Monitoring Groundwater Depletion Due to Drought using Satellite Gravimetry: A Review

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Abstract. Groundwater plays a vital role in the global water cycle as a source of water for human use in daily life. The problem of groundwater depletion attracts researchers to understand the phenomenon of terrestrial water storage (TWS) and the primary technique used to monitor changes in groundwater mass in the subsurface. Accurate quantification is subtle due to the weakness of gravity measurement methods, which cover a wide range with high precision. A global evaluation of improvements in groundwater storage used a calculation tool that may involve temporal differences in TWS. The Gravity Recovery and Climate Experiment (GRACE) and the GRACE Follow-On (GRACE-FO) satellite missions were able to monitor changes in water mass in the basin and calculate changes in water levels by measuring gravity variations and quantifying groundwater tables at 1-micron precision. This paper aims to discuss GRACE, GRACE-FO and hydrological variables in the monitoring of groundwater depletion during the drought season. This paper presents an estimation technique using satellite gravimetry and hydrological methods, as well as a study of several case studies in central Amazon (Brazil), Murray-Darling (Australia) and Mongolia Basin. Previous observations, including TWS-hydrological variables, trends in groundwater depletion and drought intensity, have been discussed as a vital outcome of the paper as a whole.

1. Introduction

Groundwater is the amount of subsurface water found below the surface of the earth, containing dirt, sand and rock. Groundwater flows through the subsurface, which formed a saturated area, an area where the aquifers are filled with water[1]. Aquifers are naturally made of sand or broken rock that allowed water to penetrate through it[2,3,4]. The maximum concentration of water on the terrestrial and marine subsurface, including soil moisture, snow, ice, plants, river and lake collectively formed marine water storage (TWS)[5,6]. According to Shiklomanov[7], groundwater is available almost everywhere on earth, and its supplies are being replenished, which means that it can be recharged by rain or snowmelt collapsing through cracks on the surface of the earth.

Extreme variations in groundwater storage are usually associated with droughts and floods[8]. In a country with severe weather conditions, drought has become the primary cause of water shortage, although groundwater is not used as much as possible[9]. This is because the water supply from the river, the dam, the lake and the other surface water basin is dry and therefore indicates that TWS has a water deficit. As groundwater in the subsurface is part of the TWS, it is considered to have a water deficit. The water cycle is dependent on the rainfall balance and, if the water level is constant, there are groundwater deficits [10,11,12,13]. Such factors have triggered the occurrence of drought and have contributed to a TWS water deficit.

The Gravity Recovery and Climate Experiment (GRACE) and the GRACE Follow-On (GRACE-FO) have been used to monitor groundwater depletion due to drought. Such satellites are capable of modelling the water mass and analyzing changes in the volume of water by calculating the fluctuations in gravity that could lead to new knowledge and overcome the weakness of ground observation in the quantification of groundwater shifts. This paper not only focuses on tracking groundwater depletion during the dry season but also discusses previous groundwater storage estimation techniques using GRACE and GRACE-FO. The case study in the severely affected areas of the central Amazon, Murray-Darling and Mongolia Basins was also presented as a pilot project and provides a real example of groundwater depletion due to a drought phenomenon.

2. The GRACE and GRACE-FO missions

2.1. An overview of GRACE and GRACE-FO

GRACE satellites were launched on 17 March 2002 at 22 May using Eurockot from Plesetsk, Russia, while GRACE-FO was launched on 22 May 2018. It was the cooperation of NASA-GFZ using SpaceX-Falcon 9 rocket from Vandenberg Air Force Base, California, United States of America (USA)[14]. GRACE is a joint project between the Center for Space Research (CSR) at the University of Texas, Austin; NASA's Jet Propulsion Laboratory, Pasadena, CA; the German Space Agency (DLR) and the German National Geosciences Research Center (GFZ), Potsdam[15]. GRACE operated from 2002 to 2017 and concluded its operation on 27 October 2017, although its replacement, GRACE-FO, continued to provide spatial-temporal variations of the earth's gravity field on a national scale. The GRACE mission consists of two identical satellites which continuously orbit the earth at a low altitude (450 km with an inclination of 89.5 °). Both identical satellites are followed at distances approximately 137 miles (220 km) apart, where GRACE-A leads GRACE-B in motion position[16] as shown in Figure 1 (left)[17]. For GRACE-FO, GRACE-FO-A disengaged from GRACE-F0-B at 0.5 m / s to assume its nominal position 220 km ahead of the trailing satellite. For GRACE-FO, the leading satellite travels ahead of the trailing satellites at approximately 0.3 m / s until the spacecraft reaches its maximum separation distance of 137 miles as shown in Figure 1 (right)[18].

