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Groundwater Storage Regime Shifts and Delayed Response to Monsoon Rainfall in the Krishna River Basin: Insights from GRACE/GRACE-FO and In-Situ Observations

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ABSTRACT:
Groundwater storage in monsoon-dominated basins is governed by complex interactions between hydroclimatic variability, delayed recharge, and long-term storage transitions, which may be obscured by conventional trend analysis. This study investigated the spatiotemporal dynamics and hydroclimatic controls of groundwater storage in the Krishna River Basin, India, during 2002-2023 by integrating GRACE/GRACE Follow-On observations, GLDAS-derived soil-moisture and canopy-water storage, rainfall, and in-situ groundwater measurements. Groundwater storage anomalies (GWSA) were evaluated using spatial and seasonal analyses, non-parametric trend tests, multiple change-point detection, and contemporaneous and lagged hydroclimatic relationships. GRACE-derived GWSA showed strong positive correlation with in-situ estimates ($r = 0.762$), reliably capturing the major phases of groundwater depletion and recovery. Change-point analyses revealed four contrasting storage regimes: 2002-2005 (deficit), 2006-2014 (relative recovery), 2015-2020 (renewed depletion), and 2021-2023 (high-storage conditions), demonstrating that basin-scale groundwater evolution is better characterized by regime shifts than by a single monotonic trend. Spatial and seasonal patterns further revealed progressive pre-monsoon depletion followed by delayed post-monsoon and winter recovery. Notably, contemporaneous rainfall showed little association with GWSA ($r = -0.15$), whereas four-month antecedent rainfall exhibited a substantially stronger positive relationship ($r = 0.68$). This lagged relationship persisted across all four storage regimes ($r = 0.60$-0.82), providing consistent evidence of a delayed basin-scale groundwater response to monsoonal water input. The findings demonstrate that groundwater variability in the Krishna Basin is spatially heterogeneous, temporally non-stationary, and strongly dependent on antecedent hydroclimatic conditions. Incorporating storage-regime transitions and delayed rainfall response into groundwater assessment can therefore improve the interpretation of groundwater dynamics and support adaptive management in monsoon-dominated river basins.

1. INTRODUCTION

Groundwater is a critical component of the terrestrial hydrological cycle and supports irrigation, domestic supply, industry, and ecosystem functioning. Its role is particularly important in monsoon-dominated regions, where surface-water availability is highly seasonal and groundwater provides an essential buffer during dry periods and droughts (Panda et al., 2022). However, increasing water demand, expansion of irrigated agriculture, population growth, and hydroclimatic variability have altered groundwater systems worldwide. Persistent abstraction exceeding natural recharge can reduce groundwater storage and threaten water security, ecosystem services, and the sustainability of irrigated agriculture (Scanlon et al., 2023). Understanding the

temporal and spatial evolution of groundwater storage is therefore essential for effective water-resource management. Groundwater monitoring traditionally relies on water-level observations from monitoring wells (Adams et al., 2022; Masood et al., 2022). Although these measurements provide direct information on aquifer behaviour, their use for regional assessment is constrained by sparse and uneven monitoring networks, missing observations, variable measurement frequencies, and spatial heterogeneity in aquifer properties (Samani, 2024). Moreover, wells represent local groundwater conditions, whereas basin-scale assessments require spatially integrated information. This mismatch presents a major challenge for evaluating long-term groundwater dynamics in large and hydrogeologically heterogeneous river basins (Wu et al., 2025). Satellite gravimetry has considerably improved regional water-storage assessment. Since 2002, the Gravity Recovery and Climate Experiment (GRACE), followed by GRACE Follow-On (GRACE-FO), has provided observations of changes in the Earth's gravity field associated with redistribution of water mass (Chen et al., 2022; M. Kumar et al., 2024). These observations enable estimation of terrestrial water storage anomalies (TWSA) and have been widely applied to investigate groundwater depletion, drought, floods, and large-scale hydrological variability (Humphrey et al., 2023; Ji et al., 2025). GRACE provides spatially integrated observations that complement conventional monitoring networks, although its coarse spatial resolution, signal leakage, measurement uncertainty, and the temporal gap between GRACE and GRACE-FO remain important limitations (Chen et al., 2022; Karki et al., 2025; Khorrami & Gündüz, 2025). Because GRACE-derived TWSA represents the combined variation of surface and subsurface water stores, groundwater storage anomaly (GWSA) cannot be measured directly. Land-surface models such as the Global Land Data Assimilation System (GLDAS) provide estimates of soil-moisture and canopy-water storage that can be removed from TWSA to estimate groundwater-storage variations(Ibrahim et al., 2024).The integration of GRACE/GRACE-FO and GLDAS has therefore become an important approach for groundwater assessment, particularly in regions where spatially continuous observations are unavailable (Park et al., 2026). Nevertheless, independent validation remains necessary because uncertainties in both satellite observations and model-derived storage components propagate into GWSA estimates. In-situ groundwater measurements provide an important means of evaluating whether satellite-derived anomalies reproduce observed groundwater behaviour despite the inherent scale difference between point-based wells and basin-integrated satellite observations.

India is particularly important for groundwater assessment because of its extensive dependence on groundwater for irrigation, domestic supply, and economic activities (Panda et al., 2022). GRACE-based studies have documented substantial groundwater depletion in northern and northwestern India, particularly in regions affected by intensive abstraction (Dharpure et al., 2025; Rana & Chamoli, 2024). However, groundwater behaviour across India is highly heterogeneous, and patterns observed in persistently depleted northern aquifers cannot necessarily be extrapolated to monsoon-dominated peninsular basins. The Krishna River Basin represents a major monsoon-dependent hydrological system where groundwater conditions are influenced by seasonal rainfall, recurrent droughts, irrigation demand, and heterogeneous hydrogeological conditions. These interacting factors may produce alternating periods of groundwater depletion and recovery rather than a uniform long-term trajectory. Consequently, a single linear trend may conceal important transitions between contrasting groundwater-storage states. Identifying change points and distinct storage regimes can therefore provide a more realistic understanding of long-term groundwater behaviour(Samani, 2024). Rainfall-groundwater relationships further complicate this assessment because groundwater does not necessarily respond immediately to precipitation. Rainfall must pass through interception, soil-moisture replenishment, infiltration, and unsaturated-zone processes before contributing to groundwater recharge. Groundwater-storage responses may consequently occur several months after rainfall, with the response time varying according to climatic and hydrogeological conditions. Evaluating lagged rainfall-groundwater relationships alongside temporal regime changes can therefore provide greater insight than simultaneous correlations alone (Ahmad et al., 2026). Despite increasing applications of GRACE in India, an integrated understanding of long-term groundwater-storage variability, regime transitions, and delayed hydroclimatic response in the Krishna River Basin remains limited (M. Kumar et al., 2024; S. Kumar et al., 2022; Rana & Chamoli, 2024). In particular, distinguishing statistically different periods of groundwater deficit and recovery and determining the timescale at which rainfall variability is reflected in groundwater storage are important for understanding basin-scale groundwater behaviour (Srivastava & Dikshit, 2022).

Therefore, this study investigates groundwater-storage dynamics in the Krishna River Basin during 2002-2023 by integrating GRACE/GRACE-FO observations, GLDAS-derived storage components, rainfall data, and in-situ groundwater measurements. The study characterizes temporal and seasonal GWSA variability, validates satellite-derived estimates against ground observations, evaluates long-term trends, identifies change points and contrasting groundwater-storage regimes, and examines contemporaneous and lagged rainfall-groundwater relationships. By moving beyond a single long-term trend toward

an integrated assessment of storage transitions and delayed hydroclimatic response, the study provides a more comprehensive framework for understanding and monitoring groundwater variability in a major monsoon-dominated river basin.

