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Is flood to drip irrigation a solution to groundwater depletion in the Indo-Gangetic plain?

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Abstract

Indian river basins are intensively managed with country-specific agricultural practices of cultivating submerged paddy and uncontrolled groundwater (GW) irrigation. Numerical experiments with the state-of-the-art land surface models, such as variable infiltration capacity (VIC), without incorporating region-specific practices, could be misleading. Here, we coupled VIC with 2D GW model AMBHAS, incorporating India-specific irrigation practices and crop practices, including submerged paddy fields. We performed numerical experiments to understand the causal factors of GW depletion in the northwest Indo-Gangetic plain (IGP). We identify widespread flood irrigation and cultivation of water-intensive paddy as critical drivers of the declining GW scenario. Our numerical experiments suggest that the introduction of drip irrigation reduces GW depletion in the northwest, but does not change the sign of GW level trends. The GW levels in the non-paddy fields of the middle IGP are less sensitive to irrigation practices due to the high return flow to GW for flood irrigation.

1. Introduction

Groundwater (GW) plays a crucial role in ensuring global water and food security. Besides direct withdrawals, it also contributes to baseflow to rivers during low rainfall conditions (Taylor *et al* 2013, Mukherjee *et al* 2018). Globally, India abstracts an enormous quantity of GW, utilizing nearly 90% of it to water almost 60% of irrigated land (CGWB 2021). After the Green Revolution, a significant shift to cereal cultivations, multiple cropping seasons, and expansion of irrigated areas ensured maximized yield, better profit, and food security but at the stake of burdened water resources (Barik *et al* 2017, Davis *et al* 2019, Zaveri and Lobell 2019). Subsequently, GW-fed irrigation became more prevalent because of its availability at the desired amount and frequency throughout the year (Shah 2009, Sekhri 2011, Dangar *et al* 2021), making the country less susceptible to famines (World Bank 2010, Pingali 2012). However, this human-induced redistribution of water has substantially affected both GW and surface hydrology.

Recent studies reported a drastic decline in GW in India, with Indo-Gangetic plains (IGPs) identified as a hotspot (Rodell *et al* 2009, Tiwari *et al* 2009, Wada *et al* 2010, Aeschbach-Hertig and Gleeson 2012, Dalin *et al* 2017). This alarming depletion rate is linked to the combined effect of reduced recharge and excessive abstraction (Scanlon *et al* 2012) due to various natural and anthropogenic factors (Bhanja *et al* 2017, 2018). India has witnessed a declining trend in monsoon precipitation post-1950s (Roxy *et al* 2015, Paul *et al* 2016), leading to reduced recharge (Asoka *et al* 2017, Nair and Indu 2021). GW pumping for domestic and irrigation purposes surged to meet the food and water demand of the drastically growing population (Godfray *et al* 2010, Davis *et al* 2018). Widespread transition to water-intensive crops like rice and sugarcane for higher profit raised the irrigation water demand (Russo *et al* 2015, Zachariah *et al* 2020). Weakening and spatiotemporal variability in precipitation (Ghosh *et al* 2016) influenced the farmers' water use decisions, making them more dependent on GW. The government policies are also indirectly responsible for unsustainable GW abstractions. Free access by virtue of land ownership and subsidies on electricity for pumping resulted in the mismanagement of GW (Shah 2009, Badiani *et al* 2012, Devineni *et al* 2013, Zaveri *et al* 2016). Moreover, inefficient water use by conventional flood irrigation further exacerbated the situation (Fishman *et al* 2015, Barik *et al* 2017).

The apparent repercussions of falling GW levels include escalated pumping costs, drying of rivers in summer, deteriorating water quality (Aeschbach-Hertig and Gleeson 2012, Döll *et al* 2014, Mukherjee *et al* 2018) and reduced crop yield, thus aggravating the future food and water crisis (Bhattarai *et al* 2021, Jain *et al* 2021). The water demand and, thereby, the stress on GW is bound to increase in the future with changing climate and rising population (Foley *et al* 2011, Gupta *et al* 2021). India actively promotes drip irrigation as a remedy for the country's declining GW status (Birkenholtz 2017, Sikka *et al* 2022). The drip irrigation scheme is considered the most effective mode of irrigation in terms of water use efficiency as it applies water directly to the crop's root zone (Leng *et al* 2014). It enhances the crop evapotranspiration while minimizing the conveyance and evaporation losses since the water distribution is through a pipe network. The irrigation is demand-driven, hence reducing the chances of overwatering. By directing irrigation exclusively at the crop rather than the entire field, bare soil evaporation losses are also reduced (Narayanamoorthy 2004, Grafton *et al* 2018, Wang *et al* 2018, Verma *et al* 2020). Besides a lower water requirement, other advantages of drip irrigation over traditional flood irrigation include improved yield, effective fertilizer application, reduced cost (except implementation cost) of cultivation, energy savings, and thus increased income of farmers (Narayanmoorthy 2009, Palanisami *et al* 2018, Jain *et al* 2019, Pool *et al* 2022).

Although the Government of India has been encouraging drip irrigation since the 1980s, the threat of climate change has boosted the efforts (Birkenholtz 2017). The Centrally Sponsored Scheme on Micro Irrigation first launched in 2006, and now the 'Per Drop More Crop' component of the 'Pradhan Mantri Krishi Sinchayee Yojana' scheme (established in 2015) aims at improving irrigation efficiency through the expansion of area under drip and sprinkler irrigation (https://pmksy.gov.in/microirrigation/index.aspx). Under this scheme, the state and the central government provide subsidies for the implementation of drip irrigation. Currently, about 4.7 million ha of cropland is under drip irrigation, which is only about 17.4% of the total potential (Jain *et al* 2019, Gupta *et al* 2022). The area under drip irrigation in states within IGP is only 0.1%–2.5% of the total potential (Palanisami *et al* 2018). According to field studies conducted across India, switching to drip irrigation reduces water use by 30%–60% (Postel *et al* 2001) and the GW quantity pumped per hectare by 30%–70% (Shah 2009) depending on crop and season. Model simulations by Sishodia *et al* (2018) revealed that GW decline in rainfall deficit years could be mitigated by flood-drip conversion. For dry seeded rice cultivated over a field in Punjab (within IGP), Sharda *et al* (2017) noted greater than 40% water savings and improved yield while shifting from flood to drip irrigation. Surveys over IGP reported 25%–80% more water savings with drip irrigation (Sharma *et al* 2009). Drip irrigation saved 46.7% of water for rice-wheat and 44.7% for maize wheat cropping systems over a study site in IGP, as observed by Jat *et al* (2019). Water savings by shifting to drip irrigation will affect the amount of GW abstraction as well as GW recharge, however how these impact on GW levels is unknown.

