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 and is impacted by climate change and anthropogenic activities. Although there have been studies on groundwater variability in India, few have concentrated on socio-economic attribution of these changes using data from industries, population, and water demand. Using the largest dataset ever collated for groundwater studies in India, we detected trends in groundwater storage based on *in situ* measurements from approximately 27,000 groundwater wells, satellite-based terrestrial water storage estimates, and hydrological model simulations. Five major hotspots of groundwater depletion were identified across India using *in situ* measurements and a variety of hitherto-unused socio-economic datasets were used to attribute these changes. Approximately 16% of the total monitoring stations in the country exhibit systematically decreasing trends in groundwater levels, and these hotspots are mostly concentrated in the northern and northwestern parts of India along with the states of Chhattisgarh, West Bengal, and Kerala. The main reasons for these depletions are identified as growth in population, increment in urbanization and number of factories and expansion of agriculture. This study can help identify zone-based adaptation strategies that could be prioritized at the policy level to ameliorate groundwater depletion and the impact it has on other sectors.

Keywords:

Groundwater depletion, socio-economic attribution, water use

Highlights (3-5 sentences as bullet points)

1. Few studies have concentrated on attributing groundwater depletion using data from industries, population, and water demand
2. Approximately 16% of the total monitoring stations in the country exhibit systematically decreasing trends in groundwater levels
3.

1. Introduction

Groundwater is a widely accessible source of fresh water that is less susceptible to quality deterioration and droughts, as opposed 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). But it is also highly susceptible to unsustainable water extraction rates (Wada et al., 2010). Rapid urbanization without sufficient piped drinking infrastructure has added to the pressure on groundwater resources and there has been a steady increase in usage of non-renewable 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 socio-economic attribution of these declines, especially in places like India with the highest amount of non-renewable groundwater withdrawals for irrigation (Gleeson et al., 2012). While the extent of groundwater depletion in India has been estimated (Long et al., 2016; Rodell et al., 2009), very few studies have attempted to attribute these changes to socio-economic factors. Haque et al. (2013) has found that urbanization has caused the depletion of groundwater due to extreme abstractions in the region of Delhi and Dhaka. Roy et al. (2020) studied the long term trends in groundwater levels in Delhi Metropolitan Region and found that population and urbanization are the major reasons behind the groundwater depletion in the region . Here, we attempt to identify regional hotspots and trends of groundwater depletion across the country using a combination of *in situ* records, satellite observations, and hydrological model outputs, and attribute these changes using hitherto-unused socio-economic datasets of industries, population, and water demand.

Quantifying groundwater variability remains a major challenge as it requires dense *in situ* networks along with good understanding of subsurface hydrologic properties such as specific yield (Chen et al., 2016). The groundwater observation network in India is extensive, but the observations are mostly not continuous or have gaps in between and the full national dataset is difficult to access through the web portal maintained by the Central Ground Water Board (CGWB) of India. Using automated web scraping scripts, we have gathered an *in situ* groundwater dataset of more than 27,000 wells, which is the largest dataset ever collated for groundwater studies in India. To quantify groundwater depletion, we have used satellite data from the Gravity Recovery and Climate Experiment (GRACE) (Save et al., 2016), which constantly monitors and records anomalies in the Earth's gravity field (Tapley et al., 2004). These anomalies in the Earth’s gravity field are converted into liquid water equivalent thickness, which is 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 and Mishra (2020) have given 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. 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 duration of 2002-2013 using GRACE TWS, model outputs, and *in situ* observations. Girotto et al.(2017) have shown 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* observations. These studies have concentrated on attributing the changes mostly to irrigation, while issues such as rapid industrialization and urbanization has been ignored. Here, we have detected the trends in groundwater storage using the largest collection till date of *in situ* measurements, satellites observations and model simulations. Five major hotspots of groundwater depletion across India and attributed the depletion in the hotspots using various hydrologic and socio-economic datasets collected from government sources.

2. Datasets

Our study area comprises whole of India with an annual groundwater extraction of nearly 245 billion cubic meters in 2017. The details of different datasets used in this study are provided below:

2.1 *In situ* groundwater level

The Central Ground Water Board (CGWB) of India is responsible for monitoring the nation's groundwater levels. We have collected data from over 27,000 groundwater wells for the duration 2003 to 2020. The majority of these wells (>85 %) are located in unconfined aquifers (CGWB, 2014). Groundwater levels are measured four times a year: pre-monsoon (April/May), monsoon (August), post-monsoon (November), and January. Groundwater level anomalies have been calculated after subtracting long-term mean values from an individual value of a particular monitoring well. Mean specific yield values vary from 0.02 to 0.13 across the nation and have been accessed from Bhanja et al. (2016).

2.2 IMD Precipitation data

We have utilized the daily gridded (0.25 x 0.25 degree spatial resolution) precipitation data from the Indian Meteorological Department (IMD) (Pai et al., 2021). Daily rainfall records from 6995 rain gauge stations in India were used with a Shephard's interpolation algorithm to produce this gridded datasets (Pai et al., 2021).

2.3 GRACE-based Terrestrial Water Storage

GRACE satellite mission was launched by NASA and 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). We have used GRACE and GRACE-FO

RL06 Mascon Solutions (version 02) data from 2002 to 2020 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.

2.4 Hydrological model outputs

Individual contributions of surface water, snow, soil water or groundwater to mass variability are not provided by GRACE data. But assimilation of TWS estimates derived from GRACE into land surface models (LSMs) have improved simulation of water storage and fluxes (Zaitchik et al., 2008). Studies have reported that GRACE data assimilation (DA) have improved the correlation of groundwater simulations by 16% and 22% at the regional and point scales, respectively (Li et al., 2019). As our primary objective is to determine changes in groundwater storage (GWS), we separated GWS from other water storage components. For this, we have used two LSM outputs products from the Global Land Data Assimilation System (GLDAS) - 1) Catchment Land Surface Model (CLSM) with GRACE DA, and 2) open loop (i.e., no DA) CLSM V2.1 (Li et al., 2019; Rodell et al., 2004). We have used the CLSM because it has been adopted for GRACE-TWS DA by many studies (e.g., 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 is lacking in most global LSMs. CLSM-based TWS is sum of the water stored as soil moisture, snow water equivalent, canopy interception and groundwater in unconfined and semiconfined aquifers.

