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PAPER

Detection and socio-economic attribution of groundwater depletion in India

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Abstract
Groundwater is a critical resource for both consumption and food security in India, where groundwater management faces significant challenges due to climate change and anthropogenic activities. Although several studies explored groundwater variability in India, few have focused on the socioeconomic attribution of these changes, utilizing data from industries, population and water demand. In this study, trends in groundwater storage were examined by leveraging the largest in situ dataset ever collated in India from ~27,000 groundwater wells, satellite-based terrestrial-water-storage estimates, and hydrological model simulations. Five major hotspots of groundwater depletion across India were identified using in situ measurements and previously untapped socioeconomic datasets to attribute these trends. Approximately 16% of Indian groundwater monitoring stations exhibited systematically decreasing trends in groundwater levels. These hotspots are primarily concentrated in the northern and northwestern parts of India as well as in the states of Chhattisgarh, West Bengal, and Kerala. The north/northwestern hotspots have experienced a staggering loss of ~6.46×10^{10} m^3 of water over the past two decades. The factors contributing to this depletion include population growth, rapid urbanization, proliferation of factories and the expansion of agriculture.

Keywords Groundwater monitoring · Data assimilation · Trends · Land surface models · India

Introduction

Groundwater is a widely accessible source of freshwater that is less susceptible to quality deterioration and droughts relative to surface water (Aeschbach-Hertig and Gleeson 2012). Groundwater serves 42% of irrigation, 36% of domestic, and 27% of industrial demand worldwide (Döll et al. 2012; Taylor et al. 2013); however, groundwater resources are also highly susceptible to depletion due to unsustainable water extraction rates (Wada et al. 2010). Rapid urbanization without sufficient piped drinking-water-distribution networks has added to the pressure on groundwater resources, and there has been a steady increase in usage of nonrenewable groundwater, i.e., extractions which will not be recharged in human time scales of 100 years or longer (Gleeson et al. 2012). There is considerable uncertainty in current and future estimates of groundwater depletion and socioeconomic attribution of these declines, especially in countries such as India, which features the highest volume of nonrenewable groundwater withdrawals for irrigation (Gleeson et al. 2012). While the extent of groundwater depletion in India has been estimated (Tiwari et al. 2009; Rodell et al. 2009; Long et al. 2016), very few studies have attempted to attribute these changes to socioeconomic factors. MacAllister et al. (2022) estimated a loss of 70 km^3 groundwater from northwest India and Central Pakistan at ~2.8 cm/year in the initial decade of the twenty-first century and ascribed this loss to anthropogenic and climatic factors. Groundwater depletion in India stems from interlinked water, energy, and food policies, fostering unsustainable practices in agriculture (Mukherji 2022). Panda et al. (2012) examined water-table records of 555 monitoring wells in Gujarat state of India and found a large number of declining trends in groundwater levels with notable spatial patterns

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that are unlikely to be associated with natural climate variability. Khara and Ghuman (2023) found groundwater extraction for irrigation in Punjab has increased from 30.3 billion m^3 in 2004 to 34.60 billion m^3 in 2017, while in Haryana it has increased from 9.1 to 11.53 billion m^3 over the same period. Sidhu et al. (2021) found Punjab's average groundwater depletion to be 8.91 m, with Barnala district experiencing the highest at 20.38 m from 2000 to 2019. Narayanamoorthy (2022) demonstrated a more than sevenfold increase in the area irrigated by groundwater from 1950–1951 to 2016–2017 across India, contributing to the depletion of groundwater resources. Consequently, as of March 2017, a total of 2471 blocks (district-scale subdivisions) out of the overall 6881 have been designated as overexploited, critical or semicritical in India. Haque et al. (2013) found that urbanization has caused groundwater depletion due to extreme abstractions in the regions of Delhi and Dhaka. Roy et al. (2020) studied the long-term trends in groundwater levels in the Delhi Metropolitan Region and found that population and urbanization are the major reasons behind the groundwater depletion in the region. Dangar and Mishra (2021) found that nonrenewable groundwater abstraction accounts for 80% of the groundwater depletion in the Ganga basin, while renewable groundwater pumping contributed to only 20% of the total groundwater depletion. There is a pronounced increase in groundwater abstraction within the Indo-Gangetic Basin, resulting in the water table descending beyond 20 m below ground level, diminishing at a rate exceeding 1 m/year between 2000 and 2012 (MacDonald et al. 2016). Here, regional hotspots and trends of groundwater depletion across the country of India are identified using a combination of in-situ groundwater-level-monitoring records, satellite observations, and hydrological model outputs. The factors responsible for these changes are identified using previously unused socioeconomic datasets associated with industries, population dynamics and water demand.

Quantifying groundwater variability remains a major challenge as it requires dense groundwater monitoring networks along with a good understanding of subsurface hydrogeologic properties such as specific yield (Chen et al. 2016). The groundwater observation network in India is extensive, but the observations are mostly discontinuous or provide inconsistent temporal coverage. Furthermore, the full national dataset of groundwater level monitoring is difficult to access through the web portal maintained by the Central Ground Water Board (CGWB) of India due to data download limitations. Using automated web scraping scripts, in-situ groundwater level observations have been gathered from more than 27,000 wells, which is the largest dataset ever collated for groundwater studies in India. To quantify groundwater depletion throughout the country, satellite data was used from the Gravity Recovery and Climate Experiment (GRACE; Save et al. 2016), which monitors and records anomalies in the Earth's gravity field (Tapley et al. 2004). These anomalies within the Earth's gravity field are converted into liquid water equivalent thickness, also known as terrestrial water storage (TWS). TWS is the sum of groundwater, surface water, canopy water, soil moisture, and snow water equivalent (Getirana et al. 2017). In India, Asoka et al. (2017) estimated a groundwater declining rate of 2 cm/year in northern India and an increasing rate of 1–2 cm/year in southern India for the duration of 2002–2013 using GRACE TWS, model outputs, and in situ groundwater level observations. Nair and Indu (2020) estimated a maximum groundwater depletion rate of 0.25 cm/month in the Karnataka region for a time period of 2009 to 2016 from in-situ groundwater level observations. Nair and Indu (2021) found that the absence of precipitation was the primary factor for groundwater depletion in the northern part of India at a rate of 3.5 cm/year. Panda et al. (2022) identified a swift decline in the water table at a rate of 15 cm/year in the West Bengal region using 15,000 groundwater monitoring wells and GRACE TWS estimates and attributed this to a policy promoting irrigation. Girotto et al. (2017) have shown a significant negative trend in northwest India with a maximum declining rate of 1.7 cm/year near Delhi for the period 2003–2015 using GRACE TWS integrated into a hydrological model and in situ groundwater level observations. Sarkar et al. (2020) established the rate of groundwater depletion in cities facing water stress in India, specifically Delhi (3.682 ± 0.8 cm/year), Meerut (3.62 ± 0.7 cm/year), Dehradun (3.1 ± 0.87 cm/year), and Chandigarh (2.73 ± 0.6 cm/year). Cao and Roy (2020) analyzed Indian groundwater trends (2002–2016), noting the steepest decline in the northeast and northwest regions of India throughout all seasons. Islam et al. (2022) studied groundwater levels in the Cuddalore district of Tamil Nadu for the period from 2001 to 2020, revealing an alarming decline. Raju et al. (2022) identified groundwater-depletion-induced land subsidence in Lucknow with two significant subsidence zones in the north and south of the city. Asoka and Mishra (2020) have provided a framework for estimating the contribution of anthropogenic groundwater pumping climate variability on TWS using the variable infiltration capacity simple Groundwater model (VIC-SIMGM) and GRACE observations. These studies have concentrated on attributing the changes mostly to irrigation, whereas issues such as rapid industrialization and urbanization have been ignored. In this study, five major hotspots of groundwater decline across India have been identified and attributed to the factors responsible for the depletion using various hydrologic and socioeconomic datasets collected from government sources.