A better understanding of GW behaviour is essential to regulate depletion and thereby mitigate water scarcity. Traditionally, the status and pattern of GW depletion in India are studied using *in-situ* well observations (MacDonald *et al* 2016, Kumar Joshi *et al* 2021) and Gravity Recovery and Climate Experiment (GRACE) satellite-based estimates (Rodell *et al* 2009, Tiwari *et al* 2009, Bhanja *et al* 2016, Long *et al* 2016, Panda and Wahr 2016). Girotto *et al* (2017) applied GRACE data assimilation into the catchment land surface model to analyse the changes in GW storage in India. Though the fluctuations of GW storage were captured well, evapotranspiration (ET) was underestimated due to the missing irrigation module in the hydrological model. Land surface modelling studies integrating GW behaviour are limited over the Indian region (Asoka *et al* 2017) since the GW component has been either excluded or overly simplified in state-of-the-art land surface model (LSM) until recently (Scheidegger *et al* 2021). For example, the variable infiltration capacity (VIC) model, widely employed for various studies over Indian basins (Chawla and Mujumdar 2015, Ghosh *et al* 2016, Joseph *et al* 2018, Niroula *et al* 2018, Shah *et al* 2019, Chandel and Ghosh 2021), does not include the GW module in default mode. Rosenberg *et al* (2013) coupled the simple groundwater model (Niu *et al* 2007) to VIC and applied it over the Colorado River basin. However, the lateral GW flow between the grids was not considered. Lately, Scheidegger *et al* (2021) addressed this limitation by parameterizing a 2D GW model to VIC (hereafter VIC_AMBHAS) that incorporates soil–GW and river–aquifer interactions. The next challenge is representation of irrigation and pumping in VIC_AMBHAS, which is increasingly relevant in Indian river basins. Joseph and Ghosh (2021) highlighted the need for separate irrigation parameterization in VIC for India considering uncontrolled flood irrigation, distinct schemes for ponded paddy fields and multiple cropping seasons and crop varieties. In the present study, we have added the new irrigation scheme proposed by Joseph and Ghosh (2021) and GW abstraction to VIC_AMBHAS (hereafter VIC_AMBHAS_IRR). The present study has multiple objectives. First, we evaluated VIC_AMBHAS_IRR in simulating the GW fluctuation over the IGP. We then performed experimental simulations with different irrigation practices to understand: (a) sensitivity of long-term GW level changes to different irrigation practices; (b) efficacy of the widely suggested interventions of changing flood to drip irrigation in improving the GW scenario.

2. Data and methods

2.1. Data

The GW component and irrigation scheme are parameterized into the Image Driver version of VIC 5 (Liang *et al* 1994, Hamman *et al* 2018). This version requires sub-daily gridded meteorological data of average temperature, total precipitation (including snow), wind speed, incoming shortwave radiation, incoming longwave radiation, atmospheric pressure and vapour pressure. Therefore, as a pre-processing step, we drove VIC 4.2.d with daily precipitation, maximum and minimum temperatures, and wind speed as the input to generate the meteorological forcings and disaggregate them to a sub-daily time scale. The inbuilt mountain microclimate simulation model (Bohn *et al* 2013) within VIC 4.2.d aided this procedure. Daily observed precipitation at 0.5° (Rajeevan and Bhate 2009) and maximum and minimum temperatures at 1° resolution (Srivastava *et al* 2009) were obtained from Indian Meteorological Department. We retrieved the daily wind data from European Centre for Medium-Range Weather Forecasts interim reanalysis (ERA-Interim).

We extracted gridded soil properties for the study region from the global soil parameter file available at 0.5° resolution (Nijssen *et al* 2001a, 2001b), freely downloadable on the VIC website (https://vic.readthedocs.io/en/master/Datasets/Datasets/#vic-input-and-output-data-sets). We used the Moderate Resolution Imaging Spectroradiometer (MODIS) land cover type product available at 500 m resolution (Sulla-Menashe *et al* 2019) to generate the fractional vegetation cover in the individual model grids. Our simulations consider two cropping seasons: Kharif (June–October) and Rabi (November–February). The season-wise total and irrigated area of particular crops within a district are available from 1998 on the Crop Production Statistics Information System compiled by the Directorate of Economics and Statistics (https://aps.dac.gov.in/LUS). We selected ten major Kharif crops and eight Rabi crops based on cultivated area and converted the district-wise crop area into grids. The total and irrigated area of individual crops is required to determine the dominant land cover type within each grid cell. The total cropland area from MODIS data in a particular year is compared with the sum of district-wise area under crops (AUCs). If the total AUC is less than MODIS cropland area, the excess area is added to grasslands. If the total AUC is more than the MODIS cropland area, the deficit area is subtracted from grasslands, open shrublands and sparsely vegetated areas. Hence, we generate two sets of vegetation fractions for each year for the Kharif and Rabi seasons. All inputs are generated at 0.05° spatial resolution, at which the simulations are performed. Furthermore, VIC requires the vegetation properties of specific land cover types such as leaf area index (LAI), root depth, at a monthly time step. We utilized the Global Land Data Assimilation vegetation parameters for all land cover types other than croplands. We obtained the total water use during the crop growth period under flood irrigation recorded by Fishman *et al* (2015) based on field surveys (table S1). The crop-specific sowing and harvesting dates were collected from the Directorate of Economics and Statistics website (https://eands.dacnet.nic.in/At_A_Glance-2011/appendix-IV.xls). Further details on the list of crops, the compilation of crop properties and crop-specific water use can be found in Joseph and Ghosh (2021). The digital elevation model for the AMBHAS inputs were taken from Shuttle Radar Topography Mission 90 m (Jarvis *et al* 2008). The aquifer properties, hydraulic conductivity and specific yield were collated from Bonsor *et al* (2017) and MacDonald *et al* (2016) for the Indo-Gangetic basin alluvial aquifers. For the remaining area the classification from Gleeson *et al* (2014) was updated with the parameterization in Bhanja *et al* (2016). The river map within the study domain were derived from MacDonald *et al* (2015). The initial GW heads were obtained from the Central Ground Water Board (CGWB) (Ground Water Year Book-India 2014b).

