Space-based gravity data analysis for groundwater storage estimation in the Gangetic plain, India

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Monthly, seasonal and annual hydrologic signals obtained by Gravity Recovery and Climate Experiment (GRACE mission) satellites are analysed and compared with storage variables of soil moisture signatures of Monsoon Asia Integrated Regional Study (MAIRS) mission and groundwater level information of Central Ground Water Board, to observe depletion trends of groundwater in the Gangetic plain, at regional scale. While the seasonal time-series showed seasonality in the groundwater storage change, the annual trends depict a decline in this region. Further, the results showed that groundwater storage had declined at a rate 3.33 mm/month from 2005 to 2010. These time-series comparisons of storage variables have agreeable R^2 (coefficient of determination) and r (correlation coefficient) at various temporal cycles.

Keywords: Groundwater storage change, satellite missions, soil moisture, storage variables.

GRAVITY Recovery and Climate Experiment (GRACE) mission was initially launched in 2002 to study temporal gravity field and total water storage (TWS) dynamics of the Earth. Now as GRACE datasets are available for virtually every region of the world, there is a scope for use of these datasets in conjunction with hydrological models to improve upon the understanding of hydrodynamics at regional scale. The month-to-month gravity variations obtained from GRACE can be inverted for global estimates of vertically integrated terrestrial TWS with a spatial resolution of a few hundred kilometres, with higher accuracy at larger spatial scales[1,2]. The ability of GRACE to monitor TWS is significant because no observation network exists globally with the necessary temporal and spatial resolution, at regional scales and to further characterize groundwater storage (GWS) estimation[3,4]. However, the limitation of GRACE is that it detects gravity anomaly for large basins (~200,000 sq. km) with fair accuracy at a spatial resolution as small as 400 km (ref. 5). With an area less than 200,000 sq. km, the uncertainty in the estimates begins to be larger and affects the water storage signal[6,7].

In situ hydrologic measurements provide discrete sampling of the surface and subsurface run-off; whereas GRACE gravity observations provide a unique quantitative measurement of TWS and its changes that are otherwise not available to hydrologists by any other practical means. Using GRACE data, hydrologists are able to provide a quantitative estimate of totally integrated water mass changes over time. More recently, Longuevergne *et al.*[8] have developed a mass concentration algorithm called spatio spectral localization, to study the US High Plain aquifer which optimizes drainage basin shape descriptions, taking into account the limited spatial resolution and noise characteristics of GRACE. Rodell *et al.*[9] have demonstrated that GWS is fast depleting (mean rate of 4.0 ± 1.0 cm/year equivalent volume of 109 km^3 of water) in the northern states of India, namely Punjab, Haryana and Rajasthan due to intensive irrigation using GRACE gravity data over a period of 6 years during 2002–2008. Tiwari *et al.*[10] have shown GWS variations over southern India (Andhra Pradesh) using GRACE data and validated with ~950 water wells of Central Ground Water Board (CGWB). They used data till 2008 and compared TWS (volume) with water table fluctuations (height variation). Chinnasamy *et al.*[11] have shown the same by studying groundwater supply estimation in Gujarat.

The theory behind measuring GWS estimates from gravity is influenced by the generalized form of Newton's universal law of gravitation. Therefore, the total gravity signal with time is influenced by different sources of gravity variation. The gravity effect of tides, polar motion and the atmosphere is well known and these influences can be removed from the gravity signals. The remaining signal is considered to be largely influenced by hydrological mass variations.

Predictions of groundwater resource availability in India at finer resolution are problematic in most parts because of limited number of monitoring sites and insufficient data quality and quantity. Understanding of groundwater systems is complex as it is controlled by varied geological and geomorphologic factors that are difficult to quantify. The launch of the GRACE mission gives a new capability to observe TWS at broad spatial scales and finer temporal scales. TWS is an integrated change in mass of all components of the hydrological

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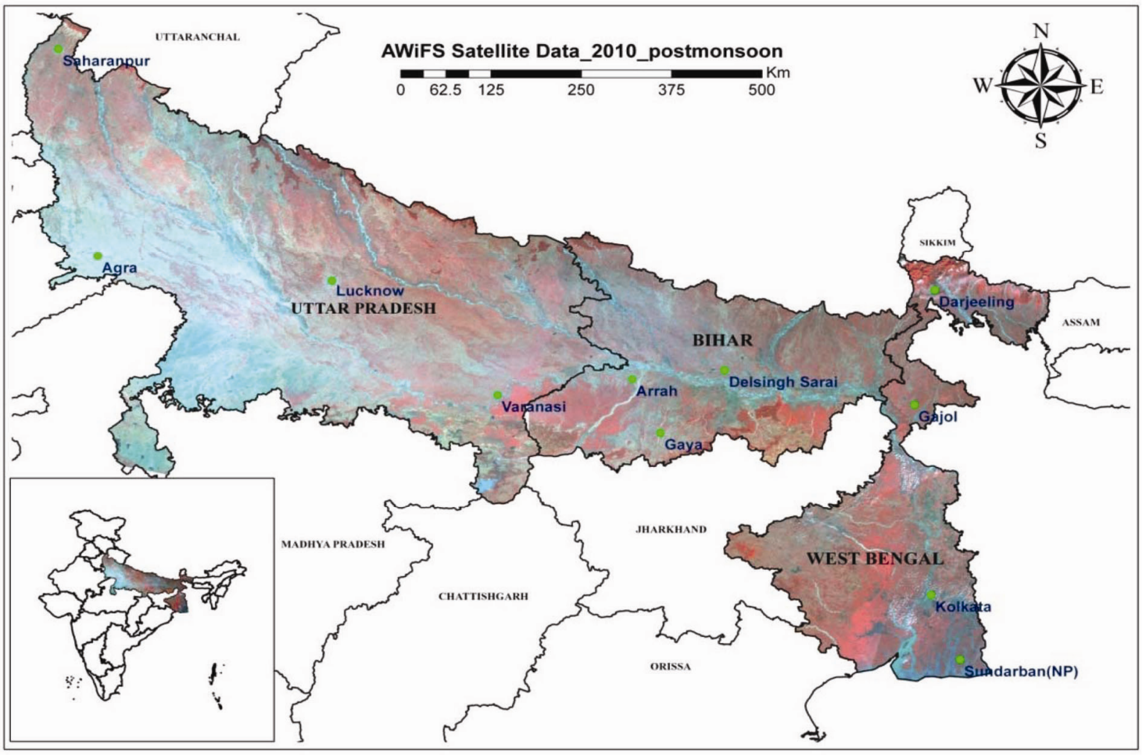


Figure 1. Study area – the Gangetic plain.

cycle, viz. storage of groundwater, soil moisture, canopy water, and ice and snow. Groundwater storage change (GWSC) has implications not only for the hydrological cycle, but also for sustainable water resource management.

The objective of the present study is to determine groundwater storage changes with time using TWS data, and also identify spatial trends as well as quantify temporal (monthly and seasonal and annual) patterns in GWS across three North Indian states in the Ganga plain. Given that geology, land use and climate differ vastly among different states in India, higher spatial, temporal and state-specific GWS estimates are necessary to advance understanding and improve groundwater management[11].

