

Research Article

Analysis of Groundwater Storage Changes in Sulawesi Island Based on GRACE Satellite

Arief Sudradjat^{1*}, Mayrina Firdayati¹, Rahdian Fathurachman²¹Environmental Management and Technology Research Group, Faculty of Civil and Engineering, Institut Teknologi Bandung, Indonesia²Master Program in Environmental Engineering Study Program, Faculty of Civil and Engineering, Institut Teknologi Bandung, Indonesia*correspondence e-mail: arief.sudradjat@itb.ac.id

Abstract

Groundwater serves as a critical resource for meeting the increasing water demands in Sulawesi Island driven by population growth; however, effective monitoring is often constrained by the limitations of conventional methods. This study aims to analyze the spatiotemporal dynamics of Groundwater Storage (GWS) across Sulawesi Island by utilizing remote sensing technology. The methodology integrates Total Water Storage (TWS) data from the Gravity Recovery and Climate Experiment (GRACE) satellite and Soil Moisture Storage (SMS) data from the Global Land Data Assimilation System (GLDAS) over the period of 2002–2024. The Mann-Kendall test and Sen's Slope estimator were employed to determine the statistical significance and magnitude of GWS trends. Results indicate a statistically significant increasing trend in GWS, with an average rate of 0.2176 mm/year over the 22-year period. The results in 2016 showed a groundwater deficit phenomenon that coincided with the El Niño event at that time which affected groundwater storage conditions in several areas of Sulawesi Island

Keywords: groundwater, GRACE, Sulawesi Island, spatio-temporal

ARTICLE INFO

Citation: Sudradjat, A., Firdayati, M., & Fathurachman, R. (2026). Analysis of Groundwater Storage Changes in Sulawesi Island Based on GRACE Satellite. *Jurnal Teknik Lingkungan*, 32(1), 21-28. <https://doi.org/10.5614/j.tl.2026.32.1.3>

Article History:

Received 11 Jan 2026

Revised 23 Apr 2026

Accepted 27 Apr 2026

Available online 30 Apr 2026



This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution 4.0 International License (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Water is a basic human need and its limited availability makes groundwater a strategic resource for meeting various needs (Badwi, 2023; Ramli & Hasrianto, 2022)]. Groundwater is part of the natural water resources located beneath the Earth's surface, where the process of groundwater formation occurs in a natural cycle known as the hydrological cycle (Badwi, 2023). Apart from being influenced by water vapor sources from the ocean carried by monsoon winds, the dynamics of groundwater storage (TWS) on Sulawesi Island also have the potential to be influenced by local precipitation recycling processes (Brubaker et al., 2001). Population growth directly increases the demand for water for domestic use, agricultural irrigation, and industry, placing significant pressure on available freshwater resources and leading to greater reliance on groundwater (Vörösmarty et al., 2000). Fundamentally, precipitation is the main meteorological input component in the hydrological cycle that controls the recharge mechanism of the aquifer system where Indonesia has diverse differences in terms of rainfall (Scanlon et al., 2018), so that knowledge of groundwater conditions is important in certain regions. Groundwater extraction occurs frequently in large cities with large populations, resulting in land subsidence (Giao et al., 2020). Groundwater resource management in Indonesia is hampered by conventional monitoring methods that are expensive, time-consuming, and have limited coverage, so comprehensive groundwater modelling has not been achieved (Julzarika & Nugroho, 2022).

Changes in groundwater storage can be effectively monitored at broader regional and global scales using GRACE satellite data and combining it with hydrological datasets from GLDAS to improve accuracy (Frappart & Ramillien, 2018). GRACE (Gravity Recovery and Climate Experiment) satellite is a satellite launched by NASA that aims to measure changes in Earth's gravity, so that it can be used to monitor changes in the storage and movement of water masses below the Earth's surface. GRACE provides data on the spatial and temporal variability of Earth's gravity field that is controlled by changes in water masses, including groundwater. GRACE data is provided in monthly intervals as equivalent water thickness and is used to monitor changes in total water storage (TWSA) and groundwater storage (GWSA) in large aquifers globally (Rateb et al., 2020). Groundwater dynamics can also be used as a parameter to detect and predict drought in large areas (Julzarika & Nugroho, 2022). Remote sensing applications in Indonesia are still very limited and tend to be general. Existing studies often ignore significant regional variations, such as those found in Sulawesi Island (Dwiputra et al., 2017; Frappart & Ramillien, 2018). Sulawesi Island is the third most populous island in Indonesia. On this island, there was a decreasing trend in groundwater recharge in Central Sulawesi from 1995 to 2011 (Sutapa, 2016). Seeing this situation, this study aims to identify and analyze the spatio-temporal variability of groundwater storage in Sulawesi Island by integrating GRACE satellite data and GLDAS hydrological data to provide a more comprehensive understanding of how groundwater conditions occur on the island of Sulawesi.