The source-wise irrigated areas for all the districts are available on the Crop Production Statistics Information System (https://aps.dac.gov.in/LUS). We calculated the fraction of GW and surface water use based on these data (table S2). We used the domestic and industrial GW use data from Dynamic Groundwater Resources of India reports prepared by the CGWB (2006, 2009, 2014a, 2017). Well observations recorded by CGWB every pre-monsoon (March/April/May), monsoon (August), post-monsoon (November) and winter (January) season (http://cgwb.gov.in/GW-data-access.html) were used to generate initial GW input and also to validate the simulated GW levels (additional inputs for running VIC_AMBHAS_IRR are listed in supporting information table S3 and detailed in text S1).

2.2. Methodology

The modelling framework is depicted in figure 1. In the VIC_AMBHAS model, a 2D single layer finite difference GW model is coupled to the soil column of VIC. Here, VIC's default baseflow formulation out of the soil column is turned off, and instead a flux between the soil and the GW table is calculated based

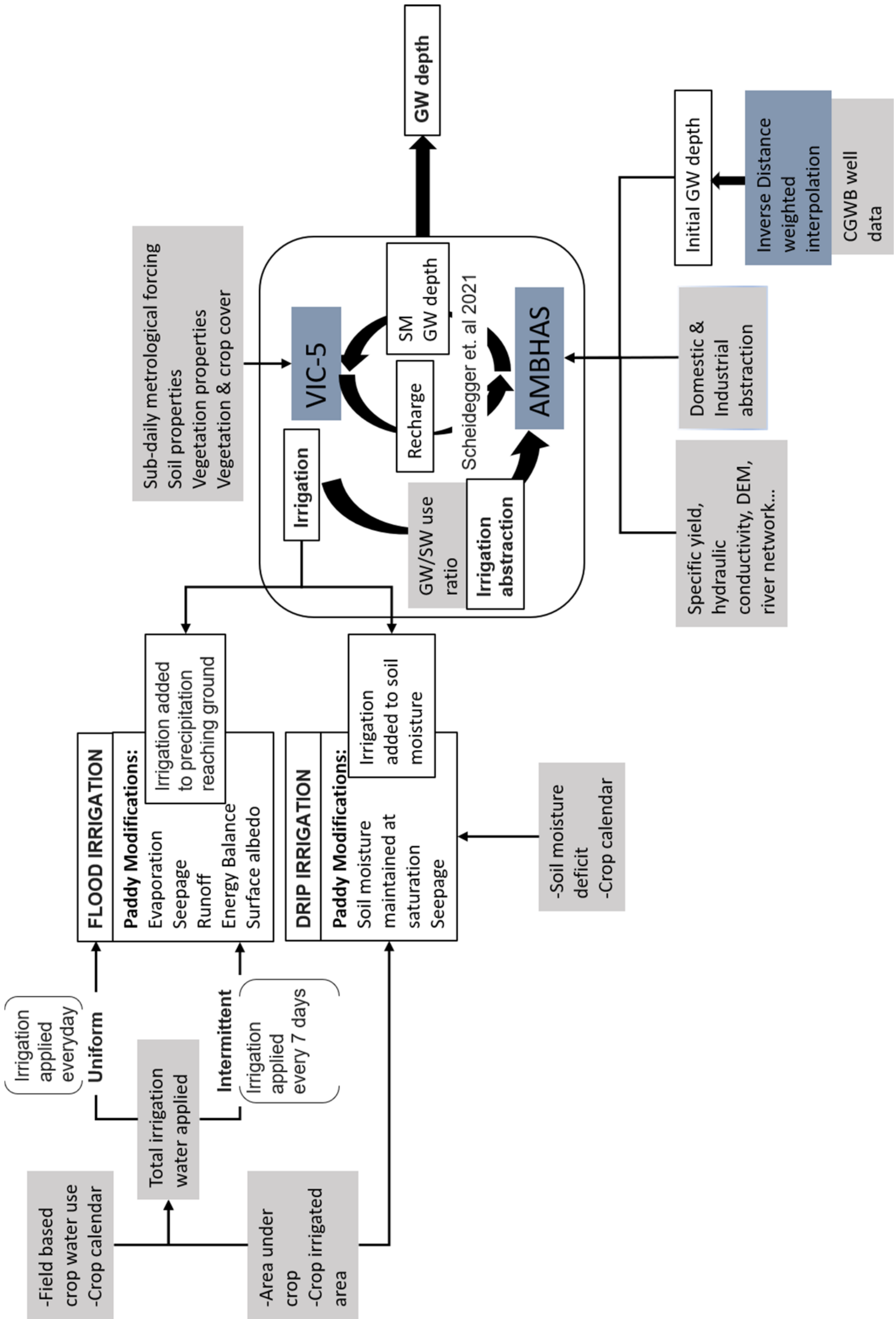

Figure 1. Schematic diagram of the applied modelling framework.

on the scheme of Niu *et al* (2007). The GW recharge depends on the water table depth and soil moisture in the VIC soil column. The GW recharge is applied to the GW model, which solves for GW flow, baseflow to rivers, and the elevation of the water table (Scheidegger *et al* 2021).