Study area

The study was conducted in the alluvial terrain of the Gangetic plain of India (Figure 1). TWS data of GRACE mission starting from 2005 to 2010 were used to derive water storage anomalies through time. The study area was selected based on the changes observed over time. Usage of groundwater is very high in the Ganga plains for agriculture and depletion of GWS affects agricultural production, which is evident from the land use and land cover (LULC) pattern observed over this time-period (Figure 2). The study area comprised of three North Indian states namely Uttar Pradesh (UP), Bihar and West Bengal (WB) comprising a total area of 430,978 sq. km. The average annual rainfall is around 1200 mm, mostly clustered during July–September. The area experiences a subtropical climate throughout the year. Average temperature ranges from 45°C (summer) to below 5°C (winter). December and January are the coldest months, while June and July are the hottest months. Average elevation is from 300 m (along the courses of the river in UP) to 0 m (near mean sea level in WB). Groundwater usage in this area is highly dynamic with intensive agriculture (double/triple crops) and high seasonal rainfall pattern.

Materials and methods

Water budget concept

TWS tends to be dominated by snow and ice in the polar and alpine regions, by soil moisture in mid-latitudes, and by surface water in wet, tropical regions[4,12]. A basic equation (eq. (1)) is formulated by explaining the components of TWS. The general explanation of change in TWS is

$$\Delta\text{TWS} = \Delta(\text{groundwater} + \text{soil moisture} + \text{surface water} + \text{wet biomass} + \text{snow and ice}). \quad (1)$$

For a particular environment one or more of these parameters can have an impact on TWS. For the present study area it is assumed that soil moisture and groundwater

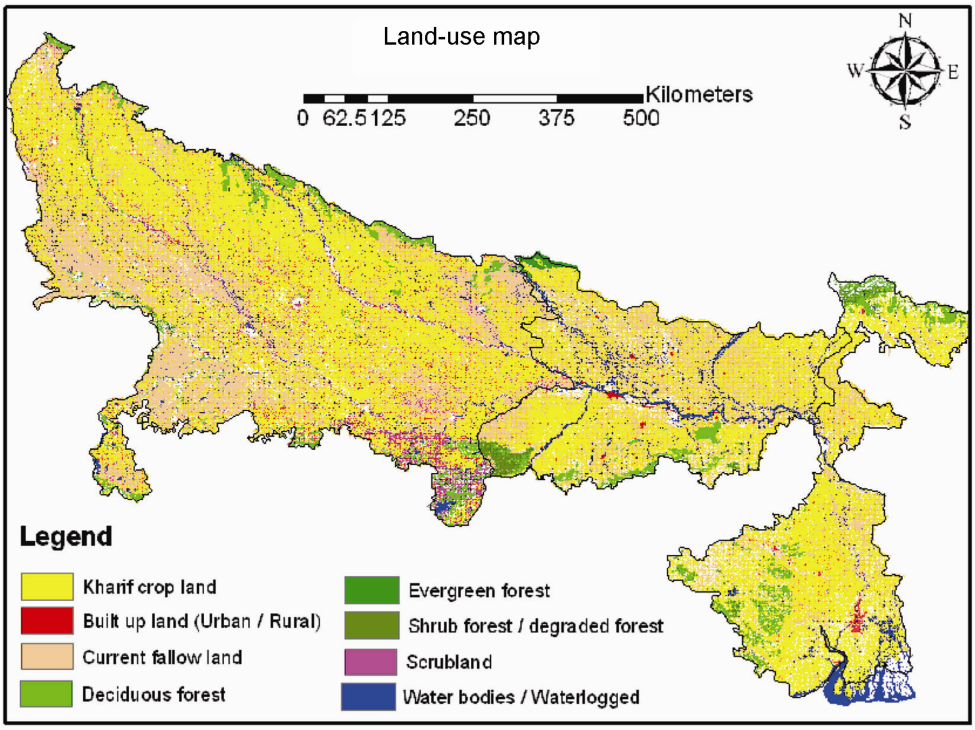


Figure 2. Land-use map showing present cropland distribution.

have more impact over TWS and in turn over GWS. This is because the region is primarily agriculture-based (*kharif* season crops) as derived from land-use map of the study area (Figure 2). Studies show that, in the mid latitudes the primary components of total water storage change (TWSC) at basin-scales are soil moisture storage change (SMSC) and GWSC[7–9,13,14]. Therefore, based on the present study area eq. (1) is modified suitably to exclude other parameters. Hence, the modified equation for the change of TWS is

$$\text{TWSC} = \text{SMSC} + \text{GWSC}. \tag{2}$$

Here, the storage terms in eq. (2) are spatial averages over the study area.

GRACE month-to-month gravity fields are inverted for TWSC, from which GWSC is computed[9]. GWSC is the residual storage content at a given time. Then GWSC is the difference between storage changes of any two successive time-steps[15]. Monsoon Asia Integrated Regional Study (MAIRS) soil moisture data are used to compute global estimates of soil moisture (SM), from which SMSC is computed.

Dataset used

1. GRACE monthly gravity anomaly solutions were computed from spherical harmonic (Stokes) coefficients (Figure 3 *a*) and were thereby prone to data leakage. During pre-processing of the data, a temporal mean is removed from each dataset and the monthly anomaly data derived are filtered using 500 km half-width Gaussian filtering for correlated N–S trending errors[1,16,17]. The fields are then spatially averaged over the study area from which TWSC is computed using an equation referred by Wahr *et al.*[18]

$$\Delta\text{TWS}(\lambda,\theta) = \frac{\rho_e R}{3}\sum_{n=0}^{\infty}\frac{2n+1}{1+k'_n}\sum_{m=0}^{n} P_{nm}(\cos\theta) \times (\Delta C_{nm}\cos(m\lambda) + \Delta S_{nm}\sin(m\lambda)), \tag{3}$$

where R is the equatorial Earth's radius (6,378,136.3 m), ρ_e average Earth's density (5517 kg/cm^3), k'_n load Love number of order n, which is again a constant, C_{nm} and S_{nm} are the spherical harmonic coefficients of degree n and order m. GRACE TWS data product (RL-05), used in this study, has been sourced from the Center for Space Research (CSR), University of Texas, Austin, USA. It constitutes significant improvements over its earlier releases[9] (viz. RL-04). The RL-05 de-stripped TWS products are available freely and in the form of time-series maps and ASCII files. The obtained values are stored in ASCII files of a simple three-column format, without a header (Figure 3 *b*) (ftp://podaac.jpl.nasa.gov/allData/grace/L2/CSR/RL05). Each line of a file contains information about one grid node

⟨Latitude⟩ ⟨longitude⟩ ⟨equivalent water layer thickness⟩.

