

An Untold Story of Groundwater Replenishment in India: Impact of Long-Term Policy Interventions



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1 Introduction

Rapid depletion of groundwater storage (GWS) at world's densest populated areas (Rodell et al. 2009; Feng et al. 2013; Voss et al. 2013; Bhanja et al. 2014) would make billions of people suffer from socioeconomic stress in the near future. Water management framework design becomes further complex due to changes in hydrological cycle in the form of increasing atmospheric water vapor content; alteration in patterns, intensity, and extremes of precipitation; snow cover reduction; and change in soil moisture as well as runoff, in the current global warming scenario (Bates et al. 2008). Most of the global hydrological models are not capable enough to simulate groundwater storage over all of the places of the globe at an optimum accuracy; it might be due to absence of groundwater pumping, irrigation, and reservoir impoundment (Sacks et al. 2009) or deficiency in groundwater or surface water components (Maxwell and Miller 2005).

The Gravity Recovery and Climate Experiment (GRACE) has been continuously monitoring the change in earth's gravity with exceptional accuracy (Tapley et al. 2004; Famiglietti and Rodell 2013). The change in gravity field has been related to

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the variation in mass in the fluidic layers of the earth, i.e., air and water. To compute terrestrial water storage (TWS) estimates, different algorithms are utilized to remove the signals lined to solid earth processes (Wahr 2007), atmospheric and oceanic waves (Flechtner 2007). Numerous studies report groundwater storage depletion across the globe (in either basin-scale or continental-scale) using satellite-based approach (e.g., Rodell et al. 2009; Tiwari et al. 2009; Reager and Famiglietti 2013; Voss et al. 2013; Richey et al. 2015). The earlier studies converted groundwater levels to groundwater storage using a constant specific yield value in the entire study region. For example, Rodell et al. (2009) and Panda and Wahr (2016) both used a uniform specific yield value of 0.12. Bhanja et al. (2016) has developed a specific yield database for the country.

In situ and satellite-based groundwater storage anomalies are estimated in this chapter. The in situ data has been retrieved from a well-maintained network of groundwater level monitoring locations in India and studied across different parts of India.

2 Methodology

2.1 *In Situ Groundwater-Level Observations*

Groundwater level (GWL) information are obtained from the Central Ground Water Board (CGWB, India) in January 2005 to November 2013. The data are collected from typically unconfined aquifers (~87%) (CGWB 2014b), from >19,000 observation wells having GWL data of four times a year (late post-monsoon (January), pre-monsoon (May), monsoon (August), and early post-monsoon (November)). To use the continuous data for anomaly analyses, observation locations are selected based on the availability of at least three seasonal data in the years. Outliers were removed following the inter-quartile approach (Davis 2002), which reduced the well numbers to 3907. CGWB has been maintaining the densely spaced monitoring wells network very well; this is linked with observation of very less spatial error that might be arising as a result of groundwater spatial variability (Bhanja et al. 2017a). GWL anomaly (GWLA) in the individual well has been estimated by subtraction of time-averaged depth to water table from the depth of water table in each observation time. The sign was reversed in the process for depth below the surface rule. The GWLA are converted to GWSA anomalies ($GWSA_{obs}$) using specific yield values for each well (Bhanja et al. 2016; MacDonald et al. 2016). $GWSA_{obs}$ median values within each grid cell were utilized to build $1^0 \times 1^0$ gridded data in the study area and for comparing with $GWSA_{sat}$.

2.2 Aquifer-Specific Yield Computation

High-resolution ($0.1^0 \times 0.1^0$) specific yield map is made using hydrogeology map of India (Bhanja et al. 2016). The tributaries and the main channel of Ganges is the largest river system in India having a catchment area of ~86.1 million ha (CWC 2010). Indus-Ganges-Brahmaputra (IGB) rivers system has created a regional aquifer system in parts of the northern and eastern India, which is considered to be one of the most prolific aquifers in the world (Mukherjee et al. 2015). On the contrary, central and southern India has been consisting of Pre-Cenozoic crystalline rocks, sedimentary formations, and multilayered basalt of the Indian craton (CGWB 2014b).

