GRACE and GRACE Follow On: On Accurate estimation of Groundwater Storage Change from Satellite Gravimetry and Beyond

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Keywords: Terrestrial water storage (TWS), Groundwater Storage, GRACE, Downscaled TWS, Ganga Basin

Abstract

The present work focused on the synergistic utilization of Gravity Recovery and Climate Experiment (GRACE) and GRACE-Follow On (FO) derived Ensemble Terrestrial Water Storage Anomaly (TWSA) from Jet Propulsion Lab (JPL), Centre for Space Research (CSR) and Goddard Space Flight Centre (GSFC), downscaled (GOU) TWSA and a gap filled JPL TWSA data and other hydrological variables to assess variability in groundwater storage (GWS) change in the last two decades (2002-2022) over Indus and Ganga river basins. The Indus basin witnessed a significant decline with a rate of change between -2.11 to -3.0 cm/yr and Ganga basin witnessed a significant decline of -1.27 cm/yr to -1.88 cm/yr after removing soil moisture estimates respectively. GWSA obtained from downscaled TWSA also indicated a significant negative trend. However, the magnitude of trend was considerably lower (0.9 cm/yr) than the ensemble (-1.27 cm/yr) and gap filled (-1.88 cm/yr) datasets. Ground observations also indicated a decline in GWSA in the Ganga basin with a rate of change -0.26 cm/yr. Validation of results with in-situ well data showed highest positive correlation (R = 0.78) and least Root Mean Squared Error (RMSE = 17.5 cm) with in-situ GWSA in the Indus basin during 2002-2022. Downscaling of GRACE TWSA employing self-supervised data assimilation can significantly reduce the general overestimation of trends in GWSA computed from GRACE and GRACE FO observations.

1. Introduction

Groundwater is a vital freshwater resource, accounting for 30% of the world’s freshwater and 2.5% of the total water stored on Earth (Richey et al., 2015). Groundwater covers 30% of the global irrigation water demand crucial for sustaining the food and water security (Zektser and Everett, 2004). Accurate monitoring of changes in global groundwater resources, thus becomes imperative to mitigate the effects of rise in freshwater demand. Due to the complex nature of global aquifers and unavailability of dense network of direct measurements, it is difficult to track the long-term changes in global and regional groundwater availability (Rodell et al., 2018; Dangar et al., 2021). A major leap in groundwater storage change detection came after the launch of Gravity Recovery and Climate Experiment (GRACE) mission in 2002 that led to the time-resolved gravimetric measurement of groundwater storage (GWS) from space (Tapley et al., 2019). GWS is estimated by integrating Terrestrial Water Storage (TWS) from GRACE and hydrological observations (soil moisture, canopy water, snow water equivalent and surface water) from satellite/model observations into the water balance residual approach (Getirana et al., 2025; Rodell et al., 2004a; Chen et al., 2022).
GRACE observations have been successfully utilized to monitor groundwater changes in major aquifer systems of the world (Long et al., 2016; Famiglietti et al., 2011; Bhanja et al., 2020; Tapley et al., 2019). GWS observed from GRACE dataset indicated a deline in 13 out of the 37 major aquifers (Famiglietti et al., 2011). Richey et al. (2015) observed that GRACE can capture the groundwater withdrawal and natural variability in major aquifer systems accurately. Frappart and Ramillien (2018) have comprehensively reviewed the measurement of groundwater storage from GRACE observations and described different approaches to estimate the changes in groundwater from GRACE TWS estimates. Similarly, various studies have employed GRACE observations to study the groundwater storage change dynamics over the Indian-Subcontinent (Bhanja et al., 2016; Dharpure et al., 2025; Kinouchi et al., 2021; Banerjee and Kumar, 2018; Shamsudduha et al., 2012; Rodell et al., 2004a). Utilizing GRACE and model observations, Tiwari et al. (2009) observed a persistent decline in north-west India (54±9 km^3 per year). Rodell et al. (2004a) also observed groundwater storage decline over northwest India and reported that unsustainable groundwater abstraction was the major cause of persistent groundwater decline. Banerjee and Kumar (2018) inferred that an increase in groundwater in river basins along southern peninsula was due to the recovery from drought and inter-annual variability in rainfall where unsustainable groundwater abstraction is not prominent. Asoka and Mishra (2020) opined that a significant variability in GRACE TWS can be explained based on groundwater storage anomaly and anthropogenic groundwater abstraction. GRACE GRACE-FO mission has been particularly successful over the Indian subcontinent where in-situ observations to validate the groundwater storage variations are available.
GRACE based groundwater storage significantly depends upon the TWS product utilized as TWS estimates from Jet Propulsion Lab (JPL), Centre for Space Research (CSR) and Goddard Space Flight Center (GSFC) results in differential trends across basins with complex hydrology and climate owing to geophysical models, parameterization and spatial constraints (Scanlon et al., 2016; Ferreira et al., 2016; Gao et al., 2023; Loomis et