2. Methodology

The research methodology is divided into study area, data, and method which are explained as follows.

2.1 Study area

Located in the central part of the Indonesian archipelago, between the islands of Borneo and the Maluku Islands, Sulawesi is one of the five Greater Sunda Islands. Geographically, the island has a unique 'K' shape, extending from approximately 2°N to 6°S latitude and 118°E to 126°E longitude. With a land area of about 189,216 km², Sulawesi is characterized by a highly complex topography featuring volcanic mountain ranges and steep valleys (Supari et al., 2017). Sulawesi experiences a humid tropical climate that is strongly influenced by monsoonal winds. The average annual rainfall varies significantly across the island (Sutapa, 2016). This rainfall distribution is uneven; regions exposed to the west monsoon, such as the southern and western parts, receive higher precipitation during the wet season. Conversely, some areas, like the Palu Valley, lie in a rain shadow, resulting in a climate that is considerably drier than the surrounding regions. main island of Sulawesi was taken as the study area, ignoring the surrounding small islands that are separated from the main island.

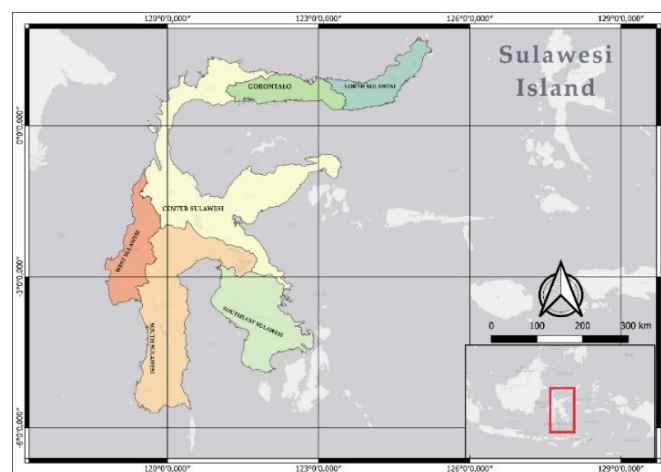


Figure 1. Study area of Sulawesi Island

2.2 Data

Groundwater storage (GWS) is calculated using equation (1) where (TWS) is total water storage, (SMS) is soil moisture storage, (CWS) is canopy water storage and (SWS) is snow water storage. Total water storage data is taken from the GRACE dataset and for soil moisture data we get it from the GLDAS dataset as shown in Table 1.

Table 1. Description of the research data used

Agency	Variable	Unit	Years
GRACE & GRACE-FO	TWS (monthly)	cm	2002-2024
GLDAS	SMS (monthly)	mm	2002-2024
GLDAS	Canopy Water Storage (CWS)	mm	2002-2024

Terrestrial Water Storage Anomalies (TWSA) for the period spanning April 2002 to December 2024 are extracted from the latest mascon solution provided by the Gravity Recovery and Climate Experiment (GRACE) and the GRACE Follow-On (GRACE-FO) missions. These data are produced by the Center for Space Research (CSR), utilizing the Release 06.3 (RL06.3). The procedural data for this analysis can be accessed through the CSR center at the University of Texas. CSR mascon products have established a robust track record in the scientific community for quantifying groundwater variability across diverse global regions, as evidenced by the works of Chen et al. (2014); Feng et al. (2018); and Voss et al. (2013).

The data processing framework also involves restoring the AOD1B "GAD" fields which are typically removed during initial processing onto the geodesic mascon grid to support integrated land-ocean applications. The treatment of these systematic errors, including geocenter motion and GIA, follows the standardized methodology established by Save et al. (2016), meaning that no independent corrections were required for this specific study. While the data is distributed on a fine grid. This implies that while the results are highly robust at regional scales, interpretations at finer spatial resolutions should be handled with caution. Since Groundwater Storage Anomalies (GWSA) are not directly observed but are instead derived using a residual approach, uncertainties from each input dataset inherently propagate into the final estimates. This limitation is particularly relevant in regions like Indonesia, where long-term in-situ groundwater observations are largely unavailable for independent validation. To maintain a continuous record, temporal interpolation was used to bridge gaps caused by satellite battery-management operations after 2011 and the transition between the original GRACE mission and GRACE-FO in 2017-2018.

