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Monthly Dynamic Groundwater Estimation using GRACE over Indonesia

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Abstract*— Indonesia is an archipelago with tropical climatic conditions, and part of it has arid areas. Monitoring groundwater dynamics effectively and efficiently is one of the challenges in a large area. GRACE is the Geodesy satellite that collects the sub-surface data. GRACE data is one of the gravity anomaly data that can be used for groundwater dynamics detection. Monthly groundwater monitoring can be used to determine the dynamic pattern of terrestrial water storage. It can be used as a parameter for the detection and prediction of drought in a large area. This study aims to model Indonesia's monthly groundwater levels based on gravity anomaly with GRACE satellite data. Anomaly gravity in GRACE's data is the main parameter in monitoring groundwater dynamics. Based on the results of monitoring during January-December 2020, three groundwater conditions were obtained in Indonesia. These conditions always have high groundwater potential, areas with diverse groundwater dynamics, and low groundwater areas. This low groundwater condition occurs in arid areas. The dynamic groundwater pattern occurred in the same month and had a similar pattern every season observed from 2002-2020. For example, the East Nusa Tenggara region has nine months of low groundwater potential. The potential and prediction of drought can be anticipated following the results of monitoring groundwater dynamics. Monitoring and predicting drought by predicting groundwater dynamics using GRACE's data can be an efficient and effective alternative for mapping, especially in Indonesia's vast and water-dominated territory.

***Keywords*— GRACE; groundwater; Indonesia; drought.**

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I. Introduction

Groundwater is the part of the water in nature below the ground surface [1]. The amount of groundwater stored on Earth varies and depends on the region's geological formation [2]. The use of groundwater by the community is increasingly developing in various sectors [3]. The level of groundwater potential in groundwater basins is determined based on quantity and quality criteria [4]. The quantity of groundwater that can be exploited is determined based on aquifer and well parameters, including continuity, type discharge, and optimum discharge [5]. Groundwater quantity criteria depend on the type of use (drinking water, industrial, agricultural, and other purposes). The quality criteria depend on the designation type, the critical parameters' determination, and the standards used to assess groundwater quality [6].

Groundwater potential represents the quantity and quality of groundwater [7]. In a groundwater basin consisting of an unconfined aquifer system and a confined aquifer system, the potential groundwater area describes groundwater's potential level in each aquifer system [8]. So far, groundwater mapping in Indonesia is still done manually and produces low precision. Groundwater mapping is still interpreted manually based on the location map of the investigation area, rainfall map, morphological map, geological map, groundwater basin map, hydrogeological unit map, hydrogeological section, aquifer depth maps, aquifer thickness map, groundwater level map, and groundwater quality map. From the 11 maps used, it is not necessarily available for all regions in Indonesia. Besides, the maps' conditions are no longer up-to-date and do not represent the potential groundwater investigation area's current condition.

Survey costs and a long time due to the investigation's extensive location are also obstacles to providing groundwater in Indonesia. Satellite data can be used as an alternative for modeling and monitoring groundwater potential in Indonesia with relatively low cost, fast mapping time and can be applied to drought applications and other applications. Drought has an association with groundwater and moisture potential [9].

There are many methods used for modeling and detecting groundwater, one of which is gravity anomaly [10]. Currently, the anomaly gravity approach from satellite data has not been applied for modeling groundwater and drought potential in Indonesia. Besides, groundwater and drought maps' accuracy and precision are still low and only applied to certain areas. Routine modeling and monitoring of groundwater levels have not been carried out comprehensively in Indonesia. GRACE's use of anomaly gravity can be used to overcome this problem. GRACE satellite data can be used to determine the groundwater level every eight days or at least every month [11]. The utilization of this data also supports the mapping of cheap and efficient costs in Indonesia.

