Groundwater Storage Assessment Using Effective Downscaling GRACE Data in Water-Stressed Regions of India

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Abstract

Globally, the groundwater is the most favourable and demandable freshwater resource. The threat to surface water resources and subsurface aquifer systems increased with climate change as well as surplus usage of groundwater in highly populated regions. Thus, in present day, groundwater is the primary resource for the sustainability of agriculture, industries and domestic activities in arid and semi-arid areas of the world. The overexploitation of subsurface water initiates land subduction. As water is the source of life on Earth, so it is essential to monitor and predict the capability of groundwater for secure sustainable management of subsurface water with the extreme climate conditions and population growth. The traditional way of keeping a check on groundwater level change is considering in situ or point measurements using the local network of well data. But these measurements are insufficient as hydrological models depend on the spatial data referring over large areas. Global Positioning System (GPS) and Gravity Recovery and Climate Experiment (GRACE) mission are perfect tools to overcome the drawbacks of the traditional groundwater monitoring. It measures the change in ice sheets and glaciers, near-surface and subsurface GWS changes, as well as sea-level changes by GRACE 1 mission and GRACE, Follow on (FO) mission. Most of the researches are based on GRACE satellite data to monitor GWS changes over a large-scale area as continental or regional achieved successful consequences. Although the past decade GRACE studies exhibited that

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GRACE solution is capable of developing accurate quantitative estimations for GWS scenarios with the high temporal resolution. Still, it restricts only to continental or regional scale studies. Therefore, most of the recent studies took the step for effective downscaling of GRACE data.

14.1   Introduction

Groundwater is the most favourable and demandable freshwater resource in the world. The threat to surface water resources and sub-surface aquifer systems increased with climate change (Wada et al. 2010; Jasrotia et al. 2019a; Bisht et al. 2020; Haque et al. 2020; Khan et al. 2020) as well as surplus usage of groundwater in highly populated regions. Thus in present day, groundwater is the primary resource for the sustainability of agriculture, industries and domestic activities in arid and semi-arid areas of the world like North-West India (Taloor et al. 2020; Jasrotia et al. 2018, 2019b; Adimalla and Taloor 2020b), Northern China, California in the USA, and regions without surrogate water resources like the Middle East and North Africa (Chen et al. 2014). The overexploitation of sub-surface water initiates land subduction like in San Joaquin valley in California (Sneed and Brandt 2015) as well as some regions in North-West India as Chandigarh and some portions of Rajasthan (Singh et al. 2017; Kim et al. 2018). As water is the source of life on Earth, so it is essential to monitor and predict the capability of groundwater for secure sustainable management of subsurface water with the extreme climate conditions and population growth (Adimalla and Taloor 2020a; Adimalla et al. 2020). The traditional way of keeping a check on groundwater level change is considering in situ or point measurements using the local network of well data (Miro and Famiglietti 2018; Verma and Katpatal 2020). But these measurements are insufficient as hydrological models depends on the spatial data referring over large areas (Western and Blöschl 1998). Even though the in situ well data measurements have given high spatial resolution estimations for local areas, it becomes problematic in detecting groundwater level fluctuations with limited observations over arid and mountainous regions (Yin et al. 2018). So, it requires better awareness about groundwater table and geospatial distribution of pumping wells. For instance, in the United States, a network of 850,000 operating monitoring wells providing fundamental measurements of groundwater quantity and quality (Taylor and Alley 2001) are not quite sufficient for regional and local level studies (Faunt 2009; Faunt et al. 2016; Miro and Famiglietti 2018). The networks of groundwater observation wells in the world often lack adequacy to provide spatial and temporal coverage of Groundwater Storage (GWS) change (Shah et al. 2000; Mogheir et al. 2005). Global Positioning System (GPS) and Gravity Recovery and Climate Experiment (GRACE) mission are perfect tools to overcome the drawbacks of the traditional groundwater monitoring like spatial limitations as sparsing, uneven and time-consuming (Chen et al. 2019), as the technologies mentioned above consist of all-weather monitoring capability, high precision and continuous space-time monitoring (Rodell et al. 2007; Castellazzi et al. 2018).

