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GRACE and GRACE-FO for Hydrological Assessment in India: a Systematic Review of Terrestrial Water Storage, Groundwater, Hydrological Extremes, and Data-Driven Approaches

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ABSTRACT
The Gravity Recovery and Climate Experiment (GRACE) and its successor, GRACE Follow-On (GRACE-FO), have revolutionized large-scale hydrological monitoring by enabling satellite-based observation of terrestrial water storage (TWS) variability. In India, where groundwater depletion, monsoon variability, rapid urbanization, and growing water demand threaten long-term water security, satellite gravimetry has become an essential tool for basin-scale hydrological assessment. This systematic review critically synthesizes 130 peer-reviewed studies on GRACE and GRACE-FO applications in India using the PRISMA 2020 framework. The review combines bibliometric analysis with a comprehensive evaluation of gravity-field products, processing techniques, hydrological component separation, validation methods, uncertainty sources, and emerging data-driven approaches. The literature demonstrates that GRACE-derived terrestrial water storage anomalies have significantly improved the assessment of groundwater depletion, drought evolution, flood-induced storage variability, glacier mass change, land subsidence, and regional water balance. Recent advances increasingly integrate GRACE observations with hydrological models, remote sensing products, geodetic measurements, and machine-learning techniques for downscaling, gap filling, forecasting, and enhanced spatial interpretation. Despite these advances, coarse spatial resolution, signal leakage, reliance on ancillary model outputs, and limited in situ observations remain major challenges for local-scale applications. Future research should emphasize multi-product validation, high-resolution data fusion, physically informed machine learning, and stronger integration with next-generation Earth observation missions. This review provides an India-focused framework for advancing satellite-based groundwater monitoring, hydrological assessment, and sustainable water-resources management.
Keywords: GRACE/GRACE-FO; terrestrial water storage; groundwater; hydrological assessment; machine learning.

INTRODUCTION

Water security has become an increasingly important challenge as population growth, urban expansion, agricultural intensification, and climate variability continue to place pressure on freshwater resources (Mishra et al., 2021). These pressures are particularly significant in regions where groundwater supports irrigation, domestic supply, industry, and drought resilience (Hund et al., 2018). Understanding changes in terrestrial water storage is therefore essential for evaluating regional water availability, identifying long-term depletion, assessing hydrological extremes, and supporting sustainable water-resource planning. Terrestrial water storage integrates groundwater, soil moisture, surface water, snow and ice, and canopy water, providing a broad measure of changes occurring across the terrestrial hydrological system (Trautmann et al., 2022). Conventional hydrological monitoring relies mainly on groundwater wells, streamflow gauges, reservoir records, meteorological observations, and hydrological models. Although these approaches remain indispensable for local and process-based assessment, their effectiveness is often constrained by sparse spatial coverage, inconsistent observation periods, uneven monitoring density, and limited data availability across large basins. These limitations are especially important in geographically extensive and hydrologically diverse regions, where point-scale measurements may not adequately represent basin-wide storage changes (Khorrami & Gündüz, 2025). Satellite remote sensing has therefore become an important complement to conventional monitoring by providing repeated and spatially consistent observations over large areas. The Gravity Recovery and Climate Experiment (GRACE), launched in 2002, introduced a fundamentally different approach to hydrological observation by measuring temporal variations in the Earth's gravity field associated with redistribution of water mass. Its successor, GRACE Follow-On, launched in 2018, extended this observational

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record and enabled continued monitoring of large-scale terrestrial water-storage variability (Bhere & Reddy, 2024; Frappart & Ramillien, 2018). Unlike optical or microwave satellite missions that generally observe

individual hydrological variables, GRACE and GRACE-FO provide an integrated measure of mass change, allowing changes in terrestrial water storage to be assessed at regional and basin scales (Rodell & Reager, 2023). This capability has substantially expanded the use of satellite gravimetry in groundwater assessment, drought monitoring, flood-related storage analysis, glacier mass-balance evaluation, land deformation studies, and basin-scale water-balance investigations. India represents a particularly important region for GRACE-based hydrological assessment because of its dependence on groundwater, strong monsoon seasonality, large climatic gradients, intensive irrigation, rapidly growing urban centers, and marked hydrogeological diversity(Cao & Roy, 2025; Rana & Chamoli, 2024). Groundwater depletion is especially important across northwestern India and the Indo-Gangetic Plain, while several peninsular basins exhibit more variable storage responses associated with monsoon recharge, reservoir regulation, basin characteristics, and groundwater use(Sarkar et al., 2022). These regional contrasts make India an important natural laboratory for evaluating the combined effects of climatic forcing and anthropogenic water use on terrestrial and groundwater storage(Asoka & Mishra, 2020). At the same time, the uneven distribution of monitoring wells and limited availability of long-term observations in some regions increase the value of basin-scale satellite gravimetry. The usefulness of GRACE has also increased through integration with complementary datasets and analytical frameworks. Land-surface and hydrological models are widely used to separate soil moisture, surface water, snow water equivalent, and canopy water from total terrestrial water storage in order to estimate groundwater-storage anomalies(Sliwinska et al., 2019). More recent approaches increasingly combine GRACE and GRACE-FO with remote sensing, geodetic observations, in situ groundwater measurements, data assimilation, and machine-learning methods. These developments have improved spatial interpretation, downscaling, gap filling, uncertainty assessment, and prediction. However, important limitations remain(Nadeem et al., 2023). Coarse spatial resolution, signal leakage, differences among processing centers, dependence on ancillary hydrological models, and spatial-scale mismatch between satellite observations and field measurements continue to affect the reliability of local and sub-basin applications(Xiong et al., 2025). The growing volume of GRACE-based research has produced several global and thematic reviews, including studies focused on terrestrial water storage, groundwater depletion, drought, and satellite gravimetry methods. India-focused reviews have also begun to emerge, particularly in relation to terrestrial water-storage monitoring. However, an integrated synthesis that combines systematic literature screening, bibliometric assessment, comparison of GRACE products and processing strategies, uncertainty evaluation, basin-specific hydrological applications, data integration, and emerging artificial-intelligence approaches remains limited. Such a synthesis is necessary to distinguish well-established findings from methodological uncertainties, identify regional imbalances in the literature, and define priorities for future research. Accordingly, this review provides a systematic and critical assessment of GRACE and GRACE-FO hydrological applications in India. The study aims to: (i) synthesize the evolution and major applications of satellite gravimetry across Indian hydroclimatic and river-basin settings; (ii) compare processing approaches, gravity products, validation strategies, and major sources of uncertainty; (iii) evaluate the integration of GRACE observations with hydrological models, remote sensing, geodetic measurements, and emerging data-driven techniques; and (iv) identify unresolved methodological and geographical gaps and propose future research priorities for more reliable and operational water-resource assessment. By combining bibliometric evidence with critical thematic synthesis, the review seeks to provide a coherent framework for advancing satellite-based groundwater monitoring, hydrological assessment, and sustainable water-resources management in India.

2. Review Methodology:

This review was conducted using a systematic and transparent methodology based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) framework to ensure a comprehensive, reproducible, and unbiased synthesis of the literature on GRACE and GRACE-FO applications in hydrological studies across India (Page et al., 2021). The overall review framework adopted in this study is illustrated in Figure 1, which summarizes the sequential stages of literature identification, bibliometric assessment, systematic screening, data extraction, thematic classification, and critical synthesis. This structured workflow facilitated the integration of quantitative bibliometric evidence with qualitative analysis, enabling a comprehensive evaluation of methodological developments, application trends, and future research opportunities.

