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Water Resources in Arid Areas: The Way Forward

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Satellite-Based Estimates of Groundwater Storage Changes at the Najd Aquifers in Oman

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Abstract The Najd aquifers in Oman, are located in one of the most arid zones in the world. In such regions, there is a shortage in the water resources where groundwater is a very critical component for human life. The main aim of this contribution is to use the satellite remote sensing data of the Gravity Recovery and Climate Experiment (GRACE) along with the Global Land Data Assimilation System (GLDAS), to estimate the groundwater storage changes at the Najd aquifers. Groundwater storage changes were calculated from both GRACE/GLDAS data and from the groundwater level measurements. It was found that the estimated groundwater storage changes from GRACE and water levels coincide in their trends showing a noticeable depletion within the time period from Oct. 2002 to Sept. 2014. The spatial distribution maps of the groundwater storage changes show slightly changes from Oct. 2003 to Sept. 2010, but a significant decreasing were observed from 2010 to 2014. The groundwater storage over Najd aquifers was decreased by about 0.44 and 0.46 km^3/year as calculated from GRACE data and

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groundwater levels, respectively. We also found that groundwater storage was affected by the strong storm events as observed in 2007 and 2010. This contribution could be helpful for the long term sustainable groundwater management in the study area and other arid regions.

Keywords Groundwater storage changes · GRACE · GLDAS · Najd aquifers · Oman

1 Introduction

The Najd aquifers are very crucial groundwater resources for Oman, therefore, an understanding of the groundwater variability is needed in order to determine the sustainability of such groundwater in this arid region. The Najd area has been categorized as one of the most aridity regions over the world, and contains about five towns and thirty villages with a population of about 21,000 residents (PAWR 1986). Generally, most of the arid regions are suffering from the scarcity of water resources. It is anticipated that the water resources in the Middle East and North Africa will be declined within the next century due to a decrease of rainfall in the range between 10 and 25%, and an increase of evaporation between 5 and 20%, which is being associated with a surge in the water consumption demand (Bates et al. 2008).

Several research studies on groundwater resources in Oman have been carried out; e.g. Clark and Fontes (1990) has applied isotopic and geochemical methods to estimate groundwater mean circulation times. Müller (2012) focused on developing a groundwater model that offers the possibility of studying potential recharge scenarios, and Herb 2011 determined the groundwater ages through radiocarbon and tritium dating assessment of the chronology of the paleotemperature record for the Dhofar groundwater, relying on noble gas measurements. Al-Mashaikhi (2011), and Al-Mashaikhi et al. (2012), focused on the groundwater chemistry and groundwater ages as well as appraisal of groundwater recharge by using hydraulics, hydrochemical and isotope evidences. As stated by Macumber et al. (1998) that extreme rainfall events can recharge the shallow aquifer system based on the study of a cyclonic storm in autumn 1992 in the Al-Wusta region in central Oman, they also concluded that the evapotranspiration losses are small, the infiltration rate is rapid, and that cyclones can produce fresh groundwater resources under the right physical conditions. However, the previous studies discussed different issues regarding groundwater, there is a noticeable gap and critical need for evaluating of the groundwater variability and changes. This could be helpful in the sustainable management of water resources in the target region using remote sensing observations. Water resources management in the study area is still a great challenge in term of population increase, economic development and urbanization expansion, therefore it is extremely important to conduct this study to evaluate and estimate of the groundwater storage changes spatially and temporally and characterize its variability.

GRACE satellite mission (Tapley et al. 2004) has been an substantial step forward in monitoring Terrestrial Water Storage (TWS) globally. Since April 2002, it has been offering monthly gravity field solutions, and has examined as an effective tool to infer groundwater storage changes by subtracting contributions from other components (Tiwari et al. 2009; Rodell et al. 2009; Famiglietti et al. 2011; Chen et al. 2014; Richey et al. 2015), the mass of ice sheets (Velicogna and Wahr 2006), snow mass (Niu et al. 2007), surface water storage (Kim et al. 2009), and also to hydrologic drought characterization (Houborg et al. 2012; Thomas et al. 2014).