Datasets

The study area comprises the whole country of India, with an annual groundwater extraction of nearly 239 bcm in 2022 (Department of Water Resources 2022). The details of different datasets used in this study are provided in the following.

In situ groundwater level observations

The Central Ground Water Board (CGWB) of India is responsible for monitoring the nation's groundwater levels. Initially, data was collected from over 30,000 groundwater wells for the duration of 2003 to 2020; however, over 3000 groundwater monitoring points were removed due to the presence of missing values and outliers, with the intention of prioritizing data quality over quantity. Figure 1 shows the spatial distribution of the groundwater wells used in this study. The majority of these wells (>85%) correspond to unconfined aquifers (CGWB 2014). Groundwater levels are measured four times a year: April/May (premonsoon), August (monsoon), November (postmonsoon), and January. Premonsoon data are collected in March for northeastern states, April for Orissa, West Bengal, and Kerala, and May for other states, reflecting regional climate variations. August data provides information on monsoon impacts, November data shows cumulative recharge and withdrawal effects, and January data reflects groundwater use for rabi crops. Groundwater level anomalies have been calculated by subtracting respective long-term mean values for a particular monitoring well. Mean specific yield values vary from 0.02 to 0.13 across the nation and were obtained from Bhanja et al. (2016).

IMD precipitation data

The daily gridded (0.25° spatial resolution) precipitation data from the Indian Meteorological Department (IMD) has been utilized in this study for the duration of 2003 to 2020. Daily rainfall records from 6995 rain gauge stations in India were used along with Shephard's interpolation algorithm to produce this long-term gridded dataset (Pai et al. 2021).

GRACE-based terrestrial water storage

GRACE satellite mission was launched by NASA and the German Aerospace Centre (DLR) jointly in March 2002 (Tapley et al. 2004). The GRACE Follow-On (GRACE-FO) was launched in May 2018 as a continuation of the GRACE mission by NASA and Helmholtz Centre Potsdam German Research Centre for Geosciences (GFZ). Monthly GRACE and GRACE-FO RL06 Mascon Solutions (version 02) data spanning the temporal range of 2003 to 2020, with a spatial resolution of 0.25°, were employed in this study. The data were sourced from the Center for Space Research (CSR) at the University of Texas at Austin (Save et al. 2016). For hydrological applications, TWS is derived from these Mascon Solutions and provided by CSR.

Hydrological model outputs

Individual contributions of surface water, snow, soil water, or groundwater to mass variability are not provided by GRACE data. However, the assimilation of TWS estimates derived from GRACE into land surface models (LSMs) has been shown to improve simulations of water storages and fluxes (Zaitchik et al. 2008). Studies have reported that GRACE data assimilation (DA) has improved the correlation between observed and simulated groundwater levels by 16% and 22% at the regional and point scales, respectively (Li et al. 2019). As the primary objective of this study is to determine changes in groundwater storage (GWS), GWS was separated from other water storage components by using two LSM outputs products from the Global Land Data Assimilation System (GLDAS): (1) Catchment Land Surface Model (CLSM) with GRACE Data Assimilation (henceforth referred to as, CLSM DA), and (2) open loop (i.e., no DA) CLSM v2.1 (Rodell et al. 2004; Li et al. 2019). Daily data were employed spanning the period from 2003 to 2020 from both the CLSM DA model and the CLSM open-loop model. The CLSM DA model exhibits a spatial resolution of 0.25°; however, due to the unavailability of higher-resolution data for the CLSM open-loop model, data with a spatial resolution of 1° was utilized for this particular model. The CLSM was adopted as it has been used extensively for GRACE-based TWS DA in many studies (Girotto et al. 2016; Kumar et al. 2016; Jung et al. 2019; Getirana et al. 2020) and it has the ability to represent changes in shallow groundwater storage, which tends to be lacking in most global LSMs.

Socio-economic data

Industry data

The industry data consists of annual counts of factories across states and union territories in India. These data were provided by the Annual Survey of Industries (ASI) and conducted by the Ministry of Statistics and Programme Implementation, Government of India (Ministry of Statistics and Programme Implementation, Government of India 2019).

Fig. 1 The map shows the locations of groundwater monitoring wells across India overlain on a geographical map of India and its neighbouring countries. NOTICE: The contents (e.g., borders and names) of this map do not conform with the contents of the United Nations map of the same region (see United Nations 2024)). This NOTICE is provided by *Hydrogeology Journal* in order to inform readers of such differences

Groundwater availability

The total groundwater availability in a region is calculated by adding the dynamic groundwater resources, the static or in-storage groundwater resources in unconfined aquifers, and the dynamic and in-storage resources in both confined and semiconfined aquifers. The data were extracted from the *Groundwater Year Book – India* (Central Ground Water Board 2010, 2020), a yearly publication from the Central Ground Water Board, Government of India.

Stage of groundwater development

The stage of groundwater development (SGWD) is defined by Eq. (1)

$$\text{SGWD} = \frac{\text{Annual groundwater draft for all uses}}{\text{Annual groundwater availability}} \times 100 \quad (1)$$

The annual groundwater draft encompasses the combined amount of groundwater extracted for irrigation as well as for other purposes. This data is also sourced from the annual *Groundwater Year Book – India* (Central Ground Water Board 2010, 2020).

Methodology

The Mann–Kendall trend test was used for trend analysis and Pettitt's change point detection test was used for detecting abrupt changes in the series with a significance level of 95%. The Mann–Kendall trend test is a nonparametric test, widely used to detect trends in environmental, hydrological and climate data series (Esterby 1996; Delgado et al. 2010). The Mann–Kendall trend test was applied to the following datasets:

a. In situ groundwater level time series
b. GRACE-based TWS data, and
c. Groundwater storage simulations

This was conducted for a common period of 18 years, from 2003 to 2020, across the entire country. The Mann–Kendall trend test was primarily used for trend detection and Pettitt's test for detecting change points in the in-situ groundwater level observations, GRACE-based TWS, and CLSM GWS series.

Results and discussion

Detection of groundwater changes

Figure 2a shows the spatial distribution of the 27,000 groundwater monitoring stations with increasing, decreasing, or no trends detected using the Mann–Kendall trend test. It was found that 16% of the monitoring stations have negative trends, i.e., groundwater level has systematically decreased with time. Using the results of Mann–Kendall trend test, the locations of groundwater depletion where a substantial number of spatially concentrated stations are showing decreasing trends have been identified and marked as hotspots in Fig. 2a. These hotspots are concentrated in the states of Punjab and Haryana (hotspot I), Uttar Pradesh (hotspot II), West Bengal (hotspot III), Chhattisgarh (hotspot IV), and Kerala (hotspot V). To detect abrupt changes in the groundwater level time series, the Pettitt change point test was also performed on the same in situ groundwater monitoring data. It was found that ~42% of stations feature a change point for the duration of 2012–2014 and ~65% of stations feature a change point after 2012 (Fig. 2b), which highlights the recent nature of these changes.