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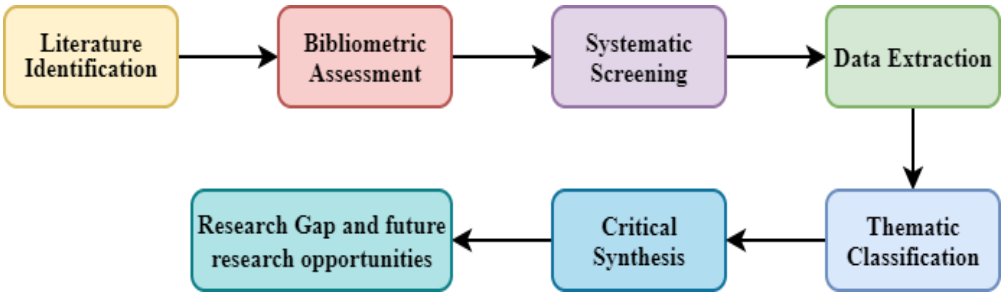


Figure 1. Workflow adopted for the review methodology.

2.1. Literature Search Strategy:

A comprehensive literature search was conducted using the Scopus database because of its broad coverage of peer-reviewed publications in hydrology, geosciences, remote sensing, satellite gravimetry, and water-resources research. The search was performed within the title, abstract, and keyword fields using terms related to GRACE/GRACE-FO, terrestrial and groundwater storage, hydrological applications, and the Indian geographical context. The search covered publications from 2002 to 2025 and retrieved 392 records.
The final Scopus search expression was:
Title-Abs-Key ("Grace" Or "Grace-Fo" Or "Grace Follow-On" Or "Gravity Recovery And Climate Experiment") And ("Terrestrial Water Storage" Or "Terrestrial Water Storage Anomaly" Or Groundwater Or "Groundwater Storage" Or "Groundwater Depletion" Or Drought Or Flood Or "Hydrological Extreme" Or "Glacier Mass Balance" Or "Glacier Mass" Or "Land Subsidence" Or "Land Deformation" Or "Surface Water" Or "Soil Moisture" Or "Water Balance" Or Downscale Or "Data Assimilation" Or "Machine Learning" Or "Deep Learning") And (India Or Indian Or "Indian Subcontinent" Or "Indo-Gangetic" Or Ganga Or Ganges Or Brahmaputra Or Indus Or Godavari Or Krishna Or Mahanadi Or Narmada Or Cauvery Or Kaveri Or Himalaya Or "Northwest India" Or "Northwestern India" Or "Peninsular India").

2.2. Eligibility Criteria:

Studies were considered eligible when they investigated hydrological applications of GRACE or GRACE-FO within India, the Indian subcontinent, or major Indian river basins and addressed terrestrial water storage, groundwater storage, groundwater depletion, drought, flood-related storage variability, glacier mass balance, land subsidence, surface-water dynamics, soil moisture, water balance, downscaling, data assimilation, or related hydrological processes. Eligible studies were required to provide sufficient methodological information and scientifically interpretable results relevant to the objectives of the review. Records were excluded when they were outside the geographical or thematic scope, did not directly use GRACE/GRACE-FO observations for hydrological assessment, lacked adequate methodological relevance, or focused primarily on non-hydrological applications. Studies with insufficient information for meaningful synthesis were also excluded during title, abstract, or full-text screening.

2.3. Bibliometric Assessment:

Bibliometric analysis was performed on the 392 Scopus records retrieved before systematic screening, while the critical thematic synthesis was based on the 130 studies retained after PRISMA screening. Keyword co-occurrence analysis was conducted using VOSviewer version 1.6.20 (van Eck & Waltman, 2010), with co-occurrence analysis, author keywords, and full counting. A customized thesaurus was applied to standardize synonymous terms, abbreviations, and spelling variants, and a minimum occurrence threshold of 5 was used. The analysis evaluated publication growth, keyword occurrence, links, total link strength, and thematic clusters. Publication output increased markedly during the GRACE-FO period, particularly after 2018. The VOSviewer network identified eight thematic clusters, collectively representing satellite gravimetry, groundwater assessment, terrestrial water storage, hydroclimatic variability, basin-scale hydrology, data-driven methods, flood-related applications, and groundwater monitoring (Figure 2). Leading keyword metrics are presented in Table 1, while the annual publication trend is shown in Figure 3. The increasing occurrence of machine learning, deep learning, and downscaling indicates a shift toward integrated GRACE-based frameworks combining remote sensing, hydrological models, climate data, and advanced computational methods.

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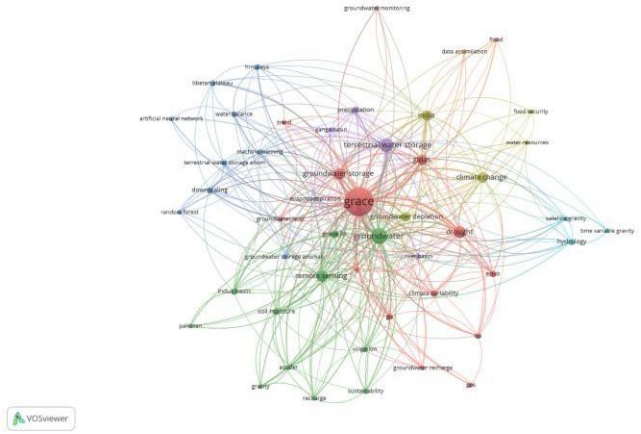


Figure 2. Keyword co-occurrence network of GRACE- and GRACE-FO-related hydrological research generated using VOSviewer.

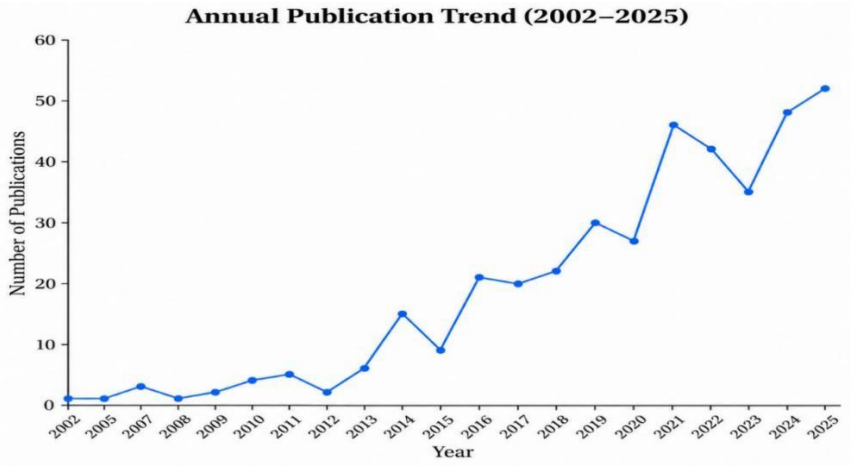


Figure 3. Annual evolution of peer-reviewed GRACE- and GRACE-FO-related publications retrieved from the Scopus database (2002–2025).

Table 1. Leading author keywords in the VOSviewer co-occurrence network, ranked by total link strength (TLS), showing cluster membership, occurrence frequency, number of links, and network connectivity.

Rank	Keyword	Cluster	Occurrences	Links	Total Link Strength
1	**GRACE**	1	194	48	368
2	**Groundwater**	2	62	38	145
3	**Terrestrial water storage**	5	48	31	107
4	**Remote sensing**	2	31	33	88
5	**Groundwater storage**	1	30	26	69
6	**GLDAS**	1	25	19	65
7	**Drought**	1	33	27	64
8	**India**	4	25	22	57
9	**Climate change**	4	25	22	56
10	**Groundwater depletion**	4	20	23	46
11	**Soil moisture**	2	12	15	36
12	**GRACE-FO**	2	14	19	31
13	**Indus basin**	2	10	15	30
14	**Precipitation**	5	12	12	26
15	**Downscaling**	3	9	12	25
16	**Aquifer**	2	6	11	24
17	**ENSO**	1	10	12	24

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18	**Recharge**	2	6	11	23
19	**Climate variability**	1	12	12	22
20	**Evapotranspiration**	5	6	16	22
21	**Hydrology**	6	9	13	22
22	**Irrigation**	2	7	12	21
23	**Machine learning**	3	7	15	21

2.4. Study Selection:
The study-selection process followed the PRISMA 2020 framework. The Scopus search identified 392 records. After removal of one duplicate, 391 records were subjected to title and abstract screening. During this stage, 261 records were excluded because they were outside the scope of the review, did not directly address GRACE/GRACE-FO hydrological applications in India, or showed limited relevance to terrestrial water storage, groundwater, and associated hydrological processes. The remaining 130 articles were retrieved and assessed in full for eligibility. All 130 studies satisfied the predefined inclusion criteria and were retained for the final systematic synthesis. The complete identification, screening, eligibility assessment, and inclusion process is summarized in the PRISMA 2020 flow diagram (Figure 4).