The spatial variability of TWS is dependent and dominated by variations in ice and snow in polar and alpine regions, surface water in wet and tropical regions, and soil moisture in mid-latitudes (Rodell and Famiglietti 2001). Global estimates of the TWS can be determined by using the temporal variations in Earth's gravity field (Wahr et al. 2004). The accuracy of the recovered mass variations increases with increasing size of the monitored basin, thus, most of the studies utilizing GRACE TWS data are targeting large watersheds for hydrological research and applications (Wahr et al. 2004). Application of GRACE-based TWS at different spatial scales ranging from continents (Syed et al. 2008), to experimental watersheds (Tamaisiea et al. 2005) have been carried out with numerous hydrological purposes. Additionally, GRACE-based TWS has been examined to estimate hydrologic fluxes in water balance computations (Syed et al. 2010) and it has been also analyzed as an essential hydrologic state (Crowley et al. 2006; Syed et al. 2008). Several quantitative analyses showed consistency in the modelled and GRACE-based TWS estimates over large regions. The spatial resolution of GRACE-TWS grids is 1° in both latitude and longitude (around 111 km at the equator) (Landerer and Swenson 2012). The consistency of GRACE data in smaller areas was not satisfactory due to the spatial resolution restrictions (Seo et al. 2009).

The main purpose of this contribution is mainly to validate and examine the potential utility of the GRACE data to assess groundwater storage changes in arid environment aquifer. In order to achieve the main objective, we first derived the groundwater storage changes from GRACE-TWS anomalies and GLDAS data. Afterwards, the results are compared with the groundwater storage changes estimated from groundwater well levels during the time period from Oct. 2002–Sept. 2014. The impacts of extreme events on the groundwater storage changes were also discussed. Finally, validation of GRACE data to monitor the groundwater storage changes applied in arid regions of Oman. This could be helpful for the sustainable groundwater management in such highly demand water resources regions.

2 Study Area

The Najd Aquifers are situated in the Dhofar Governorate, Oman, and covers an area of about 88,000 km^2. The area is internationally bounded by the Kingdom of Saudi Arabia from the north, the Republic of Yemen from the west (Fig. 1). It is flat area penetrated by major wadis (valleys), small hills and sand dunes on the north

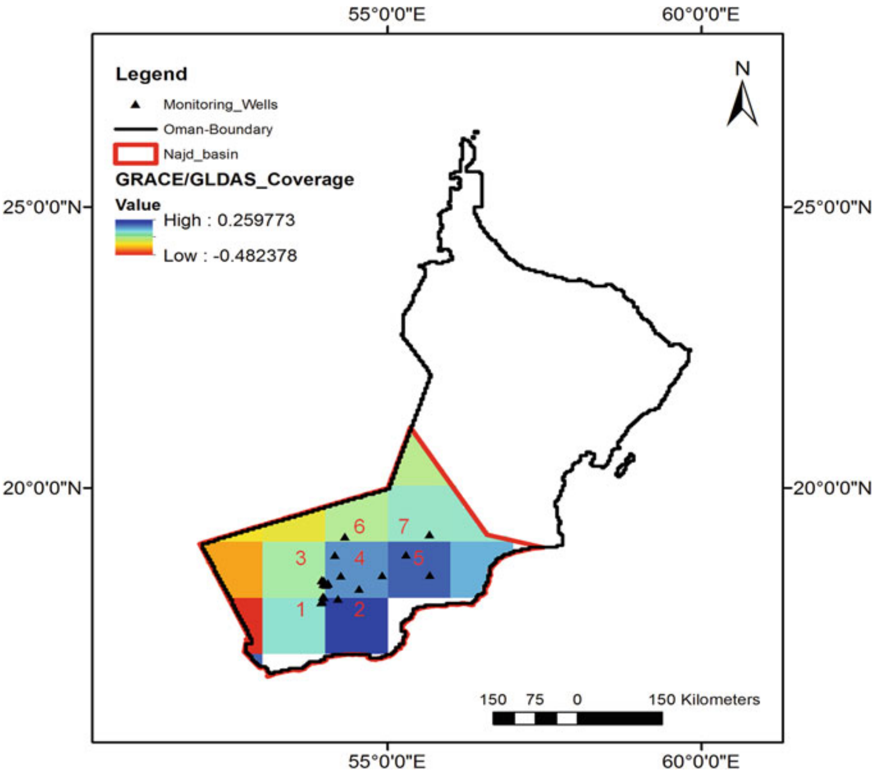

Fig. 1 Location map showing the study area of Najd aquifers in Oman, monitering groundwater wells (distribuated over GRACE/GLDAS pixels denoted from 1 to 7)

edge of the Ruba Al Khali desert (Empty Quarter desert). Vegetation is scattered and mainly consists of desert shrubs. More extensive vegetation can be found close to the Jabal chain in south (Al-Mashaikhi 2011).

