LETTER

Natural and anthropogenic drivers of the lost groundwater from the Ganga River basin

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Abstract

Ganga river basin is the most populated and among the worst water-stressed river basins in the world. The basin contributes to 40% of India’s gross domestic product. Despite the Ganga basin’s cultural, heritage, and economic importance, the interplay among the crucial factors that make the basin one of the global groundwater depletion hotspots is not well understood. Using observations from wells and Gravity Recovery and Climate Experiment satellites and simulations from a hydrological model, here we show that the Ganga river basin has lost 226.57 ± 25.22 km$^3$ groundwater during 2002–2016, which is about 20 times the storage capacity of the largest (Indira Sagar) reservoir in India. A significant ($p$-value < 0.05) decline (∼11%) in the summer monsoon (June–September) during 1951–2016, severe and frequent droughts (2009, 2014, 2015), and groundwater pumping for irrigation have contributed to groundwater depletion. However, the non-renewable groundwater abstraction is the most significant (relative contribution = 80%) contributor to the groundwater depletion in the basin. Renewable groundwater pumping contributed to only 20% of the total groundwater depleted during the 2002–2016 period. Severe and frequent droughts in the basin pose a double whammy of reducing groundwater recharge and increasing withdrawal. Changes in cropping patterns, groundwater metering, and improved water use efficiency are needed to reduce the non-renewable groundwater abstraction for irrigation, which is crucial for water sustainability in the basin.

1. Introduction

Groundwater is a vital resource that meets irrigation (42%) demands globally (Döll et al 2012), and more than 70% of total groundwater withdrawal is for irrigation (Siebert et al 2010). Terrestrial water storage (TWS) and groundwater storage based on Gravity Recovery and Climate Experiment (GRACE) satellites showed a rapid decline in the intensively irrigated regions globally (Rodell et al 2018, Tapley et al 2019). The expansion of irrigated areas to increase food production (Godfray et al 2010) resulted in groundwater exploitation (Giordano 2009, Wada et al 2012, Siebert et al 2015) in densely populated regions (Kerr 2009). Groundwater overexploitation is likely to continue, which along with climate change, will impact food and water security (Aeschbach-Hertig and Gleeson 2012, Gleeson et al 2012, Dalin et al 2017).

Both climate and human activities contribute to groundwater depletion (Asoka et al 2017, Rodell et al 2018, Asoka and Mishra 2020). Irrigation water withdrawal and reservoir storage affect surface and groundwater storage (Wada and Bierkens 2014). Groundwater storage has both renewable and non-renewable components. In contrast to non-renewable groundwater, renewable groundwater gets recharged during the summer monsoon season. The use of non-renewable groundwater for irrigation has tripled globally during the 1960–2000 period (Dalin et al 2019). Withdrawal of non-renewable groundwater for irrigation is the highest in India (Gleeson et al 2012) due to increased tube wells with cheap or
subsidized electricity (Shah 2010, Mishra et al 2018a). Non-renewable groundwater abstraction (Gleeson et al 2012, Bierkens and Wada 2019) has caused groundwater depletion in the past decades (Rost et al 2008, Wada et al 2010, Wada and Bierkens 2014, Yoshikawa et al 2014, Dalin et al 2017, Hanasaki et al 2018), which is critical to increasing water supply resilience during droughts (Taylor et al 2013, Famiglietti 2014, Goldin 2016, Panda and Wahr 2016, Van Loon et al 2016).

Ganga basin is among the most irrigated regions of the world (Siebert et al 2010), with about 57% irrigated area equipped with groundwater based irrigation. Ganga basin has 0.6% of total global land and 8% of the worldwide population. Moreover, the basin has about 10.3% of global irrigated land (Siebert et al 2015). The river basin has alluvial aquifers, where a significant decline in low-intensity precipitation during the summer monsoon plays a dominant role in groundwater recharge (Asoka et al 2018). Groundwater pumping for irrigation caused water stress in north India and resulted in a significant decline in TWS and groundwater storage over the Ganga basin (Rodell et al 2009, 2018, Shamsudduha et al 2009, Tiwari et al 2009, Gleeson et al 2012, Chen et al 2014, MacDonald et al 2016, Asoka et al 2017, Thomas et al 2017, Dangar et al 2021). Moreover, the Upper Ganges basin is one of the most stressed aquifers worldwide (Gleeson et al 2012).