3. Methodology

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

a. *in situ* groundwater level series
b. GRACE-based TWS data, and
c. groundwater storage simulations

This has been done for a duration of 18 years, from 2003 to 2020, over all Indian regions. We have used Mann-Kendall trend test primarily for trend detection while Sen's slope estimator has been used for estimating the magnitude of the trend. We have also employed Pettitt's change point detection test for detecting change point in the *in situ* groundwater level, GRACETWS, and CLSM GWS series.

4 Results and Discussions

4.1 Detection of groundwater changes

Figure 1a shows the spatial distribution of XXX stations with increasing, decreasing, or no-trend 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, we have identified the locations of groundwater depletion where substantial number of stations showing decreasing trends are spatially concentrated and marked those locations as hotspots in Figure 1a. These hotspots are mostly concentrated in northern India along with the states of Chhattisgarh, West Bengal, and Kerala. To detect abrupt changes in the data series, we also performed the Pettitt change point test on the same *in situ* data. It was found that around 42% of stations have change-point in the duration of 2012-2014 and about 65% of stations change point after 2012 (Figure 1b), which highlights the recent nature of these changes.

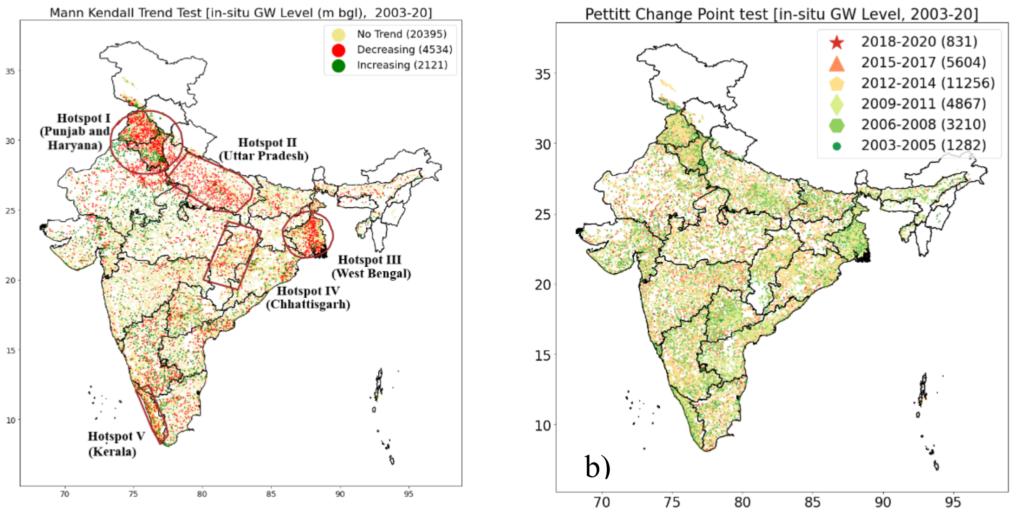

Figure 1. Trend test in (a) and change point test in (b) for *in situ* groundwater level for duration 2003-20. Five hotspots of groundwater depletion have been marked with red lines in (a).

4.2 Attribution of groundwater depletion hotspots

To quantify the extent of groundwater changes, we have used GRACE-based TWS along with LSM outputs (with and without DA) for 2003-2020 (Figure 2a). GRACE trends are negative in most of northern and southern India while most of central India exhibits no trend along with a part of the north-east. Pettitt change-point test on GRACE TWS (Figure 2b) shows that substantial portion of India have seen these changes after 2011. GRACE-based TWS results are mostly in agreement with *in situ* trends

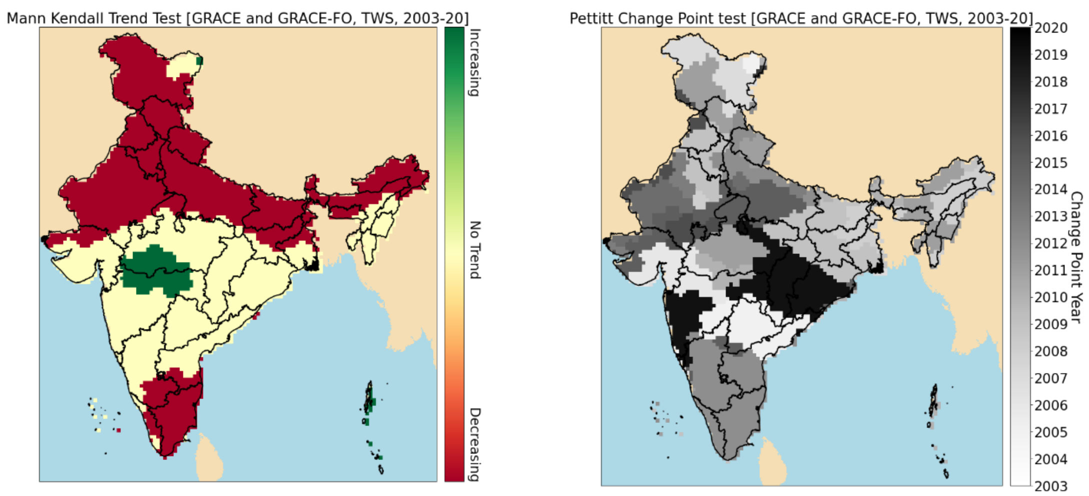

Figure 2. (a) Mann-Kendall Trend test and (b) change point test for GRACE-based TWS for duration 2003-20.

But since GRACE data are monthly averaged values, we look at open-loop simulations (CLSM OL) 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 an DA-based estimates of GWS (Figures 3a and 3b) show there is 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. Pettitt change-point test on this data (Figure 3b) reveals recent changes in central India especially in some portion of Gujarat, Maharashtra, Madhya Pradesh, Chhattisgarh after 2018 while most of the southern regions have change point around 2011 and in northern regions have change-point around 2006-2008.

