EVALUATION OF GROUNDWATER STORAGE CHANGES USING SATELLITE GRAVIMETRY MISSION IN PENINSULAR MALAYSIA

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ABSTRACT:

Water stored beneath the Earth's surface, known as groundwater is a major water supply for living things. The increase in human population leading to high urban development and industrial needs in Malaysia has made the use of groundwater more critical. The current issue faced by Malaysia is the limitation of freshwater source from dam resulting in increasing demand to gather the source of fresh water from groundwater; hence, leading to the crucial exploitation of groundwater. Therefore, this study aims to evaluate groundwater storage (GWS) using Gravity Recovery and Climate Experiment (GRACE) and Global Land Data Assimilation System (GLDAS) data in Peninsular Malaysia. GRACE data consist information on the liquid water equivalent thickness covering terrestrial water storage (TWS) of GWS, soil moisture (SM), snow water equivalent (SWE), and surface water (SW). In comparison with GLDAS data, they only consist hydrological products of SM, SWE, and SW. Therefore, the differences between the GRACE and GLDAS data are most likely to reflect the information of GWS. Due to the seasonal monsoon, the changes in GWS can also be seen in specific months. In addition, the data can also be used to identify important areas that need improvement and attention. The output of this study is expected to help authorities monitoring the changes in GWS in recharge and discharge areas for future preservation of groundwater quality. Moreover, the excessive exploitation of groundwater can also be observed for the prevention of land hazard phenomena, such land subsidence.

1. INTRODUCTION

After the polar ice caps, the major reserve of fresh water is groundwater, where water is stored beneath the Earth's surface, and the groundwater source contains 100 times more than the available freshwater streams and lakes (Edwin et al., 2016). In terms of volume per year, the world's population today extracts water from the subsoil two hundred times more than oil. In several countries, groundwater is widely utilised. (Margat et al., 2013). As one of the major freshwater resource, groundwater became the most required and preferred worldwide. Groundwater resources are used to support human daily requirements, mostly for drinking, agricultural, domestic, and industrial uses. The demand for fresh water will continue to rise as the human population grows and urbanisation occurs. Extensive groundwater pumping in several region, approximately 70% of groundwater pumped globally, particularly for agricultural irrigation, has resulted in dramatic drops in groundwater level (Marget et al., 2013: Famiglietti, 2014: Chen et al., 2016). As the demand for groundwater grows, so does the exploitation to obtain it, resulting in severe deterioration of groundwater quality. The process of recharge and discharge from the groundwater to the surface water reservoirs system balances the change in groundwater storage. Due to the exceedingly slow process of the hydrological cycle, significant groundwater recharge in the affected regions will not be entirely replenished in the future (Stagl et al., 2014).

The Gravity Recovery and Climate Experiment (GRACE) is the first dedicated satellite time-variable gravity mission, and it offers a novel technique for monitoring large-scale mass changes in the Earth system (Tapley et al., 2004: Chen et al., 2016). The principle of GRACE is mapping the Earth's gravity field by measuring the changes distance between the pair of GRACE satellites with GPS and microwave ranging along the orbiting Earth (Zulkifli et al., 2018). The gravity variations analysed by GRACE satellite include the changes of the continental water and snow storage, variations of the sea-floor pressure, the mass balance of ice sheets and glaciers, and redistribution of mass on Earth, which serve as critical input for various fields of oceanography, hydrology, glaciology, and solid Earth science. As GRACE data are widely used for hydrological studies, this study highlights the changes of GWS by implementing both GRACE data and Global Land Data Assimilation System (GLDAS).

Since the GRACE measurement data contain all components on terrestrial water storage (TWS), the GLDAS land model is used to extract the information on the groundwater storage (GWS) from the GRACE solution. This is because, GLDAS data do not include the measurement of GWS. The GLDAS land model combines satellite and ground-based data products using the data assimilation technique to produce the most accurate land surface information (Rodell et al., 2004: Zulkifli et al., 2018). The GLDAS consist of aggregated anomalies in land water storage from soil moisture (SM), snow water equivalent (SWE), and

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surface water (SW), mainly storage of the plant canopy as predicted by land surface models.