The aquifers are composed of six hydrogeological units, such as unconsolidated sedimentary aquifers; consolidated, permeable sedimentary aquifers; sedimentary aquitards; folded metasediment/metamorphic aquifers; jointed crystalline aquifers; and fractured crystalline aquifers (Bhanja et al. 2016).

The S_y values (Table 1) are segregated from the CGWB database (CGWB 2012a). The S_y information were characterized according to the aquifer hydrogeology shown in Fig. 1. Ranges and mean specific yield information are provided in Table 1. Details on S_y can be found in Bhanja et al. (2016) (Fig. 2).

Individual S_y values are allocated to the wells located in hydrogeologic formation. Observed GWS are computed by multiplying Δh and S_y values. GWS anomaly has been calculated by subtracting all time-averaged GWS from the individual data.

2.3 Gravity Recovery and Climate Experiment (GRACE)

Gridded ($1^0 \times 1^0$), monthly mean liquid water equivalent thickness (LWET) data were obtained from NASA-JPL archive. Mascon solutions (RL05) are used for 133 months in January 2003 to December 2014 (Watkins et al. 2015). Several data processing techniques are used to separate the TWS signal from the data (details can

Table 1 Specific yield values of different hydrogeologic formations shown in Fig. 1

	Hydrogeology	S_y range	Mean S_y
1	Unconsolidated sedimentary (high hydraulic conductivity)	0.06–0.20	0.130
2	Consolidated, permeable sedimentary (medium hydraulic conductivity)	Up to 0.08	0.043
3	Sedimentary aquitards (low hydraulic conductivity)	Up to 0.03	0.018
4	Folded metasediments/metamorphics (low hydraulic conductivity)	Up to 0.03	0.018
5	Jointed crystalline (low to variable hydraulic conductivity)	0.01–0.03	0.020
6	Fractured crystalline (low to variable hydraulic conductivity)	Up to 0.04	0.023