Due to the limited availability or insufficiency of continuous ground-based station records across the study area for the entire analysis period, soil moisture (SM) was estimated using the Global Land Data Assimilation System (GLDAS) model. The GLDAS framework is designed to provide high-quality land surface state variables and flux parameters related to energy and water cycles, encompassing critical data such as soil moisture, surface temperature, evaporation, and heat fluxes. For the purposes of this research, the Noah land surface model from the GLDAS suite was specifically selected. This model was chosen primarily because of its proven capability to simulate variations in water storage with a relatively lower bias compared to other models (Zhao et al., 2024).

The specific soil moisture variable utilized in this analysis represents the integrated layer from 0 to 100 cm. This depth corresponds to the total soil column typically employed in hydrogeological research for groundwater estimation and comprehensive terrestrial water balance assessments. The dataset version applied for this investigation is the GLDAS_NOAH_M.2.1, processed on a monthly timescale. Because the raw soil moisture data provided by GLDAS are absolute values rather than deviations from a norm, a transformation process was required to convert them into soil moisture anomalies (SMA). This was achieved by subtracting the long-term mean values calculated over the designated baseline period from January 2004 to December 2009. This methodological approach to anomaly calculation is intentionally designed to maintain consistency with the procedures applied to the groundwater storage (GWS) data derived from the GRACE missions.

2.3 Methods

TWS changes are estimated using satellite-based GRACE data. GRACE provides monthly measurements of TWS anomalies, which represent the total amount of water stored on and below the Earth's surface, including surface water, soil moisture, snow, and groundwater. Therefore, GWS estimation requires subtraction of non-groundwater components as previously described and used by previous studies (Mehmood et al., 2022). This estimation procedure is expressed in Equation (1).

$$\Delta TWS = \Delta GWS + \Delta SMS + \Delta CWS + \Delta SWS \quad (1)$$

Where:

Δ GWS	=	Groundwater storage Anomaly (mm)
Δ TWS	=	Total Water Storage Anomaly (mm)
Δ SMS	=	Soil Moisture Storage Anomaly (mm)
Δ CWS	=	Canopy Water Storage Anomaly (mm)
Δ SWS	=	Snow Water Storage Anomaly (mm)

In the GWS calculation, the snow water storage and canopy water storage variables will be ignored because there is no snow in Indonesia and the canopy water storage value on Sulawesi Island is very small so it will be ignored. GRACE gravity data, namely LWE TWS representation and GLDAS SMS representation, is subjected to data masking, multiplication with scaling factors and spatial aggregation with Sulawesi Island region polygon. After the data is masked, the data will be plotted in spatial and temporal form and adjusted to the equations to be used, where all is done using Python programming.

3. Results and Discussion

All The results of the GRACE satellite data analysis for the Sulawesi Island study area are presented and discussed in this section. The analysis covers changes in groundwater storage that occurred during the period 2002–2024.

3.1 Spatial patterns of GWS in Sulawesi Island

Based on the visualization of the GRACE Mascon CSR RL06 data presented in Figure 2, a spatial pattern dominated by positive anomalies is evident. The spatial distribution map reveals that nearly the entire region of Sulawesi Island is characterized by shades of blue, representing positive anomalies, with mean Groundwater Storage (GWS) anomaly values ranging from +20 to +30 mm. The highest positive intensities, indicated by concentrations of deep blue, are particularly prominent in the Northern Peninsula (North Sulawesi and Gorontalo provinces) and parts of Central Sulawesi. Furthermore, these results indicate the absence of significant deficit zones.

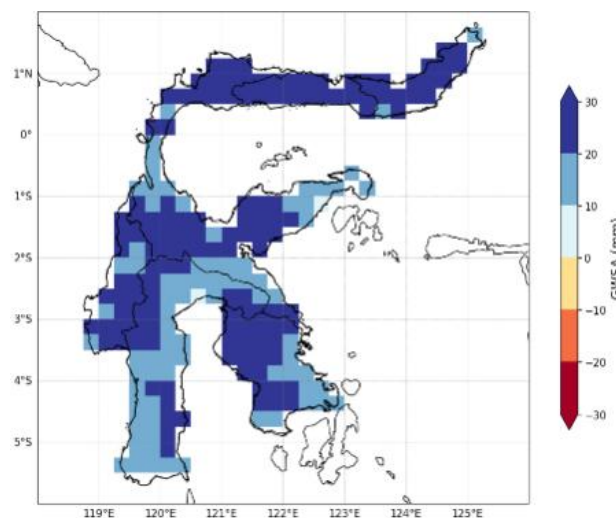


Figure 2. Spatial distribution of GWS anomalies across Sulawesi average from 2002 to 2024, based on GRACE CSR RL06.3 Mascon-derived data