2.5. Data Extraction and Thematic Synthesis:
A standardized data-extraction protocol was applied to the 130 studies retained after PRISMA screening. For each study, information was compiled on publication year, study area, river basin or hydrogeological setting, GRACE/GRACE-FO product, processing centre, auxiliary datasets, methodological approach, validation strategy, major findings, uncertainty assessment, and reported limitations. The selected studies were subsequently grouped into major thematic categories, including terrestrial water storage monitoring, groundwater storage assessment, hydrological-component evaluation, drought monitoring, flood assessment, glacier mass balance, land subsidence, uncertainty analysis, downscaling, data assimilation, and emerging artificial-intelligence applications. Rather than presenting studies individually, the synthesis compared methodological approaches, processing strategies, validation methods, regional findings, and limitations to identify consistent patterns, methodological differences, research gaps, and future priorities.

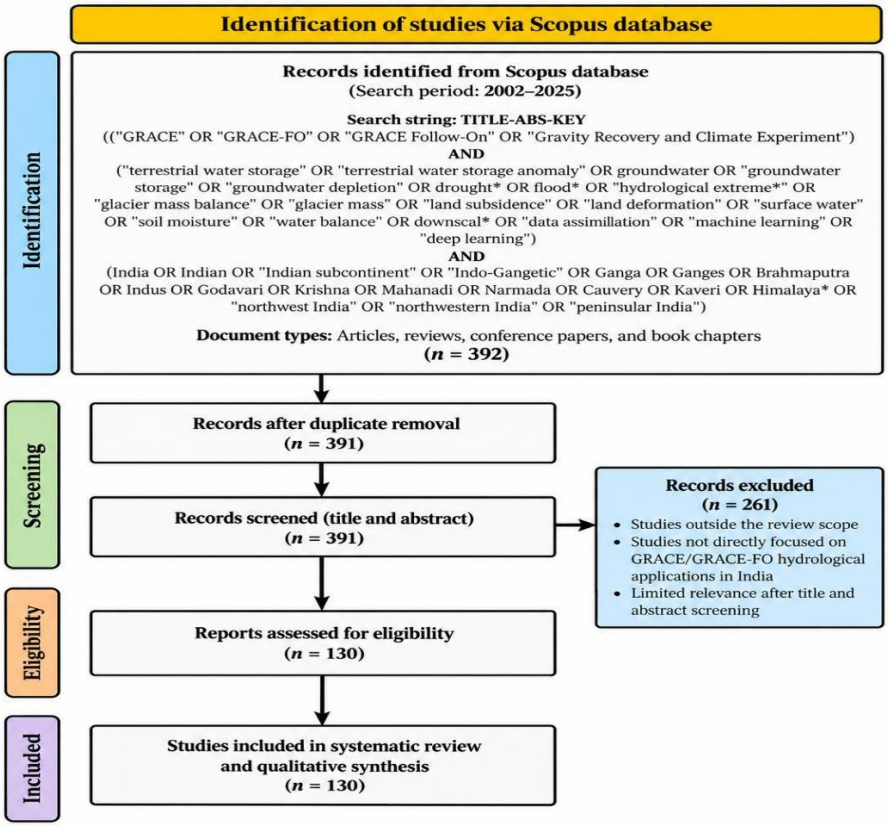


Figure 4. PRISMA 2020 flow diagram illustrating the systematic literature search, screening, eligibility assessment, and study selection process adopted in this review.

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3. GRACE AND GRACE-FO MISSION: PRINCIPLES AND HYDROLOGICAL SIGNIFICANCE:

The Gravity Recovery and Climate Experiment (GRACE), launched in 2002, and its successor GRACE Follow-On (GRACE-FO), launched in 2018, provide observations of temporal variations in the Earth's gravity field that can be related to changes in terrestrial water storage(Nikraftar et al., 2024). A schematic representation of the GRACE and GRACE-FO twin-satellite missions and their role in monitoring gravity-field variations is presented in Figure 5. Unlike conventional remote-sensing missions that monitor individual hydrological variables, GRACE and GRACE-FO respond to vertically integrated mass changes and therefore capture the combined variability of groundwater, soil moisture, surface water, snow and ice, and canopy water(M. Kumar et al., 2024). This capability has made satellite gravimetry particularly valuable for regional- and basin-scale hydrological assessment where ground observations are sparse or spatially uneven(Ayele et al., 2025). The scientific use of GRACE has evolved substantially over the past two decades. Early studies primarily focused on detecting broad terrestrial water-storage changes and groundwater depletion, whereas recent investigations increasingly combine GRACE/GRACE-FO observations with land-surface models, hydrological models, remote sensing, geodetic measurements, and data-driven approaches. This evolution has improved the interpretation of water-storage variability, strengthened uncertainty assessment, and extended the application of satellite gravimetry to drought, flood-related storage conditions, glacier mass balance, land subsidence, and long-term water-resource assessment.

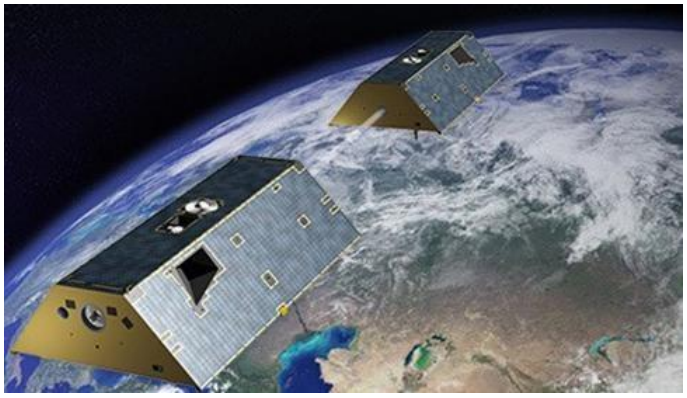


Figure 5. Schematic representation of the GRACE and GRACE-FO twin-satellite missions used to monitor temporal variations in the Earth's gravity field and terrestrial water storage (https://grace.jpl.nasa.gov/).

3.1. Gravity Retrieval and Terrestrial Water Storage Estimation:

GRACE and GRACE-FO infer mass redistribution by measuring very small changes in the separation between two satellites travelling in the same orbit. Variations in terrestrial water mass modify the Earth's gravity field, producing measurable perturbations in inter-satellite distance. These observations are processed after removing non-hydrological signals, including atmospheric, oceanic, tidal, and solid-Earth effects, to generate monthly gravity-field solutions that can be expressed as terrestrial water storage anomalies (TWSA)(Mohamed et al., 2022). TWSA represents the integrated change in terrestrial water storage relative to a reference period and includes groundwater, soil moisture, surface water, snow water equivalent, glacier storage, and canopy water. Because GRACE does not directly isolate groundwater, groundwater storage anomalies are generally estimated using a residual approach(Solovey et al., 2025) (Equation 1):

$$GWSA=TWSA-(SMA+SWSA+SWEA+CWA) \quad (1)$$

where GWSA is groundwater storage anomaly, SMA is soil moisture anomaly, SWSA is surface-water storage anomaly, SWEA is snow-water-equivalent anomaly, and CWA is canopy-water anomaly. These non-groundwater components are commonly obtained from land-surface or hydrological models such as GLDAS, VIC, PCR-GLOBWB, and W3RA. This residual methodology has become the standard approach for regional groundwater assessment, but its reliability depends on both the quality of the GRACE signal and the accuracy of the auxiliary model components. Consequently, uncertainty in soil moisture, surface water, snow, or canopy-water estimates can propagate directly into groundwater-storage estimates.

