Engineering and Technology Journal 43 (11) (2025) 920-929

Engineering and Technology Journal
Journal homepage: https://etj.uotechnology.edu.iq

Evaluation of the dynamic variations of groundwater utilizing GRACE data for the dammam aquifer within muthanna governorate, Iraq

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HIGHLIGHTS

- Fluctuations in groundwater storage (GWS) were monitored in the Dammam unconfined aquifer.
- GSFC, JPLD, CLSM, and in-situ data were used to assess GWS in the Dammam region.
- GWS_GSFC showed the highest R^2 of 0.93, while GWS_JPLD had the lowest at 0.42.
- GWS_GSFC showed better correlation than both GWS_JPLD and GWS_CLSM.
- GSFC and JPL GWS data aligned with the highest spatiotemporal depletion zones.

Keywords:

GRACE
Groundwater
Dammam
Wells data
GSFC

ABSTRACT

Recently, the worldwide drought situation has gotten worse and is posing a serious threat to many nations, including Iraq. It is now unavoidable to use modern technologies, including remote sensing, to lessen the effects of this catastrophe. This paper aims to check the consistency of groundwater storage (GWS) derived from multiple sources utilizing remote sensing data with direct measurements in wells in the Dammam unconfined aquifer, which is situated in Al-Muthanna Governorate, Iraq. This study utilizes the water-level readings from well records from January 2008 to December 2014. The groundwater results from different combinations of Gravity Recovery and Climate Experiment (GRACE) products, Goddard Space Flight Center (GSFC) mascon, Jet Propulsion Laboratory Downscaled (JPLD), and Catchment Land Surface Model (CLSM), are calibrated and validated using statistical analysis. The findings illustrate large GWS depletion rates of GWS_W, GWS_JPLD, and GWS_GSFC at -54∓10 mm/yr, -11∓5 mm/yr, -6∓5 mm/yr, respectively. The Pearson, Spearman, and Kendall correlation reaches 0.93, 0.96, and 0.90 with a P-value less than 0.05. The highest coefficient of determination (R2) was 0.93 for GWS_GSFC, and the lowest was 0.42 for GWS_JPLD. The finding of classification of the GSFC and JPL data indicated that the GWS agrees with the spatial and temporal distributions of the highest depletion in the Dammam Aquifer. The study demonstrated that GRACE estimations can accurately reflect monthly variations in groundwater stocks, making them a valuable tool for resource managers to assess the water situation and plan sustainable water use.

1. Introduction

Iraq faces a persistent water shortage due to the country's decreased share of fresh water coming from the source, which naturally leads to a deterioration in its quality brought on by pollution and climate change. Groundwater is the lifeblood of many sectors, especially agriculture and rural regions, and is the primary source of domestic water in many rural zones. The major source of the groundwater recharge is rainfall. Progress in geodetic monitoring has assisted in a deeper comprehension of water dynamics, allowing for monitoring temporal variations in water storage and identifying their underlying causes [1,2]. Hydrological dynamics are greatly impacted by climate change [3]. Climate change poses a serious threat to the management of water resources worldwide [4]. Changing climates and excessive groundwater utilization pose previously unheard-of risks to arid and semi-arid areas. Because of environmental, climatic, and administrative factors, the effects of lack of water differ from one place to another; terrain, weather trends, and management strategies are important factors. Iraq, located in an arid to semi-arid zone, has a scorching summer and a cool winter with little precipitation, an elevated evaporation rate, and water scarcity. Therefore, groundwater is an essential strategic resource. To guarantee water security in Iraq, thorough planning and long-term investment are needed [5,6]. The demand for groundwater has increased recently due to frequent droughts and growing populations [7].

http://doi.org/10.30684/etj.2025.155523.1861
Received 06 January 2025; Received in revised form 23 March 2025; Accepted 13 April 2025; Available online 24 September 2025
2412-0758/University of Technology-Iraq, Baghdad, Iraq

For measuring the groundwater storage (GWS) fluctuation, hydrological researchers depend heavily on monitoring wells [8]. Nevertheless, it is very challenging to implement monitoring well in mountainous and arid areas, which causes severe issues related to GWS data. Variations in groundwater storage are hard to estimate, given the spatiotemporal constraints in achieving finished and accurate groundwater estimates for vast geographical regions [9]. The storage of groundwater and surface water, two crucial elements of terrestrial water storage (TWS), is significantly impacted by environmental changes [10]. Conventionally, directly monitoring hydrological variables inside the water balance equation is the foundation of the TWS measuring approach [11]. Utilizing Remote Sensing (RS) to analyze data collected from an item is an efficient method [12, 13] and beneficial for modeling different hydrological processes. However, the 2002 GRACE satellite mission and its successor, GRACE-FO, revolutionized global water storage monitoring by providing a remote geodetic approach [14]. Nevertheless, the area of study selected must be greater than 200,000 km^2 when utilizing GRACE; therefore, there are many limitations and uncertainties [15].