2. MATERIALS AND METHODS

2.1 Study Area

The Krishna River Basin, a major basin of peninsular India, extends between 13°07'–19°25' N and 73°21'–81°09' E, covering approximately 258,948 km² (Figure 1). The Krishna River originates near Mahabaleshwar in the Western Ghats and flows about 1,400 km eastward to the Bay of Bengal. The basin mainly covers Maharashtra, Karnataka, Telangana, and Andhra Pradesh and includes major tributaries such as the Bhima and Tungabhadra. Its hydroclimate is strongly controlled by the southwest monsoon, resulting in pronounced seasonal and interannual rainfall variability. Much of the basin is underlain by heterogeneous hard-rock aquifers, where groundwater occurrence depends on weathering and fractures. Intensive irrigation, groundwater abstraction, recurrent droughts, and monsoon variability make the basin suitable for investigating long-term groundwater-storage dynamics using GRACE/GRACE-FO observations. Figure 2 shows the complete methodology framework.

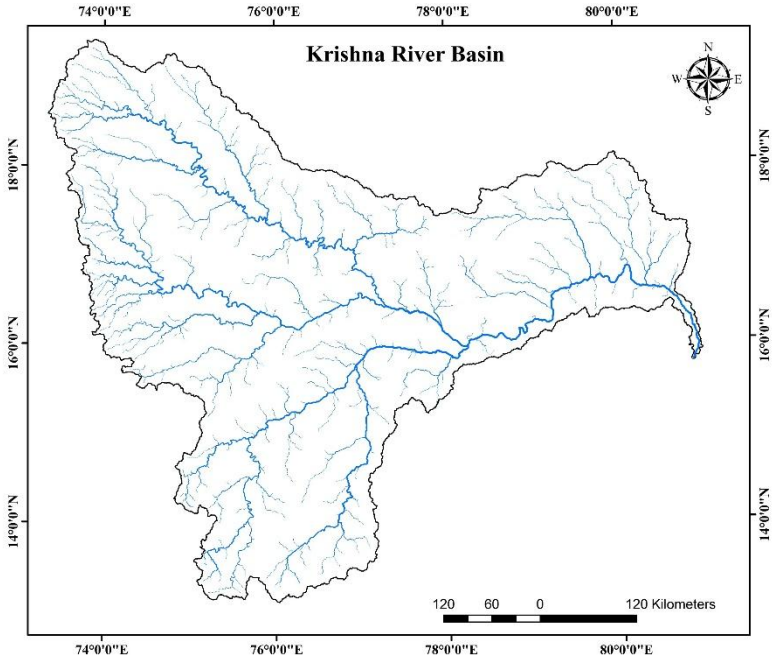

Figure 1 Study Area Map

2.2 Data Sources

A multi-source dataset covering 2002-2023 was assembled to characterize terrestrial and groundwater-storage dynamics in the Krishna River Basin. All datasets are shown in Table 1.

Table 1. Data Sources

Dataset	Variable	Temporal/Spatial resolution
GRACE/GRACE-FO	Terrestrial Water Storage Anomaly (TWSA)	Monthly / 0.25° × 0.25°
GLDAS-Noah	Soil Moisture Anomaly (SMA)	Monthly / 0.25° × 0.25°
GLDAS-Noah	Canopy Water Anomaly (CWA)	Monthly / 0.25° × 0.25°

IMD	Precipitation	Daily
In-situ monitoring wells (CGWB)	Groundwater level	Available observation frequency
Specific yield data (CGWB)	Specific yield (Sy)	-

2.3 Estimation of Groundwater Storage Anomaly

GRACE/GRACE-FO measures vertically integrated terrestrial water-storage variations and therefore does not directly represent groundwater storage. Groundwater storage anomaly was estimated by removing the GLDAS-derived soil-moisture and canopy-water components from TWSA. Snow-water storage was not included because its contribution within the Krishna River Basin is negligible. Monthly GWSA was calculated as equation 1:

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

where GWSA is groundwater storage anomaly, TWSA is terrestrial water storage anomaly, SMA is soil moisture anomaly, and CWA is canopy water anomaly. The resulting GWSA represents groundwater-storage deviations relative to the reference condition of the input datasets, with positive values indicating above-reference storage and negative values representing groundwater-storage deficits.

2.4 In-situ Groundwater Validation

The reliability of GRACE/GRACE-FO-derived GWSA was evaluated using groundwater-level observations from 510 monitoring wells obtained from the Central Ground Water Board (CGWB). The groundwater level fluctuation change (Δh) was used to compute the GWSA derived from these observation wells (GWSAobs) by multiplying with corresponding specific yield (Sy) values (equation 2).

$$GWSA_{obs,\,i} = \Delta h_i \times S_{y,\,i} \quad (2)$$

where $GWSA_{obs,\,i}$ is the groundwater storage anomaly at well i, Δh_i is the groundwater-level anomaly relative to the reference condition, and $S_{y,\,i}$ is the specific yield assigned to that well. The individual well-based storage anomalies were subsequently aggregated to obtain a representative basin-scale GWSA series for comparison with GRACE/GRACE-FO estimates.

Agreement between observation-derived and satellite-derived GWSA was assessed using the Pearson correlation coefficient (r) (equation 3):

$$r = \frac{\sum_{i=1}^{n}(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^{n}(X_i - \bar{X})^2 \sum_{i=1}^{n}(Y_i - \bar{Y})^2}} \quad (3)$$

where X_i and Y_i represent observed and GRACE/ GRACE-FO derived GWSA, respectively. The validation was performed before using the satellite-derived GWSA for temporal, spatial, and trend analyses.

2.5 Temporal and Seasonal Analysis

Temporal variability in groundwater storage was evaluated using monthly and annual GWSA over the study period. Annual GWSA was calculated from the corresponding monthly anomalies to characterize interannual variations and identify periods of groundwater depletion and recovery. Seasonal variability was assessed by grouping monthly GWSA into four climatological seasons: winter (December-February), pre-monsoon (March-May), monsoon (June-September), and post-monsoon (October-November). Seasonal GWSA was calculated by averaging the monthly anomalies within each season for each year. The same seasonal classification was applied to GRACE/GRACE-FO-derived and in-situ GWSA to enable direct comparison of their seasonal variability.

To minimize the influence of the recurring seasonal cycle on long-term trend and change-point detection, monthly GWSA was deseasonalized by subtracting the corresponding long-term monthly climatological mean from each monthly observation (equation 4):

$$GWSA'_{m,y} = GWSA_{m,y} - GWSA_m \quad (4)$$

where $GWSA'_{m,y}$ is the deseasonalized anomaly for month m in year y, $GWSA_{m,y}$ is the original monthly anomaly, and $GWSA_m$ is the long-term climatological mean for the corresponding calendar month. The deseasonalized monthly anomalies were subsequently aggregated to annual values and used for long-term trend, Pettitt, multiple change-point, and Sequential Mann-Kendall analyses.

2.6 Spatial Variation of Groundwater Storage

The spatial distribution of GWSA was analysed to identify geographical differences in groundwater-storage conditions across the Krishna River Basin. Spatially distributed monthly GWSA estimates were aggregated over relevant temporal periods to characterize persistent groundwater-storage deficits and areas exhibiting comparatively favourable storage conditions. Spatial patterns were compared across different periods to evaluate changes in groundwater-storage behaviour over the study duration. This analysis complemented the basin-averaged temporal assessment by identifying spatial heterogeneity that could not be represented by a single basin-scale time series.