The Ganga basin is a typical example of unsustainable groundwater withdrawal. The basin has tremendous importance as it provides water and livelihood to millions of people living in India, Nepal, and Bangladesh. However, understanding the primary drivers contributing to the rapid decline of groundwater in the Ganga basin is complex due to intensive irrigation and the variability of the summer monsoon season. Intensive irrigation to support food demands in the densely populated region exploits groundwater storage from renewable and non-renewable sources. The basin has experienced a decline in the summer monsoon season during the past decades (Mishra et al 2012, Roxy et al 2015). Apart from the decline in the summer monsoon rainfall, there has been a significant reduction in rainy days, contributing to groundwater recharge during the summer monsoon season (Asoka et al 2018). The Ganga river basin recently experienced frequent and severe droughts, which resulted in surface water scarcity and groundwater depletion (Mishra et al 2016). We identify the three major factors that might have contributed to the groundwater depletion in the basin, including (a) groundwater pumping for irrigation, (b) decline in the summer monsoon rainfall, and (c) frequent and severe droughts. However, the three factors’ relative contribution to the total groundwater loss in the basin is not well quantified, which is crucial for managing groundwater in one of the most stressed river basins in the world. We use satellite and groundwater well observations and a hydrological model representing the human influence of the surface and groundwater systems to estimate the total groundwater loss in the basin during 2002–2016. In addition, the relative contribution of different factors to groundwater loss in the Ganga river basin is also examined.

2. Data and methods

2.1. Observed datasets

We obtained gridded daily precipitation observations and maximum and minimum temperatures from the India Meteorological Department (IMD) for the Ganga river basin. Daily gridded precipitation at 0.25° (~30 km at the equator) spatial resolution from 1951 onwards is developed using more than 6500 rain gauge observations across India (Pai et al 2014). Gridded maximum and minimum temperatures are available at 1° (~110 km at the equator) spatial and daily temporal resolutions for the 1951–2016 period, based on more than 395 stations located across India (Srivastava et al 2009). We obtained gridded precipitation and temperature from the Princeton global forcing (Sheffield et al 2006), which are available at 0.25° spatial resolution and daily temporal resolution for the 1901–2016 period for the Ganga basin outside the Indian region. Gridded observations from IMD and Princeton global forcing compare well for the common period over the Indian region (Shah and Mishra 2016). Streamflow observations were obtained from the Global Runoff Data Centre. We used the GRanD database (Lehner et al 2011) to locate global large and medium-sized reservoirs based on their catchment area. A threshold of 1250 km² surface area equivalent to two 0.25° grid cells was used to distinguish the large and medium-sized reservoirs. A total of 16 large and 40 medium-sized reservoirs are present in the Ganga basin.

2.2. Hydrological model

We used the H08 global hydrological model at 0.25° spatial resolution considering human interventions to simulate the water budget. The enhanced H08 model (Hanasaki et al 2018) considers groundwater recharge and groundwater abstraction having renewable and non-renewable compartments. We conducted the H08 model simulations in the coupled mode, including all the human impacts available in the latest version (Hanasaki et al 2018). The model simulates abstractions from groundwater and surface water for irrigation, domestic, and industrial water requirements. We have also considered the role of reservoirs in our simulations using the generic reservoir operation rule (Hanasaki et al 2006).

The Ganga River basin is dominated by loamy soil and alluvial aquifers (MacDonald et al 2016, Asoka et al 2017) with high yield potential (CGWB 2012). MacDonald et al (2016) estimated groundwater storage within the top 200 m of the aquifer by mapping
specific yields from lithological and hydrogeological data. The total volume in the top 200 m of the Indo-Gangetic basin is estimated to be 30,000 ± 14,000 km³ (MacDonald et al. 2016). However, no estimate of total groundwater storage volume in the Ganga River basin is available. Groundwater recharge in the H08 model is empirically estimated using the algorithm developed by Döll and Fiedler (2008), which considers relief, soil texture, and hydrogeology along with precipitation intensity. The renewable groundwater storage in the H08 model in the Ganga River basin is quantified based on a fixed groundwater depth obtained from the CGWB well levels for the region in India, which has input fluxes of groundwater recharge and output fluxes of baseflow and groundwater abstraction. For the part of the basin outside the country, we used the basin average groundwater depth based on the estimates for the Indian region. Non-renewable groundwater abstraction is considered when renewable groundwater's water requirements are not met from the other sources (figure S5b (available online at stacks.iop.org/ERL/16/114009/mmedia)). Therefore, the area with non-renewable groundwater pumping in the Ganga basins is considerably lesser than with renewable groundwater pumping. More information on the estimation of groundwater pumping from renewable and non-renewable groundwater storage and recharge can be obtained from the supplemental information (text S1).

