Spatiotemporal Variability of Terrestrial Water Storage and Groundwater Storage on the Papua Island Using the GRACE and GRACE-FO Satellites

Daniar Ihza Carundyatama*, Krisna Dwi Oktabrian, La Ode Ashamad Nusriah, Farrel Fitria Nathania Kuncara, Purwanti Lely Sabrina
Program Studi Meteorologi, Sekolah Tinggi Meteorologi Klimatologi dan Geofisika, Jl. Meteorologi No.5, RT.003/RW.013, Tanah Tinggi, Tangerang, Kota Tangerang, Banten, 15221, Indonesia

*Corresponding author: daniarihza7@gmail.com

Abstract. Papua Island represents a region with complex hydrological characteristics influenced by mountainous topography and equatorial tropical climate conditions. This study aims to analyze the spatial, temporal, and seasonal variability of Total Water Storage (TWS) and Groundwater Storage (GWS) across Papua Island during the period 2005–2024 using GRACE and GRACE-FO satellite data integrated with Global Land Data Assimilation System (GLDAS) outputs. The analysis includes spatial mapping of TWS distribution for selected representative years, time-series evaluation across three sub-regions (West Papua, North Papua, and South Papua), and estimation of GWS using the residual approach. The results indicate strong spatial heterogeneity in TWS distribution, with higher storage consistently observed in West Papua and North Papua compared to South Papua. Temporally, TWS shows a positive increasing trend across all sub-regions, with the highest rate observed in West Papua at +0.43 cm/year. GWS variations exhibit a positive long-term trend of +0.38 cm/year and a clear seasonal recharge–depletion cycle, with recharge occurring during June–November and depletion during December–May. These findings demonstrate that GRACE and GRACE-FO observations provide an effective approach for monitoring regional terrestrial and groundwater storage changes, particularly in tropical regions with limited in-situ hydrological observations.

Keywords: Anomaly; GRACE; Groundwater; Satellite; Terrestrial; Water;

I. INTRODUCTION

The island of Papua has complex hydrological characteristics due to its high mountainous topography and high levels of tropical rainfall [1]. As one of the regions with significant freshwater reserves in Indonesia, understanding the dynamics of water storage is crucial for sustainable water resource management. Terrestrial Water Storage (TWS) refers to the total volume of water stored on land, whether in the form of natural or artificial reservoirs. The components of TWS encompass various forms of water storage, such as groundwater, soil moisture, surface water, snow cover, glaciers, land ice, and water stored in vegetation or biomass [2]. Changes in TWS reflect the dynamics of freshwater resource availability, which plays a vital role in the sustainability of ecosystems and human activities [3]. These conditions highlight the importance of monitoring TWS conditions in a region, particularly in areas with varied topography. However, ground-based observations in Papua are severely limited due to difficult terrain and the lack of an adequate network of hydrometeorological monitoring stations.

The scarcity of in-situ data has led to the use of remote sensing technology, particularly the Gravity Recovery and Climate Experiment (GRACE) satellite mission and its successor, GRACE Follow-On (GRACE-FO). These satellites are capable of detecting changes in Earth's gravitational anomalies, which correlate directly with changes in total water mass within a region [4]. Utilizing GRACE data enables the estimation of TWS variability over a wide spatial scale, which was previously difficult to achieve using conventional hydrological modelling [5]. The GRACE and GRACE-FO satellites measure TWS by detecting minute changes in the Earth's gravitational field caused by the redistribution of water mass on land surfaces. The system uses two identical satellites orbiting the Earth in tandem at a distance of approximately 220 km. When the satellites pass over an area experiencing an increase in water mass—for example, due to heavy rainfall, groundwater recharge, or increased soil moisture—the local gravitational force increases, causing the leading satellite to experience a small acceleration, followed by a change in relative distance from the trailing satellite [6].

