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Research paper

Quantifying groundwater depletion in Arabian Peninsula transboundary aquifer systems: Understanding natural and anthropogenic drivers

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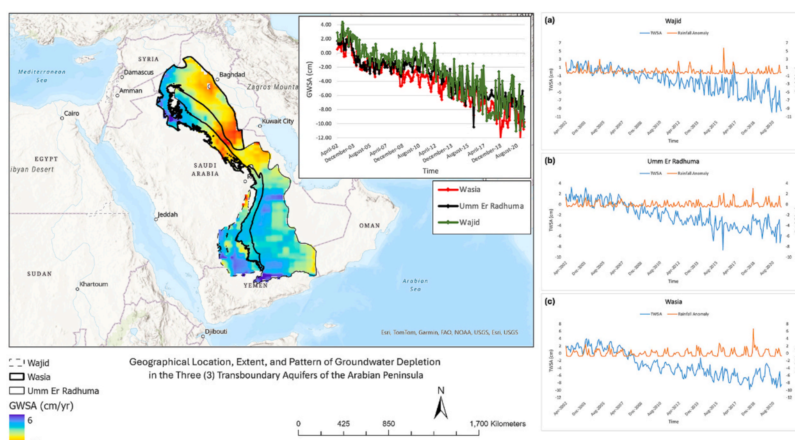
HIGHLIGHTS

- Transboundary aquifers in the Arabian Peninsula show major groundwater depletion.
- Highest decline is seen in central and north central Saudi Arabia and border regions.
- Remote Sensing-based monitoring can help efficient management of regional aquifers.

GRAPHICAL ABSTRACT



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ABSTRACT

Groundwater is the primary source of freshwater for domestic, agricultural, and industrial usage in the Arabian Peninsula countries. It is increasingly becoming a limited resource due to human activities leading to excessive depletion and contamination. Thus, sustainable management of groundwater resources in this region is critical. The groundwater in the Arabian Peninsula countries is primarily found in transboundary systems such as the Wajid, Umm Er Radhuma, and Wasia Aquifers shared between Saudi Arabia, Iraq, Syria, Yemen, and Oman. These systems have no groundwater-sharing agreements, which leads to a lack of data sharing, unsustainable and uncoordinated development, rapid water depletion, water quality deterioration, and land subsidence. This study examines the Wajid, Umm Er Radhuma, and Wasia aquifer systems from April 2002 to May 2021 by analyzing monthly gravity field solutions from GRACE and GRACE-FO satellite data, other remote sensing observations, information from the Global Land Data Assimilation System (GLDAS), as well as field data to determine how

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regional water resources are changing over time and to identify the factors that influence these resources. The sharp decline in Total Water Storage Anomalies (TWSA) and the Groundwater Storage Anomalies (GWSA) across all three systems is caused by a combination of climatic and human factors. The observed decline in Total Water Storage can be partly attributed to a decrease in regional rainfall, whereas the depletion of Groundwater Storage has a strong correlation with the rise in groundwater extraction for irrigation purposes in the 2010s. The recent rise is groundwater depletion in specific areas of central Saudi Arabia may be attributed to agricultural irrigation and rapid urban development. The results are insightful for monitoring water storage in management plans and decision-making processes to preserve and efficiently use groundwater resources.

1. Introduction

The world is going through unprecedented levels of water crisis in recent years, which influences every facet of our society, such as the environment, economy, energy, food, and health. Moreover, climatic and anthropogenic changes due to human activities and development play a significant role in ongoing water shortages, particularly in developing countries (Liuzzo et al., 2015; Moghim, 2020).

Water scarcity is especially severe and acutely felt in the vast dry regions across the Middle East and North Africa (MENA) region (Jasechko et al., 2024). The Arabian Peninsula countries are arid and semi-arid regions experiencing escalating populations and rapid growth. Groundwater is this region's primary source of freshwater, and precipitation acts as the recharging source (Fallatah et al., 2017; Kinzelbach et al., 2002; Scanlon et al., 2002; Sultan et al., 2008). Increased agricultural development and excessive groundwater extraction have caused a sharp decline in groundwater storage over the central and northern Arabian Gulf (Othman et al., 2018).

Kingdom of Saudi Arabia (KSA) is the largest country in this region, facing inveterate water insecurity. KSA's population increased almost 9 times between 1960 and 2021, and currently stands over 34 million (GASTAT, 2022). This rapid growth resulted in a significant increase in freshwater use. For instance, annual freshwater resources consumption in Saudi Arabia was estimated at 24.8 x 10^9 m^3 in 2015, but is anticipated to grow to 29.5 x 10^9 m^3 by 2050 (Fallatah et al., 2019; MEWA, 2021).