2.7 Trend Analysis

Long-term groundwater-storage trends were evaluated using the non-parametric Mann-Kendall (MK) test together with Sen's slope estimator. The MK test was used to determine the direction and statistical significance of monotonic changes without requiring the data to follow a normal distribution. For a time series $x_1, x_2, \ldots, x_n$, the MK statistic was calculated as (equation 5):

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}(x_j - x_i) \quad (5)$$

where a positive value of S indicates an increasing tendency and a negative value indicates a decreasing tendency. The magnitude of change was estimated using Sen's slope (equation 6):

$$\beta = median_{j>i}\left(\frac{x_j - x_i}{j - i}\right) \quad (6)$$

The combination of the MK test and Sen's slope therefore provided information on both the statistical significance and magnitude of long-term groundwater-storage changes.

2.8 Change-Point Analysis

Change-point analysis was performed on the deseasonalized annual GWSA series to identify significant transitions in groundwater-storage behaviour that could be obscured by a single long-term trend. Three complementary approaches were employed: the Pettitt test, dynamic-programming multiple change-point detection with Bayesian Information Criterion (BIC) model selection, and Sequential Mann-Kendall (SMK) analysis. The non-parametric Pettitt test was first applied to identify the dominant abrupt change in the GWSA series. Multiple change points were subsequently detected using a dynamic-programming segmentation approach, in which the time series was partitioned into contiguous segments by minimizing the total within-segment sum of squared errors (SSE), assuming a constant mean within each segment. A minimum segment length of three years was imposed to avoid unrealistically short groundwater-storage regimes. Candidate solutions containing zero to five change points were evaluated, and the optimal configuration was selected using BIC, with the solution yielding the minimum BIC retained as the most parsimonious representation of the temporal structure. The identified transitions were further examined using SMK analysis. Progressive (UF) and backward (UB) sequential Mann-Kendall statistics were calculated through time, and intersections between the UF and UB curves were considered complementary evidence of potential changes in groundwater-storage behaviour. The combined application of Pettitt, dynamic-programming segmentation, BIC model

selection, and SMK analysis enabled the identification of model-supported groundwater-storage transitions and distinct temporal regimes without assuming a single monotonic trajectory throughout 2002-2023.

2.9 Lagged Rainfall and Hydroclimatic Correlation Analysis

Pearson correlation analysis was used to evaluate the relationships between GWSA and rainfall, soil moisture anomaly (SMA), canopy water anomaly (CWA), and terrestrial water storage anomaly (TWSA). To quantify the delayed groundwater response to precipitation, rainfall was shifted relative to GWSA over monthly lags ranging from 0 to 12 months, and the Pearson correlation coefficient was calculated at each lag. The lag yielding the strongest positive rainfall-GWSA correlation was identified as the characteristic basin-scale response lag. This analysis identified a four-month lag (Rainfall Lag-4), which was subsequently used to represent antecedent rainfall. Correlations between GWSA and the hydroclimatic variables were also evaluated separately for the groundwater-storage regimes identified through change-point analysis to assess whether these relationships persisted under contrasting storage conditions. The identified four-month lag was interpreted as a basin-scale statistical response time rather than a uniform physical recharge time because of the hydrogeological heterogeneity of the Krishna River Basin.

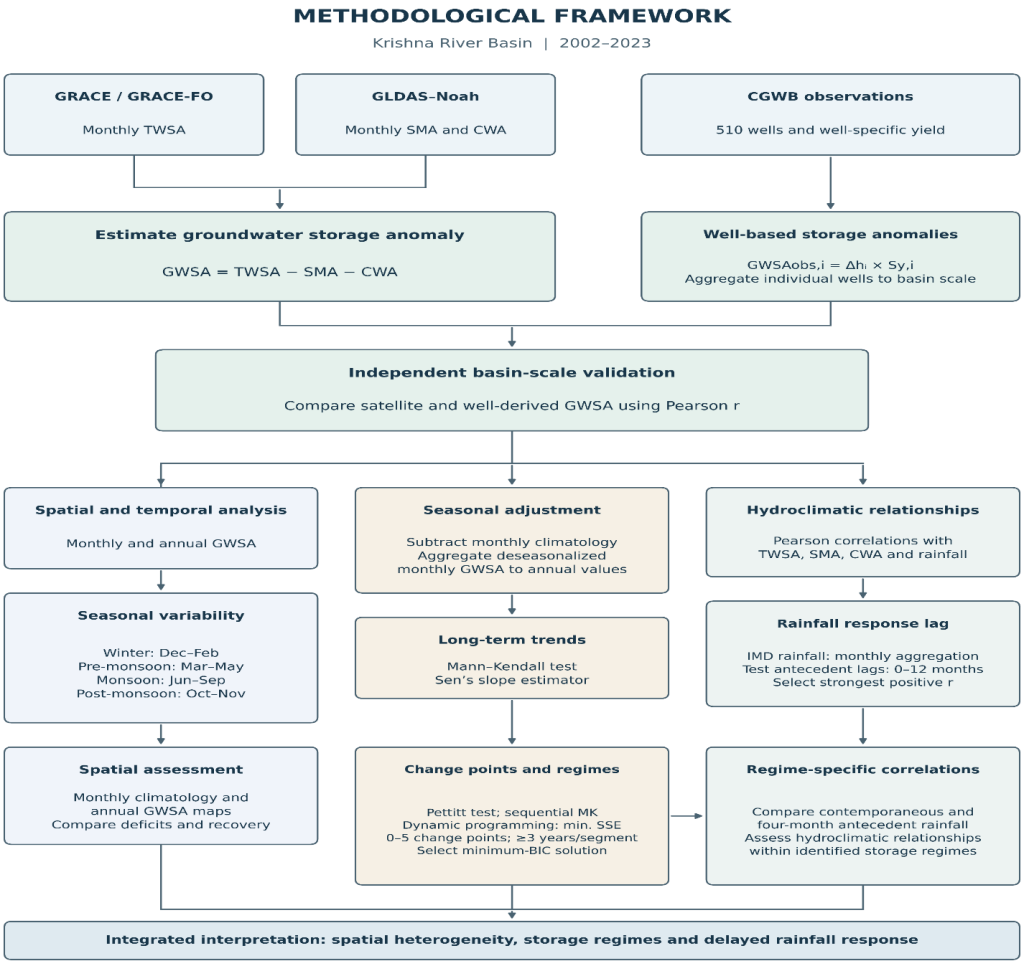

Figure 2 Methodological framework for the integrated assessment of groundwater storage dynamics in the Krishna River Basin (2002-2023)

3. RESULTS

3.1 Temporal Variability of Groundwater Storage and Hydroclimatic Conditions

Groundwater storage in the Krishna River Basin showed pronounced interannual variability during 2002-2023, with alternating periods of deficit and recovery (Figure 3). TWSA and GWSA generally exhibited coherent temporal behaviour, although TWSA showed larger fluctuations. Both anomalies declined during the early 2000s, reaching approximately −60 mm (TWSA) and −50

mm (GWSA) in 2004, indicating widespread water-storage deficits. Conditions improved after 2005, with predominantly positive anomalies during 2006-2014 and a notable GWSA peak of about 60 mm in 2011. A renewed decline occurred after 2014. TWSA remained strongly negative during 2015-2019 and reached the lowest value of the record in 2017 (approximately −155 mm), while GWSA also showed persistent deficits, particularly during 2016-2017 and 2019. A pronounced reversal occurred after 2019, with both storage components increasing rapidly. GWSA exceeded 100 mm during 2021 and reached its maximum of approximately 130 mm in 2022, accompanied by the highest TWSA (~140 mm). Although storage decreased in 2023, anomalies remained strongly positive, indicating persistence of the recent high-storage conditions. Annual rainfall varied substantially throughout the study period but did not show a consistent year-to-year correspondence with GWSA. High rainfall was not always accompanied by an immediate increase in groundwater storage, while the pronounced post-2020 recovery followed successive relatively wet years. This temporal mismatch suggests that groundwater storage responds to rainfall with a delay rather than instantaneously, providing the basis for subsequent analysis of antecedent rainfall and lagged groundwater response.