Changes in groundwater storage in an area play a role in the universal water cycle and its variability with aquifer systems [12]. Variability and climate change can affect groundwater systems. Both of these factors can influence directly and indirectly groundwater dynamics [13]. Therefore, long-term continuation must observe and analyze groundwater storage variations in space and time. Aquifer properties affect groundwater storage [14]. Besides, aquifer systems also affect the balance between the inflow and outflow of surface water bodies and groundwater [15]. The use of groundwater storage is essential to reduce the effects of drought.

Observation and estimation of the number of aquifer properties are significant groundwater wells for irrigation, household supply, and disaster mitigation [16]. Estimating the groundwater depletion rate is essential for managing resources at the regional level [17]. Conventional monitoring methods for tracking groundwater storage changes have limitations and drawbacks, especially in some developing countries. DLR and NASA's GRACE satellites, launched in March 2002, can be utilized to discover and measure large-scale space-actuated terrestrial water storage (TWS) [11], [18], [19]. TWS consists of land and below ground level [20]. The approach taken is anomaly gravity. In general, TWS consists of surface water, groundwater, soil moisture, and ice water [21]. GRACE data accuracy on three large drainage basins can be used to determine the monthly changes in water storage on land and sea [22]. Studied long-term groundwater variations monitored with GRACE data and spatial filtering techniques and found significant groundwater depletion [23]. Groundwater retention measurements are estimated with 2–3 mm accuracy by detecting soil moisture from TWS [11]. Soil moisture plays a vital role in weather and climate forecasts [24]. It is conducted a pre-launch feasibility study of GRACE data over United States upland aquifers [25]. Groundwater and hydrological mapping can be assisted by remote sensing technology [26]. Besides, regional mapping has also been used to better localize hydrological structures by comparing and validating different groundwater storage data sets with GRACE's data [27]. Estimates of soil moisture for each area from the soil surface model in the form of the Global Soil Data Assimilation system can be used for hydrological processes and potential groundwater detection [28], [29].

This study aims to model Indonesia's monthly groundwater levels based on gravity anomaly with GRACE satellite data. This modeling is only for 2020, and spatial information is extracted monthly based on gravity anomaly. The groundwater level includes TWS.

II. Material and Method

A. Study area and data

Indonesia consists of 17,504 islands located between the Indian Ocean and the Pacific Ocean [30]. This region has many volcanoes and tectonic faults. Indonesia is located between 6 ° N - 11 ° S and 95 ° E - 141 ° East. The study area of this research is Indonesia; see Figure 1.

Indonesia's territory is an equatorial area consisting of topographic conditions, and most of it is waters. The islands of Sumatra and Kalimantan consist of forests that have undergone many changes inland. Java Island is the region with the largest population and settlement distribution in Indonesia. The islands of Papua and Sulawesi still have much vegetation. The Nusa Tenggara region is an arid region with a high level of drought and has many savanna-steppes.

Since 2002, the Gravity Recovery and Climate Experiment (GRACE) satellite mission have been used to monitor Earth's gravitational field on a large spatial scale. GRACE currently measures Earth's mass redistribution with a spatial resolution of several hundred kilometers and a monthly temporal resolution. GRACE provides a map of the Earth's gravitational field to infer anomalous trends in surface mass. The leading cause of the Earth's gravitational field's temporal changes is the redistribution of water masses within the Earth's relatively thin liquid shell. The GRACE measurements have been corrected for the significant contributions to oceanic variations and atmospheric mass [31]. Therefore, the difference between the two monthly solutions mainly reflects changes in terrestrial (surface plus land) water storage between these two months. For areas of 200,000 km^2 or more, GRACE can monitor changes in total water storage with an accuracy of 1.5 cm equivalent water thickness. GRACE has the advantage of sensing changes in water retention at all levels, including snow, surface water, groundwater, and soil moisture.

There are 12 GRACE data used in this study, namely for January, February, March, April, May, June, July, August, September, October, November, and December. All data were acquisitions in 2020. The potential groundwater information from GRACE's image uses a spatial resolution of 0.25 degrees. The amount of spatial resolution is adjusted to Indonesia's mapped area and makes it easier to process data and present spatial information.

