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Relationship between groundwater level variations using Grace satellite data and rainfall

Mina Arast PhD
PhD student, Department of desert control, Faculty of Natural Resources and Earth Sciences, University of Kashan, Kashan, Iran

Abolfazl Ranjbar PhD
Associate Professor, Department of desert control, Faculty of Natural Resources and Earth Sciences, University of Kashan, Kashan, Iran
(corresponding author: aranjbar@kashanu.ac.ir)

Seyed Hojat Mousavi PhD
Assistant Professor, Department of ecotourism, Faculty of Natural Resources and Earth Sciences, University of Kashan, Kashan, Iran

Khodayar Abdollahi PhD
Assistant Professor, Department of watershed management, Faculty of Natural Resources and Earth Sciences, Shahrekord University, Shahrekord, Iran

Afshin Honarbakhsh PhD
Associate Professor, Department of watershed management, Faculty of Natural Resources and Earth Sciences, Shahrekord University, Shahrekord, Iran

Data from the Gravity Recovery and Climate Experiment (Grace) satellite and stations were used to estimate variations of the monthly groundwater level in the Zayanderud basin, Iran, over the period 2000–2018. In addition, the annual and seasonal storage of groundwater in this basin was estimated and verified using Grace satellite data, and compared with data from the previous rainfall. The results showed that the current groundwater level depends on the amount of rainfall in past years. When rainfall is on a downtrend, the trend of underground water storage fluctuations is affected by rainfall to a greater extent. In addition to the time trend, the pattern of the normalised difference vegetation index (NDVI) depends on the amount of groundwater storage variations in the Zayanderud basin. The lowest NDVI (0·078) in 2016 coincided with the lowest amount of underground water storage and recharge rate (27·36 cm). Statistical correlation analysis of Grace satellite data and recorded data from wells indicated a root mean square error of 2·23 cm, a mean absolute error of 3·28 cm and a mean bias error of 1·02 cm on the seasonal scale. The results show that Grace data can provide a good understanding of long-term variations when studying the relationship between groundwater level and rainfall, especially in large basins.

Notation

C_i	calculated value
M	mean of observed data
M_i	observed value
n	number of data points

1. Introduction

Densely populated regions of the world are facing a depletion of groundwater resources and, since the ownership rights of groundwater tables vary in different regions, it is not easy to categorise and manage underground water (Singh *et al.*, 2012). The uncontrolled development of unpolluted deep wells has been an essential factor responsible for the complexity of water table control in the Zayanderud–Isfahan basin in Iran.

It is difficult to determine the dynamics of groundwater systems at area and regional levels since monitoring water tables is both time consuming and costly. The proper management and planning of groundwater resources in the Zayanderud basin depend on an awareness of spatial and temporal changes in these resources. Therefore, the need for data on water resources in this large basin is undeniable. The installation and maintenance of monitoring equipment is very costly and the use of remote sensing techniques is thus becoming an appropriate alternative to traditional and costly techniques.

The Gravity Recovery and Climate Experiment (Grace) satellite and the Global Land Data Assimilations System (GLDAS) land surface model are two spatial techniques that provide researchers with useful information on underground water storage fluctuations. Data from Grace satellite contribute to supplementing groundwater resources budgets by supplying quantitative evaluations of comprehensive changes in water mass over time (Tregoning *et al.*, 2012). The Grace mission was triggered by the German Air and Space Organization on 17 March 2002, as a joint effort of the US National Aeronautics and Space Administration (Nasa) and the Deutsches Zentrum für Luft- und Raumfahrt. Grace is a remote sensing satellite that can estimate variations in underground water storage for the entire world based on a monthly period.

Many other researchers have used remote sensing methods for groundwater analysis. For example, Khaki *et al.* (2018) analysed changes in water table storage from Grace satellite data and rainfall measurements to study the comprehensive management of the River Nile in Africa. The results showed a strong correlation between variations in the groundwater storage and recharge rate and variations of rainfall. Castellazzi *et al.* (2018) used Grace satellite data and data from the Mexican State Water Authority to estimate the rate of groundwater discharge in central Mexico. They showed that the Grace satellite's estimation was consistent with the land-based data and was also suitable for use in water management programmes. They also revealed an increasing groundwater discharge rate and a negative trend in agricultural lands in northern Mexico. According to Banerjee and Kumar (2018), Grace satellite data show that groundwater has increased in the central and southern parts of India and Grace data are efficient enough to identify the underground water storage process. Their results indicated that rainfall is an important cause of water storage in most of these regions and shows a positive trend. Sun *et al.* (2018) showed that Grace satellite data can be used effectively to assess drought and underground water characteristics and the data are informative about the characteristics of strong and reliable droughts over vast areas. Zhou *et al.* (2016) investigated local groundwater variations at the Wuhan station, China, using Grace satellite data. Their results proved the good performance of the Grace estimation of groundwater level variations in the study area. Chen *et al.* (2016) aimed to find a method to increase the accuracy of Grace data by examining the data of this satellite in the years 2003 to 2012. The comparison of Grace groundwater storage changes indicated a trend improvement with this method. Longuevergne *et al.* (2010) evaluated Grace satellite data for an area of 200 000 km^2 over the period 2003–2007. A comparison of water storage variations obtained from the GLDAS model, Grace satellite and well data showed that Grace outperformed GLDAS in showing water change trends.

