Climate-induced shifts in irrigation water demand and supply during sensitive crop growth phases in South Asia

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Abstract

This study investigated the shifts in irrigation water demand and supply of the major staple and water-intensive crops (wheat and rice) in the Indus, Ganges and Brahmaputra (IGB) river basins of South Asia under the combined impacts of climate change and socio-economic development during the period 1981–2100. It explores irrigation water usage during climate-sensitive crop growth phases (i.e. vegetative and reproductive which required ~ 60% of the total seasonal (sowing to harvest) water demand), which is supposed to be crucial for long-term integrated crop water management. A hydrology vegetation model Lund Potsdam Jena Managed Land is forced with an ensemble of eight downscaled (5 arc-min) global climate model's using the RCP (Representative concentration pathways) -SSP (Shared socio-economic pathways) framework, i.e. RCP4.5-SSP1 and RCP8.5-SSP3. To investigate phase-specific crop water projections, trend analysis is performed. It shows a significant ($p<0.001$) increase in irrigation water demand during the vegetative phase of wheat (6 mm) and reproductive phase of rice (26 mm) and a decrease during the reproductive phase of wheat (13 mm) and vegetative phase of rice (11 mm) in selected study sites. The large decrease in projected irrigation demand for wheat can be explained by a shortening of the growing season length as a result of rising temperatures and increased precipitation. Whereas, an increase in irrigation demand for rice is a combined effect of higher temperatures and less precipitation during the reproductive phase in the region. At the same time, irrigation supply by surface water and groundwater is likely to change in future due to warmer and drier growing periods, causing a significant increase in groundwater irrigation, mainly for rice. Our major research findings show the importance of crop water assessments during the sensitive crop growth phases of wheat and rice which vary in space and time. Including crop phase-specific, climate impact assessments of regional and global projection will help improve the region's existing crop-water management strategies and adaptation practices.

Keywords Climate change · Phenology · Crop growth phases · Crop water demand · Groundwater irrigation

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1 Introduction

The Indus, Ganges and Brahmaputra (IGB) river basins of South Asia are densely populated and largely depend on the agriculture sector which is highly sensitive to climatic variations (Ali and Erenstein 2017). This region is frequently reported as a climate change and water stress hotspot (Biemans et al. 2019; Kuchimanchi et al. 2021). Water availability and demand in the region are highly variable within and between the years (Lutz et al. 2016a; Terink et al. 2015). Climatic variations play a pivotal role in changing water availability and consumption as indicated by some research studies at global, regional and national levels (Acharjee et al. 2019; Mainuddin et al. 2015). Biemans et al. (2013) estimated the water requirements and availability for current and future food production in five South Asian basins (Indus, Ganges, Brahmaputra, Godavari and Krishna) and reported an enhanced irrigation efficiency along with a rise in regional reservoir storage capacity as an adaptation measures. Another recent study has reported increased future water availability in South Asia due to increased monsoon precipitation (Wijngaard et al. 2018). However, the same study also projected a large water gap, caused by an increase in water demand. The increase in water demand is associated with several factors such as urbanization and industrialization combined with a mismatch between water supply and demand, both in quantity and in timing, which leads to water scarcity in the region (Biemans et al. 2019).

Wheat and rice are the two major staple food crops in South Asia and provide a livelihood to more than one billion people in the region (Arshad et al. 2016; Nawaz et al. 2019). In South Asian countries, about 60 – 90% of the rice-wheat cultivated areas are supported by irrigation (Ambast et al. 2006; Fujisaka et al. 1994). In arid and semi-arid regions of South Asia, more than 40% of the total agriculture production depend on irrigation supply by surface water and groundwater (Krupnik et al. 2017; MacDonald et al. 2016). The distribution of the irrigated land varies within regions and seasons, for example, in IGB river basins during kharif, a much smaller irrigated area (35 Mha) is cultivated than the one in rabi season (46 Mha) (Biemans et al. 2016). Similarly, the distribution of irrigation supply by sources also varies in region and seasons. In case of rice, mostly grown during the kharif season (June – October), a large part of the rice crop water demand in the Eastern part of IGB river basins (Bangladesh, India and Nepal) comes from monsoon rainfall (Wassmann et al. 2009). For wheat, grown during the rabi season (November – March), its water demand is mostly supported by groundwater withdrawals (Biemans et al. 2016). However, in Pakistan (the western part of IGB river basins), agriculture production during the kharif season mainly depends on water supply from surface water and groundwater due to insufficient monsoon rains. For example, in the Indus basin, up to 60% of the total irrigation withdrawals arise from a surface water source as snow and glacier melt (Biemans et al. 2019). During the rabi season, crop water supply largely depends on groundwater extraction (Bhatti et al. 2017; Cheema et al. 2014).

Crop development and growth are mostly dependent on temperature thresholds and water availability (Hatfield and Prueger 2015). A study conducted in the IGB river basins reported that a wide range of crop yields variations, i.e. 27–72% in wheat and 17–55% variation in rice yields are directly associated with the temperature variations (Ahmad et al. 2021). The authors also estimated the impacts of seasonal precipitation variations on crop yields and stated that in the absence of irrigation supply up to 39% and 75% variations in wheat and rice yields are caused by precipitation variations respectively. The increased climate variability and related extremes in the region have negatively affected the crop production which are projected to increase further in future (Ali and Erenstein 2017; Shah et al. 2021). During the crop growing

season, there are certain phases when crops are more sensitive to climatic variations. In particular, overshooting temperature thresholds and shortage of water availability during these sensitive crop growth phases may have serious implications on crop production and can even lead to crop failure (Arshad et al. 2017; Khan et al. 2015). The climate extremes are also likely to bring changes in growing season length and shifts in the timing of all crop growth phases which varies in region and seasons (Acharjee et al. 2017a).

To anticipate the impacts of climate change and to cope and adapt to these variations in space and time in future, a detailed assessment (i.e. when, where and how much) of irrigation water demand by crops and related water supply by sources is essential and should be assessed in an integrated manner (Biemans et al. 2019). A recent study investigated the impacts of climate variability on crop yields at different spatial and temporal scales where crop yields showed stronger sensitivity to phase-specific climate variations (Ahmad et al. 2021). The authors have identified the vegetative and reproductive phases as the most sensitive crop growth phases to climate variations for both wheat (rabi season) and rice (kharif season) in the IGB river basins. The authors have also reported that phase-specific climate variations have strong impacts on irrigation water demand during certain phases which can alter the net crop water demand patterns in future. However, the crop, phase and location-specific impacts of climate change on crop water use (i.e. irrigation water demand and supply) remained unexplored which are crucial for long-term integrated crop water management and sustainable crop production in the region.