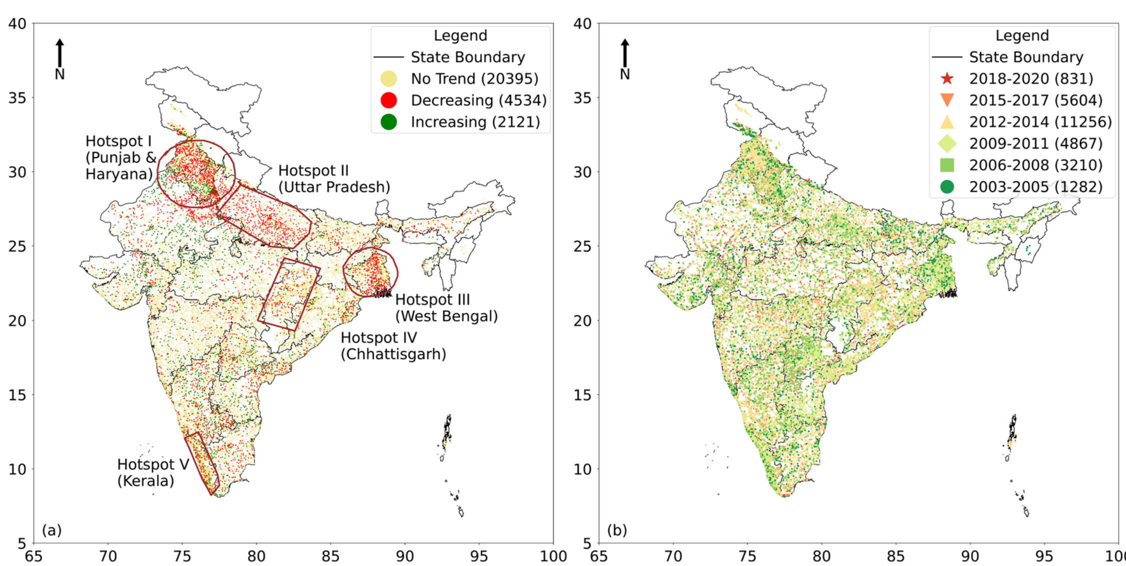

Fig. 2 Results of the **a** Mann–Kendall trend test and **b** change point detection test applied to situ groundwater level observations from 2003 to 2020. Five hotspots of groundwater depletion have been marked with red outlines (**a**). Coordinate values on the horizontal correspond to longitude (°E) and vertical axes correspond to latitude (°N)

Attribution of groundwater depletion hotspots

GRACE-based TWS along with LSM outputs (with and without DA) for 2003–2020 were used to quantify the extent of groundwater changes (Fig. 3a). GRACE trends are negative in most of northern and southern India, whereas most of central India exhibits no trend along with a part of northeast India. The application of the Pettitt change point test on GRACE TWS (Fig. 3b) shows that a substantial portion of India has experienced changes in groundwater levels after 2011. GRACE-based TWS results are mostly in agreement with the in-situ groundwater-level-monitoring trends.

As GRACE data represents monthly-averaged values, open-loop simulations (CLSM OL) are investigated, as well as data assimilated CLSM estimates (CLSM DA), which brings simulated TWS closer to the GRACE-observed TWS, while also improving groundwater storage (GWS) model estimates. Mann–Kendall trends of both CLSM OL and CLSM DA (Fig. 4a, b) show spatial variability in the area affected by groundwater depletion. CLSM OL exhibits no decreasing trend over most of India except in major portions of Rajasthan, Haryana, and Punjab and parts of Jammu and Kashmir and northeastern states. The application of the Pettitt change-point test on these data (Fig. 4b) reveals recent changes in central India, especially in certain portions of Gujarat, Maharashtra, Madhya Pradesh, Chhattisgarh after 2018, while most of the southern regions have change points around 2011, and in northern regions there are change points around 2006–2008.

The CLSM OL in Fig. 4 highlights a disagreement with groundwater levels observed in situ (Fig. 2), as well as in GRACE data (Fig. 3), which may be a result of the limitations of model simulations without DA in accounting for groundwater dynamics. So, the same tests were performed on the CLSM DA simulations.

Figure 5a shows the results of the Mann–Kendall trend tests performed on GWS estimates from CLSM DA, which is in agreement with the in-situ groundwater level monitoring and GRACE observations, highlighting the importance of DA over the Indian landmass. The northern part of India along with coastal southern states such as Tamil Nadu, exhibit declining trends, while large swathes of central India show increasing trends. The results of the Pettitt change point test applied to these data (Fig. 5b) show that northern India experienced changes in trends after 2012, while some portions of Maharashtra, Chhattisgarh and Orissa feature change points after 2018. GWS decreasing trends agree with in situ groundwater level monitoring and GRACE results, with the exception of Kerala state.

The Mann–Kendall trend test was performed on IMD precipitation data to see if the precipitation dynamics are concomitant with groundwater depletion across India. From the Mann–Kendall trend plot (Fig. 6a), daily total precipitation in western India has an increasing trend, whereas in eastern India, precipitation shows a decreasing trend, while other areas demonstrate no trends. The application of the Pettitt change-point test on precipitation data (Fig. 6b) reveals that the majority of the central part of India exhibited abrupt changes in precipitation around 2017, whereas change points in 2005 are seen in Kerala and some northeastern states such as Assam and Arunachal Pradesh.

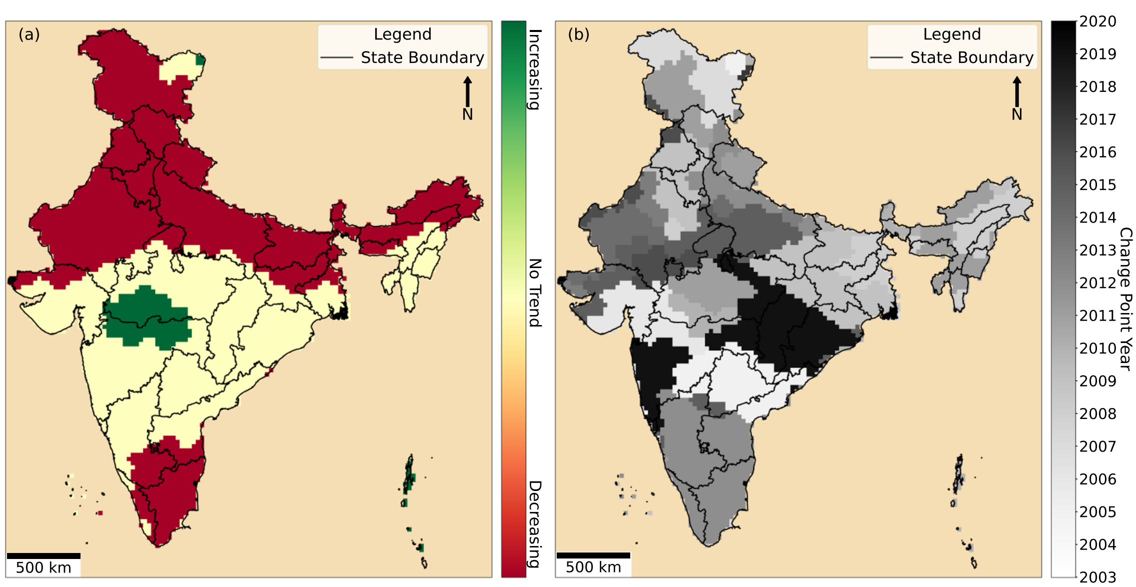

Fig. 3 Results of the **a** Mann–Kendall trend test and **b** change point detection test applied to GRACE-based terrestrial water storage estimates for the period 2003–2020