We used the industrial and domestic fraction for groundwater from Döll et al. (2012), and water requirements were obtained from AQUASTAT for the year 2000. The gridded population count then weighted the country-based estimates to have gridded estimates. The irrigation water requirement depends on the irrigated area (Siebert et al. 2010), crop types grown (Monfreda et al. 2008), irrigation efficiency, and cropping intensity (Döll and Siebert 2002). The irrigation efficiency is fixed to a constant country-wise value, which is 35% for India. A dual cropping system is used with the dominant crop type in the Ganga basin for the Rabi and Kharif seasons as wheat and rice, respectively. The H08 model computes the irrigation water demand based on the cropping calendar for the crop types in the crop growth module (Hanasaki et al. 2018).

We conducted simulations using the H08 in Natural (NAT) and human-influence (HUM) modes for the 1948–2016 period. The NAT simulations were conducted using only the H08 land surface (with groundwater recharge but no groundwater pumping) and river routing submodules. The HUM simulations were conducted considering groundwater pumping, crop growth, and the influence of dams and reservoirs. The simulations for the year 1948 ran recursively until a certain threshold of spin-up error tolerance was met to reach the steady-state of the H08 model. Daily input meteorological forcing was used for the simulations, while the analysis was performed on a monthly scale. Irrigation water demand and groundwater pumping from different sources were considered in the HUM simulations.

We calibrated and evaluated the H08 model using observed monthly river discharge at the Farakka gauge station. We used the 10 years of data (1951–1960) for the calibration while nine years (1965–1973) for the model evaluation. Our calibration and evaluation period was limited to about 10 years as observed streamflow in the Ganga river basin is not available in the public domain. The four parameters in the land surface module, including single-layer soil depth (in m), bulk transfer coefficient (a term used in potential evaporation calculation), gamma (dimensionless), and tau (in days), were manually adjusted to calibrate the model. After calibrating the model against the observed flow, the groundwater parameters (groundwater depth, gamma and tau for groundwater reservoir) were adjusted to capture the observed variability in the TWS anomaly (TWSA) derived from the GRACE. The model calibration parameters are discussed in detail in the supplementary information (supplemental text S4 and table S1). The groundwater depth estimation is based on well level observations (figure S7 and table S2), which is explained in the supplemental text S4. The dam at Farakka was built in 1974, and groundwater pumping predominantly started after the Green Revolution during the 1970s. Therefore, river discharge is not affected by human interventions for calibration and evaluation periods. The model calibration parameters for streamflow under the NAT simulation were used in the HUM simulations. In addition, we used the observed and simulated streamflow at Hardinge bridge (1985–1991), which is located downstream of the Farakka station, for further evaluation. For the upstream part of the Ganga river basin, observed streamflow at Kalanaur (calibration: 1991–1998, evaluation: 1999–2005) and Delhi road bridge (calibration: 1990–1994, 1995–1997) were used to examine the model’s performance.

2.3. Analysis
Groundwater well level observations were obtained from the Central Groundwater Board (CGWB) for the 1996–2016 period. Well observations are available for four months (January, May, August, and November) annually. More than one thousand (1419) groundwater observational wells were selected in the Ganga basin (Indian region) based on the long-term data availability (Asoka et al. 2018). We removed the mean of the entire period of each month from respective months to deseasonalize groundwater level observations. Then, we estimated standardized anomalies of groundwater level relative to the 1996–2016 mean.
We used the GRACE RL06 mascons products from the Center for Space Research (CSR) and Jet Propulsion Laboratory (JPL). We considered Mascons for our analysis as these captures the regional trend in groundwater abstraction more prominently (Save et al. 2016). GRACE dataset from CSR is available at 0.25° while JPL is available at 1° spatial and monthly temporal resolutions from April 2002–December 2016. We filled the missing GRACE data for some months using bilinear interpolation. GRACE TWSA is estimated relative to the 2004–2009 baseline mean. Therefore, TWSA from the H08 model was estimated by subtracting the baseline mean from the respective variables. Surface water storage from the H08 model includes soil moisture, snow water, river storage, and reservoir storage. We also estimated surface water storage components from the other two land surface models (VIC and Noah) that are part of the global land data assimilation system (GLDAS (Rodell et al. 2004)). For GLDAS models, the surface water storage compartment includes soil moisture at different depths, canopy water, and snow water. Further details on the estimation of TWSA and groundwater storage anomalies from GRACE can be obtained from Rodell et al. (2009) and supplementary information (supplemental text S2).