3.2. GRACE Products, Processing Centers, and Data Evolution:

GRACE and GRACE-FO gravity solutions are produced by several processing centres, including the Centre for Space Research (CSR), Jet Propulsion Laboratory (JPL), German Research Centre for Geosciences (GFZ), and

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NASA Goddard Space Flight Centre (GSFC)(J. Chen et al., 2022). Although these products originate from the same satellite observations, differences in background models, inversion methods, regularization, filtering, and leakage treatment can lead to variations in regional TWSA estimates (Table 2). Two major solution types are widely used: spherical harmonic (SH) products and mascon products. SH solutions represent the gravity field using spherical harmonic coefficients and have a long record of use in hydrological studies(P. Wang et al., 2023). However, they are susceptible to correlated errors and characteristic north-south striping, requiring filtering, smoothing, and scaling corrections. These procedures reduce noise but may also attenuate genuine hydrological signals and increase leakage across basin boundaries. Mascon solutions estimate mass changes over predefined spatial blocks and generally require less post-processing(Croteau et al., 2021). They provide improved signal localization and reduced leakage compared with conventional SH products, making them particularly suitable for basin-scale water-storage and groundwater studies. The transition from Release-05 to Release-06 further improved instrument calibration, background geophysical corrections, temporal consistency, and gravity-field processing. As a result, RL06 mascon products have become the preferred datasets in many recent hydrological investigations(Sahour et al., 2020). Nevertheless, no single product performs optimally under all hydroclimatic and geographical conditions. Product suitability depends on basin size, shape, climatic variability, hydrological signal strength, and the intended application. For this reason, recent studies increasingly recommend cross-comparison among multiple GRACE products rather than reliance on a single processing centre.

Table 2. Comparison of major GRACE/GRACE-FO processing centres and solution types, including nominal grid spacing, methodological strengths, limitations, and typical hydrological applications

Processing centre / product	Solution type	Nominal grid spacing / effective scale	Main strengths	Main limitations	Typical hydrological use
CSR	SH (RL06), Mascon (RL06M)	SH: regional scale; Mascon distributed on ~0.25° grid	Widely used; good temporal consistency; mascon solutions reduce the need for extensive post-processing	SH solutions require filtering/smoothing; leakage and scaling effects may remain	Groundwater depletion, TWS trends, basin-scale storage assessment
GFZ	SH (RL06)	Regional scale; mascon products available at gridded resolution	Stable long-term gravity solutions; useful for inter-comparison among processing centres	Correlated errors and leakage may affect regional estimates	Continental hydrology, monsoon-related storage variability, basin-scale analysis
JPL	SH (RL06), Mascon (RL06M)	SH: regional scale; mascon products commonly distributed on fine grids	Improved signal localization; reduced leakage relative to conventional SH solutions; widely used in hydrology	Differences may occur relative to CSR/GFZ because of processing and regularization choices	Groundwater storage, glacier mass balance, hydroclimatic extremes
GSFC	Mascon	Regional-scale mascon solution	Useful for mass-concentration analysis and data-assimilation applications	Comparatively less used in India-focused hydrological studies	Data assimilation and regional water-storage assessment

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SH-based products	Spherical harmonics	Effective hydrological scale generally several hundred kilometers	Long historical record; facilitates comparison among processing centres	Requires filtering and smoothing; susceptible to striping, signal attenuation, and leakage	Earlier GRACE groundwater and TWS studies
Mascon-based products	Mass concentration grids	Regional-scale information represented on finer output grids	Reduced post-processing requirements; improved signal localization; generally better preservation of regional mass-change signals	Effective resolution remains coarser than displayed grid spacing; solutions vary among centres	Groundwater, drought, subsidence, and basin-scale studies

3.3. Sources of Uncertainty and Error Propagation:

Several sources of uncertainty affect GRACE- and GRACE-FO-based hydrological assessment. The first is spatial resolution. Satellite gravimetry is most reliable at regional to basin scales, while its effective resolution remains too coarse for detailed interpretation of small catchments, local aquifers, or urban groundwater systems(Frappart & Ramillien, 2018). Signal leakage from adjacent regions and attenuation introduced by spatial filtering further complicate the interpretation of localized water-storage changes. A second source of uncertainty arises from the derivation of groundwater storage. Since groundwater is obtained by subtracting other storage components from TWSA, errors in land-surface and hydrological models propagate into GWSA(H. Chen et al., 2019). Differences in model structure, meteorological forcing, soil parameterization, runoff representation, evapotranspiration, and snow simulation can therefore produce different groundwater estimates even when the same GRACE product is used. Validation introduces an additional challenge because GRACE observations represent spatially integrated water-storage changes, whereas in situ groundwater wells and geodetic observations are point- or local-scale measurements(Shilengwe et al., 2024). Direct comparison can therefore be affected by spatial-scale mismatch. This is particularly relevant in India, where groundwater-monitoring networks are unevenly distributed across hydrogeological regions. Recent studies address these limitations through multi-product comparison, multi-model ensembles, data assimilation, and integration with independent datasets such as groundwater wells, GNSS, InSAR, SMAP, Sentinel, and SWOT. Such approaches do not eliminate uncertainty, but they improve its characterization and increase confidence in the interpretation of regional water-storage trends.

3.4. Synthesis of Methodological Advances:

The methodological development of GRACE-based hydrology can be broadly characterized by a transition from conventional spherical harmonic processing toward RL06 mascon products and increasingly integrated analytical frameworks(L. Wang et al., 2020). Improvements in gravity-field retrieval have enhanced signal recovery and reduced leakage, while advances in hydrological modelling and Earth observation have improved component separation and validation(Güntner, 2008). More recently, data assimilation, machine learning, and deep learning have been introduced for downscaling, gap filling, prediction, and uncertainty assessment. Despite these advances, the reviewed literature indicates that the reliability of GRACE-derived hydrological estimates still depends on product selection, auxiliary model quality, spatial scale, and validation strategy(Li et al., 2019). The strongest contemporary approaches therefore combine satellite gravimetry with complementary hydrological, remote-sensing, geodetic, and in situ observations rather than treating GRACE as a standalone dataset. This methodological foundation supports the diverse applications discussed in the following section.

4. APPLICATIONS OF GRACE AND GRACE-FO IN HYDROLOGICAL STUDIES:

GRACE and GRACE-FO have substantially expanded the capacity to assess large-scale hydrological variability by providing spatially integrated observations of terrestrial water storage (TWS). In India, these observations have been applied to groundwater depletion, basin-scale water-storage variability, drought and flood assessment, glacier mass balance, land subsidence, and hydroclimatic analysis(Karki et al., 2025; Sarkar et al., 2022). The reviewed literature shows a clear progression from standalone use of GRACE toward integrated frameworks

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combining satellite gravimetry with land-surface models, remote sensing, in situ observations, geodetic measurements, and data-driven techniques.

4.1. Monitoring Changes in Terrestrial Water Storage:

Terrestrial water storage is the principal hydrological quantity observed by GRACE and GRACE-FO and represents the integrated contribution of groundwater, soil moisture, surface water, snow and ice, and canopy water. GRACE-derived terrestrial water storage anomalies (TWSA) are therefore particularly useful for identifying seasonal, interannual, and long-term changes in regional water availability. Across India, the reviewed studies reveal strong spatial contrasts in TWS behaviour. Persistent declines are most evident over northwestern India and parts of the Indo-Gangetic Plain, where intensive irrigation and groundwater abstraction exert a major influence on long-term storage loss(Srivastava & Dikshit, 2022). In contrast, several peninsular basins, including the Godavari, Krishna, and Mahanadi, show comparatively stable conditions or episodic recovery during favourable monsoon periods. These contrasting responses indicate that TWS variability reflects the combined effects of precipitation, recharge, reservoir regulation, groundwater abstraction, and basin hydrogeology rather than rainfall alone(Singh et al., 2025). Methodological improvements, particularly the increasing use of mascon products, leakage correction, and integration with hydrological models, have improved basin-scale TWS interpretation. However, coarse spatial resolution and uncertainty in signal separation still restrict detailed sub-basin and local-scale applications.