Both natural and man-made variables influence water resources; the primary storage sources are rainfall and river recharge, while the main outputs are evapotranspiration, surface water, and domestic consumption of water [16]. Water storage volatility may result from temperature and precipitation variations [16,17]. According to Mo et al. [18], surface water and rainfall significantly affect water storage variations. Human activities like irrigation affect water storage variation with increased evapotranspiration and groundwater abstraction [19, 20]. Moreover, rising populations increase water supply demands [21]. According to earlier studies, variations in land cover significantly impact the global hydrological cycle [22, 23]. Aquifers are a rare source of water that is especially useful in arid and semi-arid areas where water scarcity is common, and a large amount of storage space is needed. This paper attempts to monitor variations in the hydrological situation of the Dammam Aquifer, an unconfined aquifer. It is the largest source of stored water in Iraq's Western and Southern Deserts. There is an absence of studies on the potential of monitoring the aquifer's GWS variations using remote sensing technologies. This paper aims to check complying of GWS derived from multiple sources utilizing remote sensing techniques with direct measurements in wells for the Dammam Aquifer; moreover, the study highlights the temporal and spatial analysis of GWS variations at the local scale in the absence of time series for the observation wells. Utilizing statistical analysis to assess GWS derived from RS data is a unique aspect of this study. To establish groundwater management policy, classification maps help identify depletion zones. This paper contributes to establishing a database for the groundwater level that supports informed decision-making on groundwater resource management in the Al-Muthanna Governorate, especially considering the difficulties these resources face due to interconnected environmental and human factors.

2. Material and methods

2.1 Study area

The Dammam Aquifer, an unconfined aquifer, was the study area in this research. It is extended within the borders of Al-Muthanna Governorate, in the southwestern desert region of Iraq. The region expands between longitudes 43° 48′ and 46° 41′ E and between latitudes 29° 03′ and 31° 43′ N, with a total region of approximately 46928 square kilometers [24], as shown in Figure 1. The ground's surface is defined by a gradual slope that begins at about 459 m in the southwest and decreases northeastward to less than 100 m above mean sea level (m.a.s.l) [25], as shown in Figure 2. One of the most notable geological formations with substantial groundwater aquifers is the Dammam Formation, particularly those found in unconfined aquifers in the Samawah Desert region [26,27]. The study area's climate is mostly described as arid desert, with summer temperatures consistently above 40 °C and rain only falling in the winter [28].