Previous studies have not demonstrated the applicability of Grace satellite data to estimate the long-term variations of water storage over a large arid area such as the centre of Iran. In the present study, Grace satellite data and the GLDAS model were used to investigate changes in the groundwater level of the Zayanderud basin, which has been suffering from a shortage of water and a decline in level over the years 2000–2018. After validating data of the changes in groundwater level obtained from the Grace satellite, the focus of this work to groundwater variations in different land uses and their effects on the normalised difference vegetation index (NDVI).

2. The study area

Zayanderud basin is between longitudes 53°24′E and 50°02′E and latitudes 31°12′N and 33°42′N in the centre of Iran. The basin covers an area of 41 518 km^2 and is located in Isfahan province and a part of the provinces of Chaharmahal Bakhtiari, Yazd and Fars. The basin has an elevation ranging from 1100 to 3970 m above sea level and comprises ultra-arid to semi-humid climates with annual rainfall in the range 95–274 mm. The minimum and maximum temperatures are 10°C and 18°C, respectively. Agricultural lands, grassland, forests, bare soil, saline lands, urban areas and wetlands are the important land uses in this basin (Ostad-Ali-Askari *et al.*, 2018) (Figure 1).

3. Data

3.1 Rainfall data

Rainfall data for the Zayanderud basin for the period 2000–2018 were obtained from the Iranian Meteorological Organization and the Regional Water Authority of Isfahan Province. In total, average monthly precipitation data were collected from 15 synoptic and rain gauge stations in this basin, identified as W$_1$, W$_2$, …, W$_{15}$.

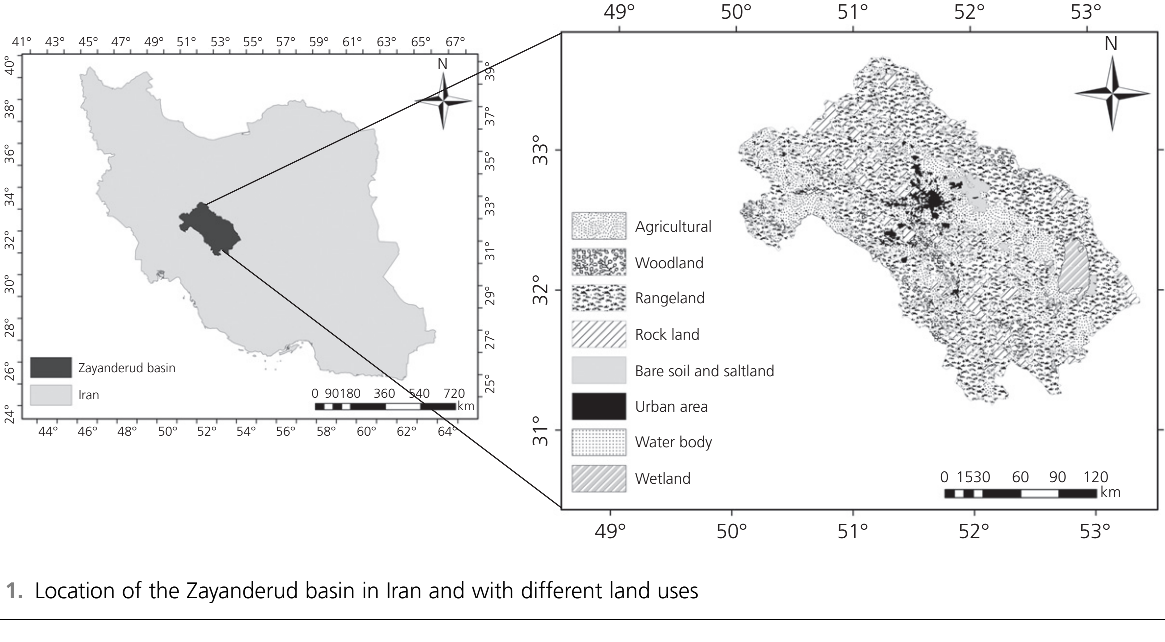

Figure 1. Location of the Zayanderud basin in Iran and with different land uses

3.2 Terrestrial water storage (TWS) data and Grace data

A scalable version of Grace processed data was used in the present study. This enabled the estimation of TWS at 1 × 1° resolution (approximately 100 × 100 km at the Equator) (Chinnasamy *et al.*, 2015a). TWS data, at monthly resolution (version RL05), are available from the website of the Nasa Jet Propulsion Laboratory (Landerer and Swenson, 2012). Relevant scale factors are also available on the internet (Podaac, 2019). It should be noted that the newly released data from Grace RLA05 reduces the errors caused by dipping and calculation mistakes, allows for higher spatial resolution and provides an assessment of large water resources such as large drainage basins (Billah *et al.*, 2015).