4.2. Groundwater Storage Assessment:

Groundwater assessment represents one of the most important applications of GRACE in India (Table 3). Because GRACE measures total water-storage change rather than groundwater directly, groundwater storage anomalies are generally estimated by removing soil moisture, surface water, snow water equivalent, and canopy-water components from TWSA(Bhanja et al., 2020; Sliwinska et al., 2019). This residual approach has enabled regional groundwater assessment where conventional monitoring networks are sparse or discontinuous. The strongest and most consistent evidence of groundwater depletion occurs across northwestern India and the Indo-Gangetic Plain, where irrigation withdrawals frequently exceed natural recharge(MacDonald et al., 2016; Mukherjee et al., 2015). Early studies established the severity of groundwater loss in these regions, while later investigations extended the analysis to major Indian river basins and incorporated in situ groundwater observations, hydrological models, and newer GRACE/GRACE-FO products. In contrast, groundwater behaviour in several peninsular basins is more variable, with periods of stability or recovery associated with monsoon recharge, reservoir operation, and lower abstraction pressure. These regional differences demonstrate that groundwater trends arise from interactions among climate variability, aquifer characteristics, irrigation intensity, land use, and groundwater management(Panda et al., 2021). The reviewed studies also show an evolution from conventional spherical harmonic solutions toward RL06 mascon products and integrated validation frameworks. Mascon products generally provide improved signal localization and reduced leakage, while comparisons with CGWB observations and hydrological models enhance confidence in derived groundwater estimates. Nevertheless, uncertainty remains substantial because errors in GRACE products and ancillary storage components propagate directly into groundwater storage anomalies.

Table 3. Representative GRACE and GRACE-FO studies in India illustrating the evolution of satellite gravimetry applications, methodologies, key contribution, and limitations.

Study	Application	Region/Basin	GRACE data / integrated method	Key contribution	Limitation
(Rodell et al., 2009)	Groundwater depletion	Northwestern India	GRACE spherical harmonics with land-surface model data	Estimated groundwater depletion at approximately 17.7 ± 4.5 km^3 yr^{-1} during 2002–2008	Coarse spatial resolution; groundwater estimates depend on model-based component separation
(Panda & Wahr, 2016)	TWS assessment	India	GRACE spherical-harmonic gravity records	Characterized spatial and temporal variability in terrestrial	TWS changes are not fully separated into climatic and anthropogenic contributions

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				water storage across India	
(Bhanja et al., 2016)	Validation	12 major Indian river basins	GRACE and land-surface-model estimates compared with in situ wells	Validated GRACE-based groundwater-storage anomalies against groundwater-level observations	Well coverage and sampling vary spatially; satellite and well observations represent different scales
(Bhanja et al., 2020)	Groundwater monitoring	Major Indian River basins	GRACE-based estimates and CGWB groundwater observations	Compared groundwater-storage changes derived from GRACE and in situ observations across major basins	Monitoring coverage and observation frequency vary among basins
(Abhishek & Kinouchi, 2021)	Basin-scale water storage	Peninsular India	GRACE, a global hydrological model, and in situ observations	Assessed water-storage dynamics during 2002–2017 using satellite, model, and groundwater data	Results depend partly on model inputs and parameterizatio n
(Kansara & Lakshmi, 2021)	Hydrological trends and land-cover linkages	Nine Indian River basins	GRACE TWSA, TRMM precipitation, MODIS evapotranspiration, and GLDAS runoff	Examined links between land-cover changes and trends in basin hydrological variables	Uncertainty in satellite and model-derived variables can affect the comparisons
(K. S. Kumar et al., 2021)	Groundwater drought	South Indian River basins	GRACE-based Groundwater Drought Index (GGDI)	Characterized monthly and seasonal groundwater drought and its links to teleconnection s	Results depend on index construction and selected drought thresholds
(Shah & Mishra, 2020)	Integrated drought assessment	India	GRACE-derived groundwater-storage anomalies and VIC-SIMGM hydrological simulations	Developed an Integrated Drought Index combining precipitation, runoff, soil moisture, and groundwater	VIC-SIMGM does not represent groundwater pumping or direct surface-water–groundwater interactions

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(Gupta & Dhanya, 2020)	Flood-potential assessment	Six Peninsular Indian river basins	GRACE TWSA with rainfall, temperature, discharge, and groundwater-level data	Evaluated the Flood Potential Index; reported good skill for Mahanadi, Godavari, and Narmada under the study's thresholds	Monthly GRACE observations limit use for short-duration or local flood events
(Mukherjee & Ramachandran, 2018)	Groundwater-level prediction	India	GRACE-derived ΔTWS and groundwater-level observations; SVR, ANN, and LRM	Compared SVR, ANN, and LRM for groundwater-level prediction; SVR outperformed ANN in the reported comparisons	Performance depends on the selected wells, input data, and model setup
(Pranjal et al., 2021)	Land subsidence	Northwestern India	GRACE gravity anomalies and Sentinel-1 DInSAR	Examined the relationship between groundwater depletion and land subsidence	Linking regional GRACE signals to local deformation requires suitable SAR and groundwater data
(Pranjal et al., 2023)	Groundwater-storage modelling	Northwestern India	GRACE, hydrological modelling, and satellite/in situ hydrometeorological data	Developed an integrated estimate of regional groundwater-storage change	Transferability depends on regional model inputs and validation data
(Pranjal et al., 2024)	Deep-learning groundwater-level prediction	Northwestern India	Satellite-derived groundwater and hydrological predictors; ConvLSTM–U-Net	Applied a ConvLSTM model within a U-Net framework to predict groundwater levels	Computational demands and transferability beyond the study region require assessment
(Dharpure et al., 2025)	Groundwater-storage trends	Indus Basin	GRACE/GRACE-FO mascon data, MissForest gap filling, and hydrological data	Reconstructed missing observations and found declining groundwater storage, with faster decline after 2015-16	Gap-filling and hydrological-component uncertainties affect the estimates

4.3. Challenges and Limitations of Groundwater Estimation:

Despite its value for regional groundwater monitoring, GRACE has several limitations. Groundwater storage is indirectly estimated, making results sensitive to the accuracy of ancillary soil-moisture, surface-water, snow, and canopy-water datasets(Rahaman et al., 2019). Differences among land-surface models may therefore produce different groundwater estimates even when the same GRACE product is used. Spatial resolution is another major constraint. GRACE observations are most reliable over large regions and are not suited to resolving individual

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aquifers, localized pumping centres, or highly heterogeneous hard-rock systems. Validation is further complicated by the mismatch between spatially averaged GRACE signals and point-based groundwater observations. In addition, conversion of groundwater storage to groundwater-level change requires reliable estimates of specific yield, which vary considerably across aquifer systems(Bhanja et al., 2016). Recent approaches using multi-product comparison, model ensembles, downscaling, data assimilation, and integration with field observations can reduce these uncertainties, but explicit uncertainty quantification remains essential for robust groundwater interpretation.

4.4. Evaluation of Hydrological Components:

Interpretation of GRACE-derived TWS requires complementary datasets capable of representing individual water-storage components(Ji et al., 2025). GLDAS-Noah is the most frequently used land-surface model in the reviewed studies because of its global coverage and availability of soil moisture, runoff, evapotranspiration, and snow information. Other products, including VIC, PCR-GLOBWB, W3RA, GLEAM, Terra-Climate, CHIRPS, and IMD gridded datasets, are used for component separation, water-balance assessment, drought characterization, and hydroclimatic validation. No single model performs consistently across all Indian hydroclimatic regions. Model performance depends on forcing data, parameterization, basin characteristics, and representation of soil-water and groundwater processes. Consequently, recent studies increasingly favour multi-model comparison or ensemble approaches over dependence on a single ancillary model. This is particularly important in monsoon-dominated regions where strong seasonal variability can amplify differences among model outputs. The major land-surface, hydrological, evapotranspiration, and precipitation datasets commonly integrated with GRACE/GRACE-FO are compared in **Table 4**.