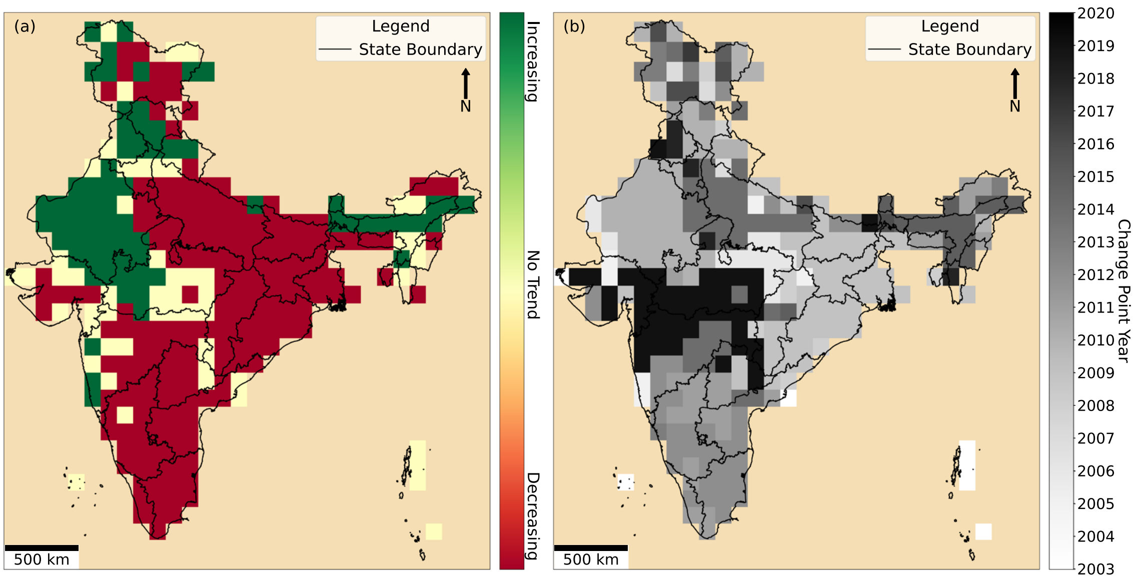

Fig. 4 Results of the **a** Mann–Kendall trend test and **b** change point detection test for CLSM open loop groundwater storage estimates for the period 2003–2020

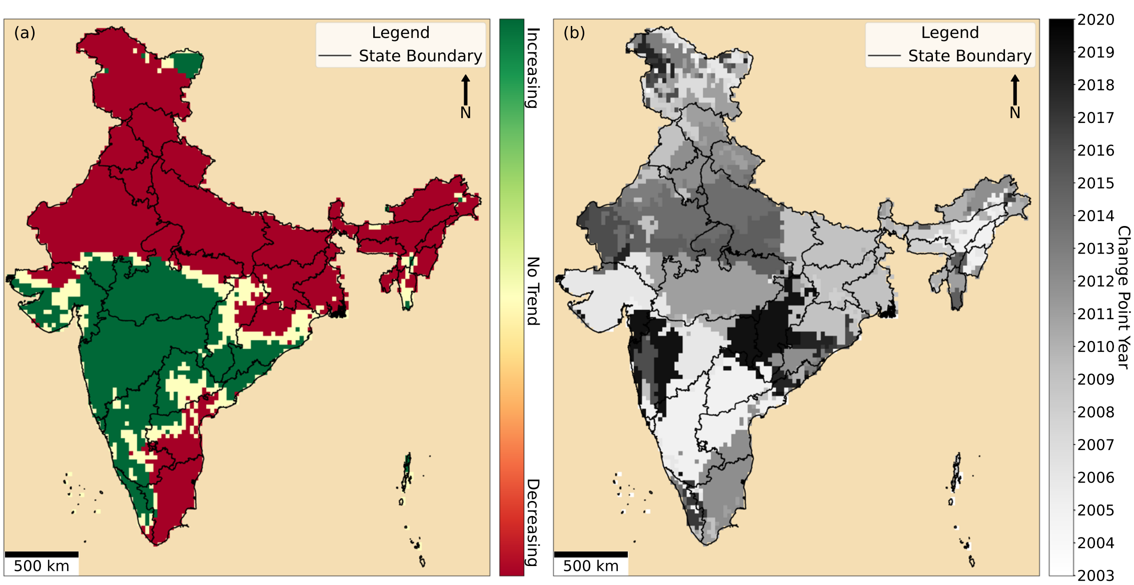

Fig. 5 Trend test (**a**) and change point detection test (**b**) applied to the CLSM data assimilated groundwater storage estimates for the period 2003–2020

The possible effects of seasonality on the Mann–Kendall trend tests performed on the various datasets were also explored. To remove the effects of seasonality, the calculated monthly climatology (the long-term average for each month) was calculated using data from 2003 and 2020 and then this was subtracted from each data point. The Mann–Kendall trend test was then applied on each time series. Figure 7a shows that seasonality has no effect on in-situ groundwater level observations, as the trends show similar results before and after removal of seasonality. Before removal of seasonality, 16% of stations showed a declining trend, which increased to 17.5% of stations showing a declining trend following the removal of seasonality. For sites with increasing trends, the number remains around 8% in both cases. As for the residual trend in precipitation (Fig. 7b), it is noted that western India has an increasing trend, whereas eastern India shows a decreasing trend. The removal of seasonality resulted in a significant increase in areas of no-trend stations.

