Journal of Hydrosciences and Environment
Available online at http://jhe.usb.ac.ir/

ISSN: 2345-5608

Assessment of Groundwater Level Variations in Different Land-Uses Using GRACE Satellite Data (Case Study: Zayanderud Basin, Iran)

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ARTICLEINFO

Article history:

Received: *26 June 2019*
Accepted: *29 September 2019*

Keywords:
Agricultural land,
Gravity recovery and climate experiment (GRACE),
MODIS product,
Root Mean Square Error,
Range land,
Remote sensing.

ABSTRACT

Reduced rainfall, groundwater resource limitations, and undesirable use of it are the main limiting factors of the development of different uses in arid and semi-arid areas. Changes in surface factors have an effective role in groundwater level because some factors such as vegetation and land use cause changes in groundwater balance. In this study, data from the GRACE satellite and the stations were used to estimate the monthly groundwater level changes in the Zayanderud Basin, Iran from 2002 to 2018. In addition, the annual and seasonal storage of groundwater in this basin was estimated and verified using the GRACE data and this trend was compared with the data from previous rainfall. Our results indicate that terrestrial water storage variations from GRACE and GLDAS are in general consistent with one another. These data show that the current groundwater level depends on the amount of rainfall in the past years. When rainfall is on a downtrend, underground water storage fluctuations are more effective than rainfall. In addition to time trend, vegetation pattern in rangelands, woodlands, and agricultural lands depends on the amount of groundwater storage variations in the Zayanderud basin. The lowest amount of that in 2016 coincided with the lowest amount of underground water storage and recharge (27.36 cm). The statistical correlation analysis of the GRACE satellite data and the observed data of wells indicated that RMSE was equal to 2.23 cm on the seasonal scale. Further, GRACE captures characteristics of groundwater drought that occur as a result of complex human activities and natural changes, thus presenting a framework to assess groundwater drought characteristics.

1. Introduction

Water is the lifeblood and the main input for most uses. Groundwater is one of the main components of regional water balance and also a key factor for proper planning to improve water use efficiency in all regions. Uncontrolled development of unpolluted deep wells has been an essential factor in complicating water table control in the Zayanderud basin in Isfahan, Iran.

Proper management and planning of groundwater resources in the Zayanderud basin depend on the awareness level of spatial and temporal variations in these valuable resources. Therefore, the necessity of soliciting data on water resources in this large basin is undeniable. Since the installation and maintenance of equipment is very costly, the use of remote sensing techniques is becoming an appropriate alternative for traditional and costly techniques (Abiy and Melesse, 2017). The Gravity Recovery and Climate Experiment (GRACE) satellite and the Global Land Data Assimilation System (GLDAS) are two techniques for spatial modeling of ground surface that provide researchers with useful information on underground water storage changes (Tregoning et al., 2012).

Some researchers have used remote sensing methods. For example, Singh et al. (2019) monitored groundwater fluctuations in India during Indian summer monsoon using the GRACE satellite and GLDAS. The GRACE data indicated the variation of 15 cm in the terrestrial water storage during the study time across India. Also, they showed that the GRACE data had good flexibility in groundwater variations. Khaki et al. (2018) analyzed the variations in water table storage in a river by the GRACE satellite and the rainfall measurement to study the comprehensive management of the Nile River in Africa. Their results showed a strong correlation between groundwater storage and recharge changes and rainfall variations. In a study in Central Mexico, Castellazzi et al. (2018) used data from the GRACE satellite and data from the Mexican State Water Authority to obtain the amount of