GRACE is a collaborative mission of NASA's Jet Propulsion Laboratory (JPL), the German Aerospace Center (DLR), the Center for Space Research at the University of Texas at Austin (CSR) and Germany's National Research Center for Geosciences, Potsdam (GFZ), launched on 17 March 2002 (Sarkar et al. 2020). It measures the change in ice sheets and glaciers, near-surface and subsurface GWS changes, as well as sea-level changes by GRACE 1 mission and GRACE, Follow on (FO) mission (Chen et al. 2019). Most of the researches based on GRACE satellite data to monitor GWS changes over a large-scale area as continental or regional achieved successful consequences (Swenson

et al. 2003; Su et al. 2020). Also, the studies about the accuracy of GRACE derived GWS variations proved that the error of GRACE derived solutions over the study realm is larger than 400,000 km^2 but less than 1 cm (Swenson et al. 2003). Although the past decade GRACE studies exhibited that GRACE solution is capable of developing accurate quantitative estimations for GWS scenarios with the high temporal resolution. Still, it restricts only to continental or regional scale studies. Therefore, most of the recent studies took the step for effective downscaling of GRACE data (Gautam et al. 2017; Kannaujiya et al. 2020).

14.2 Study Realm

The Mehsana district lies between 23° 15' to 23° 53' North and 72° 07' to 72° 26' East in the Northern part of the Gujarat alluvium plains. The semi-arid Mehsana district significantly depends on the subsurface water resource and the rate of groundwater development 151.17%. It segregates into the alluvial plain, dissected hilly terrain and piedmont plain with inselbergs. A narrow belt of 20–30 km width in North-Eastern portion of the district specializes with moderate relief alluvium, gravel beds and occasional inliers of older. The aquifer system of the district comprises multi-layers and formed beneath the Precambrian hard rocks, semi-consolidated Mesozoic and tertiary formations and unconsolidated quaternary alluvial deposits (Gupte 2011) as confined, semi-confined and phreatic. The groundwater occurs as fissured formation (hard rock) as well as porous formation (sedimentary) in the district. The soft rock formation of groundwater occurs consists of two major upper layer aquifer units in unconfined condition, denoted as A. But some regions of the aquifer system are semi-confined to confine. The lower layer of the soft rock groundwater formation is located a few hundred metres below as alternate clay and sand layers. The lower formation subdivides into B, C, D and E units

composed of coarse to fine-grained sand and occasional post-Miocene gravel beds. The F and G units of the lower aquifer system comprises fine to medium-grained sand, sandstone with interbedded clay and Miocene siltstone sediments. The groundwater in the alluvium plain is extensively developed through dug wells, tube wells and dug cum bore wells (Table 14.1).

14.3 Methodology

14.3.1 Effective Downscaling of Grace Data

The previous studies, based on effective downscaling of GRACE TWS pixels, suggest two main methods for spatial reductions that are statistical downscaling and dynamic downscaling method (Chen et al. 2014). The dynamic model has used complex data which have been obtained from multiple resources to generate high spatial resolution regional numerical models. The long term linear or non-linear relationship between two data sets develops a statistical downscaling model (Yin et al. 2018). Also, some additional data are required for multivariate statistical regression records (Piles et al. 2011). Therefore, with respect to dynamic models, statistical models are widely used due to simple and less time-consuming. The researches based on statistical downscaling employs linear, non-linear, multivariate and machine learning techniques to support vector machine model, Artificial Neural Network (ANN) and Random Forest (RF) model. Support vector machine model which had been proposed initially by Vapnik based on classification machine learning algorithms are based theoretically on Vapnik Chervonenks dimension (VC) and structural risk minimized inductive (Vapnik 1999). ANN is a processing system to identify non-linear information which stands on the simulation of the human brain, simplification and the abstraction (Ghorbani et al. 2013). The effective downscaling of GRACE-derived TWS employs a statistical regression model (Ning et al. 2014).

