Long-term variations in water storage in Peninsular Malaysia

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ABSTRACT

Information on ongoing climate change impacts on water availability is limited for Asian regions, particularly for Peninsular Malaysia. Annual flash floods are common during peak monsoon seasons, while the dry seasons are hit by droughts, leading to socio-economic stress. This study, for the first time, analyzed the long-term trends (14 years, from 2002 to 2014) in terrestrial water storage and groundwater storage for Peninsular Malaysia, using Gravity Recovery And Climate Experiment data. Results indicate a decline in net terrestrial and groundwater storage over the last decade. Spatially, the northern regions are more affected by droughts, while the southern regions have more flash floods. Groundwater storage trends show strong correlations to the monsoon seasons, indicating that most of the shallow aquifer groundwater is used. Results also indicate that, with proper planning and management, excess monsoon/flash flood water can be stored in water storage structures up to the order of 87 billion liters per year. This can help in dry season water distribution and water transfer projects. Findings from this study can expand the understanding of ongoing climate change impacts on groundwater storage and terrestrial water storage, and can lead to better management of water resources in Peninsular Malaysia.

Key words | droughts, floods, GRACE, Peninsular Malaysia, water storage

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INTRODUCTION

Information on spatiotemporal water availability is vital for water resources management and for developing scientifically validated management tools. Such information also aids in establishing water mass balances, which will lead to sustainable use of water resources. Information on temporal changes in terrestrial water availability assists in formulating management practices prepared to face future floods and droughts. Similarly, spatial information on the same would help in locating water infrastructure projects (e.g. dams, small storage structures to store floods) and where to naturally save surface water for drought seasons (e.g. lakes and other reservoirs). In addition, long-term terrestrial water and groundwater trends can indicate how a study site responds to droughts and floods, leading to more sustainable management practices. Such information is limited for Peninsular Malaysia due to limited historic observational records, low quality and low quantity of observation records (Moten 1993; Wong *et al.* 2009).

Even though Peninsular Malaysia has a high annual rainfall average (2,430 mm per year), due to the typical equatorial climate in the region there are frequent floods and drought events in the region (DID 2007). Peninsular Malaysia has been subjected to frequent and devastating flooding over the past decade (Chia 2004). Chia (2004) reports that flood occurrences are more frequent in rapidly urbanizing cities such as Kuala Lumpur, Penang and Kuching. The 2006–2007 Johor flash floods resulted in a loss of Malaysian Ringgit (MYR) 1.5 billion, one of the costliest flood occurrences in Malaysian history (DID 2007, 2015, 2014a, 2014b). According to Chia (2004), the major reasons for frequent floods in the region are: absence of flood storage, increase in runoff coefficients due to urbanization activities,

doi: 10.2166/hydro.2017.043

inadequate drainage systems, improper installations of structures that obstruct natural flow, siltation, localized heavy rainfall, tidal backwater and inadequate river capacity. The report also urges the need for river basin studies and investigations on spatial and temporal variations in water yield. Such understanding is limited and most studies in the region are outdated (Wong *et al.* 2009). In addition to the natural reasons for water variability, water management is important in Peninsular Malaysia as it houses the Johor River, from which Singapore draws 40% of its water supply (almost 1 billion liters per day). Therefore, water management in Peninsular Malaysia is also the subject of the longstanding international water conflicts between Malaysia and Singapore.

Many studies and reports have shown that the water reserves in Malaysia are steadily decreasing, which is both a national and international concern, as water is being supplied to Singapore from the Johor River. The Linggiu reservoir has seen water levels fall by 54.5% in 2015, when compared to the average levels from 2009 to 2012. This not only threatens the Johor's water needs, but also Singapore's water needs, as up to 40% of Singapore's water supply is satisfied by the international water sharing agreement. In addition, if the water levels continue to fall in the Johor River, then there is a possibility of salt seawater intruding, which could be devastating for the river ecosystem and aquifers along the river (Huang *et al.* 2015; Kog 2015). Therefore it is of utmost importance to understand the water yield dynamics along and upstream of the Johor River and to better assist management plans and develop future mitigation strategies. In addition, climate change projections indicate more stress for the Malaysian region in the near future (DID 2007; Shaaban *et al.* 2010; Lun *et al.* 2011; Suri *et al.* 2014; DID 2015). Suri *et al.* (2014) indicate that ongoing climate changes have already impacted Peninsular Malaysia, as data from 1978–1980 and 2011–2013 indicate that the mean water levels in the north and south regions have declined by 2.04 and 14.05%, respectively. In addition, the study showed that the mean groundwater table decreased from 31.02 to 30.37 m and 6.41 to 4.66 m in the north and south regions of Peninsular Malaysia, respectively. The Malaysian Meteorology Department (2013) indicates that the region will face an increase of 1.5–2.7 °C in air temperature by 2100, which could lead to a large number of droughts. Shaaban *et al.* (2010) used the RegHCM-PM climate change and hydrologic model, and indicated that the overall monthly stream flow will increase in the future (2025–2050), with an increase in high flow conditions during wet months for Peninsular Malaysia. The study also indicated that summer flow will be significantly lower, indicating the need for more water storage structures. In another report, the Department of Irrigation and Drainage (DID 2007) indicated that by 2020 Malaysia will face an increase in flood and drought related issues, and that there will be more stress on water due to increasing population and greater per capita water in urbanizing cities. However, the quantity and distribution of data are limited for the region, and hence these studies need to be augmented with large-scale data that cover the region. In such a scenario, remote sensing data can be useful to estimate water storage changes across the region.