Therefore, this study is conducted to monitor the changes in GWS focusing on the Peninsular Malaysia region, which approximately ranges between 0.5° - 8.5° for latitude and 98.5° - 105.5° for longitude. The total area of Peninsular Malaysia is 132, 265 km^2, nearly 40% of the total area of Malaysia. Peninsular Malaysia can be divided into four regions: the north region, the east region, the south region, and the west region.

2. DATA AND METHOD

2.1 Gravity Recovery and Climate Experiment (GRACE)

The GRACE mission consists of twin satellites operated from 2002 to 2017 (Frappart and Ramillien, 2018). GRACE products of Level-3, which can be obtained from the Physical Oceanography Distributed Active Archive Center (PODAAC) website, are developed by Jet Propulsion Laboratory (JPL) from California Institute of Technology and established by National Aeronautics and Space Administration (NASA) (Verma et al., 2016). In this study, the recent version of GRACE products Level-3, Release 06 (RL06) are used to derive the GWS anomaly. This is because the GRACE RL06 product is far more precise compared to the former release (Chen et al., 2016: Iqbal et al., 2016: Salam et al., 2020).

The Level-3 datasets are one of the ready-to-use products in the form of gridded observation values for every 1-degree bin. This information is derived based on the processing involving the Level-2 datasets in response to the gravity field variations. This ready-to-use product has already been corrected by implementing a specific model and filtering technique. This Level-3 data contain information on GWS, SM, SWE, and SW. Since this study intends to extract only the information of GWS, other land surface model is required to be integrated with GRACE data for further calculation.

2.2 Global Land Data Assimilation System (GLDAS)

The GLDAS was co-developed by scientists from NASA's Goddard Space Flight Center (GSFC) and the National Oceanic and Atmospheric Administration's (NOAA) National Centers for Environmental Prediction (NCEP). GLDAS data are produced by specific instances of the Land Information System (LIS) software framework for high-performance land-surface modelling and data assimilation. It contains data on SM, SWE, and SW, as slightly different to the GRACE product from Level-3, which also includes the data on GWS. Therefore, the GLDAS data are combined with GRACE Level-3 data to derive GWS information using a simple mathematical formula.

2.3 Derivation of Groundwater Storage Anomaly Rate

GRACE products Level-3 and GLDAS surface model are used to calculate the GWS anomaly. As GRACE measurement includes all information on TWS, it is necessary to include GLDAS measurement in the estimation to extract the GWS anomaly. The information on GWS can be obtained using simple mathematical calculations before the rate is determined using robust fit regression in the MATLAB programming software. Equation (1) shows the derivation of GRACE products Level-3, which covers the TWS:

$$TWS\ GRACE = SW + SM + GWS + SWE \qquad (1)$$

where *TWS* = GRACE total terrestrial water storage,
SW = Surface Water,
SM = Soil Moisture,
GWS = Groundwater Storage,
SWE = Snow Water Equivalent.

Contradict to the GRACE observation data, the *TWS* from GLDAS measurement comprises of SM, SW, and SWE (Chinnasamy et al., 2015). In revealing this data, a simple equation for GLDAS is derived as follows (Chinnasamy et al., 2015):

$$TWS\ GLDAS = SW + SM + SWE \qquad (2)$$

where *TWS* = GLDAS total terrestrial water storage,
SW = Surface Water,
SM = Soil Moisture,
SWE = Snow Water Equivalent.

This study merges two datasets to estimate GWS anomaly (GRACE and GLDAS). To measure GWS anomaly, monthly TWS GRACE data are subtracted from monthly TWS GLDAS values to produce rate of GWS in the Peninsular Malaysia region per equation (3):

$$GWSA = TWS\ GRACE - (SW + SM + SWE) \qquad (3)$$

where *GWSA* = Groundwater Storage Anomaly,
TWS = GRACE total terrestrial water storage,
SW = Surface Water,
SM = Soil Moisture,
SWE = Snow Water Equivalent.