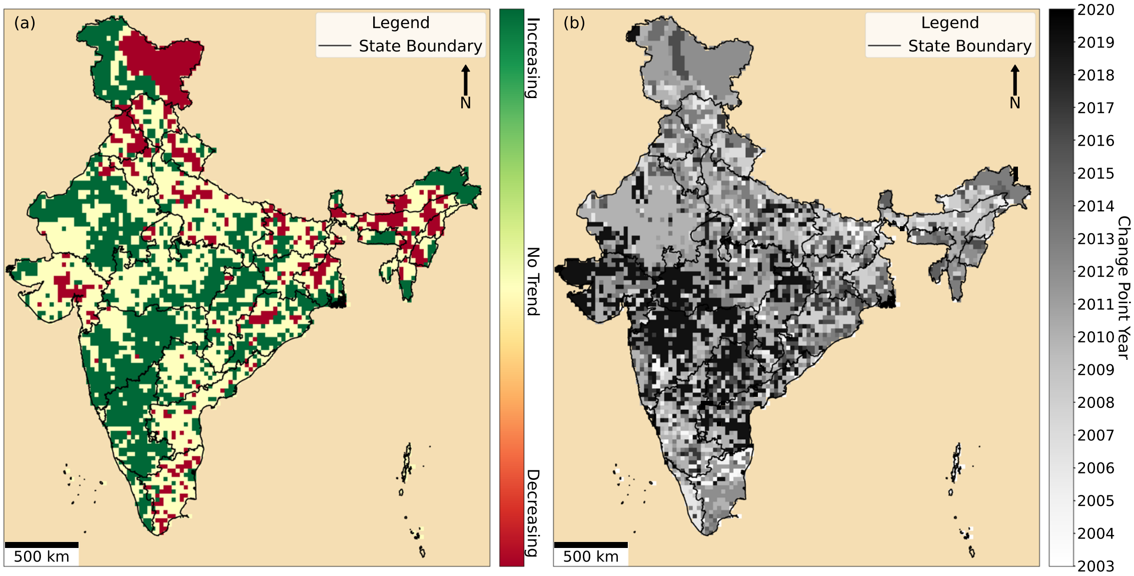

Fig. 6 Trend test (**a**) and change point detection test (**b**) applied to precipitation data for the period 2003–2020

The CLSM DA groundwater storage (GWS) residual was also considered. The application of the Mann–Kendall trend test on CLSM DA GWS residual (Fig. 7c) shows results similar to those taken prior to seasonality removal. CLSM open loop GWS (Fig. 7d) has no effect of seasonality similar to CLSM DA GWS.

Seasonal decomposition of GRACE trend over hotspots

The GRACE time series data were seasonally decomposed to account for the effect of seasonality on the trend. Figure 8 shows the different time series components of trend, seasonal, and residual data following the seasonal decomposition of the observed GRACE TWS series. Figure 8a shows the seasonally decomposed GRACE-based TWS series for a randomly selected grid point in hotspot I with a decreasing trend. Figure 8a shows the monotonicity of the decreasing trend over many years. For a grid point in a hotspot having a decreasing trend, seasonal decomposition is shown in Fig. 8b. In this figure, a trend plot shows a systematic decline. The trends shown in Fig. 8c, e demonstrate variability with an overall decline over time. In addition, Fig. 8d shows a seasonally decomposed grid point with no trends in hotspot IV.

Volume change in hotspots

The calculated groundwater volume change across all hotspot locations is shown in Fig. 9. Here, the median value of groundwater level for a grid cell within a given season for a particular hotspot was multiplied by the specific yield value corresponding to the aquifer associated with the relevant monitoring station. Groundwater level is measured in meters below ground level, and if volume change is increasing in Fig. 9, then that means the groundwater level is decreasing or that the volume of groundwater has depleted over the year.

Attribution of groundwater level changes

Hotspot I: Punjab and Haryana

Hotspot I is in the northwestern states of Punjab and Haryana (Fig. 2a), this region has been the focus of groundwater studies globally due to rapidly declining water tables. The GRACE-based TWS (Fig. 3a) shows a declining trend in this region. Furthermore, precipitation monitoring data shows either no trend or a decreasing trend (Fig. 6a) for the majority of the area associated with this hotspot. Figure 9 shows the seasonal variation of groundwater volume change, and it is evident that the extent of groundwater decline across India is highest for hotspot I. There is an overall decrease of 8–10% in irrigated areas from 2000 to 2015 (Fig. 10) inferred from analysis of remote sensing provided by Ambika et al. (2016). Population data (Fig. 11a) shows that the population in this hotspot has increased by 13%−19% from 2001 to 2011. During this decade, the level of urbanization, i.e., percentage of urban population, has increased by 10%−20% (Fig. 11b), representing one of the highest increases in urban population increase across the country. Industrial data (Fig. 11c) shows a substantial increase from 69% to 170% in the number of factories from financial year (FY) 2004–2005 to 2018–2019. During the same period, the

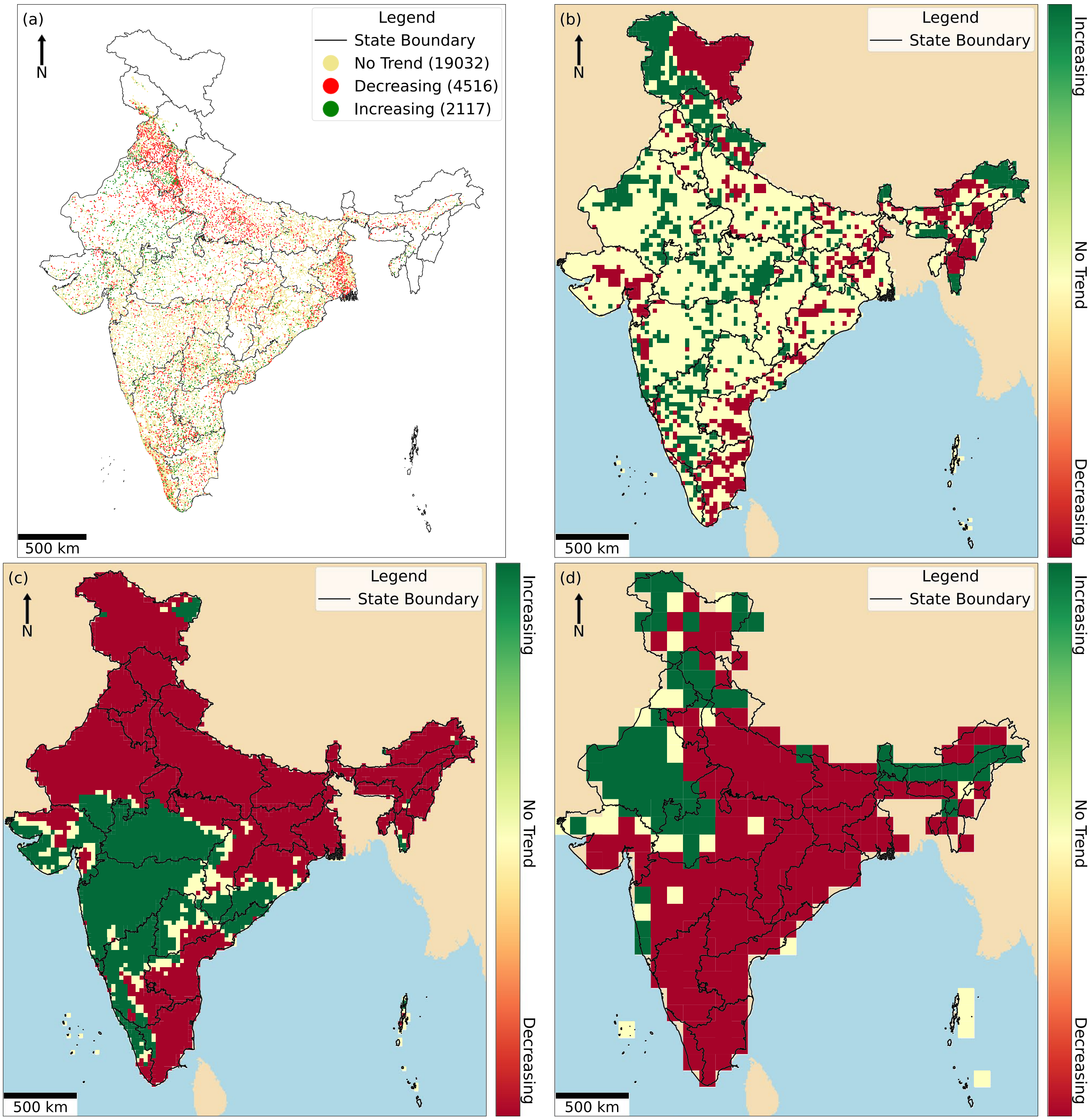

Fig. 7 Trend test applied to the residual of in situ groundwater level (**a**), precipitation (**b**), CLSM DA GWS (**c**) and CLSM open loop GWS (**d**), respectively for period 2003–2020