Considering the importance of sensitive crop growth phases and projected climate patterns, our hypothesis is that assessing climate-driven changes in growing season length and shifts in the timing of these phases will improve the crop water demand and supply projections in the region. The main objective of this study is to investigate the shifts in irrigation water demand by crops (i.e. wheat in the rabi season and rice in the kharif season) and related changes in water supply by sources (i.e. surface water and groundwater) during the sensitive crop growth phases (i.e. vegetative and reproductive) under a changing climate and socio-economic projections in the IGB river basins.

The crop yield assessment is a critical component of agricultural sustainability that requires a comprehensive analysis of crop phase-specific growth of gross primary production (GPP) that leads to net crop yields which is out of scope of this study. This study is focused on assessing the impacts of climate change on spatio-temporal distributions and changes in irrigation water demand and supply during sensitive crop growth phases (i.e. vegetative and reproductive). The climate-driven changes in growing season length and occurrence of crop growth phases which are not fixed over space are taken into account and are of utmost importance for realistic crop water plaining. To our knowledge, this is the first study in the IGB region, focusing on the identification of the crop, phase-specific trends and variations in the irrigation water demand and supply patterns under changing climate and socio-economic scenarios. Our crop and phase-specific research findings will help indicating possibilities to further improve impact assessment capabilities of regional and global model projections of climate change.

2 Material and methods

2.1 Study area

The study domain (Fig. 1) is the lower Indus, Ganges and Brahmaputra river basins corresponding to the focus area of the HI-AWARE project (nd., last visited 12 November

2022). These basins represent a range of diversified hydroclimatic, topographic and weather patterns. There is a large gradient of temperature (North to South) and precipitation (East to West) in the region which varies greatly in seasons (rabi and kharif) and locations (Fig. S1). The temperatures are highest (> 34°C) during summer with the substantive rains (>4000 mm) during kharif, commonly known as monsoon period in the IGB river basins. Trends and shifts in crop and phase-specific irrigation water demand and supply are evaluated under changing climate and socio-economic projections for the major wheat and rice-producing study sites in the middle mountain and flood plain areas excluding coastal zones of the IGB river basins of South Asia, i.e. the area within the basin boundaries of Fig. 1. The IGB river basins are the largest sources of freshwater in South Asia and home to ~ 25% of the global population (Biemans et al. 2016). Water from these river basin provides the livelihood to the people living in mountains and plane areas, i.e. the Indus River
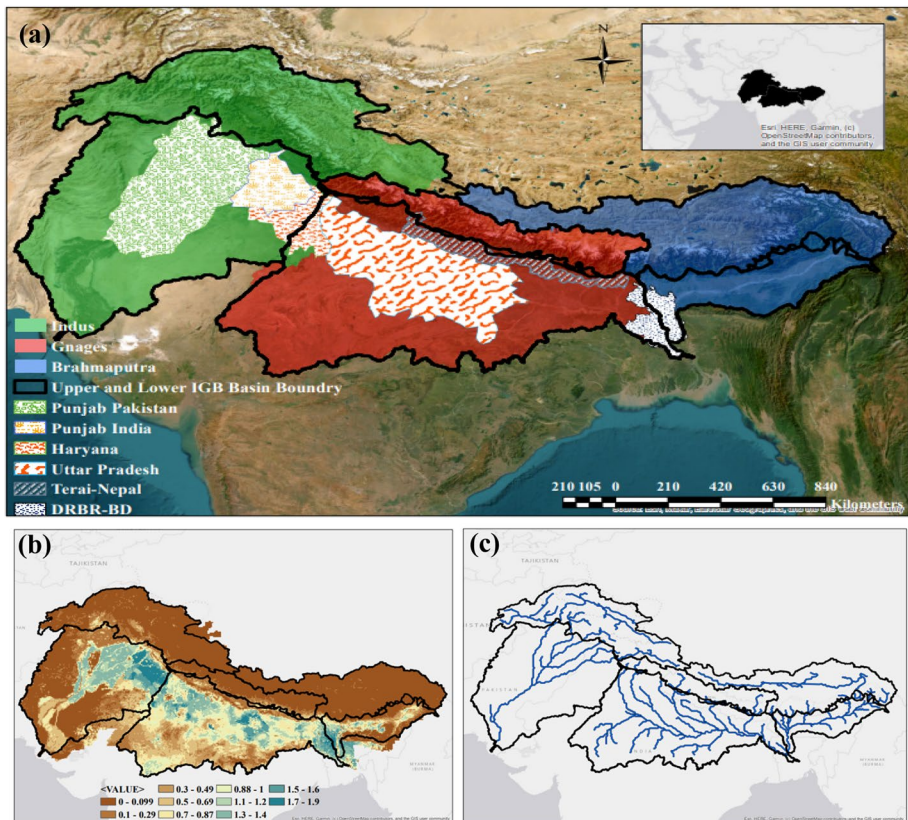
Fig. 1 **a** Area map showing the upper (mountainous) and lower (middle mountain and flood plain areas) parts of the Indus (green), Ganges (red) and Brahmaputra (blue) (IGB) river basins in South Asia. The map also shows selected six study sites including Punjab Pakistan (PP), Punjab India (PI), Haryana (HAR), Uttar Pradesh (UP), Terai region Nepal (Terai-NP) and Bangladeshi districts (DRBR-BD), **b** fraction of irrigated cropland areas in the IGB river basins, **c** major rivers in the IGB river basins. The background imagery illustrated in the above panels is taken from the ArcGIS online Base map source (last access: 02 June 2023). The MIRCA2000 dataset is used to derive irrigated crop fractional areas which have been further updated with regional agricultural statistics to correct land use changes between 2000 and 2010 (Biemans et al. 2016; Portmann et al. 2010). The river network in IGB has been taken from the published study (Wijngaard et al. 2018)

system which provides 153 BM^3 year^{-1} to the Pakistan (Hussain et al. 2016). Similarly The Ganges-Brahmaputra (GB) river basins host more than 700 million people (Papaa et al. 2015). Water availability in GB river basins is highly seasonal, mainly nourished by monsoon rainfall in summer (Moors et al. 2011).

In this study, the simulations were conducted at the pixel level. For our regional analysis, we used three aggregation levels: (1) selected districts for Nepal and Bangladesh, (2) at the sub-national level for India and Pakistan (i.e. Punjab Province of Pakistan (PP), Punjab India (PI), Haryana (HAR) and Uttar Pradesh (UP) states sites spreading from East to West of the IGB river basins) and (3) at pixel level over the whole study area. For Nepal, only the Terai region (hereafter referred as Terai-NP) in the Ganges basin and for Bangladesh, the Northwestern districts of Bangladesh, i.e. Dinajpur, Rangpur, Bogra and Rajshahi (hereafter referred as DRBR-BD) in the Ganges and Brahmaputra river basins are used, as they fall under the project and model simulation domain.