B. Terrestrial Water Storage (TWS)

The TWS is a method used to extract groundwater potential from GRACE's data. Two-step data processing is used to suppress the high degree of error noise and adjust the GRACE gravity solution's spherical harmonics [2]. The processing followed Landerer and Swenson [32] findings. Monthly harmonics were processed using a Gaussian refinement and link decoration filter [33]. The relationship decoration filter is carried out so that for a given spherical harmonic order (six and higher), the third-order polynomial function is derived by the least-squares corresponding to the GRACE solution's even or odd coefficient pairs and is removed from the monthly solution [34]. Gaussian smoothing1.53 is applied over a 500 km radius. The next thing to do is remove the gravity anomaly associated with GIA from the GRACE solution based on the geodynamic model [24], [35]. GRACE's data to infer water mass in water thickness and associated with TWS.

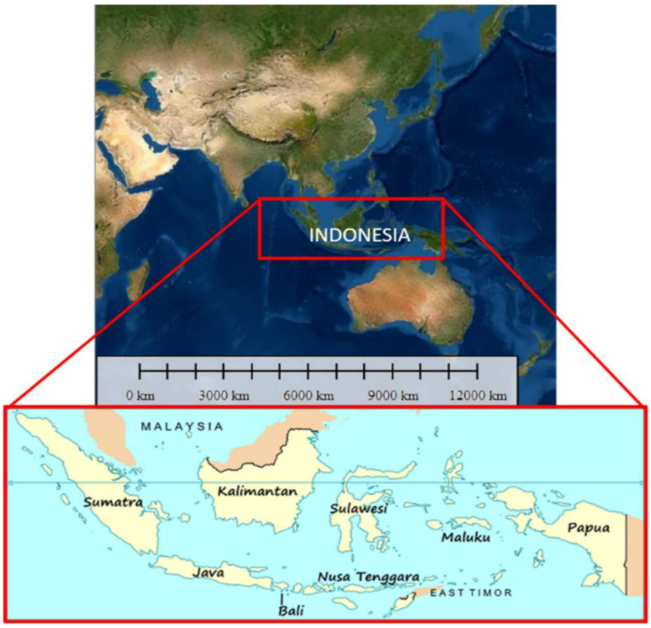


Fig. 1 Indonesia is the study area of this research.