Climatologically, the annual average of air temperature varies between 6.1 and 44.6 °C, with a mean of 26.2 °C. The orographic rainfall distribution controlled by the monsoon is the most responsible source of precipitation for the Dhofar area (Hildebrandt and Eltahir 2008). Rainfall amounts are generally low and variables, with annual average of about 31.2 mm, however, there some extreme events occurred in 1983, 1989, 1992, and 2007. The arid climate in the region also leads to high evaporation rates with annual averages of about 161.4 mm (Al-Mashaikhi et al. 2012).

3 Geology and Hydrogeology of the Study Area

The study region consists of alluvium deposits and geological formations of the Fars Group and the Hadhramaut Group (Roger et al. 1992). The area is influenced by several faults, which take the general direction southwest to northeast. The layers thicknesses are increased to north or northeast direction, however, these layers are thinning to the west of the study area nearby the boundary of Yemen, and increase towards north and northeast (Al-Mashaikhi 2011).

The Najd groundwater basin is separated into four aquifers categorized from the top to the bottom as A, B, C, and D as originally presented by Hydrotechnica (1985), and afterwards these categories were used by Mott MacDonald International (1991, 1994), PAWR (1986), and MWR (2000). Then, Al-Mashaikhi et al. (2012) stated that A aquifer consist of Rus, Dammam formation and other layers, but The aquifers of B, C and D are confined and comprised of Umm-Er-Radhuma (UER) formation. Some of the previous researches revealed that groundwater at Dhofar area was recharged during the humid times in the last 25,000 years (e.g. Al-Mashaikhi 2011; Clark and Fontes 1990). Al-Mashaikhi (2011) found that the monitored data reveals that water levels are declining in all aquifers, and the groundwater flow direction were determined based on the water levels contour maps showing the flow from south and southwest towards north and northeast.

4 Data Processing and Methodology

4.1 GRACE Products

GRACE is a collaborated satellite gravimetry mission between US and Germany that measures variations in the Earth's gravity field (Tapley et al. 2004). During the past decade, it has been the most frequently exploited satellite for TWS estimates. GRACE data have been utilized to assess water storage changes at global and regional scales as documented for several regions (e.g., Rodell et al. 2007a, b; Awange et al. 2008; Forootan et al. 2012, 2014).

In this paper, the scaled version of GRACE data processed and archived by Landerer and Swenson (2012) were used (http://grace.jpl.nasa.gov/data/get-data/monthly-mass-grids-land/). This enabled the calculation of GRACE TWS at (1° × 1°) spatial resolution. TWS data are also available in monthly temporal resolution (ver. RL05 (CSR): http://grace.jpl.nasa.gov/data/get-data/monthly-mass-grids-land/), as well as the corresponding scaling factors. Additionally, the scaling factors were provided for GRACE data errors correction, for instance, the leakage errors due to signal leakage from neighboring grids, and measurement errors due to raw GRACE data processing. In order to correct TWS estimates at the target region, the GRACE pixels were multiplied by the corresponding scaling factors. Currently, the released RL05 GRACE products enhance the spatial resolution and alleviate the data errors. This assisted to analyze groundwater storage changes at regional district (Tiwari et al. 2011; Huang et al. 2015) and for watershed scale (Billah et al. 2015) with spatial areas in the range from 30 to 7000 km^2. In the present research, GRACE TWS data are used with consecutive years starting from Oct. 2002–Sept. 2014.

4.2 Global Land Data Assimilation System (GLDAS)

GLDAS data was introduced and sponsored by NASA Goddard Space Flight Centre (GSFC) and the National Oceanic and Atmospheric Administration (NOAA) to calculate the variations in both ocean and land mass fluxes (Rodell et al. 2002, 2004, 2007a, b, 2009). GLDAS NOAH Ver.1 (http://gdata2.sci.gsfc.nasa.gov/daac-bin/G3/gui.cgi?instance_id=GLDAS10_M) were downloaded and processed to estimate the TWS components (e.g. Soil moisture and surface runoff). GLDAS NOAH are available at spatiotemporal scales (1° pixels and monthly resolutions). The total Soil Moisture (SM) was estimated as the total summation of soil moisture values of 4 layers: (0–10, 10–40, 40–100, and 100–200 cm). The total soil moisture (SM) was then subtracted from GRACE TWS to calculate groundwater storage changes (Eq. 1).