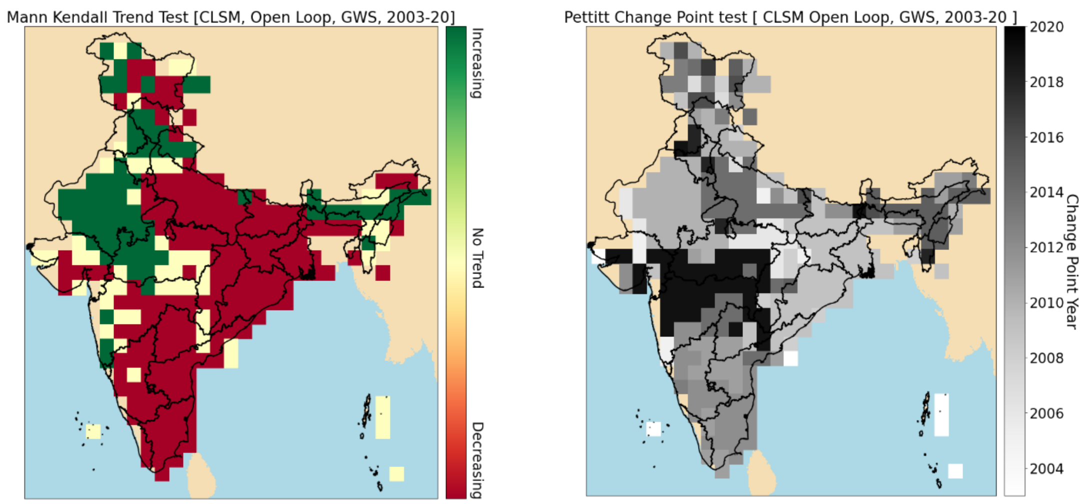

Figure 3. (a) Mann-Kendall trend test and (b) change point test for CLSM Open loop groundwater storage for duration 2003-20.

The CLSM OL in Figure 3 highlights large disagreement with ground conditions seen by *in situ* (Figure 1), as well as GRACE data (Figure 2), which points to the limitations of model simulations without DA. So, we further performed the same tests on the GRACE DA simulations.

Figure 4a shows the Mann-Kendall trend tests on GWS estimates from CLSM DA which shows agreement with *in situ* and GRACE observations, highlighting the importance of assimilation over the Indian landmass. The northern part of India along with coastal southern states such as

Tamil Nadu exhibit declining trend while large swathes of central India show increasing trend. Pettitt change-point test on this data set (Figure 4b) shows that northern India has changed trends after 2012 while some portion of Maharashtra, Chhattisgarh and Orissa have change point after 2018. GWS decreasing trends agree with *in situ* and GRACE results, except for Kerala state. Here, we can see that CLSM DA has performed better than both GRACE observations and CLSM OL estimates in estimating groundwater conditions in reference to *in situ* data.

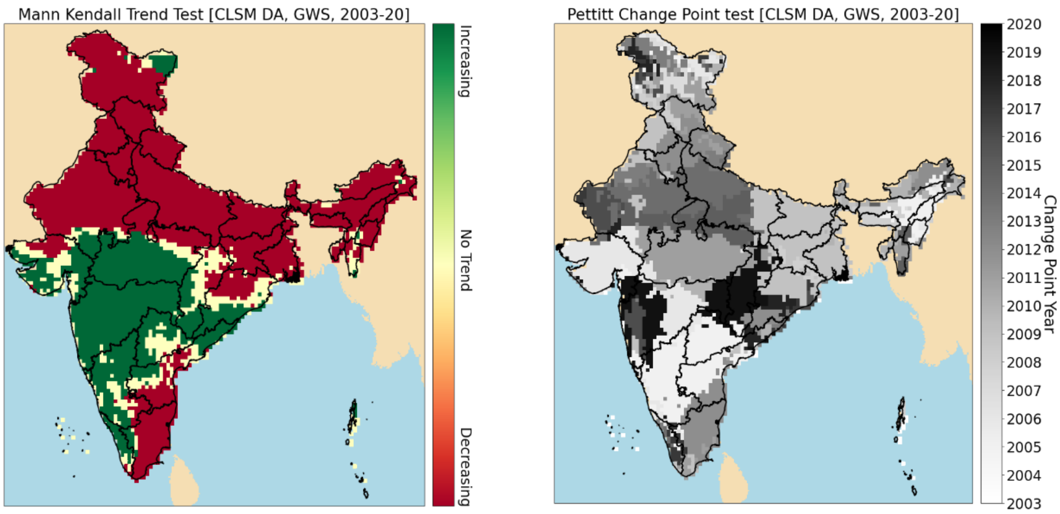

Figure 4. Trend test in (a) and change point test in (b) for CLSM data assimilated groundwater storage for duration 2003-20.

We have performed the same Mann-Kendall trend test on IMD precipitation data to see if the precipitation has a major role in groundwater depletion across. From the Mann-Kendall trend plot (Figure 5a), we can see that precipitation in western India has an increasing trend while in the eastern portion, precipitation shows decreasing trend with intermittent no-trend at various places. The Pettitt change-point test result on precipitation data (Figure 5b) reveals that most of the middle portions of India have abrupt changes in precipitation series around 2017, while Kerala and some northeastern states, like Assam and Arunachal Pradesh, have change points in 2005.

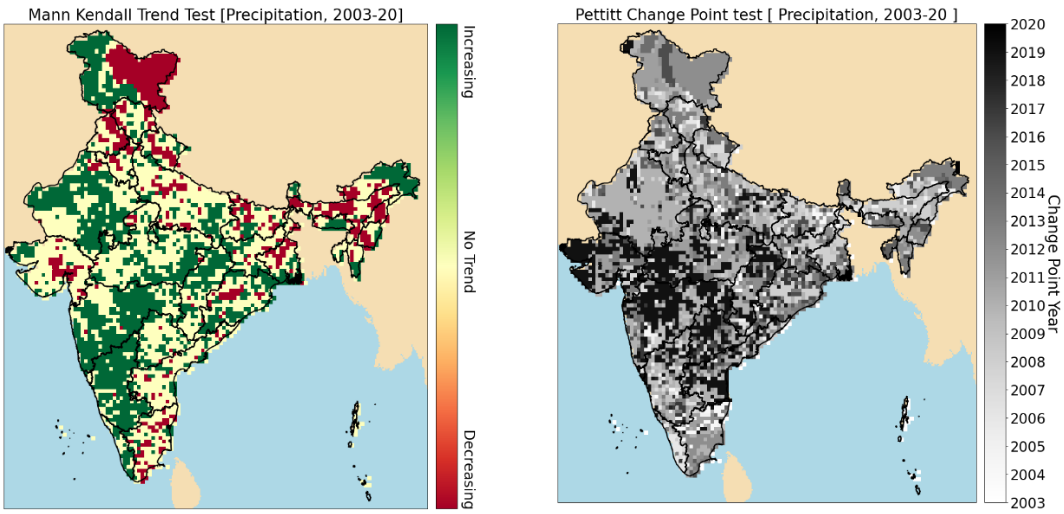

Figure 5. Trend test in (a) and change point test in (b) for precipitation for duration 2003-20.