However, the value of SWE is considered as none in Malaysia, due to its location near the equatorial line, dealing only with hot and humid weather throughout the year.

3. RESULTS AND DISCUSSION

3.1 Mean of GWS in Peninsular Malaysia

GRACE data is utilised to estimate monthly GWS changes from 2002 to 2017. GWS is computed by removing SW, SM, and SWE from GRACE data, as depicted in equation 3. From the computation of GWS anomaly, the mean of GWS is estimated. Figure 1 illustrates the average monthly GWS from April 2002 until June 2017, followed by the statistical analysis in Table 1.

The map indicates the average of GWS in Peninsular Malaysia ranges from -0.083 cm to 0.140 cm, with a standard deviation of 0.042 cm. The statistics also indicate that the average GWS between 2002 and 2017 is -0.004 cm. In addition, the central region and part of the northern region have the most significant storage capacity. In contrast, western sector of Peninsular Malaysia has the lowest storage capacity compared to the southern sector. However, the minimum and maximum values of storage region are -0.083 cm and 0.140 cm, respectively. This is mainly associated with the seasonal variations. As Malaysia experience hot and humid tropical climate year-round, the value of GWS is recorded to be high during monsoon season, while the minimum value is observed during inter-monsoon season (Bhanja et al., 2017).

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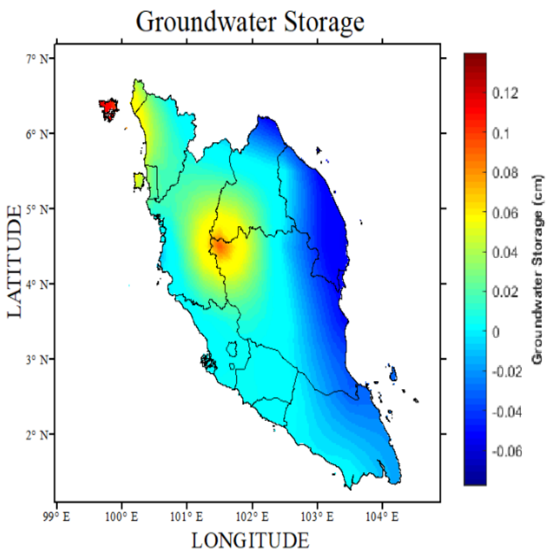


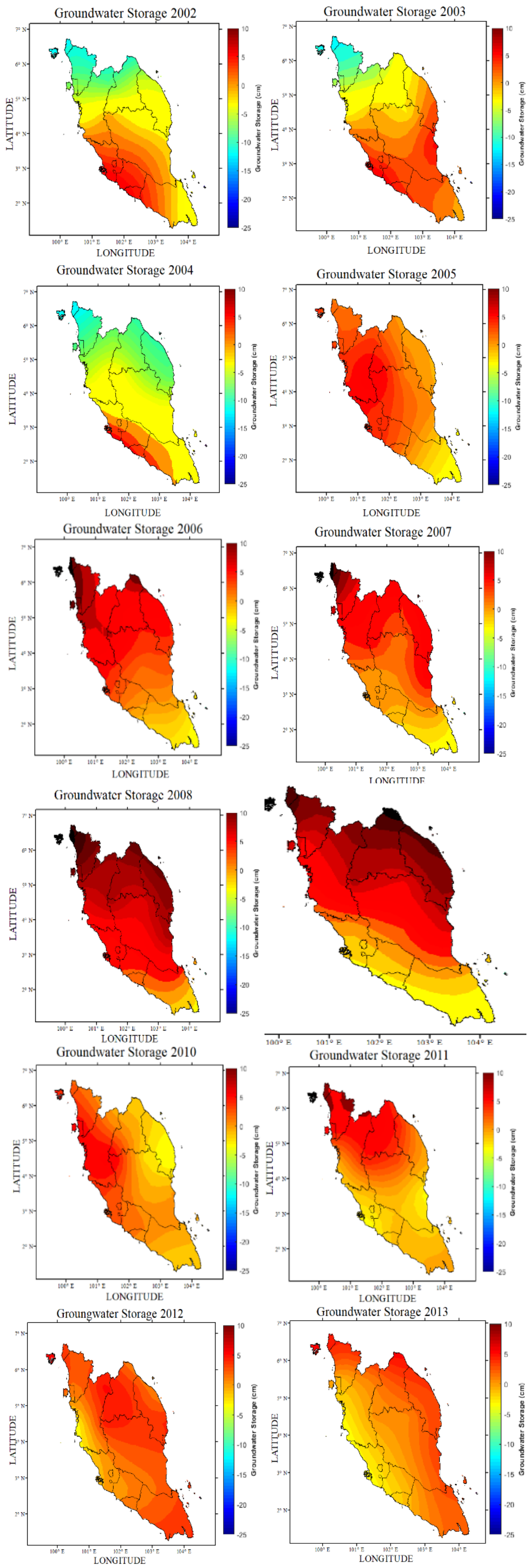
Figure 1. The average of GWS in the Peninsular Malaysia region from 2002 until 2017