Based on a spatial pattern analysis of Groundwater Storage (GWS) anomalies in Sulawesi in Figure 2, significant variations have been identified across the island. The average spatial distribution of GWSA in Sulawesi over the 2002–2024 period shows marked spatial heterogeneity, reflecting different hydrological responses between the north and south of the island. The northern peninsula region is dominated by significant positive anomalies +30 mm. This northern groundwater positive pattern is likely attributed to anti-monsoonal rainfall patterns that tend to be more evenly distributed throughout the year referencing Pratama (2021), The antimonsoonal region records an average rainfall with a figure higher than the average rainfall in the monsoonal region. In contrast, the southern peninsula shows distinct conditions dominated by lower values ranging from +20 to +30 mm. The low GWSA zone is concentrated in the central part of the island (parts of Central and South Sulawesi). This region, especially around the Palu Valley, is a rain shadow area that naturally receives much lower rainfall due to mountain barriers.

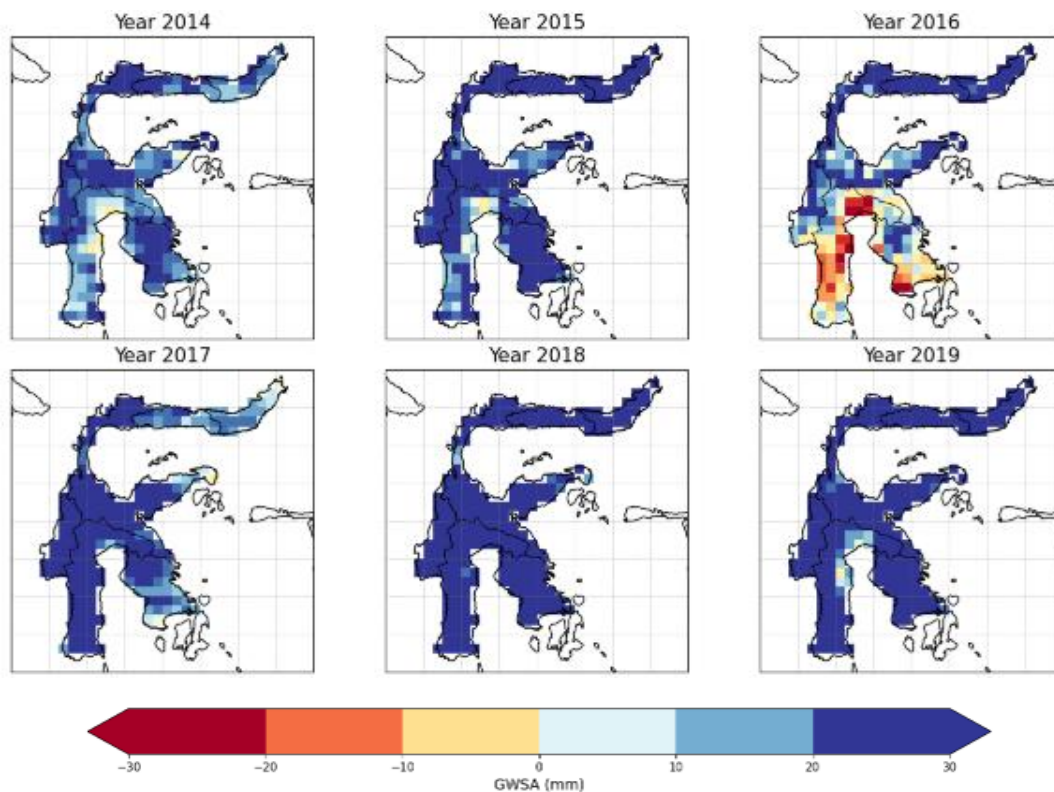


Figure 3. Spatial distribution of groundwater storage anomalies across Sulawesi 2014 to 2019

The period from 2014 to 2019 in Figure 3 showed positive conditions dominated by more than +30 in various regions and consistently showed positive conditions, but it was seen differently in 2016 which indicated a GWSA deficit condition in the southern part of Sulawesi Island of 0 to -30 mm. Historically, the emergence of this deficit zone coincided with the occurrence of a strong El Niño climate phenomenon that triggered a drastic decrease in rainfall in the Indonesian region (Supari et al., 2018). The deficit condition that coincided with a strong El Niño shows the strong influence of the ENSO phenomenon on the island of Sulawesi, especially in the southern part.