For national scale studies, acquiring large amounts of data can be tiresome due to bureaucracies involved and associated costs. In these instances indirect methods, such as satellite remote sensing data, may complement observation data as they cover national scale large areas at regular intervals and may be readily and freely available. One such remote sensing data source, the Gravity Recovery And Climate Experiment (GRACE) data, has been successful in estimating terrestrial water and groundwater storage trends in many regions of the globe (Swenson & Wahr 2006; Velicogna & Wahr 2006; Chinnasamy & Sunde 2016). For example, Rodell *et al.* (2009) employed GRACE data to understand groundwater depletion across the north-eastern Indian states of Rajasthan, Punjab and Haryana, and to assess transboundary groundwater depletion trends. Their results indicated that the groundwater depletion rate was unsustainable, and was 13.2 km^3 greater than that reported by the Indian Ministry of Water Resources (which was based on observational data). Chinnasamy *et al.* (2013), in a study conducted in the Northern state of Gujarat, showed that GRACE-derived groundwater trends were in good agreement with those of the government data, but covered more area than the latter, thus leading to more applications. The study also advocated the need for observation and GRACE data to be used in unison for collaborative groundwater management, as is done in the USA. In another study, Chinnasamy & Agoramoorthy

(2015) used GRACE data for Tamil Nadu (southern state of India), and inferred that the ongoing groundwater abstraction was unsustainable in the long term, as the annual groundwater abstraction rate was 8% more than the natural groundwater replenishment rate, thus explaining the statewide overall declining trend in groundwater storage. The study urged government agencies to invest in immediate groundwater regulatory measures that can sustain ongoing increases in agricultural water demand. Chinnasamy (2016) found that the groundwater storage depletion in Ramganga basin in the Ganges, estimated using GRACE data, has the potential to store more than 76% of the annual floods in the basin. This could reduce flood damage that runs into millions of dollars per year. The aforementioned examples showcase the different use of GRACE data, and indicate confidence in using these data for large-scale water estimations. As many studies have noted (e.g. Long *et al.* 2014; Velicogna & Wahr 2013), water storage results derived from GRACE data may contain uncertainties due to differences in data processing and associated components used (e.g. soil moisture). However, since the inception of the GRACE mission in 2002, water storage anomaly trends, derived from GRACE data, have influenced discussions on groundwater availability globally (as mentioned in the aforementioned studies), and have influenced follow-up field investigations of groundwater resources.

Objectives

The major objective of this study is to identify the long-term terrestrial water storage and groundwater storage trend for Peninsular Malaysia. The other objectives include assessing the potential of remote sensing data into estimating long-term (2002–2014) terrestrial and groundwater storage variations, for the first time, across Peninsular Malaysia, understanding annual and seasonal trends in water availability, and assessing the impact of long-term (13 years) use of total water storage across the study area. These objectives will clarify the need to increase water management activities to prevent future drought and flood stress in the study area. In addition, results derived from these objectives will gain support for using remote sensing methods to encourage investigations in regions with sparse groundwater monitoring data.

METHODS

Study area

Formerly known as Malaya, Peninsular Malaysia (or West Malaysia) is located between 1–7° north and 99–105° east (Figure 1). Covering an area of 131,587 km^2, Peninsular Malaysia is bordered by Thailand in the north, Singapore and the Strait of Johor in the south, the South China Sea in the east and the Strait of Malacca and the Andaman Sea in the west. Peninsular Malaysia is divided into 11 states and two federal territories. Based on the geographic location, it is divided into four regions: Northern region, East coast region, Central region and Southern region. Peninsular Malaysia is an important region for Malaysia as it houses the national capital, Kuala Lumpur, and is home to 80% of Malaysia's population (23.5 million as of 2012) and economy. Most of the people in this region are ethnic Malays, while industry and service sectors are the major