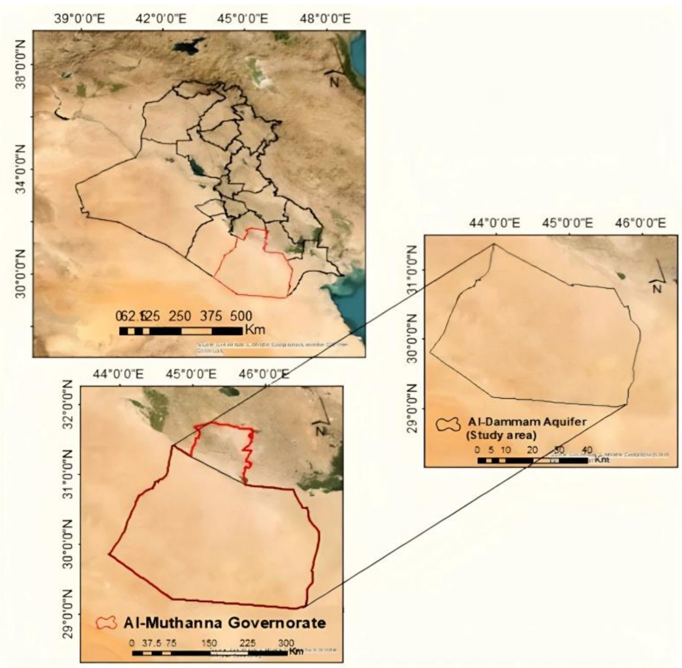

Figure 1: Location of the study area al-dammam aquifer

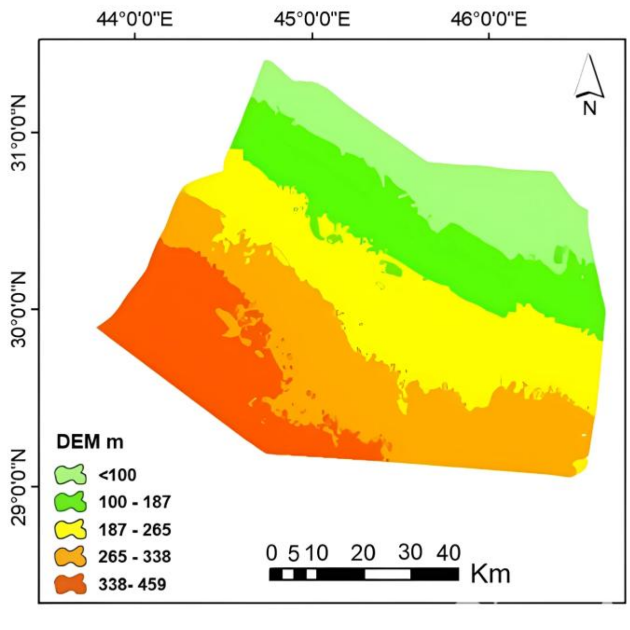

Figure 2: DEM (m) of the study area

In August, the highest recorded temperature at Al-Samawah Meteorological Station was 45.6 °C. Meanwhile, at 28.3 °C in July, the lowest temperature was recorded at its highest rate. The most precipitation was recorded in March, with 25.2 mm. Evaporation peaked in June, totaling 439.9 mm [29], in addition to winds primarily causing dunes [30].

2.2 Data sources

Estimates of monthly changes in groundwater levels from 2008 to 2014 in the studied aquifers were based on data collected from four sources, as shown in Table 1.

Table 1: Data sources utilized

No. Source	Data
1	GWS from GRACE-GSFC Mascon Data.
2	GWS from CLSM – GLDAS Model from GEE.
3	GWS from Global Mascon (CRI Filtered) from GEE.
4	GWS from in situ measurement data.

2.2.1 GRACE-GSFC mascon data

The Goddard Space Flight Center (GSFC) mascon provides access to the GRACE satellite datasets utilizing various methods [31]. GWS estimates based on GRACE satellite data were computed by subtracting non-groundwater storage components (e.g., Canopy Water (CW), Surface Water (SW), Soil Moisture (SM), and Snow Water (SW)) from TWS based on the same period [32]. This study utilized soil moisture storage at depths ranging from 0 to 2 m in the area of interest using the GLDAS model NOAH025_Mv2.1 dataset.

2.2.2 CLSM – GLDAS model

The Catchment Land Surface Model (CLSM025_DA1_D v2.2), enables climate change simulation and digitalizes land-atmosphere interactions [33]. It is based on a groundwater dynamics model stored shallowly beneath two meters of bedrock. However, it disregards the impact of human activities like pumping, reflecting the aquifer's natural variability in GWS [33].

2.2.3 Global mascon (CRI filtered) from GEE

Google Earth Engine (GEE) platform has been utilized in this study to gain GWS estimation, based on a dataset that contains gridded monthly global water storage derived from GRACE and GRACE-FO and processed at JPL utilizing the Mascon approach (RL06.1Mv03). The RL06.1Mv03 is an updated version of the previous Tellus JPL Mascon RL06Mv02. A spatial resolution of 55660 m was downscaled to 10000 m for GRACE-JPL Mascon, from 2008 to 2014.

2.2.4 In situ measurement data

The measured groundwater levels (GWL) data at 85 wells in the Dammam unconfined Aquifer for the period from 2008 to 2014, as shown in Figure 3, were provided by the General Authority for Groundwater in Iraq (unpublished data). The groundwater depths in these wells range between 8.5 to 255 m. The aquifer's depth, thickness, and permeability are crucial variables that define the ideal well placement [34], in addition to the terrain of the location [35]. The recorded static water level (GWL) was utilized to estimate the GWS derived from these wells by multiplying it with the corresponding specific yield (S_y) value Equation 1 [36]:

$$\mathrm{GWS} = \mathrm{GWL} \times \mathrm{S_y} \qquad (1)$$

The aquifer material characteristics were utilized for estimating the amount of S_y [36]. Its average was 0.01 for the unconfined zone of the Dammam Aquifer [37]. The data utilized in the study are shown in Table 2.

Table 2: Description of data utilized from 2008 to 2014

Variables	Data type	Spatial resolution	Notes
GRACE-GSFC Mascon	RL06 v 02	0.5°×0.5°	https://earth.gsfc.nasa.gov/geo/data/grace-mascons. Available format Net-CDF. Accessed on 1 October 2024.
GRACE-JPL Mascon	RL06.1Mv03	55660 m	Google Earth Engine.
CLSM025	DA1_D v2.2	27830 m	Google Earth Engine.
SMS	GLDAS model NOAH025_Mv2.1	0.25°×0.25°	https://giovanni.gsfc.nasa.gov/giovanni. Available format Net-CDF. Accessed on 1 October 2024.
SWS, CWS	GLDAS model NOAH025_Mv2.1	0.25°×0.25°	https://giovanni.gsfc.nasa.gov/giovanni. Available format Net-CDF. Accessed on 1 October 2024.
Wells in-situ	Point		