GRACE and GRACE-FO satellite data are not only used for TWS analysis, but can also be used to characterise Groundwater Storage (GWS). GWS is a key component of the global hydrological cycle, representing the volume of groundwater stored within the aquifer system [7]. Groundwater storage (GWS) analysis can be derived from TWS data by removing other water components such as soil moisture, snow and surface water using a supporting hydrological model [8]. The GWS calculation process involves combining GRACE and GRACE-FO satellite data with data from the Global Land Data Assimilation System

(GLDAS) model. GLDAS data provides information on soil moisture, snow and canopy water storage [9][10].

This study was conducted to analyze the spatial and seasonal variability of Total Water Storage (TWS) and Groundwater Storage (GWS) on the island of Papua using satellite gravimetry data. By combining data from the GRACE and GRACE-FO missions, it is hoped that patterns of water mass changes can be comprehensively identified to support national water management policies. The focus on the Papua region provides a new contribution to the literature on satellite hydrology in tropical regions, which remain largely unexplored [5]. It is hoped that this in-depth understanding of changes in groundwater will serve as a reference for mitigating the impacts of climate change in eastern Indonesia.

II. METHODOLOGY

The observation of changes in Total Water Storage (TWS) in this study focused on the island of Papua, with the analysis area divided into three spatial zones to identify regionally distinct characteristics of hydrological dynamics. This division was based on the shape of the island of Papua and its topography. The northern and southern parts of Papua are bounded by the Jayawijaya Mountains, which stretch from south to north, dividing Papua into two parts.

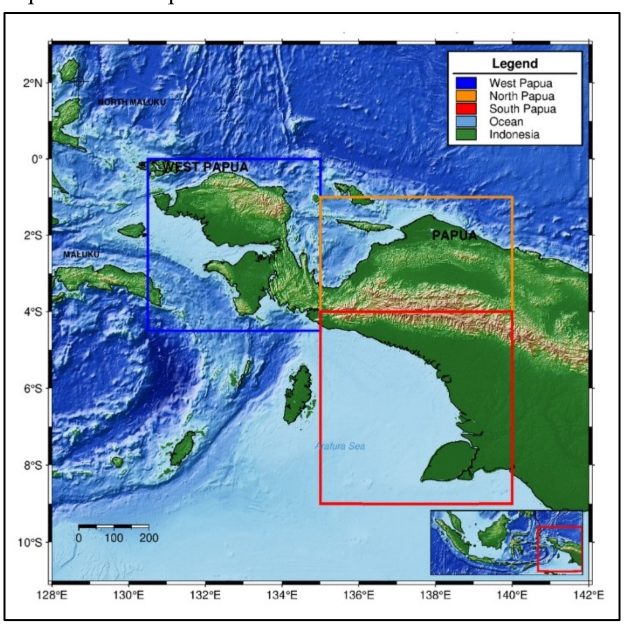

Figure 1. Map of Research Locations on the Papua Island

The regions covered under the analysis of Papua Island include:

1. West Papua, covering the coordinate range 0°LS –4.5°LS and 130.5°BT –135°BT,
2. North Papua, covering the range 1°LS –4°LS dan 135–140°BT, serta
3. South Papua, covering the range 4°LS –9°LS dan 135°BT –140°BT.

This distribution allows for a more specific evaluation of changes in TWS over time, based on the topographical, climatic and hydrological characteristics of each sub-region, thereby enabling trends in increases or decreases in water storage to be identified more accurately and in a manner that is relevant to spatial variability in Papua. The island of Papua was selected on the basis of its diverse topography and climate. The West Papua region is dominated by karst rock formations with high secondary porosity, where sandstone layers form the main aquifer zone with low to medium resistivity at a depth of 6–30 m [11]. The karst topography acts as a massive natural reservoir, allowing high rates of rainfall infiltration into the underground river system and aquifers. The northern section is dominated by the central mountain range, characterised by extremely steep topography and active tectonic structures (such as the Mamberamo thrust fault). The dense bedrock and extreme slope gradients result in low soil infiltration capacity. Hydrologically, the intense orographic rainfall in this region is more likely to be converted into surface runoff or rapid runoff [12]. Consequently, fluctuations in the TWS in this zone are expected to be highly dynamic and to respond instantly to rainfall anomalies. Southern Papua is a region characterised by low-lying plains comprising alluvial sedimentary basins and extensive wetland ecosystems (such as the Digul basin)[13].