Information on Grace data solutions (Cheng and Tapley, 2004), one-degree coefficients (Swenson *et al.*, 2008) and glacial isostatics (Geruo *et al.*, 2013) were used to process data from the Grace download page. Monthly data were downloaded from January 2002 (data from before 2002 are not available) to December 2018. It should be noted that water derived from snow was not considered in this study because there is a just a little snowfall in a small part of the north-west of the Zayanderud basin.

3.3 GLDAS model

In this study, version 2.7.1 of the National Oceanic and Atmospheric Administration (Noaa) model was used to evaluate soil moisture in a depth range of 0–200 cm. Data on the Noaa model and other GLDAS land surface models 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 at different spatial and temporal resolutions (Chinnasamy *et al.*, 2015b).

The Noaa model data in grid format, including the monthly average of soil moisture content at spatial and temporal scales (with a resolution of 1°cell/grid/month), were similar to the Grace data.

3.4 Groundwater

Underground water storage using the Grace and GLDAS models was estimated using Equation 1 (Chinnasamy and Sunde, 2015)

$$1.\quad \mathrm{GW} = \mathrm{TWS} - \mathrm{SM}$$

where TWS is the estimated groundwater storage using Grace data (cm), SM is soil moisture data derived from GLDAS (cm) and GW is the groundwater level (cm).

Since the aim of this work was to compare the estimations of Grace and Central Ground Water Board, the monthly Grace and GLDAS grids were used to estimate the groundwater level on a monthly basis for the period 2002–2018. Data from 15 observation wells in the Zayanderud basin were used to verify the accuracy of the Grace satellite data. Because the Grace data have a spatial resolution of 1°, the pixel of Grace data was considered based on the geographic coordinates of the basin for full coverage of the area.

3.5 Statistical analysis

Pearson is used to evaluate linear correlation and Kendall can be used to evaluate either linear or nonlinear correlation. Correlation analysis can be applied to water-level data from two or more monitoring wells to determine whether or not the data are strongly associated (Lenert *et al.*, 2018)

$$2.\quad \mathrm{RMSE} = \sqrt{\frac{\sum (C_i - M_i)^2}{n}}$$

$$3.\quad \mathrm{MBE} = \frac{\sum (C_i - M_i)}{n}$$

$$4.\quad \mathrm{MAE} = \frac{\sum |C_i - M_i|}{n}$$

where C_i is the calculated value, M_i is the observed value and n is the number of data points. If these three statistics are equal to zero or close to zero, the applied method can be considered very precise. The accuracy of the method decreases as these measures move further from zero (Chai and Draxler, 2014).

3.6 NDVI

The NDVI is dependent on the amount and condition of vegetation. It is calculated from data of the red and near-infrared (NIR) bands using Equation 5 (Jin *et al.*, 2013). In this study, Modis satellite images (MOD13Q1) were used to calculate this index using Equation 5 (Jin *et al.*, 2013).

$$5.\quad \mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{red}}{\mathrm{NIR} + \mathrm{red}}$$

4. Results and discussion

4.1 Rainfall trends

Hyetographs of monthly rainfall data covering 18 years (2000–2018) obtained from the Iranian Meteorological Organization for the entire Zayanderud basin were prepared for the studied stations (W_1, W_2, …, W_{15}) (Figure 2). The Zayanderud basin has mean precipitation of 135 mm and different climates ranging from wet to dry. Rainfall analysis for the period 2000–2018 showed that the highest average

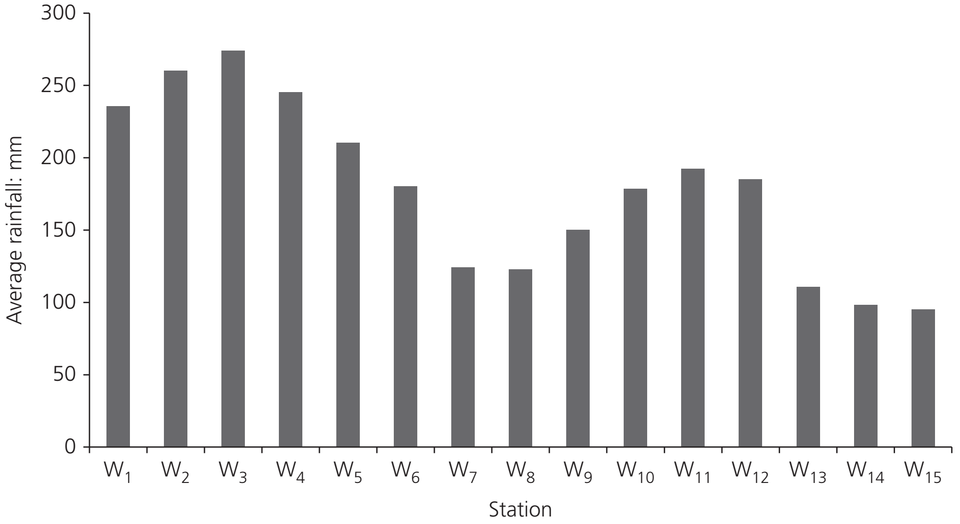

Figure 2. District-average annual rainfall in the Zayanderud basin (2000–2018)