4.3 Groundwater Storage Anomalies Estimation from GRACE/GLDAS Data

We utilized GRACE TWS estimates to evaluate the groundwater storage changes. The water components of GLDAS such as surface water and soil moisture storage were subtracted from the GRACE data. Since Oman can be considered as an arid country, the contribution of snow component has not been considered in the calculations. Therefore, the total water storage change on land (ΔS_{TWS}) can be represented by the following equation (Eq. 1). This equation can be re-arranged to be quantified to estimate the groundwater storage changes (Eq. 2). The 1° × 1° spatial and monthly temporal resolutions of GRACE TWS data and GLDAS data were averaged to calculate annual values within the time period Oct. 2002–Sept. 2014. Then, Soil Moisture and surface runoff anomalies were estimated by subtracting the average over the time period (Oct. 2002–Sept. 2014) from the soil moisture values for every month. The annual groundwater storage anomalies were then obtained by using Eqs. (1) and (2).

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

$$\Delta S_{GW} = \Delta S_{LAND} - (\Delta S_{SW} + \Delta S_{SM}) \quad (2)$$

where ΔS_{TWS} is annual TWS anomlies, SW is surface water, SM is soil moisture and GW is groundwater storage. The GRACE TWS grids were multiplied by the dimensionless scaling factors grids.

4.4 Groundwater Storage Anomalies Estimates from Groundwater Levels

Monthly groundwater levels data were collected from the Ministry of Regional Municipality and Water Resources (MRMWR), Oman. The provided data were monthly data (four measurements every year) from 2002–2013, but there are some missing years (Oct. 2006–Sept. 2009) and (Oct. 2006–Sept. 2009). The monthly data then were averaged for annual level estimates (Oct. 2002–Sept. 2014). About 25 groundwater wells were selected for the availability of the data (Fig. 1). We compared the calculated GRACE groundwater storage changes from GRACE/GLDAS data and from in situ groundwater level observations in the study area to examine the potentiality of using GRACE TWS data for deriving estimates of groundwater storage changes were evaluated by. The Groundwater storage anomalies were calculated from GRACE/GLDAS data as addressed in the previous parts, and also from groundwater wells. The available wells in the study area were 25 wells distributed over only 7 GRACE/GLDAS pixels (Fig. 1), where only (3, 1, 10, 7, 2, 1, 1) wells over Pixels (1, 2, 3, 4, 5, 6, 7) respectively. The anomalies of groundwater storage were calculated by multiplying the groundwater levels anomalies by the specific yield average range of 0.3–0.5% for the Najd aquifers. The specific yield values were highly variable in the previous researches, they used specific yield to be 0.7–5.9% (GRC 2008), and 0.5% around Helat Ar Rakah (JICA 1989). According to SAWAS model, it was estimated as 1%, but in other cases, it was estimated as 2 and 10% for the volcanic and alluvium aquifers respectively (SAWAS 1996). Additionally as stated in GRC (2014), the specific yield should not exceed 1% in the aquifer.

5 Impacts of Precipitation on GRACE TWS Anomalies

Based on some availability precipitation data at the weather station of Thumrait that located at about 80 km north of the Salalah Airport, Oman, we used precipitation data within the time period from 2002 to 2009 (collected from Al-Mashaikhi 2011) to evaluate the relationship between GRACE TWS anomalies and groundwater storage anomalies with precipitation anomalies (Fig. 2a, b). It was noticed that there are impacts of extreme rainfall events on GRACE TWS and groundwater storage

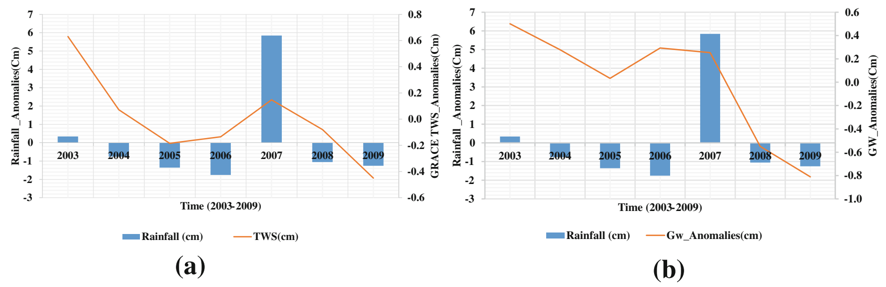

Fig. 2 Shows the relationship between rainfall anomalies and GRACE TWS anomalies (**a**) and groundwater storage anomalies within the time period from 2003 to 2009

changes as recorded in the storm events in 2007 where the TWS and groundwater were increased due to the impact of the 2007 rainfall at this station (Fig. 2).