2.1 Data

The primary data used in this study, as shown in Table 1, are derived from the Gravity Recovery and Climate Experiment (GRACE) satellite mission and its successor, GRACE Follow-On (GRACE-FO), developed by NASA and the German Research Centre for Geosciences (GFZ). Both missions provide estimates of Terrestrial Water Storage (TWS) in the form of gravity anomalies, which are converted into changes in terrestrial water mass. GRACE (2002–2017) and GRACE-FO (2018–present) have an effective spatial resolution of approximately 300–400 km and a monthly temporal resolution.

Table 1. Data used in the study

No	**Data**	**Resolution (Temporal/spatial)**	**Variable**
1	GRACE	Monthly/200-300 km	lwe_thicknes
2	GRACE-FO	Monthly/200-300 km	lwe_thicknes
3	GLDAS Version 2	Monthly/28-30 km	Soil moisture 10 cm, 40 cm, 100 cm, and 200 cm

GRACE and GRACE-FO data enable the long-term monitoring of changes in water storage across various regions, including remote areas with few observation stations. GRACE and GRACE-FO satellite data can be downloaded via the https://www.earthdata.nasa.gov/ portal, which is managed by the National Aeronautics and Space Administration (NASA). The GRACE technique involves detecting changes in the Earth's gravitational field by monitoring changes in the distance between the two GRACE satellites as they orbit together along the same orbital track, connected by a K-band microwave link to calculate the precise monthly change in distance. [14]. This satellite monitors changes in gravity caused by the movement of water on land, in the oceans, in ice and in the atmosphere, which can indirectly be used to determine how the Earth's constituent materials are distributed. The main advantage of GRACE/GRACE-FO data is its ability to consistently capture basin- to regional-scale hydrological dynamics over time, although it has limitations in terms of coarse spatial resolution, which requires filtering and correction techniques to minimise signal errors. Pre-processing of the GRACE data was carried out by converting the original GRACE coordinates which are polar coordinates into Cartesian coordinates that they could be adapted to the study area.

This study used data from the Global Land Data Assimilation System (GLDAS), which is the result of hydrological modelling based on global observational data. GLDAS provides variables relating to surface and soil water storage, such as soil moisture, snow water equivalent and canopy water storage, at a much higher spatial resolution—typically 0.25°–1°—with a temporal resolution ranging from daily to monthly [15]. The GLDAS data model is downloaded from https:/disc.gsfc.nasa.gov/datasets/, which is managed by NASA. Groundwater Storage (GWS) can be obtained by subtracting the simulated non-aquifer water storage component from GLDAS from the GRACE/GRACE-FO TWS. The integration of these two data sources is crucial for improving the accuracy of groundwater estimates, whilst providing a more comprehensive physical understanding of the terrestrial hydrological system in the analysis of long-term water mass changes.

2.2. Data Processing

The downloaded GRACE and GLDAS data were processed using the Python programming language to calculate and visualise TWS and GWS results. TWS is represented by the total amount of water—both permanent and temporary—present on a land surface. The components of TWS consist of soil moisture, canopy water, snow water equivalent (SWE), groundwater, and surface water. Data gaps for the 2017 period were addressed by averaging the 2017 data with the data from the preceding and following years for the time series data. Meanwhile, for the spatial composite calculations, the data for the 2017 period were excluded from the climatological analysis of TWS changes on the island of Papua..

GWS is calculated using a combination of GRACE satellite data and GLDAS model data. GWS represents the total volume of water stored in subsurface aquifers, including both shallow and deep aquifers. GWS reflects several factors, namely groundwater reserves, changes in groundwater volume, and long-term aquifer conditions, and is systematically expressed by the equation 1 below [16]:

$$GWS = TWS - (SM + SWE + CWS) \tag{1}$$

TWS = Terrestrial Water Storage

SM = Soil Moisture

SWE = Snow Water Equivalent

CWS = Canopy Water Storage

During the GWS processing, there are limitations and assumptions arising from data and methodological constraints, namely model bias, the assumption that surface water is negligible, low TWS resolution, the failure to distinguish between deep and shallow aquifers, and calculations based on GWS anomaly conditions. These assumptions mean that the measured GWS conditions will be slightly biased compared to the actual local conditions in a given area. Groundwater level conditions are used to indicate changes and trends over the long term across a wide area.