Table 14.1 Observed water table decline over Mehsana and surrounding districts

District	Phreatic aquifer (m)	Semi-confined aquifer (m)	Confined aquifer (m)
Mehsana	5–7	12–23	18–50
Patan	2.5–9	25–36	13–45
Banaskantha	9–18	21–28	15–111

Source Central Groundwater Board, Ahmedabad, Sinha (2014)

14.3.2 Detailed Process of Downscaling

The present study emphasizes the statistical downscaling model that has been developed based on the regression relationship between GRACE SH-derived TWS, and water mass balanced equation manipulated TWS. The time lag effect of GRACE data is reduced by using two months later, GRACE SH data for considering the month of the hydrological fluxes. The steps of developing downscaling equation are as follows:

- The spatial resolution of GLDAS hydrological parameters are 0.25° (P 0.25°), 0.25° (ET 0.25°) and 0.25° (SR 0.25°) for precipitation, evapotranspiration and storm surface runoff, respectively. These parameters have been aggregated to the low spatial resolution of GRACE SH as P 1°, ET 1° and SR 1° by using average pixel method.
- Calculate monthly TWS change (ΔS1°) with the water mass balance equation.

$$\Delta S_t^{i^\circ} = P_t^{i^\circ} - ET._t^{i^\circ} - SR._t^{i^\circ} \qquad (14.1)$$

where i° denotes the spatial resolution in degree and t represents the month.

- Level 3 JPL, CSR and GFZ model data of RL06 data product have been average to derive GRACE SH TWS 1°. The level 3 data of RL 06 data product pre-processed as TWS anomaly based on time-mean of 2004–2009 and the data has been multiplied by the corresponding scaling factor to minimize the leakage error. The missing month's data are calculated with linear interpolation of the relevant contiguous months.
- Estimate a linear empirical regression in between hydrological cycle derived ΔS1° and GRACE SH-derived TWS 1°. Liner regressions have been obtained from the several trials and select the equation which has given dominant highest R^2 value in all trails. Therefore, the estimated equation is only applicable to the post-monsoon season of the period from 2003 to 2019.

$$\hat{y} = \beta_1 \cdot x + \beta_\circ \qquad (14.2)$$

$$GRACE_{t+2}^{i^\circ} = \Delta S_t^{i^\circ} \cdot \beta_\circ + \beta_1 \qquad (14.3)$$

$$GRACE_{t+2}^{i^\circ} = 0.656 \cdot \Delta S_t^{i^\circ} + 0.034 \qquad (14.4)$$

where i° denotes the spatial resolution in degree, t denotes the month, x or ΔS_t^i is regressor (predictor), y or $GRACE_{t+2}^{i^\circ}$ is dependent (predictor), β_1 is slope and $\beta_\circ$ is the intercept of the linear regression equation.

- Manipulating ΔS0.25° with Eq. (14.1) by using P 0.25°, ET 0.25°, and SR 0.25° and then calculate GRACE SH-related TWS 0.25° from Eq. (14.4).
- In the downscaling process, removing system residual is an essential step. The results generated from Eq. (14.4) are subtracted from the system residual derived from the difference between GRACE TWSA 1° obtained from ΔS 1° and GRACE SH directly derived TWS 1°.

14.4   Implications from Grace Data Downscaling in Mehsana District, Gujarat

The results of downscaled high spatial resolution GRACE SH pixels ($0.25° \times 0.25°$) gets validated with the results procured from JPL mascon solution pixels ($0.5° \times 0.5°$) of GRACE and groundwell data from the Mehsana district (Fig. 14.1). This downscaled GRACE-derived GWSA (Fig. 14.2a) varies from -7.00 ± 5.00 to 45.00 ± 5.00 mm/year, and JPL mascon derived GWSA (Fig. 14.2c) varies from -80.00 ± 5.00 to -0.00 ± 5.00 mm/year. According to the distribution of both solutions, Mehsana district experiences groundwater depletion throughout the considered period. But downscaled GRACE SH-derived GWS distribution has exhibited detailed picture with respect to JPL mascon-derived GWS distribution. GRACE -derived TWS solutions consist of uncertainties due to inherent data errors and data leakage errors. Therefore, GRACE-derived GWS solutions include GRACE errors and error accumulated within the global land surface (GLDAS) model. Figure 14.2b and d represents two-dimensional maps of GWSA-related uncertainties of downscaled GRACE SH and JPL mascon, respectively. The maximum uncertainty accumulation of downscale GRACE SH derived-GWSA is ± 15.04 mm/year, and JPL Mascon-derived GWSA is ± 8.50 mm/year.