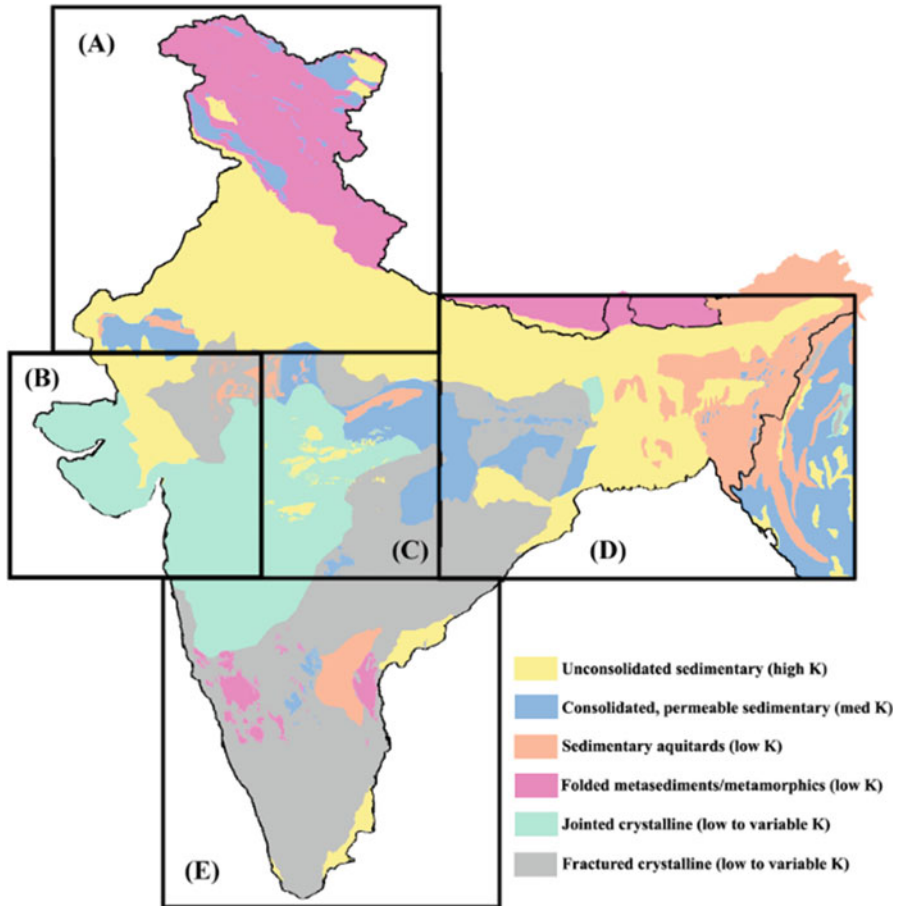


Fig. 1 Hydrogeology map of the ISC. The five HMZs are marked. (Modified from Bhanja et al. 2016)

be found in http://grace.jpl.nasa.gov/data/get-data/jpl_global_mascons/ accessed on 26 April, 2016). Degree 2 and order 0 coefficients are substituted using the coefficients obtained from Satellite Laser Ranging (Cheng and Tapley 2004). Geocenter corrections have been retrieved from Swenson et al. (2008). Glacial isostatic adjustment (GIA) values in the data are separated following Geruo et al. (2013). One of the major differences between SH and mascon approach is linked to the division of the globe in spherical, 3^0 equal area mass concentration blocks in mascon approach (Watkins et al. 2015). Further, use of the a priori values leading to the omission of correlated noise (stripes), as a result, post-processing filters are no more required to be used in mascon approach (Watkins et al. 2015). Another benefit of mascon

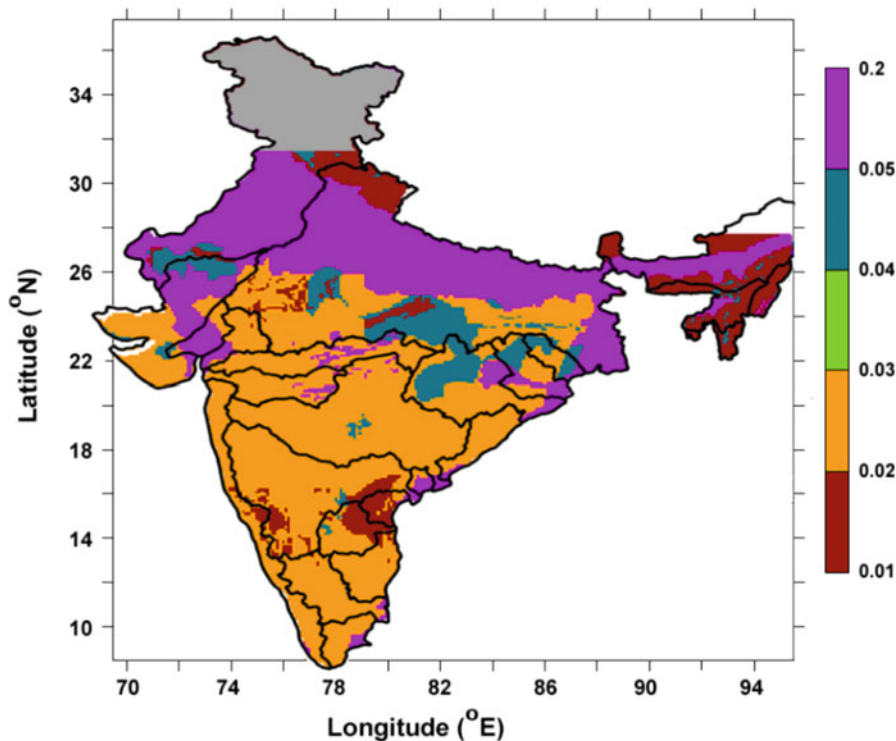


Fig. 2 Specific yield map ($0.1^\circ \times 0.1^\circ$) of the study region. Specific yield fractions are shown in color bar. (Modified from Bhanja et al. 2016)

approach over the spherical harmonics solutions deals with the comparatively lower dependency on scale factors for estimating the mass change calculations in the river basins (Watkins et al. 2015). The scale factors are multiplied with the TWS solutions for consideration of local-scale phenomena.