III. RESULT AND DISCUSSION

3.1 Spatial Variability of TWS

Figure 1 shows the spatial distribution of Terrestrial Water Storage (TWS) derived from GRACE satellite observations for the month of July in the years 2006, 2012, 2018 and 2024. This visualisation provides an overview of the spatial variation in water storage on the island of Papua, as well as the changes in patterns observed between representative years, and can therefore be used as a basis for analysing the characteristics of TWS variability in the region. July was selected as the peak of the dry season in the Papua region, which has an equatorial rainfall pattern [1].

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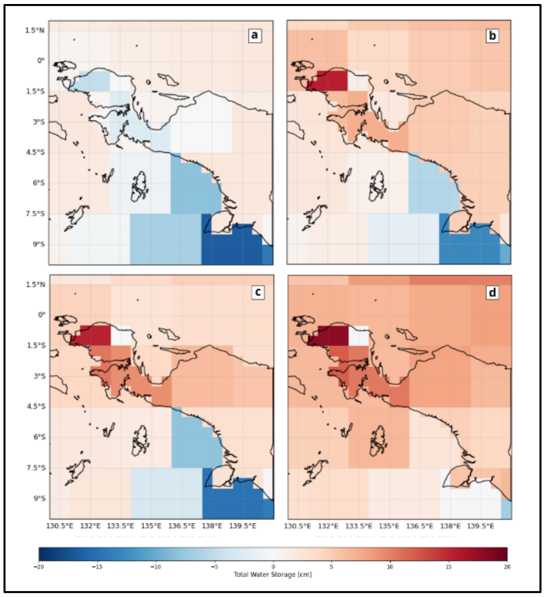

Figure 2. Spatial distribution of Terrestrial Water Storage (TWS) on the island of Papua in July 2006 (a), 2012 (b), 2018 (c) and 2024 (d) based on GRACE data.

An analysis of the spatial distribution of GRACE TWS in July for the years 2006, 2012, 2018 and 2024, shown in Figure 1, reveals spatial and temporal variations across the island of Papua, with consistent contrasts between the north-western and southern regions. In 2006, most of the region was dominated by negative anomalies ranging from −5 to −15 cm, reflecting a deficit in water storage, particularly in South Papua, whilst the north-western region was relatively more humid with values approaching neutral to slightly positive. These conditions changed significantly in 2012, when very strong positive anomalies, exceeding +15 cm, were concentrated in western Papua and surrounding areas, indicating a widespread increase in water storage in the west. In 2018 and 2024, the pattern became more stable, with a dominance of moderate positive anomalies of around +5 to +10 cm in West and Central Papua, whilst Southern and Eastern Papua continued to show weaker variations. This pattern confirms the presence of strong spatial heterogeneity, with Western and Northern Papua tending to maintain higher water storage compared to Southern Papua, which is more vulnerable to deficits during the same period.

The interannual comparison in Figure 2 reveals strong interannual dynamics, marked by a shift from deficit conditions in 2006 to an extreme surplus in 2012, followed by more moderate conditions in 2018 and 2024. The year 2006 was characterised by the dominance of widespread negative anomalies, whilst 2012 showed a sharp increase in positive anomalies, particularly in the western regions; by 2018, these had begun to be distributed more evenly with moderate positive values, continuing through to 2024 with slight increases in some areas. It should be noted that the peak in positive anomalies recorded in 2012 was not an immediate response to rainfall, but rather reflected the delayed accumulation of water storage due to the processes of infiltration and percolation into the aquifer. This is consistent with the findings [17] which indicates that changes in terrestrial water storage do not respond directly to precipitation, but are influenced by processes of water storage and redistribution within the hydrological system. A notable shift around the period from 2011 to 2012 suggests that conditions of extreme wetness peaked before returning to more stable conditions.