The research work carried out recently over Ahmedabad and Gandhinagar using integrated GRACE SH (Level 3) and GPS study exhibits the GWS depletion rate of -0.6 mm/year and deformation rate of -5.20 mm/year from 2009 to 2017 (Chopra et al. 2013). The current research values obtained from JPL mascon for GWS change are 5.71 ± 5.50 mm/year, -8.14 ± 5.50 mm/year and -1.43 ± 5.50 mm/year for 2003–2007, 2008–2013 and 2014–2019, respectively, which correlates very well with the GPS measurements of the previous work. Whereas for the same periods the downscaled GRACE SH pixels-derived GWS changing rates are -39.30 ± 7.04 mm/year, -80.2 ± 7.04 mm/year

and -104.91 ± 7.04 mm/year showing more enhanced measurements with respect to GPS, GRACE SH and JPL mascon (Table 14.2).

Based on early facts and history, GRACE solution doesn't share direct analogue with the ground-based values. Still, in recent research, it has been justified that GRACE solution does correlate with in situ well data, mainly over water-stressed regions in India (Sarkar et al. 2020). So, downscaled GRACE SH and JPL mascon-derived GWSA correlates with in situ well data-derived groundwater level change anomaly, across Mehsana district from 2005 to 2015. With respect to JPL mascon-derived GWSA, the downscaled GRACE SH-derived GWSA has shown great accord with groundwater level change anomaly along with the same upliftment and depletions (Fig. 14.3). But due to high temporal resolution of GRACE solution, it has not coincided with the real-time, and the upliftment or depletion observed by ground well data got detected one year later by GRACE. The same phenomena repeat the observations also for the low altitude areas (Ning et al. 2014). A possible cause is that in tropical regions precipitation is the most significant component for TWS change, and the combined effect of precipitation, evapotranspiration and surface runoff does not complete in a short period like GRACE temporal resolution (Fig. 14.3).

14.5   Conclusion

Though JPL mascon has provided the regional scale solution for TWS change, it is not sufficient to derive GWSA for water management scale studies. Effective downscaling of GRACE pixels enhanced sensitivity of the data, and those data have more capability to measure GWS change accurately for water management. The present study develops a model for the post-monsoon season of the 15 years based on linear statistical regression implication between GRACE SH obtained TWS and hydrological parameters derived TWS. The comprehensive studies about
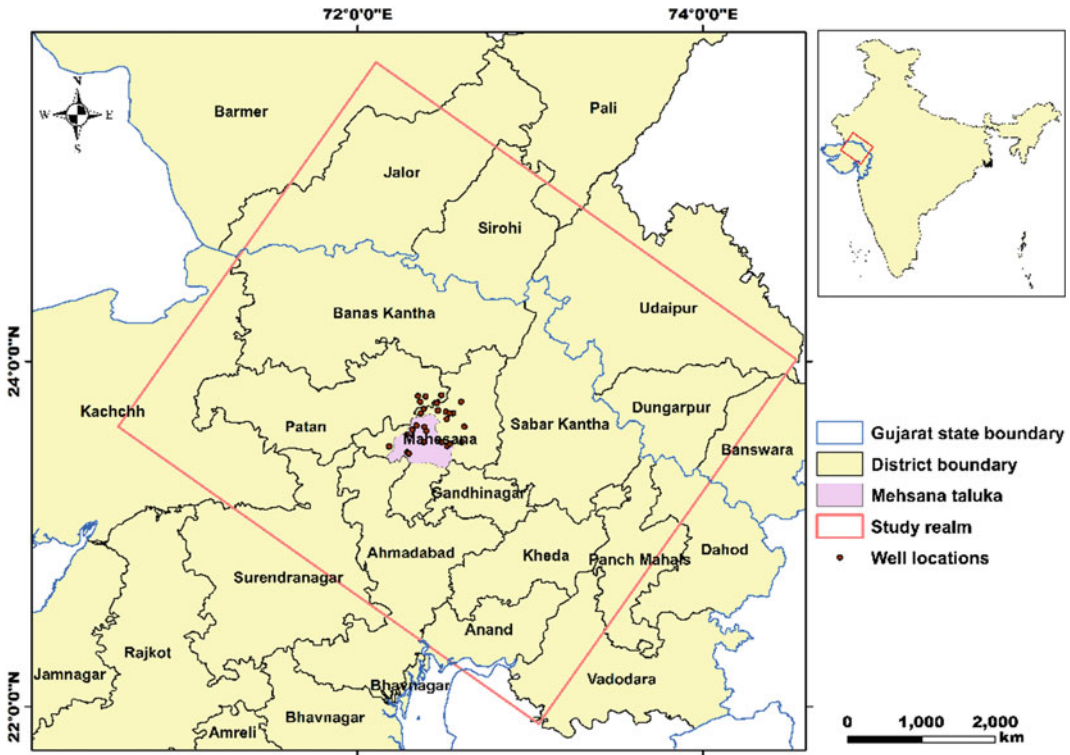
Fig. 14.1 The map represents the study realm (red rectangle) covering the Mehsana district, and a significant part of North Gujarat. (*Source* Authors Contribution)