2.4 *Satellite-Based Groundwater Storage Anomaly Estimation*

The anomaly in satellite-based groundwater storage (ΔGWS) has been estimated after separating the anomalies of other water components such as the soil moisture anomaly (ΔSM) and surface water (ΔSW) equivalents (surface runoff data used here). The study region has never experienced snow accumulation (exception is the northernmost Himalayan region); hence, snow data are not used. Time-averaged data has been removed from individual data to compute the anomaly (Δ). Continuous

observation data for SM and SW were not available; we used the model estimates from the NASA Global Land Data Assimilation System (GLDAS) (Rodell et al. 2004). The combination of three different GLDAS models' output, such as the Community Land Model (CLM), Variable Infiltration Capacity (VIC), and Noah models, is used to avoid any bias associated with a particular model. The CLM simulation includes soil moisture in ten different soil layers (0–343 mm) and other models, while VIC and Noah simulation includes soil moisture in three layers (0–190 mm) and four layers (0–200 mm), respectively. For estimating anomaly in any of the components, time-averaged value for that component has been subtracted from the individual data. Finally, the groundwater storage (Δ GWS) anomaly is estimated by removing anomalies of Δ SM and Δ SW from the TWS anomaly.

3 Results and Discussions

3.1 Groundwater Storage Estimation

In situ groundwater level trends show simultaneous occurrence of wells with increasing and decreasing water level between 2005 and 2013 (Fig. 3). However, parts of the IGB basin mostly show reducing groundwater levels, whereas parts of western and southern India show increasing trends (Fig. 3). The GWS anomaly shows strong spatial variability in the study region (Figs. 4 and 5). Observed GWS data indicate renewal in GWS in western (HMZ B) and southern (HMZ E) zones at a rate of 1.06 ± 0.03 and 0.31 ± 0.02 km³/year. On the other hand, the northern (HMZ A) and eastern (HMZ D) zones are experiencing rapid GWS depletion at rates of 4.55 ± 0.11 km³/year and 3.59 ± 0.14 km³/year, respectively (Figs. 4 and 5). Satellite-based estimates indicate rapid depletion in northern (zone A) and eastern (zone D) zones at a rate of -1.40 ± 0.14 and -1.16 ± 0.35 cm/year (-14.02 ± 1.37 km³/year and -14.49 ± 4.36 km³/year) in the study period, respectively (Fig. 5). These depletion observations are in line with the satellite-based findings of northwest (17.7 km³/year, between 2002 and 2008) (Rodell et al. 2009) and northern (54 km³/year in 2002–2008) (Tiwari et al. 2009) India and Bangladesh (located at eastern zone) (Shamsudduha et al. 2012). Corroborating the above observations, comparison of field measured groundwater level fluctuation of decadal mean (2001–2010) to 2011 by Indian government authorities, in general, suggests groundwater decline in northern, northwestern, and eastern India and rise in southern and western India for most seasons (CGWB 2012b). They reported a declining water level trend for pre-monsoon during 2007 to 2012 with >55% of measured wells ($n = 11,024$) having groundwater level drop of ≥ 1 m/year (MoWR 2013).

The fertile alluvial plains of the IGB basin are extremely conducive for irrigational activities. Consequently, the IGB plains have been one of the cradles