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groundwater discharge in this region. Their study showed that the GRACE satellite estimation was consistent with ground-based data and it was also suitable for the use in water management programs. This study also showed that there was more groundwater discharge and a negative trend in agricultural lands in Northern Mexico. According to Banerjee and Kumar (2018), the GRACE satellite data show that the groundwater has increased in the central and southern parts of India and that the GRACE data has a good efficiency in identifying underground water storage process. The results of this study indicate that rainfall is an important cause of water storage in most parts of these regions and it has a positive trend. Sun et al. (2018) reported that the GRACE satellite data could be used effectively to assess drought and underground water characteristics and these data could consider strong and reliable drought characteristics in vast areas. Thomas et al. (2017) presented an approach to evaluate the occurrence of groundwater drought based on observations from the GRACE satellite mission in the Central Valley of California. The results showed that GRACE captured characteristics of groundwater drought rooted in complex human activities and natural changes, thus presenting a framework to assess groundwater drought characteristics. Abiy and Melesse (2017) evaluated watershed scale variations in groundwater with the application of the GRACE satellite imagery data. They explained that GRACE could provide an accurate estimate of the changes in total terrestrial water storage at a coarser, regional resolution. Zhou et al. (2016) used the GRACE satellite data to investigate local groundwater variations at the Wuhan station. The results indicated good performance in the GRACE estimation results for obtaining groundwater level changes in their study area. Chen et al. (2016) aimed to find a method to increase the accuracy of GRACE data in order to examine the data of this satellite in the years 2003 to 2012. Zhou et al. (2016) recovered the terrestrial water storage variations in the Poyang Lake Basin from the GRACE gravity data from January 2003 to March 2014 and compared them with GLDAS hydrological models. Their results indicated that the terrestrial water storage variations from GRACE and GLDAS had a general consistency. The terrestrial water storage trends in the Poyang Lake Basin determined by GRACE and GLDAS were increasing at 0.0141 m^3 and 0.0328 m^3 during the investigated period, respectively. Chen et al. (2014) re-assessed long-term groundwater storage variations in the northwest of India using an extended record of GRACE time-variable gravity measurements and a fully unconstrained global forward modeling method. The GRACE analysis indicated that the neighboring province of Pakistan (especially Northern Punjab) has apparently experienced significant groundwater depletion during the same period too, which has partly contributed to the new regional groundwater depletion estimates. The comparison of GRACE groundwater storage changes indicated a trend improvement (Singh et al., 2019). Langon evaluated the GRACE satellite data in an area of 200,000 km^2 over the period 2003-2007. After comparing the process of water storage variations obtained from the GLDAS model, the data of the GRACE satellite and wells, the results indicated that the GRACE method revealed the trend of water variations better than the GLDAS model.

The Zayanderud basin is faced with a shortage of and a decline in groundwater, so regarding over-exploitation of this basin, we analyzed data based on GRACE and GLDAS for groundwater balancing in different land uses over a vast area covering the entire Zayanderud basin in 2002-2018.

2. The Study Area

The Zayanderud basin is located between the eastern longitudes of 50˚02' and 53˚24' and northern latitudes of 33˚42' and 31˚12' with an area of 41518 km^2. The basin has an elevation ranging 1100-3970 m above sea level and its rainfall range is 95-274 mm. Minimum and maximum air temperatures are 10 and 18°C, respectively. Agricultural lands, grasslands, forests, bare soils, saline lands, urban areas, and wetlands were considered as the important land uses in this basin (Fig. 1).