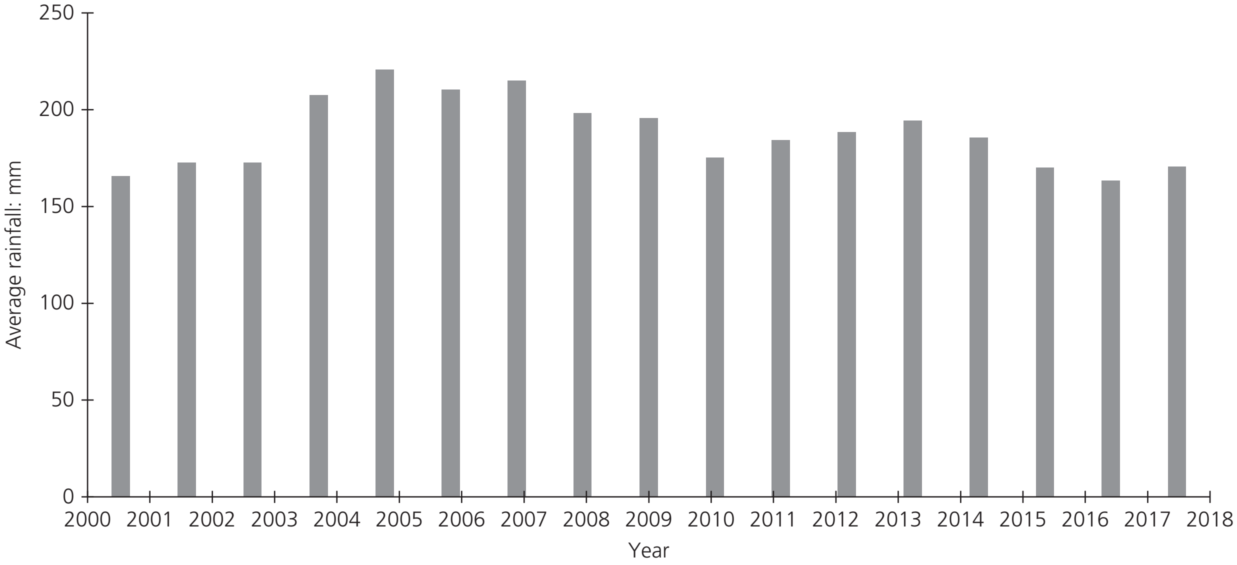

Figure 3. Average rainfall in the Zayanderud basin (2000–2018)

precipitation was 274 mm (W_3) and the lowest was 95 mm (W_{15}), with the average rainfall being about 185 mm. During this period, the lowest rainfall was about 155 mm (in 2000 and 2001) and the highest was 220 mm (in 2006) (Figure 3).

4.2 State-level groundwater storage anomalies

An overview of underground water storage variations in the basin is presented in Figure 4 for the month of February (the end of the winter rainfall period for the Zayanderud basin) over the period 2002–2018. In this study, groundwater storage is interpreted with a positive value; if the storage is more or less than moderate, it will be interpreted to be negative. Figure 4 shows a negative trend after 2004. This may indicate that the underground water storage gradually changed to negative, meaning that the process of underground water storage in this basin depends on the previous moisture state.

4.3 Effect of rainfall on variation of groundwater storage

The precipitation data were compared with estimations of the net reserves of groundwater in order to analyse the effect of rainfall patterns on groundwater storage fluctuations (Figure 5). The net groundwater storage and the difference in groundwater estimation by Grace data was similar between