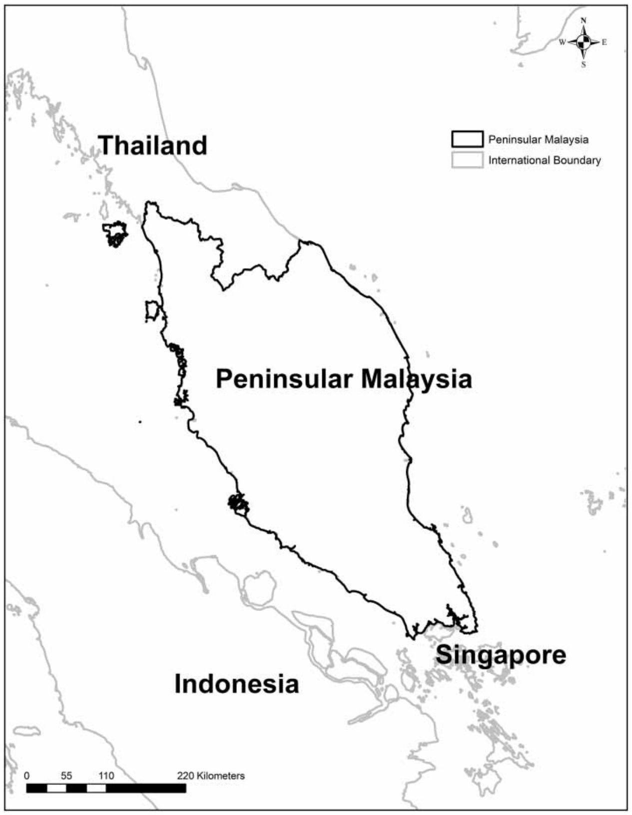

Figure 1 | Peninsular Malaysia study site.

sectors in the region (Camerlengo & Demmler 1997; Suhaila & Jemain 2009).

Peninsular Malaysia has an equatorial climate with high temperature and humidity. The northeast (November–February) and southwest monsoons (April–September) bring most of the rainfall, with the former bringing the most to the region. The annual average rainfall is 2,420 mm per year, with the east coast receiving higher rainfall. Between these monsoons, the inter-monsoon transition period brings extreme events such as conventional thunderstorms with short but heavy downpours, leading to many flash floods. The east coast and south regions are mostly flooded by these events and the northeast monsoon (Camerlengo & Demmler 1997; Chia 2004; Suhaila & Jemain 2009).

Terrestrial water storage anomaly (TWS) data from GRACE

The GRACE mission data were used in the study to estimate spatial and temporal trends in water storage anomalies across the Peninsular Malaysia. As a combined effort between the National Aeronautics and Space Administration (NASA) and the Deutsches Zentrum für Luft- und Raumfahrt (DLR) from the German Aerospace Agency, the GRACE satellite mission was launched on 17 March 2002. It is to be noted that GRACE is the first and only remote sensing satellite capable of calculating global gravity anomalies which are later converted to water storage thickness data (both surface and groundwater) on a monthly time scale. The two GRACE satellites record changes in gravitational pull on the satellites due to mass changes on the Earth. The changes in mass between months are attributed to water mass changes which are later converted to changes in equivalent water storage thickness (in units of cm). The GRACE team then converts these to terrestrial water storage (TWS) at monthly scales (Swenson & Wahr 2006; Landerer & Swenson 2012). While deducing the water storage anomalies, a priori models are used to estimate different water components (e.g. soil moisture estimates from land surface models (LSMs), discussed later). There are some errors associated with the aforementioned conversions, and hence scaling coefficients are provided that incorporate adjustments for the errors. Therefore, a GRACE scaled version, processed and archived by Landerer & Swenson (2012), was employed in this study, which had TWS spatially distributed at $1 \times 1^{\circ}$ grids (approximately 111×111 km at the equator). TWS data, at monthly time scales, in $1 \times 1^{\circ}$ grid-cells format (version RL05) were accessed from the NASA Jet Propulsion Laboratory's GRCTellus Land grids website (ftp://podaac-ftp.jpl.nasa.gov/allData/tellus/L3/land_mass/). The aforementioned website also had the scaling factors (Landerer & Swenson 2012), which were discussed earlier. In particular, the scaling factors corrected the GRACE data errors, i.e. leakage errors (caused by GRACE signal leakage from neighboring land and ocean grids) and measurement errors (caused by errors in processing the raw GRACE data). To arrive at TWS, the GRCTellus Land grids were multiplied by the corresponding scaling coefficients (also as grids). The recently released RL05 GRACE data alleviated more leakage and measurement errors, compared to the previous GRACE data versions (Landerer & Swenson 2012). Also, GRACE data were only available as monthly anomalies with a baseline average (i.e. mean monthly actual TWS from January 2004 to December 2009) removed. The GRACE data processing team defines the baseline period (i.e. January 2004–December 2009), and hence any studies using other data with the GRACE data should incorporate this baseline average. For the current study, data from April 2002 to December 2014 were used. There are now many studies which have applied GRACE TWS data (e.g. Rodell *et al.* 2009; Chinnasamy *et al.* 2013, 2015a, 2015b; Chinnasamy & Agoramoorthy 2015, 2016; Chinnasamy & Sunde 2016; Chinnasamy 2016, 2017).