6 Comparison of GRACE-TWS Estimates Versus In Situ Changes in Groundwater

In this study, we conducted the comparison between groundwater storage anomalies derived from GRACE/GLDAS and groundwater derived from in situ observations of groundwater levels at Najd aquifers. The study area of Najd aquifers are captured by about 15 of GRACE/GLDAS pixels (partial pixels). The available groundwater wells are distributed randomly over only 7 pixels (their locations are labeled from 1 to 7 in Fig. 1). For that reason, we compare the total average of groundwater anomalies derived from in-situ water levels with groundwater anomalies derived from GRACE/GLDAS by two scenarios. The first scenario is to compare the entire basin and the second one is to compare pixel by pixel. In the first case, the comparison shows an acceptable agreement (Fig. 3) between groundwater anomalies derived from both GRACE and water levels with coefficient of determination (R^2 = 85). On the other hand, the pixel to pixel comparison (Fig. 6), shows the following coefficient of determination (R^2 = 0.81, R^2 = 0.66, R^2 = 0.7, R^2 = 0.65, R^2 = 0.67, R^2 = 0.73, R^2 = 0.47) at pixels (1–7) respectively. It was noticed that the pixels covered by more groundwater wells exhibit good correlations such as in pixel numbers 1(3 wells), 3 (13 wells) and 4 (7 wells) (Fig. 3b, c, d), show some acceptable agreement such as in pixel 5 (Fig. 4b), but the pixels which covered by only one groundwater well exhibits non acceptable correlation such as in pixels number 2, 6, and 7 (Fig. 4a, c, d). Consequently, it is recommended to study the validation of groundwater changes estimated from GRACE and water levels to use enough coverage of groundwater wells. This will be useful for better evaluation and validation of the groundwater storage changes.

The comparison of groundwater storage anomalies estimated from GRACE TWS and in situ observations of groundwater wells shows that the

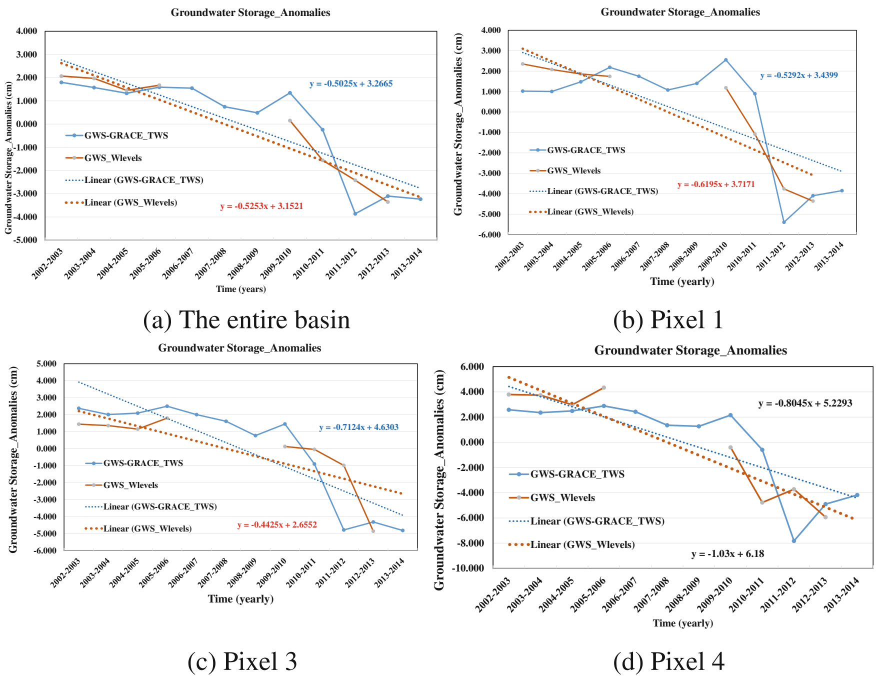

Fig. 3 Comparison between groundwater changes anomalies estimated from GRACE/GLDAS (cm) and groundwater changes anomalies estimated from observed groundwater levels (cm) for the time period from Oct. 2002 to Sept. 2014, at the entire basin of Najd aquifers (Pixels numbers are denoted as 1, 3, and 4)