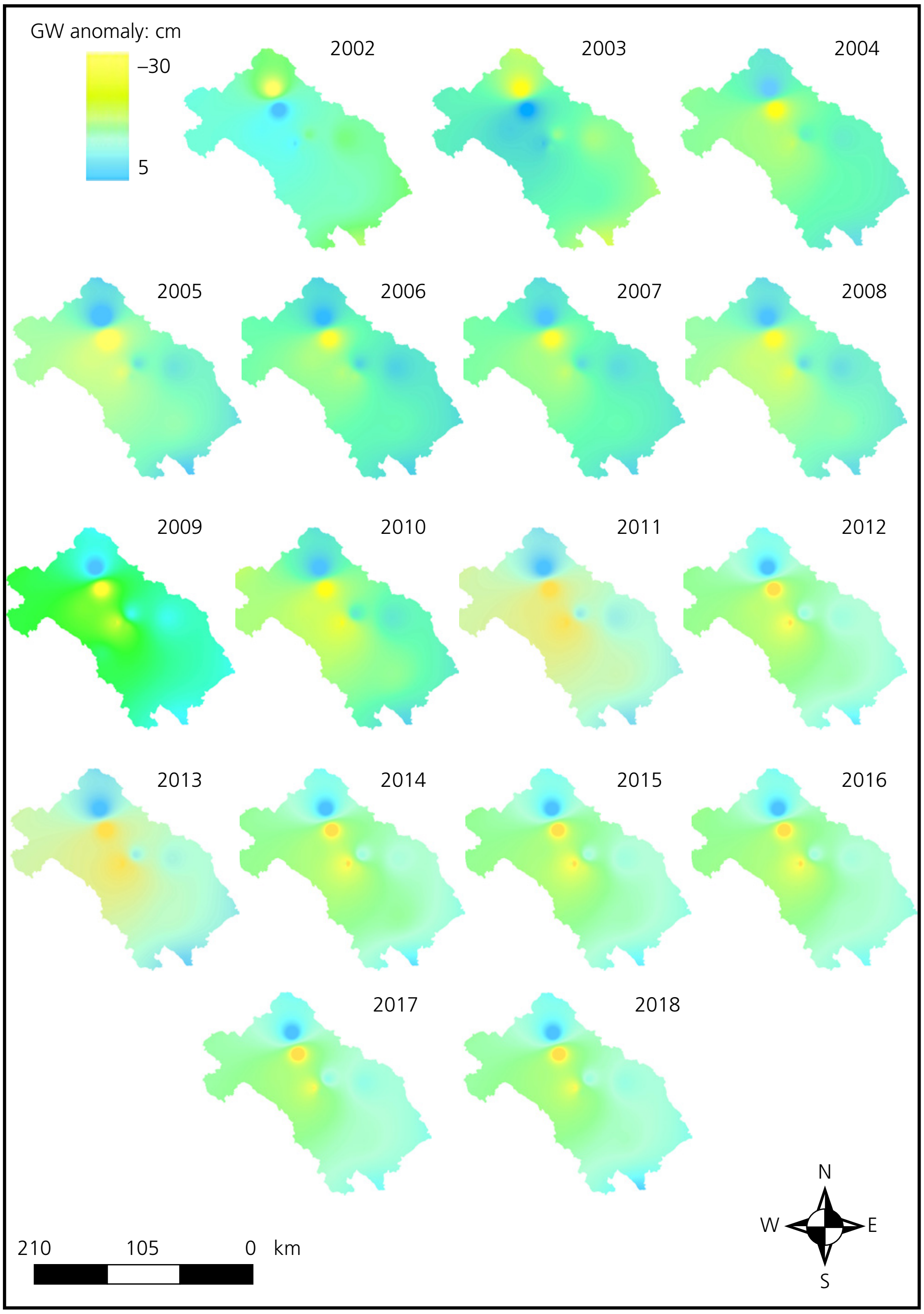

Figure 4. Assessment of water table store for the Zayanderud basin according to Grace satellite data (2002–2018)

February (the last of the winter precipitation) and September (the last days of summer) for each calendar year.

As the Grace mission began in 2002, Grace data for the period 2000–2001 are unavailable. The dry period during 2002 and 2003 (the lowest rainfall in the study period) corresponded to lower groundwater storage in the basin and drying of the Zayanderud River. This trend remained constant until 2006. Figure 5 shows a gradual improvement in underground water storage after an average rainfall of about 10 mm in 2004 and 2005. The delay in the aquifer response to the increased rate of rainfall in 2005–2008 can be explained by the fact that, during the widespread drought period, the soil profile was dry and rainfall increased the storage in 2005–2008. Subsequent rainfalls caused drainage under the soil profile and recharged the aquifer (Cai *et al.*, 1994). In other words, after several

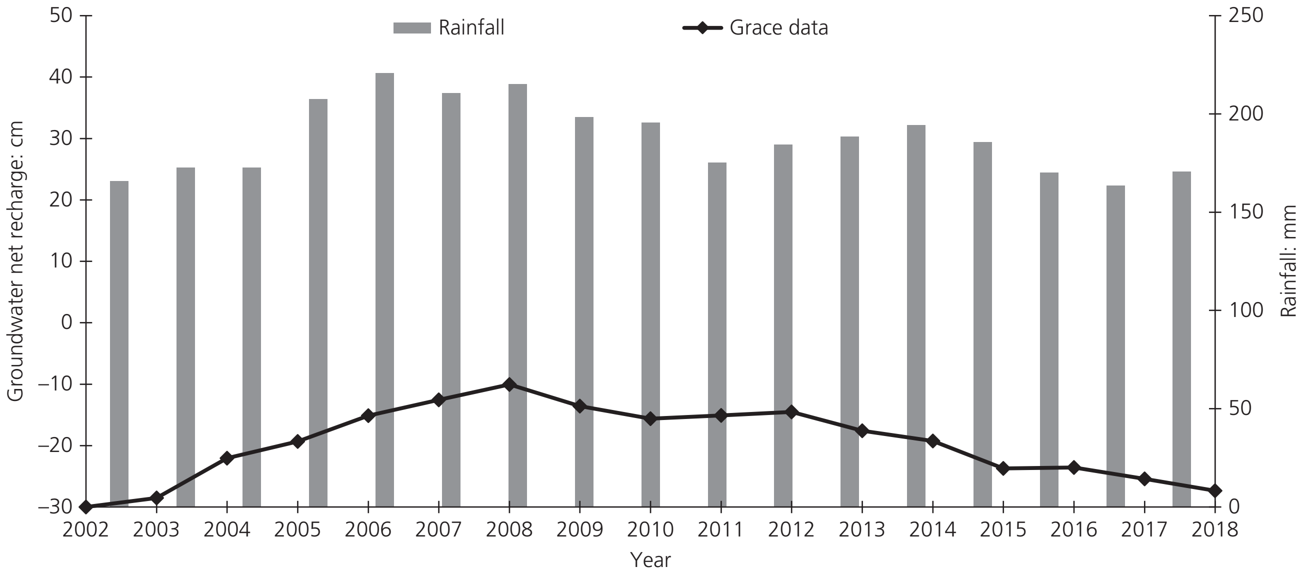

Figure 5. Comparison of annual mean rainfall and groundwater net recharge (Grace data)

years of continuous drought, a longer recharging period will be required even when several relatively wet years are experienced.