We estimated precipitation anomaly by subtracting long term mean (1951–2016) during the summer monsoon (June–September). Precipitation anomalies less than −15% are taken as drought years, while a surplus of more than 10% was considered wet years. We estimated anomalies (%) for groundwater components (renewable and non-renewable abstraction and groundwater recharge) considering the mean of the 2002–2015 period for the water year (June–May). The groundwater withdrawal for each district of the Indian state in the Ganga basin is taken from the CGWB dynamic groundwater reports for the assessment years of 2004, 2009, 2011 and 2013 (http://cgwb.gov.in/Dynamic-GW-Resources.html). The TWS and GWS storage changes are based on the H08 model, GRACE, and GLDAS estimates. Water storage changes are estimated using the non-parametric Mann–Kendall test and Sen’s slope. The uncertainty was quantified using one standard deviation for the two GRACE products (CSR and JPL) and surface water storage from the three (Noah, VIC and H08) models.

We used the dominance analysis approach (Azen and Budescu 2003) to quantify the relative contribution. In dominance analysis, relative importance is measured in a pairwise manner, and two predictors are compared considering all the other possible predictors’ subsets. $R^2$ is used as the measure of the variance proportion in regression, and the additional contribution is measured by an increase in $R^2$ from adding predictors in the regression model (please see supplemental information for more details, text S3). For TWSA, renewable groundwater, non-renewable groundwater, and surface water storage contributions from the H08 model were taken as predictors after removing the seasonality. Similarly, for GWSA, renewable and non-renewable storages were considered, and within renewable groundwater storage changes, recharge and abstraction components were included as predictors.

3. Results

3.1. Observed changes in climate in the Ganga River basin

A large part of the Ganga river basin is dominated by groundwater-based irrigation (Asoka et al. 2017) (figure 1(a)). Irrigation in the Ganga basin has expanded after the Green Revolution in the 1970s with considerable environmental implications (Ambika and Mishra 2021, Shah 2009, Shah et al. 2018, Ambika and Mishra 2019, Mishra et al. 2020). First, we examined the observed changes in the summer monsoon season (June–September) precipitation and air temperature in the Ganga basin during 1951–2016 (figures 1(b)–(d)). Based on the observations from IMD, we find that summer monsoon precipitation has significantly (p-value = 0.045) declined (−11%) during 1951–2016. The three (Climate Research Unit: CRU; Princeton University: Princeton; and University of Delaware: UDEL) other gridded precipitation observations also show a significant decline of ~12.5%–15% in the summer monsoon precipitation in the basin during the same period (figure S1(a)). Since the summer monsoon season precipitation is the primary source of groundwater recharge (Asoka et al. 2017, 2018) other than the canal network (MacDonald et al. 2016), the significant decline in rainfall can have implications for groundwater sustainability in the region. Along with the declining precipitation, eight droughts with a precipitation deficit of more than 15% occurred during the 1951–2016 period (figure 1(b)). Moreover, out of eight droughts during the 1951–2016 period, three occurred during the recent decade (2006–2016). The consecutive drought of 2014–2015 was among the most severe droughts, which affected the region’s surface and groundwater resources (Mishra et al. 2016).

The Ganga basin has experienced a significant (p-value < 0.05) warming (+0.53 °C) in the summer monsoon season during 1951–2016, as shown by the IMD observations (figure 1(c)). Moreover, the air temperature has increased more rapidly (+0.65 °C) during the non-monsoon season (October–May) than the summer monsoon (figure 1(d)). The other two (CRU and Princeton) observational datasets also showed significant warming in the range of 0.45 °C–0.48 °C and 0.57 °C–0.74 °C in the monsoon and non-monsoon seasons, respectively (figures S1(b) and (c)). Both declining summer monsoon precipitation and rising air temperature in the Ganga...
Figure 1. Observed changes in climate in Ganga river basin during 1951–2016. (a) Area irrigated with groundwater expressed as a percentage of total area equipped for irrigation for the Ganga basin. Irrigated area was obtained from AQUASTAT—FAO’s Global Map of Irrigation Areas version 5.0 for the year 2005. Areas with no irrigation are masked in white. Inset shows the Indian subcontinental basins with the Ganga basin shaded in light violet. (b) Precipitation anomaly for the summer monsoon season (July–September) for 1951-2016. Years having precipitation anomaly less than $-15\%$ (dark green line) are marked in orange lines and are considered as drought. (c) Basin averaged air temperature for the summer monsoon for 1951–2016. (d) Basin averaged air temperature for the non-monsoon (October–May) for 1951–2016. Dashed lines in (b–d) show the trend in the summer monsoon season in precipitation and temperature. Trend was estimated using non-parametric Mann–Kendall test and Sen’s slope. $P$-values less than 0.05 show statistical significant trend at 5% significance level. Change in the summer monsoon precipitation and temperature was estimated using trend slope (per year) multiplied by the total duration (1951–2016).