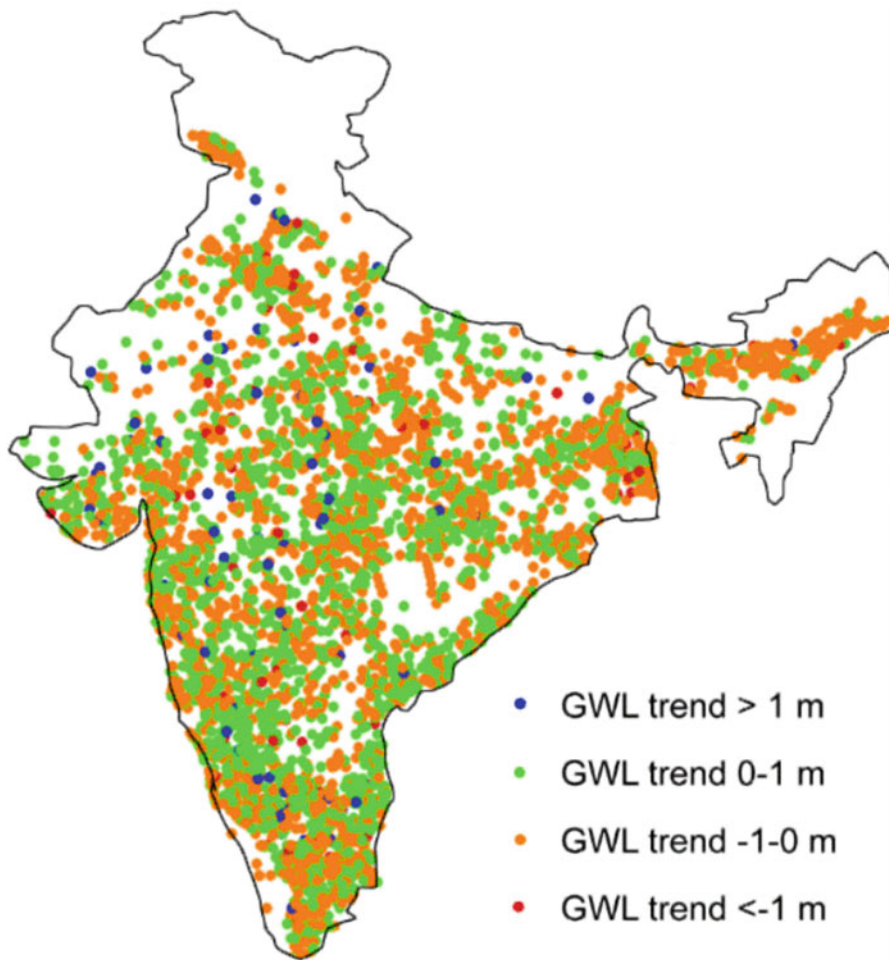


Fig. 3 Maps of in situ groundwater level trends in 2005–2013

of human civilization, and presently it is known as one of the most densely populated parts in the world. The rapidly accelerating groundwater demands in these areas are directly proportional to the increasing population, introduction of water-intensive crops (e.g., boro rice), and changes in cropping pattern (e.g., replacing food crop by cash crop) (FAO 2013) and coincide with the areas showing highest GWS depletion. Most of Bangladesh (percentage of gross irrigated area to gross cropped area, >60%; FAO 2013) and Indian states such as Punjab (98%), Haryana (85%), Uttar Pradesh (76%), Bihar (61%), and West Bengal (56%) are all located in these depletion zones (MoA 2012). More than 4 m groundwater decline have been observed during the last decade in Indian states of Delhi, Haryana, Punjab, Rajasthan, and West Bengal (CGWB 2014a). The drastic groundwater level depletion in Ganges basin has been