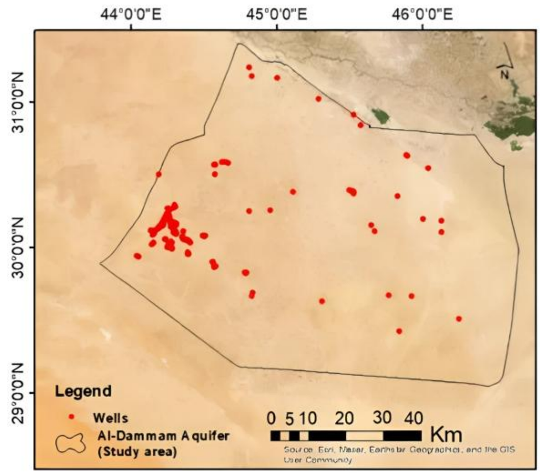

Figure 3: Location of groundwater wells in the study area

2.3 Methodology

The GEE platform was utilized to process GRACE satellite data by downscaling and computing the GWS monthly in Tiff format, following a seamless download. An ArcGIS 10.8 raster calculator was utilized to convert the data yearly. Figure 4 summarizes the adopted methodology for estimating GWS_GSFC from 2008 to 2014. The study area lacks a snow water equivalent depth. Furthermore, the components, such as canopy and surface water storage, did not have a substantial impact because their mean values were very close to zero. Therefore, they were ignored.

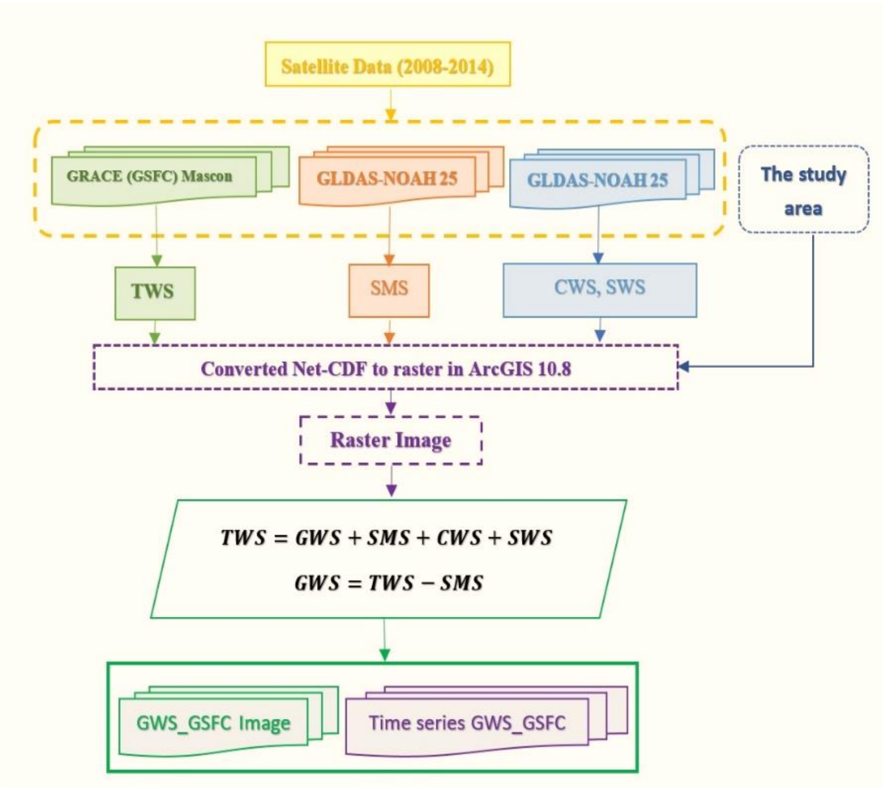

Figure 4: Methodology of estimating GWS_GSFC from 2008 to 2014

3. Results and discussion

The calculated fundamental statistics of the GRACE data in Table 3, the findings show that GRACE-JPLD and GSFC, located in an unconfined aquifer zone of the Al-Muthanna Governorate, have the highest negative GWS, at -52.99 cm and -47.67 cm, respectively. The overuse of groundwater pumping causes to decline in rainfall and an increase in evaporation, as well as activities of humans in this region, as pointed out by [38, 39]. In contrast, conversely, in GWS_CLSM, the minimum surplus of GWS +34.56 cm was found. At the same time, GSFC and JPLD have the highest deficits of -38.66 cm and -34.64 cm, respectively. But at GWS_CLSM, the maximum surplus was 50.24 cm. Thus, the arithmetic mean and median declined for the GWS_GSFC and GWS_JPLD, whereas CLSM rose. Notably, the Coefficient of Determinate (R^2) values of 0.93, 0.45, and 0.42 for the GWS_GSFC, GWS_CLSM, and GWS_JPLD, respectively. The variation between the CLSM model and the GRACE satellite data may be due to the CLSM model's unsuitability to local climatic conditions [40].