The irrigation module can be run in either flood or drip irrigation mode. Flood irrigation is represented by adding irrigation to the precipitation reaching the ground. The energy and water balance of paddy crop tiles within the grid cell are calculated separately since it is grown in ponded conditions. In the drip irrigation scheme, water is applied to the root zone of the crop based on soil moisture deficit. In this mode, we check every day at 6 am if the root zone soil moisture has fallen below the critical level, i.e. when transpiration is limited. The soil moisture is raised to field capacity under such conditions. The root zone of paddy crop tiles is maintained at saturation throughout the irrigation months (see details on the paddy formulations under flood and drip irrigation in supporting information text S2 and Joseph and Ghosh (2021)). In India, there is a scarcity of accurate information regarding irrigation application intervals. Various factors like meteorological conditions, crop type, seed type, soil type, local knowledge, crop growth stage, and water availability influence irrigation frequency (O'Keeffe *et al* 2018). Based on the farm-scale interviews conducted by Roy *et al* (2021), the irrigation frequency ranged from daily to every seven days. Hence, we tested the effect of frequency of flood irrigation water application by simulating irrigation scenarios, either irrigating the crops daily or intermittently at 7 d intervals.

The GW abstracted for irrigation (q_{irr}) is calculated using the GW to total water use ratio (f_{gw}) given by:

$$q_{\mathrm{irr}} = f_{\mathrm{gw}} \times \mathrm{irr} \tag{1}$$

where, irr is the irrigation applied to the fields at a given time step. f_{gw} varies yearly and is computed using the source-wise irrigated areas data discussed in section 2.1. The total GW pumped (q_{p}) from the aquifer is the summation abstraction for irrigation, domestic (q_{dom}) and industrial water use (q_{ind}) given by:

$$q_{\mathrm{p}} = q_{\mathrm{irr}} + q_{\mathrm{dom}} + q_{\mathrm{ind}}. \tag{2}$$

2.3. Experiment design

Figure 2(a) illustrates our study domain comprising mainly northwest (Punjab, Haryana, Delhi, and Rajasthan) and central (Uttar Pradesh and Bihar) IGP and a few districts of Uttarakhand, Madhya Pradesh, Chhattisgarh, and Jharkhand. The CGWB well locations within the domain are shown in figure 2(b). Analysis based on satellite observations by Rodell *et al* (2009) revealed GW depletion over this region attributed to the predominance of GW fed irrigation. We observe a high GW to total water use ratio in figure 2(c), specifically over the northwestern part, corroborating the over-reliance of irrigation on GW. The seasonal irrigation water use over the study domain during Kharif and Rabi are noted in figures 2(c) and (d), respectively. The model simulations were performed at 0.05° spatial resolution from 1998 to 2014, retaining only one (the dominant) land cover type per model grid. We generated the initial GW levels from well observations for January 1998 by the inverse distance interpolation method. We conducted four sets of runs: VIC_AMBHAS, VIC_AMBHAS_IRR, VIC_AMBHAS_INTER and VIC_AMBHAS_DRIP. In the VIC_AMBHAS run, we do not consider any irrigation and GW abstractions. We implement unconstrained flood irrigation and GW abstractions at daily time intervals in the VIC_AMBHAS_IRR simulation. This run represents the current scenario of irrigation practices over Indian croplands. In the VIC_AMBHAS_INTER run, irrigation application and abstraction occur at 7 d intervals. The mode of water application in the VIC_AMBHAS_DRIP experiment is drip irrigation at a daily time step. We performed a spin-up of 5–7 years for all the experiments until the GW levels and soil moisture stabilized. The results and analysis are presented in the following section.

3. Results and discussions

We divided the study domain into four based on the GW levels: Region 1 (Punjab and Haryana), Region 2 (Uttar Pradesh and Bihar), Region 3 (Rajasthan) and Region 4 (districts of Madhya Pradesh, Chhattisgarh and Jharkhand within the study domain) for better visualization and interpretation of the results. Region 4 is a considerably smaller area at the boundary with lesser irrigation activities and therefore was not taken into account in the analysis of results. Prior to the final simulations, we evaluated the performance of the model using combinations of the minimum, mean, and maximum specific yield (Sy) and aquifer hydraulic conductivity (K) derived from the parameterizations of Bonsor *et al* (2017) and Bhanja *et al* (2016) and chose the best global performance against observed GW levels (supporting information figure S1). We initialized the model by running repeated years composed of average daily climate until a dynamic equilibrium was reached, prior to running historical simulations.

3.1. Model performance

The simulated depths to GW from VIC_AMBHAS_IRR and VIC_AMBHAS experiments are compared against the CGWB well observations in figure 3. We generated the time series of simulated and observed depths to GW spatially averaged over Region 1,