Also, most of the groundwater in the Arabian Peninsula is stored in transboundary aquifer systems (TBS) such as the Wajid, Umm Er Radhuma, and Wasia aquifers shared between Saudi Arabia, Yemen, Iraq, Syria, and Oman. As these countries do not have any groundwater sharing treaties, it leads to a lack of sharing data, unsustainable and uncoordinated development, increased water depletion, water quality and quantity, and land subsidence issues (Abdulrazzak et al., 2020; Mechlem, 2011).

The primary technologies used for artificial aquifer recharge in arid and semiarid regions include recharge basins, floodwater spreading systems, injection wells or recharge wells, and recharge dams (Mohammadzadeh-Habili and Khalili, 2020). Among the 213 dams distributed over KSA (Table 1), only two are located inside the aquifer area, and are expected to serve as recharge dams. One is shown in the Wasia Aquifer region, named the Altamriyah dam, an earthen type situated in Riyadh province; the other is in the Umm Er Radhuma region, called the Safar dam, which is an earthen type located in Eastern province. Three dams on Wasia's border areas (4∼15 km) are also considered to be recharge dams named Boudha (rock fill type), Haer Jouy, and Asheera dams (earthen type). Similarly, five dams on Wajid's borders (4–32 km) named Alhawatah, Hilwah, Lassad, Alhareeq dams (earthen type), and Alghaeel dams (concrete type), are contributing towards recharging the aquifer (MEWA, 2021).

Table 1
Dams in KSA.

KSA Province	Dams	Type
Riyadh	55	Concrete, Earthen, and Rock-fill
Mecca	22	Concrete, Earthen, Rock-fill, and underground
Eastern	1	Earthen
Almadinah	17	Concrete, Earthen, and Rock-fill
Bahah	26	Concrete, Earthen, and Rock-fill
Aljawf	2	Earthen
Northern Borders	0	
Alqassim	4	Concrete, Earthen
Hail	18	Concrete, Earthen
Asir	58	Concrete, Earthen, and Rock-fill
Jizan	4	Concrete, Earthen
Tabuk	0	
Najran	6	Concrete, Earthen
Total	213	

Recently, satellite remote sensing has significantly improved our capability to monitor large scale changes in water resources of arid regions (Fallatah et al., 2017, 2019; Famiglietti, 2014; Famiglietti et al., 2013). For instance, the Gravity Recovery and Climate Experiment GRACE is a joint project between NASA and German Aerospace Centre launched in March 2002. GRACE has produced monthly gravity field solutions from April 2002 to June 2017, and GRACE-FO has continued that record from June 2018 onwards (https://www.gfz-potsdam.de/en/grace). The gravity solutions can be used to deduce the anomalies in total water mass, involving all water cycle components, over a specified geographic region (spatial resolution 0.25^o x 0.25^o). In addition, the Global Land Data Assimilation System (GLDAS), which incorporates satellite and ground-based observational data products can be used for advanced land surface modeling and data assimilation. The remotely sensed data drives four land surface models: Noah, Mosaic, Community Land Model (CLM), and the Variable Infiltration Capacity model (VIC) (Rodell et al., 2004; Rui and Beaudoing, 2020). Combining the total water storage information from GRACE and GRACE-FO observations and hydroclimatic variables from GLDAS simulations now provide us an improved and more accurate method of estimating the time series of water cycle components of arid region watersheds and aquifer systems, where data are not easily available.

Using such an approach, this study quantifies the spatiotemporal variations of water resources available in the transboundary aquifer systems of the Arabian Peninsula region. It also analyzed the evolving water demand in Wajid, Umm er Radhuma, and Wasia aquifer systems over the last two decades by combining earth observations, and climate and land surface components from GRACE, GRACE-FO, and GLDAS, respectively. The use of a satellite remote sensing-based approach allows us to monitor large scale changes in water resources over the vast arid and semi-arid landscape of the Middle East, where local water demand and withdrawal data are hard to obtain. The research objectives of this study are: 1) Quantify the rate of terrestrial water storage and groundwater usage and depletion, 2) Corroborate the finding of the remote sensing observations with land surface modeling results and ground observations, 3) Identify the climatic and anthropogenic factors driving water demand growth, groundwater depletion, and environmental changes in this region. Results show spatiotemporal changes in water storages, depletion, and the necessity of tracking groundwater resource changes for decision-makers and stakeholders to preserve the water resources and reduce their depletion rates.

2. Data and methods

2.1. Study area

The climate of the Arabian Peninsula is characterized by low precipitation and high annual temperature (Fallatah et al., 2017). The central part of the peninsular is extremely hot in summer but relatively cold in winter, particularly at night and early morning. Northern and southern part of the Arabian Peninsula experience freezing temperatures in winter and sometimes snow in the north (Edgell, 2006). Geographically, the Arabian Peninsula can be classified into desert islands, coastal plains, salt flats, deltas, sand deserts, plateau, mountains, and scrap mountain regions (Brown et al., 1989; Edgell, 2006; Vegetation of the Arabian Peninsula," 1998). This region has experienced significant changes in its climate over the past decades, with rising temperatures and shifting weather patterns (Almazroui et al., 2020). It also experienced a steady increase in average temperatures, resulting in more frequent and intense heat waves, due to both natural climate variability and human-induced global warming.

