RESEARCH

Estimation of groundwater storage change in the Helmand River Basin (Afghanistan) using GRACE satellite data

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Abstract

Understanding groundwater storage dynamic changes and quantifying the trends of groundwater fluctuations in the Helmand River Basin (HRB) aquifers, where the groundwater is the main source for drinking and irrigation applications, is significantly important in order to effectively manage groundwater resources. This case study quantifies the changes in groundwater storage over 18 years (i.e., from 2003 to 2021) in the HRB by employing the Gravity Recovery and Climate Experiment (GRACE) observations and Global Land Data Assimilation System (GLDAS) data due to sparse groundwater monitoring networks and lack of ground-based information. The data of observation wells was applied to validate the results of the GRACE and GLDAS outputs. The results indicate that changes in groundwater storage on average from 2003 to 2021 are equal to $(-98.6 \pm 226.84$ mm or -1.9 ± 4.38 km^3/year). On average, during 2003 to 2021 groundwater table decline was -2.6 m in the HRB. The study indicates relatively strong correlation (0.75) between the GRACE derived data and direct in-situ measurements. This study highlights the effectiveness of the GRACE-derived data for the reliable estimation of groundwater storage changes in the HRB and may contribute to sustainable groundwater resources management in the region.

Introduction

Southern areas of Afghanistan, Helmand River Basin (HRB), is characterized by a semi-arid climate dominated by dry plains. In these regions, groundwater is of great significance

due to its domestic, agricultural and industrial purposes. Therefore, for better management and proper use of groundwater storages in this area, it is a considerable step to study temporal and spatial variation of groundwater. Since in large areas the installation and maintenance of monitoring equipment for groundwater observation are costly. In such cases, the remote sensing technology application could be a suitable alternative to traditional techniques (Shukla et al. 2021).

One of the critical indicators in studying groundwater storage changes is the Earth's gravitational field and studying its changes. In this regard, the GRACE[1] mission is the first satellite utilizing directly to receive variations in groundwater storage in any topographic zones (Rodell et al. 2004). The GRACE satellite is much exposed to changes in water level, and by providing an estimate of the Earth's gravitational field on a monthly and average basis in the dimensions of several hundred kilometers, settling a correlation between water level changes and monthly changes in Earth's gravity (Voss et al. 2013).

GRACE Gravitational Satellite mission is a joint mission of the American Aeronautical Research Organization

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[1] Gravity Recovery and Climate Experiment.

NASA[2] and the German Aerospace Center, which ended on 27 October 2017, although its substitution was GRACE-FO[3] with time changes (Mohamad et al. 2020).

GRACE satellite is a twin satellite that has been orbiting the Earth at a relatively low average altitude of about 450 km and with a slope of 89.60, the distance between these twins is 220 km (Frappart and Ramillien 2018). Twin satellites took detailed measurements of Earth's gravity field anomalies from its launch in March 2002 (Chen et al. 2016). Earth's gravitational anomalies are the result of mass redefinition changes in various components of the Earth's system, including the atmosphere, the ocean, the hydrosphere, the cruciform, and the solid part of the Earth.

GRACE observational changes can be applied as a result of changes in the TWS[4] groundwater reservoir, which is a snow water equivalent (SWE), surface water (SW), soil moisture (SM) and groundwater storage change (GWSC), considering that other geophysical factors of land gravity anomaly can be estimated and omitted (Chen et al. 2009). In non-glacial regions, GRACE gravitational changes reflect TWS changes. Therefore, when stored water changes in snow, surface water, and soil are specific, GRACE gravitational measurements are an alternative and complementary equipment for quantifying changes in GWSC groundwater storage, particularly in large areas (Chen et al. 2016).

In many applications, GRACE observations are integrated with global land data administration GLDAS[5] observations. GLDAS aims to collect satellite data and in situ data, along with advanced ground-level modeling and integration techniques (Rodell et al. 2004).

GLDAS comprises 28 sorts of data, including vegetation, soil and precipitation observation and downward emission effects (Birylo and Rzepecka 2020).

In recent years, only few researchers have applied to identify considering research on the accurate estimated TWS water storage of the GRACE satellite over the entire arid area, indicating that the larger the study area, the fewer errors the estimated TWS water storage of the GRACE satellite shows (Swenson et al. 2006). Overall, the ground-based reputation of satellite data products is necessary to refine algorithms associated to data acquisition (Bhanja et al. 2016).

The GRACE satellite provided observations of the temporal and spatial dynamics of terrestrial water storage anomalies from April 2002 to June 2017. But the GRACE satellite mission was ended in June 2017, subsequently the GRACE Follow-On (GRACE-FO) was launched in May 2018 to collect data accordingly. However, there is about one-year observation gap between GRACE and GRACE-FO (from July 2017 to May 2018). Therefore, Mo et al. (2021) recently attempted to employ Bayesian convolutional neural networks for filling the gap between GRACE and GRACE-FO satellite data. Recently, Ali et al. (2021) endeavored to increase the resolution of GRACE products using downscaling techniques.

Castellazzi et al. (2016) carried out an extensive literature review regarding potential and limitations of GRACE and InSAR derived data for assessing groundwater depletion and dynamics. The GRACE observations have been employed in many studies to assess temporal and spatial changes of groundwater storage (Rodell et al. 2007; Yosri et al. 2016; Nanteza et al. 2016; Bhanja et al. 2016; Thomas et al. 2017; Yin et al. 2017; Castellazzi et al. 2018; Thomas and Famiglietti 2019; Rateb et al. 2020; Mohamad et al. 2020; Liu et al. 2021; Akhtar et al. 2022). A few researchers' integrated GRACE observations with Global Land Data Assimilation System (GLDAS) derived data to quantify groundwater storage changes (Birylo and Rzepecka 2020).

The study area is distinguished by arid and semi-arid climate with an average annual precipitation of 205 mm. Groundwater is the primary source of water for human consumption as well as agricultural application in the KRB. In recent years, groundwater is extensively abstracted from the HRB aquifers using solar panels. This study aims to quantify the changes in groundwater storage from 2003 to 2021 in the HRB using GRACE and GLDAS derived data. To the best of our knowledge, this paper is the first to utilize remotely sensed data for assessing groundwater storage changes and sustainable management of groundwater resources in Afghanistan.