cumulative groundwater storage volume over Najd aquifers has decreased by about 0.44 and 0.46 km^3/year respectively, during the time period of Oct. 2002–Sept. 2014 (Fig. 3a). These calculations were performed based on the linear regression for both groundwater storage changes curves derived from GRACE and water levels. The groundwater storage changes in the entire region shows slightly variation with very gentle declining rate from Oct. 2003 to Sept. 2007, then starts declining until Sept. 2009, but from Sept 2009 to Sept 2010 the groundwater storage increased. Afterwards, the storage decreased with very steep declining rate until the end time of the analysis. We found form this analysis that the groundwater storage changes have two main stages, the first stage is exhibiting slight declination in the total groundwater storage in the whole region from Oct. 2002 to Sept. 2010. Within this stage, we noticed the occurrence of two uprising peaks of groundwater storage at 2007 and 2010 (Fig. 4d), this might be due to the flash floods impacts as observed during these two years, there are extreme rainfall events, as well as strong cyclones. On June 6, 2007, Tropical Cyclone Gonu has hit the Gulf coast of Oman. At that time, the greatest storm had lost significant power and was considered as a category 1 cyclone. Also, Cyclone Phet with a Category 3 storm had hit Oman and Gulf of Oman on June 4, 2010 (http://earthobservatory.nasa.gov/IOTD/view.php?

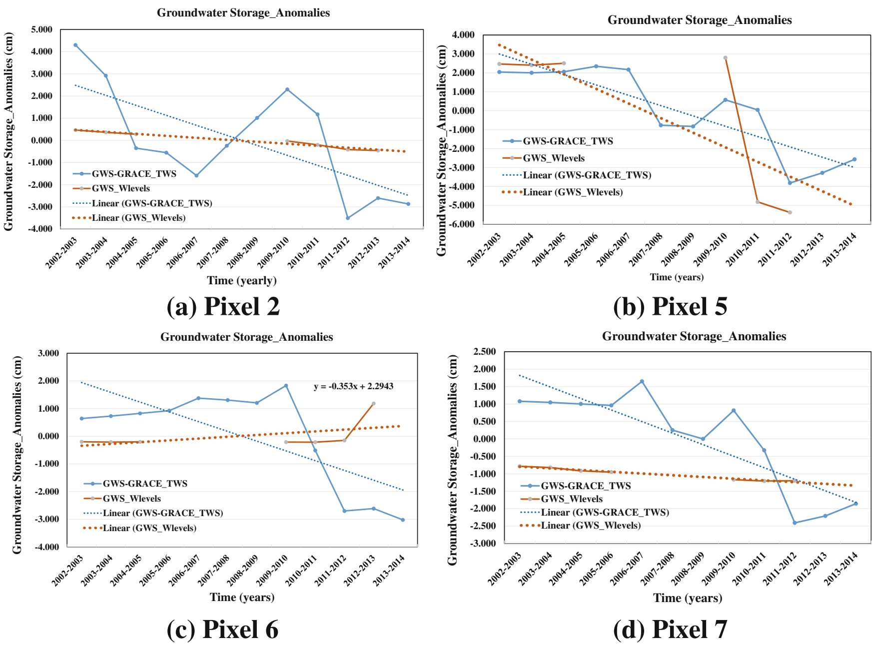

Fig. 4 Comparison between groundwater changes anomalies derived from GRACE/GLDAS (equivalent thickness in cm) and groundwater changes anomalies derived from observed groundwater levels (cm) for the period from 2002 to 2014, at pixels numbers (2, 5, 6, and 7)