net annual groundwater availability (Fig. 11d) has dropped up to 4% from 2004 to 2020 and the stage of groundwater development (Fig. 11e) has substantially increased by ~13–22% in this hotspot region, whereas the increase in groundwater demand for irrigation has increased by 8%–15% (Fig. 11f). In addition, groundwater demands for domestic and industrial use (Fig. 11g) show a significant increase of 26%–228%. Thus, despite government interventions and no perceptible decline in precipitation, groundwater demand has accelerated leading to depletion. Previous studies done at regional levels also corroborate the findings of this study. Kaur et al. (2017) attributed rapid groundwater depletion in Punjab to excessive groundwater abstraction facilitated by free electricity and intensive agricultural practices, whereas Sidhu et al. (2021) identified rice–wheat cropping systems as the key factor for declining groundwater levels in Punjab.

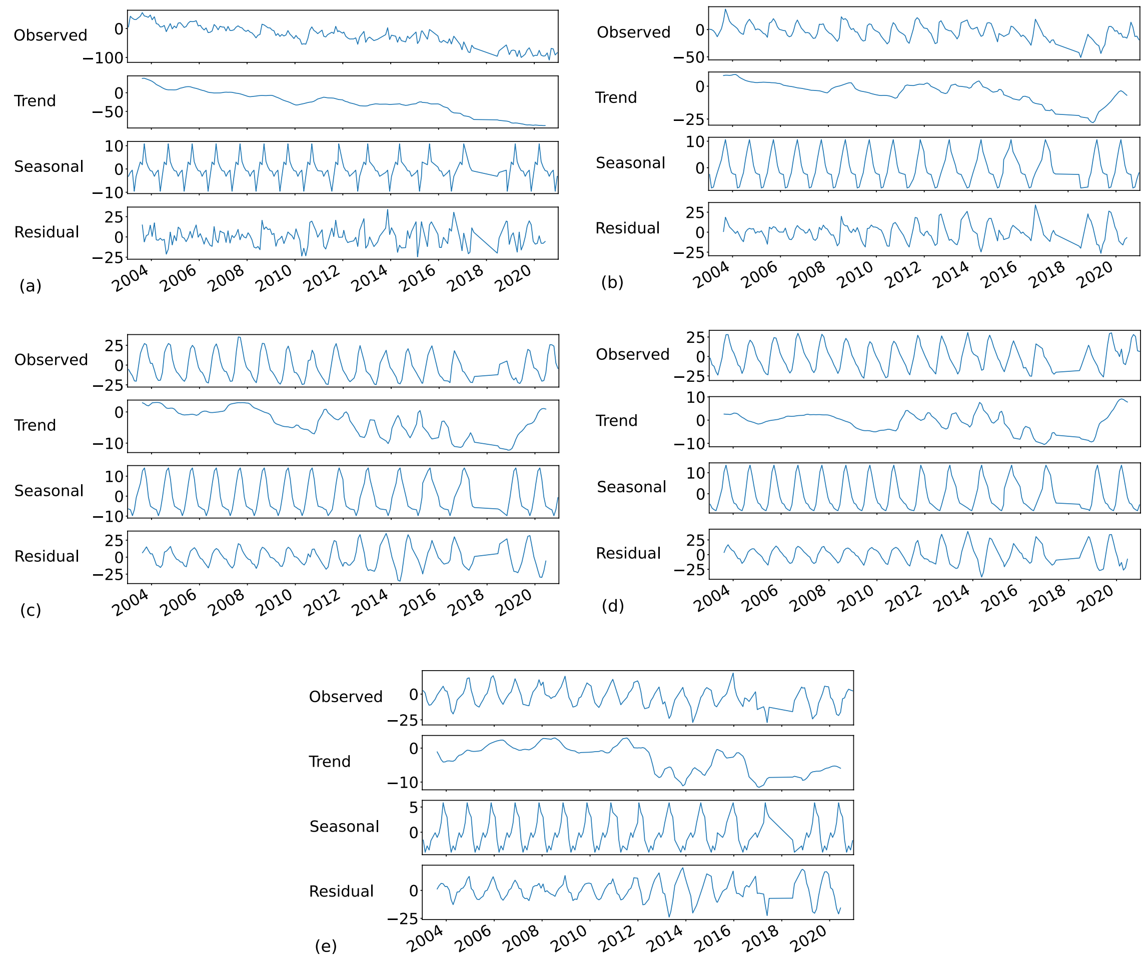

Fig. 8 Seasonal decomposition of the GRACE grid over randomly selected grid points in **a** Hotspot I, **b** Hotspot II, **c** Hotspot III, **d** Hotspot IV, and **e** Hotspot V

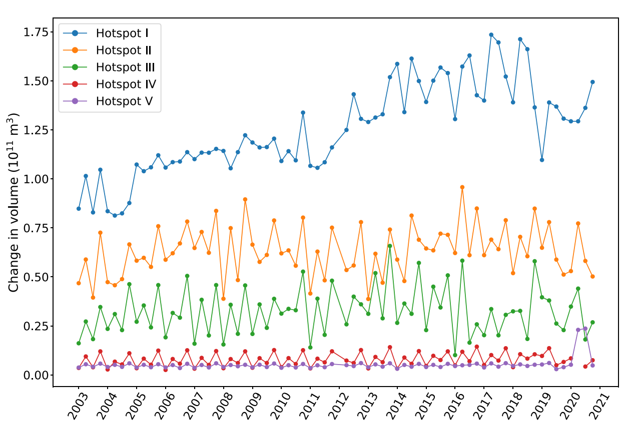

Fig. 9 Groundwater volume change across the five identified hotspot regions (spatial median value of groundwater level change × specific yield)