Materials and methods

Study area description

The Helmand River is the longest river in Afghanistan and the primary watershed for the endorheic Sistan Basin. This position is due to its location in the sub-desert environment and receiving low annual downpour (Fig. 1). The basin is located between latitudes 29° 18′ to 34° 48′ and longitudes 60° 18′ and 69° 36′. The basin covers the central, southern and southwestern provinces of Afghanistan. Its total area is approximately 340,000 square kilometers, covering approximately 52% of Afghanistan, 31% of agricultural land and 28% of the Afghan population. The basin is bordered by Iran to the west and Pakistan to the south.

The aquifers in the Helmand River Basin are generally of two types: consolidated and unconsolidated sediments. The upper parts of the basin are mainly composed of igneous and metamorphic rocks, and the lower parts consist of sedimentary deposits (Uhl et al. 2003).

Figure 2 shows the climate parameters of the HRB, prepared by employing GLDAS model remote sensing data.

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[2] National Aeronautics and Space Administration.

[3] GRACE Follow-On.

[4] terrestrial water storage.

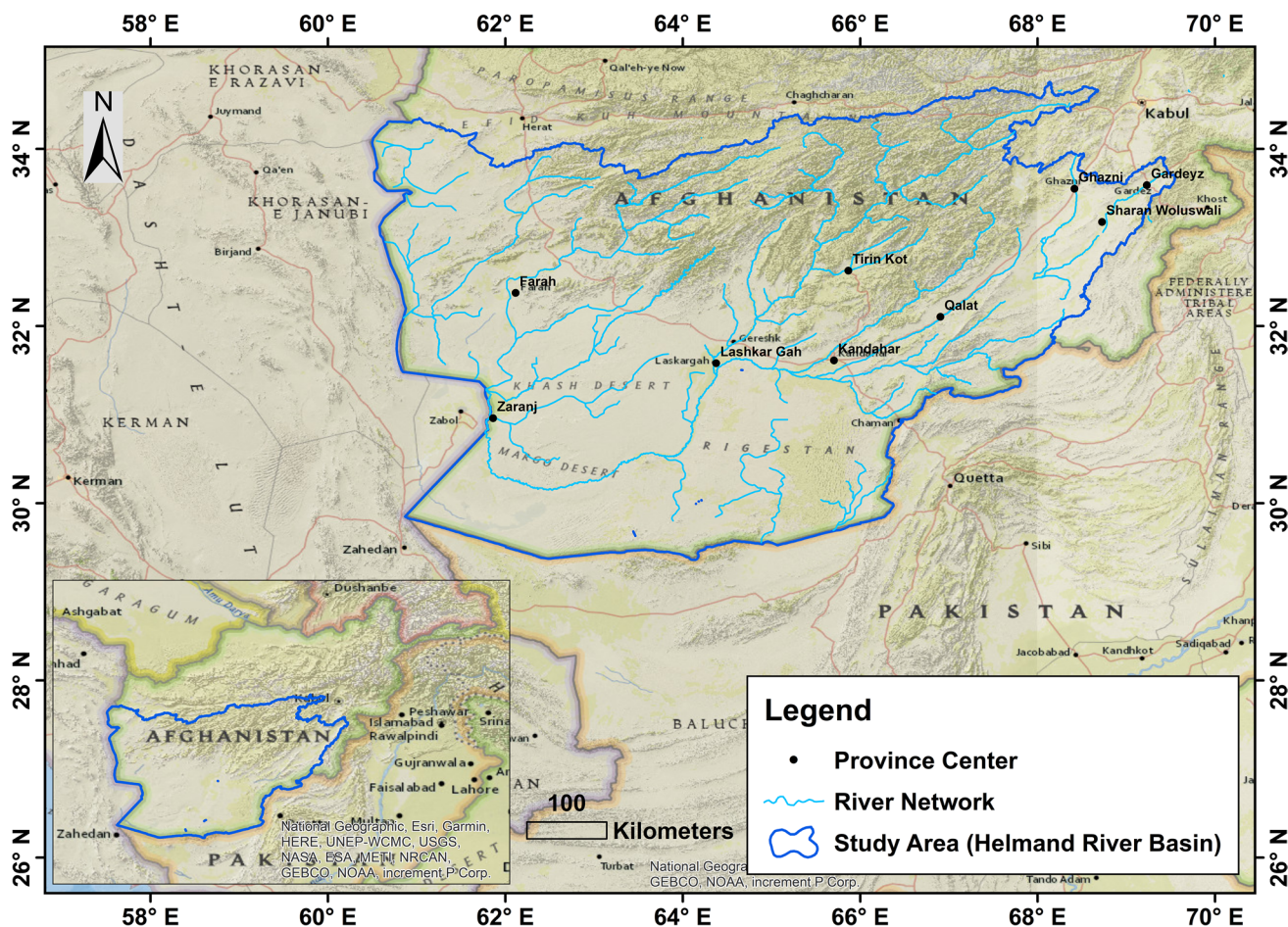[5] Global Land Data Assimilation System.

Fig. 1 Study area location (Helmand River Basin)

Based on the graph, the average temperature is 16.9 °C, and the annual rainfall is 205 mm per year. Figure 2 indicates that the average annual precipitation recorded at the hydrological measuring sites is relatively the same as GLDS model outputs.