We have explored the possible effect of seasonality on Mann-Kendall trend tests on the various datasets. To remove the seasonality, we have first calculated the monthly climatology using data from 2003 and 2020 and then subtracted from each data point. After that we have applied the Mann-Kendall trend test on each data series. Figure 6a shows that seasonality has no effect on *in situ* groundwater level because before and after removal of seasonality, trends show similar results. Before removal of seasonality, 16% of stations shows declining trend, which increases to 17.5% of stations showing declining trend after removal of seasonality. For increasing trend, the number remains around 8% in both the cases. As for precipitation residual trend (Figure 6b), it is noted that western India has an increasing trend while eastern India shows a decreasing trend. But only the difference after removal of seasonality is that there is a significant increase in areas of intermittent no-trend regions.

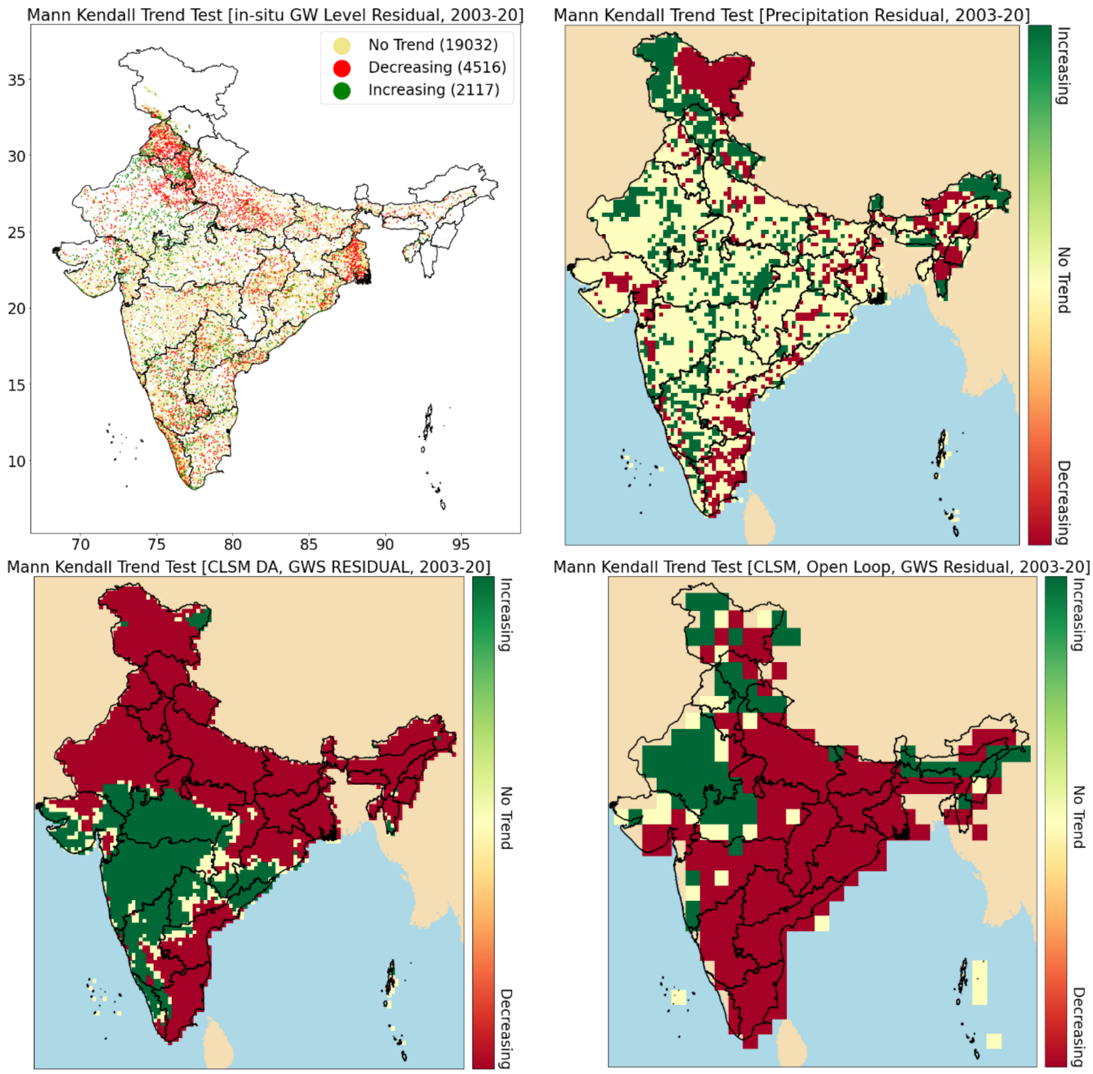

Figure 6. Trend test on in situ residual, precipitation residual, CLSM DA GWS residual and CLSM open loop GWS residual in (a, b, c, d) respectively for duration 2003-20.

We also consider the GRACE DA CLSM groundwater storage (GWS) residual. Mann-Kendall trend test on CLSM DA, GWS residual (Figure 6c) shows results similar to before seasonality removal. CLSM open loop GWS (Figure 6d) has too no effect of seasonality like CLSM DA GWS.

4.3 Seasonal decomposition of GRACE trend over hotspots

Further, for GRACE data, we have seasonally decomposed the data series to have a look at the effect of seasonality on the trend. In Figure 7, we can see the different series of trend, seasonal, and residual data after seasonal decomposition of observed GRACE TWS series. For a randomly selected grid point showing declining trend in Hotspot I, we have seasonally decomposed the GRACE-based TWS series (Figure 7a), which was originally showing decreasing trend. Figure 7a shows how monotonically trend has declined over the year. For a grid point in hotspot having decreasing trend, seasonal decomposition is shown in Figure 7b. In this figure, trend plot shows overall decline with ups and downs. Similarly for figure 7c and 7e, trend plot shows several ups and downs with an overall decline over the years. But for figure 7d, we have seasonally decomposed the grid point having no-trend for hotspot IV. Trend plot of this figure shows no trend with ups and downs with no clear decline or increase.