The study region covers the three most significant transboundary aquifers in the Arabian Peninsula (AP), the Wajid, Umm Er Radhuma, and Wasia aquifers systems illustrated in Fig. 1. The Wajid aquifer is in the southern region of the AP, shared by Saudi Arabia and Yemen, and covers approximately a total area of 124,837 Km^2. The Umm er Radhuma aquifer is one of the most significant aquifers in the Arabian Peninsula, which extends from northern to southern AP, and covers approximately 463,416 Km^2; the Wasia aquifer, extending from the northern to southern part of the AP, is one of the most fertile groundwater sources in Saudi Arabia, providing freshwater resources to the capital city Riyadh (Alfaifi et al., 2017; Khogali et al., 2020). Its area is approximately 352,622 Km^2 (MEWA, 2021).

The Wajid aquifer serves more than 13 million people including 90% living in KSA, and 10% in Yemen, while the Umm Er Radhuma aquifer serves more than 20 million people including 73% living in KSA, 20% in Iraq, 5% in Yemen, and 2% in Oman. In addition, the Wasia aquifer serves more than 34 million people including 52% living in KSA, 41% in Iraq, 3% in Yemen, and 4% in Syria (Table 2) (GASTAT, 2022; MEWA, 2021).

The Wajid Aquifer System is situated within the Wajid Sandstone Formation, a component of the sedimentary rock layers across the Arabian Peninsula. This aquifer system is mainly composed of porous sandstone beds formed over millions of years. Typically deposited in old river channels, deltas, or coastal areas, these sandstone formations gradually solidify as sand grains bind together, forming a porous rock capable of storing and transmitting water. Meanwhile, the Umm Er Radhuma aquifer lies within the Umm Er Radhuma Formation, situated in the Arabian Peninsula. This aquifer system is primarily composed of carbonate rocks like limestone and dolomite, which have accumulated over extensive periods. These carbonate deposits typically stem from ancient marine settings, where sediments rich in calcium carbonate