III. RESULTS AND DISCUSSION

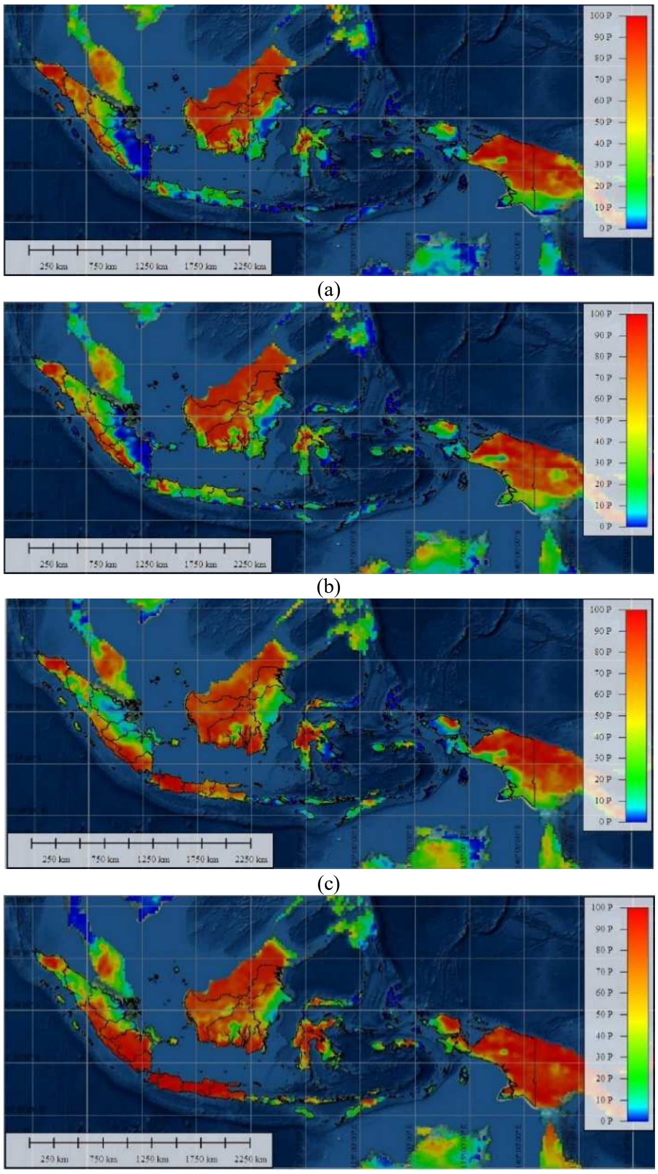
A. Groundwater Extraction from Space

The results of this research are the monthly groundwater information in 2020. The information was extracted from GRACE satellite data. Using the TWS, the information can extract the information every eight-day, but we only use data per month in this research. We use the first data every month to extract the groundwater information. The result will display the dynamic of monthly groundwater; see Figure 2.

Figure 2 is the groundwater extraction from space. The information includes monthly from January, February, March, and April 2020. In January 2020, the image of GRACE used was January 6, 2020. This month, some groundwater potential in Indonesia is low. Blue, green, and yellow colors indicate potential low groundwater. Low groundwater indicates low groundwater reserves and has implications for drought.

Meanwhile, the orange color indicates high groundwater potential. Sumatra Island has low groundwater potential, only in Aceh and several areas in the Bukit Barisan region with high groundwater potential. The majority of areas in Java and Sulawesi have low groundwater potential. The islands of Kalimantan and Papua have a flat area of low and high groundwater potential. All areas of Nusa Tenggara and Maluku have low groundwater potential.

In February, GRACE's data used was February 3, 2020. Almost all areas in Indonesia have low groundwater. Some areas in Kalimantan and Papua islands still have high groundwater potential. The Nusa Tenggara, Java, and Maluku region can still face drought due to their low groundwater potential. Likewise, the eastern region of Sumatra and Kalimantan islands is still at the lowest groundwater potential level.



(a)

(b)

(c)

(d)

Fig. 2 Groundwater extraction from space (a). January 2020; (b). February 2020; (c). March 2020; (d). April 2020

In March 2020, GRACE's data used was March 2, 2020. The majority of Nusa Tenggara and Maluku still have low groundwater levels. This area could indicate a high level of drought. Sumatra's regions, Papua and Sulawesi, still have a balance of potential for low and high groundwater. Most Java and Kalimantan have high groundwater potential.

Monitoring in April used GRACE's data dated April 6, 2020. This month, the majority of Java, Kalimantan, and Papua have high levels of groundwater. It is different from Sumatra and Sulawesi, which have a balance of high and low groundwater levels. The Nusa Tenggara and Maluku regions are still areas with low groundwater levels. Overall, the territory of Indonesia this month has a higher groundwater level than the previous three months.