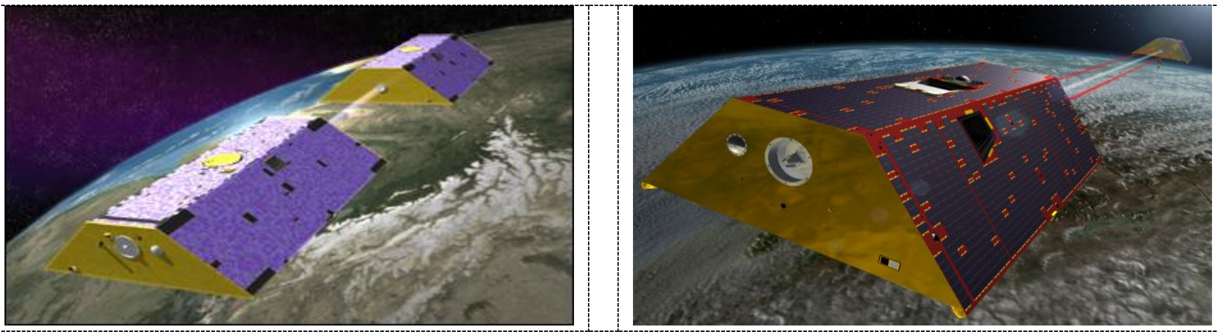

Figure 1. The image of GRACE (left) [17] and GRACE-FO (right) [18]

GRACE-FO configuration and orbit track are the same as its predecessor, GRACE except for the accuracy of instantaneous distance and relative speed measurement between the two tailing satellites. GRACE worked with a K-Band Microwave Ranging (KBR) radar telemeter based on Microwave Instruments (MWI). GRACE-FO, on the other hand, still used KBR but supplemented it with a Laser Ranging Interferometer (LRI) for calculating improvement accuracy by a factor of 25[19]. Laser orbiting and the current microwave network will boost the measurement capacity while preserving consistency with the initial GRACE measurements. The MWI provides 1-micron precision measurements between two satellites and changes in Earth's gravity by quantifying the microwave signals transmitted by the GRACE receiver [20,21,22]. Each satellite transmits signals at two frequencies; 24 gigahertz (K-band) and 32 gigahertz (Ka-band) for ionospheric corrections. However, LRI has the potential to improve the accuracy of variability measurements by a factor of 10 due to the laser wavelength that is 10,000 times shorter than the microwave wavelength[23]. These improvements allow satellites to detect gravitational differences at a higher accuracy from 1μm (KBR) to 80 nm (LRI).

2.2. An Overview of Science Data System (SDS)

It needs three sections of data processing to generate a GRACE-derived earth-gravity model. The first level is Level 0 (L0), defined as raw telemetry data obtained at DLR every 24 hours. These telemetry data stored in the Science Instrument and Spacecraft Data streams which require two files from each satellite pass are available in the RDC's rolling archive. The data includes KBR, Star Camera Assembly (SCA), Global Positioning System (GPS) orbits, Superstar Accelerometer (ACC), GPS occultation and housekeeping data[24,25]. For Level 1 (L1) data, instrumental corrections (time tag corrections) were applied to all data forms, including:

- KBR – KBR biased range, range rate and range of acceleration
- SCA – SCA quaternion
- GPS orbits – Receiver Independent Exchange Format (RINEX)
- ACC – ACC acceleration along three axes
- GPS occultation

SCA quaternion and GPS orbit RINEX production will concentrate on KBR bias range, range rate and range of acceleration as well as RINEX GPS orbits for geo-potential field model output. GPS orbit RINEX also underwent a precision orbital determination, primarily based on GPS data obtained at ground stations and ACC acceleration along three axes to create a geo-potential field model[26]. In Level 2 (L2) processing, the previous outcome of L1 processing, including KBR bias scale, scale and range of acceleration as well as ACC acceleration along three axes, orbital precision and external data (pressure, temperature, IGS data) combined to generate a geo-potential field data model. The occultation of the GPS was also carried out in L2 stages. Description of the GRACE SDS workflow shown in Figure 2.