The ENSO phenomenon, specifically during its El Niño phase, significantly modulates the climate over the Indonesian Maritime Continent by shifting the Walker Circulation, which suppresses atmospheric convection and drastically reduces water vapor in the region. During the extreme 2015–2016 El Niño event, this atmospheric shift resulted in a prolonged dry season and a severe precipitation deficit across most of Indonesia, including Sulawesi (Avia & Sofiati, 2018). This severe lack of rainfall directly limits the natural infiltration and recharge processes of local aquifers. Consequently, as continuous groundwater extraction for agricultural and domestic needs was met with little to no surface replenishment, the region experienced the pronounced groundwater storage deficit observed in the 2016 GRACE data. This condition aligns with broader hydro-meteorological observations in Indonesia, where strong El Niño periods consistently exhibit a strong negative correlation with groundwater availability (Agdialta, 2019), thereby highlighting the extreme vulnerability of Sulawesi's regional aquifers to global climate anomalies.

Figure 4 shows that the beginning and end of the year (December-February) marked the beginning of the red deficit zone in the south, followed by the northern part of Sulawesi Island, and continuing through June. The northern part of Sulawesi Island began to show excess groundwater storage in March and continued to turn blue until the end of the year, while the southern part of Sulawesi Island only began to experience excess groundwater in July. This phenomenon appears inconsistent with the monsoon-seasonal region of South Sulawesi, considering that this period should be the peak of the rainy season with the highest rainfall intensity. The deficit observed at the beginning of the rainy season indicates that aquifer conditions are at their lowest point after experiencing severe drought during the previous long dry season, and the initial rainfall input is insufficient to immediately restore the deficit. Meanwhile, for the Central and North Sulawesi regions (anti-monsoon), the deficit during this period is normal because it is the minimum rainfall phase. However, if the deficit in the southern region is too extreme when rainfall peaks and there is still no surplus in the following months, this indicates a mismatch between the decline and increase in groundwater storage and the seasonal pattern on Sulawesi Island.