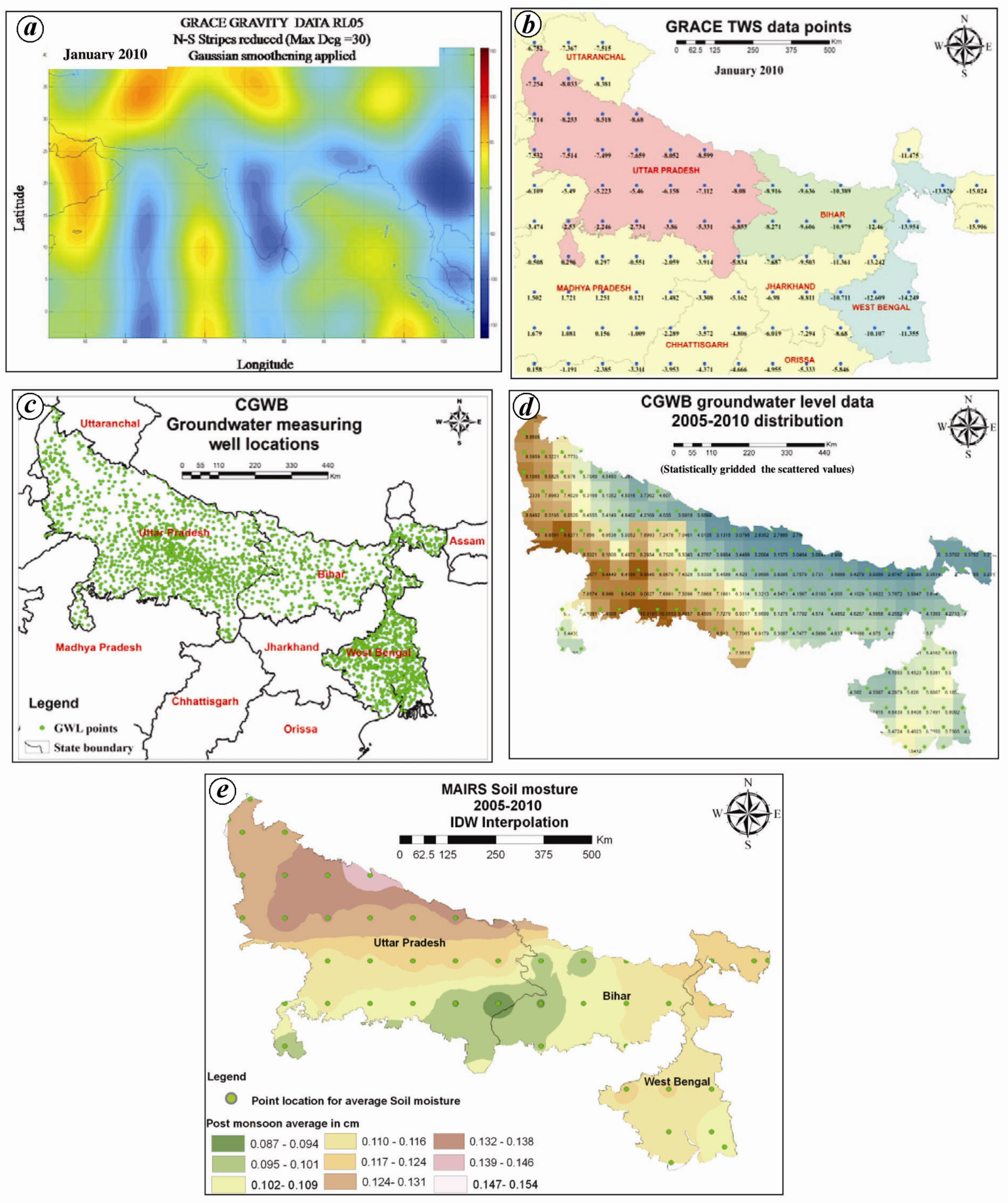


Figure 3. ***a***, Raw GRACE gravity data with Gaussian filtering; ***b***, Total water storage (TWS) output of GRACE; ***c***, CGWB well locations; ***d***, Statistically gridded values of groundwater level from CGWB wells; ***e***, MAIRS soil moisture data.

2. CGWB measures depth to groundwater level (GWL) data for approximately 2500 location points in pre- and post-monsoon periods (January, May, August and November) every year. These data have been taken and resampled statistically to gridded points (within 1° × 1° grid cell) using nearest neighbour statistical approach (Figure 3 *c* and *d*) to match with the gridded data of GRACE. Then the data are converted into the storage variable GWS by multiplying a standard specific yield component based on the terrain condition and lithology.

3. Land surface soil moisture observations (MAIRS) from Aqua satellite are used, which provides global

monthly soil moisture mean in gm/cm^3. The level-3 dataset used in this study contains mean monthly soil moisture statistics (average values and standard deviation) for 1° × 1° grid cells. The source for the data is MAIRS AMSR-E monthly (monthly average of a summation of daily data) estimates of soil moisture. The data used (Figure 3 *e*) in this study span from January 2005 to December 2010, same as the GRACE data of NASA (http://www.mairs-essp.org).

Error estimation

The coefficient of determination or R^2 is a measure of how well the regression line represents the data. The coefficient of determination is the ratio of the explained variation to the total variation. It is useful as it gives the proportion of the variance (fluctuation) of one variable that is predictable from the other variable. It is a measure that allows determining how certain one can be in making predictions from a certain model/graph. R^2 is measured for the GRACE-derived TWS, CGWB groundwater level and MAIRS soil moisture data through year/month and season. RMSE represents the sample standard deviation of the differences between predicted values and observed values. RMSE can be derived by subtracting the estimated values from the observed values considering the GWL data observed by CGWB and MAIRS AMSR-E soil moisture data.

Errors were reduced with averaging of TWS data, assuming that errors in the monthly TWS are not correlated[19] (because each monthly solution is processed separately). Based on the analyses, the average uncertainty/bias in the datasets is calculated using the following equation

$$\partial_N = \frac{\partial_i}{\sqrt{N}}, \tag{4}$$

where ∂_N is the estimated uncertainty in TWS averaged over N months and ∂_i is the estimated uncertainty in one month data. Using eq. (4) for seasonal (three-month) periods, estimated uncertainty bias in GRACE TWS is approximately 3 cm.

Methodology

GRACE monthly TWS datasets are available in the form of equal 1° × 1° regular grid shapes in ASCII format covering the whole globe. Each value represents the midpoint averaged over the grid. These regular global mass grids are masked with the coordinates encompassing the study area and stored using MS-Excel worksheets. The purpose of this masking is to remove the excessive unwanted data and to keep the regular grid shape just over the area of interest. The method of masking is applied for MAIRS state variables data which are also in 1° × 1° regular grid shapes. The grid points are converted into .dbf format and further to shape file, making it possible to use in Arc Map for further processing of the data. SRTM-DEM was downloaded for the study area from BHUVAN portal (NRSC, ISRO) and used to analyse the drainage system of the region. Additionally land-use maps of each state are taken from Land Resource Group at NRSC for assessing agriculture pattern in the study region. Finally these datasets are put in GIS environment for interpretation of controlling factors and for further analysis. The general methodology to carry out this study is shown in Figure 4.