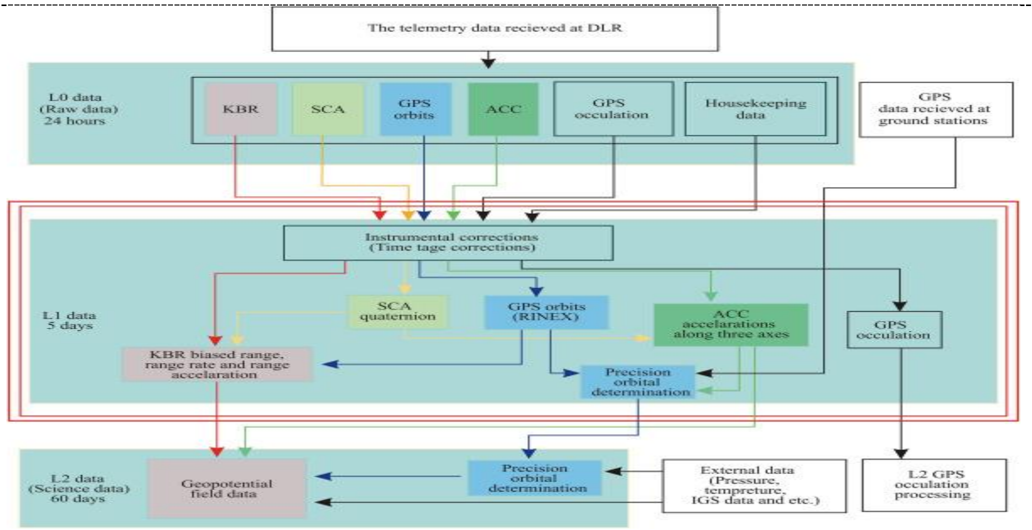

Figure 2. GRACE SDS workflow [27]

Unlike GRACE, the GRACE-FO SDS workflow consists of four stages. The first three levels are identical to GRACE but are complemented by an additional level, Level 3 (L3). L1 data contains two groups which are L1-A and L1-B. Time tag integer second uncertainty is calculated by adding the time of data collection to the time of the satellite receiver. L1-B data is re-tagged or re-sampled to GPS

Time, followed by a lower rate of data filtration and/or converted into quantities used in L2 processing. For L2, orbit solutions and a monthly average estimate of Earth's gravitational potential (spherical harmonics) or spherical cap mass concentrations are performed. L3 data contains monthly L2 gravity anomalies in surface mass anomalies that have been mapped to a spatial grid. Based on the type of L2 input data, various post-processing filtering and data corrections are performed, including correlated error and/or spatial smoothing filter, ocean load reconstruction, and glacial isostatic effects. Description of the GRACE-FO SDS workflow shown in Figure 3.

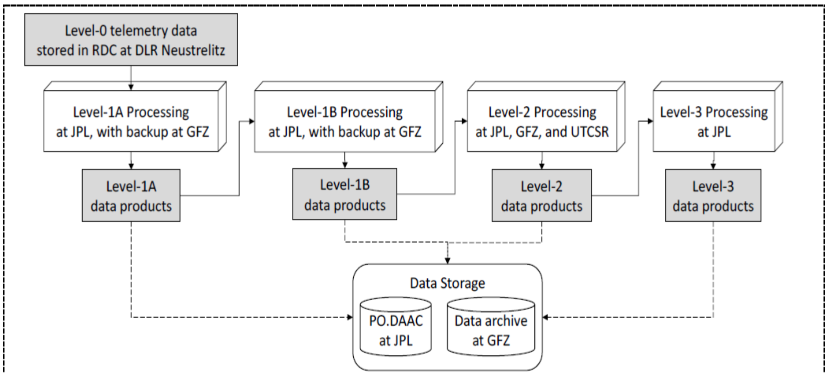

Figure 3. GRACE-FO SDS workflow [28].