al., 2019). Further, soil moisture input also plays a significant role in accurate groundwater storage detection from the mass balance residual approach (Kalu et al., 2025; Park et al., 2025; Getirana et al., 2025). Other challenge of utilizing GRACE-GRACE FO dataset to compute GWS is the temporal discontinuity in TWS time series. In-situ validation of GRACE derived GWSA is often challenging as ground observations lack spatial homogeneity and often indicate groundwater change in shallow aquifers (Bhanja et al., 2016; Dangar et al., 2021). To address the limitations and challenges, the present work aims to (1) Compute an ensemble TWSA dataset using the Generalized three cornered hat method (2) Compute a gap-filled TWSA using seasonal time series decomposition and climate driven TWS. (3) Estimate long-term groundwater storage change using the ensembled, gap-filled and downscaled TWSA from Gou and Soja (2024) and upper zone soil moisture from satellite observation. (4) Validate the obtained GWSA against a dense network of ground based water level and specific yield information.

2. Data and Methods

2.1 Study Area

Long-term changes in terrestrial water storage and groundwater storage change was analyzed over the Indus and Ganga river basins in the Indian subcontinent. Figure 1 represents the geographical location of the river basins and wells used to compute in-situ groundwater storage trends for the two basins respectively. The Indus River catchment area in India covers approximately 321,289 sq. km while the Ganga basin is the largest Indian river basin, with a total catchment area of 8,61,404 sq. km (India-Water Resource Information System). Indus and Ganga basin along north and north-western India are characterized by below average rainfall during Indian Summer Monsoon. The basins are known for intensive irrigation and the demand for water is met by unsustainable groundwater abstraction (Dharpure et al., 2025; Shamsudduha et al., 2012). After the pre-processing and subsequent quality control algorithm, we obtained 166 well in the Indus basin and 1141 wells in the Ganga basin to compute in-situ groundwater storage anomaly (IGWSA).

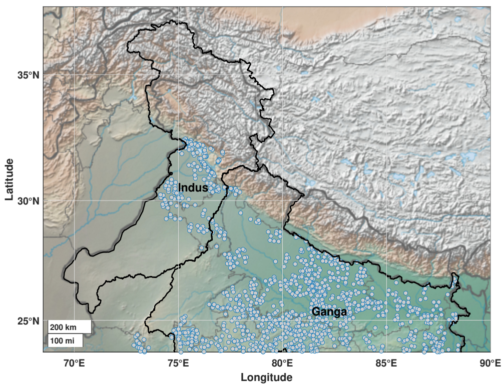

Figure 1. Geographical location of the Indus and Ganga Basin. Dots represents the wells used to compute in-situ groundwater storage anomaly over the basins.