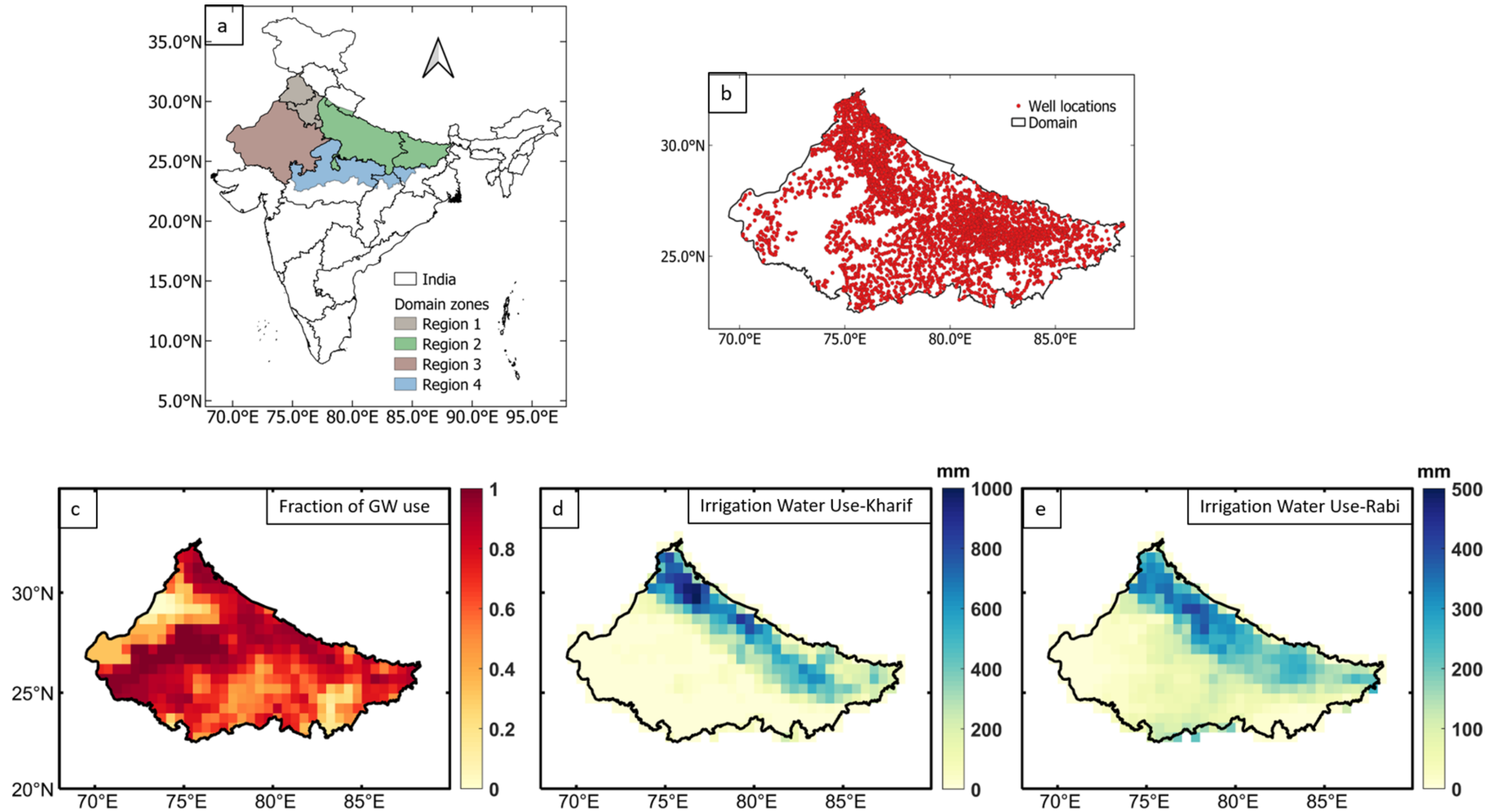

Figure 2. (a) Geographical location of the study region in India subdivided into Region 1, Region 2, Region 3 and Region 4. (b) CGWB well locations within the study domain. (c) Mean fraction of GW to total water used for irrigation averaged over the years 1998–2014. Mean seasonal irrigation water uses for Kharif (d) and Rabi season (e) in mm averaged over the years 1998–2014.

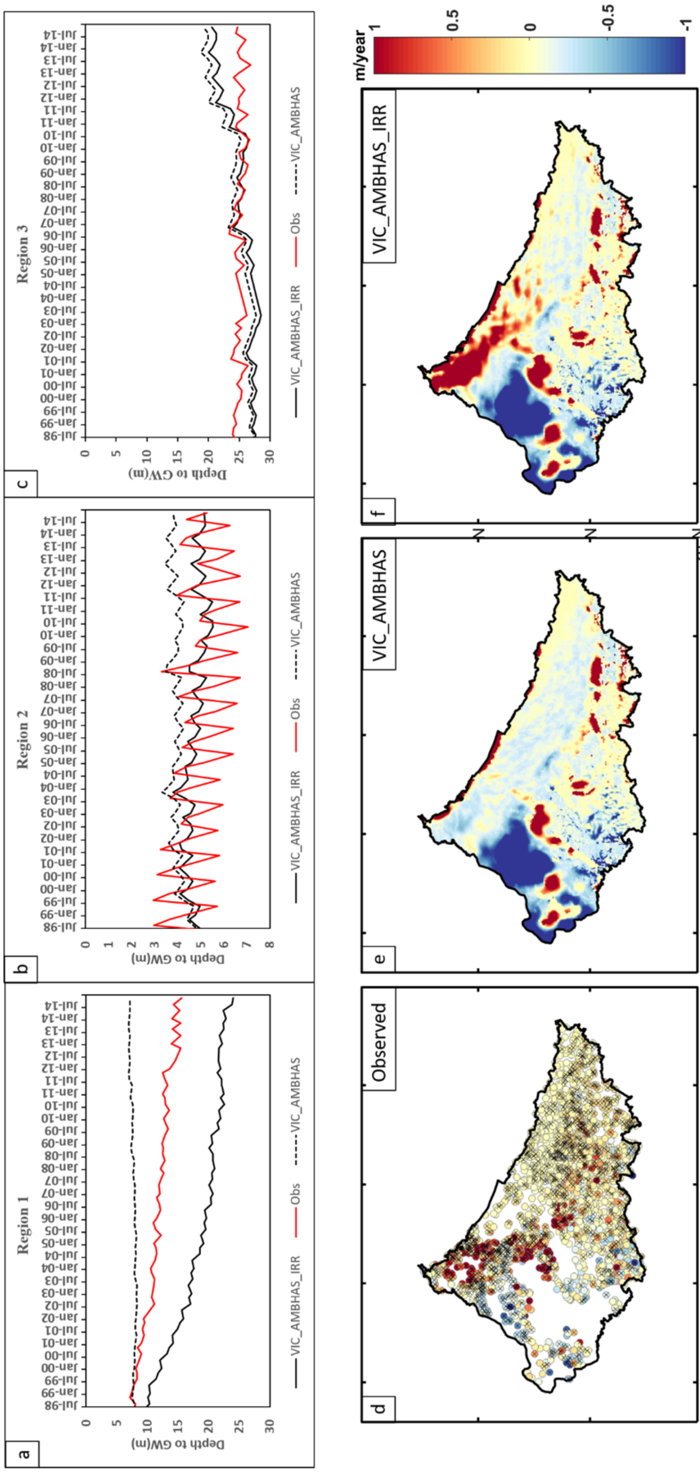

Figure 3. Validation of simulated depth to GW (m bgl) against *in-situ* well observations. Time series of depth to GW spatially averaged over Region 1 (a), Region 2 (b) and Region 3 (c) from 1998 to 2014. Here, depth to GW for January, May, August and November are selected for each year from 1998 to 2014 based on well observation data availability. Annual trend in GW depth from 1998 to 2014 for (d) observed (e) VIC_AMBHAS simulated and (f) VIC_AMBHAS_IRR simulated.