2.3. Accuracy of GRACE and GRACE-FO-based over land products

Previous research shows a few millimetres of equal water height (EWH) over 400 km by 400 km. It was expected that the TWS retrieval would have a noise effect in the shorter wavelengths[29]. Based on the predicted accuracy, GRACE-TWS anomalies may be observed if they exceed 1.5 cm of EWH over an area of 200,000 km2. The GRACE-TWS precision is 0.7 cm EWH for a drainage area of 400,000 km2 and 0.3 cm for a drainage area of 4,000,000 km2[30]. The latest GRACE-TWS products had a spatial resolution of around 200 km for the Mascons and environmental solutions and 330 km for the 03 to 05 releases for a standard 60-km truncation. The calculated error would be about 40 mm in the Equator and decreased to 15 mm in polar regions.

3. Groundwater storage estimation using satellite gravimetry

3.1. TWS changes

TWS is a hydrological parameter derived from GRACE and GRACE-FO time-series monitoring. The main objective of the GRACE satellite is to track the variations in the Earth's gravity field based on TWS anomaly retrieval from GRACE data[29,30,31]. GRACE-TWS water changes are based on a combination of hydrological and LSM models [31,32,34,35,36,37]. It offers time-series temporal changes consisting of surface water, soil, groundwater and snowpacks in broad river basins[34]. Errors are induced by indirect factors, including flow rate and precipitation in some hydrological models. Preliminary, the GRACE-TWS anomaly is part of hydrological simulation models (such as GLDAS and CPC) that do not provide ground-truth data.

A direct approach to groundwater storage calculation requires the elimination of a GRACE-based TWS phenomenon based on the contribution of the various hydrological reservoirs. TWS anomalies equation has been defined as equation (1):

$$\Delta TWS = \Delta SM + \Delta SW + \Delta GW \tag{1}$$

Where SW is the sum of surface water supply, including lakes, reservoirs and dams; SM is the sum of soil moisture, and GW is the sum of groundwater stored in aquifers[38]. These terms are expressed in volume (km3) or mm of equivalent water height. The equation (1) then transitions to the equation (2):

$$\Delta GW = \Delta TWS - \Delta SM - \Delta SW \tag{2}$$

One advantage of the GRACE data assimilation system is the ability to degrade the vertically integrated GRACE-TWS signal into groundwater, soil moisture and snow[39]. Hu et al.[38] found that groundwater storage in the Yangtze River was capable of reaching 3.4 cm in spring and early autumn. In the other study, Zhong et al.[41] calculated the depletion of groundwater storage in the northern central region of China at an annual rate of 2.4 cm of water equivalent height using 5-year GRACE-TWS results. Meanwhile, Wang et al.[40] conducted an effective retrieval of TWS water anomaly in the Nordic region and North America by combining GRACE and GPS network observation data and demonstrated that there had been a significant increase in water accumulation in North America over the last decade.

3.2. Drought monitoring

Based on the time-series of GRACE-TWS shifts, severe events such as drought and floods may be tracked and alarmed. The deficit in drought and groundwater storage is a regular disaster-related occurrence that contributes to crop losses and an economic cataclysm. Droughts are part of the TWS deficit associated with multiple hydrological parameters such as precipitation, evapotranspiration and surface runoff[43].

Monthly groundwater storage depletion levels were observed based on magnitude, M (km3) volumetric deviations from standard hydrological conditions, or average groundwater prices. M reflects a monthly calculation of the rate of depletion, while a standard deviation of the residual time series and the plot is calculated for further reference.