Data collection and processing

The Total Water Storage (TWS) is the sum of all above and below surface water storages, including canopy water, rivers and lakes, soil moisture and groundwater, and it represents

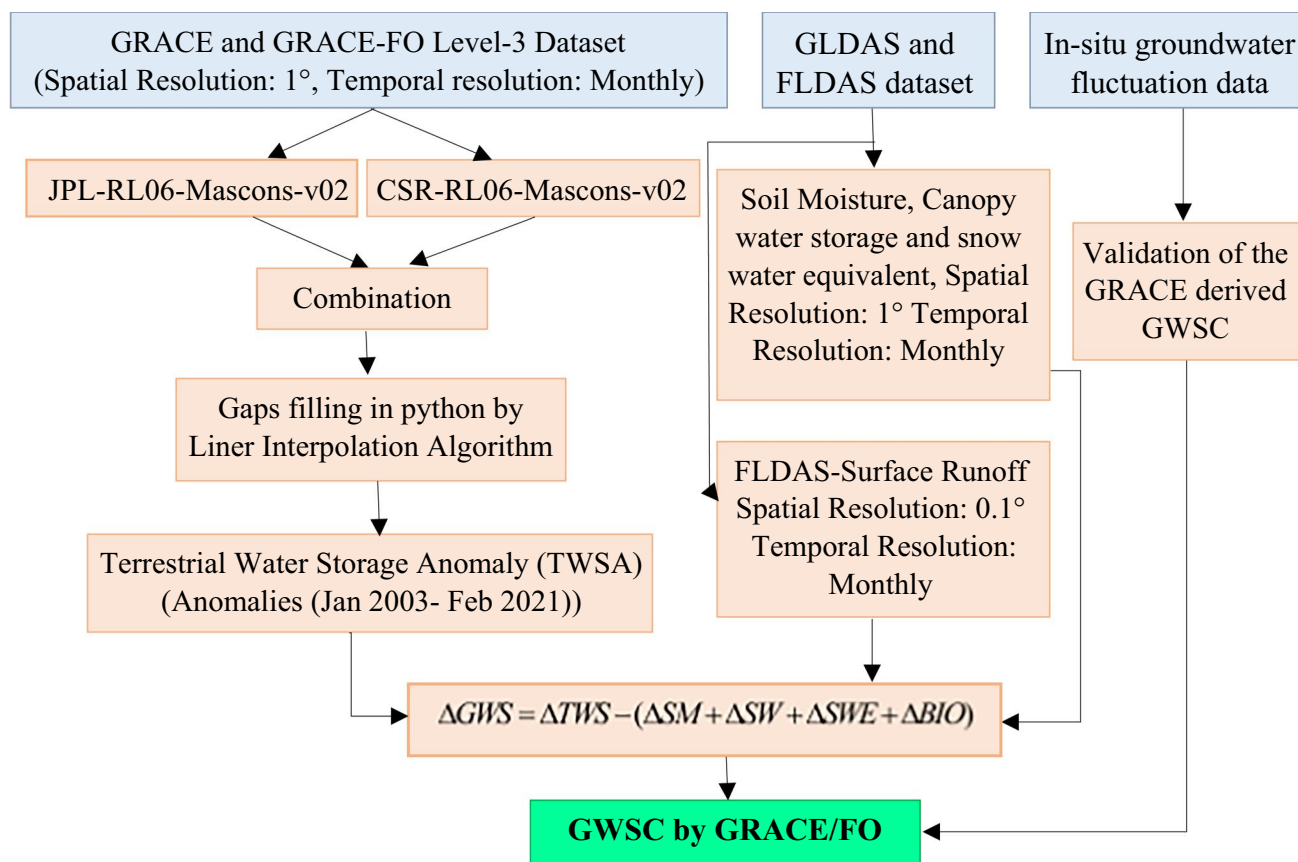**Fig. 2** The HRB climate profile graph
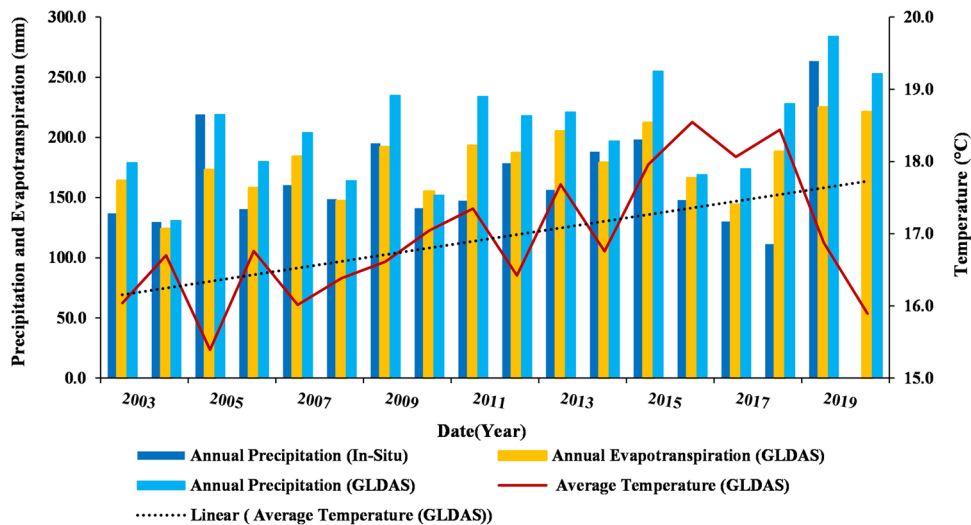
Fig. 3 Methodology flow chart

a synthetic proxy of the dynamic of slow-responding hydrological quantities. According to previous studies, groundwater anomalies and soil moisture play the main role in these variations, and changes in snowmelt and glaciation have little effect on these changes (Khaki et al. 2018). Since the precipitation range in the HRB is from 50 to 250 mm per year, while the evaporation rate is high, it has virtually no snow and glaciers; thus, the main influential parameter in total water storage changes come from variations in groundwater storage followed by variations soil moisture. In general, principal changes in water storage (TWS) are equivalent to the sum of changes in groundwater (GW), changes in soil moisture (SM), changes in surface water (SW), water changes equivalent to snow and glacier (SWE), and changes in the biosphere (BIO).

$$\Delta TWS = \Delta GWS + \Delta SM + \Delta SW + \Delta SWE + \Delta BIO \quad (1)$$

As a result, the changes in groundwater storage are computed (Bonsor et al. 2010).

$$\Delta GWS = \Delta TWS - (\Delta SM + \Delta SW + \Delta SWE + \Delta BIO) \quad (2)$$

In the end, according to the Fig. 3, the results obtained from the above-mentioned method have been compared and validated

with monitoring data wells. Since there are no regular monitoring wells in the HRB, the outcomes are compared with recently established monitoring wells in some areas for their better accuracy. The water table and precipitation data were obtained from Ministry of Energy and Water of Afghanistan and DACAAR.