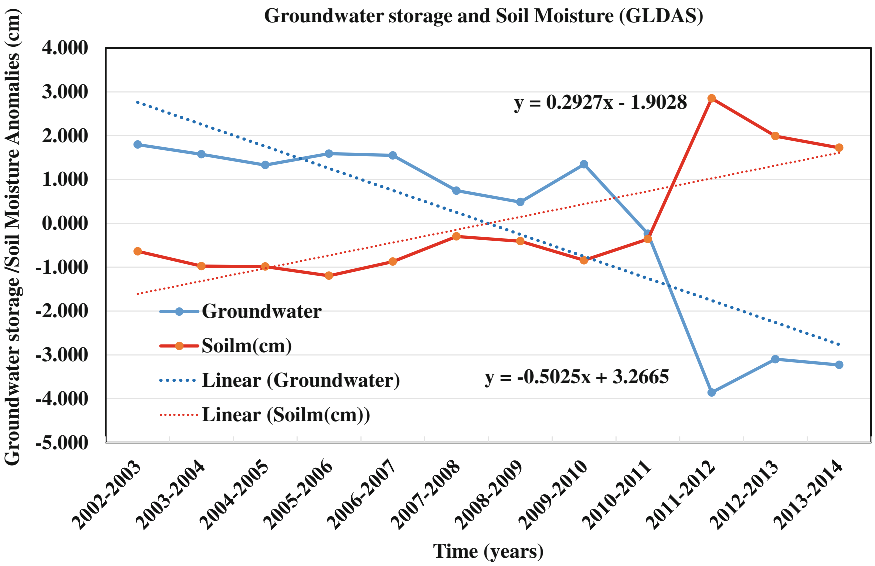

Fig. 5 The relationship between groundwater storage anomalies and soil moisture anomalies at Najd Aquifers

id=44189&eocn=image&eoci=related_image). In the second stage, we noticed that the groundwater storage changes was showing a significant declining rate indicating a great lose in the groundwater storage in this region, and then start slightly to increase in 2013. This might be due to groundwater over-drafting for the agriculture and domestic activities in the region. Additionally, Fig. 5 shows the relationship between groundwater storage and soil moisture anomalies estimated from GLDAS data. It was noticed that total water storage was significantly decreased but soil moisture was increased which might be due to increasing the agriculture activities at the region especially after 2010 as stated by GRC (2014).

7 Groundwater Distribution Maps Over Najd Aquifers

The spatial distribution maps of the groundwater changes were conducted in order to understand the spatial variability over Najd aquifers. As we noticed in the temporal analysis for groundwater storage changes in the time period from Oct. 2002 to Sept 2014, we observed that the distribution maps over the study area exhibit stability or slightly changes within the time from Oct. 2006 to Oct.

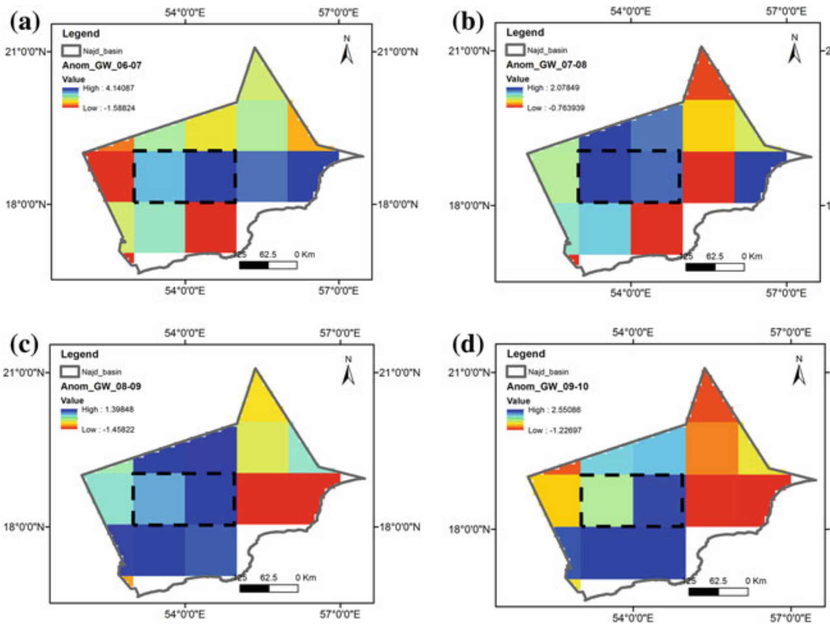

Fig. 6 Spatial distribution maps showing the changes of groundwater storage at Najd aquifers within the time periods: **a** Oct. 2006–Sept. 2007, **b** Oct. 2007–Sept. 2008, **c** Oct. 2008–Sept. 2009, and **d** Oct. 2009–Sept. 2010. The selected two pixels (*black rectangular*) exhibit that the groundwater storage is slightly increasing of keeping in steady conditions