Various studies have already been conducted in the region to estimate the sector-specific (agriculture, domestic and industrial) consumption of surface and groundwater sources (Hanasaki et al. 2018; Wijngaard et al. 2018). Both studies have highlighted the intricate relationship between different water sources and usage patterns. However, to address our study objectives, i.e. to investigate the shifts in irrigation water demand by crops (i.e. wheat in the rabi season and rice in the kharif season) and related changes in water supply by sources (i.e. surface water and groundwater) during the sensitive crop growth phases (i.e. vegetative and reproductive), all assessments are made only for cropland areas presently equipped for irrigation under a double-cropping system in major wheat (rabi season) and rice (kharif season) areas which are commonly practised in the large areas of the IGB river basins. It is worth mentioning here that the triple cropping system as being used in Bangladesh with an additional rotation of rice sown during the dry rabi season, also known as Boro rice (Acharjee et al. 2017b; Acharjee et al. 2017a), is not taken into account in our study.

2.2 Lund Potsdam Jena Managed Land (LPJmL) model

LPJmL is a physically based, fully distributed model which combines the vegetation dynamics, agricultural land use and water balance calculations to simulate the interactions between land use, climate and water resources (Bondeau et al. 2007; Sitch et al. 2003). LPJmL simulates key ecosystem processes such as photosynthesis through coupled carbon and water fluxes (Farquhar et al. 1980), carbon allocation, evapotranspiration and phenology of 9 plant functional types (PFTs) (Sitch et al. 2003), and of 12 crop functional types as agricultural crops (CFTs) (Bondeau et al. 2007). LPJmL also simulates several hydrological processes including water balances, daily irrigation water demand and supply in a grid-based framework (Rost et al. 2008). The LPJmL model has been applied at a global scale for several climate impacts assessment applications, i.e. water availability and requirements for food production (Gerten et al. 2011; Kummu et al. 2014), effects of precipitation uncertainty on river discharge (Biemans et al. 2009), irrigation requirements (Rost et al. 2008), crop yields (Fader et al. 2010), environmental flows sustainability (Jägermeyr et al. 2017), dams reservoir operations (Biemans et al. 2011) and simulation of cropping systems using climate-dependent sowing dates (Waha et al. 2012).

The LPJmL model has also been applied over the IGB river basins of South Asia. In the earlier applications of LPJmL in South Asia, the crop yields have been improved by taking spatial heterogeneity in the region (Biemans et al. 2016, 2019). The modeled yield has been

calibrated using sub-national statistics as shown in Fig. S5 of Biemans et al. (2019). Biemans et al. (2016) also used LPJmL model to estimate seasonal irrigation-water demand in South Asia. The author found that improved seasonal land use and cropping period details led to lower estimates of irrigation-water demand patterns in the region which are in line with the statistics. The authors made these developments in results through a rigorous process of model calibration and validation with a better representation of spatio-temporal heterogeneity in the region which provides confidence in its ability to simulate crop water demand at a higher spatio-temporal scale.

The South Asian model version, used in this study, includes representation of double-cropping patterns with zone-specific monsoon dependent sowing dates for kharif and fixed sowing dates for rabi season (Biemans et al. 2016). It also includes the application of water-saving potential by the implementation of different irrigation systems (Jägermeyr et al. 2015). Additional developments include improved spatial resolution, i.e. from 0.5 degrees to 5 arc-min using high-resolution gridded climate dataset (Lutz et al. 2016b), representation of a groundwater reservoir together with groundwater withdrawals leading to groundwater depletion and representation of large -cale irrigation through extensive canal systems (Biemans et al. 2019; Wijngaard et al. 2018). For details, please refer to the LPJmL model section in the Online Resource.

2.3 Input data

For the control period (1981–2010), the LPJmL model is forced with the recently developed reference climate data including daily mean air temperature, precipitation, long and shortwave radiation (Lutz and Immerzeel 2016). For the scenario period (2011–2100), we used the RCP-SSP framework to investigate the shifts in crop phase-specific water use under a range of climate and socio-economic projections (van Vuuren and Carter 2014). The LPJmL model is forced with the gridded climate data which is based on CMIP5 multimodel ensemble of four different, downscaled (5 arc-minutes) global climate models (GCM) for each of the two combinations of emission scenarios, i.e. RCP4.5 and RCP8.5 and the two shared socio-economic pathway (SSP), i.e. SSP1 and SSP3 (Supplementary Table S1). The selected GCM are downscaled using the reference climate data by applying a quantile mapping approach and have been validated over the whole IGB region (Biemans et al. 2019; Lutz et al. 2016b).

The LPJmL model requires non-climatic datasets as well. For details, please refer to the Online Resource and the setup section of the following references (Biemans et al. 2019; Wijngaard et al. 2018).

2.4 Model runs

To estimate the crop-specific irrigation water demand and supply by sources, the LPJmL model is first run to establish an equilibrium between the carbon pools (soil and vegetation) and water fluxes (soil and surface water). For this, the model is run for two spin-up periods, i.e. 1000 years with natural vegetation and 300 years with the land-use file, using daily climate input of WATCH forcing data ERA-Interim (WFDEI). Subsequently, the model is run for a control period (1981–2010) and a scenario period (2011–2100) over the whole IGB river basins at grid cell level of 5 arc minute spatial resolution. To simulate crop-specific (wheat and rice) irrigation water demand and supply data, 1st November is used as a single sowing date for wheat in the rabi season throughout the study domain. For rice in

the kharif season, zone-specific monsoon dependent sowing dates are used, which helped to capture existing hydro-climatic heterogeneity in the region (Biemans et al. 2016). In our modeling setup, we applied surface irrigation system which is mostly practised in the IGB river basins for irrigated cropland areas (FAO 2011). The irrigation system (i.e. surface irrigation) and the crop sowing dates remained the same throughout the simulation period and no other management and adaptation options were taken into account. To estimate the crop-specific irrigation water demand and supply by sources (surface water and groundwater), we used two different irrigation options: All crop water demand is fulfilled, i.e. the irrigation water demand is completely fulfilled by water supply from surface water and groundwater, assuming that groundwater is only applied when surface water is not available. Only that part of the crop water demand is fulfilled as available from surface water. The difference between the two model run is used to estimate the irrigation water supply from groundwater.