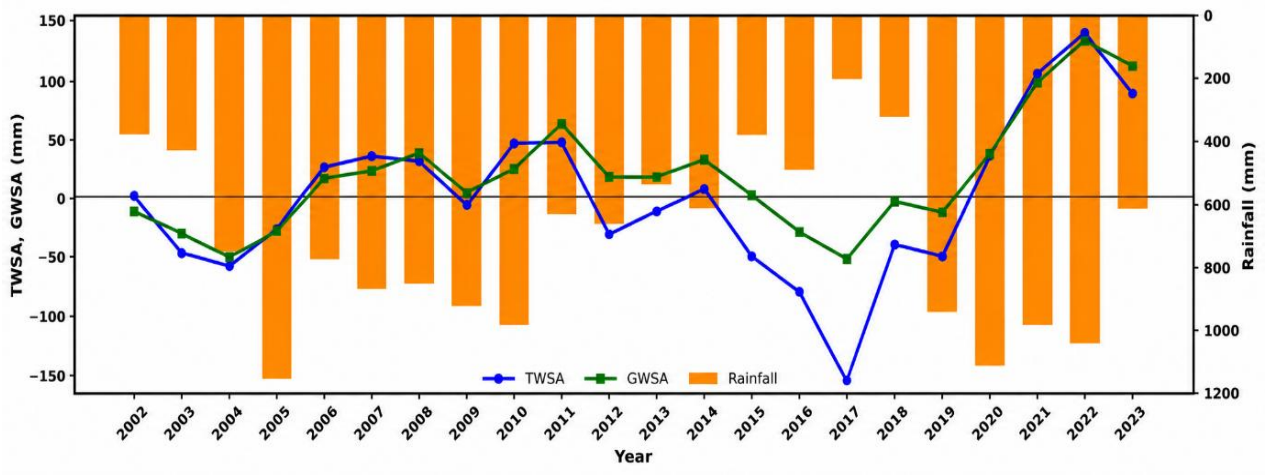

Figure 3 Interannual variability of terrestrial water storage anomaly (TWSA), groundwater storage anomaly (GWSA), and annual rainfall in the Krishna River Basin during 2002-2023. Rainfall is shown on the inverted secondary y-axis.

3.2 Spatial Variability of Groundwater Storage

The spatial distribution of groundwater storage anomaly (GWSA) showed pronounced seasonal and interannual variability across the Krishna River Basin (Figure 4). Monthly climatological maps revealed a clear annual storage cycle. Positive GWSA generally prevailed during November-February, followed by progressive depletion during March and April. Groundwater deficits intensified during May-June, with June showing the most widespread negative anomalies, particularly across the western, central, and southern parts of the basin. Despite the onset of monsoon rainfall, negative anomalies persisted during July, indicating that groundwater recharge did not occur immediately. Storage conditions improved during August, while widespread positive anomalies developed during September-November. This seasonal progression indicates a delayed groundwater response to monsoonal water input, consistent with the lagged rainfall response identified in the temporal analysis. Annual GWSA maps further revealed substantial spatial reorganization during 2002-2023 (Figure 5). The early period (2002-2005) was dominated by negative anomalies, with extensive groundwater deficits across the central, eastern, and southern parts of the basin. Conditions improved after 2005, and positive anomalies expanded across much of the basin during 2006-2014, although considerable interannual variability remained. Particularly favourable storage conditions occurred around 2011, when positive GWSA covered large portions of the central and eastern basin.

Groundwater conditions deteriorated again after 2014. Negative anomalies became increasingly widespread during 2016-2019 and were particularly pronounced in 2017, especially across the western, central, and southern basin. A major reversal occurred after 2019, with positive GWSA expanding substantially in 2020 and becoming widespread during 2021-2023. The strongest basin-wide positive storage condition occurred in 2022, with particularly high anomalies over the central and southern regions. Although storage decreased somewhat in 2023, positive anomalies remained widespread. Overall, the spatial patterns reveal a distinct transition from early groundwater deficits (2002-2005), relative recovery (2006-2014), renewed depletion (2015-2020),

and a recent high-storage state (2021-2023). The monthly maps additionally demonstrate progressive pre-monsoon depletion followed by delayed post-monsoon recovery. These spatial patterns complement the basin-averaged temporal analysis and provide geographical evidence for the contrasting groundwater-storage regimes identified in the subsequent change-point analysis.

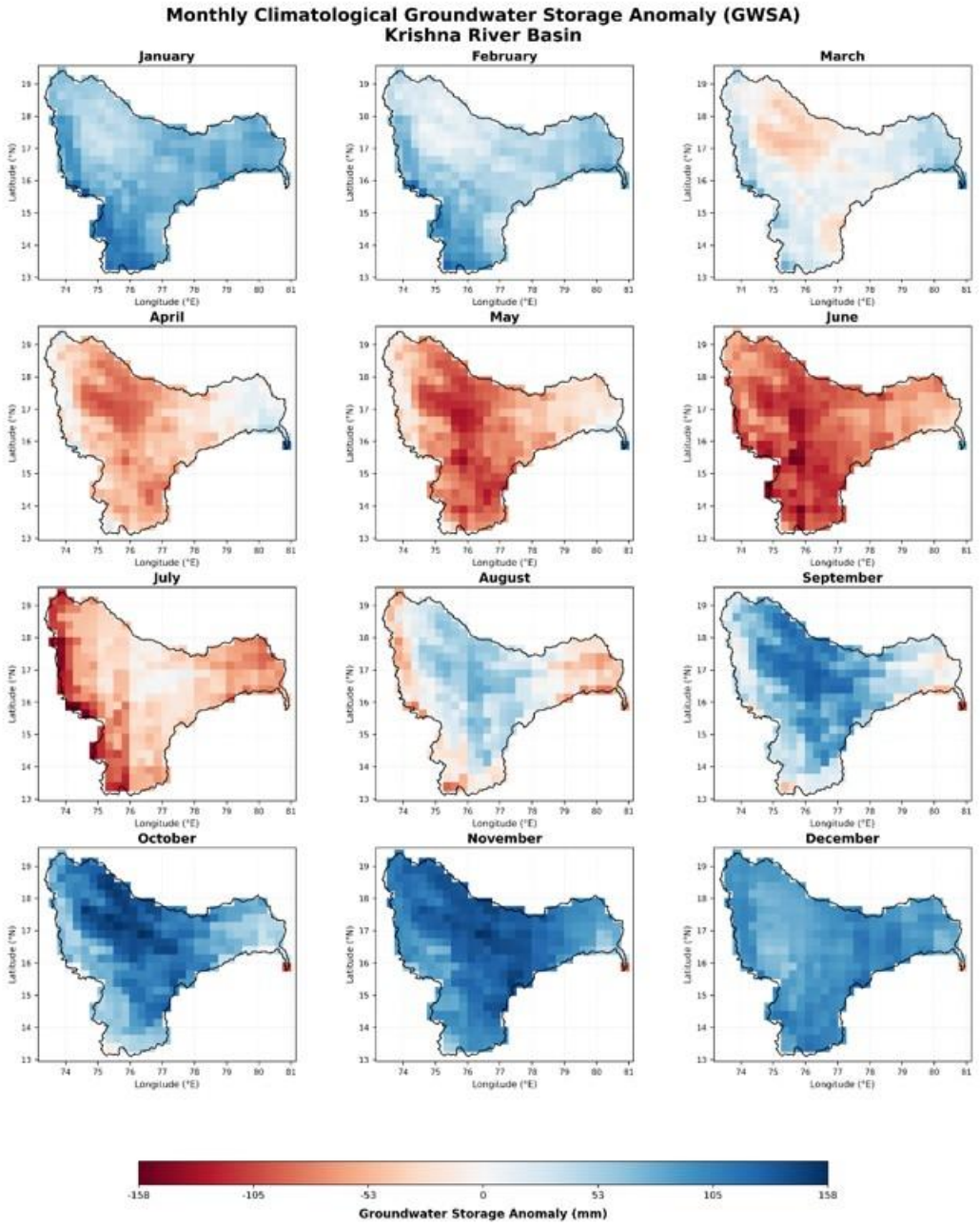

Figure 4 Monthly climatological spatial distribution of groundwater storage anomaly (GWSA) across the Krishna River Basin during 2002–2023, showing seasonal groundwater depletion and recovery patterns.