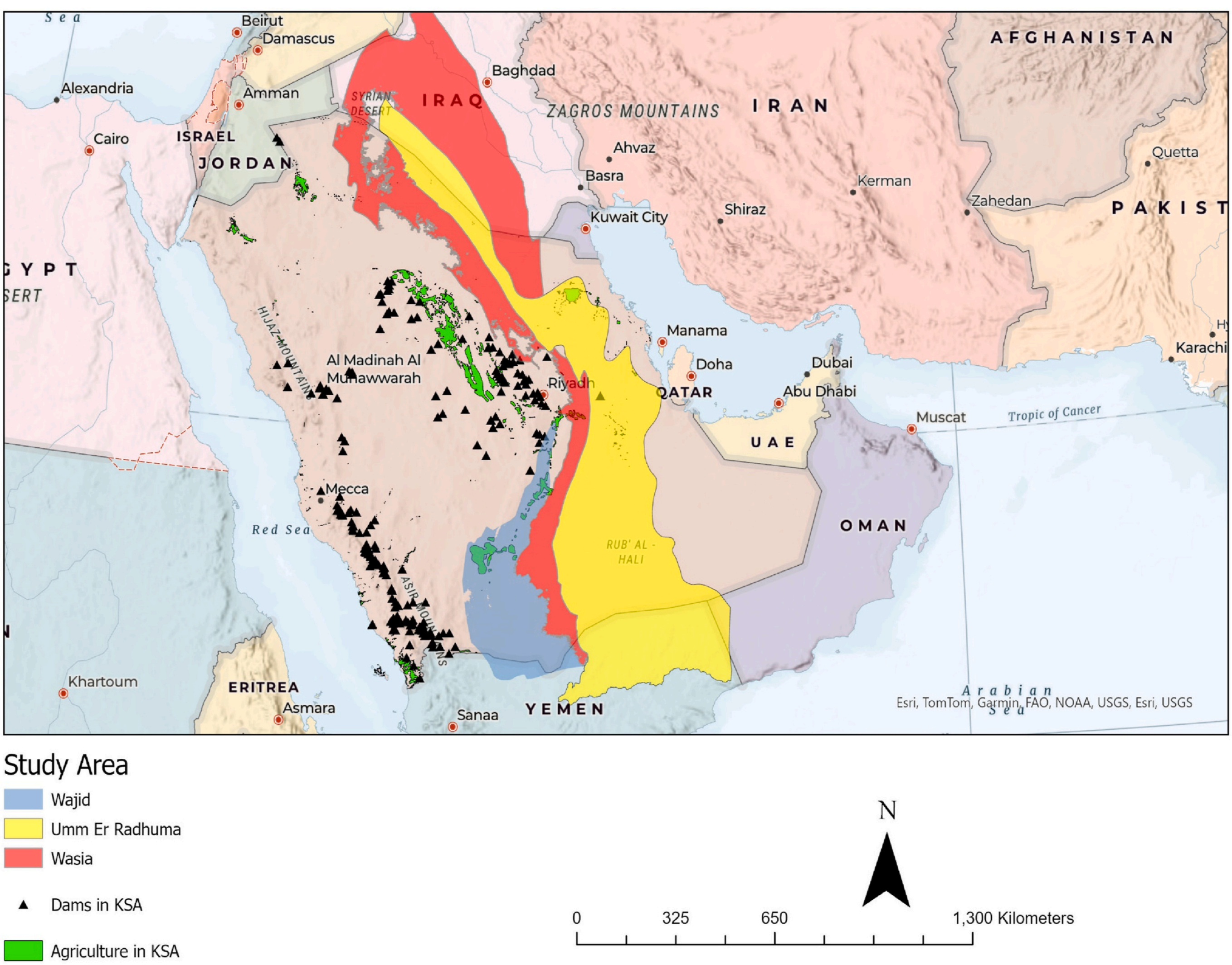

Fig. 1. Study Area: the locations of the three transboundary aquifer systems, Dams, and Agriculture in KSA.

Table 2
Aquifer Areas in each Arabian Peninsula country (MEWA, 2021).

Countries/Aquifer	Wajid (Area)	Umm Er Radhuma (Area)	Wasia (Area)
KSA	112038 km^2 90%	320480 km^2 69%	183010 km^2 52%
Yemen	12799 km^2 10%	106674 km^2 23%	2045 km^2 0.6%
Iraq	N/A	30805 km^2 7%	166269 km^2 47%
Oman	N/A	5457 km^2 1%	N/A
Syria	N/A	N/A	1298 km^2 0.4%
Total	124,837 km^2	463,416 km^2	352,622 km^2

settle and compress over time, forming porous and permeable layers of rock, renowned for its capacity to store and transmit groundwater. In addition, the Wasia Aquifer System is predominantly situated within the Wasia Formation, primarily composed of porous limestone and sandstone layers that have built up over millions of years. Originating from past marine settings, these sediments, such as sand and calcium carbonate, gather and compress over time, forming permeable rock layers. The porous quality of the limestone and sandstone enables the storage and movement of groundwater (GASTAT, 2022; MEWA, 2021).

2.2. Data and methods

2.2.1. GRACE & GRACE- FO derived Total Water Storage Anomalies data

GRACE detects spatiotemporal fluctuations in vertically integrated Total Water Storage (TWS). Variations in the GRACE-derived TWS indicate changes in one or more of the reservoirs listed below: snow/ice, surface water, soil moisture, groundwater, and wet biomass (Wahr et al., 1998). GRACE data have been widely utilized to calculate aquifer recharge and depletion rates (Ahmed et al., 2011, 2016; Al-Zyoud et al., 2015; Castellazzi et al., 2016; Chinnasamy and Agoramoorthy, 2015; Döll et al., 2014; Ellett et al., 2006; Fallatah et al., 2017; Feng et al., 2013; Huang et al., 2015; Jiang et al., 2016; Joodaki et al., 2014; Lezzaik and Milewski, 2018; Moghim, 2020; Saber et al., 2020). The monthly mass concentration GRACE and GRACE-FO derived Total Water Storage Anomaly (TWSA) datasets generated by the University of Texas, Center of Space Research (UT-CSR) with a spatial resolution of 0.25^0 x 0.25^0 has been utilized for this study (Table 3). A positive anomaly indicates water mass gain, and a negative value means mass loss. A simple seasonal decomposition method named STL (Seasonal and Trend decomposition using Loess) was used to fill out missing values and the gap between the GRACE and GRACE-FO mission observations.

2.2.2. GLDAS derived soil moisture storage anomaly (SMSA)

The Global Land Assimilation System (GLDAS) land surface model setup provides a worldwide dataset from 1948 that includes radiation, heat fluxes, hydrological components, and meteorological variables at 3-hourly and monthly resolutions (Rodell et al., 2004; Rui and Beaudoing, 2020). This study utilizes monthly soil moisture anomalies from April 2002 to May 2021 (Table 3). To estimate soil moisture anomaly, a vital component of the TWS, we use the GLDAS-2.1 Noah land surface hydrology model at a monthly timestep. The Soil Moisture Storage (SMS) Anomaly can be estimated as the total summation of the outputs of soil moisture values of top four soil layers (0–10, 10–40, 40–100, and 100–200 cm). Groundwater Storage Anomaly is then computed based on the following equation:

$$\Delta \text{GWSA} = \Delta \text{TWSA} - \Delta \text{SMSA} \quad (1)$$

Where ΔGWSA: is the change in groundwater storage anomalies, ΔTWSA: is the change in terrestrial water storage anomalies, ΔSMSA: is the change in soil moisture storage anomalies.