The controlled recharge structures of an aquifer can play an important role in absorbing rainfall and maintaining it below the surface, and an increasing rate of absorption leads to an increase in groundwater recharge and water storage.

From 2009 to 2012, with a further decline in rainfall compared with previous years, storage and recharge was disrupted and showed a constant trend. Due to the limited rainfall until 2018, there was a slowdown in underground water storage. Therefore, the pure recharge process of underground waters follows disorders in precipitation. The results also show that the Grace data provide insight into how groundwater levels fluctuate with rainfall over a long period of time (18 years) over large areas.

Chinnasamy and Agoramoorthy (2015) studied the effects of rainfall fluctuations on Grace groundwater levels and showed that, during the period 2002–2013, the net underground recharge process was dependent on precipitation and followed its changes. Maheshwari *et al*. (2014) also demonstrated the role of rainfall enhancement in storing and increasing groundwater levels in Gujarat and Rajasthan, India, over the long term. In a study of underground water changes in the River Nile in Africa, Khaki *et al*. (2018) showed a negative trend in underground water storage due to significant rainfall over the previous decade and extensive irrigation in this region. The results of all these studies are consistent with the results of the current research.

Grace data provide net volumes of water table reserves. For the studied basin, the difference between the maximum and minimum storage of groundwater extracted from Grace data (from 2002 to 2018) was found to be approximately 14 cm in height if groundwater recharge methods and facilities are suitable. This important finding has potential for the storage of groundwater in the Zayanderud basin.

4.4 Relationship between Grace results and GLDAS model

A statistical analysis of the data on water storage and groundwater level variations is provided in Table 1. The GLDAS data were estimated higher than the Grace data (to be 0·16 cm) and the RMSE was estimated to be 1·13 cm in between the two series of data. In present study, the results of the correlation of Pearson and Kendall between water storage variations according to the GLDAS model, the Grace satellite data and observation data showed correlation coefficients of 0·45 and 0·41, which were statistically significant..

According to the statistical analysis and indicators, the Grace data has good accuracy. From statistical analysis of data on the variations of water storage obtained from the Grace

Table 1. Statistical analysis of data on the variations of water storage and groundwater level (cm)

	RMSE	MAE	MBE
Change in water storage (monthly), Grace – GLDAS	1·13	2·42	0·16
Groundwater level change (seasonal), Grace – wells	2·23	3·28	1·02

satellite data and the computational quantities of the GLDAS model at the monthly scale, Moiwo *et al.* (2012) found the RMSE to be 26·7 mm. Ramillien *et al.* (2008) evaluated Grace satellite data from 2002 to 2006 for the Amazon basin. Data from two stations in the basin were also used and, after correction of the Grace satellite data, the trend in groundwater level variations was evaluated. The results of that research indicated that the estimated Grace data were equal to ±400 mm compared with the station data in the Amazon basin. The results also showed that the final results were highly dependent on how Grace data were modified.

4.5 Comparison of changes in groundwater level from observation wells and Grace data

The variations in groundwater level at the observation wells and those estimated using Grace satellite data were compared. Considering that the Grace satellite provides data on the total amount of water change, including total groundwater, soil moisture and surface water, it was necessary to subtract the total soil moisture and surface water from the values of the water reserve variations estimated by Grace in order to convert water reserve variations into groundwater level variations.

Figure 6 shows the seasonal variations in average groundwater level according to Grace data and observations for the period 2002–2018. During the period 2002–2005, the trends were roughly the same, but in 2006–2009, which coincided with reduced rainfall and drought (Figure 3), the results showed a time delay.

Statistical analysis of data from the Grace satellite and the observation wells indicated a RMSE of 2·23 cm, a MAE of 3·28 cm and a MBE of 1·02 cm on a seasonal scale (Table 1). The positive value of the MBE represents an overestimation of the amount of groundwater level variations obtained from the Grace satellite relative to the observational data. The variations in the water table level and increases in the water level were also found to be more evident in winter than in autumn. The trends of underground water change were roughly the same, but the Grace satellite data indicated that the trends were more intense in some years (2006, 2007 and 2018).

4.6 Changes in groundwater net recharging for different land uses

The net recharging of groundwater according to Grace estimations for different land uses is shown in Figure 7. Water supply in the years 2002 to 2004 was almost constant for all the studied land uses. The variations for agricultural land in 2005 showed a greater change than the base average, with net recharge rate decreasing by two times in agricultural lands in 2005 compared with 2004. There were no significant changes for other land uses compared with the base average. Despite the increase in rainfall in 2005 (Figure 5), the decline in water savings can be attributed to increased irrigation and more water consumption: the increased groundwater withdrawals for agricultural lands did not allow for water recharge and retention. This trend continued until 2009 and intensified as rainfall declined in 2012–2018. Wetland and woodlands also showed a significant drop in net recharging in 2009 and 2010, respectively.