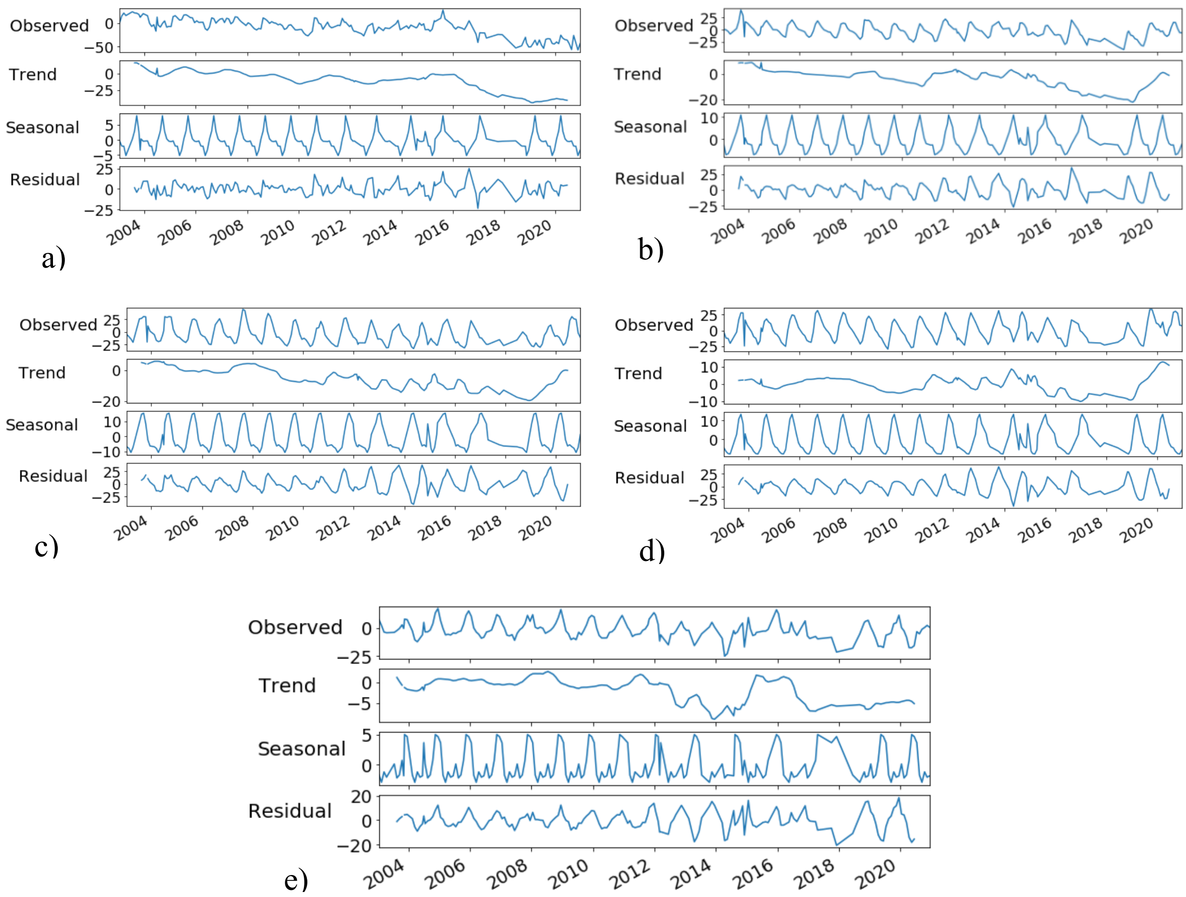

Figure 7. Seasonal decomposition for GRACE grid (a) (30875,73.375) showing decreasing trend in Hotspot I, (b) (26.375,81.375) showing decreasing trend in Hotspot II, (c) (24.125,88.125) showing decreasing trend in Hotspot III, (d) (21.125,82.125) showing no-trend in Hotspot IV, and (e) (8.625,77,125) showing decreasing trend in Hotspot V.

4.4 Volume change in hotspots

We have calculated the volume change across all hotspot locations (Figure 8). The spatial median value of groundwater level for a season for a particular hotspot is multiplied by the specific yield value of aquifer for that monitoring station. Groundwater level is measured in meter below ground level and if volume change is increasing in Figure 8, it means groundwater level is going down or that volume of groundwater has depleted over the year.