2.2 Datasets

To study the variability in terrestrial water storage and estimate groundwater storage change, we computed an Ensemble TWSA dataset utilizing three monthly mass concentration block (mascon) solutions. The monthly mascon solution (JPL RL06.1Mv03) from GRACE and GRACE-FO with Coastal Resolution Improvement (CRI) was obtained from the Jet Propulsion Laboratory (Wiese et al., 2016). The dataset consists of monthly global mass change fields derived from the GRACE (2002–2017) and GRACE-FO (2018–present) satellite missions, processed using the Mascon (mass concentration) approach. The Monthly mass anomaly grids from GRACE and GRACE-FO retrieved from CSR RL06.2 processing (RL0603M) were obtained from the Center for Space Research (Save et al., 2016). The dataset is distributed at a 0.25° x 0.25° grid resolution, equivalent to a 1° × 1° geodesic grid at the equator and the anomalies represent changes in total water storage relative to long-term mean (Save et al., 2016). We further utilized the monthly gravity solution from GRACE and GRACE FO provided by the Goddard Space Flight Center (GSFC RL06 v2.0 mascon solution). The mascon solution is available at 0.5° grid; however, the native resolution of the data is 1-arc-degree equal-area mascon (Loomis et al., 2019). The most profound limitation of GRACE dataset is the relatively coarse spatial resolution (300 km) due to the smoothing and filtering required to reduce noise in the gravity solutions. To address the limitation of coarse resolution and investigate the efficacy of GRACE downscaling, the study utilized a Global High-Resolution TWSA from Self-Supervised Data Assimilation Using Deep Learning data product developed to provide much higher spatial detail than traditional GRACE/GRACE-FO products by combining satellite gravimetry with model information through machine learning (Gou and Soja, 2024). For this study, we used the Combined v09.1 soil moisture dataset generated by merging the active microwave based and passive microwave-based sensors provided by the European Space Agency under the Climate Change Initiative (Dorigo et al., 2017). To validate the Groundwater Storage Anomaly (GWSA) obtained from multiple satellite and model-based observations, we used in-situ well observations from the Central Groundwater Board (CGWB) (CGWB, 2023). CGWB monitors groundwater levels at stations spread across India, four times in a year during the months of January, May, August, and November (CGWB, 2023). Finally, canopy water and snow water equivalent dataset were obtained from the Global Land Data Assimilation System (GLDAS) that generates products of changes in land surface fields and fluxes like soil moisture, evapotranspiration and temperature by integrating satellite and ground-based observations using advanced land surface modeling and assimilation techniques (Wang et al., 2016).

2.3 Methodology

To compute an ensemble TWSA dataset, we used the generalized three cornered hat (GTCH) method that computes the error variance in in JPL, CSR, and GSFC solutions (Ferreira et al., 2016; Kinouchi et al., 2021). The estimated weights computed from the inverse-variance of the errors are combined optimally to obtain a combined TWSA dataset (hereafter referred to as EN). The GTCH method can be expressed as

$$\mathrm{TWSA}^t_{\text{Ensemble}} = \sum_{j=1}^{3} w^t_j \, \mathrm{TWSA}^t_j \tag{1}$$

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$$w_j = \frac{\frac{1}{\text{var}(r_j)}}{\sum_{j=1}^{3} \frac{1}{\text{var}(r_j)}} \tag{2}$$

where w_j = weight of the TWSA dataset
r = relative uncertainty in each dataset
$var(r_i)$ = variance of r_i

Eleven months of discontinuity in GRACE derived TWSA limits its application in hydrological studies that require long term time series data. To address the issue, we adopted the methodology proposed by (Yang et al., 2021) to fill the gaps in GRACE and GRACE-FO TWSA and compute a continuous TWSA time series dataset over India. Instead of linear decomposition, we decomposed the TWSA datasets using the seasonal time series decomposition using the Loess (STL) method. In general, the methodology combines the long-term trend component from GRACE/GRACE-FO TWSA and the de-trended and de-seasonal TWSA from the climate driven reconstructed TWSA by Humphrey and Gudmundsson (2019) to reconstruct long-term TWSA time series. The reconstruction of TWSA can be expressed as

$$TWSA_{\text{gap-filled}} = GRACE_{\text{long-term}} + HGD_{\text{total}} - HGD_{\text{long-term}} \tag{3}$$

$$HGD_{\text{total}} = HGD_{\text{reconstructed}} + GRACE_{\text{seasonal}} \tag{4}$$

where HGD refers to the Humphrey and Gudmundsson climate driven TWSA dataset. We estimated Groundwater Storage Anomaly (GWSA) by subtracting modeled and satellite derived hydrological components from the GRACE TWSA following the expression

$$GWSA_{GRACE} = TWSA - SMA - CWS - SWE \tag{5}$$

where SMA = soil moisture anomaly
CWS = canopy water storage
SWE = snow water equivalent