Table 4. Summary of land-surface and hydrological models and climate datasets used alongside GRACE/GRACE-FO for storage-component estimation, drought analysis, and hydroclimatic validation in Indian basins

Dataset / model	Nominal resolution	Main variables used with GRACE	Main strengths	Main limitations	Typical application
GLDAS-Noah	0.25° for GLDAS-2.1 monthly Noah	Soil moisture, SWE, and canopy water for storage analysis; runoff and ET for water-balance interpretation	Frequently available land-surface simulations; widely used in GRACE studies	Model and forcing uncertainty; does not include groundwater or surface-water storage; runoff and ET are fluxes	Groundwater-storage residual estimation; TWS decomposition
GLDAS-VIC	1° for GLDAS-2.0 monthly VIC; varies by product	Soil moisture and SWE for storage analysis; runoff and ET for hydrological analysis	Physically based land-surface model; useful for seasonal water-balance analysis	Product resolution and available fields vary; standard VIC does not directly provide groundwater or surface-water storage	Soil-moisture/SWE correction of TWS; drought and water-balance analysis
PCR-GLOBWB 2.0	5 arc-minutes (about 10 km at the equator); 30-arc-minute version also available	Soil moisture, groundwater, snow, surface water, and channel storage	Represents multiple storage components and human water use	Results depend on forcing, model structure, and water-use inputs	Groundwater assessment; water-use impacts; basin water-balance analysis

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W3RA	Commonly 0.5°; configuration-dependent	Soil-water stores, groundwater, surface water, snow, and vegetation water	Provides internally consistent estimates of multiple water-storage components	Coarse grid; results depend on model configuration and parameterization	GRACE TWS decomposition; regional storage analysis
GLEAM	0.1° for GLEAM4; 0.25° for GLEAM v3	ET components and soil moisture; potential evaporation and related variables	Detailed ET estimates; GLEAM4 has finer grid spacing than earlier versions	Does not provide a complete TWS decomposition, including groundwater and surface-water storage; ET is a flux	ET analysis; drought and water-balance interpretation
TerraClimate	About 4 km (1/24°); monthly	Precipitation, temperature, PET, actual ET, and soil-water/climatic water-balance variables	Long monthly record and fine grid for regional climate-hydrology analysis	Monthly and model-derived/interpolated; check variable definitions before treating values as storage estimates	Regional drought and climate–TWS analysis
CHIRPS	0.05° (about 5 km); daily, pentadal, or monthly	Precipitation	Long record beginning in 1981; combines satellite estimates and station data	Uncertainty can be higher in complex terrain and areas with sparse gauges; does not provide storage components	Rainfall–TWS relationship; drought analysis
IMD gridded data	Rainfall: 0.25°; daily temperature: commonly 1°	Rainfall; maximum and minimum temperature, depending on product	India-specific, gauge-based datasets with long records	Interpolation uncertainty and uneven station coverage; rainfall and temperature grids differ	Forcing, validation, and interpretation of GRACE-derived TWSA/GWSA

4.5. Drought Monitoring and Assessment:

GRACE has provided an important extension to conventional drought monitoring because TWSA captures integrated water deficits rather than precipitation anomalies alone(Wu et al., 2023). Traditional indices such as SPI and SPEI primarily describe meteorological conditions, whereas GRACE-based indicators can reflect cumulative deficits in groundwater, soil moisture, and surface water. In India, GRACE-derived drought indicators have been applied across the Indo-Gangetic Plain, northwestern India, and several peninsular basins(Nandi & Biswas, 2024). The reviewed studies indicate that hydrological drought often persists after meteorological conditions improve, reflecting delayed groundwater and subsurface recovery. This lag is particularly important in heavily irrigated regions where continued abstraction can prolong storage deficits even after rainfall recovery. Integration of GRACE with precipitation, soil moisture, hydrological models, and conventional drought indices provides a more comprehensive representation of drought propagation from meteorological to agricultural and groundwater systems(S. Kumar et al., 2022). However, the monthly temporal resolution and coarse spatial footprint of GRACE limit its use for local or near-real-time drought warning.

4.6. Flood Monitoring and Water Extremes:

GRACE and GRACE-FO can contribute to flood assessment by providing information on antecedent basin-scale water-storage conditions. Positive terrestrial water-storage anomalies before intense rainfall may indicate elevated catchment

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wetness and reduced storage capacity, thereby increasing the likelihood of flood-generating conditions(Rateb et al., 2025). In this role, satellite gravimetry complements rather than replaces precipitation observations, streamflow measurements, hydraulic modelling, and satellite-based inundation mapping. In India, GRACE-derived water-storage information has been used to investigate flood susceptibility and antecedent hydrological conditions, including recent applications in the Mahanadi River Basin (Bhere & Reddy, 2024). Integration of GRACE/GRACE-FO observations with rainfall, soil moisture, topographic information, and hydrological models can improve understanding of basin wetness, seasonal storage accumulation, and post-event recovery. However, the monthly temporal resolution and coarse effective spatial scale of GRACE restrict its application for short-duration or local flood forecasting. Its principal value therefore lies in characterizing large-scale antecedent storage conditions and long-term hydroclimatic variability associated with flood-prone periods, rather than functioning as a standalone real-time flood-warning system.

4.7. Land Subsidence Monitoring:
Excessive groundwater abstraction can induce aquifer-system compaction and land subsidence, particularly in heavily exploited alluvial aquifer regions. GRACE and GRACE-FO do not directly measure surface deformation; rather, they provide regional-scale information on groundwater-storage variability that can be integrated with geodetic observations such as InSAR and GNSS to investigate groundwater-related land deformation (Adams et al., 2022). In India, integrated satellite gravimetry and geodetic approaches have been increasingly used to examine the relationship between groundwater depletion and land-surface deformation, particularly in groundwater-stressed regions of northern and northwestern India. In such studies, GRACE provides the regional groundwater-storage signal, whereas InSAR and GNSS resolve localized deformation patterns at substantially finer spatial scales. This complementary interpretation can improve understanding of aquifer compaction and help distinguish broad groundwater-storage decline from localized deformation processes. However, direct comparison between GRACE-derived storage changes and geodetic deformation remains challenging because of differences in spatial resolution, temporal sampling, aquifer properties, and the nonlinear relationship between groundwater withdrawal and land subsidence (Pranjal et al., 2021). Robust assessment therefore requires integration with groundwater-level observations, aquifer characteristics, geological information, and, where available, groundwater-withdrawal data.

4.8. Glacier Mass Balance Assessment:
GRACE and GRACE-FO have contributed to regional assessments of glacier and cryosphere mass change across the Himalayan and adjoining high-mountain regions. Unlike optical remote sensing, which primarily detects changes in glacier area or surface characteristics, satellite gravimetry responds directly to changes in mass and therefore provides complementary information on long-term cryosphere water-storage variability. The reviewed literature indicates substantial spatial variability in glacier mass change across the Himalayan region, reflecting differences in elevation, temperature, precipitation regime, glacier geometry, and local climatic conditions. Integration of GRACE/GRACE-FO with satellite altimetry, optical imagery, digital elevation models, and glacier models improves the interpretation of cryosphere mass change and its implications for downstream water availability (Tong et al., 2024). However, glacier applications remain challenging because the effective spatial resolution of GRACE is much coarser than the dimensions of individual glacier systems, while hydrological, snow, and glacier signals may overlap in mountainous terrain (J. Chen et al., 2025). GRACE and GRACE-FO are therefore more suitable for regional-scale glacier and cryosphere mass assessment than for monitoring individual glaciers. For India-specific interpretation, GRACE-derived glacier signals should be combined with higher-resolution cryosphere observations and regional validation datasets.