Region 2 and Region 3 separately. A decline in GW levels can be noted in both VIC_AMBHAS_IRR simulated and observed depths to GW over Region 1. Previous studies have also reported declining GW levels over this region linked to the widespread cultivation of intensive water crops like paddy and sugarcane (Ambast *et al* 2006, Humphreys *et al* 2010). Additionally, the low permeability layer created beneath the soil to ensure ponded conditions limits the recharge over paddy fields. Therefore, high abstraction and low recharge can occur over paddy croplands. However, we see an overestimation of depletion in the VIC_AMBHAS_IRR run. The recharge over Punjab and Haryana mostly occurs through sources other than rainfall (60%–70%), including seepage from canals, tanks, ponds and other water-holding structures and irrigation return flows (CGWB 2009, MacDonald *et al* 2016, Joshi *et al* 2018). VIC_AMBHAS_IRR does not consider recharge contributions from these sources, simulating higher depletion than observed. Since this region shares boundaries with the Indus basin, discrepancies in the GW model's boundary conditions could be another reason for the mismatch in simulated and observed GW levels. Both observed and simulated GW levels are shallowest in November due to lesser irrigation activities after the Kharif harvest. In VIC_AMBHAS runs, simulated GW levels are rising, in contrast to VIC_AMBHS_IRR output. This suggests agricultural pumping activities as the main contributing factor to accelerated depletion over Region 1, as highlighted in previous studies (Asoka *et al* 2017, van Dijk *et al* 2020, Nair and Indu 2021).

The VIC_AMBHAS_IRR simulated and observed depth to GW table show good agreement over Region 2. The observations show high seasonal variations; however, the long term trends of both observations and VIC_AMBHAS_IRR simulations are similar. Except for the western areas, this region has relatively less paddy cropland. Hence, the depletion rates here are much lower compared to Region 1. In the VIC_AMBHAS experiment, the depths to GW reduce similarly to Region 1.

Over Region 3, the relatively stable GW table is attributable to the non water-intensive agricultural practices suitable for arid climate over Rajasthan. However, the both VIC_AMBHAS and VIC_AMBHAS_IRR simulations show rising GW levels. We have compared both the simulations with the observed data to highlight the explicit impacts of GW abstraction and changes on the GW decline in the IGP. We found that the changes in rainfall patterns cannot produce the GW decline, whereas adding irrigation produces the GW depletion hotspots. The annual spatial trend (statistically significant) of depth to GW simulated in the VIC_AMBHAS_IRR experiment is similar to the observed trend (figures 3(d) and (f)) highlighting GW depletion hotspots over Regions 1 and 2. The simulations show GW levels rise over Region 3, and there are a limited number of well locations to validate the same. The GW levels over Region 1 are declining at an excessive rate of approximately 1 m yr^{-1}. The VIC_AMBHAS simulations (figure 3(e)) do not show depleted GW, and hence the GW depletion in the IGP cannot be attributed to the decline in monsoon. The trends of observed GW depths in January, May, August and November are spatially similar to the annual trends. The slight declining trend for a few wells in Region 4 during January and November can be linked to the irrigation abstractions for Rabi and Kharif, respectively. In VIC_AMBHAS and VIC_AMBHAS_IRR simulations, the trend in GW depth in Region 4 does not display any seasonal variations (supporting information figure S2). This could be because of a boundary effect.

3.2. Response of GW level to different irrigation practices

We tested the effect of irrigation technique and interval of water application. In figures 4(a)–(c), the time series of depth to GW table spatially averaged over Region 1, Region 2 and Region 3 are shown for VIC_AMBHAS_IRR, VIC_AMBHAS_DRIP and VIC_AMBHAS_INTER experiment. The VIC_AMBHAS_IRR and VIC_AMBHAS_INTER simulated GW depths overlap, implying that GW levels are unresponsive to the change in the frequency of water application, irrespective of the region. As expected, the adoption of drip irrigation led to water savings over Region 1. Though the depletion rate is substantially lessened in the VIC_AMBHAS_DRIP experiment, it is not reversed. A similar inference was reported over this region in the analysis performed by Fishman *et al* (2015). Their study showed that even though the improved irrigation efficiency can manage unsustainable GW abstraction to some extent over northwest IGP, where cereals are extensively cultivated, the trend in GW decline cannot be reversed. Over Region 2, we noted a very low difference in the simulated GW levels between VIC_AMBHAS_IRR and VIC_AMBHAS_DRIP. The modelled GW depths over Region 3 do not show sensitivity to the change in the mode of irrigation.

The differences in GW savings between Regions 1 and 2 could be linked to the variation in the Kharif recharge pattern over the two regions. The recharge over Region 1 remains the same regardless of the technique of irrigation (supplementary figure S3). The recharge over croplands under flood irrigation is expected to be higher; however, that is not the case for Region 1, due to the widespread cultivation of paddy, as shown in figure 4(d). The plow sole created to maintain flooded conditions over paddy fields limits the drainage of water to lower layers of soil. Since the upper soil layer is maintained at saturation in both the irrigation techniques, the recharge is unaffected (figure 4(e)) even after introducing