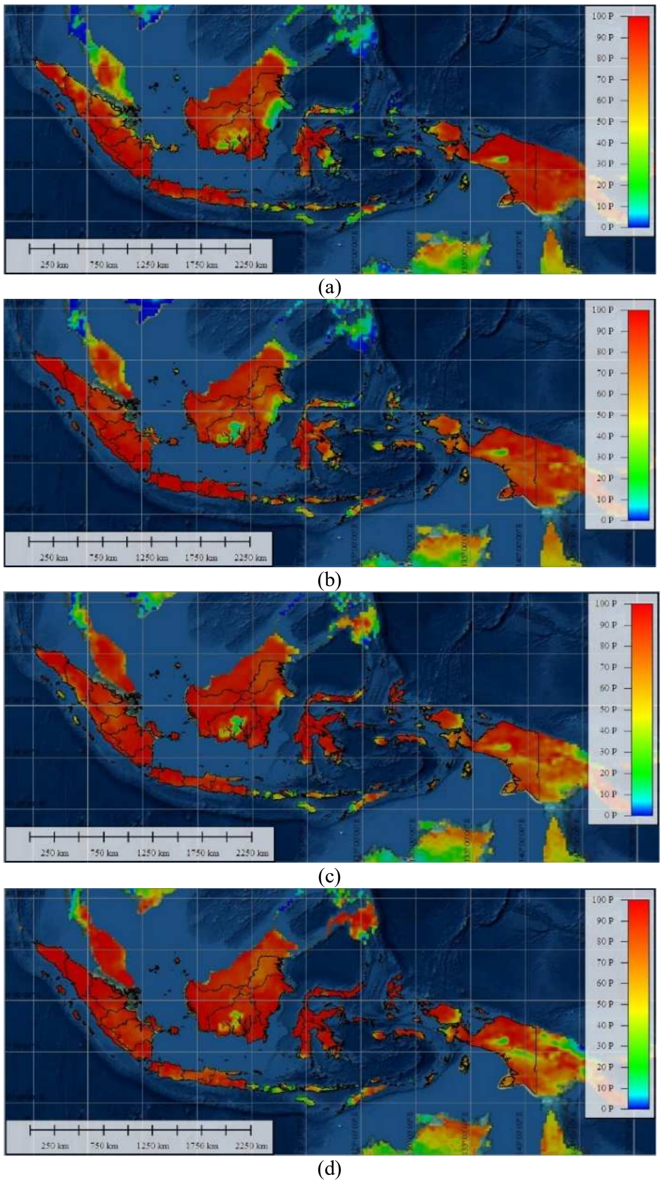


Fig. 3 Groundwater extraction from space (a). May 2020; (b). June 2020; (c). July 2020; (d). August 2020

Figure 3 shows the groundwater in May, June, July, and August 2020. They were extracted from space imagery data. In May 2020, monitoring used GRACE's data dated May 4, 2020. This month, almost all Java, Sumatra, Kalimantan, and Papua areas have high groundwater potential. Sulawesi region has a potential balance of low and high groundwater. The Nusa Tenggara and Maluku regions still have low groundwater potential. The potential for drought will still occur in areas such as Nusa Tenggara.

Different things happened in June 2020. GRACE data used is June 1, 2020. This month, almost all regions in Indonesia have high groundwater levels. Likewise what happened in Nusa Tenggara and Maluku. Some areas in Nusa Tenggara, Kalimantan, and Sulawesi still have low groundwater levels.

In July 2020, the Nusa Tenggara region again had a low groundwater level. This area still has the potential for drought, but other areas in Indonesia experience high groundwater levels. Some areas in Kalimantan and Papua have low groundwater levels. In this month, the GRACE data used is July 6, 2020. Overall the level of drought in Indonesia this month is still low.

In August 2020, the regions of Java, southern Sumatra, several areas in Kalimantan and Papua experienced a potential reduction in groundwater levels. Overall, Indonesia still has a high groundwater level. The Nusa Tenggara region has a low groundwater level. Sulawesi and Maluku regions still have high groundwater levels. GRACE data used in this period is August 3, 2020.