5. RESEARCH GAPS AND FUTURE PERSPECTIVES:
Despite substantial progress in the use of GRACE and GRACE-FO for hydrological assessment in India, several methodological, spatial, and operational limitations remain. The reviewed literature shows that most studies are concentrated on groundwater depletion, terrestrial water storage variability, and drought assessment, whereas comparatively fewer investigations address uncertainty propagation, high-resolution monitoring, operational forecasting, and systematic comparison of alternative GRACE products and ancillary hydrological models. Future research should therefore move beyond detection of water-storage change toward more integrated, validated, and decision-oriented frameworks.

5.1. Spatial Resolution and Downscaling:
The coarse effective spatial resolution of GRACE remains a major limitation for application to small catchments, urban aquifers, hard-rock groundwater systems, and highly heterogeneous hydrogeological regions. Although RL06 mascon products improve signal localization and reduce leakage, they do not fully resolve local-scale

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variability. Recent downscaling approaches based on machine learning and multi-source remote sensing show promise, but their transferability and physical consistency remain insufficiently tested across Indian hydroclimatic settings. Future studies should combine GRACE with high-resolution observations from Sentinel-1/2, InSAR, Landsat, SWOT, and other Earth-observation products, while explicitly evaluating downscaling uncertainty and spatial generalizability.

5.2. Improving Groundwater Estimation:
Groundwater storage anomalies are derived indirectly by subtracting non-groundwater components from GRACE-derived TWSA, making the estimates sensitive to the choice of auxiliary models. Most Indian studies rely heavily on GLDAS, whereas systematic comparison among GLDAS, VIC, PCR-GLOBWB, W3RA, and other hydrological models remains limited. Future investigations should adopt multi-model ensembles, uncertainty propagation frameworks, and regionally calibrated models to reduce dependence on a single ancillary dataset. Greater use of long-term groundwater observations is also needed to constrain storage estimates and improve hydrogeological interpretation.

5.3. Artificial Intelligence and Data Fusion:
Machine learning and deep learning are increasingly being applied to GRACE data for downscaling, gap filling, prediction, and groundwater-level estimation. However, most applications remain strongly data-driven and are rarely implemented in operational groundwater-monitoring systems. Model interpretability, uncertainty estimation, data scarcity, and physical consistency remain important concerns. Future research should emphasize physics-informed machine learning, hybrid hydrological–AI approaches, explainable models, and uncertainty-aware prediction frameworks rather than purely statistical optimization. Such approaches may improve predictive capability while maintaining consistency with known hydrological processes. The principal machine-learning and deep-learning approaches used for GRACE-based groundwater and terrestrial water-storage applications are summarized in Table 5.

Table 5. Data-driven, machine-learning, and deep-learning approaches used with GRACE/GRACE-FO data for groundwater prediction, spatial downscaling, gap filling, and hydrological forecasting.

ML / DL method	Main purpose	Typical inputs	Main advantage	Main limitation	Representative study/application
Random Forest (RF)	Spatial downscaling of GRACE TWSA and estimation of groundwater storage changes	GRACE TWSA; land-surface and hydroclimatic predictors, including soil moisture, evapotranspiration, runoff, precipitation, and land-surface temperature	Captures nonlinear relationships; predictor importance can be assessed; tested across contrasting Indian hydrogeological basins	Performance and useful predictors vary by basin; groundwater estimates matched observations in three of the four study basins	(Jyolsna et al., 2021)
Support Vector Regression (SVR)	Groundwater-level prediction	GRACE TWS and groundwater observations	Effective nonlinear regression for relatively limited datasets	Sensitive to kernel selection and hyperparameter tuning	Mukherjee & Ramachandran (2018)
Artificial Neural Network (ANN)	Groundwater-level prediction and model comparison	GRACE TWS and groundwater observations	Flexible nonlinear modelling capability	Performance depends strongly on network architecture and training data	Mukherjee & Ramachandran (2018)
Conv LSTM with U-Net framework	Spatiotemporal groundwater-level prediction	Satellite-derived hydrological variables, precipitation, soil	Simultaneously captures spatial and temporal dependencies	Computationally demanding and requires	Pranjal et al. (2024)

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		moisture, evapotranspiration, and in-situ groundwater levels		sufficient training data	
LSTM-based deep-learning downscaling	Downscaling GRACE TWSA and mapping groundwater-level anomalies at 0.25°	GRACE spherical-harmonic and mascon TWSA; 11 hydroclimatic variables reduced to three principal components; observed groundwater levels for evaluation	Uses sequential information and a 12-month lag to represent temporal dependencies; compared two GRACE solution types	Performance differed between GRACE solutions; the spherical-harmonic solution underestimated peaks (reported bias: 7.83 cm)	(Gorugantula & Kambhammettu, 2022)

5.4. Multi-Sensor Integration:
A large proportion of GRACE-based studies in India continue to rely mainly on land-surface model outputs for interpretation. More extensive integration with complementary Earth-observation systems could substantially improve process understanding. GRACE should increasingly be combined with InSAR and GNSS for deformation studies, SWOT for surface-water dynamics, Sentinel and Landsat for land and water-surface characterization, SMAP for soil moisture, and ICESat-2 for cryosphere and surface-water applications. Multi-sensor fusion can help bridge the scale gap between regional gravity observations and local hydrological processes while improving validation and uncertainty assessment.

5.5. Underrepresented Hydrogeological Regions:
The geographical distribution of GRACE research in India remains uneven. Most studies are concentrated in the Indo-Gangetic Plain, northwestern India, and a limited number of major river basins. Hard-rock aquifers, Himalayan watersheds, coastal groundwater systems, urban aquifers, and transboundary basins remain comparatively underrepresented. These regions differ markedly in recharge mechanisms, storage properties, geology, pumping intensity, and climate sensitivity. Future studies should therefore expand beyond frequently investigated basins and develop region-specific approaches that account for local hydrogeological characteristics.

5.6. Validation and Uncertainty Assessment:
Validation practices remain inconsistent across GRACE-based studies. Differences among CSR, JPL, GFZ, and GSFC products, solution types, filtering methods, leakage corrections, scaling procedures, and auxiliary hydrological datasets can lead to substantial differences in derived TWSA and GWSA. Yet relatively few studies compare these sources of uncertainty systematically under identical conditions. Future work should adopt standardized validation protocols that combine multiple GRACE products, long-term groundwater observations, hydrological models, and uncertainty propagation analysis. Reporting confidence intervals, sensitivity ranges, and product-dependent variability would improve comparability and reproducibility. The major methodological limitations and corresponding future research priorities identified from the review are synthesized in **Table 6**.

Table 6. Summary of the major research gaps, current limitations, and future priorities for advancing GRACE and GRACE-FO applications in groundwater and terrestrial water storage assessment across India.

Research area	Current limitations	Future research priorities
Spatial resolution	The coarse spatial resolution (≈300-400 km) limits the application of GRACE products to small catchments and local aquifer systems.	Develop higher-resolution gravity missions and integrate downscaling approaches using machine learning, InSAR, and multisource remote sensing.
Groundwater estimation	Groundwater storage anomalies are indirectly estimated and strongly depend on ancillary land surface models (e.g., GLDAS, PCR-	Improve groundwater estimation through multi-model ensembles, assimilation techniques, and

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	GLOBWB), introducing model-dependent uncertainty.	extensive validation using in situ groundwater observations.
Validation and uncertainty	Validation approaches vary considerably among studies, making intercomparison difficult and increasing uncertainty in groundwater estimates.	Develop standardized validation protocols incorporating groundwater monitoring wells, hydrological models, and uncertainty quantification frameworks.
GRACE data processing	Differences among processing centres (CSR, GFZ, JPL, GSFC) and solution types (SH and Mascon) can lead to inconsistent estimates of terrestrial water storage.	Establish harmonized processing strategies, improved leakage correction, and standardized recommendations for selecting GRACE products in different hydrological applications.
Artificial intelligence integration	Machine learning applications remain largely research-oriented and are rarely incorporated into operational groundwater monitoring systems.	Develop physics-informed artificial intelligence, hybrid hydrological-AI models, and digital twin frameworks for real-time groundwater forecasting and decision support.
Geographical coverage	Most Indian studies focus on the Indo-Gangetic Plain and a few major river basins, whereas hard-rock aquifers, Himalayan watersheds, coastal aquifers, and transboundary basins remain underexplored.	Expand GRACE-based investigations to underrepresented hydrogeological regions through integrated satellite observations, field measurements, and basin-specific studies.