It is worth noting that the TWS includes snow, soil moisture and snow water. Therefore, to arrive at groundwater storage, it is necessary to remove these storage components (collectively called Total Soil Moisture in this study) from the TWS, which is done by using storage estimates derived from a priori models (e.g. GLDAS LSMs for soil moisture estimates).

Total soil moisture (SM) data – GLDAS

The Global Land Data Assimilations System (GLDAS) program was started and maintained to archive information on land and ocean mass fluxes by the NASA Goddard Space Flight Centre (GSFC) and the National Oceanic and Atmospheric Administration (NOAA), from the USA (Rodell *et al.*

2009). This team uses LSMs to calculate global soil moisture at different spatial and temporal resolutions. It is noted that remote sensing data are used to drive LSMs. Noah, the Common Land Model (CLM), Mosaic, and the Variable Infiltration Capacity (VIC) model are widely used LSM models.

In this study, Noah version 2.7.1 was used to estimate soil moisture ranging from 0 to 200 cm in depth, snow water and canopy storage as equivalent water thickness (in cm). Noah was chosen as it was widely used in the Asian region (e.g. Rodell *et al.* 2009; Chinnasamy *et al.* 2013; Chinnasamy 2016). Noah data (and LSMs) and information on the methodology can be accessed from the Goddard Earth Sciences Data and Information Services Centre (http://ldas.gsfc.nasa.gov/gldas/).

For the current study, Noah data in gridded format at relevant spatial and temporal scale (1° grid-cells/monthly resolution) were accessed (similar to the grid size of the GRACE data). The total soil moisture (SM) estimates (sum of soil moisture, snow water and canopy storage) were then subtracted from TWS data to arrive at groundwater storage.

Groundwater storage (GW)

As per the methodology used in past investigations (e.g. Rodell *et al.* 2009; Chinnasamy *et al.* 2013), groundwater storage was estimated as:

$$GW = TWS - SM \quad (1)$$

where, TWS is GRACE based terrestrial water storage (cm), SM is GLAS based total soil moisture (cm), and GW is groundwater storage (cm). Since the intent of this study was to study long-term trends, monthly GRACE and GLDAS grids from April 2002 to December 2014 were used to estimate GW for each month. It is noted that similar to TWS, the GW data will also be as anomalies, with a long-term average removed.

RESULTS

Total terrestrial water storage anomaly trend

The long-term terrestrial water storage anomaly (TWS) shows high seasonal variation for Peninsular Malaysia (Figure 2). From 2002 to 2004, the TWS was always above the baseline average; however, that scenario changed after 2004. For the entire period, the peak storage values were recorded in December and January (from the northeast monsoon), with the highest value recorded on Jan 2003 at 32.27 cm. On the other hand, August (peak post

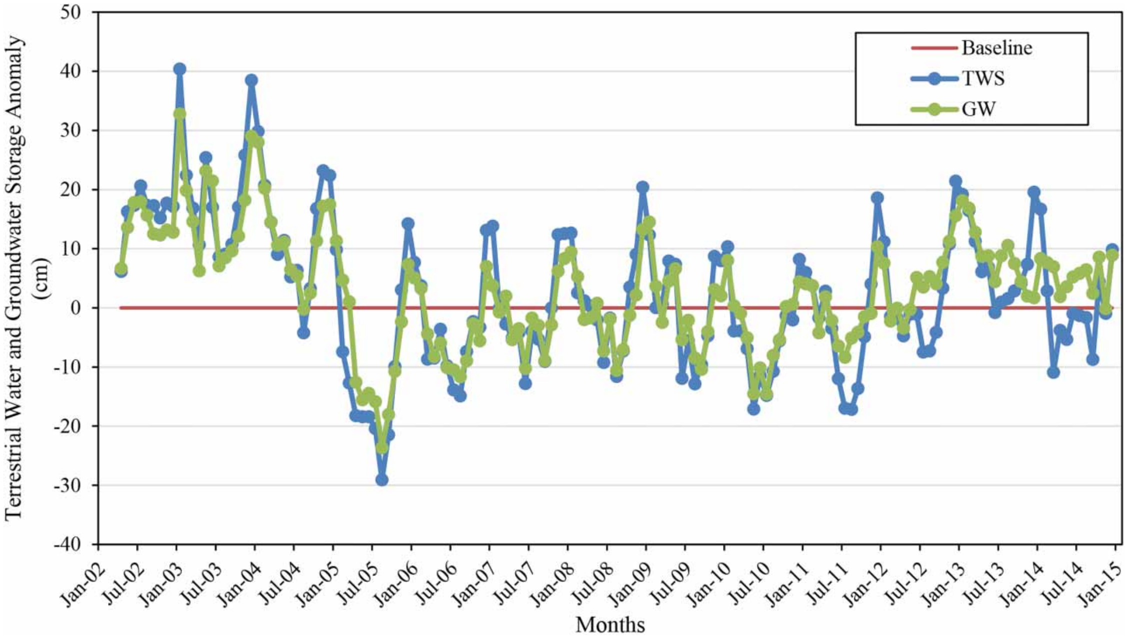

Figure 2 | Terrestrial water storage anomaly (TWS) and groundwater storage anomaly (GW) for Peninsular Malaysia.