To compute anomalies of other water balance components, we used the same reference period as GRACE TWSA i.e. 2004-2009. To compute in-situ groundwater storage, groundwater level data for each station was multiplied by its specific yield value obtained (Kuruva et al., 2025)

$$GWSA_{in-situ} = GWLA \times specificyield \tag{6}$$

where $GWLA$ = groundwater level anomaly

is expressed as

$$GWLA = GWL - mean(GWL_{2004-2009}) \tag{7}$$

3. Results and Discussion

3.1 Evaluation of Terrestrial water storage change

To explain the variability in TWSA over the Indus and Ganga basin, long-term changes in TWSA derived from Ensemble, GOU and GF-JPL were analyzed. Figure 2 exhibits temporal variability in TWSA along Indus and Ganga basin obtained from the three TWSA datasets. It was inferred that the three datasets showed similar distribution in TWSA between 2002-2022 for both the basins indicating that the gap-filled TWSA and downscaled TWSA from Gou and Soja (2024) accurately captures long-term changes in TWSA. It was observed that GOU TWSA indicated moderate decline for Ganga (-1.11 cm/year) and Indus basin (-1.79 cm/year) in comparison to EN (-1.69 cm/yr and -2.24 cm/yr) and GF (-2.02 cm/yr and -1.90 cm/yr) respectively, particularly after 2018 over the Ganga basin while EN and GF TWSA portrayed a consistent decrease during 2002-2022. TWSA from GRACE and GRACE-FO are characterized by difference in geophysical models and constraints, catchment area and hydro climatic regime of the basins studied. Independent processing of GRACE and GRACE-FO gravity fields using different geophysical models, parameterization and filtering methodologies by multiple centers (JPL, CSR, GSFC) results in variable TWSA trends across basins characterized by diverse hydrological regime (Save et al., 2016; Scanlon et al., 2016).

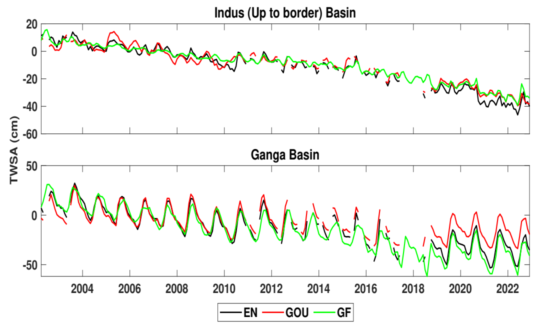

Figure 2. Temporal variability in TWSA computed from Ensemble, Gou and gap-filled data over Indus and Ganga basin

Investigating the differences in multiple GRACE solutions is crucial to assessing the advantages and limitations of the datasets crucial for hydrological applications. An important aspect of uncertainties in TWSA is the spatial resolution and basin scale dependencies (Ferreira et al., 2023). The uncertainty is related to mean latitude, linear trends in TWSA and annual oscillations. Basins with higher water vapor exchange and higher annual rate of change in TWSA captures more noise. The uncertainties arise mainly due to the downscaling methodology, GTCH ensemble reconstruction and the complex hydro-climatic regime of Indian river basins characterized by significant anthropogenic influence.

3.2 Spatio-temporal variability in Groundwater Storage

In the present work, we estimated groundwater storage anomaly from the ensemble TWSA dataset that represent the overall TWSA with minimum residual error and root zone soil moisture obtained from ESA CCI. Further, we evaluated GWSA derived from downscaled TWSA and GF-JPL datasets to investigate the efficacy of the downscaling and gap-filling technique along Indus and Ganga basin respectively.