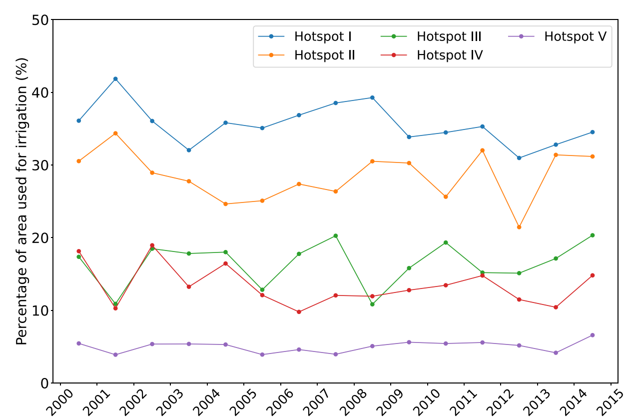

Fig. 10 Percentage total area used for irrigation for selected hotspot areas

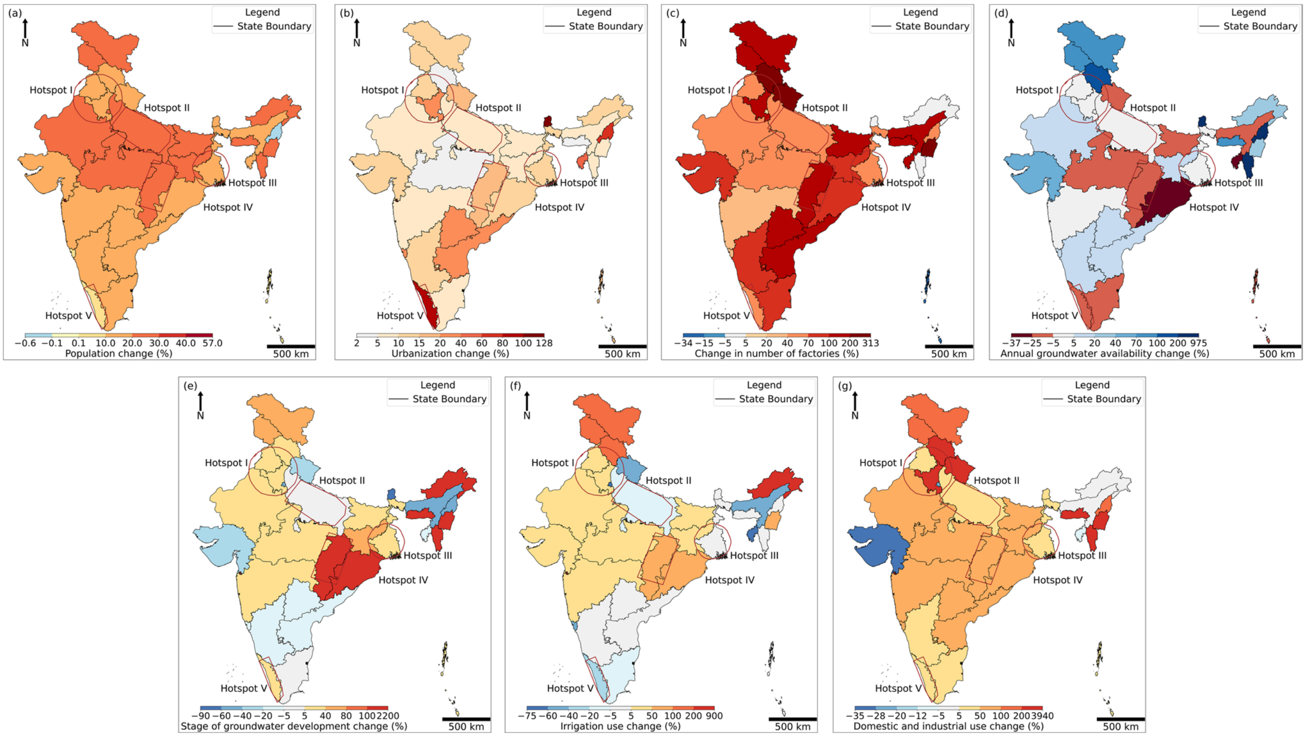

Fig. 11 Percent change in **a** population, **b** level of urbanization from 2001 to 2011, **c** number of factories from financial year 2004–2005 to 2018–2019, **d** annual groundwater availability, **e** stage of groundwater development, annual groundwater required for **f** irrigation and **g** domestic and industrial use from 2004 to 2020

Sagwal et al. (2022) also linked groundwater depletion to rice–wheat cropping system in the Haryana region; however, Aneja (2017) found that cultivation of water intensive crops was not the only reason for groundwater level decline, as other regions in hotspot I such as Faridabad and Gurgaon, where paddy cropping is minimal, are also experiencing significant groundwater depletion.

Hotspot II: Uttar Pradesh

Hotspot II is in the state of Uttar Pradesh (Fig. 2a), which is India's most populous state with more than 200 million residents. GRACE-based TWS (Fig. 3a) displays a declining trend in this region as well. Precipitation (Fig. 6a) shows either no trend or a decreasing trend in most areas within this hotspot. In Fig. 8b, seasonal decomposition of GRACE-based TWS was performed for a randomly selected grid point in hotspot II, which originally showed a decreasing trend. The trend subplot of Fig. 8b highlights a systematically decreasing trend in GRACE-based TWS. Figure 9 shows the variation of groundwater volume change and volume of groundwater lost over the year. These changes may be attributed to the changes in the socio-economic condition of the region. In hotspot II, there is an increase in irrigated areas by more than 3% (Fig. 10) from FY 2000–2001 to 2014–2015. Population has increased by more than 20% from 2001 to 2011 (Fig. 11a) and urbanization has increased by ~7% during the same period (Fig. 11b). There is a significant increase of more than 65% in the number of factories in this region (Fig. 11c) from FY 2004–2005 to 2018–2019. Net annual groundwater availability has decreased by more than 4% (Fig. 11d) and the stage of groundwater development has decreased by ~1% (Fig. 11e) from 2004 to 2020, whereas groundwater demand for irrigation has decreased by ~8% from 2004 to 2020 (Fig. 11f). Groundwater required by domestic and industrial uses (Fig. 11g) has increased by more than 38% from 2004 to 2020. Thus, population growth, rapid urbanization, high water demand, etc., have contributed to the groundwater depletion in this region as shown in Fig. 9. A previous study by Panda and Wahr (2016) linked groundwater depletion in Uttar Pradesh to intensive irrigation practices and high population density. Another regional study in Agra, by Biswas et al. (2018), attributed groundwater depletion to the expansion of very dense urban areas and excessive water abstraction accompanied by a decline in rainfall.

Hotspot III: West Bengal

Hotspot III is in the state of West Bengal (Fig. 2a), a populous state with large paddy cultivation. GRACE-based TWS (Fig. 3a) have shown a decreasing trend in roughly half of the region of hotspot III. The precipitation trend (Fig. 6a) shows either no trend or a decreasing trend (nearly 40% of the region) in most of the portions in this hotspot. In Fig. 8c, a seasonal decomposition plot for a randomly selected grid point in the GRACE-based TWS series of hotspot III, which originally showed a decreasing trend, is noted. Figure 8c shows how the trend has varied over the years with some variability, but with an overall systematic decline. Figure 9 captures the variation of groundwater decline and volume lost over the years. There is an increase in irrigated areas by more than 16% (Fig. 10) from FY 2000–2001 to 2014–2015. Population has increased by greater than 13% from 2001 to 2011 (Fig. 11a) and the level of urbanization has increased by ~14% (Fig. 11b). There is a substantial increase of more than 54% in the number of factories in this region (Fig. 11c) from FY 2004–2005 to 2018–2019. Net annual groundwater availability has decreased by more than 3% (Fig. 11d) and the stage of groundwater development has increased by greater than 5% (Fig. 11e) from 2004 to 2020. Groundwater demand for irrigation has a minor change increment of ~0.09% from 2004 to 2020 (Fig. 11f). Groundwater required by domestic and industrial use (Fig. 11g) has increased by greater than 24% from 2004 to 2020. All these factors have caused the groundwater to deplete in this region, despite groundwater demand for irrigation remaining largely the same. Bardhan (2016) found that the water level dropped by 7–11 m between 1958 and 2003 in Kolkata and Salt Lake City due to overexploitation driven by population increase. Another regional study by Biswal et al. (2020) in three management blocks of West Bengal revealed significant groundwater depletion due to excessive abstraction for agriculture. Kundu and Ghosh (2022) also linked groundwater depletion to irrigation in alluvial Khari basin focusing on Purba Bardhaman, Birbhum, Murshidabad and Nadia.