Table 3: GRACE data's fundamental statistical parameters

Parameters	GWS_JPLD	GWS_CLSM	GWS_GSFC
Minimum (cm)	-52.99	34.56	-47.67
Maximum (cm)	-43.64	50.24	-38.66
Mean (cm)	-46.55	41.92	-42.78
Median (cm)	-46.21	43.39	-42.43
Skewness	-1.50	-0.50	-0.45
Kurtosis	2.65	2.21	-2.00
Coefficient of determinate R^2	0.42	0.45	0.93
Stander Deviation	3.23	6.51	2.70
Root Mean Square Error RMSE (m)	0.33	6.2×10^{-3}	0.10

The finding illustrates the study's ability to assess groundwater levels over a small region, with a Root Mean Square Error (RMSE) ranging from 6.2×10^{-3} to 0.33 m. From a temporal perspective, the most significant temporal variability was observed in the CLSM and JPLD, with standard deviations of 6.51 and 3.23, respectively. The least variable was GSFC, which had a standard deviation of 2.70. Figure 5 compares GWS variations of the wells data and RS data in the water level of the Dammam Aquifer. The time series reveals a high concordance between the spatiotemporal fluctuation in GWS obtained from GRACE data (JPLD, GSFC, CLSM) and direct measurement data from in-situ wells from 2008 to 2009 and from 2012 to 2014, where GWS continued to decline in the aquifer, according to this data. Due to the region's proximity to the Kingdom of Saudi Arabia and its shared aquifer, variations in groundwater levels in wells may be caused by regional or international groundwater fluctuations.

According to the GRACE satellite data, the histograms, shown in Figure 6, the distribution of probabilities of the GRACE data is either normal or inclined to be such. Skewness values for GSFC and CLSM are minimal (-0.5 < Skewness < 0.5), with the exclusion of JPLD, which illustrates a value < - 0.5, indicating a negatively skewed distribution. Furthermore, all Kurtosis numbers are modest < 3 and negative, suggesting a Platykurtic distribution with light tails or no outliers. The GWS_W's depletion rates are higher than those of the GWS_JPLD and GWS_GSFC, as shown by depletion trends of -54±10, -11±5, and -6±5 mm per year, respectively. Thus, the RS data GWS_JPLD and GWS_GSFC trend were negative, which also matches those submitted by [38, 41, 42]. The negative trend in the study area is closely associated with groundwater extraction rates that exceed recharge rates to support agricultural activities, threatening the sustainability of water resources; researchers [38, 39, 43] attribute these declines to the drought in late 2007 in Iraq. Table 4 illustrates the correlations between the GWS derived from GRACE and GWS_W according to the findings of the Pearson, Kendall, and Spearman correlation analyses.