	Min (cm)	Max (cm)	Mean (cm)	Standard Deviation (cm)
Groundwater Storage	-0.083	0.140	-0.004	0.042

Table 1. Statistical analysis of the average GWS in Peninsular Malaysia from 2002 until 2017

3.2 Variation of GWS from 2002 to 2017 in Peninsular Malaysia

In Peninsular Malaysia, the GWS of 16 years are mapped annually from 2002 until 2017 to visualise the pattern of GWS behaviour throughout the study period (Figure 2). Referring to the GWS map from 2002 to 2004, the grading colour blue (the smallest value) of the GWS values tends to change into green-yellow in the northern to west regions of Peninsular Malaysia. On the other hand, the value of the GWS increases in the central part and down to southern region of Peninsular Malaysia from 2002 to 2004. From 2005 until 2009, the amount of GWS start to increase gradually, turning to red colour as the values of GWS increase mainly in the northern region of Peninsular Malaysia. However, starting from 2012, the amount of GWS in the western Peninsular region starts to decrease, followed by the north region in 2016. However, the groundwater at southern Peninsular Malaysia seems to became positive when the yellowish colour changes to orange-red until 2017.



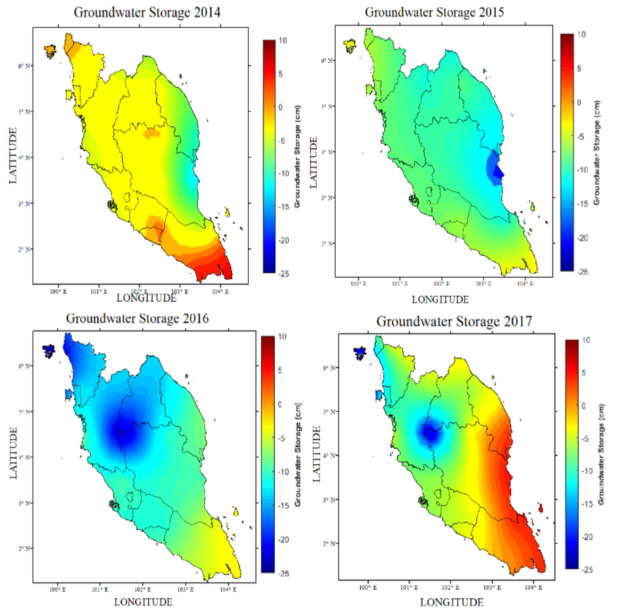


Figure 2. Yearly GWS from 2002 until 2017

3.3 Seasonal Variation of GWS

The monthly GWS anomaly from 2002 until 2017 is categorised into four different seasons for further climatological analysis. As stated by Su et al. (2020), the study of the seasonal variation gives further opportunity to study the dynamic changes of GWS. The behaviour of GWS relative to the seasonal climate in Peninsular Malaysia is presented on the climatology map, as shown in Figure 3. The seasonal variation in GWS can be closely related to the seasonal event in Malaysia: the first are inter-monsoon and southwest monsoon, and the second are inter-monsoon and northeast monsoon.