Table 3
The Datasets used in this study.

Variables	Sources and Processing	Units	Time
GRACE & GRACE-FO Terrestrial water storage (TWS)	*Monthly average CSR* (0.25^0 *x* 0.25^0)	*(cm)*	*April 2002 - May 2021*
GLDAS Soil moisture storage (SMS)	*NOAH model SMS for four layers (0–10, 10–40, 40–100,100-200) Converted to anomaly* (0.25^0 *x* 0.25^0)	*(cm)*	*April 2002 - May 2021*
GLDAS-2.0 & GLDAS-2.1 Rainfall	*NOAH model* (0.25^0 *x* 0.25^0)	*(mm)*	*Jan 1970 - May 2021*
Field Data	*Dams and Agriculture by MEWA*		*2021*

2.2.3. Field data

Agricultural data of 29 polygons (8665 Sq Km) distributed over the Wajid Aquifer system, 116 polygons (2161 Sq Km) distributed over the Umm er Radhuma Aquifer system, and 27 polygons (2870 Sq Km) distributed over the Wasia Aquifer system in Saudi Arabia were used to overlay agricultural water usage information over the groundwater source regions (Fig. 1). In addition, the locations of 213 dams over KSA were added to the geospatial analysis to overlay potential recharge inputs over the study area, as shown in Fig. 1. The data was maintained by the Ministry of Environment, Water, and Agriculture in the KSA, and collected and analyzed specifically for this study (Table 3).

2.2.4. Rainfall data

Rainfall data are used to explore the hydroclimatic controls on the temporal variations in the TWS observed over Wajid, Umm er Radhuma, and Wasia Aquifer systems. The monthly GLDAS Noah land surface model version 2.0 and version 2.1 were used in this study from Jan 1970 to May 2021 at a spatial resolution 0.25^0 x 0.25^0. GLDAS Noah land surface model version 2.0 was used to provide data from Jan 1970 to Dec 2014 and GLDAS Noah version 2.1 was used to provide data from Jan 2000 to May 2021 (Table 3). After that, the average of overlapping data period was calculated over each aquifer.

3. Results

3.1. Terrestrial water storage anomalies by GRACE and GRACE-Follow on

The monthly regional mean of TWSA over the three transboundary aquifers was calculated from UT-CSR mascons for the study period April 2002 to May 2021 (Fig. 2). In the case of the Wajid Aquifer, the linear trend showed a decline rate of 2.14 cm/year, equivalent to about -0.87 $km^3/year$. The trend at Umm Er Radhuma is estimated at a decline rate of 1.98 cm/year, which is about -2.79 $km^3/year$, and the Wasia Aquifer is estimated at a decline rate of 3.11 cm/year, which is about -3.16 $km^3/year$. Within the Wajid Aquifer, the northern part experienced maximal depletion, whereas the southern part shared with KSA and Yemen experienced minimal depletion. Wasia Aquifer results also indicate that the area of the southern part, which is shared with KSA and Yemen, experienced minimal depletion whereas the area center and northern part, which is shared with Iraq and a small part of Syria experienced maximal depletion. In the case of Wasia Aquifer, approximately 2870 Km^2 of irrigation is distributed over the entire aquifer in KSA, particularly in the central part of the aquifer. However, this area is also surrounded by large agricultural areas in the Riyadh, Alqassim, and Hail provinces. These agricultural zones, spanning an impressive 12,589 Km^2, are located approximately 40–50 km from the aquifer, relying on it for the essential pumping and transfer of water resources.

In addition, Umm Er Radhuma results indicate that the southern part of the aquifer area shared with Oman and Yemen experienced minimal

