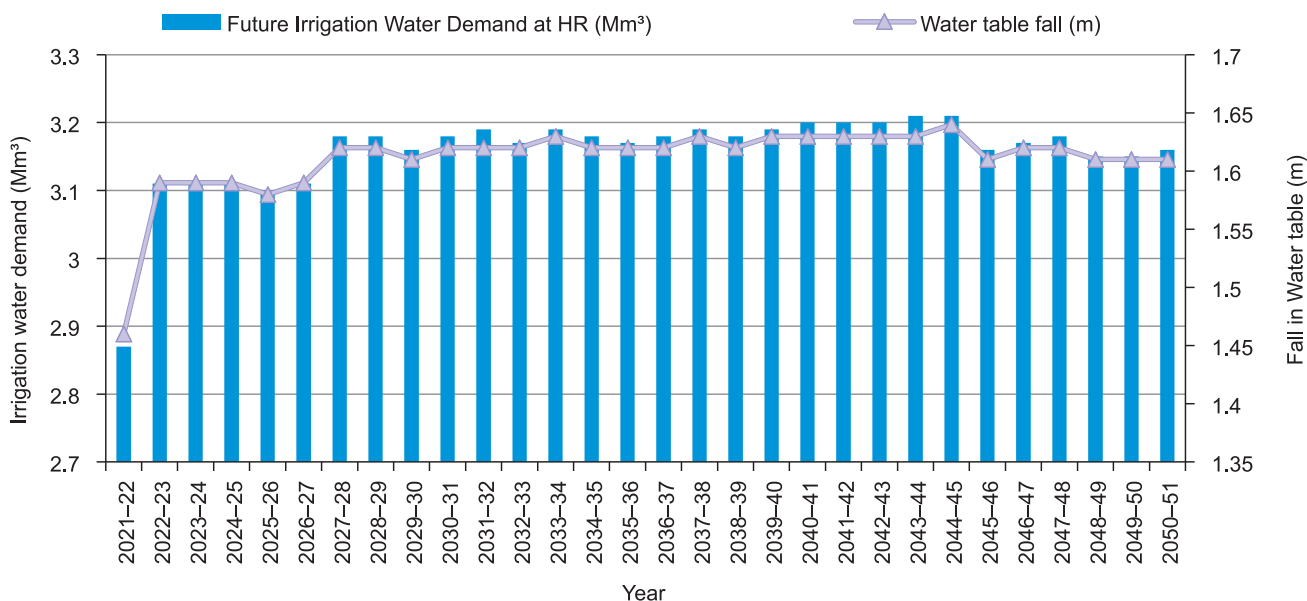


Fig. 3 Future irrigation water demand and average existing irrigation supply gap for *rabi*. HR, Head regulator.

season) and *Terai* region of Nepal (*kharif* season), where groundwater supply predominates (up to 70%) (Ahmad *et al.* 2023). The shortfall in *rabi* irrigation water demand could be fulfilled by groundwater sources, resulting in the declination of groundwater table. It was reported that in the Bhadra command area, crop water requirement (CWR) increased during the *kharif* season under both SSP 245 and 585. However, monthly irrigation water requirement (IWR) for the *kharif* season experienced a significant decrease, except for June. In the Tungabhadra command area, CWR showcased a decreasing trend, while monthly IWR increased for both seasons in future periods (Rudraswamy and Umamahesh 2024). The results enhanced comprehension of water demand dynamics in agricultural areas, assisting policymakers and stakeholders in devising effective strategies to address climate change impacts on agriculture and encourage sustainable practices. The uncertainty in the climate projections will affect future crop water demands and irrigation demands. It is mandatory to estimate crop water requirement for the command area in the future period to know the effect of climate change on individual crops (Rudraswamy and Umamahesh 2024).

Climate projections from GCMs, considering various climate scenarios, have been utilized in several studies to determine the future irrigation demand of a command area (Sunil *et al.* 2021, Sharma and Tare 2022). There exists a mismatch between demand and supply at the command area level (Kumar *et al.* 2022, Rudraswamy and Umamahesh 2024). A significant amount of water is lost to seepage and evaporation before reaching crops, particularly from May to September when high water guzzling crops are cultivated (Khan and Zahid 2024). The amount of water required for irrigation is found to be relatively low in August and June due to heavy rainfall in these two months. As, the future irrigation water demand is based on the optimal cropping pattern, so the irrigation water demand is marginally lower

for future *kharif* periods than the existing 10-year average supply (Mishra *et al.* 2016, Dalai 2023). Results indicated that the supply-demand gap is increased due to rising temperature and falling rainfall (Khan and Zahid 2024). The scenario analysis indicated that the adaptation of high-water requiring crops, i.e. sugarcane must be replaced with crops that consume less water for demand reduction and that will in turn save water (Khalid and Khan 2020). A combination of alteration in cropping patterns and irrigation-system improvement is necessary and more effective in reducing irrigation water demand (Hao *et al.* 2015). Lining of canals and application of a sprinkler irrigation system maximize system reliability up to 17% and 25%, respectively (Hassan *et al.* 2017). For climate change scenarios, the water shortage difference primarily arises when water use rate is highest. Climate change largely effects water use, but it has comparatively small effects on irrigation water supply as well as its availability (Hao *et al.* 2015). Under climate change scenarios, it has been clearly shown by the results that unmet demand will rise in the future as compared to the reference scenario (Berredjem and Hani 2017). Results also displayed that unmet water demand is higher under the climate change scenario with RCP 4.5 as compared to the climate change scenario with RCP 8.5 (Arsiso *et al.* 2017). Demand site water management approaches, i.e. variable cropping structure and improved irrigation systems, will be effective in reducing adverse climate change impacts (Hao *et al.* 2015).

The average result over a decade shows that there is a significant discrepancy between supply and demand because there's an inconsistency between the supply of canal irrigation water and the demand for agricultural water during the *kharif* season of future years. Thus, by making efforts like accurate evaluation of crop coverage, crop water demand and effective flow delivery through enhanced canal operation, the supply with the demand for each year

should be balanced. October is the critical month, in the *kharif* season, where a significant discrepancy between the supply and demand has been observed. Therefore, this season needs special arrangements of automated canal gate closure system with regard to supply of water for irrigation to prevent waterlogging in the canal command. Cropping intensity and productivity are low due to canal's inconsistent operation and the huge gap between the irrigation supply and the demand during *rabi* season. It is consequently advised to use the groundwater resources, which are abundant in the research area, to provide the necessary demand. In order to satisfy the canal command's crop water demand, surface water and groundwater must be used in concert. Optimising the timing of canal deliveries can help somewhat narrow the gap between supply and demand.

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