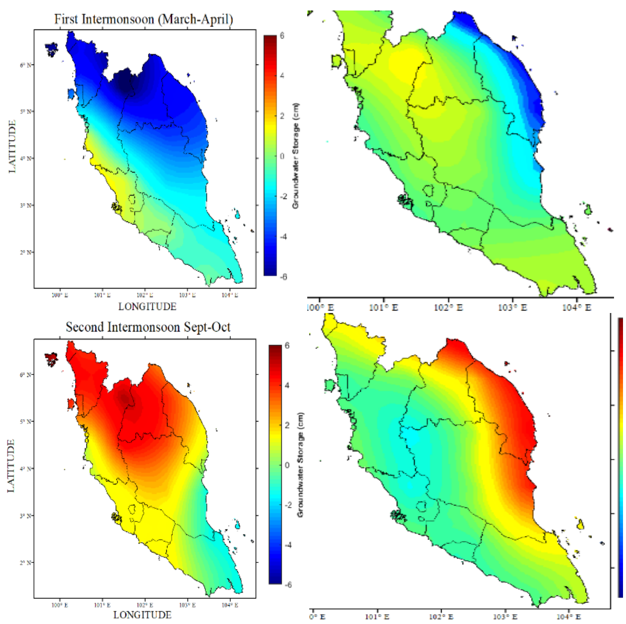


Figure 3. Monsoon seasons in Malaysia

From Figure 3, the monsoon events can be clearly observed from the GWS pattern from 2002 until 2017. The amount of GWS increases due to the effect of the northeast monsoon from November to February at the east region and part of north region of Peninsular. However, during the southwest monsoon season, which occurs in May until August, the southwest area shows positive values of the GWS. The maps presented the GWS variation pattern based on seasonal influences for the research area. Besides, these maps consider representing the long-term normal GWS pattern for each month. As stated by Xu (2021), the characteristics of seasonal variation in the GWS are related to the precipitation, agricultural irrigation, and exploitation of groundwater. From that, these maps might serve as a point of reference when calculating the GWS anomaly for a certain month.

3.4 Groundwater Storage at Tube Well JMG

The changes of GWS rate at the tube well have been analysed on the selected tube well across Peninsular Malaysia provided by Department of Mineral and Geoscience (JMG). As the coordinate of every point of the tube well has been provided, any changes in behaviour of groundwater storage on the tube well can be determined and monitored (Salam et al., 2020). Monitoring groundwater is essential for water resource management and preservation (Rzepecka and Birylo, 2020). Figure 4 shows the distribution of the JMG tube well in Peninsular Malaysia. Meanwhile, the rate of changes of GWS on the selected tube well from 2002 to 2017 is tabulated in Table 2. The GWS rate is estimated to be -7.920 mm/yr at CHTP and -0.184 mm/yr at JHBH. However, the lowest rate of change is -7.920 mm/yr at the CHTP tube well, followed by -7.644 mm/yr at RAUB and -7.639 mm/yr at KGSR, where these tube wells are located at the minimum recharge storage area as shown in Figure 6. However, further research is necessary to determine the actual source of the high incidence rates of GWS.