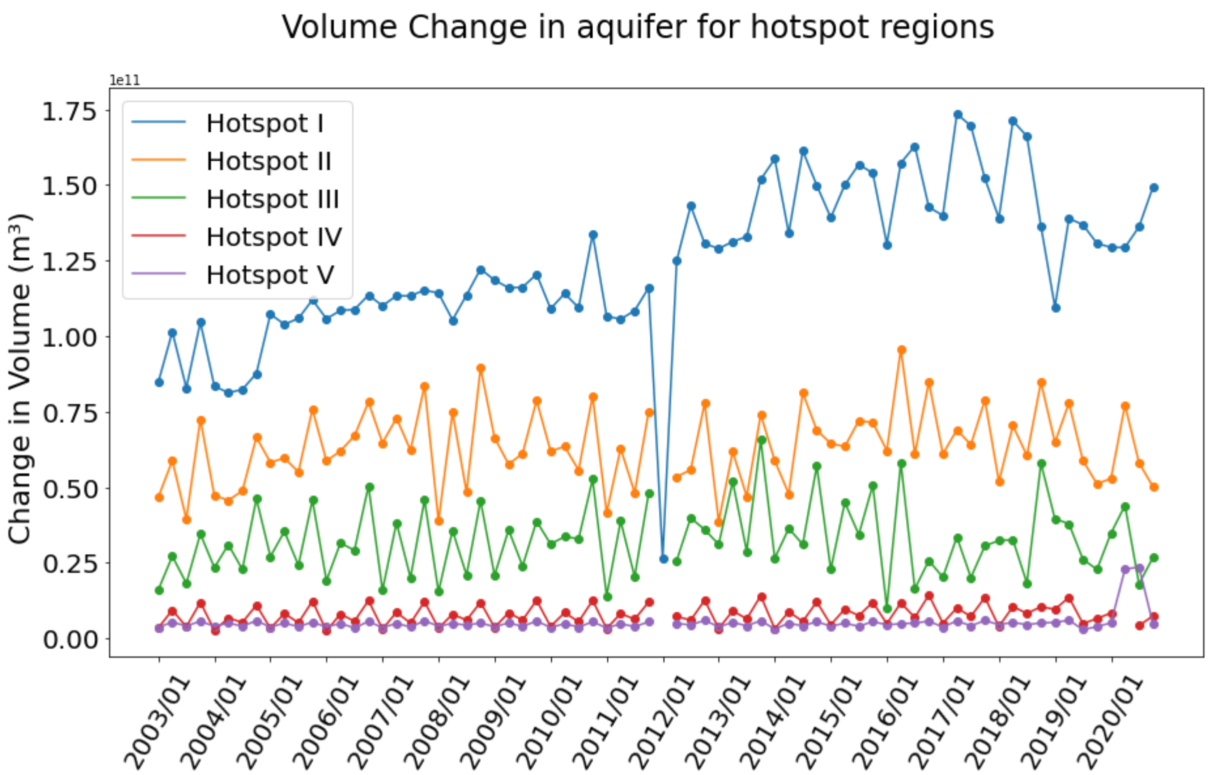

Figure 8. Volume change across five identified hotspot regions (spatial median value of GW level change*specific yield).

5. Attribution of changes

5.2.1 Hotspot I - Punjab and Haryana

Hotspot I is in the northwestern states of Punjab and Haryana (Figure 1a), which have been the focus of groundwater studies due to the rapidly declining water tables. GRACE-based TWS (Figure 2a) shows declining trend in this region. Further, precipitation has either no trend or decreasing trend (Figure 5a) in most part of this hotspot. Figure 8 shows the seasonal variation of volume change. Groundwater decline is maximum for this hotspot which is evident from this figure. There is overall decrease of 8-10% in irrigated area (Figure 9) (Ambika et al., 2016) from FY 2000-01 to 2014-15. Population data in Figure 10a show that the population in this hotspot has increased by 13 to 19% from 2001 to 2011. During this decade, level of urbanization i.e., percentage of urban population has increased by 10-20% (Figure 10b), one of the highest in the country. If we look at industrial data (Figure 10c), we can see that there is substantial increase from 69 to 170% in number of factories from financial year (FY) 2004-05 to 2018-19. During the same period, the net annual groundwater availability (Figure 10d) has dropped up to 4% from 2004 to 2020 and stage of groundwater development (Figure 10e) has substantial increased by about 13-22% in this hotspot region. There is increase of 8 to 15% in groundwater demand for irrigation (Figure 10f). Groundwater demands for domestic and industrial use (Figure 10g) shows a significant increase of 26 to 228%. Thus, despite government interventions and no perceptible decline in precipitation, groundwater demand has accelerated leading to depletion.

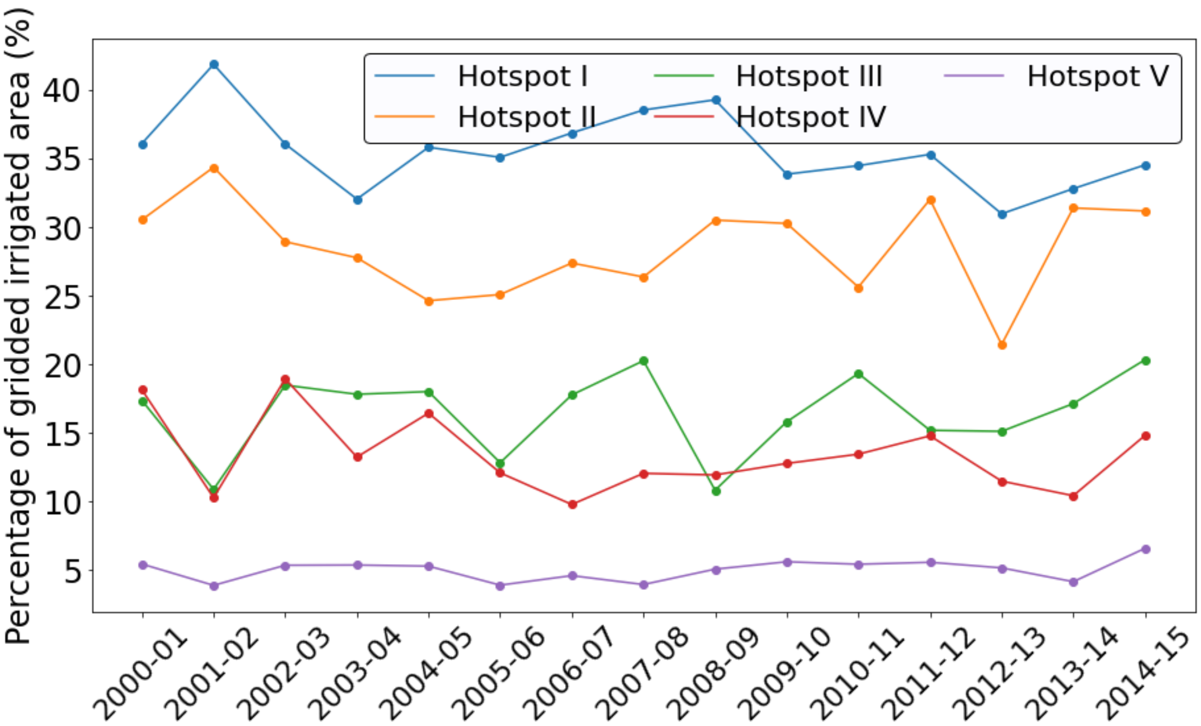

Figure 9. Percentage of remotely sensed irrigated area for selected hotspots regions