basin resulted in unfavourable conditions for groundwater storage variability. For instance, the decline in summer monsoon rainfall results in a deficit in groundwater recharge (Asoka et al 2018). On the other hand, increased warming can lead to enhanced atmospheric water demands during the dry season (Mishra et al 2020), leading to a rise in the irrigation water demands (Wada et al 2013, Haddeland et al 2014, Aadhar and Mishra 2020). Overall, the long-term changes in precipitation and temperature have been unsupportive to groundwater sustainability in the Ganga basin.

3.2. Modelling of observed changes in groundwater storage variability

Next, we used the calibrated and evaluated H08 model (figure S2) to examine the groundwater storage variability using well observations from Central Groundwater Board (CGWB) and GRACE in the Ganga River basin (figure 2). Well observations from CGWB show local variations in groundwater level during 1996–2016 (figure 2(a)). A majority (about 71% of the total 1419 wells) of groundwater wells show a declining trend in groundwater level during 1996–2016. Groundwater observation wells in the southwest part of the basin show both positive and negative trends in groundwater level (figure 2(a)). The southwest part of the basin has a relatively lesser area under irrigation from groundwater. Since most of the observation wells are located in shallow aquifers (depth less than 20 m), these do not capture groundwater storage variability in deep aquifers, which predominantly contribute to irrigation (Asoka et al 2018, Mishra et al 2018a).

We used the coupled H08 model with human interventions (see methods for details) to examine the groundwater and TWS variability in the basin (Hanasaki et al 2018). We calibrated and evaluated the H08 model against the observed streamflow and GRACE based TWSA (figures S2(b)–(e)). The model performance to simulate monthly streamflow at different locations in the basin was satisfactory, with Nash Sutcliffe efficiency (NSE) more than 0.8 for both calibration and evaluation periods (figure S2). As the model incorporates irrigation and reservoir operations, the influence of these human activities was noted on streamflow simulations. Reservoir operation results in increased flow during the
Figure 2. Terrestrial and groundwater storage variability from the GRACE and well observations in Ganga river basin. (a) Groundwater observation wells (1419 wells) with positive trends (412 wells) in blue and negative trends (1007 wells) in red in the Indian region of the Ganga basin. Trends in groundwater observation wells from Central Groundwater Development Board (CGWB) were estimated using non-parametric Mann–Kendall trend and Sen’s slope for 1996–2016 period. (b) Basin averaged terrestrial water storage anomaly (TWSA) estimated from the Gravity Recovery and Climate Experiment (GRACE) CSR RL06 mascon product (in red) and simulated using the H08 model (in blue). (c) Groundwater storage anomalies (GWSA) from the GRACE satellites (in red) and simulated using the H08 model (in blue) for 2002–2016 period. The anomalies in (b) and (c) are relative to 2004–2009 mean. (d) The renewable groundwater storage from the H08 model (in blue) is compared (correlation, \( r = 0.85 \)) with CGWB well observations (in red) using anomalies for four available months (January, May, August, and November) in a year. Data is deseasonalized before calculation of standardized anomaly.

dry season, while excessive groundwater pumping reduces streamflow (figure S6). The influence of the Farakka reservoir was noted on the simulated streamflow at Hardinge Bridge station. In contrast, the influence of groundwater abstraction was observed on the low flow during the dry season (figures S2(d) and S6). Overall, our hydrological modelling framework captures the variability and trends in GRACE-TWSA \((-1.43 \text{ cm yr}^{-1} \) from GRACE and \(-1.62 \text{ cm yr}^{-1} \) from the H08 model\) (figure 2(b)) with NSE of 0.95 and correlation of 0.97 (figure 2(b)).