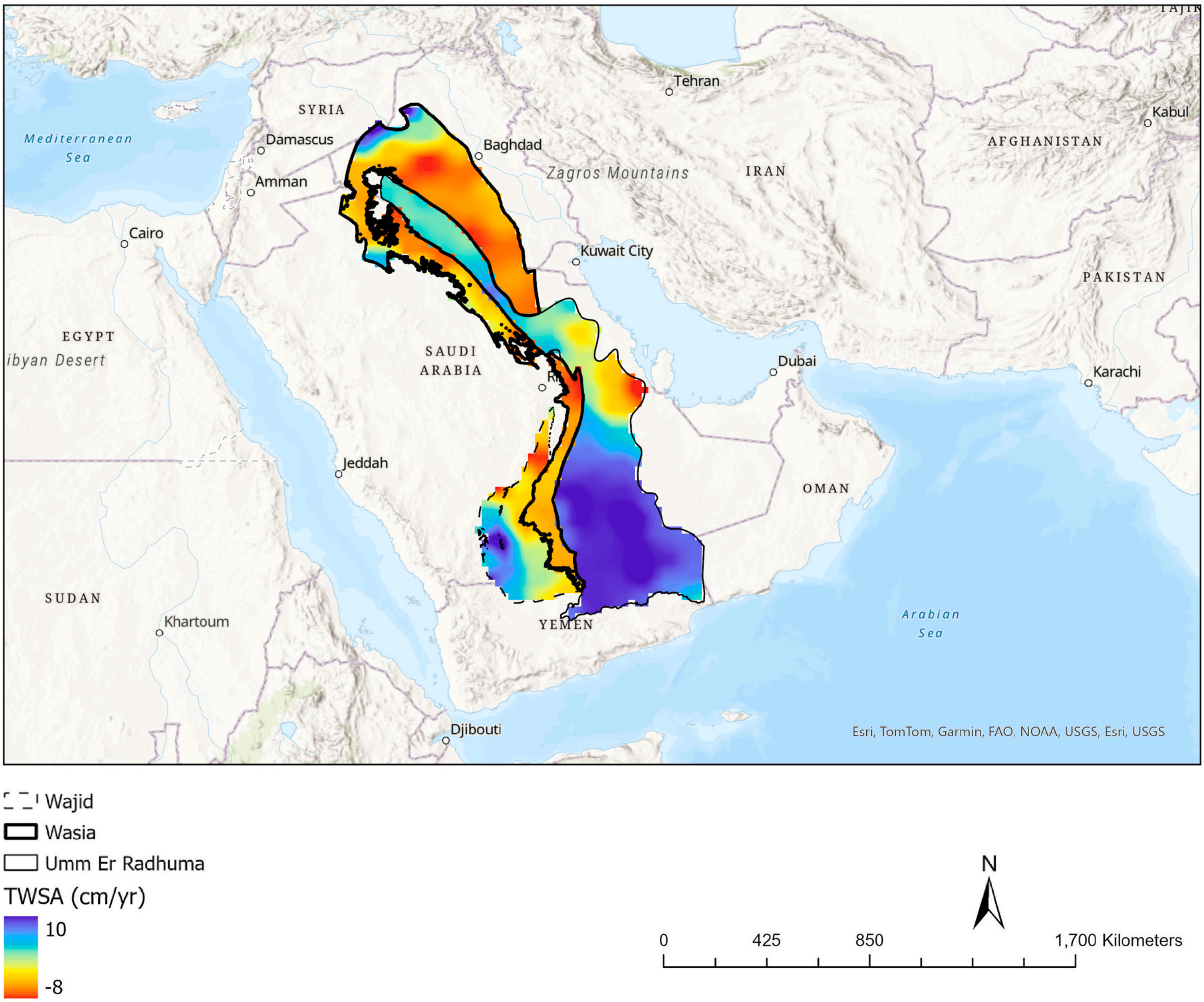

Fig. 2. Secular trend image of TWSA from GRACE and GRACE-FO generated from UT-CSR mascons dataset over the Arabian Peninsula from April 2002 to May 2022.

depletion and may have gained in total water storage. Furthermore, the area of the northern part, which is shared with Iraq, experienced minimal depletion. In contrast, most of the central parts of the aquifer near the capital city of Riyadh experienced high depletion rates. Overall, the southern part of our study region tends to have minimal depletion rates, around the border with Yemen and Oman, while the northern border regions shared between KSA, Iraq, and Syria and the central parts of the study region are experiencing maximum depletion (Fig. 2).

3.2. Gridded rainfall observations by GLDAS

Fig. 3(a and b and c) illustrates the temporal variations of rainfall over the study area during the time series. Our findings indicate that the total average of rainfall over Wasia received the highest quantity of average annual precipitation in the amount of 88.63 mm/year, Wajid received the amount of rainfall of 68.55 mm/year, while Umm Er Radhuma received the lowest annual average rainfall of 63.41 mm/year during the same time. Over the TBS under consideration, observations show that the wettest months are March and April, and the driest months are September and October; however, June to October are the driest months in the Wasia Aquifer region.

From temporal variations of total rainfall, there are three peaks observed for Umm Er Radhuma, which were in 1976, 2018, and 2020; four peaks for Wasia, which were in 1972, 1982, 2018, and 2019; whereas six peaks for Wajid, which are in 1976, 1983, 1988, 1993, 2013, and 2016 (Fig. 3). The aquifers received the highest anomalous rainfall during these years compared to their low averages (Fig. 4). The annual average rainfall over Waisa shows two trends, until 1999, the rainfall decreased, but after 1999 the rainfall increased. In the case of Umm Er Radhuma, the rainfall dropped before 1990 and increased after 1990. Whereas for Umm Er Radhuma the rain had a long decrease until 2014, thereafter it has increased in recent years (Figs. 3 and 4).