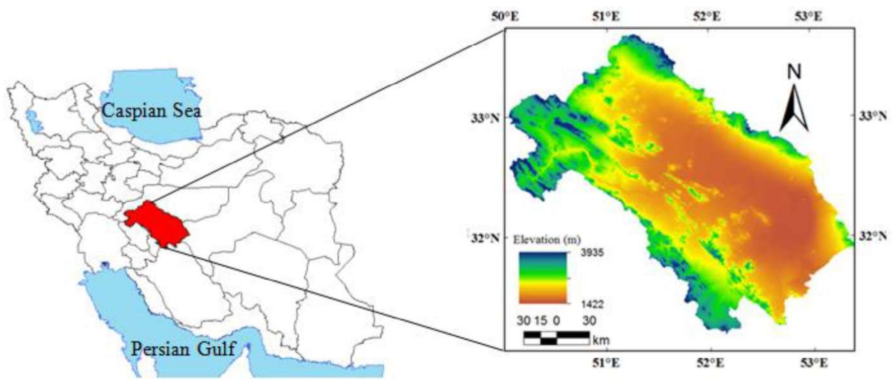

Fig. 1. The elevation of the Zayanderud basin

3. Data and Methodology

3.1. Rainfall Data

The rainfall data were obtained for the basin from 2000 to 2018 from the Iranian Meteorological Organization and the Regional Water Authority of Isfahan Province. In total, the average monthly precipitation data were collected from 15 synoptic and rain gauge stations in the basin (Table 1).

Table 1. The precipitation data in study area (2010-2018)

Year	Precipitation (mm)	Year	Precipitation (mm)
2010	210.32	2015	168.38
2011	190.41	2016	165.54
2012	203.25	2017	178.9
2013	201.55	2018	237.45
2014	182.34		

3.2. Satellite data

The GRACE mission was launched on March 17, 2002 as a joint effort between the United States National Aeronautics and Space Administration (NASA) and the Centre Deutschen Zentrum für Luft- und Raumfahrt (DLR) from the German Aerospace Agency. GRACE is the first remote sensing satellite that can estimate groundwater storage anomalies for the entire globe on a monthly basis. The satellite records changes in mass that affect the gravitational pull on the two satellites, which is later converted into land mass grid solutions. A scalable version of GRACE-processed data was used for the present study. This allowed the Terrestrial Water Storage (TWS) to be estimated at the Equator of approximately 100x100 km (Chinnasamy et al., 2015). The TWS data, with monthly resolution (version RL05), is available from the NASA Jet Propulsion Laboratory website (Landerer and Swenson, 2012). The relevant scale factors are also available on the website (Billah et al., 2015). Monthly data were downloaded from January 2002 (data were not available before 2002) to December 2018.

In this study, version 2.7.1 of the NOAA model was used to evaluate soil moisture in a depth range of 0-200 cm. The data on the NOAA model and other GLDAS-LSMs can be obtained from the Goddard Center for Data Services and Earth Sciences. The GLDAS model is used to estimate the total moisture contents of the globe in different spatial and temporal resolutions (Chinnasamy et al., 2015). The NOAA model data in the grid format, including the monthly average soil moisture content at spatial and temporal scales (with a resolution of 1° cell/g/month), were similar to that of GRACE.

NDVI is a profile dependent on the amount and condition of vegetation that is calculated from the data of Red and Nir bands using equation (Jin et al., 2013). In this study, MODIS satellite images (MOD13Q1) were used to calculate this index from www.earthexplorer.usgs.gov. The corresponding maps were used in GIS 10.3.

3.3. Ground Water (GW)

Groundwater storage was estimated using the GRACE and GLDAS models and the following equation (Chinnasamy and Sunde, 2015):

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

where *TWS* is the estimated groundwater storing using GRACE (cm), *SM* is the soil moisture data using GLASA (cm), and GW is groundwater (cm). To compare the GRACE and CGWB estimates, monthly GRACE and GLDAS networks were used to estimate GW on a monthly basis from 2002 to 2018. Data from 15 observation wells in the Zayanderud basin were employed to verify the accuracy of GRACE satellite data. Since the GRACE data has a spatial resolution of 1 degree, the GRACE pixel is considered based on the geographic longitude coordinates of the basin for the full coverage of the area. The Microsoft Office Excel software was used to draw charts.

3.4. Statistical Analysis

In this study, Pearson and Kendall correlation and quantitative index of Root Mean Square Error (RMSE) were used for data analysis of groundwater level variations. It is derived from the following equation (Chai and Draxler, 2014):

$$RMSE = \sqrt{\frac{\sum(C_i - M)^2}{n}} \qquad (2)$$

in which C_i, is the observed value, *M* is the mean of the observed data, and *n* is the number of data. If this statistic is equal to zero or close to zero, it indicates that the method used is very precise. With the distance from zero, the accuracy of the intended method decreases (Chai and Draxler, 2014).