Total Water Storage (TWS) data collection and processing from GRACE and GRACE-FO Level-3

In this study, the third level GRACE satellite data from CSR[6] (RL06 v02 Mascon) and JPL[7] (RL06 v02 Mascon) data processing center were employed from January 2003 to July 2021. CSR RL06 v02 Mascon solutions data set is a monthly time series of global mass anomaly grids computed from GRACE and GRACE-FO on an equal area geodesic grid representation where the size of each hexagonal mascon tile is approximately 120 km wide. CSR RL06 GRACE and GRACE-FO Mascons are calculated with the same approaches as the CSR RL06 spherical harmonics solutions using GRACE level-1 observations (NASA 2022). The JPL

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[6] Corporate social responsibility.

[7] Jet Propulsion Laboratory.

RL06 v02 dataset contains gridded monthly global water storage anomalies relative to a time-average, obtained from GRACE and GRACE-FO and processed at JPL using the Mascon approach. The water storage/height anomalies are given in equivalent water thickness units (cm) (NASA 2020).

The third level TWS data is available at no cost in the platform (https://grace.jpl.nasa.gov/data- analysis-tool /). The HRB CSR and JPL data ($1^9 \times 1^9$) have some time irregularities for several months. One of the pros of GRACE satellite data is its complete spatial and temporal data over a large area provision. Also, despite its low resolution, it has the advantage of recording changes in total TWS water storage (Bhanja et al. 2016). The data gap between GRACE and GRACE-FO was filled using linear interpolation algorithm in Phyton.

Global Land Data Assimilation System (GLDAS) data collection and processing

Since soil moisture, surface water, canopy water storage, snow and glaciers water equivalent are integral elements in computing changes in groundwater storage, and albeit the accurate measurement of these parameters, obtaining these data in spacious areas is challenging. As a result, global GLDAS large-scale hydrological changes are better than other devices. The GLDAS NASA aims to employ advanced surface modeling and data correlation methods to capture satellite and terrestrial observational data outcomes to generate flow fields and optimize ground surface conditions (Rodell et al. 2009). In this study, The GLDAS model soil moisture to a depth of 2 m, canopy water storage, snow water equivalent, and surface water and the FLDAS[8] model is used for estimation of hydrological changes. The data is available in this open source: (https://giovanni.gsfc.nasa.gov/giovanni/).

In-situ groundwater table measurements and aquifer characteristics

There are no sufficient in-situ measurements in the HRB. DACAAR is the only organization monitored and recorded groundwater tables in some parts of the study area (DACAAR 2010). Since 2019 groundwater monitoring networks have been established in urban centers of southern provinces of Afghanistan by Ministry Energy and Water of Afghanistan. Due to the lack of regular and monthly monitoring well data in the HRB, groundwater monitoring data of DACAAR organization and MEW from 2003 to 2021, are employed to analyze the annual average groundwater table changes, and then compared with the annual average changes of the GRACE satellite

groundwater. Changes in groundwater storage are determined utilizing monitoring well data by the following formula:

$$\Delta GWS = S_y * \Delta h_{swl} \tag{3}$$

Groundwater level changes in monitoring wells (h_{swl}) are equal to the difference in static groundwater levels in a time interval. Since the above data had a timing irregularity, the unknown numbers were derived using the linear interpolation method. (S_y) The confined aquifer special discharge is one of the geological characteristics of the region. Due to the lack of specific yield of different materials in the study area, we have determined the average specific yield based on aquifer types and the specific yields of aquifer materials for the HRB is presented in Table 1.

Based on geological profiles of Kandahar plain, and lithological logs of wells drilled in the Lashkar Gah region, revealing the unconfined aquifer beds consist of loams, having mud, sand and silt (Shroder and Ahmadzai 2016). In addition, according to the permeability tests of exploration boreholes being drilled in Kamal Khan Dam, Nimroz province, the results indicate a specific yield of 4.5% (MEW and SCGC 2019). Based on geological map of the study area, the upper parts of the basin are composed of igneous and metamorphic rocks, and the lower parts consist of sedimentary deposits. The following formula obtains the average specific yield for unconfined beds:

$$S_{yavg} = \sum_{i=1}^{n} S_i * A_i / \sum_{i=1}^{n} A_i \tag{4}$$

In this equation, Si is the specific yield of the 1st aquifer bed, and Ai is the area of the 1st aquifer bed. Figure 4 shows the types of aquifers in the HRB. Based on this map, the main part of the study area consists of loams with sediments accumulated in the lower parts of the basin, and the upper parts of the basin composed of consolidated sediments and bedrocks. Therefore, according to aforementioned description, 3.7% was considered as an average specific yield of the formations for the whole basin.

Statistical analysis

In this study, the root mean square error (RMSE) index is used to evaluate the results. It is presented in the following formula:

$$RMSE = \sqrt{\sum_{i=1}^{n} (O_i - S_i)^2 / n} \tag{5}$$

Here O and S stand for the observed and simulated values, respectively, and n for the number of data. The lower the RMSE value, the closer the data generated by the model is to the real data (Arast et al. 2019).

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[8] Famine Early Warning Systems Network (FEWS NET) Land Data Assimilation System.

Table 1 Specific yields of different geologic formations in the HRB (Johnson 1992; US Army Corps 2009)

No	Type of aquifers	S_y range	Mean S_y in the HRB)
1	Unconsolidated sedimentary aquifers	0.01 to 0.28	0.07
2	Consolidated sedimentary rocks (sandstone, conglomerate, siltstone)/aquifers	0.01 to 0.10	0.035
3	Consolidated sedimentary rock (limestone) / aquifers	0.03 to 0.26	0.058
4	Bedrock/ fractured aquifers	0.0 to 0.005	0.0025

Results and Discussion

Monthly changes in hydrometeorological parameters from GLDAS model

TWS-GRACE displays overall changes in the water resources. Biosphere changes (BIO) are assumed to be trivial, and the changes in groundwater storage are calculated by subtracting soil moisture changes, snow equivalent water, plant water storage (canopy water storage) and surface water from TWS GRACE GWSC.

The GLADS model, with a spatial resolution of one degree and a monthly interval, calculates changes in soil moisture to a depth of 2 m, water equivalent to snow and glacier, and water stored in plant leaves from January 2003 to January 2021. In the current study, changes in soil moisture have the predominant impact on changes in surface water storage (Fig. 5).