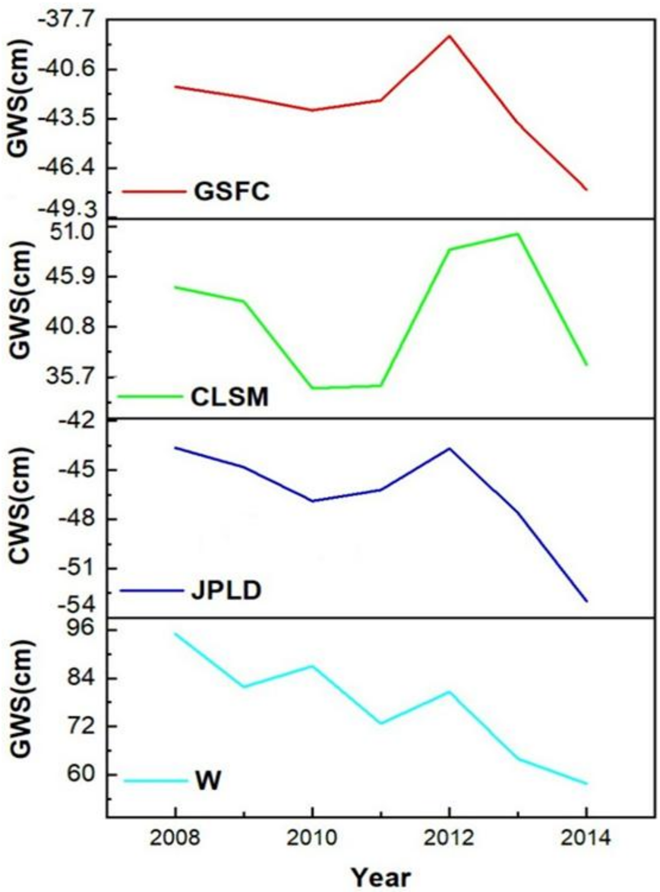

Figure 5: The fluctuations of the GWS based on various sources

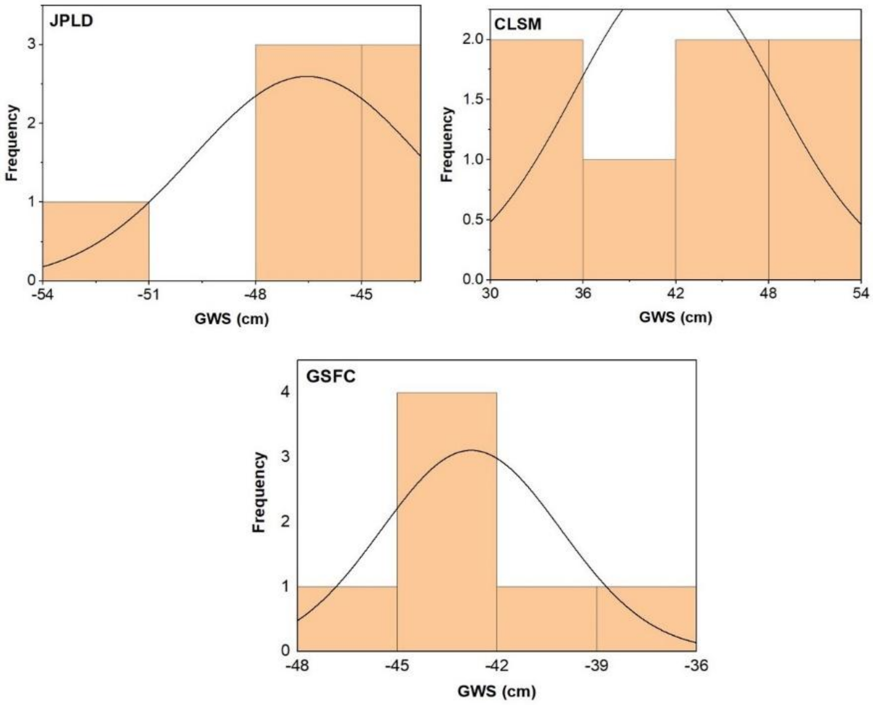

Figure 6: Data histograms from GRACE

Table 4: Correlations of GWS-derived satellite data with recorded well data in Dammam, an unconfined aquifer

Parameter GWS	Pearson		Spearman		Kendall	
	Correlation	P-value	Correlation	P-value	Correlation	P-value
GWS_JPLD	0.42	0.34	0.25	0.58	0.23	0.45
GWS_CLSM	0.44	0.31	0.29	0.53	0.33	0.29
GWS_GSFC	0.93	0.002	0.96	0.0004	0.90	0.004

The results from the Pearson, Spearman, and Kendall correlation analyses in Table 4 present the relationships between the GWS-derived GRACE and GWS_W. The results of the correlation analysis showed that GWS_GSFC has a strong positive Pearson, Spearman, and Kendall correlation; if the p-value > 0.05, it indicates not statistically significant, and if it is < 0.05, it shows statistically significant [44, 45]. Then, GWS_JPLD and GWS_CLSM have a weak positive (non-significant) Pearson, Spearman, and Kendall correlation. Groundwater is the primary water source in the study area for household, agricultural, and industrial uses. There were perhaps 70 public and 700 private benefit wells. [46], as shown in Figure 7. It is apparent from Figure 7 that the wells are highly concentrated in the study area's northern part, with a less dense distribution in the southern and eastern parts. The aquifers in the north may contain more water, encouraging more wells to be drilled. There may be a higher concentration of population in the north, raising the demand for water sources.

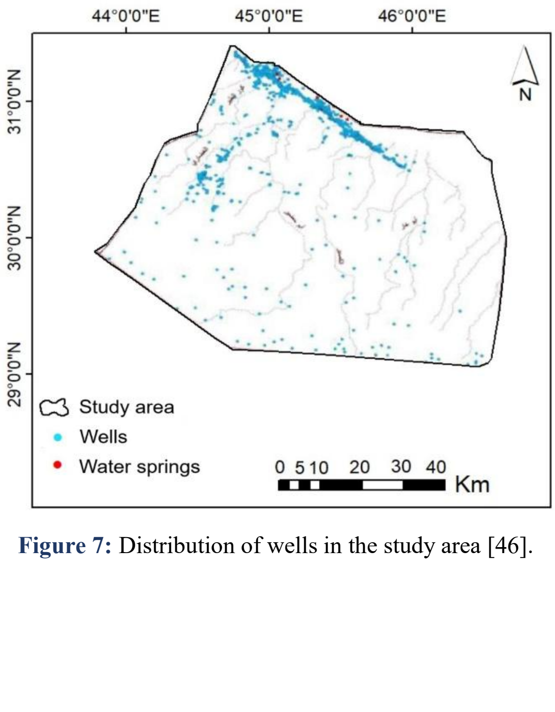

Figure 7: Distribution of wells in the study area [46].