Data analysis and results

The analysis is mainly divided into three parts. In the first part, a comparison is made between yearly trend and post-monsoon seasonal variation of TWS, CGWB groundwater level data and MAIRS soil moisture over six years of study (i.e. 2005–2010). In the second part, a time-series calculation is done on fluctuations observed in the changes observed in values of TWS, GWS data and soil moisture storage parameters. These time-series spans over five intervals (starting from 2005–06 to 2009–10) and show the trend in yearly and post-monsoon winter season (December–February) variations over time. The analysis will help us to see the variation in different storage components and how TWS from GRACE increases or decreases with the passage of time. Post-monsoon winter season maps for GRACE, CGWB groundwater level data and MAIRS soil moisture give the storage variations over different seasons within the basin and the shift of surface mass with each month. In the third and final part, few assumptions are made. The GWL data obtained from CGWB were statistically resampled and converted into GWS data and was added with the soil moisture storage. Then the combined product is compared with the GRACE-derived TWSC at seasonal and yearly scale. The multi-temporal cycle analysis is done not only for the purpose of comparisons, but also for multi-level decision-making and policy/strategy measures[9,20].

TWS spatial distribution

TWS maps derived from GRACE mission are analysed using inverse distance weighted (IDW) interpolation method for each month and segmented into pre- and post-monsoon seasons for six years (Figure 5 *a* and *b*). A general depletion trend is found in the eastern part of the Gangetic plain, primarily spreading over eastern UP, Bihar and WB (Figure 5 *a* and *b*). The values indicate that TWS is lesser in the study area during post-monsoon months (Figure 5 *b*). TWS variability depends on terrain

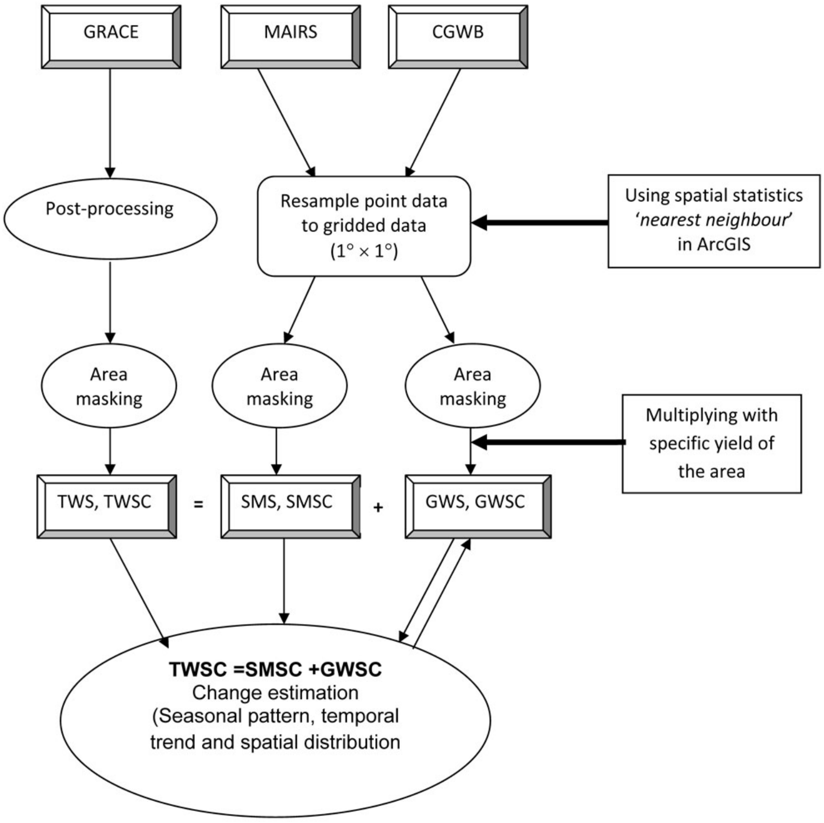


Figure 4. Flow chart showing methodology.

conditions[4,12]. TWS over land is not constant with time; it changes continuously with climatic variations. Based on this analysis we have found that the eastern part of the study area, i.e. lower reaches of the Ganga plain are suffering from a loss in TWS with time (Figure 5 *b*).

TWS trend analysis

Time-series analysis of soil moisture, GWL and TWS in the study area during 2005–2010 at seasonal and yearly cycles is shown in Figure 6. It is clear from the Figure 6 *b* and *d* that the post-monsoonal seasonal trends in both GWL and TWS are increasing with time. Similar to the seasonal trends, the yearly trends in TWS and GWL are also negative (Figure 6 *a* and *c*). On the contrary, the soil moisture patterns show decreasing trend yearly but increasing seasonal trend (Figure 6 *e* and *f*). R^2 values of TWS plots are high compared to the low R^2 values of GWL and soil moisture data.

Groundwater level fluctuation

The GWL data (measured in metres below ground level) obtained from CGWB mainly in two seasons, i.e. during pre-monsoon (January and May) and post-monsoon months (August and November) were analysed to understand the dynamics of GWL fluctuation. Figure 7 shows an overall declining trend of post-monsoon GWL in the study area.

Calculation of groundwater storage change

Depth to GWL was multiplied by aquifer specific yield (S_y) to get GWS anomaly, from which GWSC was computed[7]. In the present study the storage calculation was done assuming S_y of the Gangetic aquifer in unconfined condition as 0.25. This means that for 100 mm of storage volume loss, the water level is drawn down by 0.4 m (or 400 mm)[21]. The GWL response is in a way magnified by the aquifer

$$\text{Groundwater drawdown in unconfined aquifer (m)} = \frac{\text{Groundwater storage loss}}{\text{Specific yield}}. \quad (5)$$

Therefore,

$$\text{Groundwater storage loss} = \text{Groundwater drawdown in unconfined aquifer} \times \text{specific yield}. \quad (6)$$