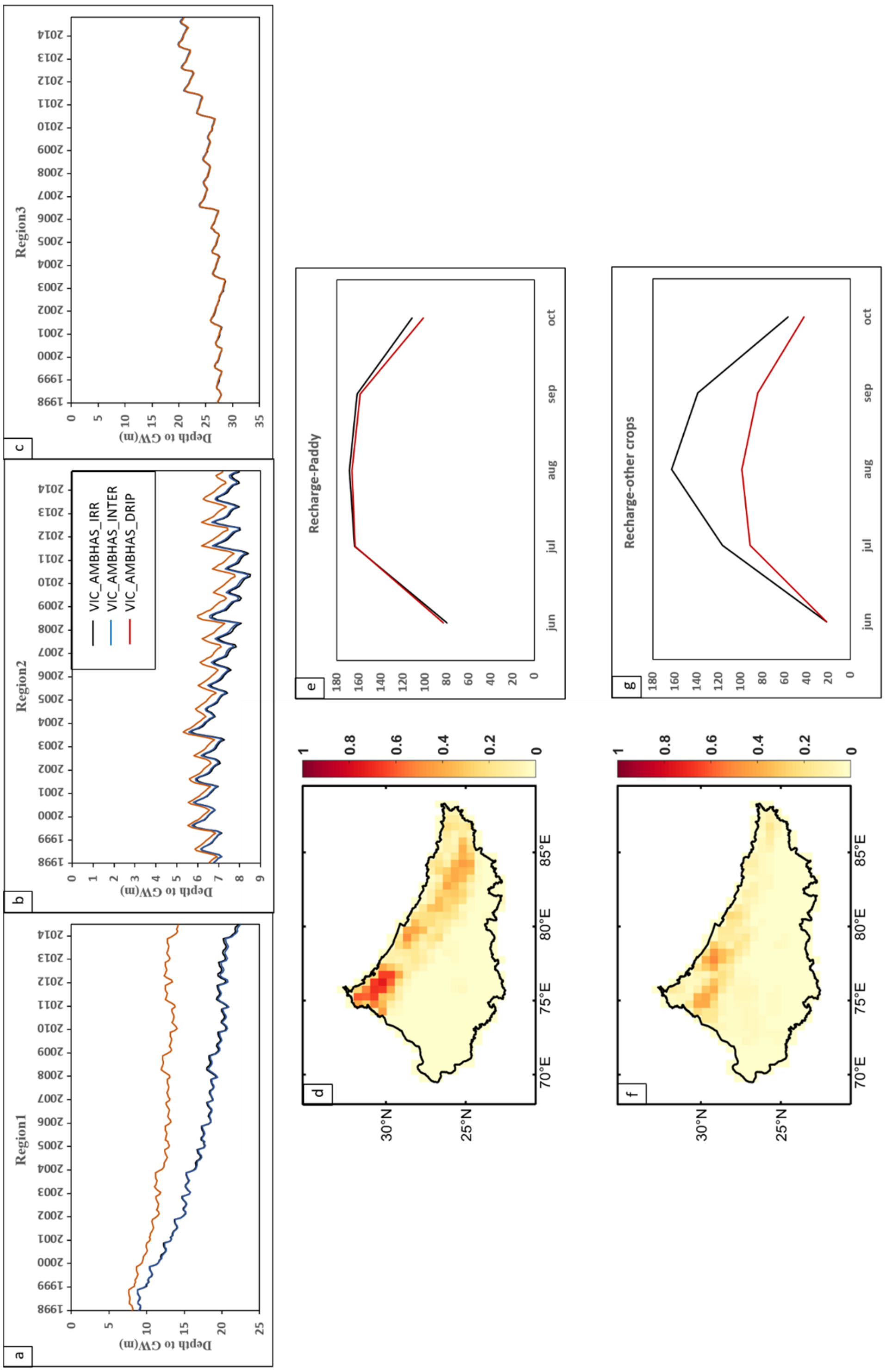

Figure 4. GW response to the change in irrigation technique and interval. Time series of depth to GW spatially averaged over Region 1 (a), Region 2 (b) and Region 3 (c) for VIC_AMBHAS_IRR, VIC_AMBHAS_DRIP and VIC_AMBHAS_INTER experiments for a period 1998–2014. (d) Mean fraction of paddy croplands in Kharif season averaged for years 1998–2014. (e) Climatology of recharge spatially averaged over paddy croplands in Kharif season calculated for years 1998–2014. (f) Mean fraction of other croplands in Kharif season averaged for years 1998–2014. (g) Climatology of recharge spatially averaged over other croplands in Kharif season calculated for 1998–2014.

drip irrigation. The abstraction is lesser for the drip irrigation.

Conversely, over Region 2, we observed a reduction in recharge associated with the drip irrigation technique (supporting information figure S3). The fraction of paddy cultivation is comparatively less over Region 2 (figures 4(d) and (f)) than Region 1. For other crops, under flood irrigation and in the absence of plow sole, a significant portion of flooded water goes back to the GW, increasing recharge (figure 4(g) and supplementary figure S3); hence, the net decline in GW gets reduced. When the crop fields are watered by drip irrigation mode, the recharge declines substantially (Pool *et al* 2022). Ward and Pulido-Velazquez (2008) reported reduced deep soil percolation for crops under drip irrigation. Hence, the GW savings are nominal over Region 2 even though the water requirement is less than flood irrigation. During Rabi season, the differences in recharge simulated by VIC_AMBHAS_IRR and VIC_AMBHAS_DRIP are analogous over Region 1 and Region 2. Over Region 3, since irrigation water use itself is less (as shown in figure 2(e)); hence, the irrigation mode does not affect the GW levels.

It is noteworthy that these results are relevant under a theoretical scenario where farmers' behaviour is not taken into account. Based on several interviews conducted in Rajasthan, Birkenholtz (2017) reported that the farmers' rationale for converting to drip irrigation is to increase their income rather than mitigate GW depletion. Farmers tend to expand irrigated crop areas when more water is saved or switch to more water-intensive crops to maximize their profit. They also increase the number of cropping cycles per year and grow crops that are not typically grown during a particular season. Water trading and reallocation for other purposes is yet another possibility that may result in water use and GW perturbation (Pfeiffer and Lin 2014, Fishman *et al* 2015, Grafton *et al* 2018, Shekhar *et al* 2020). Considering the factors mentioned above needs more data and field surveys, which can be a potential area of future research.