Figure 8 illustrates the spatial variation in GWS throughout the study area. Significant variation in GWS can be clearly seen. Some parts experienced a considerable decline in GWS, as clear in the northern part, where the average GWS was -51.79 and -51.00 cm/yr for the GSFC and JPLD, respectively. While other parts experienced a lesser decrease, as in the eastern part, where the average GWS is -35.80 and -36.73 cm/yr for the GSFC and JPLD, respectively, this significant variation is due to the inconsistent distribution of wells. This illustrates that exceedingly large GW withdrawals from deep wells impact the GRACE satellite data and are not limited to shallow wells.

To show and evaluation the distribution and difference in the computed depletion of groundwater, the average GWS's spatiotemporal variation was classified into five classes (≤ -50, -47 to -43, -43 to -41, -41 to -39, and ≥ -39), Figure 9 and Table 5. These classes represent the ratio of groundwater depletion within the Dammam Aquifer from 2008 to 2014.

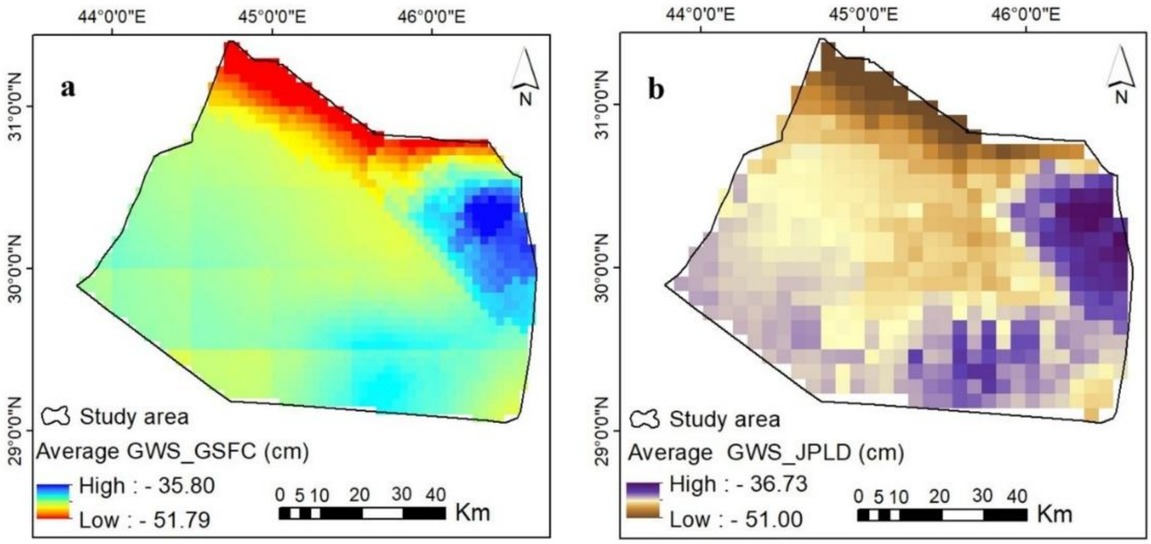

Figure 8: Average GWS's spatiotemporal variations from 2008 to 2014in the dammam aquifer a) GSFC and b) JPLD