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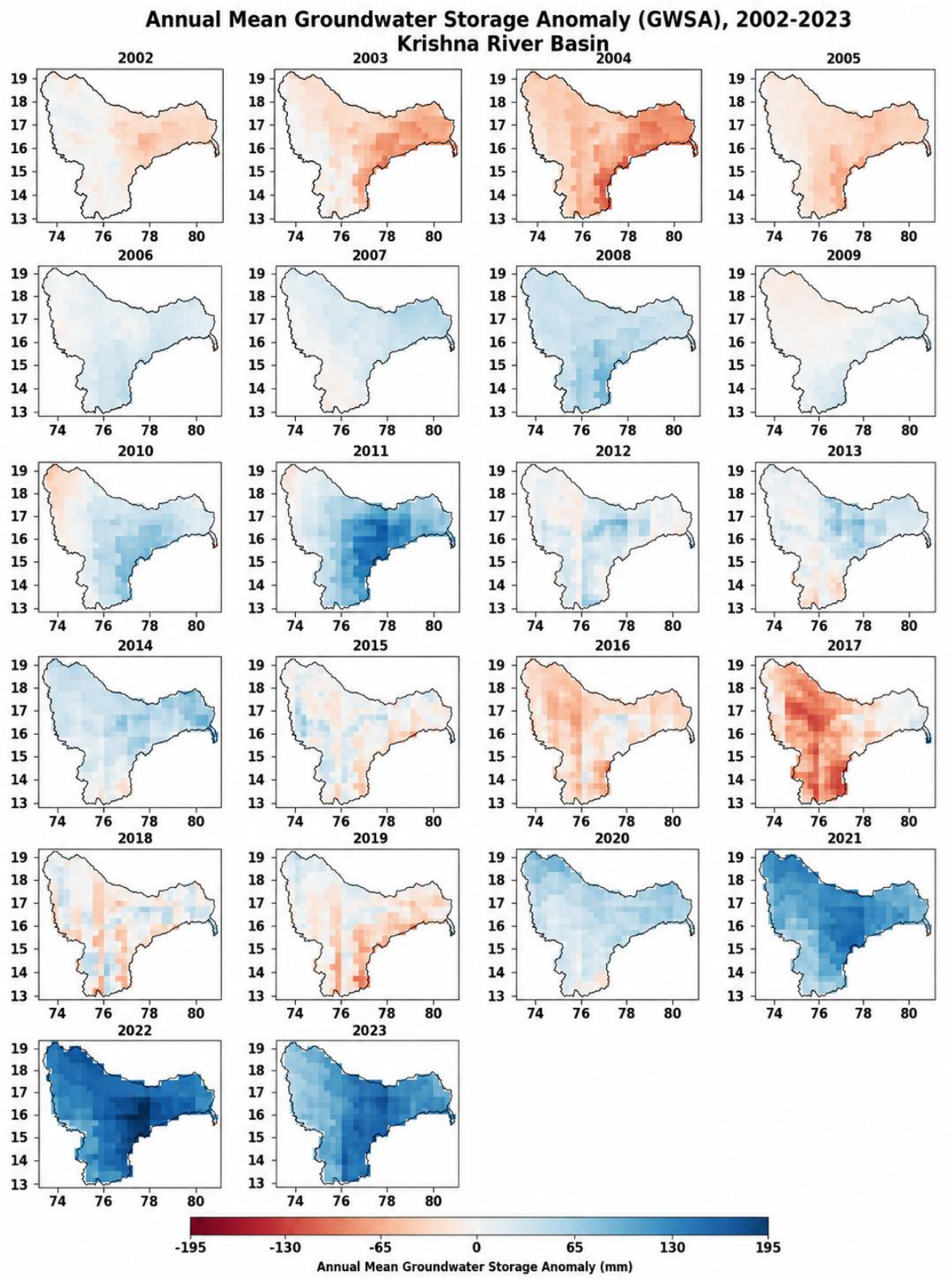

Figure 4 Spatial distribution of annual mean groundwater storage anomaly (GWSA) across the Krishna River Basin during 2002-2023, illustrating interannual variability and transitions between groundwater deficit and recovery periods.

3.3 Validation of GRACE/GRACE-FO-Derived Groundwater Storage Anomalies

The GRACE/GRACE-FO-derived GWSA was evaluated against groundwater storage anomalies obtained from in-situ observations to assess its ability to represent basin-scale groundwater variability (Figure 6). The two datasets showed a strong positive association, with a Pearson correlation coefficient of r = 0.762. The positive slope of the fitted regression line further demonstrates that increases and decreases in observed groundwater storage were generally reproduced by the satellite-derived estimates. The temporal comparison also showed broad agreement in the direction of major groundwater-storage variations. Both observed and GRACE-derived GWSA indicated negative groundwater conditions during the early 2000s, followed by improvement after approximately 2005. Similarly, both datasets captured the deterioration in groundwater conditions during the latter half of the 2010s and the pronounced recovery beginning around 2020. The observed series increased from negative anomalies around 2019 to approximately 30 mm during 2020-2022, while GRACE-derived GWSA showed a considerably stronger increase over the same period, reaching more than 130 mm in 2022. Despite the strong overall correspondence, differences in magnitude were evident between the two estimates. GRACE-derived GWSA generally exhibited a larger amplitude than the observation-based series, particularly during years characterized by strong positive or negative anomalies. This divergence was especially apparent around 2011, 2017, and 2021-2023. For example, the satellite-derived series showed a pronounced negative anomaly of approximately −50 mm in 2017 and a strong positive anomaly exceeding 130 mm in 2022, whereas the corresponding in-situ estimates displayed considerably smaller variations. Consequently, the agreement was stronger in terms of the direction and temporal evolution of groundwater-storage variability than in the absolute magnitude of individual annual anomalies. Nevertheless, the correlation of 0.762 demonstrates that GRACE/GRACE-FO-derived GWSA captures a substantial component of the observed groundwater-storage variability at the basin scale. The validation therefore provides support for using the satellite-derived GWSA series in the subsequent trend, change-point, groundwater regime, and hydroclimatic-control analyses.