A significant groundwater depletion occurred during the 2002–2016 period in the Ganga basin, as shown by the GRACE observations (figure 2(c)). Observations from the GRACE satellites show that groundwater depleted significantly (\( p \)-value < 0.05) with a rate of 15 mm per year in the Ganga basin (figure 2(c)). Moreover, the rate of groundwater depletion has increased during recent years, which can be attributed to frequent and severe droughts (Mishra et al 2018b) and groundwater pumping. Groundwater storage anomalies (GWSA) from the GRACE satellites and H08 model compare well for the common period of 2002–2016 (figure 2(c)). The model simulated GWSA captured both anomalies and trends with an NSE of 0.85 (figure 2(c)). The comparable trends of TWSA and GWSA estimated using the GRACE satellites, and the H08 model show that groundwater depletion is the primary driver of the declining trend of TWSA (figures 2 and 3).

Trends in TWSA estimated using the hydrological model, and the two GRACE products (CSR and JPL) are comparable (figure S3(a)). Similarly, combining the two GRACE products and the three land surface models (H08, Noah, and VIC) provides us with a range of 189–254 mm change in the groundwater during 2002–2018 (figure S3(b)). The depth of observational groundwater wells in the Ganga basin ranges up to 35 m, with approximately 92.5% of wells have depth within 20 m (shallow wells). These shallow wells are recharged by the summer monsoon precipitation (Asoka et al 2017, 2018). Therefore, well observations are compared with the renewable groundwater simulated using the H08 model after standardization (figure 2(d)). Observed groundwater variability and trends from the CGWB well observations are satisfactorily captured by the H08 model for the 1996–2016 period (figure 2(d)). However, we did not compare the model estimates for the change in the non-renewable groundwater storage against the well observations due to the lack of deep groundwater wells. Overall, we find that H08...
Figure 3. Changes in terrestrial water and groundwater storages in the Ganga river basin during 2002–2016. (a), (b) Trends (cm/year) in TWS and groundwater storage anomalies from the GRACE satellites estimated using non-parametric Mann–Kendall trend and Sen’s slope method. (c) Total changes in TWS and groundwater storage estimated using GRACE products (in green) and the H08 model (in pink) during 2002–2016. Error bars show uncertainty estimated using one standard deviation of TWS and groundwater storage estimates from all the products (GRACE and GLDAS). (d) Relative contribution of non-renewable groundwater, renewable groundwater, and surface water storage to the total change in TWS and groundwater storage. Relative contribution of groundwater recharge and renewable groundwater abstraction to renewable groundwater storage in the Ganga basin during 2002–2016.

3.3. The relative contribution of renewable and non-renewable groundwater abstraction

The GRACE derived TWSA and GWSA show declining trends in most of the Ganga river basin during 2002–2016 (figures 3(a) and (b)). TWSA from the GRACE satellites exhibits a significant decline in the northwestern part of the basin (figure 3(a)). Consistent with the TWSA, GWSA from the GRACE satellites also showed a considerable decrease in the northwest part of the Ganga basin (figure 3(b)). A few regions in the basin experienced a decline in TWSA and GWSA by more than 4–5 cm per year during 2002–2016 (figures 3(a) and (b)). The regions with the rapidly decreasing TWSA and GWSA overlap with the intensively irrigated areas (figure 1(a)). We estimated basin averaged change in TWS and groundwater storage from the GRACE products and H08 model in the Ganga river basin (figure 3(c)). The GRACE based estimates show a decline of 237.2 km$^3$ (±24.14 km$^3$) in TWS in the Ganga river basin during 2002–2016 (figure 3(c)). The changes in TWS estimated based on the H08 model are comparable (249.64 km$^3$) with the GRACE-based estimates (figure 3(c)).