Figure 3 indicate spatial distribution of long-term mean GWSA in April month (pre-monsoon) computed from the three datasets. It was inferred that the significant decline in TWSA is limited to mid Indus and western Ganga basin. This region is

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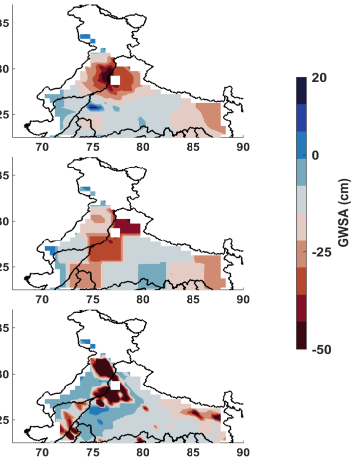

Figure 3. Spatial variability in GWSA for April Month between 2002-2022 for Ensemble, Gap-Filled and GOU TWSA respectively

characterized by unsustainable groundwater abstraction (Rodell et al., 2004a; Dangar et al., 2021; Asoka and Mishra, 2020). It is evident from Figure 3 that all the datasets captures the hotspot of groundwater decline (GWD). It was further inferred that downscaled TWSA can capture the hotspot of GWD accurately along northwest India indicating the efficiency of self supervised data assimilation technique to downscale GRACE TWSA.

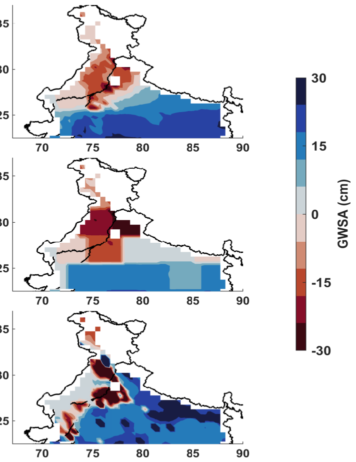

Figure 4. Spatial variability in GWSA for September Month between 2002-2022 for Ensemble, Gap-Filled and GOU TWSA respectively

Figure 4 shows the spatial distribution of long-term mean GWSA for September month (post-monsoon) computed from the three datasets. It is evident from the figure that all the three datasets capture the seasonal variability in GWSA. Further, it was inferred that due to excessive groundwater abstraction, the northwest India witnessed a persistent negative groundwater anomaly during post monsoon. Figure 5 shows the temporal variability in GWSA along Indus and Ganga basin during 2002-2022. It was observed that GWSA followed similar distribution as TWSA over the rivers indicating that groundwater decline significantly influence the overall water availability in the two basins.

Figure 6 shows the trend in groundwater storage computed from the three GRACE TWSA datasets and groundwater level observations from CWGB respectively. GWSA obtained from downscaled TWSA accurately captures the spatial distribution of groundwater decline along northwest India. It was further observed that GWSA obtained from Ensemble and Gap-filled GWSA overestimated the magnitude of groundwater change. Validation of GRACE GWSA against in-situ observations indicated that the methodology adopted to detect GWSA accurately reproduced GWSA from satellite observations. Along the Indus basin, correlation between GRACE and in-situ GWSA was found to be 0.79, 0.79 and 0.76 for EN, GOU and GF GWSA indicating that all the three datasets captured the decline in groundwater. Similarly, R value was found to be 0.81, 0.87 and 0.60 for the three datasets over Ganga basin. It was inferred that downscaled TWSA produced high correlation for both the basins indicating the ability to capture localized groundwater decline. Further, the RMSE (8.11 cm) was also found to be lowest among the three datasets (EN = 10.40 cm, GF = 13.23 cm).