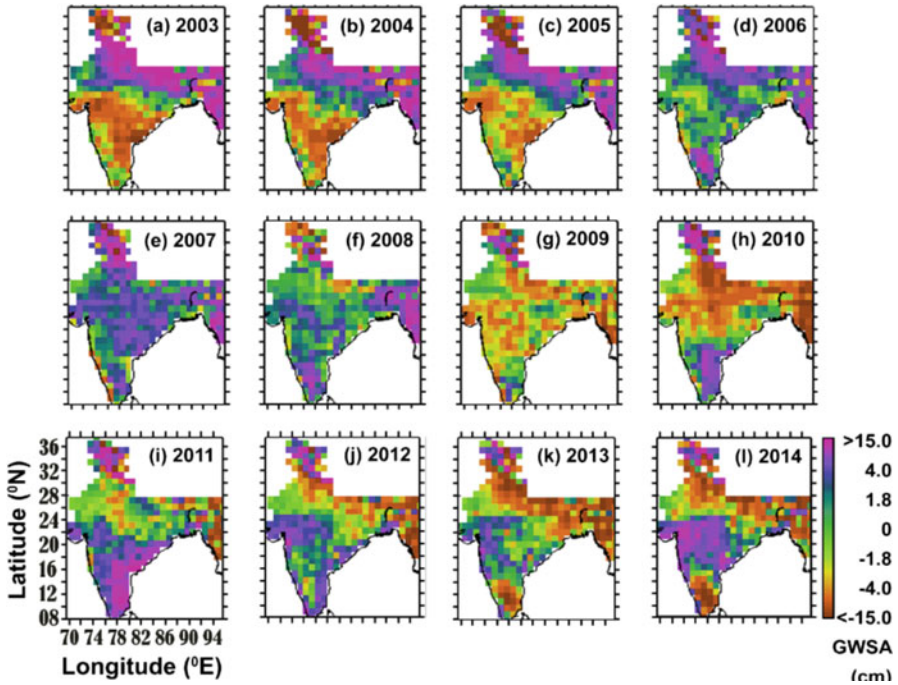


Fig. 4 Maps of the annual mean groundwater storage (GWS) anomalies (cm)

found to be linked with surface water quantity reduction in Ganges river during recent summers (Mukherjee et al. 2018).

3.2 Groundwater Storage Replenishments and Policy Interventions

Despite rapid GWS depletion in northern and eastern parts, GWSA replenishments have been observed in southern, central, and western parts of India (Figs. 4, 5, and 6). In situ estimates show groundwater level replenishing trend in Andhra Pradesh, Maharashtra, Gujarat, Tamil Nadu, and Chhattisgarh between 2005 and 2013. The estimates are consistent with published reports of CGWB (CGWB 2013, 2014b). Based on the satellite-based estimates, it has been found that several districts of the western, central, and southern study regions have been subjected to GWS replenishments. The reasons for the replenishment are investigated in detail in Bhanja et al. (2017b). Reasons include reduction in irrigation-linked groundwater withdrawal, change in agricultural practice, increasing artificial recharge, surface water irrigation increase, etc. (Bhanja et al. 2017b, and references therein).

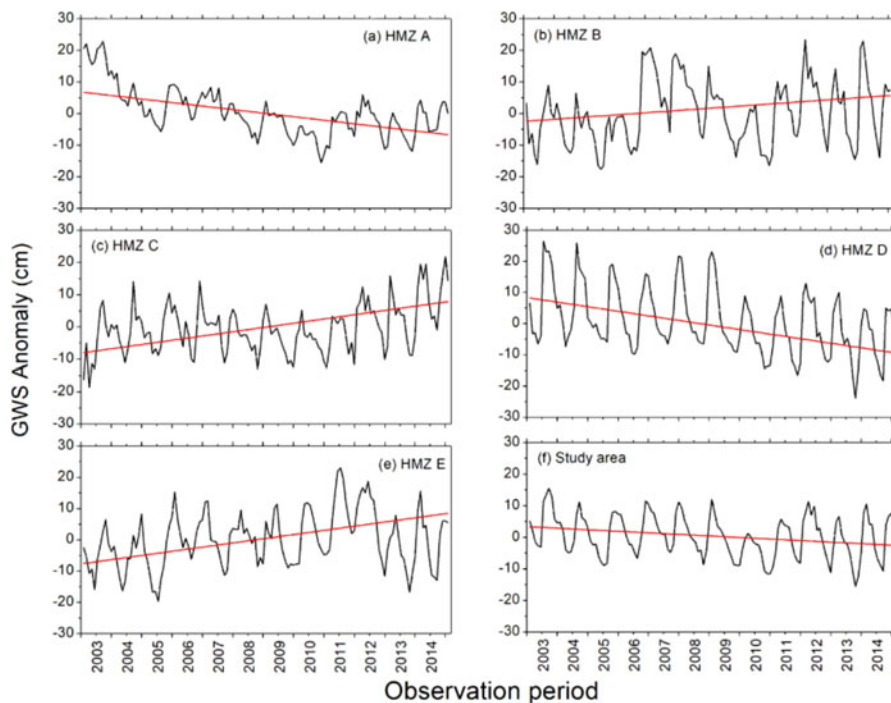


Fig. 5 Time series of GWS anomaly in (a) northern (HMZ A), (b) western (HMZ B), (c) central (HMZ C), (d) eastern (HMZ D), (e) southern (HMZ E), and (f) the entire study area