To extract the crop growth phase-specific (vegetative, reproductive and ripening) irrigation water demand and supply data, we used the crop phenological development variable simulated by LPJmL following the approach developed by (Ahmad et al. 2021). Based on this methodology, start and end dates of each phenology phases were used to extract crop-specific irrigation water demand and supply data for the different phenology phases for each year and each grid cell using a script developed in R version 3.6.1 (Xie et al. 2018).

2.5 Trend analysis

The Mann–Kendall test based on Kendall's τ method is used to estimate the trends in the long term, i.e. 1981–2100 time series of phase and crop-specific temperatures, precipitation, irrigation water demand and supply data over the six study sites. The Mann–Kendall trend estimator is a non-parametric statistical test (Kendall 1948; Mann 1945) widely used to estimate the monotonic trends of time series with an unknown distribution of the data as it is less sensitive to outliers and missing values in data (Karmeshu 2015; Khatiwada et al. 2016). The magnitude of the trend was estimated using a non- parametric Theil−Sen's (TS) slope method (Sen 1968). The statistical significance of the trends, i.e. the probability (p value) associated with the Mann–Kendall statistics was estimated at three different significance levels, i.e. $p < 0.001$ or 99.9% confidence level (***), $p < 0.01$ or 99% confidence level (**), $p < 0.05$ or 95% confidence level (*).

3 Results

3.1 Changes in growing season length and shifts in the timings of crop growth phenological phases

Our results show that the simulated timing and length of phenological phases (i.e. vegetative, reproductive and ripening) occurred earlier in the growing season (Fig. S2a-b). Moreover, the length of each crop growth phase also decreased noticeably in future with prominent shift for wheat in the rabi season as shown in case of Punjab Pakistan. The shift in the timing of crop growth phenological phases and changing growing season length (Fig. S2c-d) are directly linked with the location and season-specific temperature patterns in the region. These changes have a significant impact on crop and phase-specific irrigation water demand and supply patterns in the region as presented in the following sections.

3.2 Irrigation water demand by crops during sensitive crop growth phases

The trends and patterns of irrigation water demand of wheat and rice during vegetative and reproductive growth phases in Punjab Pakistan are given in Fig. 2a–b. For wheat in Punjab Pakistan (Fig. 2a), the irrigation water demand during the control period (1981–2010) is on average almost equal in both crop growth phases, i.e. (80 ± 4.4 mm) and (77 ± 1 mm). During 2011–2100 period, there is only a slight increase projected in water demand during the vegetative phase. In contrast, for the reproductive phase there is a relatively large decrease projected in wheat water demand. These changes lead for both crop phases combined to a total decrease in future water demand for wheat. For rice the trends are in the opposite direction: a decrease of the water demand in the vegetative phase and an increase in the reproductive phase. For both wheat and rice the reproductive phase shows the strongest erratic behavior between years. The irrigation water demand gap during both crop growth phases will be widened in the future (especially towards the end of the century). These crop phase-specific changes in irrigation water demand are strongly linked with patterns of phase-specific temperature and precipitation projections (Supplementary Table S2).

Fig. 2c–f shows the spatio-temporal distribution of irrigation water demand statistics during sensitive crop growth phases of wheat and rice for all selected study sites. Our analysis revealed that on average ~ 60% of the total irrigation water demand, i.e. 114 mm out of 164 mm for wheat and 249 mm out of 321 mm for rice, is needed during the vegetative and reproductive crop growth phases in almost all study sites (Supplementary Table S3a). Whereas, the remaining 40% of irrigation water demand is allocated to other crop growth phases beyond the vegetative and reproductive stages. Supplementary Table S3b revealed similarities among most study sites in particular the direction of changes in a season, but with a variable degree of magnitude between locations. For example, consistent with our results in Punjab Pakistan (Fig. 2a–b), the irrigation water demand patterns in other study sites will also increase during the reproductive phase of rice (26 mm ± 19 mm, ranging from 0 to 45 mm), and for the vegetative phase of wheat (6 mm ±1.04 mm, ranging from −1.67 to 15 mm except for selected districts of Bangladesh where a slight decrease is projected). During the vegetative phase of rice, a decrease (11 mm ± 19 mm, ranging from −40 to 18 mm) is predicted, with the exception of Uttar Pradesh (Supplementary Table S3c). These statistics are estimated for the selected study sites where changes are aggregated over six study sites for period 2011–2100. In Uttar Pradesh a significant increase of 0.27 mm per year is found. During the reproductive phase of wheat, the substantive decrease (13 mm ± 9 mm on average, ranging from −13 to −1.1 mm) in irrigation water demand is quite uniform across all study sites (varying from −0.01 to −0.28 mm per year). This decrease could be linked with more water becoming available from rain and snow and glacier melt (see negative correlations in Supplementary Table S4).

Consistent with the long-term trends, the analysis of 30-year means revealed a gradual progression of trends over the four periods (1981–2010, 2011–2040, 2041–2070 and 2071–2100) (Fig. 2c–f). The projected change in irrigation water demand is consistent among the four periods during both crop phases of wheat and the reproductive phase of rice in all study sites (Fig. 2c–d, f). Whereas, these 30-year mean values show less consistency during the vegetative phases of rice during the kharif season (Fig. 2e). These latter changes are more pronounced especially during the second half of the century (Fig. 2). Our results show that the shifts in phase-specific irrigation water demands are more prominent in case of RCP8.5-SSP3 as compared to the RCP4.5-SSP1 scenario (Supplementary Table S5).
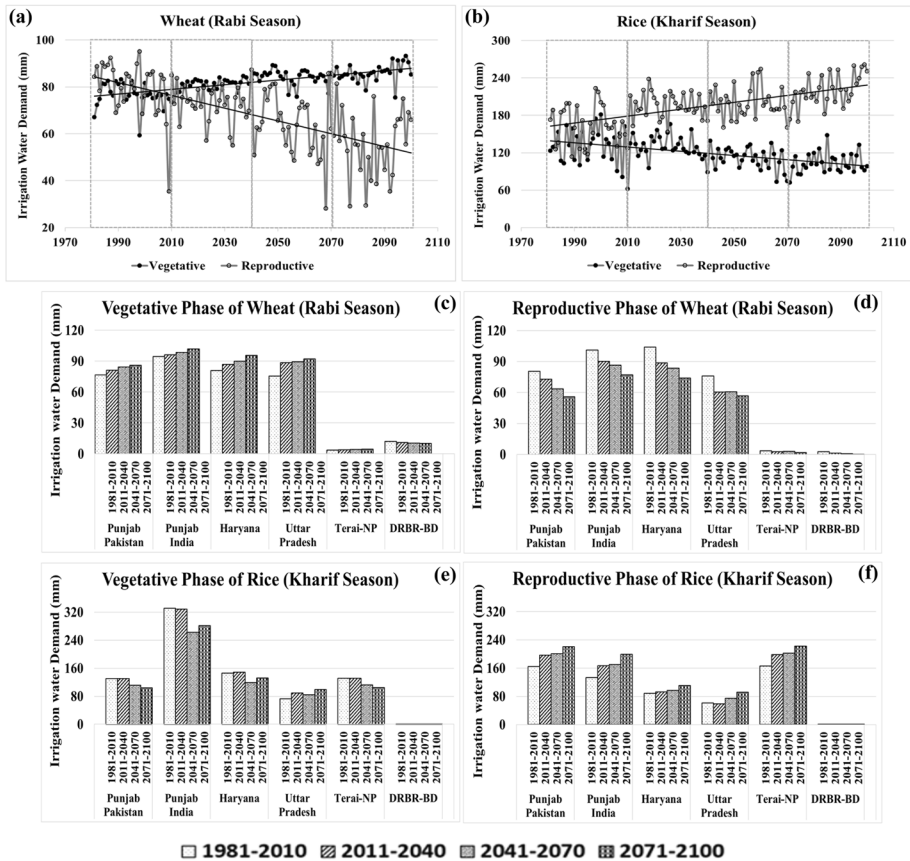
Fig. 2 Inter-annual variations and trends of irrigation water demand (mm) of wheat (**a**) and rice (**b**) during the vegetative and reproductive crop growth phases for the period 1981–2100 for Punjab Pakistan. Panels **c–f** show the projected 30 years' mean irrigation water demand (mm) of wheat (**c–d**) and rice (**e–f**) for six study sites during the period 1981–2010, 2011–2040, 2041–2070 and 2071–2100 using the ensemble mean of four GCM's of RCP4.5-SSP1 emission scenarios