4. Conclusions

Our study has developed a new modelling framework to understand the effects of GW fed irrigation over the IGP by incorporating a realistic irrigation scheme to the VIC_AMBHAS model. Here the irrigation is not demand-driven, unlike current-generation models. Instead, we employ unrestrained flood irrigation based on agricultural census data, a common practice in Indian croplands. We also included separate energy and water balance formulations for paddy fields. In contrast to traditional GW coupled LSMs, VIC_AMBHAS accounts for lateral GW flows, which allows the water cycle to be closed within a catchment. Our model shows an overall good performance in simulating the GW levels, specifically over Uttar Pradesh and Bihar. We see a high overestimation of GW level decline over Punjab and Haryana. Our model does not consider the recharge from non-precipitation sources like canal leakage, return flow from crop fields, leakage from water conservation ponds, etc, significant in Region 1. Besides, it is challenging to estimate the magnitude of errors due to the non-consideration of these recharge sources. The model also showed limitations in simulating the spatially averaged GW variability for Region 2 and the trend for Region 3. There is a need for further fine-tuning of model parameters for more accurate estimation of GW levels. This can be achieved by employing automated calibration techniques that demand huge number of simulations; however, we were constrained by the computation expenses involved in the initialization and execution of the model at a fine resolution of 5 km. Moreover, the regional agricultural practices and crop type vary greatly even within the grid, making calibration of the model difficult without fine resolution data. Therefore, we have not performed further calibration of the model. Despite this limitation, the model could identify the depletion hotspots as observed in the well data (figure 3(f)). We also tested the influence of irrigation technique and water application interval on the GW levels. Our results show that the frequency of water application does not affect the GW levels. A substantial reduction in the declining GW levels is simulated over Region 1 when the drip irrigation scheme is adopted. Interestingly, GW decline by flood irrigation is lesser in Region 2 due to higher recharge. These differences attribute to the contrasting recharge patterns of non-paddy and paddy crop fields.

Some limitations of this study are listed below:

- The agricultural census data are subject to uncertainties due to the under-reporting of irrigated areas and discrepancies in data collection, as highlighted by Ajaz *et al* (2019).
- The irrigated fraction and district-level area under each crop are assumed to be distributed uniformly throughout the region. As a result, there is some uncertainty regarding the exact location of individual crop fields.
- The inadequate spatial distribution of the CGWB wells and low measurement frequency (once every season) with several missing data can lead to biases in model initialization and validation (Dangar *et al* 2021).
- The local heterogeneity in soil attributes is not taken into account because of the coarse resolution of the soil data.
- Although the fraction of GW to total irrigation water use may depend on the cropping season, the agricultural census data used in this study provides just a single value per district per year. This may result in inaccuracies in simulated GW abstraction.

- We have not incorporated farmers' water use decisions as discussed in section 3.2.
- While transforming from flood to drip irrigation, farmers build low-cost unlined reservoirs to ensure water availability during shortage periods (Kumar 2012). Depending on the regional soil properties, significant recharge can also occur from such water storage structures. Sharda *et al* (2006) estimated this recharge to be 7.5% of the annual rainfall over a semi-arid agroclimatic region (Gujarat) in India. Our modelling framework does not account for the recharge from on-farm water storage structures.
- The conclusions derived in the present analysis are also sensitive to the unaccounted recharge sources like leakage from water storage structures and agricultural return flows.

Despite these limitations, our model is useful in analysing the relative trends of GW depletion at a large spatial scale. A more practical conclusion on the sensitivity of GW levels to the mode and interval of irrigation can be drawn when more information on irrigation technology, crop cultivation technology, irrigation timing and norms, GW level at fine resolutions is available.

Recent studies have reported lowered crop yields linked to GW depletion (Bhattarai *et al* 2021, Jain *et al* 2021). Sishodia *et al* (2018) warned that the GW crisis is likely to worsen in the future if the current irrigation practices continue. Pool *et al* (2021) emphasized the importance of considering the effects of irrigation techniques when estimating future water availability over irrigated regions. Hence, our modelling framework is useful in identifying the prospective GW depletion hotspots facilitating the policy-makers to make informed decisions for sustainable GW management. Also, we infer that efficient irrigation techniques do not always imply enhanced water savings. Studies have suggested reduced return flows to GW on shifting to drip irrigation (Ward and Pulido-Velazquez 2008, Grafton *et al* 2018), which is also evident from our study for non-paddy crops. Perry (2017) highlighted the increased energy consumption in drip irrigation as water conveyance must be pressurized. Besides, we find that rice cultivation abstracts more and replenishes less GW. Therefore, shifting to water-efficient crops like millets and maize is a more desirable solution, as suggested by Davis *et al* (2018). Water pricing, incentivizing water savings, artificial recharge, restoring canal water supply etc, are alternate adaptation strategies. Since GW replenishes slowly, a prompt revamp is inevitable to regulate and mitigate the GW crisis of India.

Data availability statements

The gridded precipitation, maximum and minimum temperature data were obtained from IMD available at www.imdpune.gov.in/Clim_Pred_LRF_New/Grided_Data_Download.html. ERA-Interim wind data was downloaded from the European Centre for Medium-Range Weather Forecasts (ECMWF) website (https://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=sfc). Once we register on the website, the login credentials are emailed. The data can be for each time step selecting the desired options. The LULC data is procured from MODIS (https://lpdaac.usgs.gov/products/mcd12c1v006/). When the 'access data' icon is selected, multiple option like AppEEARS, Data Pool, NASA Earthdata Search, USGS EarthExplorer, OPeNDAP, DAAC2Disk Utility and LDOPE appears. We may use any of them to download the data. Area under crops, crop irrigated area and is source-wise irrigated areas for all the districts is downloaded from the Directorate of Economics and Statistics (https://aps.dac.gov.in/LUS). 'Districtwise Land Use Statistics' option has to be selected. From the drop-down menu, we can select the desired state, district and year. The data can be downloaded as pdf or csv file. The details on sowing and harvesting months for each crop was also obtained from the Directorate of Economics and Statistics available at (https://eands.dacnet.nic.in/At_A_Glance-2011/appendix-IV.xls). The DEM was obtained from SRTM 90 m (https://cgiarcsi.community/data/srtm-90m-digital-elevation-database-v4-1/). Well observations used to generate initial GW input and validate the simulated GW levels is downloaded from the WRIS website (https://indiawris.gov.in/wris/#/groundWater).

No new data were created or analysed in this study.

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