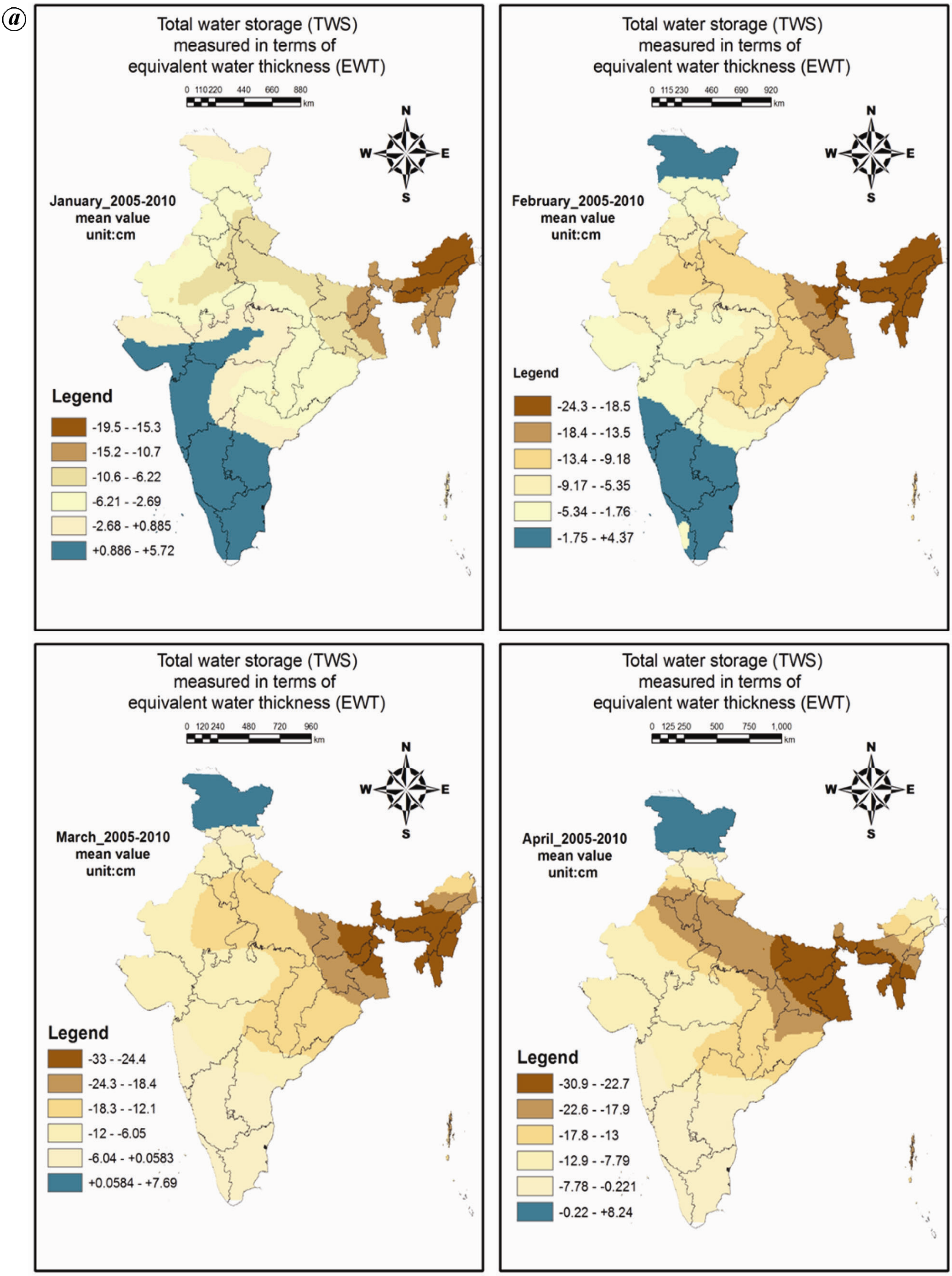


Figure 5 *a*. Total water storage change in pre-monsoon months.

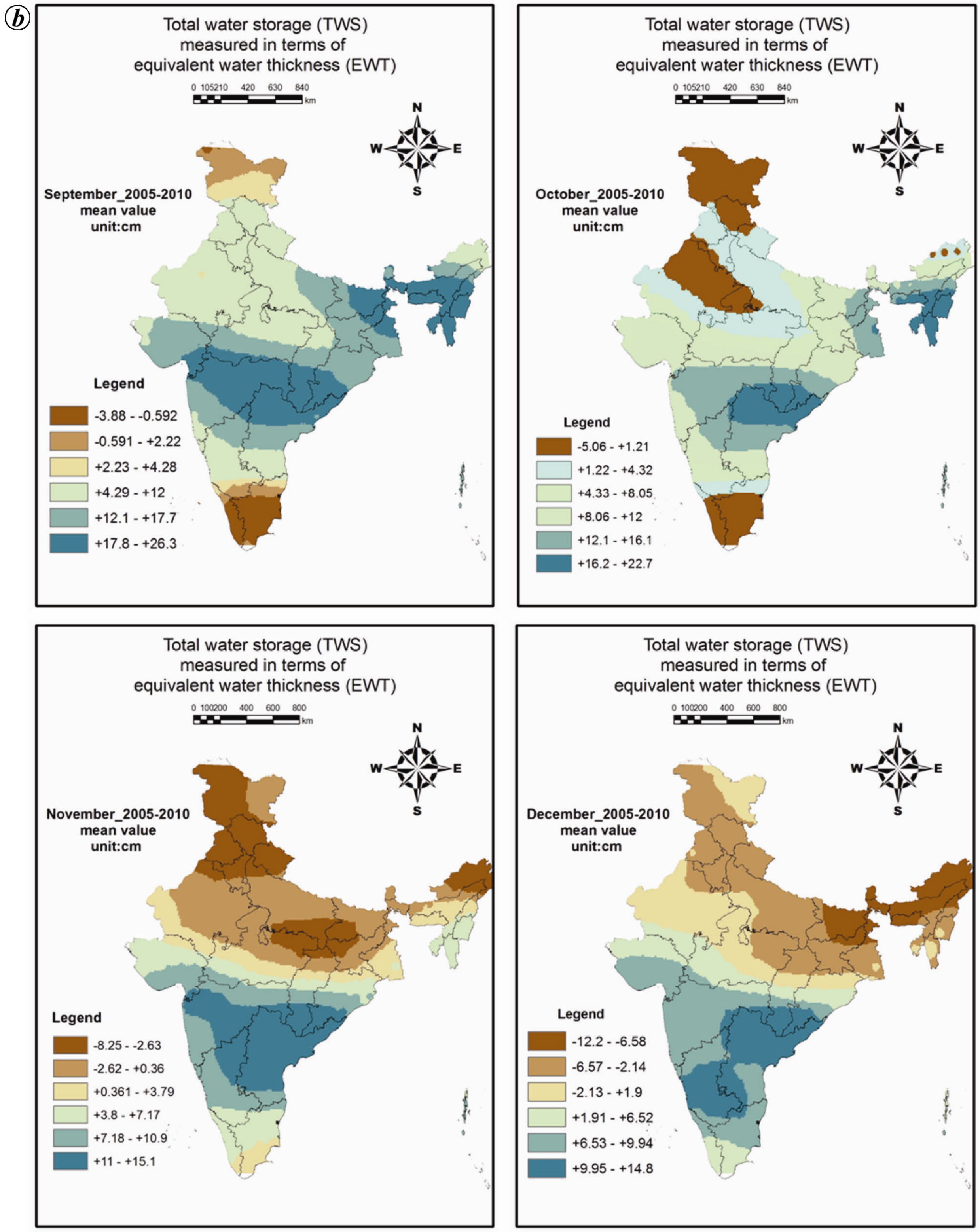


Figure 5 *b*. Total water storage change in post-monsoon months.

In Figure 7, the average trend in drawdown is shown to be 0.8 m in 5 years. So the average decline in storage (Figure 8 *b*) is 0.2 m in 5 years, i.e. 40 mm/year or 3.33 mm/month (approximately).