3.3. Soil moisture storage anomaly (SMS) by GLDAS

The analysis of temporal variations in soil moisture anomaly for the top four layers over the study area illustrate the cyclic gain and loss moisture due to changes in rainfall (Fig. 5). The total average in the top layer of soil tends to decrease for the three aquifers, which reduces about −0.23 mm per year over Wajid, 0.20 mm per year over Umm Er Radhuma, and 0.04 mm per year over Wasia. The decline in the top layer shows the same driest and wettest seasons for every aquifer in terms of rainfall from April 2002 to May 2021, which corroborate our findings. Additionally, the results indicate an increase in soil moisture for

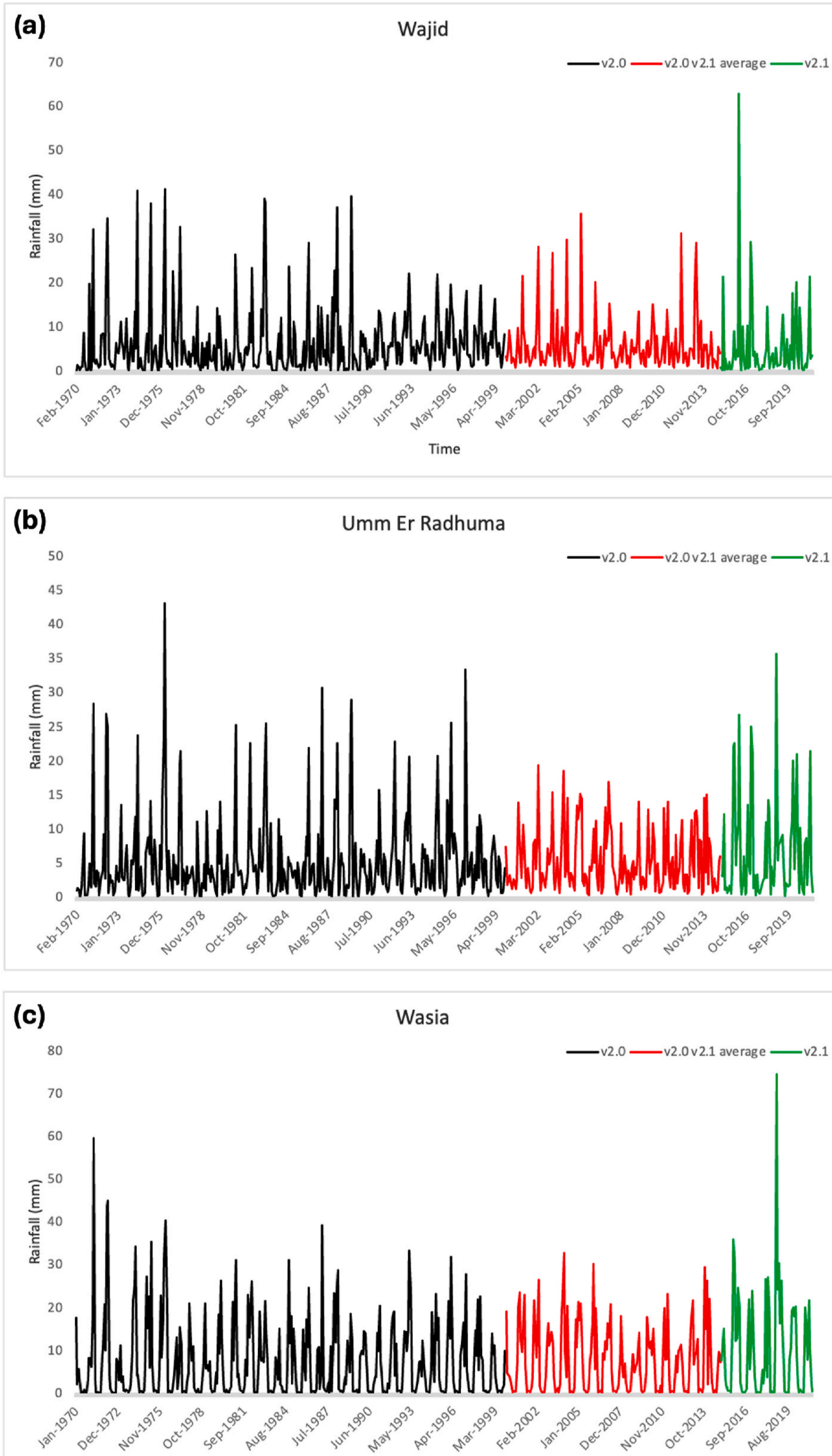

Fig. 3. Temporal variation in monthly rainfall extracted from GLDAS and averaged over (a) Wajid aquifer system (b) Umm Er Radhuma aquifer System, (c) Wasia aquifer system during Jan 1970–May 2021.

underneath layers for the whole aquifers during the time series (Table 4). The cumulative soil moisture volume in the top four layers were subtracted from the terrestrial water storage anomaly to obtain the groundwater storage anomaly (Equation (1)).