monsoon/summer) recorded the lowest TWS values in a calendar year, with August 2005 recording the lowest value of −23.63 cm. The average for the entire period was 3.14 cm, indicating a net positive trend, while the standard deviation was 9.75. The long-term trend (Figure 2) also indicates that the TWS values closely follow the northwest monsoon period (November–February) in recording above average values for the region, while the summer period between March and September shows below average TWS.

It is noted that the GRACE data are also sensitive to large earthquakes. As noted from Figure 2, there is a small 'jump' in the data between December 2004 and January 2005, and it could be due to the Sumatra earthquake in 2004 (de Linage *et al*. 2009).

Peak flood and drought event

In a calendar year, December and January are the wettest months, while August is the driest and the most hit by droughts (Ahmad & Low 2003; Ahmad & Hashim 2010; Chia 2004). On the same note, long-term TWS data (i.e. 2002–2014) for December and August were used to analyze the spatial distribution of high water storage (Figure 3) and high drought conditions (Figure 4), respectively. Long-term wet month TWS data indicate that the northern parts have higher water storage anomalies when compared to the southern regions. Even though most of the discharge is from north to south (due to elevation gradients), as the water is not stored in the peninsular, most excess water

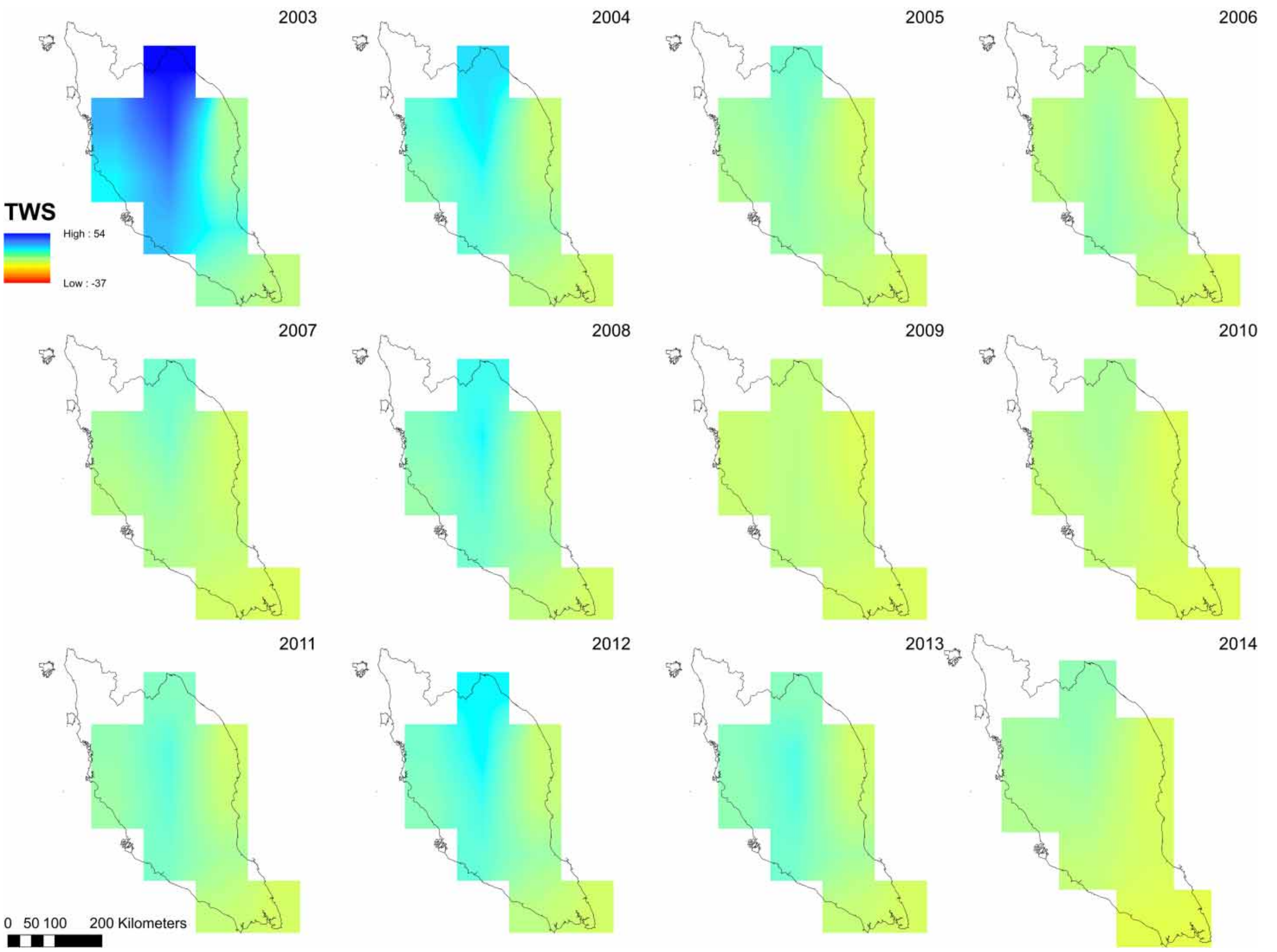

Figure 3 | Long-term total water storage anomaly (TWS) estimates for wettest month (December) for Peninsular Malaysia. Only GRACE grids that fall significantly on the study area were used.

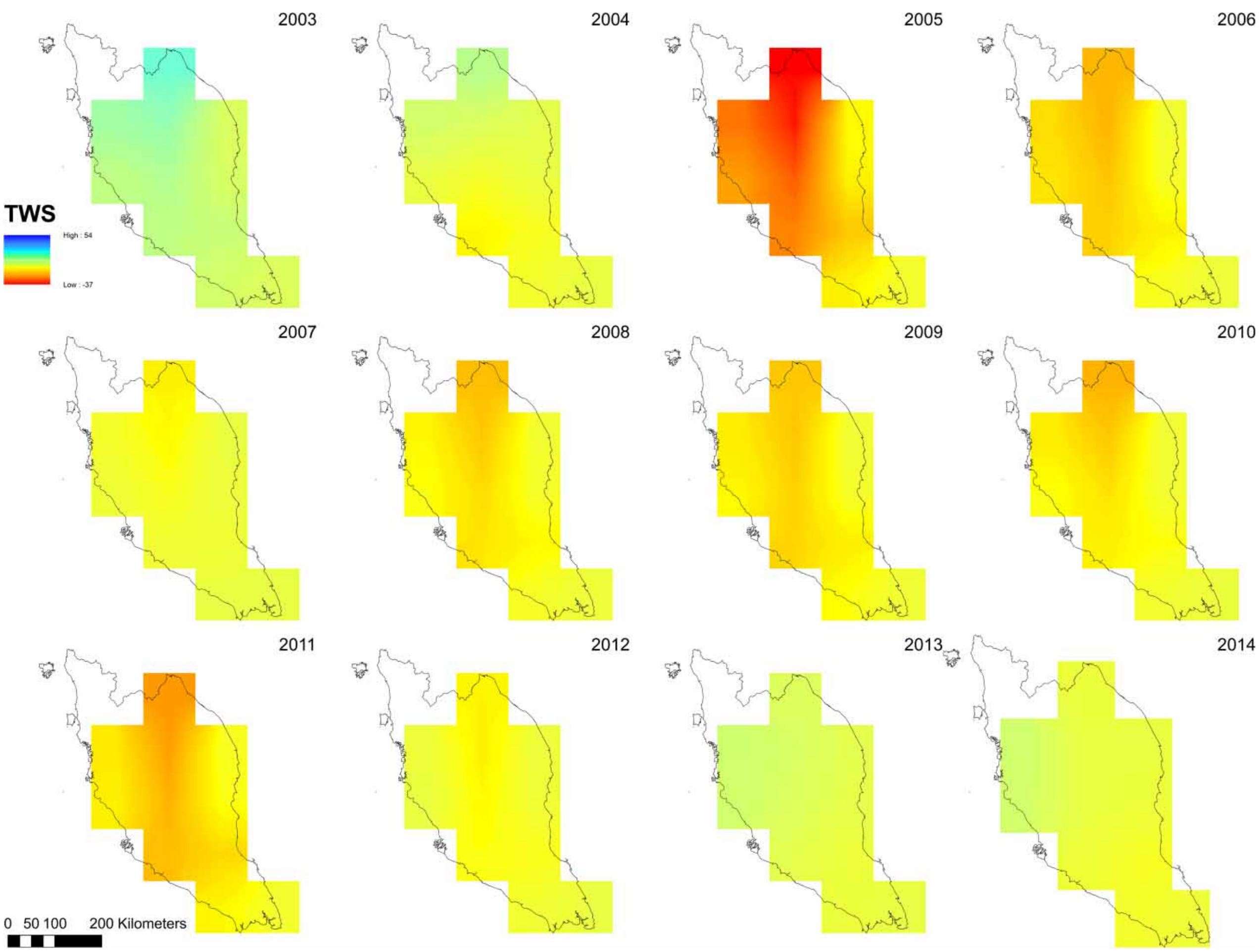

Figure 4 | Long-term total water storage anomaly (TWS) estimates for driest month (August) for Peninsular Malaysia. Only GRACE grids that fall significantly on the study area were used.

mixes with surrounding ocean. Similarly, an analysis of the long-term drought TWS data indicates that the northern and northwestern regions have less water storage anomalies than the other regions, which is consistent with the study by Sanusi *et al.* (2015).