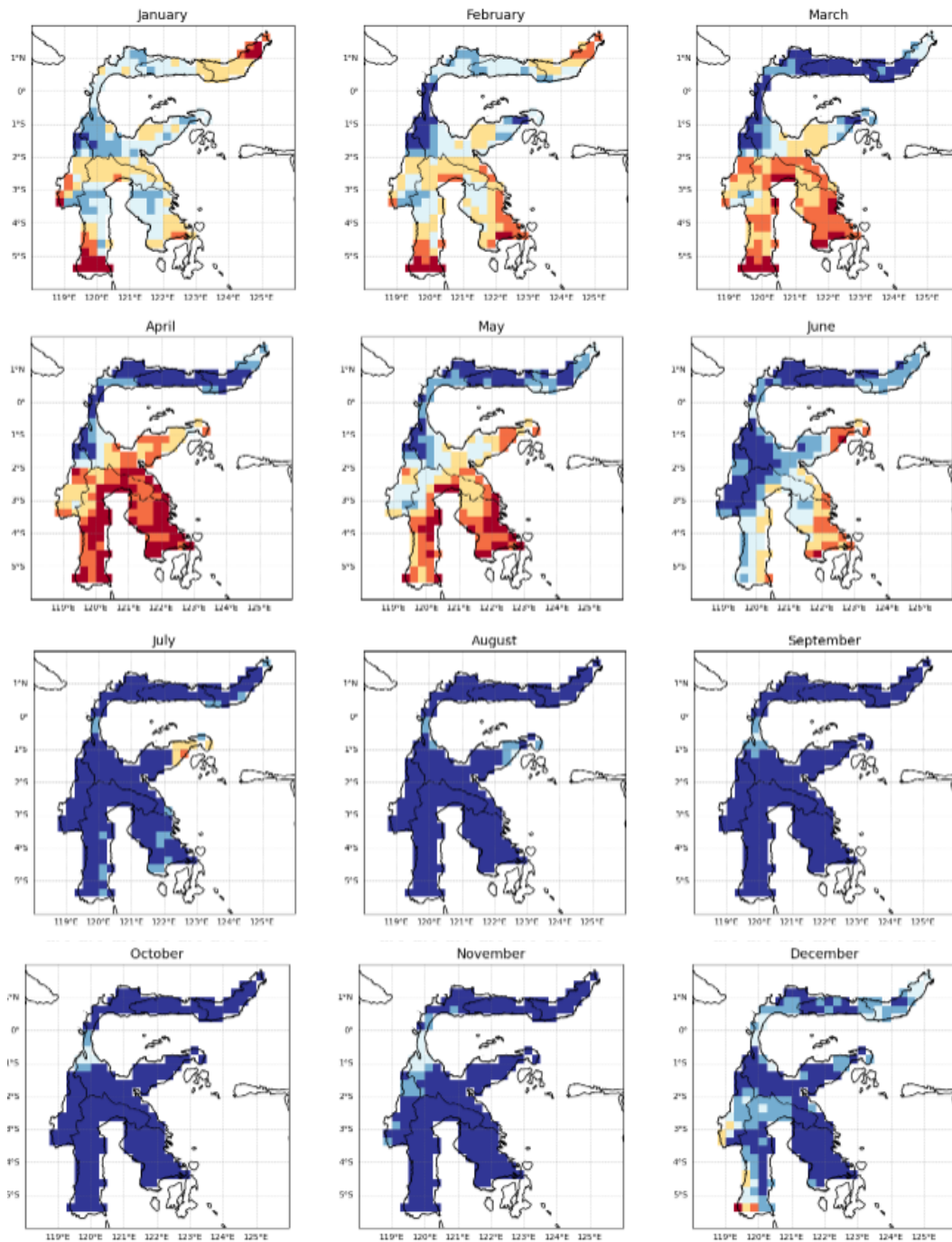


Figure 4. Spatial anomalies in monthly average groundwater storage

The spatial pattern reflects the time lag between peak rainfall and peak soil air storage. Although maximum rainfall in the southern region occurs in January and ends in February, the maximum groundwater storage (GWS) signal appears to peak only in that month. This lag phase represents the physical infiltration and percolation of air through the unsaturated zone before finally filling the aquifer.

3.2 Temporal analysis of GWS in Sulawesi Island

Variability analysis was also conducted on the temporal phase. The time series analysis of average Groundwater Storage Anomalies (GWSA) in Sulawesi Island from 2002 to 2024 is presented in Figure 5. The graph visually exhibits GWS fluctuations from year to year, while the linear regression line shows an overall increasing trend over the 22 years. This regular annual cycle underscores that groundwater fluctuations in Sulawesi are highly influenced by the seasons, which is a critical aspect of water resource management, especially for anticipating year-end deficit periods. To test the statistical significance of the observed trend, a Mann-Kendall test was applied to the average GWS time series. The test confirmed that a significantly

increasing trend in the magnitude was measured using the Sen's Slope method, resulting in an average GWS increase rate of 0.2176 mm/year ($p < 0.001$).

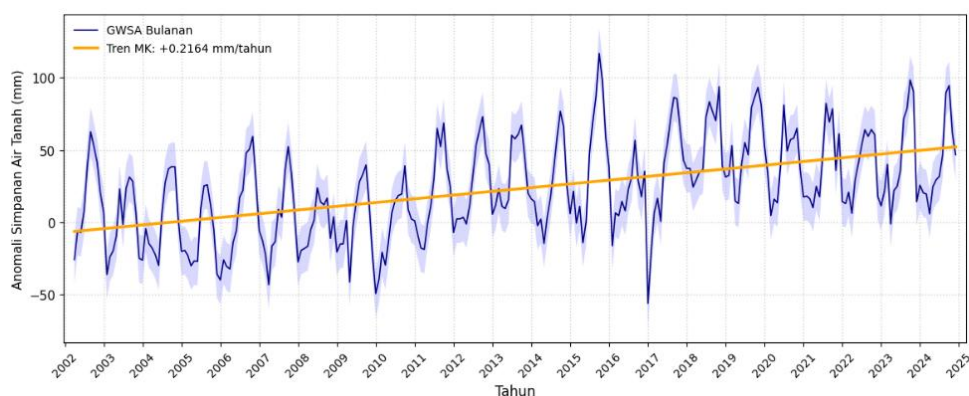


Figure 5. Average monthly GWS anomalies in Sulawesi Island from 2002 to 2024.