4. Results and Discussion

4.1. Rainfall Trend

According to the histograms of the monthly rainfall data, the Zayanderud basin has mean precipitation of 135 mm in the presence of a different climate. The rainfall analysis for 18 years shows that the highest precipitation is 274 mm and the lowest is 95 mm. However, the average rainfall was about 185 mm from 2000 to 2018. During this period, the lowest was about 155 mm (in 2000 and 2001) and the highest was 220 mm (in 2006) (Fig. 2).

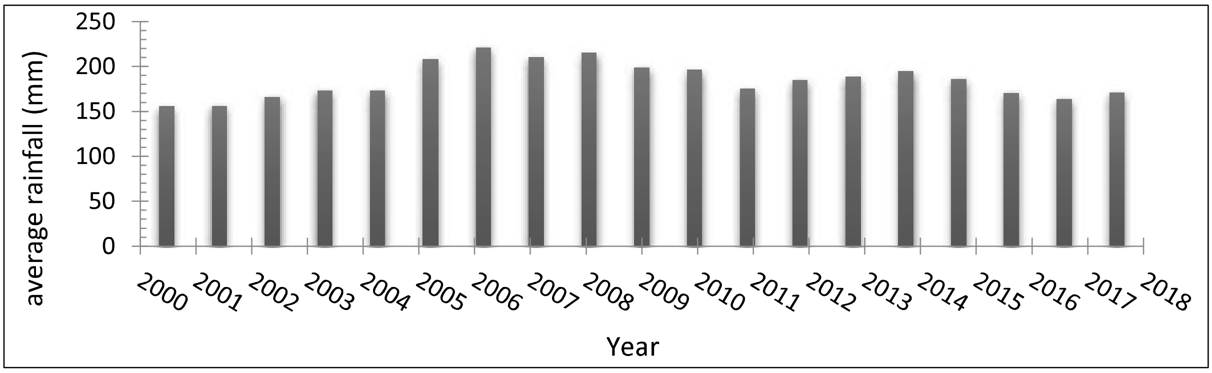

Fig. 2. Rainfall histogram of the Zayanderud basin (2000-2018)

4.2. State Level Groundwater Storage Anomalies

An overview of the underground water storage changes in the basin in February is presented in Fig. 3. In this study, the estimation of groundwater storage is interpreted with a positive amount and if its storage is more or less than moderate, it will be interpreted negatively. February shows the end of the winter rainfall for the Zayanderud basin. Therefore, the current study only shows the image of this month. This image shows a negative trend after 2004. It may indicate that the process of groundwater storage gradually changes to the negative, meaning that the process of groundwater storage in this basin depends on the state of the preceding moisture.