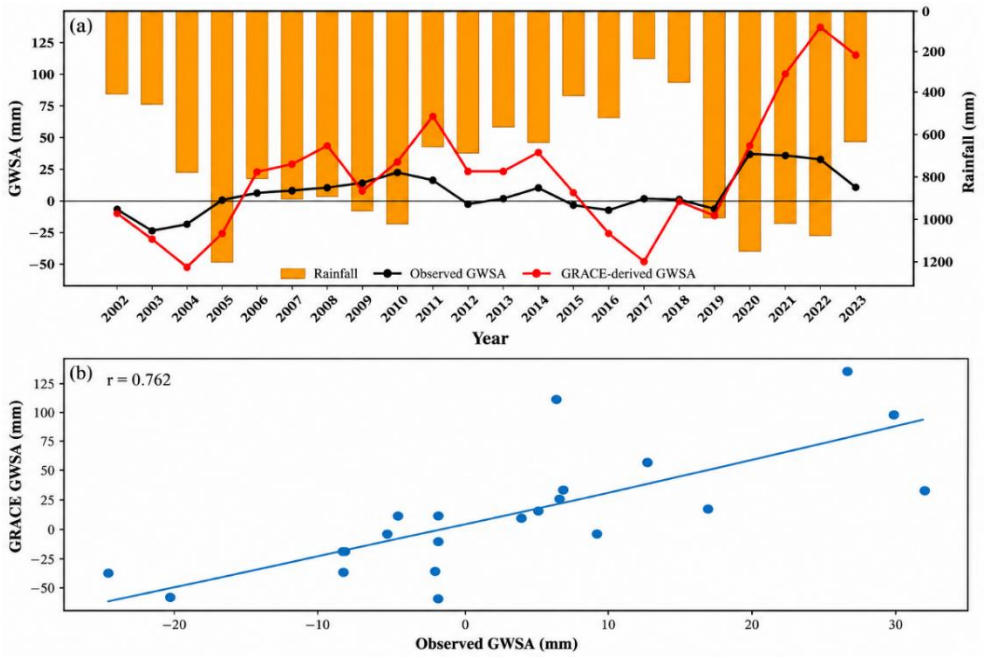

Figure 5 Validation of GRACE/GRACE-FO-derived groundwater storage anomalies against in-situ groundwater observations in the Krishna River Basin during 2002-2023: (a) temporal comparison of observed GWSA, GRACE-derived GWSA, and annual rainfall. (b) relationship between observed and GRACE-derived GWSA.

3.4 Seasonal Variability of Groundwater Storage

Seasonal analysis revealed pronounced variability in groundwater storage across the Krishna River Basin during 2002-2023 (Figure 7). Pre-monsoon conditions were predominantly characterized by negative GWSA, reflecting progressive groundwater depletion during the dry period when recharge is limited. Although GRACE-derived anomalies showed greater interannual

variability than the in-situ estimates, both datasets indicated substantial improvement after 2020. During the monsoon season, GWSA remained highly variable and did not show an immediate or consistent increase with rainfall onset. GRACE-derived GWSA remained negative during several monsoon years, indicating that monsoonal precipitation was not instantaneously translated into groundwater-storage gains. In contrast, post-monsoon conditions were predominantly positive, with substantially higher GWSA particularly after 2019. Positive storage conditions also persisted into winter, with pronounced increases during 2020-2023. The stronger post-monsoon and winter anomalies relative to those during the monsoon indicate that groundwater replenishment generally continued beyond the principal rainfall season.

This seasonal progression provides evidence of a delayed basin-scale groundwater response to monsoonal water input. Rainfall likely first replenishes soil and near-surface storage before percolating through the unsaturated zone and contributing to groundwater recharge. Conversely, declining recharge and continued groundwater losses contribute to the predominantly negative pre-monsoon conditions. Despite differences in anomaly magnitude, GRACE/GRACE-FO and in-situ observations reproduced the broad seasonal evolution and recent storage recovery. These seasonal patterns therefore support the subsequent lag analysis, which further evaluates the delayed relationship between antecedent rainfall and groundwater-storage variability.

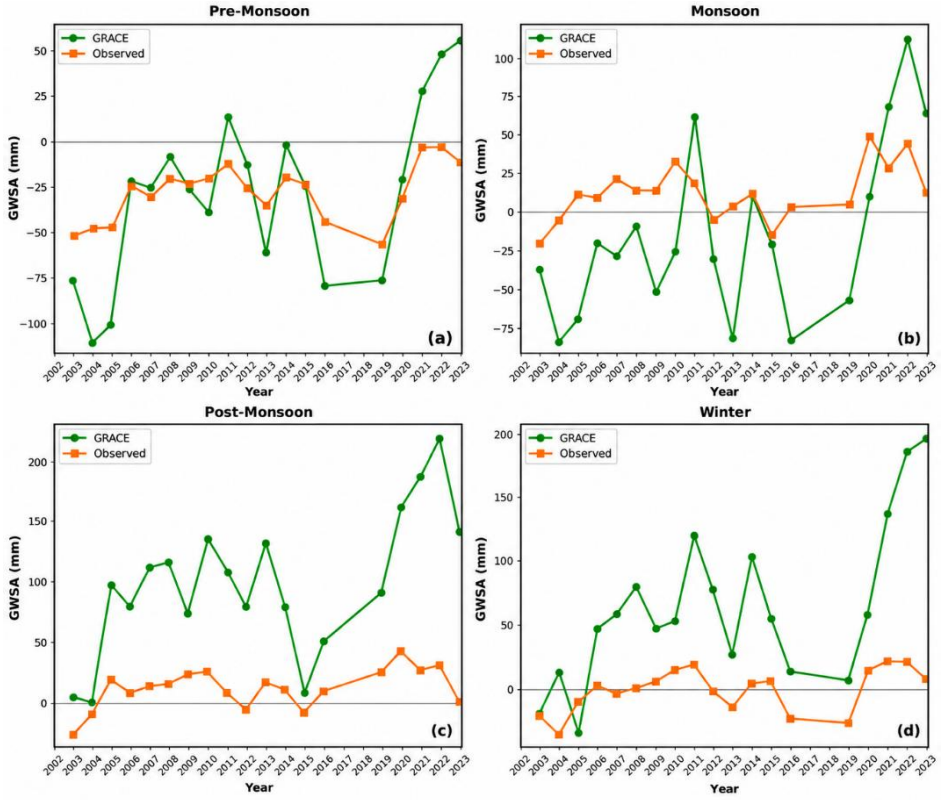

Figure 6 Seasonal comparison of GRACE/GRACE-FO-derived and in-situ groundwater storage anomalies (GWSA) in the Krishna River Basin during 2002–2023: (a) pre-monsoon, (b) monsoon, (c) post-monsoon, and (d) winter.

3.5 Long-Term Trends and Groundwater Storage Regime Shifts

Long-term analysis of deseasonalized annual GWSA revealed pronounced non-stationary behaviour in the Krishna River Basin during 2002–2023 (Figure 8). The Pettitt test identified 2005 as a potential transition point ($p = 0.122$), although this change was not statistically significant at the 95% confidence level. Before this transition, mean GWSA was approximately −59.3 mm, with a declining trend of −5.16 mm yr^{-1}. In contrast, the post-2005 period exhibited a substantially higher mean GWSA of 10.3 mm and an increasing trend of 2.03 mm yr^{-1}, indicating an overall shift from groundwater deficit toward recovery, despite considerable interannual variability. The post-2005 period was not homogeneous. The dynamic-programming change-point analysis, evaluated using BIC, identified the minimum BIC (−23.84) for a three-change-point solution, supporting four distinct groundwater-storage regimes with transitions around 2005/2006, 2014/2015, and 2020/2021. The 2002–2005 regime represented the initial low-storage state, with consistently negative anomalies. During 2006–2014, groundwater conditions

improved markedly, with the mean shifting toward positive storage despite year-to-year fluctuations. This recovery was interrupted during 2015–2020, when GWSA again became predominantly negative, indicating renewed groundwater-storage stress.

The most pronounced model-identified transition occurred around 2020–2021, initiating a distinctly positive 2021–2023 regime. Deseasonalized GWSA increased to approximately 78 mm in 2021, exceeded 110 mm in 2022, and remained above 80 mm in 2023, representing the highest-storage state within the study period. Accordingly, median storage was negative during 2002–2005 and 2015–2020, positive during 2006–2014, and strongly positive during 2021–2023. The Sequential Mann–Kendall analysis further indicated multiple intersections between the forward and backward statistics, suggesting potential changes in groundwater-storage behaviour. Collectively, the Pettitt, BIC-based change-point, and sequential trend analyses suggest that groundwater evolution in the Krishna Basin is better characterized by successive contrasting storage regimes rather than a single monotonic long-term trend.