3.3 Contribution to irrigation water supply by surface water and groundwater during sensitive crop growth phases

Crop phase-specific irrigation supply from surface water and groundwater showss different contributions and varying patterns in Punjab Pakistan (Fig. S3). Similar to the irrigation water demand changes, irrigation supply by surface water and groundwater show increase during the vegetative phase of wheat (5 mm and 1 mm) and reproductive phase of rice (11 mm and 15 mm) with a substantive decrease during the reproductive phase of wheat (5 mm and 8 mm) and the vegetative phase of rice (6 mm and 5 mm) (Supplementary Table S6).

Fig. 3a–d shows the spatial distribution and quantitative contribution of irrigation–supply from surface water and groundwater during the vegetative and reproductive growth phases of wheat and rice for the selected study sites in IGB river basins. Surface water irrigation is largely used in Punjab Pakistan and Uttar Pradesh. While groundwater is also a very important source of irrigation and plays a significant role in Punjab India, Haryana and
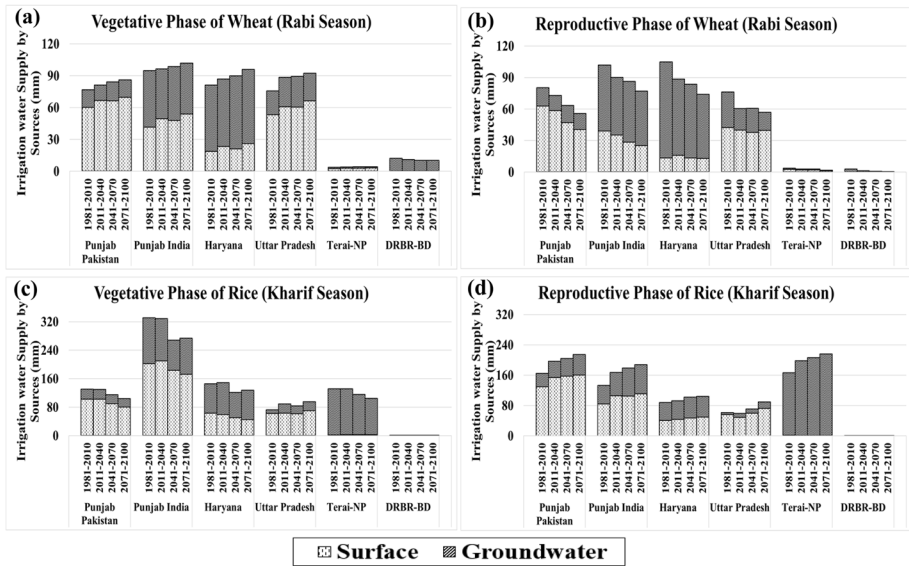
Fig. 3 Projected 30 years mean irrigation supply (mm) by sources (surface water and groundwater) during the vegetative (**a, c**) and reproductive (**b, d**) phases of wheat during rabi season (**a, b**) and of rice during kharif season (**c, d**) for six study sites for the periods 1981–2010, 2011–2040, 2041–2070 and 2071–2100 using the ensemble mean of four GCMs of RCP4.5-SSP1 emission scenarios

Uttar Pradesh providing about 56%, 77% and 30% of crop water demand during the vegetative phase and 61%, 87% and 44% during reproductive phase respectively. Phase-specific irrigation supply by sources is negligible in Terai-NP and DRBR-BN which is associated with the fact that in the eastern part of the IGB river basins monsoon rains are sufficient to fulfil the rice water demand and no irrigation is needed. However, during the rabi season, additional water is required from groundwater to fulfil the irrigated wheat water demand. The phase-specific estimates of irrigation supply by surface water and groundwater are relatively large under the RCP8.5-SSP3 scenario (Supplementary Figure S4).

3.4 Future changes in spatial distribution of irrigation supply from groundwater during sensitive crop growth phases

For wheat cultivated areas in the IGB river basins, Fig. 4 shows future changes in irrigation supply from groundwater relative to the control period (1981–2010, see Fig. S5(a-b)).