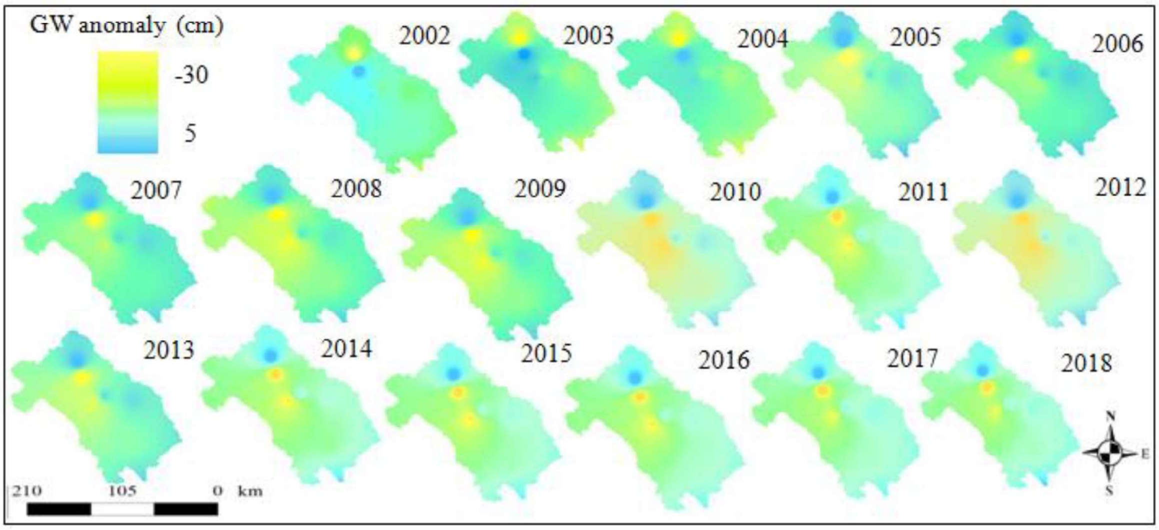

Fig. 3. GRACE's evaluation of water table store anomaly

4.3. Effects of Rainfall Amounts on Groundwater Storage Change

Precipitation data were compared with the estimation from net reserves of groundwater for data analysis of groundwater storage fluctuations influenced by variations in rainfall patterns (Fig. 4). The net storage of GRACE water table is similar between February (the last days of winter precipitation) and September (the last days of summer). The data collected for 2000 and 2001 were not available for GRACE because the GRACE mission began in 2002. The dry period during the years 2002 and 2003 (the lowest rainfall in the study period) corresponded to the lower storage of groundwater in the basin and the drying of the Zayanderud River. Then, until 2006 this trend remained constant. Fig. 4 shows the gradual improvement of the underground water storage after an average rainfall of about 10 mm in 2004 and 2005. From 2009 to 2012, with a further decline in rainfall compared to previous years, the storage and recharge were disrupted with a constant trend. Due to limited rainfall by 2018, there was a slowdown in underground water storage. Therefore, the pure recharge process of underground waters follows a precipitate disorder. The study found that GRACE could provide insights as to how groundwater levels fluctuate with rainfall over a long period of time (18 years) in a larger area. The results of Chinnasamy et al. (2015)'s study on the effects of rainfall fluctuations on GRACE groundwater levels showed that during the 2002-2013 period, the net underground recharge process was dependent on precipitation and its variations. Maheshwari et al. (2014) also demonstrated the role of rainfall enhancement in storing and increasing groundwater levels in a long time in Gujarat and Rajasthan, India. In a study on underground water variations in the Nile River in Africa, Khaki et al. (2018) showed a negative trend in underground water storage, which could be due to the significant rainfall in the past decade and extensive irrigation in this region. All of these studies are consistent with the results of our research. GRACE provides the net volume of water table reserves. The difference between the maximum and minimum storage of groundwater extracted from GRACE (from 2002 to 2018) would be approximately 14 cm in height if groundwater recharge methods and facilities were suitable for the studied basin.