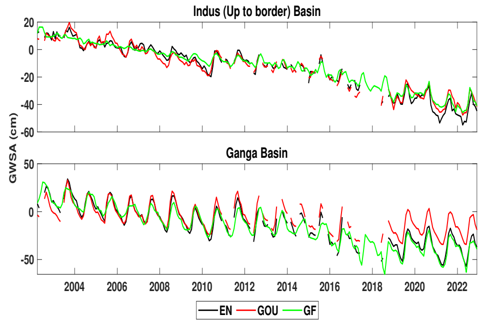

Figure 5. Temporal variability in GWSA computed from Ensemble, Gou and gap-filled data and ESA Soil Moisture over Indus and Ganga basin

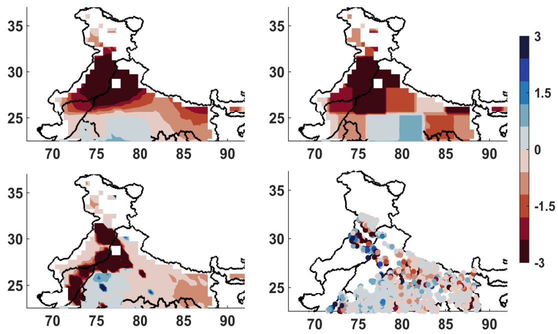

Figure 6. Spatial Distribution of trends in GWSA obtained from Ensemble, Gap-Filled, GOU and in-situ well observation over Indus and Ganga basins between 2002-2022 respectively

Multiple studies have analyzed groundwater storage change using the water balance residual approach over the Indian subcontinent. In general, Indo-Gangetic basins along Northwest India exhibit a persistent decline (Bhanja et al., 2016; Dharpure et al., 2025; Rodell et al., 2004b). The significant decline in GWSA along Indus and Ganga basin is primarily driven by anthropogenic groundwater abstraction to support intensive irrigation and domestic water supply during periods of low rainfall (Asoka and Mishra, 2020). The present work indicates that the significant negative trend persists for all the TWSA datasets employed for groundwater storage change detection over Indus and Ganga basin implying dominant human-induced signal can be effectively captured by the water balance residual approach irrespective of the dataset. However, the magnitude of change may vary depending on the gravity fields processing in GRACE, depth of the soil moisture and spatial constraints (Scanlon et al., 2016; Ferreira et al., 2016). Multiple studies have highlighted the limitations of sporadic distribution of ground well observations, single specific yield value for the entire basin and intrinsic errors in the groundwater level measurements (Bhanja et al., 2016; Kuruva et al., 2025). GRACE GWSA captures groundwater change for the entire vertical column of the water table (Dangar et al., 2021; Frappart and Ramillien, 2018). On the other hand, ground well observations capture groundwater variability in shallow aquifers as observations from deep well aquifers are limited. Our work validates the GWSA against a dense network of groundwater level wells across the study area and specific yield for each station. The validation results are largely affected by the uncertainty in water balance residual approach, mismatch between GRACE GWSA resolution and point based groundwater level measurement and the heterogeneity in well characteristics (depth, density, and aquifer type). However, an accurate and dense network of ground well observations and specific yield values for each station significantly improves the validation results as evident from the results in the present work.

4. Conclusion

The present work investigated variability in terrestrial water storage anomaly and groundwater storage over the Indus and Ganga basins utilizing multiple satellite and modeled observations. Ensemble TWSA captured the intrinsic variability in total water storage for both the river basins due to reduced uncertainties, weaker regularization, more observation driven and ability to better capture extreme hydrological events. The method adopted in the study to fill gaps in TWSA time series using seasonal time series decomposition was found to be effective in capturing long-term trends. Validation of Groundwater Storage Change against in-situ ground well observations indicated that all the datasets captured the significant decline along the Indus and Ganga basin with varying magnitude of change. Downscaled TWSA using self-supervised data assimilation captured long-term changes in TWSA and GWSA accurately. It was inferred that GWSA computed from downscaled TWSA produced good correlation and lowest RMSE among the datasets used indicating the efficacy of downscaling methodology and validation approach. The comprehensive analysis of TWSA and its contribution in accurate monitoring of groundwater storage change provide valuable scientific insights for hydrological applications.

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