During the vegetative phase, a positive change, indicating an increase in groundwater required for irrigation, is concentrated in the Southwestern part of the Ganges basin and in the Central Indus. The biggest change in groundwater demand in the vegetative phase is expected to take place in the first period 2011 – 2040 (Fig. 4a). In the two later periods the changes are not so prominent (Fig. 4b, c). During the reproductive phase of wheat, a negative change in irrigation groundwater demand is large in extent and takes place in all three periods, as shown by the blue color in Fig. 4b, d, f. These decreases in future groundwater demand are mainly attributed to the increased winter precipitation in the Eastern parts of the IGB river basin. This decrease in future irrigation from groundwater is projected for most parts of the IGB basin, except for the areas of the Central Indus and South Ganges. For these

Vegetative Phase of Wheat   **Reproductive Phase of Wheat**
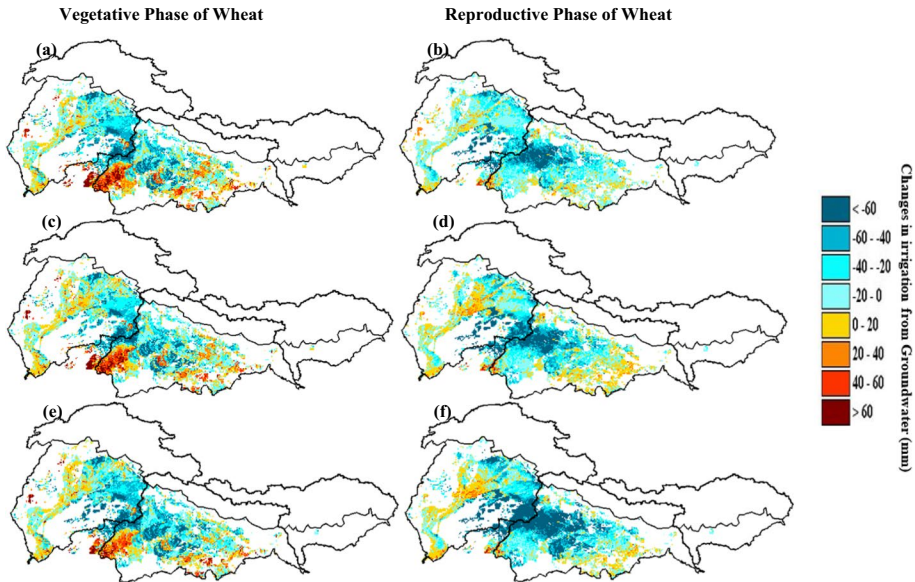
Fig. 4 Projected changes in irrigation from groundwater (mm) during the vegetative (**a, c, e**) and reproductive (**b, d, f**) phases of wheat over the whole IGB river basins for three reference periods, i.e. 2011–2040 (**a-b**), 2041–2070 (**c–d**) and 2071–2100 (**e–f**). Changes are relative to the 30 years' mean groundwater supply for the control period 1981–2010 (Fig. S1a). Positive values indicate the groundwater supply is increasing relative to the control period

two areas, the change in groundwater supply, relative to 1980–2010, is about 40 to 60 mm in 2011–2040 and reduces to 10 to 40 mm in 2071–2100. Comparing the vegetative phase with the reproductive phase shows a possible balance in the need of groundwater between the two phases, but also implies an earlier need of groundwater in the vegetative phase.

For rice, the irrigation need from groundwater is expected to increase (> 60 mm) in future (see yellow and red color in Fig. 5a, b). Especially in the reproductive phase a continuous increase over the three periods is observed.

During the vegetative phase a large increase (> 60 mm) is projected in the first period 2011–2040 (see the Ganges basin in Fig. 5a), but this increase is becoming weaker, and in some areas even changes towards a relative decrease in the periods 2041–2070 and 2071–2100 (see Fig. 5c, e). In the Eastern Indus area (e.g. Punjab India) a decreasing trend in groundwater demand during the vegetative phase is followed by an increasing demand during the reproductive phase. These trends are projected to increase in quantity and extent to Punjab Pakistan and Haryana by the end of the century.

This change in groundwater demand may imply the need to store water in the vegetative phase, to be used in the reproductive phase.

During the reproductive phase of rice, the largest positive increase in groundwater demand, i.e. > 60 mm, is projected for the Indus basin. Also, the Central-Eastern part of the Indus and the central part of the Ganges basin with exceptions in some Southern parts of the Ganges basin show a continuous positive increase (see Fig. 5b, d, f). The continuous increase in future groundwater demand for irrigation during the reproductive phase of rice in most areas of the IGB river basins is attributed to increasing weakening of the monsoon rains during this period.

Vegetative Phase of Rice   **Reproductive Phase of Rice**
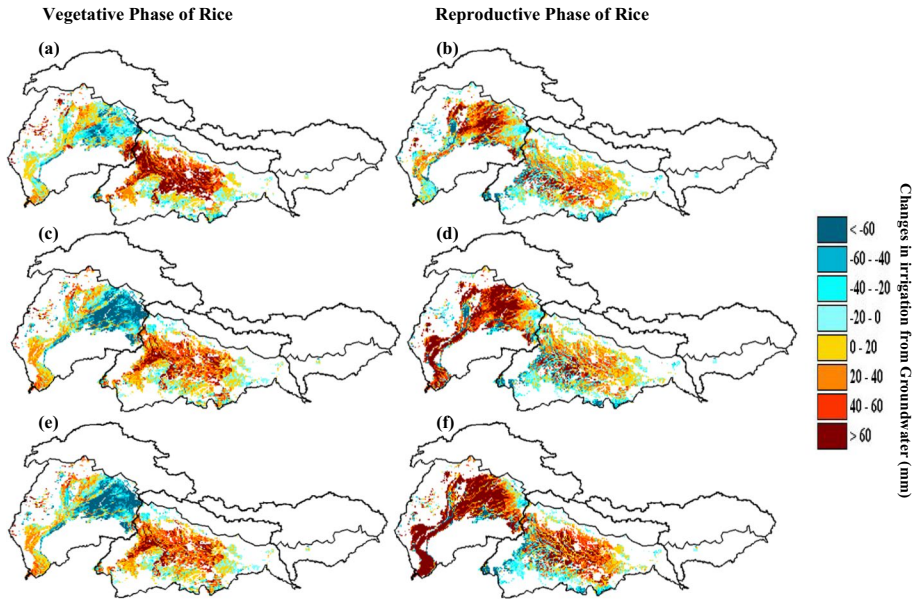
Fig. 5 Projected changes in irrigation from groundwater (mm) during the vegetative (**a, c, e**) and reproductive (**b, d, f**) phases of rice over the whole IGB river basins for three reference periods, i.e. 2011–2040 (**a–b**), 2041–2070 (**c–d**) and 2071–2100 (**e–f**). Changes are relative to the 30 years' mean groundwater supply for the control period 1981–2010 (Fig. S1b). Positive values indicate the groundwater supply is increasing relative to the control period

In the central and Southern parts of the Indus, the groundwater demand is projected to shift from the vegetative phase towards the reproductive phase. This shift will intensify at the end of the century. In the Ganges basin, the change in groundwater demand will take place in the period 2011–2040 in the vegetative phase. This change will cause a shift towards an increased demand in the reproductive phase in the period 2071–100 for the Ganges basin.

4 Discussion

In this study, we presented the projections of crop, phase and location-specific estimates of irrigation water demand and supply under changing climate which can improve timely crop water strategies in South Asia.