Ganga River basin has witnessed a remarkable depletion in groundwater during 2002–2016. For instance, GRACE based estimates show that the basin has lost about 226.57 km$^3$ (±25.22 km$^3$) groundwater (figure 3(c)). Consistent with the GRACE estimates, the H08 model-based estimates also show a loss of approximately 253.8 km$^3$ of groundwater in the basin (figure 3(c)). The average annual groundwater depletion in the Ganga River basin is about 15 mm yr$^{-1}$, consistent with the estimates from the GRACE satellites and the H08 model. A moderate overestimation in the model-based estimates of groundwater loss in the basin can be attributed to the H08 model parameterization. However, the model-based assessment of the groundwater loss falls within the uncertainty range because of different GRACE products (figure S3). We estimated uncertainty (Van Loon et al 2017) in the GRACE based TWS and groundwater storage change using one standard deviation based on the surface water storage and groundwater from the
different GRACE and global land data assimilation (GLDAS) products (figure S3). We also compared our model-based estimates against the groundwater draft from CGWB reports, available for 2004, 2009, 2011 and 2013 assessment years for the same geographical domain (figure S4). The model overestimates the reported abstraction as the CGWB assessment is commonly computed from the available number of abstraction structures and their seasonal draft. Moreover, abstraction estimates in the CGWB report are based on the district level analysis while the model was implemented at 0.25°. Therefore, differences between CGWB and model-based estimates are expected. Nonetheless, the model estimates are comparable with the estimates from the GRACE satellites. The groundwater loss (226.57 ± 25.22 km³) from the basin is higher than the live storage capacity of the 123 major reservoirs in India. The lost groundwater from the basin is almost 20 times the storage capacity of the Indira Sagar dam, which is the largest reservoir in India.

Changes in TWS and groundwater storage in the Ganga basin can be driven by the decline in the summer monsoon precipitation, frequent droughts, and groundwater abstraction for irrigation. We assessed the relative contribution (see methods for details) of renewable and non-renewable groundwater storage on TWS and groundwater storage (figure 3(d)). Our results show that the non-renewable groundwater pumping contributes the most to TWS and groundwater storage (figure 3(d)). For instance, non-renewable groundwater abstraction contributes about 63.4% to the decline in TWS during 2002–2016. On the other hand, the relative contribution of renewable groundwater pumping and surface water storage to the changes in TWS is 19.5% and 17.1%, respectively (figure 3(d)). Similarly, non-renewable groundwater abstraction is the most significant (80.7%) contributor to the total groundwater loss in the Ganga basin during 2002–2016 (figure 3(d)). The relative contribution of renewable groundwater abstraction to the total groundwater loss is less than 20% (figure 3(d)). Since non-renewable groundwater does not get renewed, the cumulative volume of non-renewable component is considerably higher than the mean annual renewable groundwater abstraction at decadal timescales. The cumulative non-renewable groundwater loss contributes to declining TWS and groundwater storage in the Ganga basin. On the other hand, renewable groundwater storage is dependent on recharge and abstraction. The relative contribution of recharge (70.4%) is higher than abstraction (29.6%) on the renewable groundwater storage change (figure 3(d)). Therefore, variability in the summer monsoon precipitation in the basin plays a dominant role in renewable groundwater storage. The total groundwater and terrestrial storage declines are primarily driven by non-renewable groundwater abstraction in the Ganga basin.

3.4. Impacts of droughts on groundwater storage
Non-renewable groundwater pumping is the primary cause of the rapid depletion of groundwater in the Ganga basin during 2002–2016. We examined the variation in groundwater abstraction and recharge during drought and extreme wet years. The three severe droughts in the Ganga basin occurred in 2009, 2014, and 2015 (Mishra et al., 2016, 2019). Precipitation anomaly composite (mean of anomalies for all the years) for the three drought years (2009, 2014, 2015) shows that the central part of the basin experienced the highest (40%–50% of long-term mean) deficit (figure 4(a)). Groundwater storage anomaly composite from the GRACE satellites for the three drought years shows five times more groundwater deficit compared to 2002–2016 mean (figure 4(b)). The dependence on groundwater for irrigation increases during drought compared to normal summer monsoons due to a lack of surface water storage. Moreover, groundwater abstraction is higher during drought years to meet the irrigation water requirements (figure S5(d)). Precipitation deficit during the summer monsoon reduces groundwater recharge, as shown by the negative anomalies across the Ganga basin (figure 4(c)), which leads to a decline in renewable groundwater storage (figure S5(c)). Our results show that summer monsoon droughts can cause reduced water availability for renewable groundwater abstraction (figure S5(a)). On the other hand, groundwater abstraction is 15%–20% higher during droughts than in normal years (figure 4(d)).