The box-whisker plot analysis in Figure 6 demonstrates that GWS dynamics in Sulawesi are characterized by a distinct seasonal pattern. During the first quarter (January–March), although rainfall reaches its maximum in the south, the median GWS anomaly stays within a low-to-moderate range, eventually dropping to a deficit mean in April. This period signifies the initial recharge phase in the southern region, where the aquifer response is delayed, a common feature of tropical hydrogeology. Groundwater storage subsequently increases until it peaks in October, marking the annual maximum storage. At this stage, the median anomaly reaches its maximum positive value, reflecting the full accumulation of infiltration from the northern region's anti-monsoonal wet season. These results suggest that the overall rainfall input is spatially dominated by the northern region, due to both its higher average precipitation and larger land area.

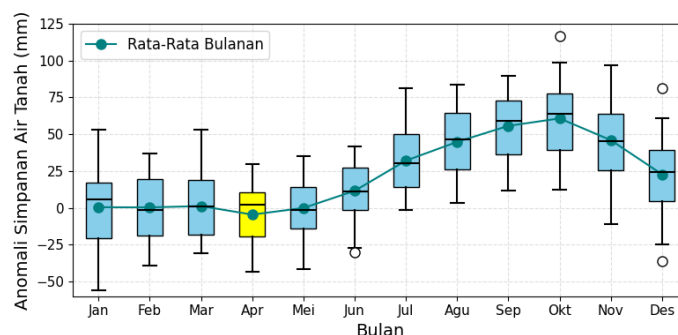


Figure 6. 22 year average monthly GWS anomalies in Sulawesi Island

4. Conclusion

This study concludes that the dynamics of groundwater storage on Sulawesi Island during the period 2002–2024 showed a significant increase of 0.2164 mm/year, but had a heterogeneous spatial response between the northern (anti-rainy season) and southern (rainy season) regions. The variability of the aquifer system is controlled by seasonal cycles and is significantly influenced by global climate anomalies in the Sulawesi Island region. Although this GRACE-based estimate has limitations in spatial resolution and coastal signal effects that make it a regional indicator, these findings provide a broad picture of the condition of groundwater storage on Sulawesi Island.

Acknowledgement

This research was made possible entirely thanks to the financial support of P2MI. Therefore, the author expresses his deepest appreciation for the opportunity and facilities provided to complete this study.

Reference

- Agdialta, R. (2019). Effect of Strong El-Nino and Strong La-Nina Periode on Groundwater Availability in Palembang City. *Sriwijaya Journal of Environment*, 4(2), 97–103. <https://doi.org/10.22135/sje.2019.4.2.97-103>