4.1 Impact of climate change on growing season length and crop growth phenological phases

Climatic variations play a critical role in crop growth processes (Arshad et al. 2017). There are indeed other factors that can influence the crop growth, productivity and growing season length, including photoperiodism, vernalization requirements, soil moisture availability and specific crop management practices (Asseng et al. 2015; Hatfield and Prueger 2015). Moreover, this is also a known fact that temperature is the major factor in terms

of heat units (growing degree days, GDD) which determines the growing season length of a crop (Kukal and Irmak 2018). Higher temperatures together with reduced soil moisture decreases growing season length of crops which can alter the stages of plant growth resulting in yield reduction (Ruiz-Vera et al. 2015). Significant decrease in growing season length and crop water use has also been reported in Bangladesh under higher temperature (Acharjee et al. 2017b). A study conducted in the Swat and Chitral districts of Pakistan reported a substantive decrease in the wheat growing season length as a result of increasing temperature (Hussain and Mudasser 2007). The decrease in growing season length can have significant impacts on crop water use and yield (both in terms of quality and quantity). Increasing and varying temperatures can affect the crop's physiological and growth procedures by fastening maturing of the crops and ultimately early harvesting (Mahmood 1998; Rosenzweig et al. 2014). Accelerated phenological development in response to a warmer climate is also reported in a global modeling study by Elliott et al. (2014). This accelerated development is in line with the substantial decrease in the growing season length of both wheat and rice as simulated by our model over six study sites during the period 1981–2100 (Fig. S2(c-d)).

4.2 Climate impacts on irrigation water demand during sensitive crop growth phases

Our findings showed that crop phase-specific changes in irrigation water demand are strongly linked with temperature (Supplementary Table S4a). Impacts of change in precipitation on water demand are less clear.

Our wheat results showed increasing irrigation water demand during the vegetative phase in all study sites as a result of lower amounts of rain (negative relationship of irrigation water demand with precipitation Supplementary Table S4b). These results coincide with the findings of De Vrese et al. (2016). These authors reported that in India, irrigation demand is highest from December to March due to low soil moisture content. Our results show a significant decrease in wheat irrigation water demand during the reproductive phase as a result of higher projected temperature and precipitation. These results coincide with the findings of Hanasaki et al. (2013) and Konzmann et al. (2013). These authors showed a decrease of wheat irrigation water requirements in future in India and Pakistan as a result of elevated CO_2, shorter growing periods and regional precipitation increase. An abate in irrigation water demand during the reproductive phase of wheat in the rabi season could relate to the earlier maturity of wheat under elevated winter temperatures in the region (Mahmood 1997; Sánchez et al. 2014). Similarly, other studies in region reported the shortening of the growing season length and evapotranspiration as a result of increased winter temperature which ultimately caused a decline in net wheat water demand and hence irrigation (Asseng et al. 2015; Wijngaard et al. 2018; Xiao et al. 2020).

Our rice water demand estimates decreased during the vegetative phase and increased significantly during the reproductive phase for all study sites throughout the century. The decreasing rice water demand during the vegetative phase could be associated with the low leaf area growth in response to rising CO_2 concentration in the atmosphere. During the initial crop growth phase, a smaller leaf area requires less water. The large and increased irrigation water demand during the reproductive phase of rice in the kharif season in our study domain coincides with the time of the year when a lower amount of water is available from snow and glacier melt and monsoon precipitation. In addition, higher water demand for irrigation can be the result of higher temperatures intensifying

atmospheric evaporative demand and consequently increasing the irrigation crop water requirements (Wada et al. 2013).

4.3 Phase-specific impacts of climate change on contribution of irrigation supply by sources

Understanding the linkages between changing climate and related impacts on surface water and groundwater during sensitive crop growth phases is crucial to enable informed water management decisions (Hirji et al. 2017). Future changes in irrigation water supply from surface water and groundwater sources are expected due to projected increase in temperature and precipitation variations in region (Kraaijenbrink et al. 2017; Qin et al. 2020).

Our results showed an increasing trend in surface water during the vegetative phase of wheat and reproductive phase of rice and a decreasing trend during the reproductive phase of wheat and vegetative phase of rice (Fig. 3). We observed that under higher temperatures, crops need more water (r = 0.60 in case of Wheat-veg Pakistan), but with higher precipitation, these additional crop water requirements are minimal ($r= -0.33$ in case of Wheat-veg Pakistan) (see Supplementary Table S2 and Table S4). During the sensitive crop growth phases of both wheat and rice, irrigation from surface water shows a stronger correlation with temperature as compared to groundwater, except in Haryana and Uttar Pradesh where groundwater shows strong correlations, particularly during the reproductive phase of both crops (Supplementary Table S4). These results are also supported by the study of Clifton et al. (2010) who reported that surface water is strongly influenced by temperature, whereas, groundwater shows a relatively weak correlation with temperature variations.

Our results on spatial distribution of irrigation supply from groundwater shows large variations (increase and decrease both in extent and size). For example, our results for wheat revealed a negative change in future irrigation supply from groundwater during both phases in IGB river basin with largest change during the reproductive phase in Southwest Ganges (Fig. 4). A large and continuous water shortage during the reproductive phase of wheat can cause a decrease in leaf area, growth rates and dry matter accumulation and hence ultimately can reduces net crop production and quality (Eyshi Rezaei et al. 2015). For rice, our results show an increase in groundwater irrigation during both phases in the entire IGB river basins with a consistent and larger increase during the reproductive phase until the end of the current century (Fig. 5). More groundwater extraction for agriculture in response to reduced precipitation is also reported by Yuan and Shen (2013). A substantial increase in groundwater irrigation as a result of an increased irrigated area (threefold) in the Upper Kharun Catchment, Chhattisgarh, India is observed between 1991 and 2011 (Kumar et al. 2018). Our study revealed that projected change in groundwater irrigation is related to the temperature and precipitation projections which can influence the groundwater management; these results are in line with the findings of Mukherji et al. (2015).

The areas highlighted with the largest positive change in future groundwater irrigation can hamper the sustainability of the crops due to increased pressure on groundwater resources and increased competition between different users (Zaveri et al. 2016). The groundwater irrigation changes are used as a proxy to identify possible water gaps (between demand and supply) in regions and times which may hamper crop growth and production.

4.4 Uncertainty and limitations of the study

Crop water models forced with climate projections are commonly used to estimate future crop water requirements (Acharjee et al. 2017a; Liu et al. 2017; Xiao et al. 2020). A number of uncertainties in the results can be associated with the model and data used. For a discussion on the uncertainty in the data used see Dahri et al. (2021) and Wijngaard et al. (2018).