For the estimation of groundwater depletion, the severity or S(t) of the monthly hydrological drought event as the product of the average depletion shall be defined from the initial phase of the depletion period, M(t) (km3) and the duration (t) (months) from the initiation of the drought as shown in equation (3):

$$S(t) = M\ (t) \times D\ (t) \tag{3}$$

Severity estimates S as equal to M multiplied by D for the groundwater depletion period. S, M, and D are determined after the drought event and then used for the cross-comparison of the groundwater deficiency. Around the same time, M reflects the severity of the occurrence of hydrological droughts, such as the deficit in instant water storage[44].

Drought conditions are categorised into a few categories based on drought indices. Characterisation focused on the Standardised Precipitation Index (SPI) and the Standardised Precipitation Evapotranspiration Index (SPEI)[46]. SPI is based on precipitation data from meteorological stations and satellite platforms such as the Tropical Rainfall Measurement Mission (TRMM) or the Global Precipitation Measurement (GPM). At the same time, SPEI was developed based on the value of the SPI. Table 1 indicates the categories of drought severity dependent on SPI and SPEI indices comprising D0 (no drought), D1 (mild drought), D2 (moderate drought), D3 (severe drought) and D4 (extreme drought).

Table 1. Drought severity based on SPI/SPEI and WSDI [46].

Category	Drought Condition	SPI/SPEI	WSDI
D0	No drought	$-0.5 < S$	$0 < W$
D1	Mild drought	$-1 < S \leq -0.5$	$-1.0 < W \leq 0$
D2	Moderate drought	$-1.5 < S \leq -1.0$	$-2.0 < W \leq -1.0$
D3	Severe drought	$-2.0 < S \leq -1.5$	$-3.0 < W \leq -2.0$
D4	Extreme drought	$S \leq -2.0$	$W \leq -3.0$

4. Results and discussion

The first case study was conducted in the central Amazon Basin. Figure 4 shows the comparison of changes in TWS in the central Amazon Basin under seasonal and non-seasonal conditions[36]. Three separate data, including GRACE (CSR RL04), the National Environmental Prediction Centre (NCEP) and GLDAS, were used to display the time-series pattern of TWS changes from 2002 to 2008. As a result, the drought ended at the end of 2005, and the central Amazon endured a rainy season at the beginning of 2006. This finding is confirmed by the Global Precipitation Climatology Project (GPCP) precipitation data showing a higher precipitation rate compared to other years.

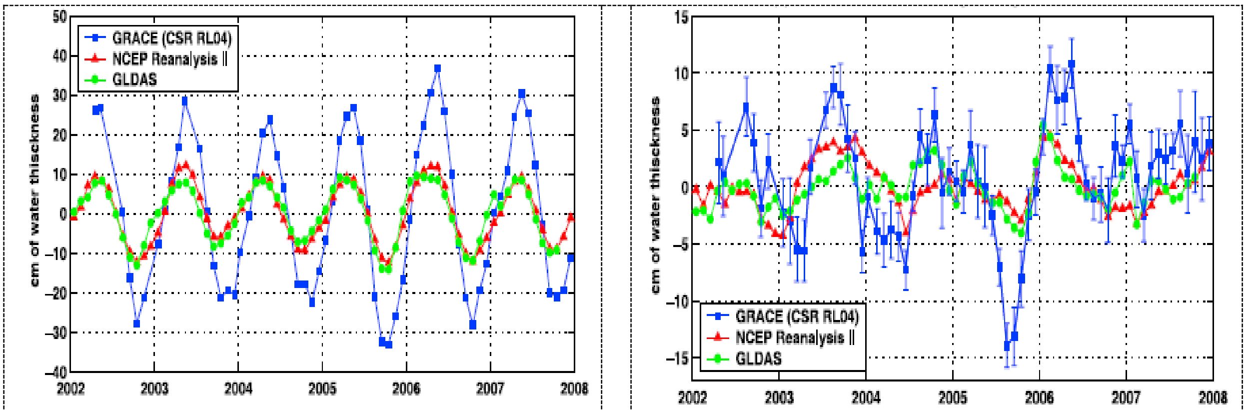

Figure 4. TWS changes in the central Amazon Basin; Seasonal water storage changes (Left); Non seasonal water storage changes. [36]