- Avia, L. Q., & Sofiati, I. (2018). Analysis of El Niño and IOD Phenomenon 2015/2016 and Their Impact on Rainfall Variability in Indonesia. *IOP Conference Series: Earth and Environmental Science*, 166, 012034. <https://doi.org/10.1088/1755-1315/166/1/012034>
- Badwi, N. (2023). Identifikasi potensi air tanah di sub das jeneberang hulu kabupaten gowa provinsi sulawesi selatan. *Jurnal Environmental Science*, 6(1). <https://doi.org/10.35580/JES.V6I1.53967>
- Brubaker, K. L., Dirmeyer, P. A., Sudradjat, A., Levy, B. S., & Bernal, F. (2001). A 36-yr Climatological Description of the Evaporative Sources of Warm-Season Precipitation in the Mississippi River Basin. *Journal of Hydrometeorology*, 2(6), 537–557. [https://doi.org/10.1175/1525-7541\(2001\)002<0537:AYCDOT>2.0.CO;2](https://doi.org/10.1175/1525-7541(2001)002<0537:AYCDOT>2.0.CO;2)
- Chen, J., Li, J., Zhang, Z., & Ni, S. (2014). Long-term groundwater variations in Northwest India from satellite gravity measurements. *Global and Planetary Change*, 116, 130–138. <https://doi.org/10.1016/j.gloplacha.2014.02.007>
- Dwiputra, G., P., Rangkuti, N., S., Yoni, D., R., & Zakaria, Z. (2017). Model Hidrogeologi Dan Sistem Panas Bumi Daerah Koalarawa, Kabupaten Sigi, Sulawesi Tengah. *Seminar Nasional Kebumihan Ke-10 Peran Penelitian Ilmu Kebumihan Dalam Pembangunan Infrastruktur Di Indonesia*, 1463–1475.
- Feng, W., Shum, C., Zhong, M., & Pan, Y. (2018). Groundwater Storage Changes in China from Satellite Gravity: An Overview. *Remote Sensing*, 10(5), 674. <https://doi.org/10.3390/rs10050674>
- Frappart, F., & Ramillien, G. (2018). Monitoring Groundwater Storage Changes Using the Gravity Recovery and Climate Experiment (GRACE) Satellite Mission: A Review. *Remote Sensing*, 10(6), 829. <https://doi.org/10.3390/rs10060829>
- Giao, P. H., Hue, V. T., Han, N. D., Anh, N. T. H., & Minh, N. N. (2020). Land subsidence prediction for a new urban mass rapid transit line in Hanoi. *Underground Space*, 5(2), 93–104. <https://doi.org/10.1016/j.undsp.2018.11.002>
- Julzarika, A., & Nugroho, J. T. (2022). Monthly Dynamic Groundwater Estimation using GRACE over Indonesia. *International Journal on Advanced Science, Engineering and Information Technology*, 12(3), 1113. <https://doi.org/10.18517/ijaseit.12.3.14734>
- Mehmoed, K., Tischbein, B., Flörke, M., & Usman, M. (2022). Spatiotemporal Analysis of Groundwater Storage Changes, Controlling Factors, and Management Options over the Transboundary Indus Basin. *Water*, 14(20), 3254. <https://doi.org/10.3390/w14203254>
- Ramli, R., & Hasrianto, H. (2022). Penyelidikan Jenis Akuifer Air Tanah Daerah Tonrokassi Kecamatan Tamalatea Kabupaten Jeneponto Provinsi Sulawesi Selatan. *Mining Science And Technology Journal*, 1(2), 116–123. <https://doi.org/10.54297/minetech-journal.v1i2.384>
- Rateb, A., Scanlon, B. R., Pool, D. R., Sun, A., Zhang, Z., Chen, J., Clark, B., Faunt, C. C., Haugh, C. J., Hill, M., Hobza, C., McGuire, V. L., Reitz, M., Müller Schmied, H., Sutanudjaja, E. H., Swenson, S., Wiese, D., Xia, Y., & Zell, W. (2020). Comparison of Groundwater Storage Changes From GRACE Satellites With Monitoring and Modeling of Major U.S. Aquifers. *Water Resources Research*, 56(12). <https://doi.org/10.1029/2020WR027556>
- Scanlon, B. R., Zhang, Z., Save, H., Sun, A. Y., Müller Schmied, H., van Beek, L. P. H., Wiese, D. N., Wada, Y., Long, D., Reedy, R. C., Longuevergne, L., Döll, P., & Bierkens, M. F. P. (2018). Global models underestimate large decadal declining and rising water storage trends relative to GRACE satellite data. *Proceedings of the National Academy of Sciences*, 115(6). <https://doi.org/10.1073/pnas.1704665115>
- Supari, Tangang, F., Juneng, L., & Aldrian, E. (2017). Observed changes in extreme temperature and precipitation over Indonesia. *International Journal of Climatology*, 37(4), 1979–1997. <https://doi.org/10.1002/joc.4829>
- Sutapa, I. W. (2016). Effect of the climate change on groundwater recharging in Bangga watershed, Central Sulawesi, Indonesia. *Environmental Engineering Research*, 22(1), 87–94. <https://doi.org/10.4491/eer.2015.127>
- Vörösmarty, C. J., Green, P., Salisbury, J., & Lammers, R. B. (2000). Global Water Resources: Vulnerability from Climate Change and Population Growth. *Science*, 289(5477), 284–288. <https://doi.org/10.1126/science.289.5477.284>
- Voss, K. A., Famiglietti, J. S., Lo, M., de Linage, C., Rodell, M., & Swenson, S. C. (2013). Groundwater depletion in the Middle East from GRACE with implications for transboundary water management in the Tigris-Euphrates-Western Iran region. *Water Resources Research*, 49(2), 904–914. <https://doi.org/10.1002/wrcr.20078>
- Zhao, J., Li, G., Zhu, Z., Hao, Y., Hao, H., Yao, J., Bao, T., Liu, Q., & Yeh, T.-C. J. (2024). Analysis of the spatiotemporal variation of groundwater storage in Ordos Basin based on GRACE gravity satellite data. *Journal of Hydrology*, 632, 130931. <https://doi.org/10.1016/j.jhydrol.2024.130931>