4.7 Effect of groundwater storage changes on the NDVI

To investigate the effect of the Grace-estimated groundwater storage changes on vegetation, NDVIs were calculated and the results are shown in Figure 8. It is clear from Figure 8 that

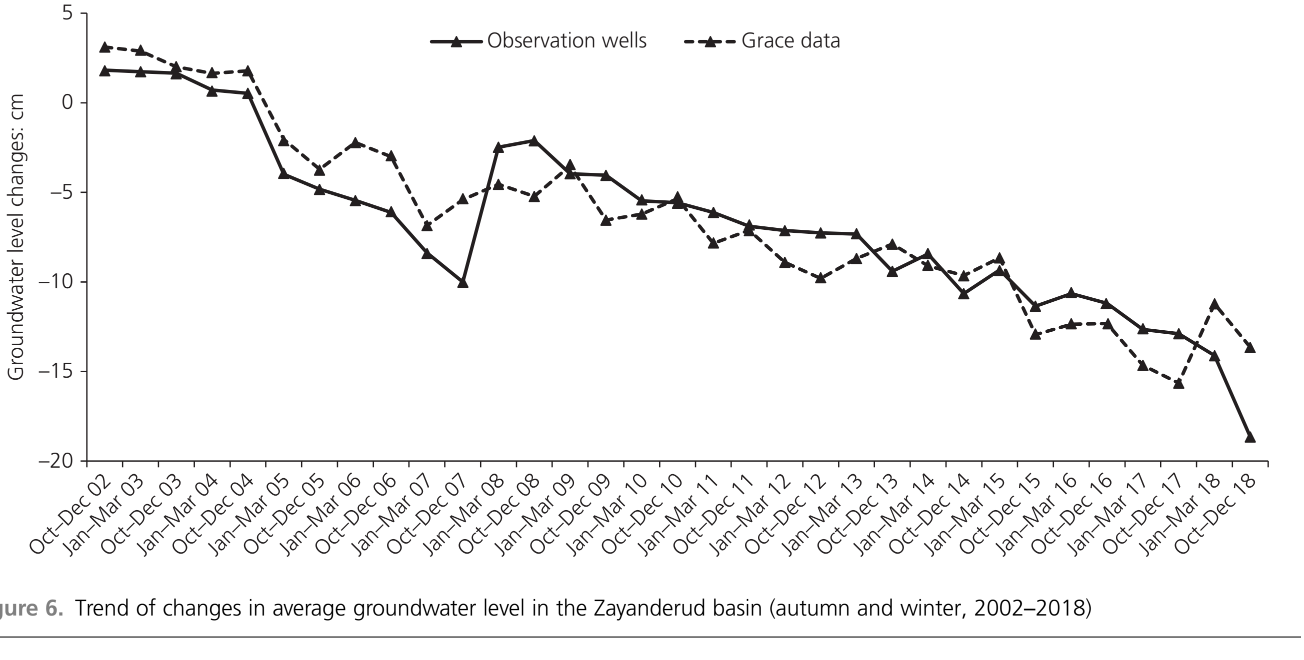

Figure 6. Trend of changes in average groundwater level in the Zayanderud basin (autumn and winter, 2002–2018)