The spatial patterns of TWS in Figure 2 reveal a close correlation with the geographical conditions and climatic characteristics of Papua, particularly in shaping consistent differences between the southern and north-western regions. Southern Papua consistently exhibits lower TWS values, particularly in July, indicating a tendency towards water storage deficits, whilst Western and Northern Papua maintain higher and relatively stable values. These differences reflect the influence of topography and geographical position in controlling the distribution of water storage, where the southern region is more affected by dry conditions, whilst the north-western region is more conducive to water accumulation. Conditions of TWS surplus and deficit in the Papua region depend on existing topographical conditions. Topographical features such as tropical rainforest relief and river basins will exhibit TWS surplus values, as shown by the research findings [18] in China.

3.2 Temporal Variability of TWS

The Terrestrial Water Storage (TWS) time series for each sub-region of Papua over the period 2005–2024 is presented in Figure 3. This visualisation illustrates the temporal development of water storage, encompassing long-term trends and inter-annual fluctuations, thereby providing an overview of the dynamics of TWS changes and the differing characteristics of variability in West Papua, North Papua and South Papua.

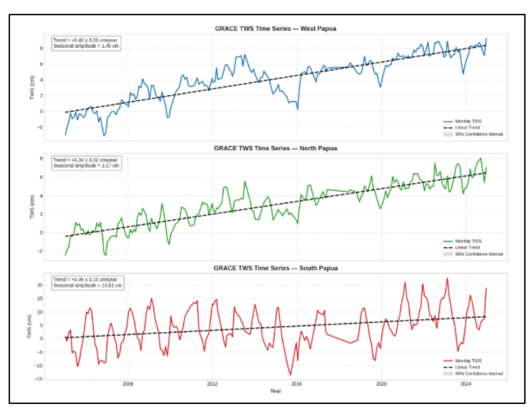

Figure 3. Time series of Terrestrial Water Storage (TWS) anomalies in West Papua, North Papua and South Papua for the period 2005–2024 based on GRACE data.

The TWS time series analysis in Figure 3 shows a consistent upward trend across all sub-regions of Papua during the period 2005–2024, with West Papua recording the highest rate of approximately +0.43 cm/year, followed by South Papua (+0.39 cm/year) and North Papua (+0.38 cm/year). The uniformity of this positive trend indicates a gradual increase in water storage over the past two decades. This pattern of increase is not linear but is accompanied by seasonal and inter-annual fluctuations, reflecting the hydrological system's response to indirect rainfall, where TWS peaks tend to occur after rainy periods due to infiltration and groundwater recharge. Furthermore, this upward trend points to conditions becoming progressively wetter, likely influenced by the strengthening of the regional hydrological cycle and the dominance of wet periods over the past decade.

The interpretation of Figure 3 reveals significant interannual fluctuations, particularly in South Papua, which exhibits the highest amplitude of variation compared to other regions. TWS values in this region fluctuate sharply from deficit to surplus conditions, with the most pronounced decline occurring during the 2015–2016 period when values reached a minimum, whilst West and North Papua exhibit more stable variations with smaller amplitudes. These conditions indicate a strong response to extreme dry spells, leading to a reduction in water storage over a relatively short period. Conversely, periods with high positive anomalies reflect water surplus conditions that have the potential to increase runoff.

Interannual variability on the island of Papua indicates that TWS dynamics in the southern region are highly sensitive to regional climate fluctuations that govern the balance between precipitation, evapotranspiration, and runoff. These findings are consistent with the results of research [19] in the Lancang–Mekong River basin, which shows that GRACE-based changes in TWS are strongly correlated with regional climate variability on medium to long timescales and exhibit a delayed temporal response to precipitation, thereby indicating that fluctuations in TWS in Papua also reflect the integration of regional hydrological processes influenced by atmospheric dynamics and the characteristics of the terrestrial water storage system.