6. DISCUSSION:

The synthesis of 130 studies shows that GRACE and GRACE-FO have substantially advanced hydrological assessment in India by enabling regional-scale monitoring of terrestrial water storage, groundwater depletion, drought, flood-related storage variability, glacier mass change, and land subsidence. The literature also shows a clear methodological transition from standalone GRACE analysis toward integrated use with hydrological models, remote sensing, geodetic observations, and data-driven approaches. A consistent finding is that groundwater variability in India reflects both climatic and anthropogenic controls. Persistent depletion across northwestern India and the Indo-Gangetic Plain is strongly associated with intensive abstraction, whereas several peninsular basins show more variable behaviour linked to monsoon recharge, reservoir regulation, hydrogeology, and groundwater use(Swain et al., 2022). This indicates that GRACE-derived storage changes should be interpreted within a basin-specific hydroclimatic and anthropogenic context rather than through rainfall variability alone. Methodological improvements, particularly RL06 mascon products, have improved signal recovery and reduced leakage, but differences among processing centres, filtering methods, scaling procedures, and ancillary hydrological models continue to introduce uncertainty(Neves et al., 2020). Because groundwater storage is derived indirectly from TWSA, errors in soil moisture, surface water, snow, and canopy-water estimates can propagate into GWSA. Multi-product comparison, multi-model ensembles, and validation against in situ observations are therefore essential for robust interpretation(Fatolazadeh et al., 2022). The growing integration of GRACE with InSAR, GNSS, hydrological models, and other Earth-observation datasets has improved interpretation across multiple applications. Machine learning and deep learning further support downscaling, gap filling, and prediction, although issues related to physical consistency, transferability, interpretability, and uncertainty remain(J. Chen et al., 2025). Future research should therefore emphasize physically informed and uncertainty-aware data-driven approaches rather than relying solely on predictive accuracy. Research coverage also remains geographically uneven, with comparatively limited attention to hard-rock aquifers, coastal groundwater systems, urban aquifers, Himalayan catchments, and transboundary basins. Overall, the greatest value of GRACE and GRACE-FO lies in complementing, rather than replacing, conventional observations. Future progress will depend on integrating multiple gravity products, hydrological models, field measurements, geodetic observations, and high-resolution satellite datasets within standardized and uncertainty-aware frameworks for groundwater monitoring and water-resources management in India.

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6.1. Conceptual Framework and Research Roadmap:

Based on the reviewed literature, a conceptual framework is proposed in which GRACE and GRACE-FO observations form the basis for regional terrestrial water storage assessment and are integrated with hydrological models, remote-sensing products, in situ groundwater observations, and geodetic measurements. This integration supports hydrological component separation, uncertainty assessment, and improved interpretation of groundwater depletion, drought, flood-related storage variability, glacier mass change, and land subsidence (Figure 6). The resulting research roadmap emphasizes three priorities. In the short term, standardized validation procedures, multi-product comparison, and explicit uncertainty quantification are needed to improve consistency among GRACE-based studies. In the medium term, integration with high-resolution missions such as SWOT, Sentinel, NISAR, ICESat-2, and SMAP, together with data assimilation and physically informed machine-learning approaches, can improve spatial interpretation and predictive capability.

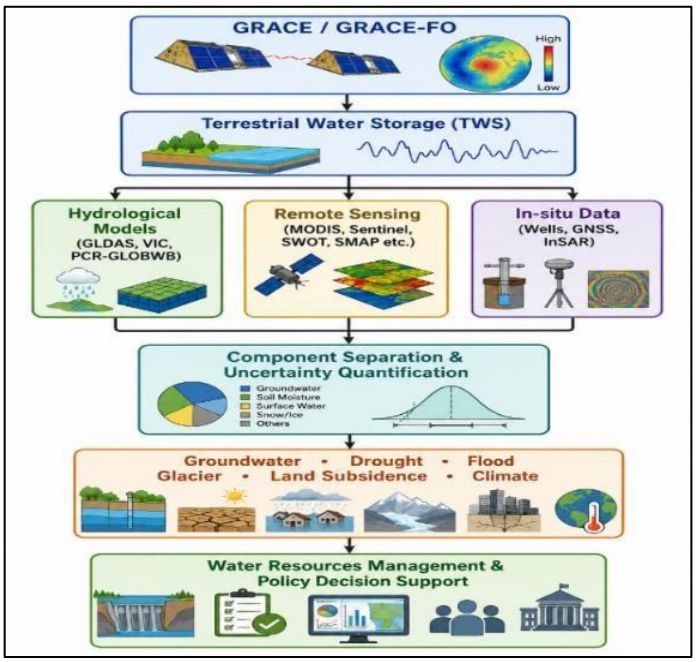


Figure 6. Conceptual framework showing the integration of GRACE and GRACE-FO observations with complementary datasets for terrestrial water storage assessment and hydrological applications.

In the longer term, next-generation gravity missions, cloud-based geospatial platforms, and digital hydrological frameworks could support the transition of satellite gravimetry from primarily research-oriented applications toward operational water-resources monitoring and decision support in India.

7. CONCLUSIONS:

This review provides a systematic and critical synthesis of 130 studies on the hydrological applications of GRACE and GRACE-FO in India. The evidence shows that satellite gravimetry has become an important tool for assessing terrestrial water storage, groundwater depletion, drought, flood-related storage variability, glacier mass change, land subsidence, and basin-scale hydrological dynamics, particularly in regions where conventional monitoring networks are sparse or uneven. The reviewed literature demonstrates a clear methodological progression from conventional spherical harmonic solutions toward RL06 mascon products and increasingly integrated frameworks combining GRACE observations with hydrological models, remote sensing, geodetic measurements, and in situ groundwater data. These advances have improved the interpretation of regional water-storage variability, although important uncertainties remain due to coarse spatial resolution, signal leakage, differences among processing centres, dependence on ancillary model outputs, and limited field validation. Groundwater-storage changes across India are shown to reflect the combined influence of climatic variability, recharge, aquifer characteristics, irrigation practices, reservoir regulation, and groundwater abstraction, emphasizing the need for region-specific interpretation. Future research should prioritize multi-product comparison, multi-model ensembles, standardized validation, explicit uncertainty quantification, high-resolution multi-sensor integration, and physically informed machine-learning approaches. Greater attention is also required for underrepresented settings such as hard-rock aquifers, coastal groundwater systems, urban aquifers, Himalayan catchments, and transboundary basins. These advances

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have direct relevance to SDG 6 (Clean Water and Sanitation) through improved groundwater and water-resource monitoring, SDG 13 (Climate Action) through drought, flood, and climate-risk assessment, SDG 11 (Sustainable Cities and Communities) through land-subsidence and urban groundwater evaluation, and SDG 15 (Life on Land) through improved understanding of terrestrial water availability. Overall, GRACE and GRACE-FO are most effective when used as complementary components of integrated hydrological monitoring frameworks that support sustainable water-resources management and climate resilience in India.

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Kaushlandra Bairwa, Ajay Singh Jethoo and Aman Yadav contributed to the conceptualization and design of the review. Kaushlandra Bairwa conducted the literature search, data compilation, bibliometric analysis, and initial synthesis. Kaushlandra Bairwa prepared the original manuscript, and Ajay Singh Jethoo critically reviewed and revised the manuscript for important intellectual content. All three authors reviewed and approved the final manuscript.

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All authors have read, understood, and complied as applicable with the statement on "Ethical responsibilities of Authors"
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