Table 14.2 Downscaled GRACE SH and Mascon JPL manipulated groundwater storage change as flux and as quantity over Mehsana and surrounding districts

Time period	Trends as flux		Trends as storage	
	Downscale GRACE SH ± 7.04 mm/year	Mascon JPL ± 5.50 mm/year	Downscale GRACE SH ± 0.54 km³/year	Mascon JPL ± 0.43 km³/year
2003–2007	−39.38	−5.71	−3.05	−0.44
2008–2013	−80.22	−8.14	−6.22	−0.63
2014–2019	−104.91	−1.43	−8.13	−0.11

(*Source* GRACE data)

the capability of different GRACE solutions with the different basin sizes, climate, and intensity of usage of irrigation water had shown various merits with the mentioned variabilities. As an example, CSR mascon had shown higher uncertainty for large-scale basins with respect to JPL mass. Therefore, the current study has suggested innovating new downscaling models with different GRACE solutions based on different basin-scales, irrigation indexes and climate conditions.
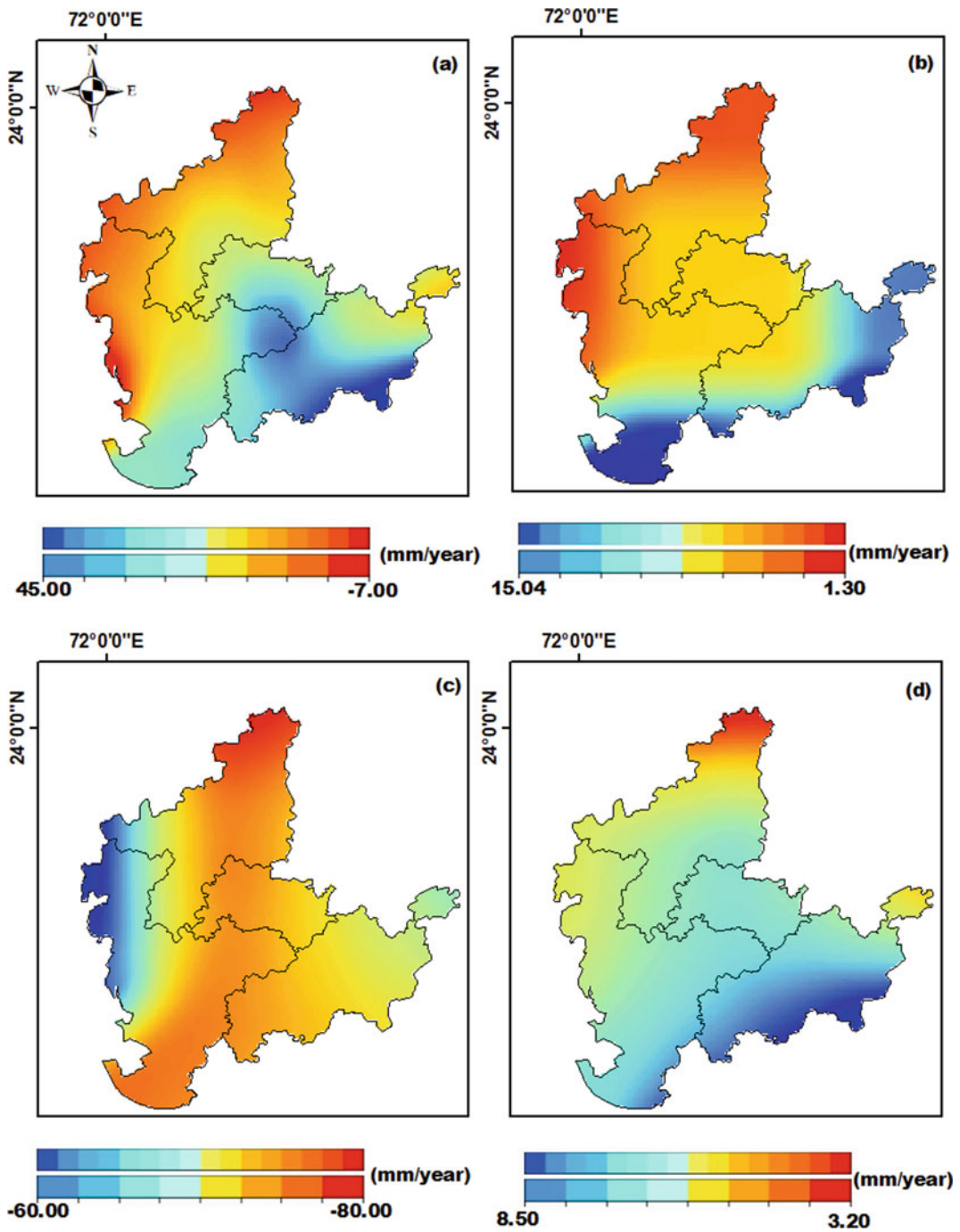
Fig. 14.2 a and **c** represents GWS change rate across Mehsana and surrounding districts in the post-monsoon season for a period of 2003–2019. **b** and **d** represents uncertainty distribution related to downscaling GRACE SH and JPL MASCON derived GWS change over the same area and the same period, respectively (*Source* GRACE data)
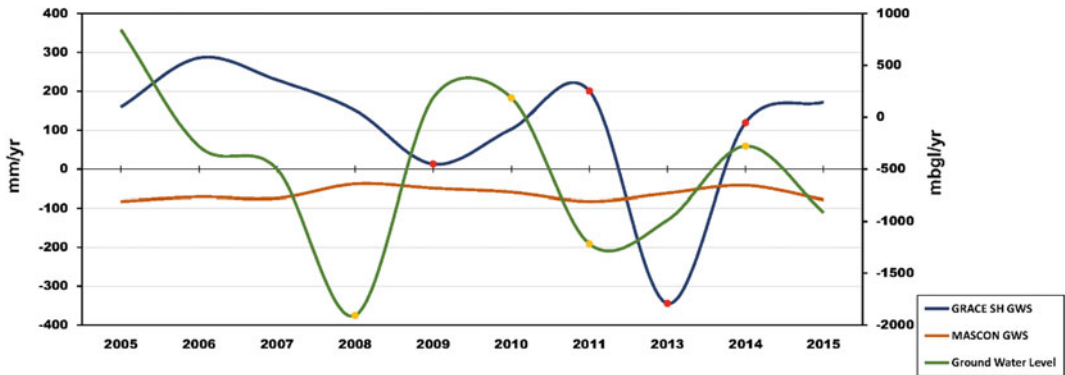
Fig. 14.3 It shows a correlation between different GWSA derived from downscaled GRACE SH solutions, JPL mascon solutions and the groundwater level change anomaly over Mehsana district during the post-monsoon period from 2005 to 2015. (*Source* GRACE data and CGWB India)

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