Uncontrolled withdrawal for increasing irrigation of water-intensive cropping practice (e.g., boro rice paddy) has been leading to one of the most critical groundwater depletion in human history. Recent shift in Indian government policies on groundwater withdrawal and incorporation of management strategies are facilitating increasing groundwater storage. Policies such as inhibition of subsidized electricity for irrigation, creation of large-scale recharge systems in crystalline aquifers (e.g., ~700 million USD allocated to the Tapi river Mega Recharge Project), targeted artificial recharge of 85 BCM/year in ~0.5 million km² through creation of ~10 million structures, and increased recharge as a function of the interlinking of river catchments (such as the Narmada-Sabarmati interlinking) have been implemented. Based on these, we hypothesize to have probably started replenishing the groundwater storage, as evident in GWL and GWS trends in parts of India (Bhanja et al. 2017b).

The potential implications of groundwater management policies are studied using the longterm (between 1996 and 2014), groundwater level information from the Indian states of Gujarat and Andhra Pradesh. The GWS were characterized as trends and cycles using the Hodrick-Prescott (HP) filter approach. The result suggests reducing groundwater trends from 1996 to 2002–2003 in Gujarat, at a rate of 5.81 ± 0.38 km³/year (linear trend), and trend reversals to increasing GWS have been observed at a rate of 2.04 ± 0.20 km³/year between 2002–2003 and 2014. A

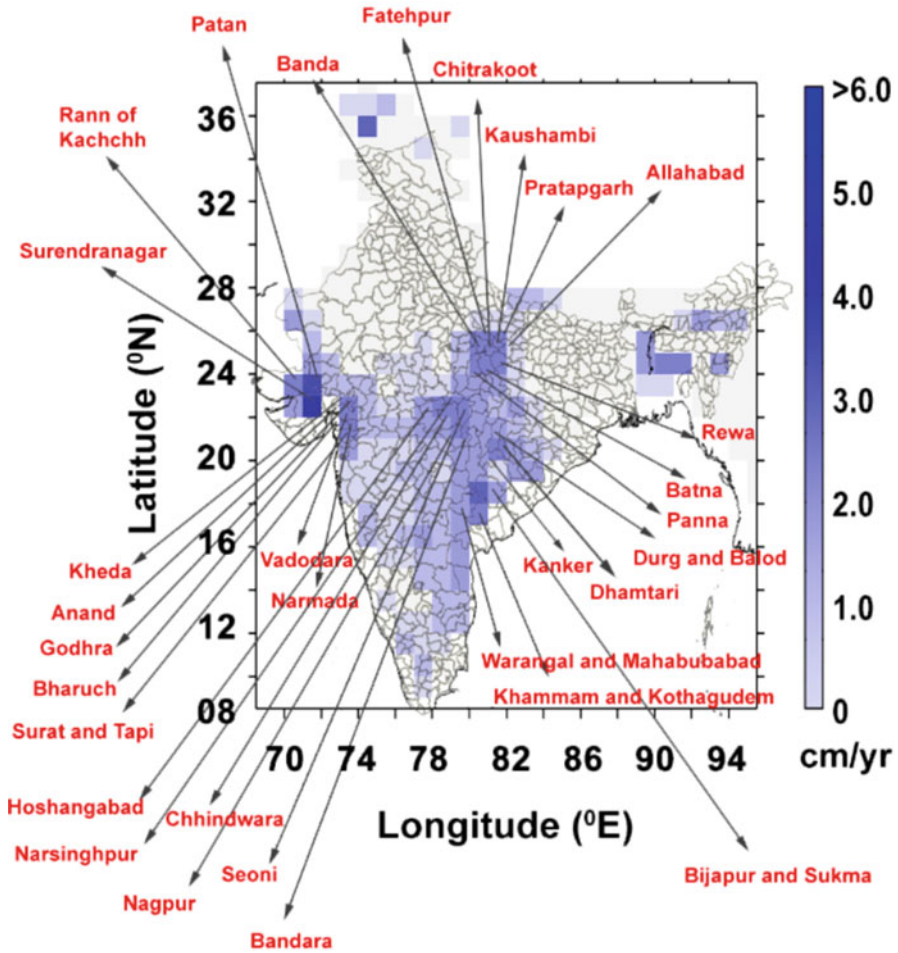


Fig. 6 District-wise groundwater replenishment from satellite-based observations. Districts with more than 2 cm/year are marked here