The second case study was conducted in the Murray-Darling Basin, Southeast Australia[38]. The resulting GRACE-TWS indicates a deficit of around 130 mm between August 2002 and December 2006 around the basin of ~140 km3 (Figure 5a). Between 2000 and 2007, the monthly average of soil moisture anomalies ranged from 44 km3 in December 2006 to 22 km3 in July 2005 (Figure 5c), with a linear trend of 2 km3 a-1. Soil moisture decreased rapidly during the dry season and stabilised once the optimum drying period has been reached[45]. The apparent groundwater deficits occurred between 2001 and 2003, following a drought in 2001 (Figure 5b). Eventually, GW lost 59 km3 between 2003 and 2007 (Figure 5b). The years 2002 and 2006 had seen a significant decrease in TWS, which revealed the gross amount of water to annual soil moisture and groundwater. Changes in overall surface water storage are marginally comparable compared to other large water storage sites in the basin. 3 km3 of the average annual volume of surface water is marginally increased between 2003 and 2005, while the overall loss of surface water between 2002 and 2006 is 2 km3 (Figure 5d). Although 83 per cent of the water loss is groundwater, soil moisture is 14 per cent and 3 per cent is the remaining percentage of surface water accounts for most of the GRACE-observed TWS loss.

The third case study was conducted in Mongolia[46]. Drought occurrences in this area were focused on the WSD (Water Storage Deficit Index) and the WSDI (Water Storage Deficit Index). WSD is GRACE-TWS based on equation (1) while WSDI is based on the monthly deviation of GRACE-TWS. Figure 6 demonstrates the contrast between the WSD and the annual WSD in Mongolia from 2002 to 2017. Significant water storage depletion occurred between 2007 and 2011, suggesting long-term drought during this period. The most severe drought occurred in 2007/02–2009/12 and lasted 38 months with a total WSD of-290.75 mm, although the average water storage deficit of-7.65 mm was less than that of-10.03 mm in 2011/08–2012/07.

Monitoring of groundwater storage using satellite gravimetry is efficient, particularly in terms of time-series observation and availability of historical data. Groundwater storage is always changing due to climate conditions and requires past and present data for TWS comparison. GRACE-TWS, precipitation, evapotranspiration, surface runoff and hydrological simulations were able to imagine the shifts and effects of TWS due to drought conditions. However, the result would be better if the down-scaling method is used along with ground-truth measurements such as tube well and surface stratigraphy results.