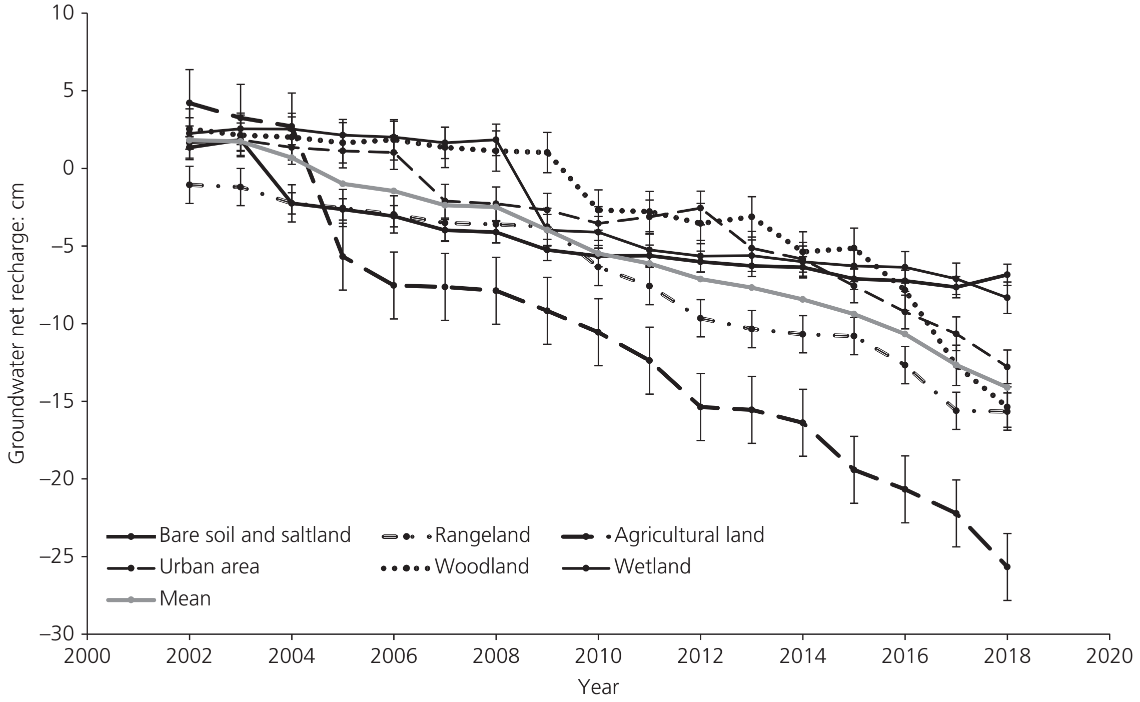

Figure 7. Variation in Grace data for different land uses (net annual water table recharge) in the Zayanderud basin; the bars indicate standard error

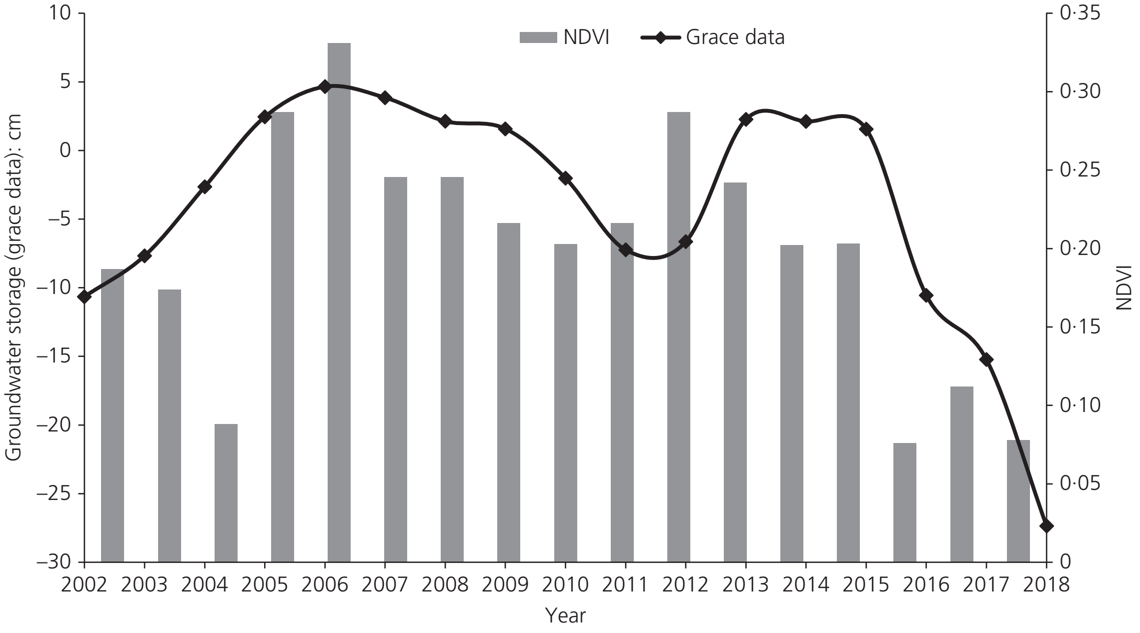

Figure 8. Comparison of groundwater storage change according to Grace data and the NDVI

the NDVI was enhanced with increasing water supply in the Zayanderud basin. In the period 2005–2008, with increased rainfall, both the recharge rates and NDVI increased. From 2008, the NDVI showed a decline, resulting in a reduction in water reserves. The highest NDVI (0·331) was observed in 2006 with the highest groundwater storage of

4·65 cm. There is thus a direct connection between groundwater and vegetation.

Aguilar *et al.* (2012) also showed that NDVIs are lower in dry years than in wet years due to the removal of more groundwater. The results are consistent with the findings of Chen *et al.* (2014), who showed that rainfall changes had an effect on groundwater storage and groundwater storage changes would the NDVI.

According to these above results, the time course of the NDVI model depends on the amount of rainfall and the amount of water table storage variations in the Zayanderud basin.

5. Conclusions

The basic objective of this study was to evaluate the overall remote estimation of water storage from Grace satellite data in order to estimate groundwater table storage changes in the Zayanderud basin, Iran. It was found that use of Grace data provides a reasonable estimate of groundwater storage for different land uses. Analysis of the data revealed that the process of underground water storage depends on the rainfall in previous years and therefore on the previous moisture state. In addition, in the case of drought, water table storage does not respond to rainfall quickly but changes incrementally over time. When rainfall shows a descending trend, underground water supply fluctuations are heavily dependent on the precipitation trend. In addition, the time course of the NDVI pattern depends on the amount of precipitation and the level of water table storage changes. The results of this study also suggest that, in short periods of rainfall, it is necessary to accelerate and raise recharge through aquifer management.

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