Figure 5 shows the changes in soil moisture from 2003 to 2021 in the HRB. According to this graph, in 2005 the amount of humidity indicates a significant rise compared to 2003 and 2004, and from 2005 to 2012, shows almost
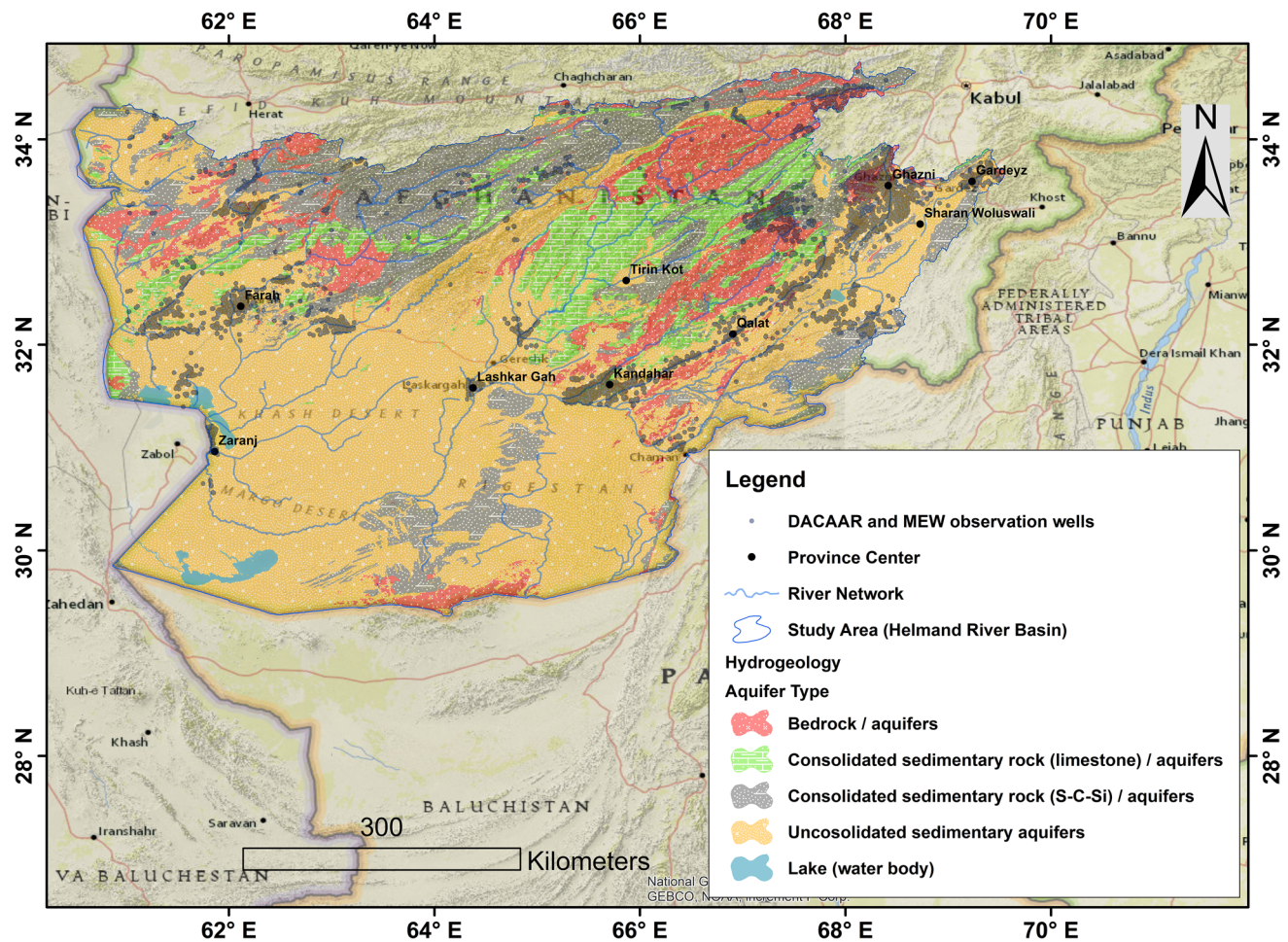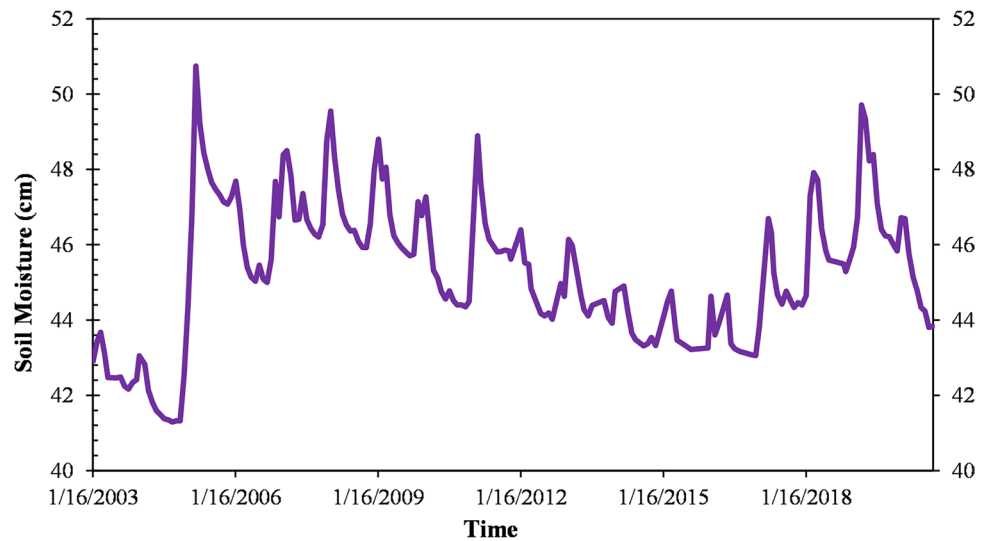

Fig. 4 Specific yield of geologic formations in the HRB

Fig. 5 Soil moisture variations in the HRB from 2003 to 2021

the same fluctuations. However, between 2006, 2007 and 2010 there was a decrease in soil moisture. From 2012 to 2019, there was a slow downward trend in soil moisture content. The amount of soil moisture in 2020, like in 2005, reveals a significant increase compared to the years before and after. These two graphs possess similar fluctuations to the soil moisture graph (Fig. 5). According to the historical record of Ministry of Energy and Water of Afghanistan, the study area received more rainfall in 2005 and 2020 than other years.