5.2.2 Hotspot II – Uttar Pradesh

Hotspot II is located in the state of Uttar Pradesh (Figure 1a). GRACE-based TWS (Figure 2a) is showing declining trend as well in this region. Precipitation (Figure 5a) shows either no-trend or decreasing trend in most of the portions in this hotspot region. In Figure 7b, we have shown a seasonal decomposition plot for a randomly selected grid point GRACE-based TWS series of Hotspot II which was originally showing decreasing trend. Trend subplot of Figure 7b is showing how the trend has varied over the years with an overall decline. Similarly, all grid point of hotspot II will show a similar subplot with some variations. Figure 8 shows the variation of groundwater volume change and volume of groundwater lost over the year. These changes are occurring due to following mentioned changes in the socio-economic condition of the region. There is increase in irrigated area by more than 3% (Figure 9) from FY 2000-01 to 2014-15. Population has increased by more than 20% from 2001 to 2011 (Figure 10a) and level of urbanization has increased by about 7% over this duration (Figure 10b). There is significant increment of more than 65% in number of factories in this region (Figure 10c) from FY 2004-05 to 2018-19. Net annual groundwater availability has decreased by more than 4% (Figure 10d) and stage of groundwater development has a decrement of about 1% (Figure 10e) from 2004 to 2020. but groundwater demand for irrigation has dropped by approximately 8% from 2004 to 2020 (Figure 10f). Groundwater required by domestic and industrial use (Figure 10g) has increased by more than 38% from 2004 to 2020. These factors have contributed to the groundwater depletion in this region as shown in the Figure 8.

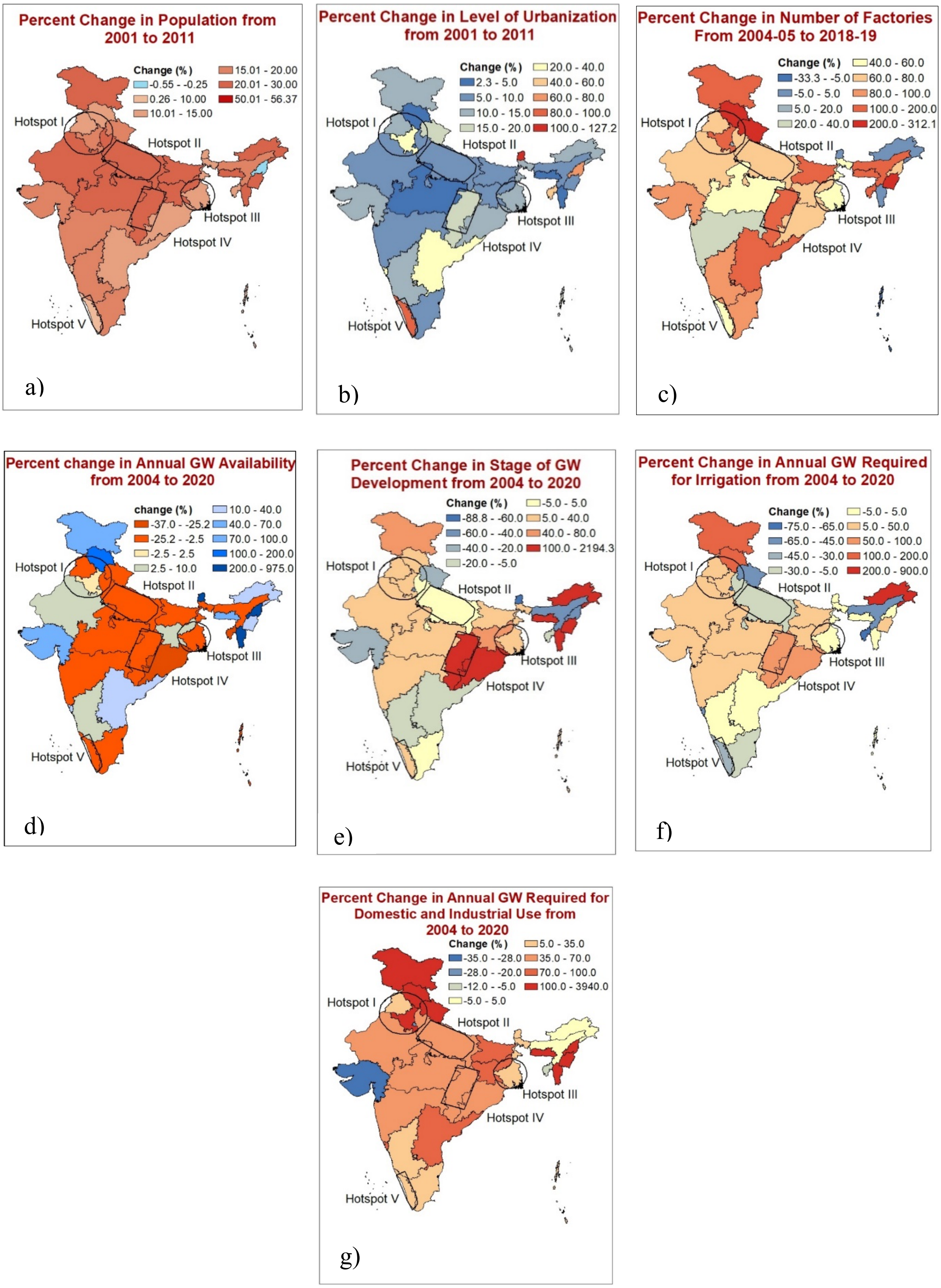

Figure 10. Percent change in (a) Population, (b) Level of Urbanization from 2001 to 2011, (c) number of factories from FY 2004-05 to 2018-19, (d) annual groundwater availability, (e)

stage of groundwater development, annual groundwater required for (f) irrigation and (g) domestic and industrial use from 2004 to 2020

5.2.3 Hotspot III – West Bengal

Hotspot III is identified in the region of West Bengal (Figure 1a). GRACE-based TWS (Figure 2a) have shown decreasing trend in the half of the region of hotspot III. Precipitation trend (Figure 5a) has either no-trend or decreasing trend (nearly 40% of the portion) in most of the portions in this hotspot region. In Figure 7c, we have shown a seasonal decomposition plot for a randomly selected grid point GRACE-based TWS series of Hotspot III which was originally showing decreasing trend. Trend subplot of Figure 7c is showing how the trend has varied over the years with some ups and downs and with an overall decline. Similarly, all grid point of hotspot III will show a similar subplot with some variations. Figure 8 captures the variation of groundwater decline and volume lost over the years. These changes are occurring due to following mentioned changes in the socio-economic condition of the region. There is increase in irrigated area by more than 16% (Figure 9) from FY 2000-01 to 2014-15. Population has increased by >13% from 2001 to 2011 (Figure 10a) and level of urbanization has an increment of about 14% over this duration (Figure 10b). There is substantial increment of more than 54% in number of factories in this region (Figure 10c) from FY 2004-05 to 2018-19. Net annual groundwater availability has decreased by more than 3% (Figure 10d) and stage of groundwater development has an increment >5% (Figure 10e) from 2004 to 2020. Groundwater demand for irrigation has a minute increment of about 0.09% from 2004 to 2020 (Figure 10f). Groundwater required by domestic and industrial use (Figure 10g) has increased by >24% from 2004 to 2020. These all factors have caused the groundwater to deplete in this region.