declining GWS trend has been observed in Andhra Pradesh ($0.92 \pm 0.12 \text{ km}^3/\text{year}$) in 1996–2003. Similar to Gujarat, the GWS trend has been following increasing trend in 2003–2014, at a rate of $0.76 \pm 0.08 \text{ km}^3/\text{year}$. The trend reversals are found to be associated with implementation of several groundwater policy modifications in these two states (Bhanja et al. 2017b). In the same time period (i.e., 1996–2014), no distinct changes in HP trends of precipitation have been found in the two states (Fig. 3b and d), hence reducing possibilities of influence of precipitation on the groundwater storage trends.

A net decrease in agricultural power supply from 16 to 10 billion units in 2001–2006 resulted in 20–30% decrease in groundwater withdrawal in Gujarat.

Results of our analyses show electricity usage for groundwater irrigation (P value <0.05) was found to have negative influence on GWS anomaly in Gujarat, indicating the decrease in electricity usage facilitating reduction in groundwater pumping from 2002, possibly resulting to GWS replenishment in Gujarat. In Andhra Pradesh, UN FAO conducts program for farmers, associated with groundwater sustainable management training practice in 2004–2008. Another scheme named APWELL was associated with large-scale groundwater development in Andhra Pradesh (Bhanja et al. 2017b). An overall enhancement in surface water irrigation is observed 1996 onward ($\sim 20\%$ increase in surface water irrigation have been recorded in 2003–2014 comparing the 2002 level), thus possibly inducing the increased non-meteoric recharge.

4 Summary and Conclusion

Over the past decade, the issue of diminishing groundwater resources in India has garnered significant concern worldwide. Several studies have shown the rapid depletion of groundwater storage as a consequence of intensifying crop irrigation and rapid urbanization. Our studies have identified replenishment of groundwater storage at regional scale in parts of southern and western India. In recent times, large parts of the country experience severe water crisis during every summer. Pervasive, unregulated groundwater withdrawal for enhancing irrigation of water-intensive cultivation is linked to one of the most severe groundwater depletion in the world and may be ascribed as “largest groundwater abstraction in human history.”

Our study shows that a recent crucial shift in the Indian groundwater management policies for water utilization might be associated with the aquifer replenishment by increasing storage in western and southern India. We observed, in parts of western (Gujarat) and southern (Andhra Pradesh) India, groundwater storage had been decreasing at rates of $-5.81 \pm 0.38 \text{ km}^3/\text{year}$ and $-0.92 \pm 0.12 \text{ km}^3/\text{year}$ in 1996 to 2001–2002, respectively. Consequently, the groundwater storage has been found to increase at rates of $2.04 \pm 0.20 \text{ km}^3/\text{year}$ in Gujarat and $0.76 \pm 0.08 \text{ km}^3/\text{year}$ in Andhra Pradesh, respectively, during 2002–2003 to 2014.

The groundwater replenishment is probably caused by a combination of government policy changes and the grassroots efforts of local communities, who have undertaken several projects over the last several years in the form of efficient groundwater management and utilization policies. Recent changes in Indian government’s policies on groundwater management processes, such as inhibition of subsidized electricity for irrigation, distinct electricity distribution for agriculture (e.g., Jyotigram Yojana), creation of large-scale recharge systems in crystalline aquifers (e.g., the Tapi river Mega Recharge Project), artificial recharge of 85 Billion cubic meter/year in approximately 0.5 million km^2 by creation of ~ 10 million structures (e.g., Pradhan Mantri Krishi Sinchayee Yojana), and increasing recharge by interlinking of rivers (e.g., Narmada-Sabarmati interlinking), are worth to be noted. The sustainable policy implementation is possibly starting to replenish the

aquifers in the form of increasing groundwater storage in the future. Hence, the results of our study illustrate a potentially optimistic scenario, where under conducive groundwater management policies India can transform from a “groundwater-scarce” to a “groundwater-sufficient” country.

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