Figure 6 depicts the changes in surface water, snow water equivalent and canopy water storage in the HRB from 2003 to 2021. Surface flow was computed using the FLDAS model over the considered period (Fig. 6). The changes in surface water storage and plant storage

possess relatively similar fluctuations to the soil moisture graph (Fig. 5).

Monthly changes of Total Water Storage (TWS) and groundwater storage

The gravity field models employing JPL, CSR variables are utilized to compute total water storage changes. Albeit there are little differences in a few months, the entire result is invariant. The mean of JPL and CSR variables are utilized to determine the changes of TWS, and according to the changes of GLDAS surface water model, the trend of GWSC groundwater storage is determined.

According to Fig. 7, overall water reserve variations and groundwater storage have been relatively stable between

Fig. 6 Surface water, snow water equivalent and canopy water storage changes in the HRB from 2003 to 2021
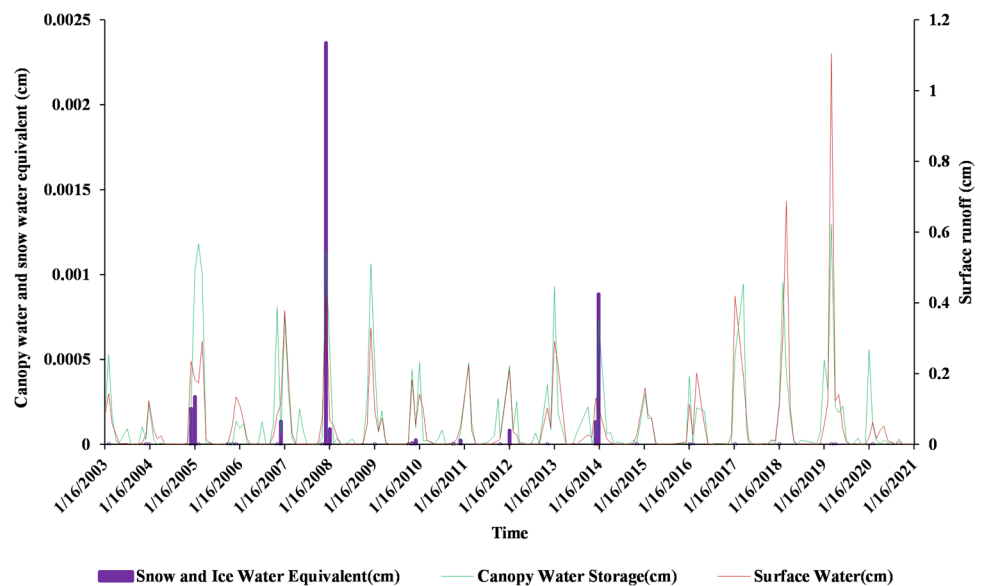
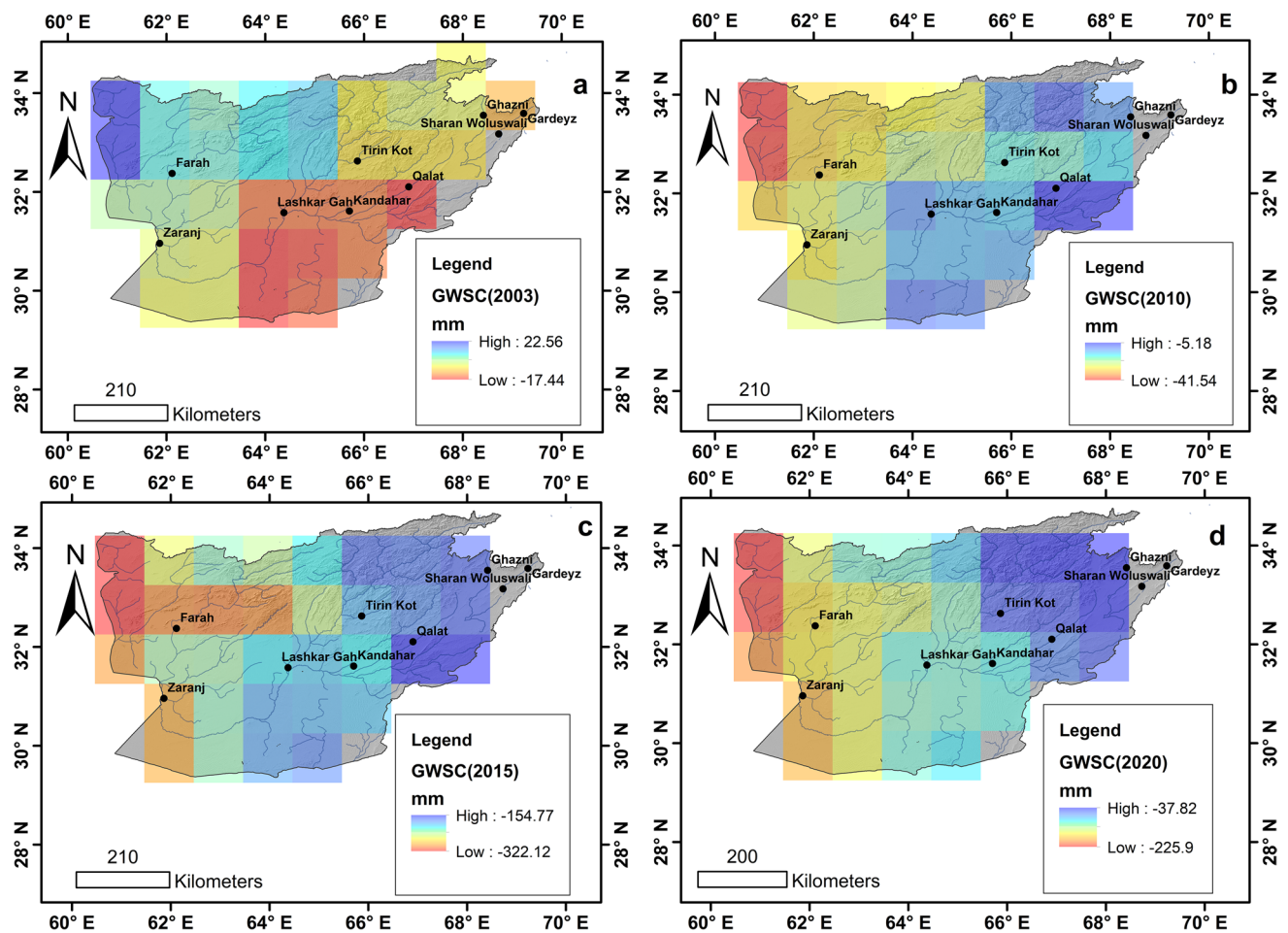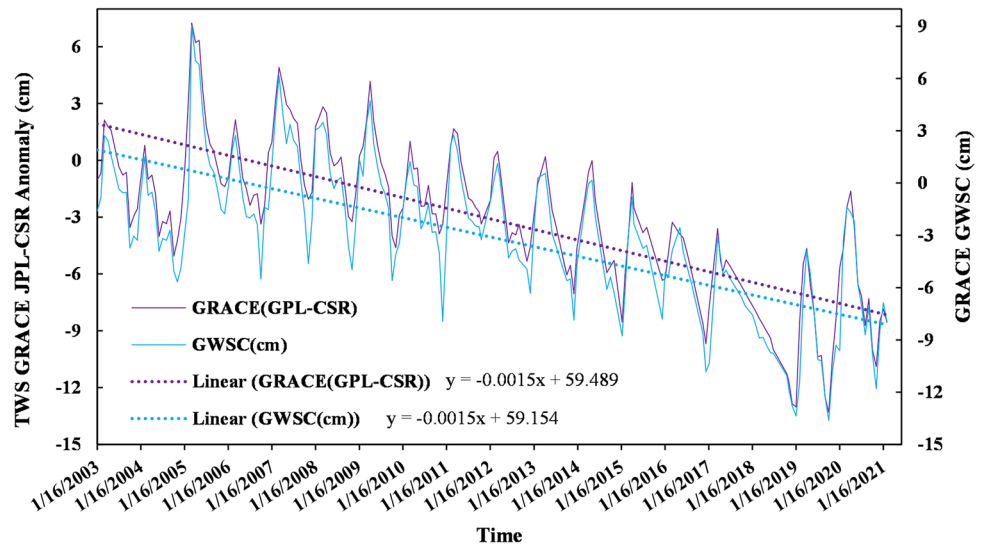**Fig. 7** TWS and GWSC in the HRB from 2003 to 2021