Storage change comparison

A time-series analysis was done with monitoring the patterns of SMSC, GWSC and TWSC in the study area at

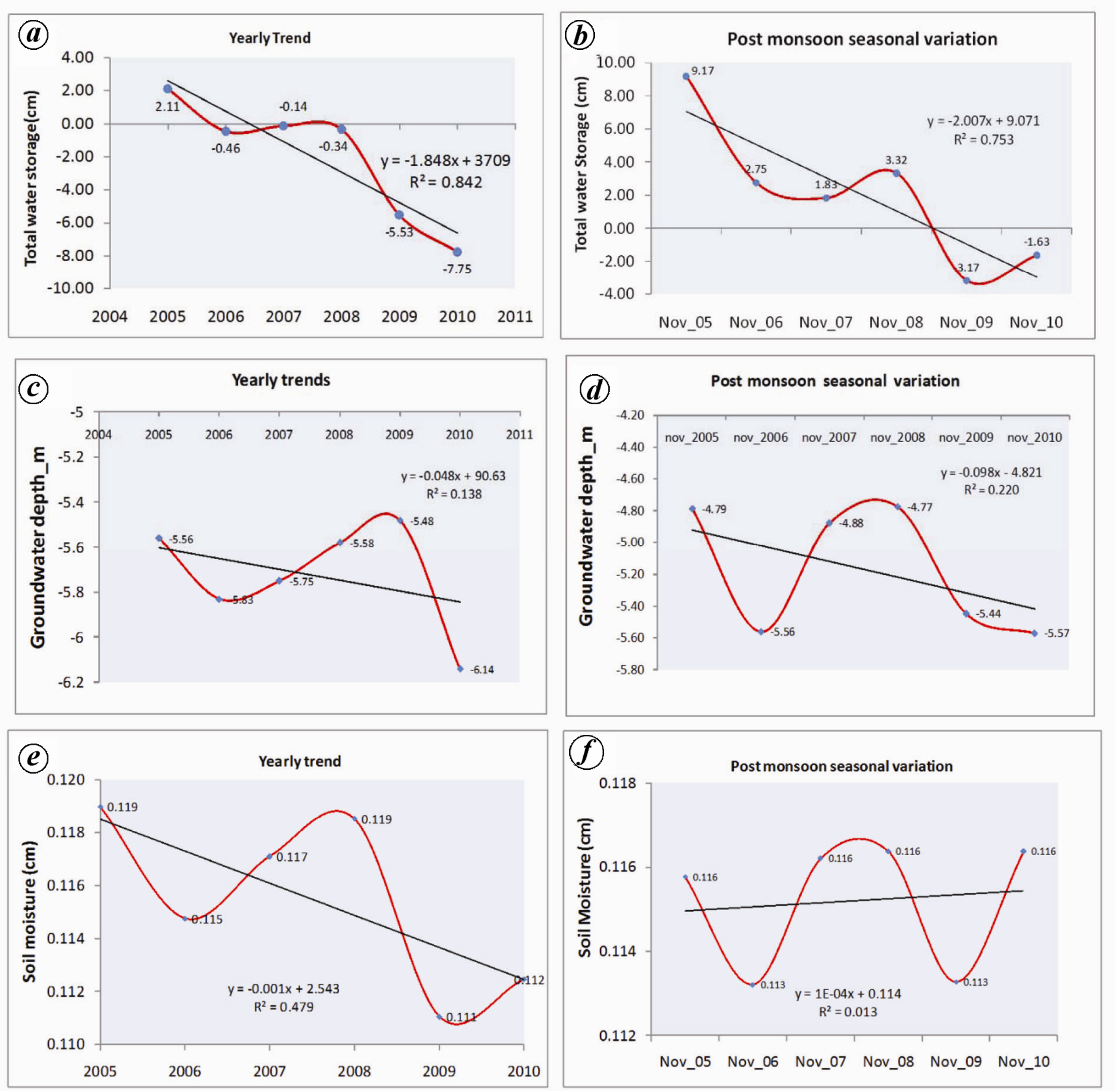


Figure 6. Plots of post-monsoonal seasonal (right) and yearly (left) trends in GRACE total water storage change (TWSC) (***a***, ***b***), Groundwater depth (***c***, ***d***) and soil moisture (***e***, ***f***), for 2005 to 2010 over the Gangetic plain.

seasonal and yearly cycles (Figure 9 *a* and *b*). The combined SMSC and GWSC was compared with the TWSC values, considering that TWS in this region is influenced by soil moisture and groundwater, eliminating the negligible component of surface storage mainly in ponds. It is observed that the trends match well with high correlation coefficient (*r*) values of 0.7 and 0.8 in seasonal and annual scale respectively (Figure 9 *a* and *b*). The seasonal as well as the annual trends in storage change show highest peak in 2009. However, the storage change is lowest in 2008 in annual scale, whereas it is lowest in 2007 in seasonal scale. The dynamics in the trend can be attributed to the seasonal influence of agro-hydrologic processes for this region.

Storage spatial distribution

Spatial distributions of linear trend maps of storage variables derived from the monthly soil moisture, groundwater and GRACE TWS maps from 2005 to 2010 are plotted in Figure 10. The average annual precipitation distribution in this time-span is sourced from monthly GPCP_RAIN_ACC.2.2 product of Tropical Rainfall Measuring (TRMM) mission of NASA (http://trmm.gsfc.nasa.gov/). Spatial interpolation of this accumulated rainfall data, measured in mm (2005–2010) shows increase in rainfall from west to east of the study area (Figure 10 *b*). The corresponding GRACE-derived TWS (Figure 10 *a*) is also increasing towards east but the soil moisture trend

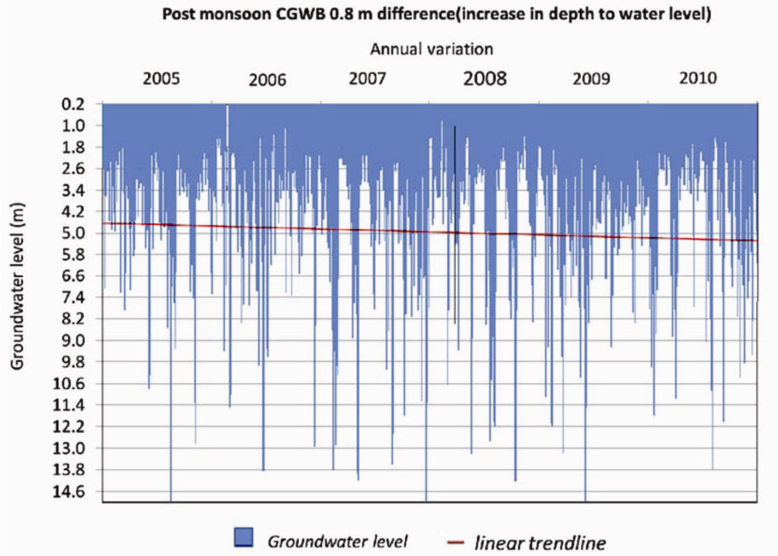
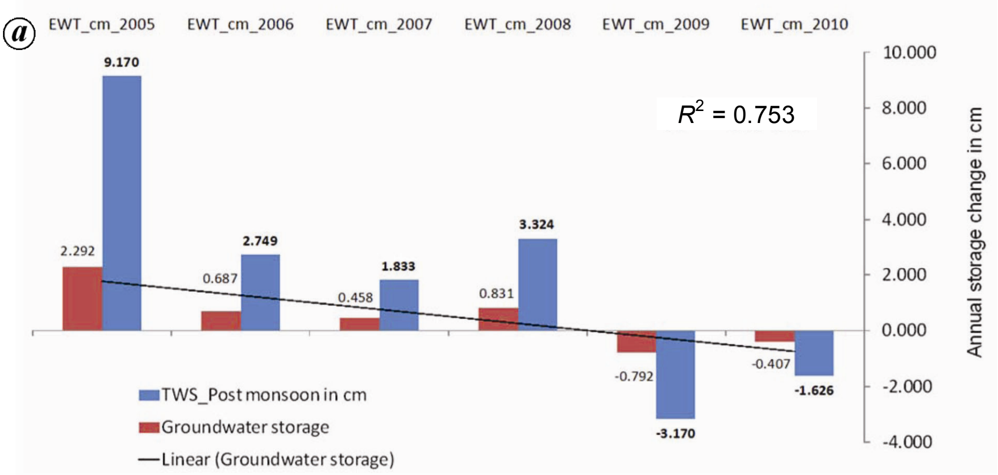


Figure 7. Change in groundwater level from 2005 to 2010; a drawdown of 0.8 m in post-monsoon season in the study area.