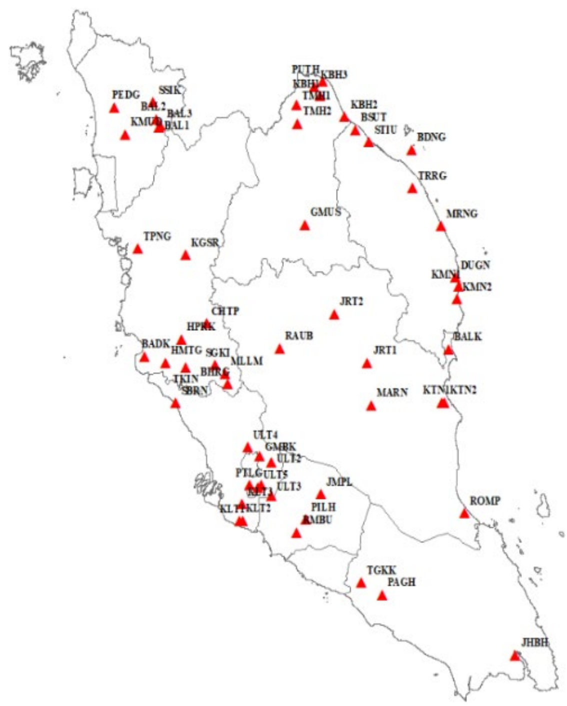


Figure 4. Distribution of JMG tube well in Peninsular Malaysia

Figure 5 shows the time series graph of groundwater storage anomaly for the tube well, highlighting the patter of water level. Red lines represent the original data and the green lines represent smoothed data using moving average method. The blue solid line represents the robust fit simulation, while the black dashed line represents robust fit regression. The groundwater rates for the tube well are -3.782 mm/yr at BDNG, Pulau Bidong, Terengganu and -4.041 mm/yr at DUGN (Kampung Tanjung Hutan, Terengganu). The GWS anomaly are determined to be varied; from 2002 to 2017. However, the anomaly is observed to decline constantly from 2008 to 2017. This condition may emerge as a result of rising groundwater usage, as demand for groundwater abstraction increases at a rate of 2.5% each year (NAHRIM, 2014: Zulkifli et al., 2018).

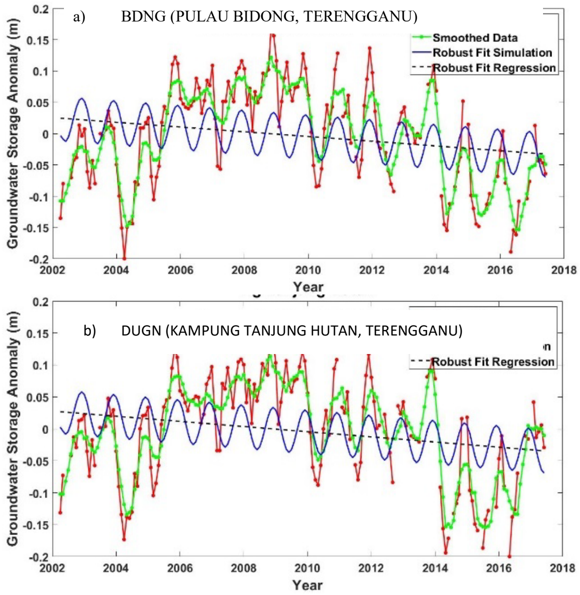


Figure 5. The rate of GWS at JMG tube well at BDNG, Pulau Bidong and DUGN, Kampung Tanjung Hutan, Terengganu