Hotspot IV: Chhattisgarh

Hotspot IV is in the state of Chhattisgarh (Fig. 2a), which is rich in natural resources and home to a significant mining industry. Contrary to the in-situ groundwater level monitoring trend results, GRACE-based TWS (Fig. 3a) has shown no trend in hotspot IV. Precipitation (Fig. 6a) either shows no trends or an increasing trend in most parts (>95% of the portion) of this hotspot. Figure 8d shows a seasonal decomposition plot for a randomly selected grid point GRACE-based TWS series of hotspot IV, which was originally showing no trends. The trend subplot of Fig. 8d shows how the trend has varied over time without any significant decline. However, the in-situ groundwater-level monitoring trend results have shown a decreasing trend across the hotspot region. Variations of volume change, i.e., amount of groundwater that has been lost over the years, are shown in Fig. 9. These changes are happening as a result of the ongoing development of the socioeconomic conditions in the region. There is a decrease in irrigated areas by more than 18% (Fig. 10) from FY 2000–2001 to 2014–2015. Population has increased by more than 22% from 2001 to 2011 (Fig. 11a) and the level of urbanization has increased by ~16% during this period (Fig. 11b). There has been a huge increase of more than 166% in the number of factories in this region (Fig. 11c) from FY 2004–2005 to 2018–2019. Net annual groundwater availability has decreased by more than 15% (Fig. 11d) and the stage of groundwater development has also demonstrated a huge increase by more than 126% (Fig. 11e) from 2004 to 2020. Groundwater demand for irrigation has substantially increased by ~96% from 2004 to 2020 (Fig. 11f). Groundwater required by domestic and industrial use (Fig. 11g) has increased by ~68% from 2004 to 2020. A significant increase in factories and consequent water demand has contributed to groundwater depletion in this region as confirmed by the in situ data. A similar previous regional study by Srivastava et al. (2018) in Chhattisgarh analyzed groundwater levels from 323 wells between 2004 and 2014, finding that 20% of the wells showed a significant decline, while 70% showed no significant change.

Hotspot V: Kerala

Hotspot V has been identified in the state of Kerala (Fig. 2a), a coastal state that is subject to significant rainfall and flooding. GRACE-based TWS (Fig. 3a) has shown decreasing trends in almost half of the area of this hotspot. Precipitation (Fig. 6a) shows either no trends or increasing trends in more than 95% of this hotspot. Figure 8e shows a seasonal decomposition plot for a randomly selected grid point GRACE TWS series of hotspot V which was originally showing a decreasing trend. Figure 8e shows how the trend has varied over the years with some variability, but overall has declined. These changes are occurring due to the aforementioned socioeconomic changes in the region. The area of irrigation has increased by ~16% (Fig. 10) from FY 2000–2001 to 2014–2015. Population has increased by ~5% from 2001 to 2011 (Fig. 11a) and urbanization has increased by 83% during this period (Fig. 11b). Also, there is an increase of more than 40% in the number of factories in this region (Fig. 11c) from FY 2004–2005 to 2018–2019. Net annual groundwater availability has decreased by more than 17% (Fig. 11d) and the stage of groundwater development has increased by more than 10% (Fig. 11e) from 2004 to 2020. Groundwater demand for irrigation has a drop of ~36% from 2004 to 2020 (Fig. 11f). Groundwater required by domestic and industrial use (Fig. 11g) has increased by more than 34% from 2004 to 2020. Thus, despite the large drop in irrigation demand, groundwater has continued to be depleted due to rapid urbanization and industrialization. Previously, Karunakaran (2014) found that crop diversification in Kerala's Kasaragod district, specifically the shift from food to nonfood crops, has led to severe land degradation, groundwater depletion, and chemical pollution. Nandakumaran et al. (2014) reported that unregulated sand mining in Kerala has lowered river beds by 6 m over two decades, significantly reducing groundwater levels. George (2016) observed that the continuous use of groundwater abstraction boreholes has caused a decline in water levels in open wells across Kerala.

Conclusion

Depletion in groundwater levels is a significant and concerning issue in India. Previous studies have shown that irrigation is a major driver of groundwater depletion in various parts of the country (Kaur et al. 2017; Kishore et al. 2021). However, this study reveals that the drivers of groundwater depletion vary between the different identified hotspots across the country. Notably, in regions such as Kerala and West Bengal, where irrigation demand has either significantly decreased or remained stable, groundwater levels continue to decline due to the pressures of urbanization and industrialization. The combined impact of climate change, erratic monsoons and India's rising population is leading to an increased dependence on groundwater for drinking, irrigation and industry demands (Siebert et al. 2010). Furthermore, Panda et al. (2021) investigated groundwater depletion in northern India, mainly for the states of Punjab, Haryana, Delhi, Rajasthan, Uttar Pradesh, West Bengal and Bihar. They attributed this depletion to socio-political and policy transitions leading to an increase in water use. To investigate these hotspots, a comprehensive approach was employed, analyzing groundwater level trends using in situ observations, satellite data, and outputs from hydrological models with and without data assimilation. Subsequently, the drivers of groundwater depletion in these hotspots were attributed to various socioeconomic factors:

- Within all designated hotspots under consideration, irrigation stands out as a prominent contributor to groundwater depletion in each respective region.
- Hotspot I (Punjab and Haryana): Apart from irrigation, key factors contributing significantly to groundwater depletion in this region include the expansion of industrial facilities, declining precipitation over time, population growth, and urbanization. These factors have substantially increased the demand for water for both domestic and industrial purposes, resulting in a staggering loss of approximately 6.46×10^{10} m^3 of water in this area over the past two decades.
- Hotspot II (Uttar Pradesh): The contributing factors are increased irrigation, industrialization and urbanization, which have driven higher demands for industrial, domestic, and agricultural water use.
- Hotspot III (West Bengal): In addition to irrigation, the factors contributing to groundwater depletion encompass a notable increase in the number of industrial facilities, concurrent with population growth and urbanization. This has led to an increased demand for water, despite a predominantly stable requirement for irrigation water.
- Hotspot IV (Chhattisgarh): Noteworthy contributing factors other than irrigation encompass a substantial escalation in the number of factories, significant population growth, and urbanization.
- Hotspot V (Kerala): In addition to irrigation, the principal contributing factors entail a notable rise in the number of factories coupled with an increase in urbanization. It is noteworthy that, unlike in other hotspots, there has been no observed elevation in population or demand for irrigation in Kerala.

This study is one of the first to compile socioeconomic datasets across India from multiple government resources and connect them to groundwater decline in the five identified hotspots. This study utilizes auxiliary datasets from government sources that were previously unused in groundwater depletion studies. For future studies, a more sophisticated mathematical approach could be employed to conduct an attribution analysis of these factors.

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