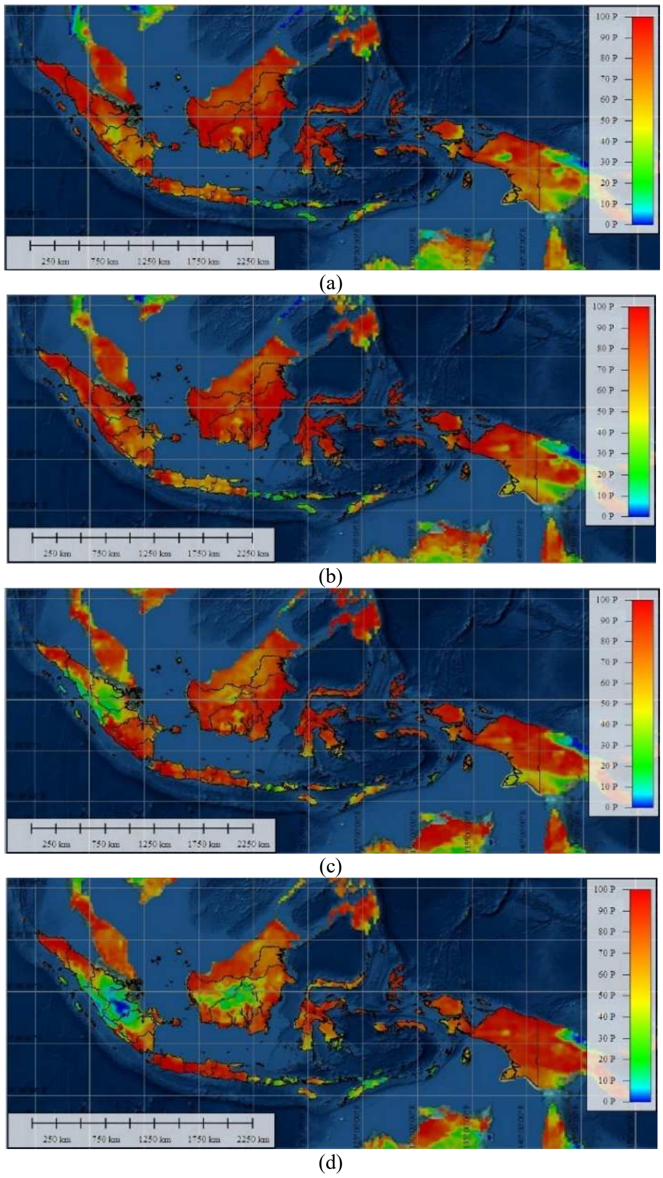


Fig. 4 Groundwater extraction from space (a). September 2020; (b). October 2020; (c). November 2020; (d). December 2020

Figure 4 explains the groundwater information. The information was extracted from the satellite data from September to December 2020. In September 2020, groundwater potential in the Java, Sumatra, and Papua regions declined compared to the previous month. The Nusa Tenggara region continues to have the lowest groundwater level in Indonesia. The potential for drought still dominates the Nusa Tenggara region, but Kalimantan, Sulawesi, and Maluku regions still have high groundwater levels. GRACE data used this month is September 7, 2020.

By October 2020, most of Java had low groundwater levels. Likewise, the Sumatra and Papua regions have a balance of low and high groundwater levels. The regions of Kalimantan, Sulawesi, and Maluku still have high groundwater levels. The Nusa Tenggara region still has the lowest groundwater levels and making it prone to drought. GRACE's data dated October 5, 2020, were used to model Indonesia's groundwater level in October 2020.

Most of Sumatra experienced low groundwater levels in November 2020. GRACE data used is November 2, 2020. Kalimantan, Sulawesi, and Papua regions experienced a decrease in groundwater levels compared to the previous month. Java region experienced a slight increase in groundwater levels compared to the previous month. The NTT region remains the region with the lowest groundwater level and has the potential to experience drought.

In December 2020, the groundwater level in the central Sumatra region experienced the lowest value. Likewise, the Kalimantan region experienced low groundwater levels. Sulawesi and Maluku regions are starting to have a balance of high and low groundwater levels. The Papua region is experiencing a decrease in groundwater levels. The Nusa Tenggara region continues to experience low groundwater levels. The area still has the potential to experience drought. GRACE's data used for modeling is December 7, 2020.

B. Water Equivalent Thickness

One of the quality checks of groundwater modeling based on gravity anomaly is the water equivalent thickness. Checks were carried out by modeling the groundwater level from 2002-2020. 2002 was chosen because GRACE's data availability started that year. Checks are carried out randomly in Indonesian territory. Two areas were selected: areas with relatively high groundwater levels throughout the year, areas with low groundwater levels, and high dynamic groundwater levels. The area with relatively high groundwater throughout the year is West Java. The region selected is with the coordinates 6.96535 S, 106.3213 E - 6.20955 S, 107.6616 E.