Tube Well	State	Longitude	Latitude	GWS Rate (mm/yr)
TGKK	JOHOR	102.6302	2.1970	-4.0755
JHBH	JOHOR	103.9382	1.6205	-0.1844
PAGH	JOHOR	102.8076	2.0971	-3.5178
TMH1	KELANTAN	102.0781	5.9752	-2.6420
TMH2	KELANTAN	102.0860	5.8284	-2.8203
KBH1	KELANTAN	102.2819	6.0429	-3.2516
KBH2	KELANTAN	102.4904	5.8811	-3.6977
PUTH	KELANTAN	102.2980	6.1591	-3.3684
GMUS	KELANTAN	102.1490	5.0276	-3.4516
KBH3	KELANTAN	102.2333	6.1167	-3.1669
RAUB	PAHANG	101.9337	4.0477	-7.6437
KTN1	PAHANG	103.3149	3.6218	-5.8926
ROMP	PAHANG	103.5075	2.7468	-3.7695
KTN2	PAHANG	103.3363	3.6190	-5.9093
JRT1	PAHANG	102.6833	3.9333	-4.6036
MARN	PAHANG	102.7167	3.6000	-5.2143
JRT2	PAHANG	102.4035	4.3188	-4.2706
BALK	PAHANG	103.3710	4.0400	-5.0221
HPRK	PERAK	101.0991	4.1209	-6.4555
CHTP	PERAK	101.3145	4.2436	-7.9200
KGSR	PERAK	101.1405	4.7869	-7.6387
TPNG	PERAK	100.7305	4.8379	-5.7501
BADK	PERAK	100.7876	3.9848	-5.8312
HMTG	PERAK	100.9634	3.9339	-5.6715
TKIN	PERAK	101.1398	3.8988	-5.7396
SBRN	PERAK	101.0526	3.6160	-6.4898
SGKI	PERAK	101.3878	3.9166	-7.1117
BHRG	PERAK	101.4958	3.7653	-7.0610
MLLM	PERAK	101.4734	3.8502	-7.2691
KMN1	TERENGGANU	103.4572	4.5369	-4.0465
DUGN	TERENGGANU	103.4313	4.6097	-4.0415
TRRG	TERENGGANU	103.0659	5.3176	-3.8079
BDNG	TERENGGANU	103.0580	5.6212	-3.7815
MRNG	TERENGGANU	103.3061	5.0161	-3.9260
STIU	TERENGGANU	102.6966	5.6808	-3.7161
BSUT	TERENGGANU	102.5796	5.7752	-3.7075
KMN2	TERENGGANU	103.4439	4.4361	-4.1664
PILH	N. SEMBILAN	102.1603	2.6964	-5.5654
JMPL	N. SEMBILAN	102.2864	2.8944	-5.1831
RMBU	N. SEMBILAN	102.0821	2.5934	-6.0115
ULT1	SELANGOR	101.7835	2.9667	-6.2289
ULT2	SELANGOR	101.8667	3.1500	-5.6292
GMBK	SELANGOR	101.7667	3.2000	-5.8043
PTLG	SELANGOR	101.6833	2.9667	-6.5482
KLT1	SELANGOR	101.6246	2.6796	-7.3134
KLT2	SELANGOR	101.5972	2.6833	-7.3935
ULT3	SELANGOR	101.8667	2.8833	-6.1305
KLT3	SELANGOR	101.6167	2.8167	-7.0646
ULT4	SELANGOR	101.6667	3.2667	-5.9796
ULT5	SELANGOR	101.7500	2.9500	-6.3692
PEDG	KEDAH	100.5282	5.9564	-3.0715
KMUD	KEDAH	100.6246	5.7411	-3.4691
BAL1	KEDAH	100.9067	5.7957	-3.2997
BAL2	KEDAH	100.8895	5.8618	-3.1746
SSIK	KEDAH	100.8583	5.9952	-2.9206
BAL3	KEDAH	100.9265	5.8100	-3.2668

Table 2. The rate of change of GWS at JMG tube well from 2002 to 2017

3.5 Rate of GWS from 2002 until 2017

Figure 6 shows the mean of GWS in 2002 and 2017, as well as magnitude of the GWS from 2002 to 2017 in Peninsular Malaysia. In general, the value of GWS is observed to increase from 2002 to 2017as reflected by the magnitude of GWS in Figure 6 (c). However, it must be noted that there are some data gaps in certain months. According to Fu et al. (2015), gravity readings from one of the GRACE satellites were unavailable in January and June 2011, May and October 2012, and March, August, and September 2013 due to the active battery management.