Peak floods for the study region were recorded for 2006 (December–January), 2007 (December), 2010 (November) and 2014 (December–January). However the long-term TWS does not show an increase in TWS. This is because the aforementioned floods were mostly flashfloods (MMD 2009, 2013; DID 2014a) and hence did not stay in the basin long enough to impact the TWS.

Similarly, the drought seasons were not prolonged in the TWS longer-term trend, indicating that water input (i.e. rainfall) was available for the basin; however there was no infrastructure to store the water and enhance water availability across the basin (Figure 2). Most studies have attributed the Malaysian droughts to the El Nino event (e.g. from 1997–1998 and 2014), mostly in the southwestern region (Ahmad & Low 2003; Ahmad & Hashim 2010; Sanusi *et al.* 2015). During droughts, most of the water supply is sent to domestic and industrial sectors, leading to a disruption of usual activities.

The aforementioned analysis indicates that the flood and drought episodes in the study area are short term, and hence with appropriate measures can be highly regulated. In addition, the saved water can address increased water demands. DID (2015) suggests that the national water demand will increase by 1.2% per year and will be 25,884 and 14,069 million liters per day (MLD) in 2050 and 2100, respectively. In addition, even though the annual rainfall is expected (from scenario analysis) to increase by 5–10%, there will also be dry years, e.g. 2028, 2029, 2034, 2042 and 2044 are all anticipated to be drought years (NAHRIM 2009; Wisetjindawat 2010). In the case of Peninsular Malaysia, an increase in flash floods increases flood damage and associated drought damage (as less water is available for storage). Under natural conditions, Sanusi *et al.* (2015) indicated that the ongoing severe drought conditions in Malaysia can recover to non-drought status within 2–3 months, on average. However, there is sufficient economic and social stress due to drought and the requisite recovery time. Hence, if natural recharge rates are accelerated by environmentally friendly measures (e.g. distributed recharge methods, managed aquifer recharge methods), there will be an increase in groundwater status, which can lead to a water resource substitute that can be used during drought conditions (Agoramoorthy *et al.* 2016; Varua *et al.* 2016; Chinnasamy *et al.* 2017; Shah *et al.* 2016).

Groundwater storage anomaly trend

The groundwater storage anomaly (GW) long-term trend (Figure 2) also follows the trend of the TWS, and mostly follows the seasonal trends of the monsoon and summer. From 2002 to 2004, the GW was always above the baseline average; however, that scenario changed after 2004, when the average GW fluctuated around the baseline. Post-2011, the GW seems to have improved steadily, but is still close to the baseline average. For the entire period, similar to the TWS, December and January recorded the highest peak storage values, with the overall highest value recorded on January 2003 at 40.38 cm. On the other hand, August recorded the lowest TWS values in a calendar year, with August 2005 recording the lowest value of −29.09 cm. The average for the entire period was 2.64 cm, indicating a net positive trend (within the studied time period), while the standard deviation was 12.30. The long-term trend (Figure 3) also indicates that the water storage anomaly values closely follow the northwest monsoon period (November–February) by recording above average values for the region, while the summer periods between March and September show below average GW. Therefore, the seasonal TWS patterns reflect the monsoon occurrences. In addition, the GW follows the TWS trend (Figure 4), indicating that most of the TWS water does make it to the groundwater aquifers and that most of the water abstraction is from the shallow aquifers. This is because water recharge and discharge from deep aquifers will normally show a lag time due to longer recharge times to deep aquifers. In addition, the well-drained nature of Peninsular Malaysia soils aids in rapid shallow aquifer recharge and discharge, which is reflected by comparing the total terrestrial water and the groundwater storage anomalies (Figure 2).

A close analysis of Figure 2 indicates that there is more potential to recharge the groundwater resources from excess TWS water. For example, the equivalent water thickness gap between the TWS and GW (Figure 2) can be used to recharge groundwater storage. This recharged water can then be used to satisfy dry season water demand. This is under the assumption that December is the peak month for demand, with annual excess flow. In December, an average of 6.6 cm of water thickness (TWS) can be stored as groundwater. This equates to an annual storage of 8.7 km^3 of water, which is equal to 870 billion liters. Even with estimating water need for environmental flows and water losses (leakage loss, evaporation, etc.), and assuming that 10% of this water is stored, it still equates to 87 billion liters per year. For perspective, Singapore draws up to 83 million liters per day, which adds up to 30 billion liters per year. Therefore, by properly managing the excess water in the peak monsoon months, Malaysia can save up to three times the water it exports to Singapore, on an annual basis. However, the major management challenge would be identifying technical and policy interventions that can augment recharge rates to capture excess water, at required scales.