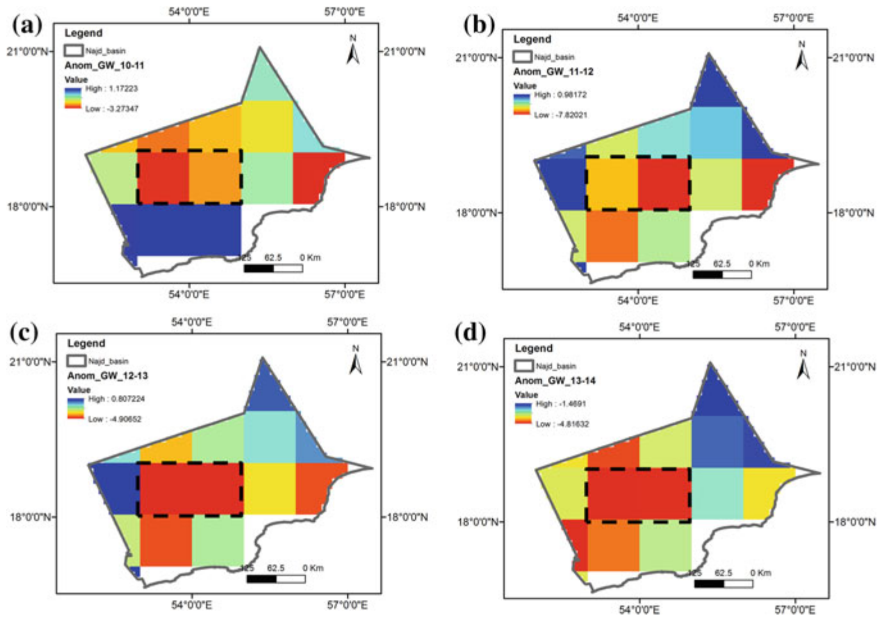

Fig. 7 Spatial distribution maps showing the changes of groundwater storage at Najd aquifers within the time periods: **a** Oct. 2010–Sept. 2011, **b** Oct. 2011–Sept. 2012, **c** Oct. 2012–Sept. 2013, and **d** Oct. Oct. 2013–Sept. 2014. The selected two pixels (*black rectangular*) exhibit that the groundwater storage is showing dramatic decreasing within after 2010 until 2014

2010 (Fig. 6) as shown in pixels 3 and 4 (black rectangular). Also, we found that the changes of groundwater storage shows significant decrease (Fig. 7) at the same pixels (3 and 4) after 2010 until 2014, and this might be due to the extraction of Groundwater from agricultural wellfield in Hanfeet area as observed by GRC (2014).

8 Conclusions

Evaluation of the potential utility of GRACE TWS/GLDAS datasets to estimate or monitor the groundwater changes was conducted. The groundwater storage anomalies estimated from GRACE/GLDAS data were successfully compared with and groundwater storage anomalies derived from in situ groundwater levels showing a reasonable correlation. It was found that the groundwater storage at the study region of Najd aquifers showing declining in the groundwater storage with the time period from Oct. 2002 to Sept. 2014. The comparison have done between the total average of ground levels with the entire groundwater anomalies derived from GRACE revealing good agreement in the decline trends with a correlation about (R^2 = 85), and the cumulative groundwater storage volume over Najd aquifers has decreased by about 0.44 km^3/year using the GRACE TWS data, and about 0.46 km^3/year from groundwater levels during the same time period. Also, the correlation between GRACE pixels and the corresponding groundwater well pixels showing that the correlation is reasonable and acceptable if the groundwater wells coverage is enough number with good distribution over the pixels (e.g. coefficient of determination (R^2 = 0.7, R^2 = 0.65) (Pixels numbers 3 (13 wells) and 4 (7 wells)) respectively. It was also observed that the groundwater storage changes in the study area has been affected by the flash floods events as noticed in 2007 and 2009. Additionally, the time series analysis and spatial distribution maps of the groundwater storage changes over the study area show slightly changes from Oct. 2003 to Sept. 2010, but after 2010 until 2014, the groundwater storage changes exhibit a significant decreasing over the region. This study provide results of the groundwater storage changes from satellite remote sensing data validated by the in situ observations of groundwater wells at the Najd aquifers, as well as the spatial and temporal variability data which could be helpful for the future sustainable groundwater management.

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