5.2.4 Hotspot IV - Chhattisgarh

Hotspot IV is located in the state of Chhattisgarh (Figure 1a). Contrary to *in situ* trend result, GRACE-based TWS (Figure 2a) has shown no trend in the region of hotspot IV. Precipitation trend (Figure 5a) has either no-trend or increasing in most of the portions (>95% of the portion) in this hotspot region. In Figure 7d, we have shown a seasonal decomposition plot for a randomly selected grid point GRACE-based TWS series of Hotspot IV which was originally showing no trend. Trend subplot of Figure 7d is showing how the trend has varied over the years with lots of ups and downs without any significant decline in the trend. But *in situ* trend result has shown decreasing trend across the hotspot region. Variations of volume change i.e., amount of groundwater has lost over the years, is shown in the Figure 8. These changes are occurring due to following mentioned changes in the socio-economic condition of the region. There is decrement in irrigated area by more than 18% (Figure 9) from FY 2000-01 to 2014-15. Population has increased by >22% from 2001 to 2011 (Figure 10a) and level of urbanization has an increment of about 16% over this duration (Figure 10b). There is huge increment of more than 166% in number of factories in this region (Figure 10c) from FY 2004-05 to 2018-19. Net annual groundwater availability has decreased by more than 15% (Figure 10d) and stage of groundwater development has a huge increment of >126% (Figure 10e) from 2004 to 2020. Groundwater demand for irrigation has a substantial increment of about 96% from 2004 to 2020 (Figure 10f). Groundwater required by domestic and industrial use (Figure 10g) has increased by >68% from 2004 to 2020. These socio-economic factors have contributed towards groundwater depletion in this region.

5.2.5 Hotspot V - Kerala

Hotspot V has been identified in the state of Kerala (Figure 1a). GRACE-based TWS (Figure 2a) have shown decreasing trends in almost half of this hotspot. Precipitation trend (Figure 5a) has either no-trend or increasing in most of the portions (>95% of the portion) in this hotspot region. Figure 7e shows a seasonal decomposition plot for a randomly selected grid point GRACE TWS series of Hotspot V which was originally showing decreasing trend. Figure 7e shows how the trend has varied over the years with some ups and downs and with an overall decline. Similarly, other grid point of hotspot IV will show a similar subplot with some variations. Volume of groundwater has been lost over the year is shown in figure 8. This figure also shows the seasonal variation of groundwater volume change. These changes are occurring due to following mentioned changes in the socio-economic condition of the region. There is an increment in irrigated area by >16% (Figure 9) from FY 2000-01 to 2014-15. Population has an increment of about 5% from 2001 to 2011 (Figure 10a) and level of urbanization has a huge increment of > 83% over this duration (Figure 10b). There is an increment of >40% in number of factories in this region (Figure 10c) from FY 2004-05 to 2018-19. Net annual groundwater availability has decreased by more than 17% (Figure 10d) and stage of groundwater development has an increment of >10% (Figure 10e) from 2004 to 2020. Groundwater demand for irrigation has a drop of about 36% from 2004 to 2020 (Figure 10f). Groundwater required by domestic and industrial use (Figure 10g) has increased by >34% from 2004 to 2020. These factors are responsible for the groundwater depletion.

5 Discussions and Conclusion

Depletion of groundwater level is a major concern in India. Previous studies have shown that irrigation is a major driver of groundwater depletion in various parts of the country (e.g., Kaur et al., 2017; Kishore et al., 2021). In this study, we have assessed groundwater trends using *in situ* and satellite (GRACE and GRACE-FO) data and hydrological model outputs (with and without DA). We then attempted to attribute these hotspots to various socio-economic factors:

- In hotspot I (Punjab and Haryana), the major contributing factors for depletion are the increase in the number of factories, the decrease in precipitation over the duration, the increase in population, and urbanization, which has led to a substantial increase in demand for water for domestic and industrial use. Over the years, this region has lost nearly $6.46 * 10^{10}$ cubic meter of water.

- In hotspot II (Uttar Pradesh), the contributing factors are increased industrialization, urbanization, and irrigation, which have created higher demands for industrial, domestic and agricultural water use.
- In hotspot III (West Bengal), the contributing factors are surge in number of factories along with growth in population, urbanization and expansion in irrigation have created a larger demand for water.
- In hotspot IV (Chhattisgarh), the contributing factors are the large increment in number of industries, substantial growth in population, and urbanization have put huge demands for water.
- In hotspot V (Kerala), the major contributing factors are the surge in the number of factories along with increment in urbanization, and expansion in irrigation have created a huge demand for water. Unlike other hotspots, there was no observed increase in population in this region.

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Data Availability:

The datasets used in this study are available from the following sources:

- *In situ* groundwater level data from Central Ground Water Board (CGWB) and Streamflow data from the Central Water Commission: https://indiawris.gov.in/wris/
- GLDAS datasets from NASA Earth: https://earthdata.nasa.gov/
- IMD precipitation: https://www.imdpune.gov.in/Clim_Pred_LRF_New/
- GRACE and GRACE-FO , Center for Space Research (CSR), The University of Texas
- State wise Annual Groundwater Availability, Irrigation, Domestic and Industrial uses volume, Groundwater Year Book 2009-10 to 2019-20
- Level of Urbanization (1991, 2001, 2011), Handbook of Urban Statistics 2019

- Number of Factories data, Source: Annual Survey of Industries (ASI), Ministry of Statistics and Programme Implementation, Government of India.
- Specific yield: Bhanja et al. (2016)

Compliance with Ethical Standards

The authors declare that they have no conflict of interest.

Author Contributions

MS and AG conceived and designed the analysis. AP wrote the scripts for downloading groundwater well datasets. GK collected the data and performed the analysis. GK led the paper with active contribution from MS and AG.

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