Limitations

It is to be noted that the grid size distribution of GRACE data is approximately 111 km at the study site and may contain errors due to signal leakages from neighboring grids, other dominant geophysical features (e.g. mountains) and ocean mass grids (Landerer & Swenson 2012) near the Malaysian Peninsular. A 'rescaling' approach, as discussed in the methods section, is used to account for these errors. Long *et al.* (2015) discuss this scaling factor approach and associated uncertainties, especially when dealing with small basins. In addition, since there are different methods to process and use GRACE data, the resulting TWS anomalies would differ by the method used. As a result, for monthly analysis, amplitude uncertainties may be found, depending on the spatial size of the study site and the methods used for the GRACE data analysis (Longuevergne *et al.* 2010). However, while analyzing long time series, the overall trend in TWS anomalies can be deduced, from which long-term groundwater trends can be investigated, as done in the current study.

In the current study, it is assumed that any signal leakage errors would be homogenous across Peninsular Malaysia, and therefore the errors will cancel out when calculating anomalies. In addition, over past years GRACE data have been effective in analyzing groundwater storage anomaly levels in regions smaller than the current paper's study area. However, the authors do agree that the remote sensing data can be fine-tuned with the help of good quality observation data. Therefore, future studies should investigate methods to incorporate remote sensing data with observation data to aid in surface water and groundwater storage assessments that can lead to better water resource management plans.

FUTURE DIRECTIONS

Future methods need to include cropping pattern scenarios, climate projection scenarios, and social stress for surface and groundwater use while formulating water supply and water storage plans.

Installing and managing water storage projects (for surface and groundwater) can be challenging due to physical (e.g. terrain, elevation, land suitability, soil suitability) and social constraints (e.g. willingness of people to cooperate, governance, and upstream/downstream issues). Therefore, such projects need to be integrative in nature, wherein a holistic approach in identifying key players and key needs of the regions is conducted.

Climate variables, especially rainfall, play a vital role in quantifying water yield across large spatial and temporal scales. Due to some challenges, the current study could not procure those data; however, future studies should incorporate observed climate data in analyzing long-term spatiotemporal trends in water yield. In addition, inter-annual and intra-annual variations (as done in the current study) in climatology should be analyzed to understand climate change impacts on seasonal and annual climatology.

Remote sensing data, given their cost effectiveness and usefulness, need to be used along with field based physical measurements to improve water yield and groundwater storage volumes, which will be useful while formulating future mitigation plans. In addition, such exercises using remote sensing data need to be validated using observation data. Since groundwater observation data are limited in the region, it is necessary to invest in groundwater monitoring networks across the region.

CONCLUSIONS

This study analyzed the long-term trends in terrestrial water storage anomalies and groundwater storage anomalies for Peninsular Malaysia. Results indicate that the region's water yield is highly seasonal in nature, with higher than average water during monsoon months and lower than average water during drier periods. With reference to the start of the study period (2002), there is a decline in net terrestrial and groundwater storage anomalies in recent years (e.g. 2010–2014). In terms of spatial differences, the northern regions are more affected by droughts (especially in August), while the northern region had the most water yield during monsoon months (especially in December). Similarly, long-term variations in groundwater storage anomaly trends indicate strong coupling with the seasonal and terrestrial water cycles. Therefore, most of the groundwater used is from the shallow aquifer, while the deep aquifer water is less impacted by ongoing climate change and anthropogenic use. The difference between the terrestrial water storage and yield and groundwater storage was used to estimate potential water storage during peak monsoon seasons, which can be used for dry season water supply. The results indicated that, with proper planning and management, excess monsoon water can be stored in large water storage structures (centralized or decentralized) up to the order of 87 billion liters per year, which can aid in dry season water distribution and water transfer projects. Findings from this study can aid in understanding ongoing climate change impacts on groundwater storage and terrestrial water storage. Such findings can eventually contribute to improved water resource management in Peninsular Malaysia.

AUTHOR CONTRIBUTIONS

Pennan Chinnasamy carried out the analysis and wrote the paper, while Revathi Ganapathy aided in translating reports and data from Malay language to English.

ACKNOWLEDGEMENTS

The authors thank Dr Sean Swenson from the Gravity Recovery And Climate Experiment (GRACE) mission for providing the land water storage data and the GLDAS team for the soil moisture data, respectively. The author declares no conflict of interests. The authors also thank Dr Laurent Longuevergne for critically reviewing the manuscript.

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First received 23 April 2016; accepted in revised form 22 August 2017. Available online 7 November 2017