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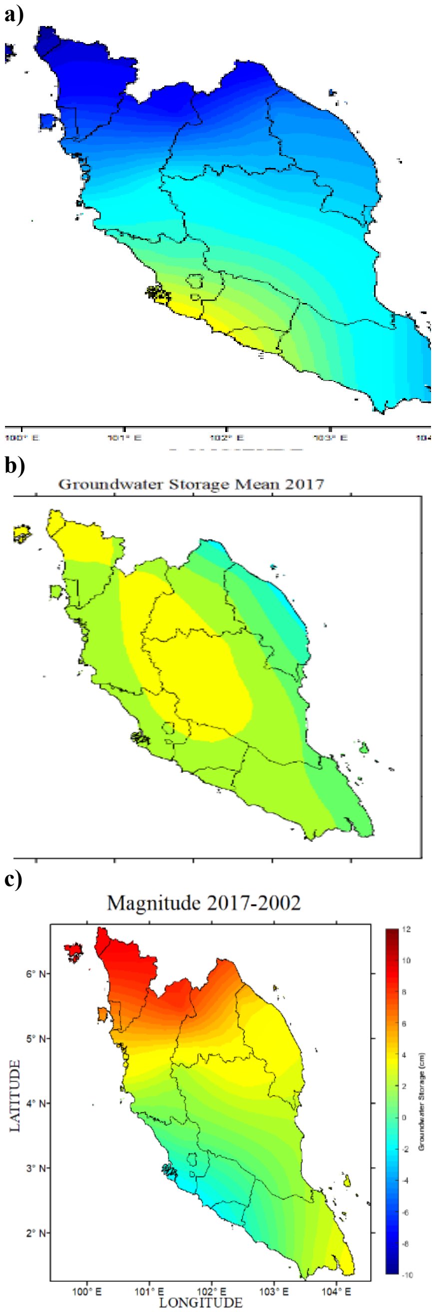

Figure 6. (a) Mean of GWS in 2002, (b) mean of GWS in 2017, and (c) magnitude of GWS from 2017-2002

The rate of GWS changes (mm/year) has been analysed by grid across the Peninsular Malaysia region to identify which part of Peninsular Malaysia has the minimum and maximum recharge value. According to Jalota et al. (2018), the recharge and discharge process of GWS can range from days to thousands of years. As shown in Figure7, the largest storage recharge value (red colour) is in the south region and part of the north region. While the rate indicated by the blue colour is the lowest storage recharge value, located at the centre west of the Peninsular region. This is due to the location of the lowest storage recharge, which is near quarry area, where the activities of quarrying in limestone reservoirs is one of impeding factor of the groundwater flow (Green et al., 2003).

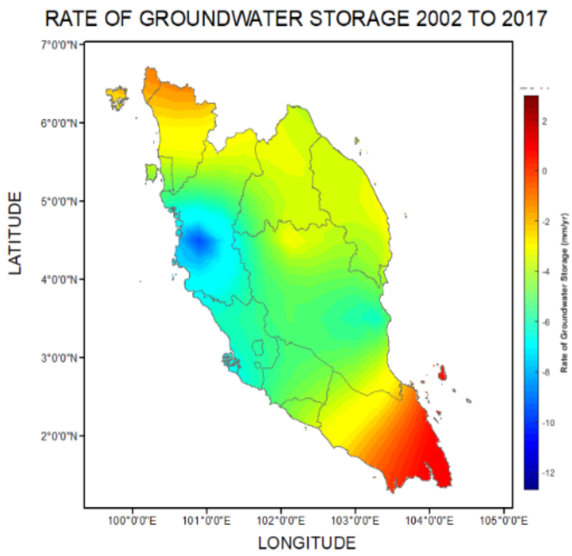

Figure 7. The rate of GWS from 2002 to 2017 in Peninsular Malaysia

4. CONCLUSION

This study involves TWS anomalies from the GRACE and GLDAS measurement data to calculate the changes in GWS from April 2002 until June 2017. The findings of the study show that the rate of GWS in Peninsular Malaysia ranges from -12 mm/yr to 2mm/yr. Due to the seasonal variation effects, GWS changes can also be seen in specific months. Therefore, it can be stated that GWS derivation utilising GRACE satellite missions is reliable to assess the quality of GWS while providing related information for water resource management. The study in extracting the GWS rate at the tube well also gives significant ideas of the recharge and discharge storage area along the Peninsular Malaysia region, where the behaviour of GWS can be monitored. Therefore, this study on groundwater behaviour has given scientific understanding of the issue as well as providing an effective management system for further action.

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