In our modeling setup, we have assessed the combined impacts of climatic and socio-economic change on crop and phase-specific irrigation water demand and supply projections. Uncertainties in the model setup can be associated with the use of the land-use data, a fixed irrigation system and a single sowing date. The uncertainty in our results could be associated with the land use data where we made some adjustments in the observed MIRCA2000 dataset. MIRCA is a global data set that contain information on irrigated and rainfed monthly crop areas for 26 crop classes around the year 2000. For our study, the adjustments were made first to aggregate the crop classes as available in the LPJmL model. Next the seasonal cropped areas from the monthly MIRCA cropping calendars were decided, i.e. the kharif season area is defined as the area under cultivation per crop as in September and the area per crop in January is taken as rabi cropped area. The adjustments were also made in crops rotation and crop areas. The crop sowing dates and areas under cultivation were adjusted in line with South Asia cropping patterns. For further details, see Biemans et al. (2016). The sowing dates remained fixed throughout our simulation period, i.e. 1st November for wheat in the rabi season and zone-specific monsoon dependent sowing dates for rice in the kharif season (Biemans et al. 2016). However, in reality, they are not fixed and change each year. Implementation of changing sowing dates in space and time can further improve the results.

Our estimates of growing season length and shifts in crop growth phase are in line with the following published studies (Acharjee et al. 2017a; Asseng et al. 2015) and revealed a shortening of growing season length in response to increasing temperatures (Hussain and Mudasser 2007; Kukal and Irmak 2018). However, the impacts of management factors such as changes in irrigation systems (i.e. drip and sprinkler) with improved irrigation efficiency, variation in rainfed to irrigated areas, genetically modified seeds requiring less water, soil moisture availability and potential contributions of photoperiodism and vernalization to the determination of growing season length have not been taken into account. Inclusion of these factors can expand the discussion on the potential impacts of other factors on cropping duration in the region.

Our crop, and location-specific irrigation water demand projections, are in reasonably good agreement with studies (Hanasaki et al. 2013; Konzmann et al. 2013) when compared at seasonal scale. As only a few studies are available at the crop phase-specific time scale for comparison, our results can be used as a benchmark when assessing crop phase- specific assessments in the IGB river basins. The use of multi-crop model ensembles can help to better quantify the uncertainties related to the relationship between climate variables and crop growth physiology (Asseng et al. 2019).

In this study, we analyzed the contribution of irrigation supply from surface water is higher than groundwater during both phases of wheat and rice in almost all study sites, and future projections of groundwater irrigation are used as a proxy to identify possible water gaps (between demand and supply). Particularly, in the case of wheat during the rabi season, there may be instances of under or overestimation of groundwater use. These evaluations necessitate dedicated attention in subsequent research, as they are integral to shaping sustainable water allocation and food production strategies in the future.

It is important to mention that in our study, we have analyzed irrigated wheat and rice areas only cultivated during the rabi and kharif cropping seasons under a double cropping system respectively. There are other crops grown in these seasons which are not studied in this research. For example, in Bangladesh, more than 60% of the total rice production is grown during the rabi season, known as Boro rice which mainly depends on groundwater irrigation. Studies reported that the dry season Boro rice cultivated in the North-West part of Bangladesh showed declining trends of Boro rice water requirement in future as a result of decreasing crop evapotranspiration and shortening of growing season length (Acharjee et al. 2017a; Acharjee et al. 2017b; Mahmood 1997). However, in our study, we assessed major wheat and rice-producing study sites in the IGB river basins cultivated under double cropping systems only, i.e. wheat during the rabi season and rice during the kharif season. For further analyzing the shifts in irrigation water demand and supply projection of other crops, i.e. Boro rice as practiced under triple cropping system in Bangladesh, it is suggested to implement a multiple cropping system in the LPJmL model.

5 Conclusions

Our research presented climate-induced crop phase and location-specific estimates of irrigation water demand and supply of wheat and rice in the Indus, Ganges and Brahmaputra river basins using two emission scenarios, i.e. RCP4.5-SSP1 and RCP8.8-SSP3 during the period 1981–2100. Our model simulated a substantial decrease in the growing season length of both wheat (on average 15–20 days) and rice (on average 08–12 days) with considerable shifts in the timing of the phenological phases in the IGB river basins by the end of the century. In our study sites on average 60% of the total irrigation water demand, i.e. 114 mm out of 164 mm for wheat and 249 mm out of 321 mm for rice, is needed during the vegetative and reproductive crop growth phases. The shift and changes in crop water demand during these two crop phases can have serious implications. This study has the following main conclusions:

- Irrigation water demand estimates reveal a significant increase in the vegetative phase of wheat (6 mm) and reproductive phase of rice (26 mm) with a substantive decrease in the reproductive phase of wheat (13 mm) and vegetative phase of rice (11 mm) in the selected study sites of the IGB river basins during the period 2011–2100. These changes in irrigation water demand are linked with the changes in the timing and length of the crop growth phases which indicates a surplus amount of water for wheat and a shortage of irrigation water for rice in future. These projected changes suggest time and location-specific water allocation and distribution strategies ensuring provision of the right amount of irrigation required during a certain crop phase for sustained and enhanced crop production.
- The contribution of irrigation supply from surface water is higher than groundwater during both phases of wheat and rice in almost all study sites except in Haryana (during the rabi season) and Terai region of Nepal (during the kharif season) where groundwater supply is dominant (up to 70%).
- Irrigation water supply from surface water and groundwater supplies show large variations during the crop growth phases, i.e. increase during the vegetative phase of wheat (5 mm and 1 mm) and reproductive phase of rice (11 mm and 15 mm) with a substantive decrease during the reproductive phase of wheat (5 mm and 8 mm) and vegetative

phase of rice (6 mm and 5 mm). These changes indicate reduced stress on groundwater during the wheat cropping season with a significant increase during the reproductive phase of rice, leading to greater unsustainability in the region. It is also pertinent to mention here that these changes vary throughout the region and plea for a crop phase, location and water source-specific evaluation in the region.

- Wheat shows a high dependency on groundwater irrigation during the vegetative phase in most parts of the IGB river basins. In the Central Indus and Ganges basin, the large and increasing dependency of rice on groundwater irrigation during the reproductive phase is of great importance and can affect rice production in future.

Our results show the importance of crop water assessments during sensitive crop growth phases of wheat and rice which vary in space and time. Including crop growth phases specifically in climate impact assessments of regional and global projection will help to improve the existing water management strategies and adaptation practices in the region. Further improvements in the projections can be expected by introducing more detailed information on irrigation efficiencies, planting dates and other crop management information.

Declarations

Competing interests The authors declare no competing interests.

Disclaimer The views expressed in this work are those of the authors and do not necessarily represent their institutions.

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