Fig. 8 **a** Map of groundwater storage variations in 2003, **b** Groundwater storage in 2010, **c** Map of groundwater storage variations in 2015 and **d** Map of groundwater storage variations in 2020
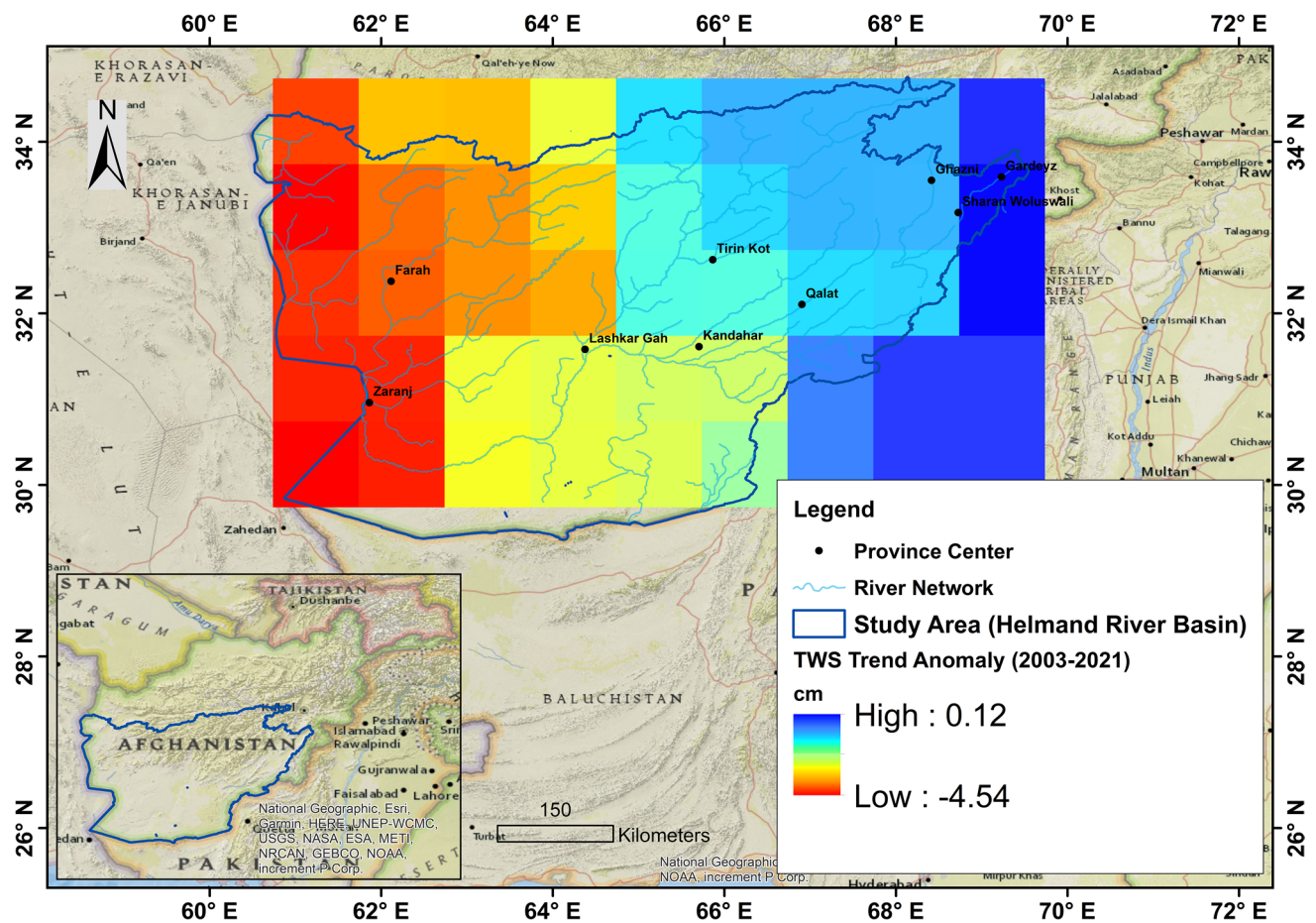
Fig. 9 TWS anomaly map of the HRB

2003 and 2008, followed by a sharp decline trend from 2008 to 2021. Groundwater has been extensively abstracted from the aquifers for irrigation purpose over the last decade using solar panels (MEW 2021).