3.3 Variation of GWS

The spatial distribution of Groundwater Storage (GWS) on the island of Papua shows clear dynamics over the period from 2006 to 2024, with values ranging from −55 to −75 cm, representing the results of GRACE residual estimates for soil moisture and surface water components. In Figure 4a for 2006, the West Papua region exhibits the highest relative GWS values, approaching −55 cm, whilst the central to northern regions fall within the range of −62 to −65 cm, and the southern to south-eastern parts of Papua show a deeper deficit of −68 to −70 cm, indicating initial differences in groundwater storage conditions between regions. Changes began to be evident in Figure 4b for 2012, where GWS values in West Papua decreased to a range of −60 to −63 cm, whilst the central to northern regions also experienced a decline to −63 to −67 cm, indicating the widening of the deficit and a delayed response of the groundwater system to changes in rainfall.

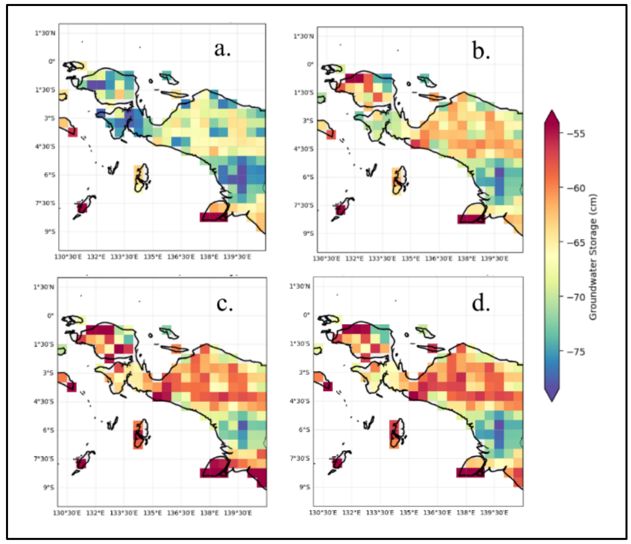

Figure 4. Spatial distribution of Groundwater Storage (GWS) on the island of Papua in (a) 2006, (b) 2012, (c) 2018, and (d) 2024.

In Figure 4c for 2018, the patterns in the western and central regions remained relatively unchanged compared to 2012; however, southern to south-eastern Papua showed an increasingly severe deficit zone with values approaching or falling below −75 cm, reflecting the cumulative impact of dry conditions during the preceding period. Furthermore, in Figure 4d for 2024, the southern to south-eastern regions began to show recovery with an increase in values, although they remained in a deficit state, whilst West Papua remained within the range of −61 to −65 cm and had not yet returned to its initial condition as in 2006.

The interpretation pattern indicates that GWS dynamics in Papua are influenced by processes that do not occur directly, but rather through the gradual response of the aquifer system; consequently, the changes that occur are delayed and do not always return to initial conditions within a short timeframe. This pattern is consistent with the findings [20] which indicates that changes in terrestrial water storage observed by GRACE can be non-linear and do not always revert to their initial state on a decadal timescale, as a result of a combination of climate variability and complex hydrological processes. Conditions in Papua also differ from changes in the global water cycle in other regions. As shown by [21] a significant decline in GWS has been observed in several regions of China due to the dominant influence of human activities, whereas GWS dynamics in Papua better reflect the natural response of the hydrological system to regional climate variability rather than intense anthropogenic pressures.

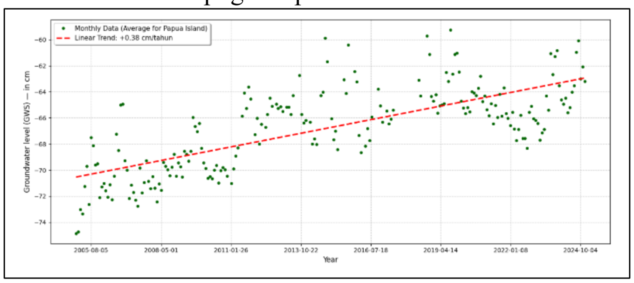

Figure 5. The linear trend in monthly soil moisture content on the island of Papua during the period 2005–2024.