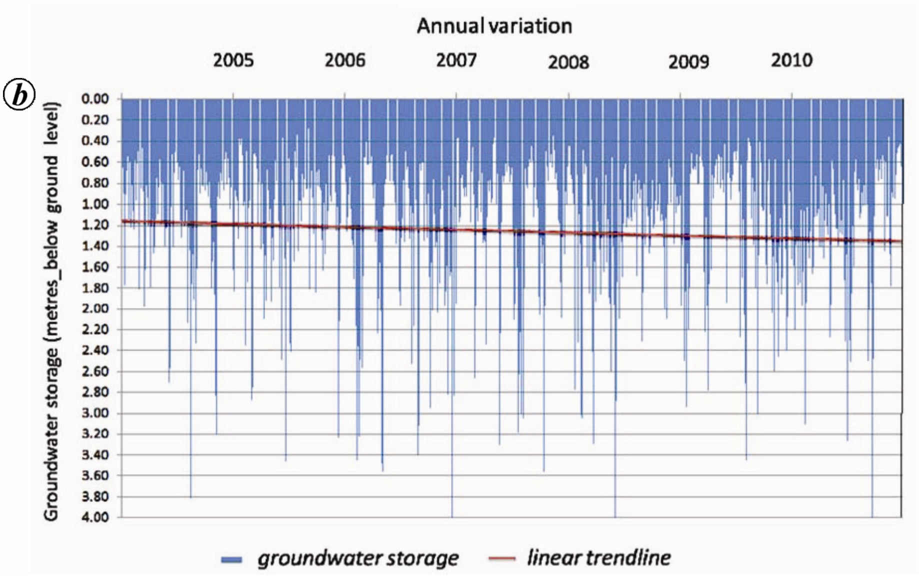


Figure 8. ***a***, Quantitative storage loss comparison with post monsoon TWS and groundwater storage (in cm). ***b***, Linear trend of storage loss calculated is of 0.40 mm/year, i.e. 3.33 mm/month.

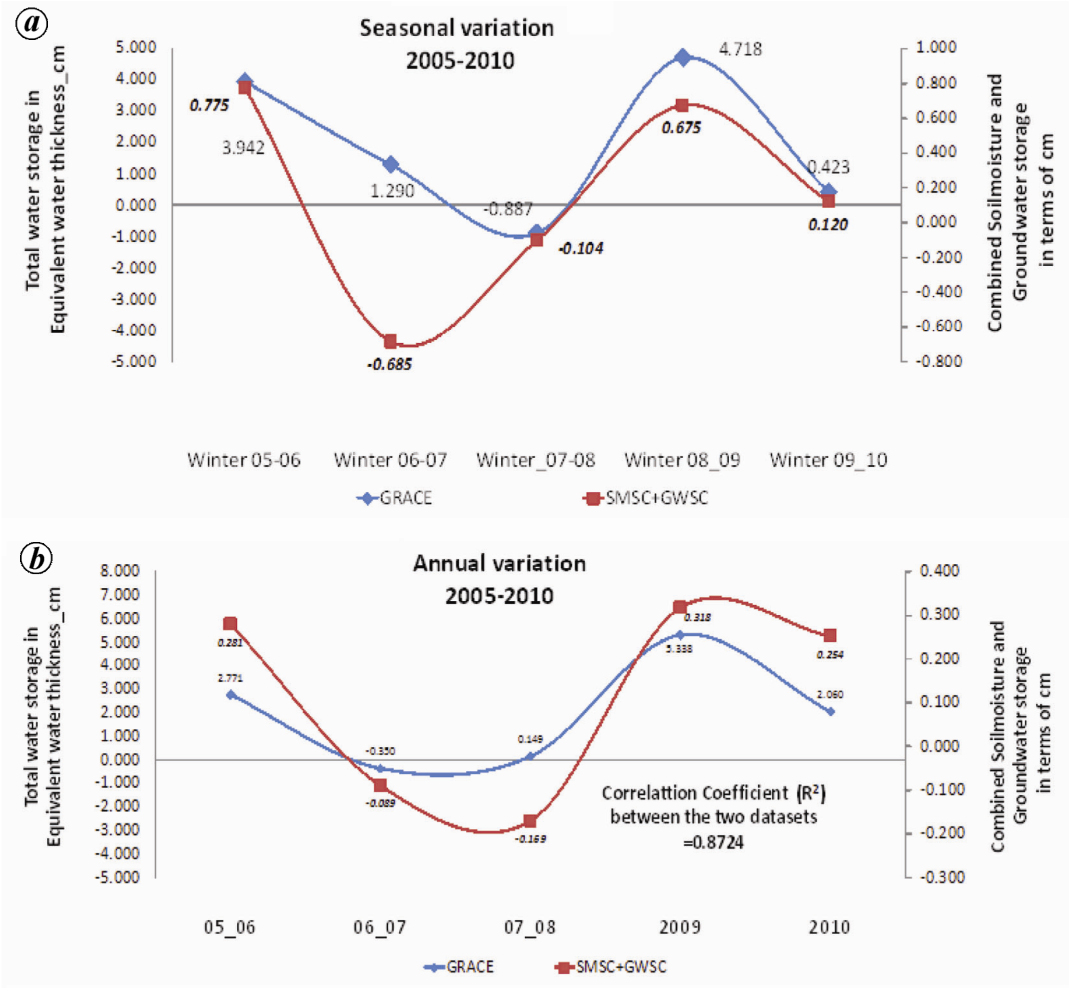


Figure 9. Time-series plot comparisons of TWSC derived from GRACE with that from combined soil moisture and groundwater storage (SMSC + GWSC) at (***a***) seasonal and (***b***) yearly scales.

(Figure 10 *d*), is more concentrated in the central region from the north through the south, and in patches to the west. High moisture zones are also apparent along the drainage courses. The GRACE storage trend not only suggests an overall storage loss, but also high storage loss regions of higher GWL depletion in the western part of the study area (Figure 10 *c*).

Discussion

The main hydrologic inputs in the study area are soil moisture and GWL that lead to an output of GWSC monitoring. The trends in the post-monsoon seasonal and yearly curves in Figure 6 *a* and *b* also confirm steady rate in TWS depletion. The trends in the post-monsoon seasonal and yearly curves of GWL and soil moisture level in Figure 6 *c–f* suggest depletion in these parameters as well. Interestingly, the post-monsoon seasonal trends of CGWB-derived GWS in Figure 8 *b* also suggests depletion with time. All the seasonal plots depict a clear seasonality of storage in the region. As intensive groundwater irrigation is the main mode of agriculture in the region (Figure 2), a probable gain in GWS could be indicative of agricultural water-saving, soil pore/aquifer compaction or merely noise in the dataset. Seasonal storage dynamics is equally critical for sustainable water resources management strategies in the study area. As outlier effects on data behaviour decrease at higher temporal and averaging levels, the yearly trends in Figures 6, 8 and 9 are more reflective of the storage dynamics, which indicates a general storage loss with time. Storage loss in the region could have negative implications for agriculture and the livelihood of people[22].