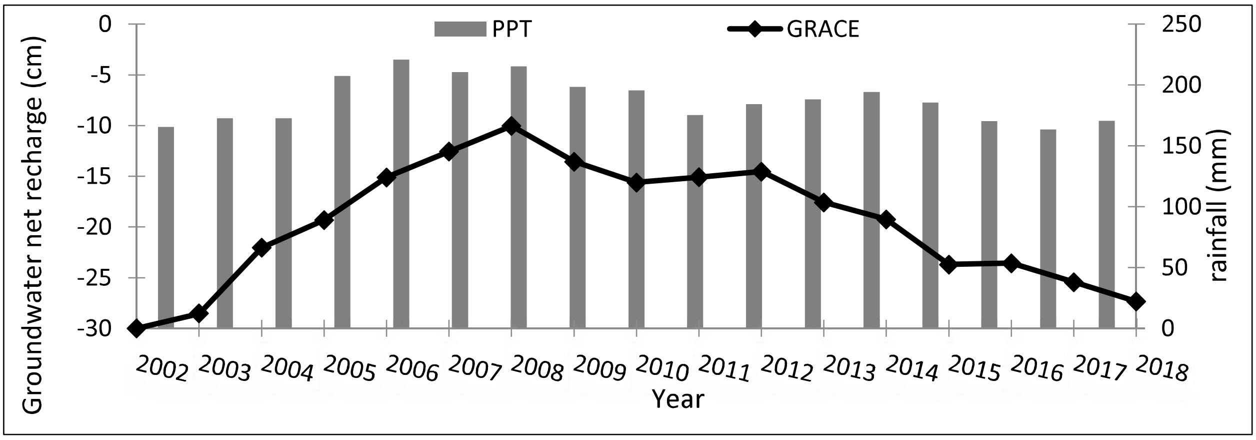

Fig. 4. The comparison between the annual mean rainfall and the GRACE data

4.4. The Comparison between the Observation Wells and GRACE and GLDAS Model

This section compares the changes in the groundwater level of the observation wells and groundwater level changes estimated by the GRACE satellite. Given the fact that in this satellite, the total amount of water change includes total groundwater, soil moisture, and surface water, there is a need for the total fraction of the amount of soil moisture and surface water to convert the amount of groundwater variations. The seasonal variations in the GRACE and GLDAS data and the observations for the years 2002 to 2018 are shown in Fig. 5. During the period 2002-2005, the trend of variations in the GRACE data and wells and observations were roughly the same, but from 2006 to 2009, which coincided with the drought and reduction of rainfall (Fig. 2), a time delay can be observed in the data of the basin.

The results of statistical analysis of the GRACE satellite data and observation wells data indicate that RMSE = 2.23 cm on a seasonal scale. Moiwo et al. (2009) found that the RMSE was equal to 26.7 mm from the statistical analysis of the variations in the storage of water obtained from the GRACE satellite and the computational quantities of the GLDAS model. Also, the process of the water level variations in the basement and the increase in the water level in winter is quite evident towards the fall. In both figures, the trend of underground water changes is the same with the difference that the GRACE satellite shows that the trend of these variations is more intense in some years (2006, 2007, and 2018).

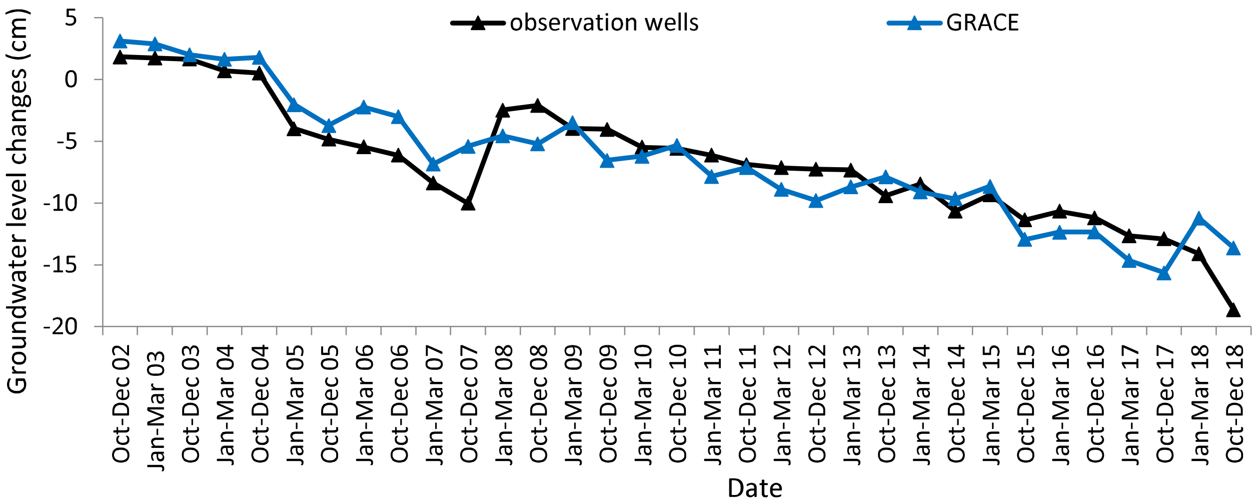

Fig. 5. The trend of variations in average groundwater level (cm) (autumn and winter, 2002-2018)