The increasing trend in GWS is supported by Figure 5, which shows a positive linear trend of +0.38 cm/year with high statistical significance. The long-term trend presented in Figure 5 was quantified using linear regression analysis applied to the monthly GRACE-derived GWS time series, allowing the rate of groundwater storage change to be estimated systematically over the observation period. The shift in the average GWS from around −70 cm at the start of the period to −63 cm at the end of the period indicates a gradual accumulation of groundwater storage over the long term. The climatological dynamics of the GWS on a monthly basis will better illustrate how climatic conditions respond to the average monthly GWS cycle on the island of Papua.

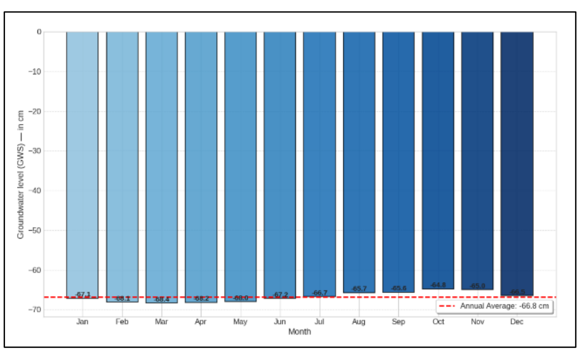

Figure 6. Monthly cycle of average soil moisture on the Papua Island (2005–2024)

The average monthly cycle of groundwater levels on the island of Papua for the period 2005–2024, shown in Figure 6, indicates that there is a pattern of recharge–depletion that varies from month to month. The depletion period generally occurs from December to May, characterised by groundwater levels that are lower than the annual average. Meanwhile, the recharge period occurs from June to November.

This pattern of recharge–depletion in Papua differs from that of most other regions in Indonesia. This is due to the characteristics of rainfall patterns in Papua, which are dominated by the equatorial zone, featuring a relatively even distribution of rainfall throughout the year with distinct rainfall peaks, unlike monsoon-type regions which have two rainy season peaks in February and October. These differing characteristics result in the dynamics of groundwater levels in Papua exhibiting a distinctive seasonal pattern, influenced by the existing vegetation cover. Seasonal rainfall and dry conditions can indicate the recharge and discharge phases of the GWS on the island of Papua, as shown in Figure 7 below.

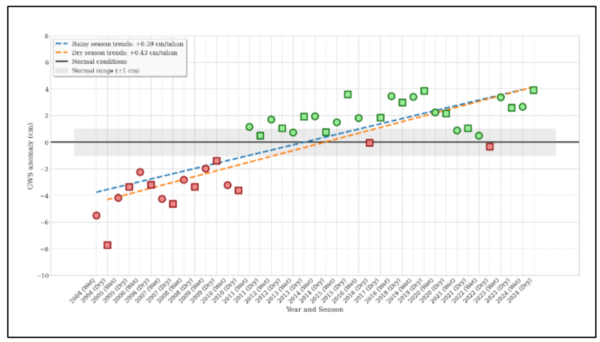

Figure 7. Seasonal anomalies in groundwater levels on the island of Papua (2005–2024)

Based on the GWS anomalies for 2005–2024 (Figure 7), it can be seen that during the rainy season in Papua, the trend in GWS anomalies tends to be higher than during the dry season. This indicates a consistent pattern whereby groundwater levels generally increase during the rainy season. However, in certain years, a decrease in groundwater storage levels is observed despite it being the rainy season. This condition may be caused by several factors, including changes in soil conditions that become drier, thereby reducing infiltration capacity, which causes more rainwater to flow as runoff rather than being absorbed into the soil. Furthermore, other factors such as uneven rainfall distribution, increased evapotranspiration, and local geological characteristics may also influence the groundwater recharge process.

GWS on the island of Papua shows a pattern consistent with the research findings [22] in several basins in Sub-Saharan Africa, which show a trend of increasing GWS driven by natural factors, particularly rainfall variability and vegetation conditions, thus indicating that humid tropical regions generally exhibit a strong recharge response to seasonal hydrological dynamics. Furthermore, the patterns of seasonal GWS fluctuations in Papua also display characteristics similar to those found in the research findings [23][24] in southern China, which shows a trend of increasing groundwater reserves as a result of natural climatic factors prevailing over the pressures of intensive groundwater extraction.