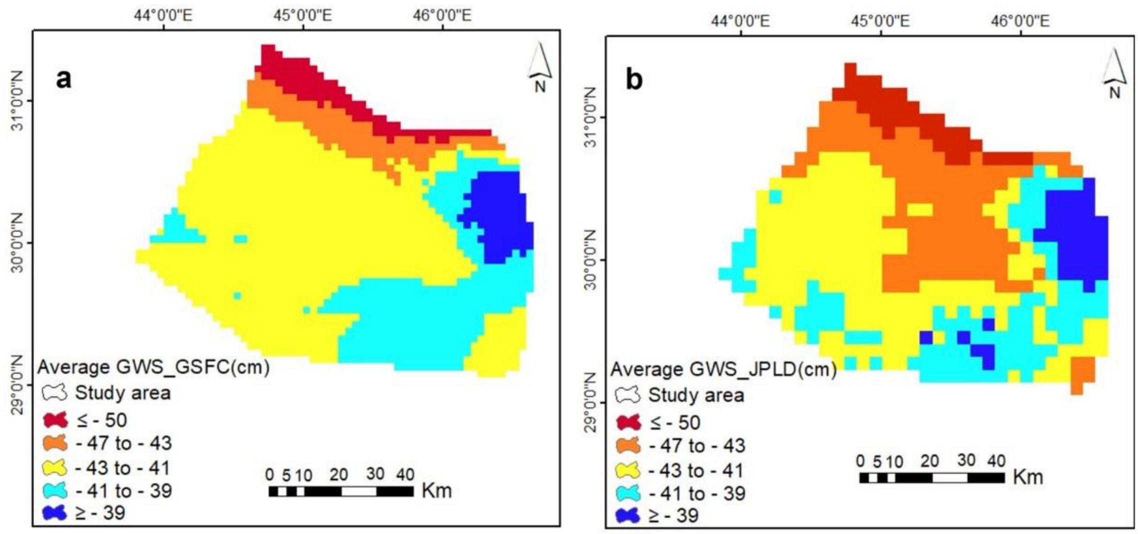

Figure 9: Classify average GWS a) GSFC and b) JPLD in the Dammam Aquifer

Table 5: Groundwater depletion ratio in the dammam aquifer is categorized based on the area it occupies

Class	Average GWS_GSFC		Average GWS_JPLD	
	Ratio %	Area (Km^2)	Ratio %	Area (Km^2)
≤ -50	6	2562	7	3175
-47 to -43	8	3697	25	11729
-43 to -41	59	27124	39	18166
-41 to -39	22	10406	21	9789
≥ -39	5	2509	8	3439

The finding of the classification that class (-43 to -41) is the most common, occupying 59% and 39% of the study area, equivalent to 27124 km^2 and 18166 km^2 for the GWS_GSFC and GWS_JPLD, respectively. In contrast, class (≥ -39) is the least common, occupying only 5% of the area (2509 km^2), which represents the minimal level of groundwater consumption for the GWS_GSFC, but class (≤ -50) is the least common, occupying only 7% of the area (3175 km^2), which represents the higher level of groundwater consumption for the GWS_JPLD. When comparing the ratio of areas classified as class (≤ -50) according to GSFC and JPLD data, the finding is that JPLD data shows a wider distribution of areas suffering from severe depletion of the groundwater storage. The variation probably results from JPLD data's increased sensitivity in identifying water changes that cause depletion. While the class (-47 to -43) is classified as moderately depleted, there is a significant varies in the estimate of its area and ratio when comparing the GSFC and JPLD data. The class (-43 to -41) was widely distributed in both datasets, indicating a widespread moderate decline in the consumption of groundwater storage. The class (-41 to -39), with similar ratios for both data, represents areas with relative stability in groundwater storage consumption. Class (≥ -39), the GSFC data represented a small ratio compared to the JPLD data. It represents the areas with the lowest groundwater storage consumption, possibly due to the lesser number of wells or minimal human activity.

4. Conclusion

This paper suggests the ability of GRACE to detect GWS fluctuations over an unconfined aquifer at a smaller geographic scale than the usual spatial resolution of GRACE in southern Iraq. Generally, the unconfined Dammam Aquifer has experienced groundwater depletion over the last seven years. The highest rate of groundwater depletion during the study period from January 2008 to December 2014 for GWS_W at -54±10 mm/yr, whereas the depletion based on the RS data ranged from -54±10, -11±5 to -6±5 mm per year. The study's findings indicate that the GRACE-MASCON can be utilized over a small region to estimate groundwater levels, achieving an RMSE of 0.10 m and an R^2 of 0.93. On the other hand, the results of the correlation analysis showed that GWS_GSFC has a strong positive Pearson, Spearman, and Kendall correlation.

The primary drivers of GWS depletion are human activity, climate change, drought, and a rise in the demand for water in agriculture. This led to a lower amount of groundwater recharge than groundwater consumption. Furthermore, groundwater withdrawals from all shallow or deep wells impact GRACE satellite data. This paper highlights the utility of using GRACE-GSFC gravity data to detect GWS variation in data scarcity and to create an integrated database of wells in situ and GWS derived from RS to monitor the aquifer from expected depletion.

Author contributions

Conceptualization, **M. Al-Khafaji**, **I. Alwan**, and **H. Mohammed**; data curation, **H. Mohammed**; formal analysis, **H. Mohammed**; investigation, **M. Al-Khafaji, I. Alwan**, and **H. Mohammed**; methodology, **I. Alwan**, **M. Al-Khafaji**, and **H. Mohammed**; resources, **M. Al-Khafaji**, **I. Alwan**, and **H. Mohammed**; software, **H. Mohammed**; supervision, **I. Alwan**, **M. Al-Khafaji**; validation, **M. Al-Khafaji**, **I. Alwan**, and **H. Mohammed**; visualization, **I. Alwan**, **M. Al-Khafaji**, and **H. Mohammed**; writing—original draft preparation, **H. Mohammed**; writing—review and editing, **M. Al-Khafaji**, **I. Alwan**, and **H. Mohammed**. All authors have read and agreed to the published version of the manuscript.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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