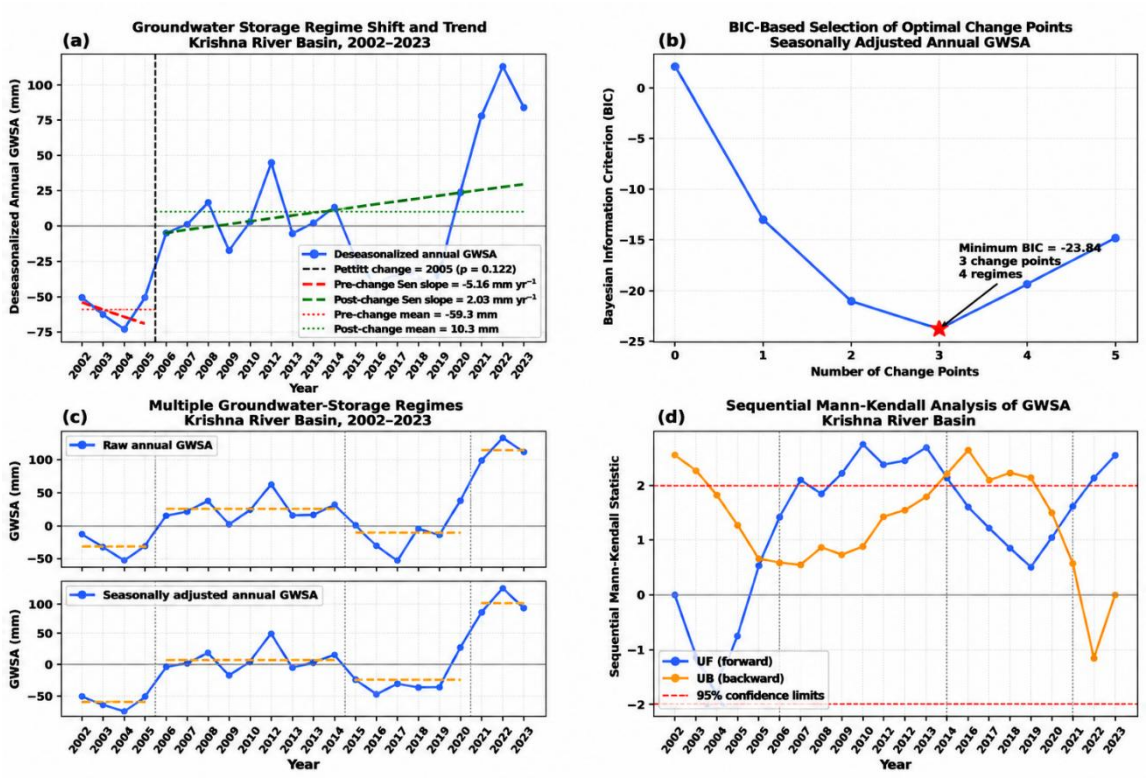

Figure 8. Long-term groundwater-storage trends and regime shifts in the Krishna River Basin (2002–2023): (a) Pettitt change-point analysis and Sen's slopes; (b) BIC-based change-point selection; (c) raw and seasonally adjusted GWSA with regime means; and (d) Sequential Mann–Kendall analysis with 95% confidence limits.

3.6 Hydroclimatic Controls and Delayed Rainfall Response of Groundwater Storage

Correlation analysis revealed marked differences in the relationships between GWSA and the individual hydroclimatic variables (Figure 9). Among the analysed variables, TWSA showed a strong positive association with GWSA ($r = 0.81$), reflecting their expected covariance because TWSA contributes directly to the derivation of GWSA. In contrast, the relationship between contemporaneous rainfall and GWSA was weak and slightly negative ($r = -0.15$), demonstrating that groundwater-storage variations were not directly synchronized with rainfall occurring during the same month. A substantially different relationship emerged when antecedent rainfall was considered. Rainfall shifted by four months showed a strong positive correlation with GWSA ($r = 0.68$), compared with only $r = -0.15$ for contemporaneous rainfall. Thus, incorporating the previously identified four-month lag substantially strengthened the rainfall-groundwater relationship. This result demonstrates a delayed response of basin-scale groundwater storage to rainfall and indicates that antecedent precipitation provides a more representative hydroclimatic indicator of GWSA variability than simultaneous rainfall.

The terrestrial storage components showed contrasting relationships with groundwater storage. SMA was positively correlated with GWSA (r = 0.29), whereas CWA exhibited a weak-to-moderate negative relationship (r = −0.27). The correlation structure among the explanatory variables was also pronounced. Rainfall was strongly correlated with CWA (r = 0.90) and positively associated with SMA (r = 0.72), whereas SMA was strongly related to TWSA (r = 0.79). These interrelationships indicate substantial covariance among the different components of the basin water-storage system. The importance of the delayed rainfall response was also evident when the analysis was performed separately for the four groundwater-storage regimes (Figure 9b). The correlation between contemporaneous rainfall and GWSA remained weak or negative during the first three regimes, with coefficients of −0.22, −0.35, and −0.15 for 2002-2005, 2006-2014, and 2015-2020, respectively. During 2021-2023, the corresponding relationship was only weakly positive (r = 0.09). In contrast, four-month lagged rainfall maintained a consistently positive relationship with GWSA in every regime, with correlations of 0.80, 0.75, 0.82, and 0.60, respectively.

The strongest lagged rainfall-GWSA relationship occurred during the 2015-2020 regime (r = 0.82), closely followed by 2002-2005 (r = 0.80). Although the strength decreased during the recent 2021-2023 recovery period, the relationship remained moderately positive (r = 0.60). The persistence of positive correlations across all four regimes indicates that the delayed rainfall response was not confined to a single storage phase but remained a consistent characteristic of groundwater variability throughout the study period. TWSA exhibited an even more stable relationship with groundwater storage across the four regimes. The regime-specific TWSA-GWSA correlations were 0.80, 0.77, 0.80, and 0.81, respectively. In comparison, SMA showed weaker but consistently positive correlations with GWSA (r = 0.43, 0.27, 0.33, and 0.29), while CWA remained

negatively associated with GWSA in all regimes (r = −0.27, −0.36, −0.32, and −0.30). Collectively, these results show that groundwater-storage variability in the Krishna River Basin was more closely associated with antecedent rainfall and terrestrial water-storage conditions than with contemporaneous rainfall. In particular, the increase in rainfall-GWSA correlation from −0.15 at zero lag to 0.68 at a four-month lag, together with consistently positive regime-specific lagged correlations of 0.60-0.82, provides clear evidence of a temporally delayed groundwater response.