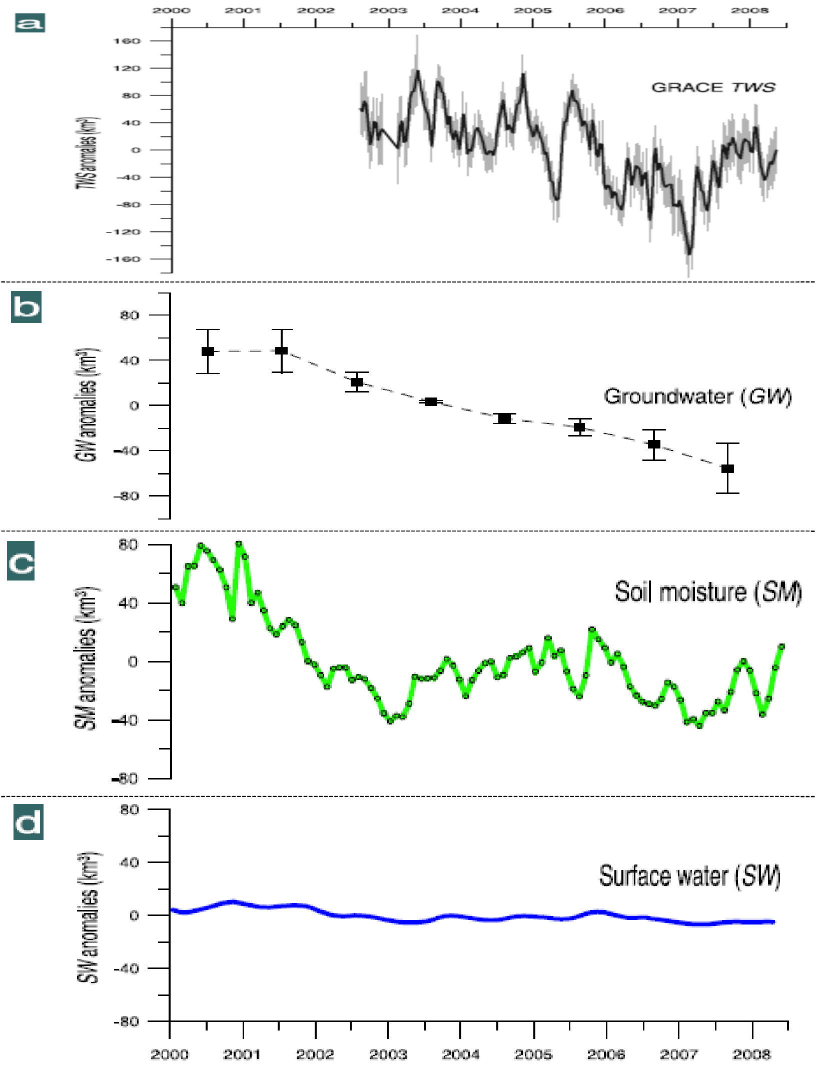

Figure 5. Change in water storage in the main water stores of the Murray-Darling Basin during the multi-year drought. (a) TWS deviations are relative to the 10-day mean of GRACE solutions. (b) irregularities in surface water quality (GW). (c) Anomalies in soil moisture content (SM). (d) Irregularities in surface water storage (SW). [38]

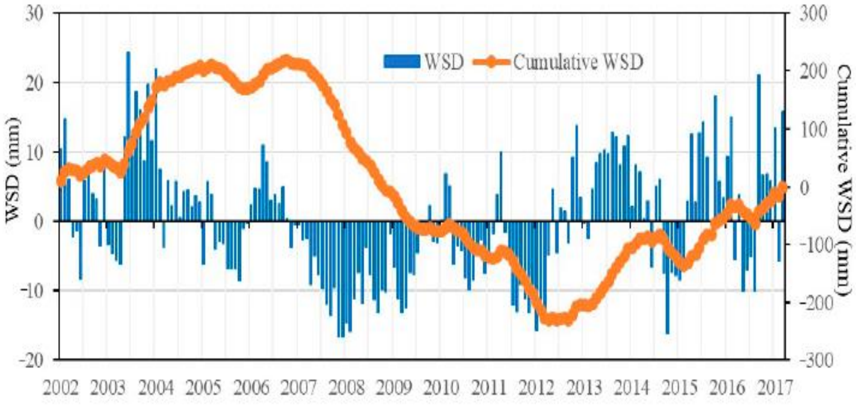

Figure 6. Time-series monitoring of WSD and cumulative WSD in Mongolia from 2002 to 2017. [46]

5. Conclusion

NASA's GRACE mission provides an opportunity to calculate changes in groundwater directly from space. Through observing changes in the Earth's gravitational field, scientists have been able to measure changes in the amount of groundwater contained in an area that has caused a phenomenon to change. GRACE has a data archive of more than ten years for scientific research. This analysis helps scientists and water managers to understand the long-term trends in our water consumption.

GRACE-derived TWS observations are critical to demonstrate the extent of drought at the subsurface level of the earth. The monitoring of the GRACE-TWS time-series allowed the monitoring of the total water deficit over a long period and the monitoring of multi-year droughts. GRACE-derived TWS showed a positive correlation between the TWS estimates and the measured river flow, suggesting that the data assimilation has the ability to downscale GRACE data for hydrological applications.

The central Amazon, Murray-Darling Basin and Mongolia case studies have shown that TWS anomalies from GRACE can determine the total water storage deficit due to drought phenomena. The groundwater storage continues to decline with significant losses, as demonstrated by the time-series drought monitoring from GRACE-TWS by integrating multiple variables, including precipitation, evapotranspiration and surface runoff. This combination of satellite-based data is essential for monitoring changes in groundwater from a regional to a global scale.

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