This area has a stable groundwater potential value from 2002-2020; see Figure 4. The decrease and increase of the potential water equivalent thickness in this area indicate that the groundwater conditions are still good throughout the year, from January to December. This area has experienced low groundwater potential around 2007, 2010, 2016, and 2020. This condition can cause drought in a relatively short period because the groundwater potential will immediately increase in the following period.

Checks on areas with dynamic groundwater potential were carried out in South Sumatra. In this area, the potential for high groundwater varies and tends to decrease. The area dominated by peat is also planted and replaced with oil palm plantations, resulting in massive water absorption. This condition is the leading cause of the decrease in groundwater potential. The decline occurred from 2002-2020. Since 2000, oil palm plantations have begun to dominate this area. Oil palm plantations replace the function of forests in maintaining the stability of groundwater. There are dynamics of groundwater changes due to the rainy and dry seasons' influence in other years. The potential reduction at the lowest point occurred in 2016 and 2020. Figure 6 is a water equivalent thickness pattern at coordinates 2 S, 103 E-1 S, 104 E.

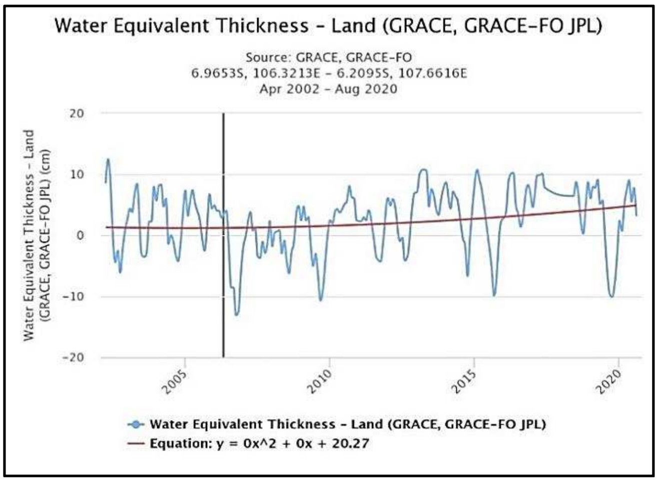


Fig. 5 Water equivalent thickness in West Java (April 2002-August 2020)

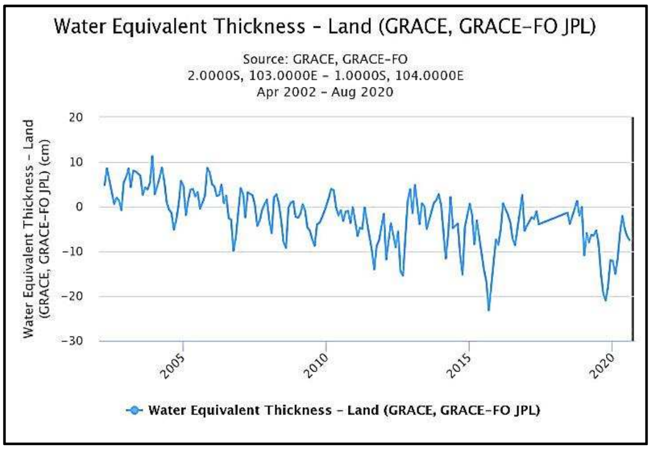


Fig. 6 Water equivalent thickness in South Sumatra (April 2002-August 2020)

Checks on areas with low groundwater potential were carried out in the East Nusa Tenggara area. Areas that have arid conditions have a shortage of surface water. Based on monitoring GRACE's image, the area also has low groundwater potential. In a year, this area only has three months with high groundwater potential conditions. For nine months, this area has low groundwater potential. Since the period 2002-2020, the groundwater potential condition has remained low, but in 2010-2012 this area had high groundwater potential. However, in 2012-2017, it experienced a drastic decline. Figure 7 is the water equivalent thickness pattern at the coordinates 9 S, 125 E - 8 S 126 E.