3.4 GWS Response Anomaly

Regional differences in response are illustrated in Figure 8, which shows variations in the rise in the groundwater level in West Papua, North Papua and South Papua. West Papua experienced the most significant rise, ranging from +15 to +20 cm, indicating relatively stable conditions in terms of groundwater accumulation. North Papua shows a moderate increase of around +5 to +10 cm, with more controlled variations. In contrast, South Papua exhibits a more heterogeneous pattern, with some areas experiencing limited increases, whilst others, particularly in the south-east, show changes approaching zero or slightly negative.

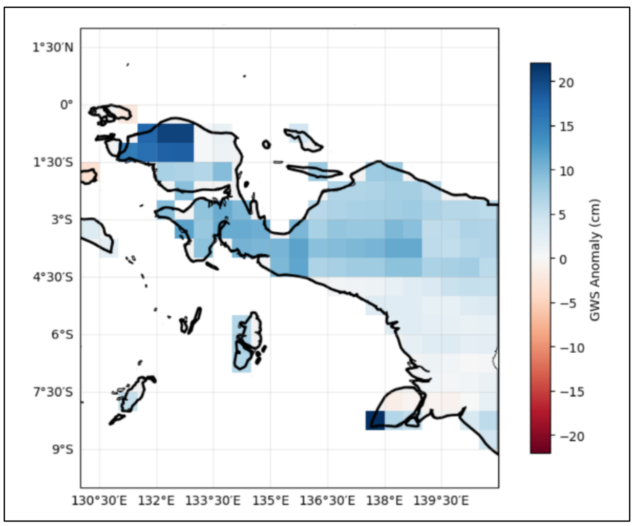

Figure 8. A map of cumulative changes in Groundwater Storage (GWS) on the island of Papua from 2006 to 2024, showing the spatial distribution of surplus and deficit areas.

The difference indicates that South Papua is more sensitive to climate variability, meaning that changes in rainfall have a more immediate impact on groundwater reserves. Meanwhile, West Papua tends to be more stable and acts as a region with greater water storage capacity, whilst the mountainous areas and their surroundings serve as the primary groundwater recharge zones.

IV. CONCLUSION

The results of analysis Terrestrial Water Storage (TWS) and Groundwater Storage (GWS) on the island of Papua for the period 2005–2024 using GRACE and GRACE-FO indicate that the variability in terrestrial water storage exhibits heterogeneous spatial characteristics and strong temporal dynamics in response to the influence of regional climatic factors and the physiographic conditions of the region. Spatially, the distribution of TWS reveals a consistent contrast between West Papua and North Papua, which tend to maintain higher water storage compared to South Papua. TWS variability across Papua indicates a long-term increase in terrestrial water storage during 2005–2024, with West Papua showing the highest increasing trend of approximately +0.43 cm/year, followed by South Papua at +0.39 cm/year and North Papua at +0.38 cm/year. Pemeriksaan. The pattern of TWS indicates that TWS system in Papua is influenced not only by short-term rainfall conditions, but also by the gradual processes of water accumulation and redistribution within the hydrological system.

An analysis of groundwater storage (GWS) on the island of Papua for the period 2005–2024 indicates that groundwater storage dynamics exhibit spatially heterogeneous patterns and a gradual long-term upward trend in response to regional climate variability and the characteristics of local aquifer systems. Regionally, West Papua consistently exhibits relatively higher groundwater storage values compared to Southern Papua, which shows a more dominant deficit; meanwhile, a positive linear trend of approximately +0.38 cm/year has been identified, indicating a gradual accumulation of groundwater over the observation period. Seasonal variations reveal a pattern of recharge from June to November and depletion from December to May, closely linked to the characteristics of the equatorial rainfall pattern in the Papua region, and reinforced by seasonal anomalies showing an increase in GWS during the wet season compared to the dry season.

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