Figure 7 indicates the spatial groundwater storage changes in the HRB aquifers. The average rate of change in groundwater storage from 2003 to 2021 are equal to

(-98.6 mm ± 226.84 mm). Figure 8 shows the trend of spatial–temporal groundwater changes in the HRB using the GRACE satellite between 2003 and 2021. As it can be seen, at first, the changes were close to zero, but from 2008 to 2021, more drastic changes are observed.

Figure 9 indicates that due to climate change causing melting snow and glaciers, overall water storage changes

Fig. 10 a Validation graph of groundwater changes results using the GRACE satellite with monitoring well data in the HRB, **b** Mean annual groundwater storage changes from 2003 to 2021 based on in-situ measurements and the GRACE-derived data observations
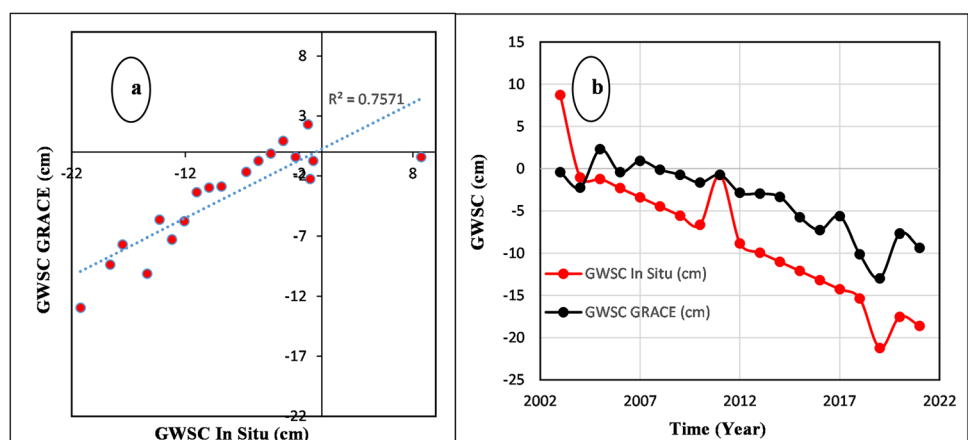
are positive in the eastern and southeastern parts of the study area. But in the western and southwestern parts of the basin, the overall water storage changes from 2003 to 2021 are negative due to the increase in population in major city centers such as Kandahar, Lashkar Gah, Zaranj and Farah, over-cultivation and climate change. During the considered period, many Karezes and significant number of shallow wells have been already dried up due to over abstractions in the aforementioned areas (Uhl 2006; Macpherson et al. 2017; USAID's SWP 2021). The groundwater level has experienced local decline in some parts of the aquifers in the Eastern Helmand Basin (Qalat and Kandahar), but this decrease is not noticeable in Fig. 9 (USAID's SWP 2021).

Validation of the GRACE-based groundwater storage changes and in situ observations

Generally, the outputs of GRACE-based estimation are necessary to be validated using direct in-situ measurements. Therefore, the GRACE-derived estimation of the GWSC was compared to observation data from monitoring wells. The annual changes in groundwater storage simulated using GRACE satellite data highly correlated (0.75) with groundwater storage variations obtained from observation wells (Fig. 10a). The comparison was performed based on yearly time scale as shown in Fig. 10b. The high consistency between GRACE derived GWSC and in situ GWSC suggests that GRACE observations fairly estimated the dynamics of groundwater storage changes in the HRB. The graph shows a slight downward trend in groundwater storage changes in the HRB. It reveals that groundwater storage gradually decreased over the HRB due to over-abstraction and climate changes.

Conclusion

The HRB is one of the largest river basins in Afghanistan which is characterized by arid and semi-arid climate. Groundwater is the main source of water for drinking and agricultural consumptions in the study area. Due to lack of groundwater monitoring networks and in-situ measurements in the HRB, inadequate data is available about groundwater storage changes. In this research, attempts were made to integrate and employ remotely sensed (GRACE and GLDAS) derived data to evaluate the temporal and spatial changes in groundwater storage in the HRB over the period from 2003 to 2021. The GRACE and GLDAS observations have recently been identified as effective tools for monitoring and quantifying groundwater storage changes in areas with lack of direct in situ measurements and large-scale basins. The study indicated a slight

downward trend in groundwater storage changes during the considered period, where groundwater table decline was -2.6 m in the HRB. The study showed a strong correlation (0.75) between in situ observations and GRACE-based groundwater storage changes in the HRB. The results of this study revealed that groundwater storage depletion is likely to increase in the future due developing traditional irrigation practices across the basin. It will have adverse consequences on water and food security in the region. It is recommended for policy makers and stakeholders to improve and enhance direct water level measurements in the HRB for better sustainable management of groundwater resources. It is expected that downscaling and data assimilation approaches can be employed to improve the resolution of remotely sensed data in the future.

Author contributions All authors contributed to the study conception and design, material preparation, data collection and data analysis were performed by Aref Nazari, Abdulhalim Zaryab and Abdullah Ahmadi. The first draft of the manuscript was written by Aref Nazari. All authors read and approved the final manuscript.

Data availability The data supporting the findings of this research are available from the corresponding author upon reasonable request.

Declarations

Competing interests The authors declare no competing interests.

Conflict of interest The authors declare no conflict of interest.

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