GRACE's data can be used for monitoring TWS as in the research of [36]. TWS can also be used as a parameter in drought and flood detection. The parameters for drought prediction have been carried out in the study of Frappart and Ramillien [37] for monitoring the North American region. Similar conditions were also found in monitoring the potential groundwater conditions in Indonesia. The East Nusa Tenggara area monitored with GRACE's data also has low groundwater potential. This condition is an indication of areas experiencing drought. TWS anomalies are not comparable for different hydro-climatic regions because these data have a small spatial resolution.

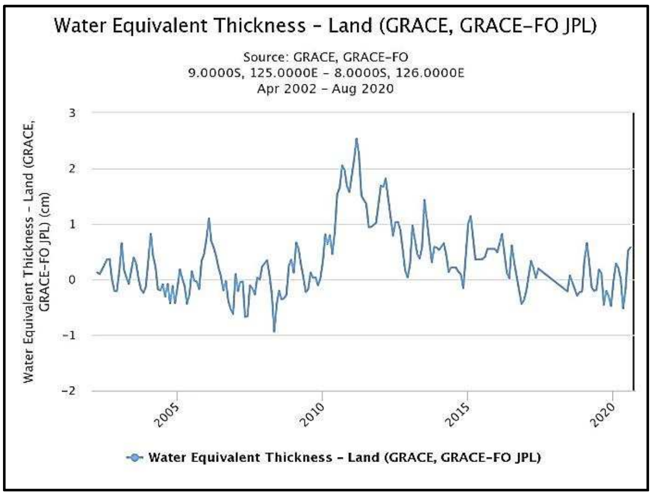


Fig. 7 Water equivalent thickness in East Nusa Tenggara (April 2002-August 2020)

GRACE's data that can be used for drought detection and prediction has also been proven in the study of Liu *et al.* [38]. Their research was conducted to monitor major basins in China in 2002-2017. The availability of data with long historical data helps monitor groundwater dynamics. This condition is similar to the monitoring of Indonesia's territory in the 2002-2020 period. GRACE's data, which can be obtained every eight days, can be used in monitoring Indonesian regions, which are mostly experiencing high dynamics and are influenced by seasonal changes.

Monitoring of drought in arid areas such as East Nusa Tenggara can describe small-scale aquifers' conditions. In another study conducted by Mohamed and Gonçalvès [23], it was concluded that groundwater with drought in the semi-arid region of Brazil was concluded. This proof can also be found in the results of low groundwater potential in Indonesia's Arid region by utilizing GRACE's data.

Drought prediction using GRACE's data can also be made by studying groundwater's dynamic patterns from historical data. This drought prediction has been proven in the study of Getirana *et al.* [39] by predicting drought based on groundwater season patterns. This condition is also possible to apply in Indonesia. The prediction of drought in East Nusa Tenggara only experiences three months with relatively high groundwater dynamics. During nine months, there was a decrease in low groundwater dynamics. This pattern is similar every year based on 2002-2020 data. This similarity occurs in the same month every year. Based on this condition, it can be predicted that the potential for drought in East Nusa Tenggara for nine months can be predicted. Monitoring and predicting drought by predicting groundwater dynamics using GRACE's data can be an efficient and effective mapping alternative. Besides, the availability of GRACE's data every eight days can make it easier to monitor Indonesia's vast and dominated waters.

IV. Conclusion

This study concludes that the anomaly gravity in GRACE's data can be used for monthly groundwater monitoring in the form of TWS. Besides, groundwater dynamics can be used as a parameter for detecting and predicting drought in a large area. Monitoring can be done every eight days, and information on groundwater dynamics every month can be known. The Indonesian region has various groundwater dynamics. Some areas always have high groundwater potential, such as West Java. Some areas have low groundwater in the Arid region, such as East Nusa Tenggara. Likewise, areas that have diverse groundwater dynamics, such as South Sumatra.

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