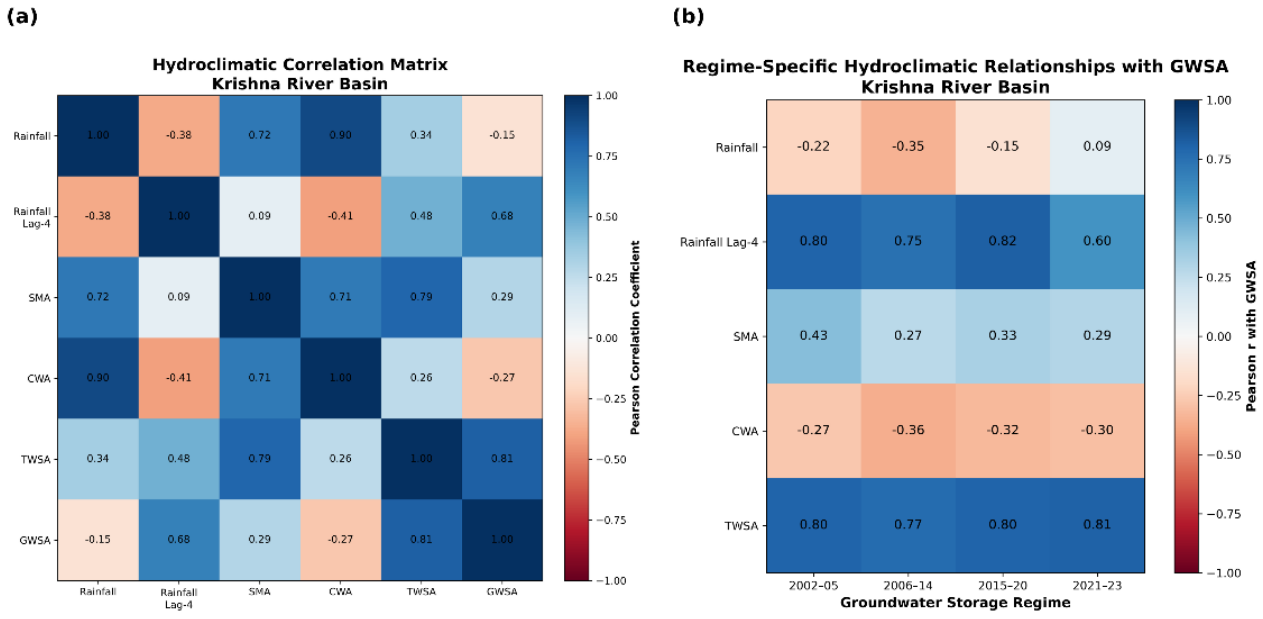

Figure 9. Hydroclimatic controls on groundwater storage anomaly (GWSA) in the Krishna River Basin: **(a)** Pearson correlation matrix among rainfall, four-month lagged rainfall (Rainfall Lag-4), soil moisture anomaly (SMA), canopy water anomaly (CWA), terrestrial water storage anomaly (TWSA), and GWSA; and **(b)** regime-specific Pearson correlations of GWSA with hydroclimatic variables across the four identified groundwater-storage regimes (2002-2005, 2006-2014, 2015-2020, and 2021-2023).

4. DISCUSSION

Groundwater storage in the Krishna River Basin exhibited pronounced non-stationary behaviour during 2002-2023, with alternating periods of depletion and recovery. Change-point analyses identified four distinct regimes: 2002-2005, 2006-2014, 2015-2020, and 2021-2023. The initial groundwater deficit was followed by relative recovery during 2006-2014, renewed depletion during 2015-2020, and a pronounced positive shift after 2020. The Pettitt test identified 2005 as a potential transition point, although it was not statistically significant ($p = 0.122$), while BIC-based analysis supported transitions around 2005/2006, 2014/2015, and 2020/2021. These results demonstrate that groundwater evolution is better represented by contrasting storage regimes than by a single monotonic trend. Spatial and seasonal patterns supported these temporal transitions. Widespread deficits occurred during the early 2000s and mid-to-late 2010s, whereas positive anomalies expanded substantially after 2020. Seasonally, groundwater storage declined during the pre-monsoon period, with pronounced deficits during May-June that frequently persisted into July despite monsoon onset(Saha et al., 2026). Storage subsequently improved and became predominantly positive during the post-monsoon and winter periods, suggesting that groundwater replenishment continues beyond the principal rainfall season. This delayed response was confirmed by the rainfall-GWSA relationships. Contemporaneous rainfall showed only a weak correlation with GWSA ($r = -0.15$), whereas four-month antecedent rainfall exhibited a substantially stronger positive relationship ($r = 0.68$). Importantly, lagged rainfall remained positively correlated with GWSA across all four storage regimes ($r = 0.60$-0.82), demonstrating that delayed groundwater response is a persistent basin-scale characteristic. This behaviour is hydrologically plausible because monsoon rainfall must replenish near-surface and soil-water deficits before infiltration and deep percolation contribute to groundwater storage. The four-month lag should, however, be interpreted as a basin-scale effective response rather than a uniform aquifer recharge time because of substantial hydrogeological heterogeneity across the basin.

Independent validation further strengthened confidence in the satellite-derived estimates. GRACE/GRACE-FO-derived GWSA correlated strongly with in-situ observations ($r = 0.762$) and reproduced the principal periods of depletion and recovery, although GRACE exhibited larger anomaly amplitudes because satellite and well observations represent different spatial scales. The pronounced 2021-2023 positive anomalies therefore represent a recent high-storage regime rather than evidence of permanent groundwater recovery. Uncertainties associated with GRACE and GLDAS components, spatial-scale differences, missing observations, and the absence of consistent groundwater-abstraction data limit climatic-anthropogenic attribution. Nevertheless, the combined evidence demonstrates that groundwater storage in the Krishna Basin is spatially heterogeneous, temporally non-stationary, and strongly influenced by antecedent hydroclimatic conditions, highlighting the importance of incorporating regime shifts and delayed rainfall response into basin-scale groundwater assessment and management.

5. CONCLUSIONS

This study provides an integrated assessment of groundwater-storage dynamics in the Krishna River Basin during 2002-2023 using GRACE/GRACE-FO, GLDAS, rainfall, and in-situ groundwater observations. The results demonstrate that groundwater storage is characterized by pronounced spatial and temporal variability and does not follow a single monotonic trajectory. Instead, four distinct storage regimes were identified: 2002-2005, characterized by groundwater deficit; 2006-2014, representing relative recovery; 2015-2020, marked by renewed depletion; and 2021-2023, representing the highest-storage state within the study period. GRACE/GRACE-FO-derived GWSA showed a strong positive correlation with in-situ estimates ($r = 0.762$), reproducing the major phases of groundwater depletion and recovery despite differences in anomaly magnitude. Spatial and seasonal analyses further revealed progressive pre-monsoon depletion and delayed recovery during the post-monsoon and winter periods. A key finding was the delayed response of groundwater storage to rainfall. While contemporaneous rainfall showed a weak relationship with GWSA ($r = -0.15$), four-month antecedent rainfall exhibited a substantially stronger correlation ($r = 0.68$). This relationship remained positive across all four groundwater-storage regimes ($r = 0.60$-0.82), indicating that delayed rainfall response is a persistent characteristic of basin-scale groundwater variability. The results therefore suggest that antecedent hydroclimatic conditions provide more meaningful information on groundwater response than simultaneous rainfall alone. Although the pronounced positive anomalies during 2021-2023 indicate substantial recent recovery, they should not be interpreted as evidence of permanent groundwater restoration, particularly in the absence of consistent groundwater-abstraction data. Overall, integrating satellite gravimetry, in-situ observations, spatial analysis, change-point detection, and antecedent rainfall relationships provides a robust framework for identifying groundwater-storage transitions and can support adaptive groundwater monitoring and management in the Krishna Basin and other monsoon-dominated river basins.

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AUTHOR CONTRIBUTIONS

Ajay Singh Jethoo and Kaushlandra Bairwa conceptualized and designed the study and contributed to data collection. Kaushlandra Bairwa performed the data analysis and interpretation. Both authors contributed to manuscript preparation, critically revised the manuscript, and approved the final version for publication.

CONFLICT OF INTEREST

The authors have no relevant financial or nonfinancial interests to disclose.

ETHICS STATEMENT

All authors have read, understood, and complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors.

DATA AVAILABILITY STATEMENT

Data are available from the corresponding author upon reasonable request.

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