The spatial distributions in Figure 10 *a* (especially that of GRACE water storage) suggest overall TWS depletion in the region. Further analysis shows (Figure 8 *b*) that average storage depletion in the study area is 40 mm/year (3.33 mm/month), following the eq. (5). This finding could negatively impact the fragile semi-tropical region that not only depends on groundwater discharge, but also recharge of the groundwater system[22]. For the restoration, preservation and sustainability of the region, it is critical

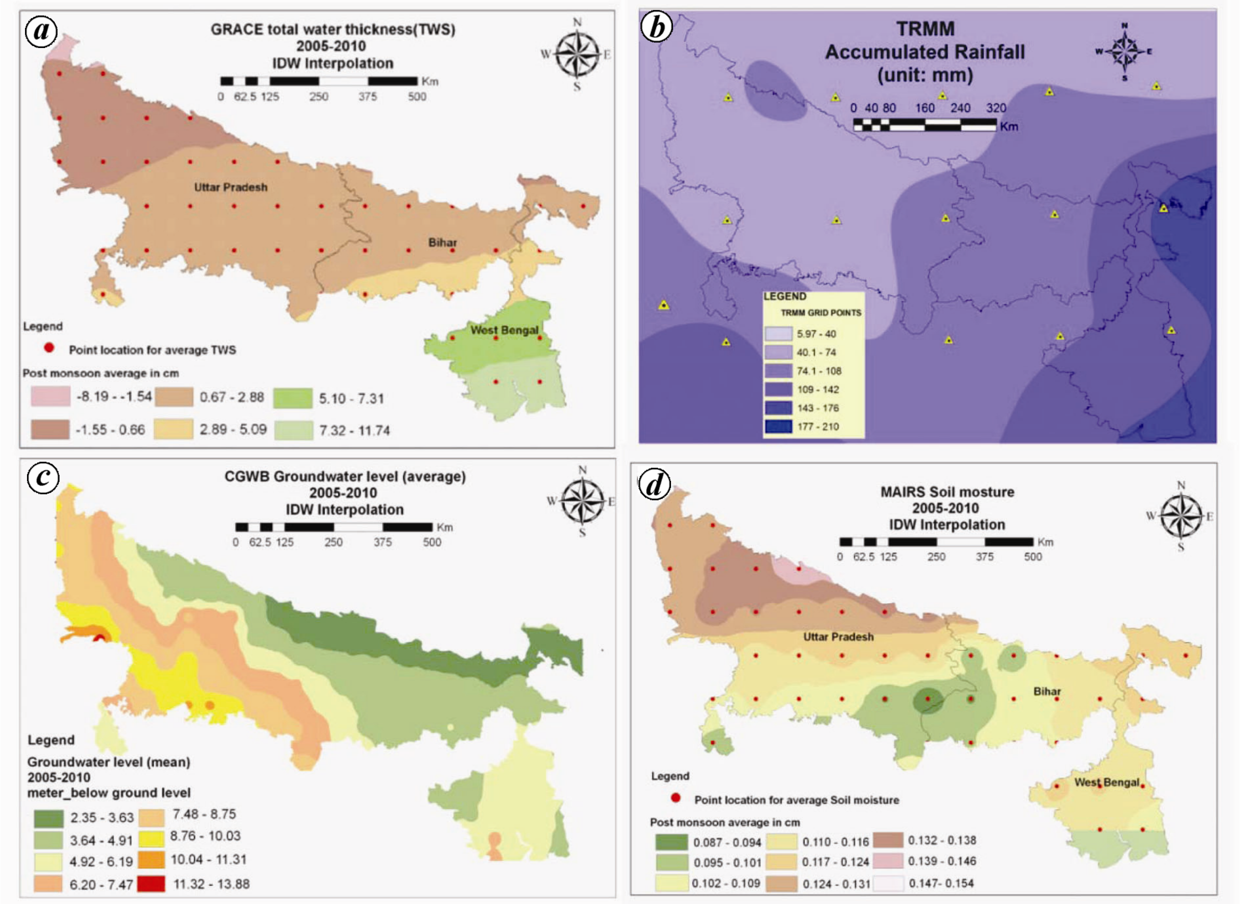


Figure 10. Plots of spatial distribution of (***a***) average annual TWS, (***b***) TRMM accumulated rainfall, (***c***) linear trend maps of groundwater level, (***d***) linear trends of soil moisture for 2005–2010 in the Ganga plain.

to develop water resources management strategies that limit groundwater extraction rates to recharge rate. The favourable comparisons of TWS in Figure 9 at two different temporal scales suggest that GRACE sufficiently detects storage signal in the study area.

Conclusions

In this study, GWS in the Ganga plain has been analysed for 2005–2010 using GRACE TWS, MAIRS SMS and CGWB measured GWL data products. The results were compared at seasonal and yearly cycles, all of which showed favourable agreement in the trend (Figure 9). The results presented at the spatial and various temporal scales allowed not only comparisons, but also the development of parallel water resources management policies/strategies in the region. Over 80% of the amplitudes of the monthly storage change were within 40 mm/year, showing a trend in average magnitude of storage fluctuation in the study area. While the seasonal time-series showed a clear seasonality of storage change in the region, the yearly trends clearly depicted storage loss. The average monthly trends showed that storage was highest in summer and lowest in autumn months. This implies that GRACE satellite gravity data are relatively cost-effective and can be used as a regional-scale groundwater assessment tool[11]. The method is viable when coupled to available recorded groundwater data to understand the groundwater hydrologic regime in many global regions. Land-use map compared with TWS maps suggests that water storage in the region occurs mainly in soil moisture and groundwater. In other words, the assumptions in eq. (2) hold true for the study area. It then implies that in the region, sustainable water resources management strategies should largely focus on optimizing soil moisture and GWS. Hence, for alluvial terrain of India, TWS maps alone can be used to delineate the zone of depletion and these zones are primarily caused by groundwater depletion.

Based on this decision-makers/stakeholders of water resources in the region should focus on water-saving measures on the monthly basis and calculating storage loss. This comprehensive approach ensures the preservation and sustainability of water resources which will, in turn, ensure a sustained livelihood for the millions of people in the region and beyond.

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ACKNOWLEDGEMENTS. This study is fully supported by Hydrogeology Group, NRSC, Hyderabad and its RGNDWM mission sponsored by the Ministry of Drinking Water and Sanitation, Government of India. We thank CGWB, Hyderabad for sharing the information of water level fluctuations. We also thank the Land Resource Group for providing Land-use maps and BHUVAN Web portal for providing SRTM DEM elevation layer respectively, for the study area. We also thank an anonymous reviewer for comments on the manuscript.

Received 14 August 2013; revised accepted 18 May 2014