4.5. Variations in Groundwater Net Recharging in Land use

The net recharging of groundwater from the GRACE estimation in different applications is shown in Fig. 6. Water storing in the years 2002 to 2004 was almost constant in all studied applications. Agricultural land variations in 2005 showed more changes than the base average so that in this year, net recharge was decreased by 2 times in agricultural lands as compared to 2004.

There were no significant changes in other uses than the base average. Despite the rising rainfall in 2005 (Fig. 4), the decline of water savings can be attributed to the increased irrigation and more water consumption. Therefore, more groundwater withdrawals in agricultural lands have not allowed water recharge and retention. In addition, this trend continued until 2009 and intensified as rainfall declined in 2012-2018. Wet and woodlands also had a significant drop in 2009 and 2010, respectively.

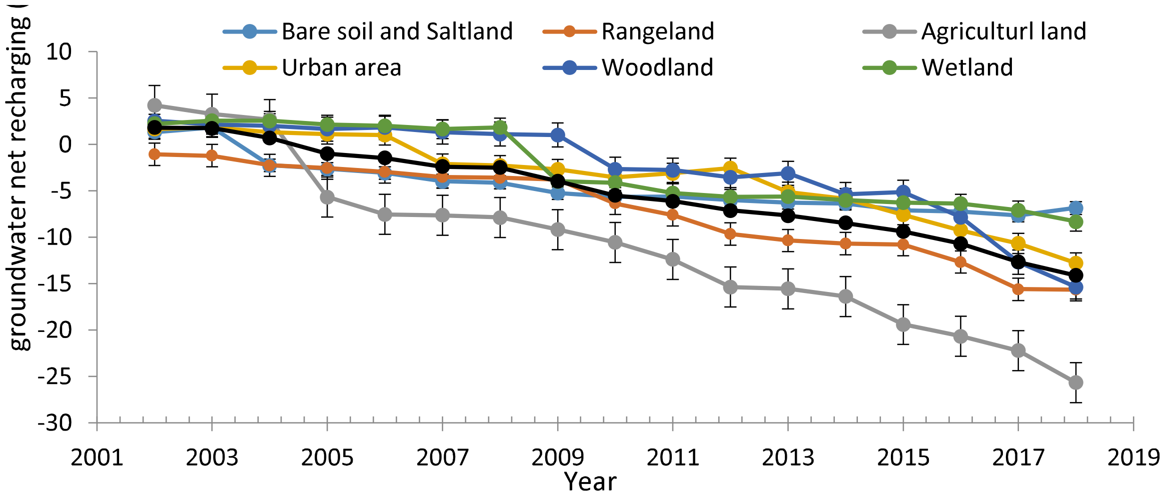

Fig. 6. Variations in land uses GRACE data (net annual water table recharge). Bars indicate standard error

5. Conclusions

The basic objective of our study was to evaluate the composition of the total remote estimation of the water storage from GRACE for use in estimating groundwater storage variations in the Zayanderud basin. This study shows that the GRACE data approach provides a reasonable process for land use variations in groundwater storage. Data analysis shows that the process of underground water storage in past years depends on rainfall and, as a result, depends on the state of the previous moisture.

In addition, due to the droughts struck the Zayandehrud River, water table storage does not respond to rainfall quickly, but incrementally changes over time. When the rain has a descending trend, ground water supply fluctuations are heavily dependent on the precipitation trend. In addition, the time course of the vegetation pattern depends on the amount of precipitation and the amount of water table storage variations in the Zayanderud Basin. The study also suggests that in short periods of rainfall, there is a requirement to accelerate and raise recharge through aquifer management.

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