The percentage anomaly for dry (2009, 2014, 2015) and wet (2003, 2011) years are comparable but opposite. The Ganga basin experienced the highest summer monsoon precipitation deficit (−30.4%) in 2014. As the 2014 precipitation deficit continued in 2015 (−17.2%), the groundwater abstraction was 16.2% higher in 2015 than in normal years. On the other hand, groundwater recharge in 2015 was 13.6% lesser than normal (figure 4(e)). Therefore, severe droughts impact both groundwater abstraction and recharge. Moreover, during wet years, groundwater abstraction declines while recharge increases (figure 4(e)). Overall, our results show that the recent decades’ decline in summer monsoon precipitation, frequent and severe droughts and non-renewable groundwater pumping have significantly impacted groundwater storage in the Ganga basin.
4. Discussion and conclusions

Groundwater pumping for irrigation from confined aquifers has been a concern for groundwater sustainability in many parts of the country (Mishra et al. 2018). Our assessment based on the H08 model also shows the influence of non-renewable groundwater pumping on the loss of groundwater storage in the Ganga River basin. While we calibrated and evaluated the model against GRACE and well observations and observed streamflow, our modelling framework has limitations. One of the main limitations is the availability of the observed datasets. For instance, GRACE data is available only from...
2002 to 2016, while the basin has limited streamflow observations. Streamflow observations are classified as the Ganga is a transboundary river. The other limitation is associated with the static nature of input datasets used in the hydrological modelling. Model inputs such as land use/land cover and irrigated area are based on a single year and do not change every year, influencing the estimates. In addition, the representation of renewable and non-renewable groundwater in the H08 model also has limitations. For example, the H08 model does not consider any capillary rise. Therefore, water from renewable groundwater reservoir does not move into the above lying soil column. Non-renewable groundwater storage is a hypothetical reservoir of infinite volume, which does not assume any recharge from the renewable storage or capillary rise. If cropland is equipped with groundwater irrigation facilities, all irrigation water requirements are met from groundwater pumping. Water is first abstracted from renewable groundwater storage to meet the irrigation water requirements. Water is abstracted from the non-renewable groundwater storage if the renewable groundwater is depleted. Since non-renewable groundwater does not get recharged, pumping from these reservoirs contributes to considerable groundwater storage depletion. Notwithstanding these limitations in the input datasets, observations, and the model, H08 based estimates of trends in TWS and groundwater storage compares well against the GRACE based estimates.

We showed that non-renewable groundwater abstraction for irrigation is the primary driver of more than 200 km² loss of groundwater from the Ganga basin during 2002–2016. While the human footprint dominates the massive loss of groundwater in the basin, the long-term (1951–2016) changes in the climate have also not been supportive. For instance, a significant decline in the summer monsoon season precipitation, frequent droughts, and warming have contributed to the rapid groundwater depletion in the basin. The occurrence of severe droughts has intensified the groundwater abstraction in the Ganga basin during recent decades. In addition, droughts pose double-whammy impacts with increased pumping and reduced recharge in the basin. For example, groundwater abstraction was increased by ~14%, while recharge was reduced by ~13% during the drought of 2015. The non-renewable groundwater abstraction from confined aquifers is a vital resource that would hamper water availability during droughts once depleted. The water scarcity caused by declining summer monsoon rainfall and depleted groundwater in the basin can disrupt ecosystem functionality and agricultural production. Moreover, groundwater depletion in the Ganga basin causes a reduction in streamflow during dry seasons (Mukherjee et al. 2018).

Understanding the drivers and implications of groundwater depletion in the basin can help stakeholders and policymakers. The overdependence on groundwater in certain regions has to be reduced, given the negative impacts of over-withdrawal. The groundwater pumping rates have already significantly exceeded the natural groundwater recharge rate in the many areas of north India (Mishra et al. 2018a). The lost groundwater storage can be retrieved either by increasing recharge or by diminishing the abstraction by enhancing irrigation efficiency and cropping patterns, growing drought-resistant crops, and metering groundwater pumping (Dalin et al. 2017). Managed aquifer recharge, incentives to enrich renewable groundwater resources, and having a tariff-based extraction policy for unsustainable groundwater abstraction can have considerable implications on the groundwater depletion rate in the Ganga basin (Fishman et al. 2015, 2016). Intensive groundwater irrigation with changing precipitation (recharge) patterns and increasing climate extremes (such as drought and heatwaves) can worsen groundwater availability in the future. The aforementioned better groundwater management practices determine the future of groundwater sustainability in the Ganga basin.

Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

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Author contribution

VM conceived the idea and designed the study, SD developed the modelling framework, performed the analysis, and wrote the first draft. Both the authors worked on improving the discussion and writeup.

Conflict of interest

Authors declare no competing interests.

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