Moreover, our findings show a sharp decline in the annual soil moisture amounts in the underneath layers from 2006 to 2012 over Wajid, and 2005 to 2012 over Umm Er Radhuma and Wasia. This trend can potentially be linked to past wheat production efforts in KSA during the study period (Ferragina and Canitano, 2014). Wheat is a water-intensive crop and necessitates massive quantities of groundwater

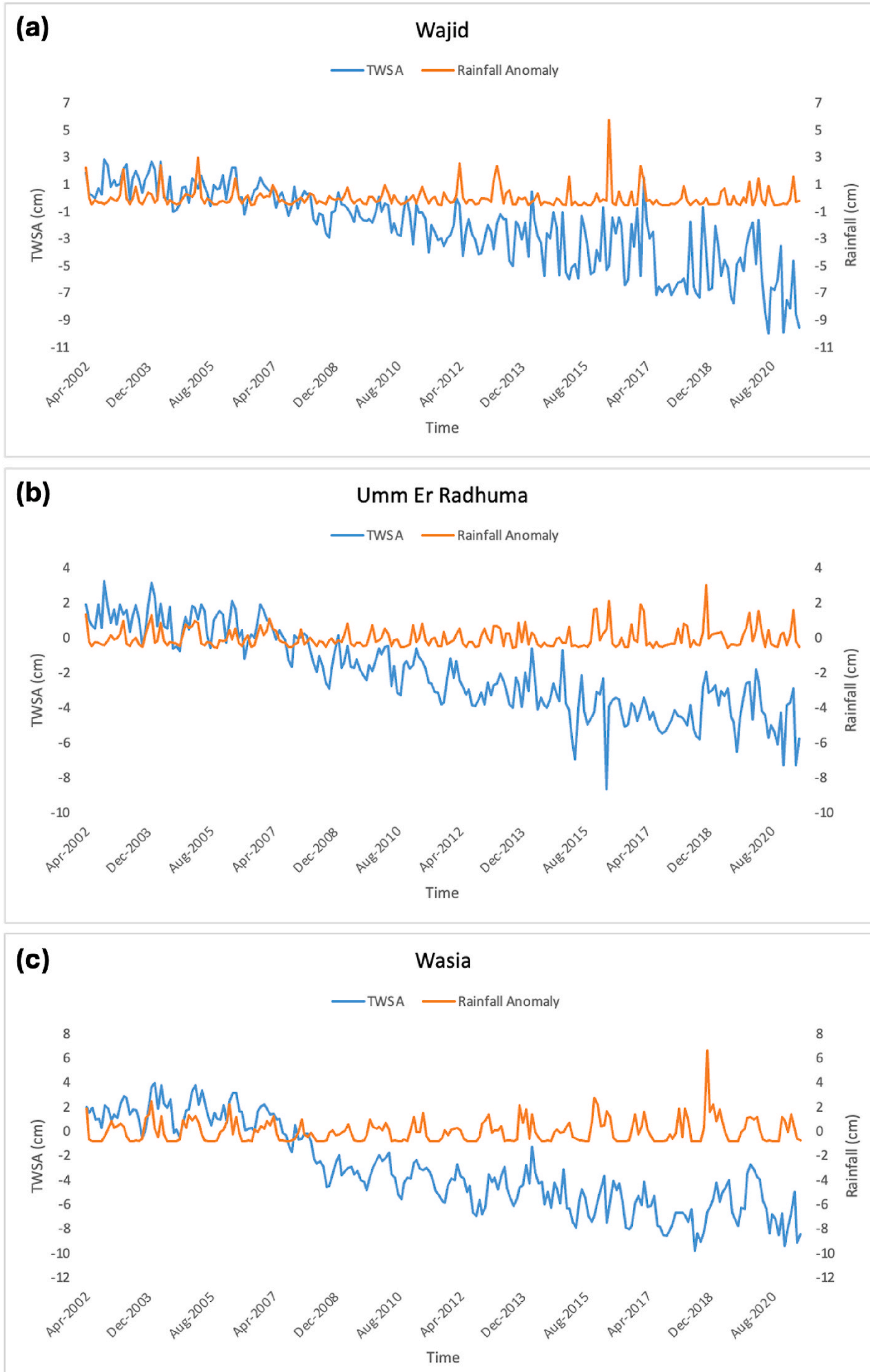

Fig. 4. Temporal variation anomalies in monthly TWS extracted from GRACE & GRACE-FO and Rainfall data averaged over the study area from April 2002–May 2021.

extraction ($\sim$1.0 $km^3/year$). Since 2000, the region has also seen significant growth of urbanization, construction of new transportation routes, agricultural expansion and accompanying irrigation projects (Fallatah et al., 2017). In 2008 however, KSA decided to abandon the project of becoming self-sufficient in wheat production in order to preserve groundwater sustainability. The country eventually ended its domestic wheat production programs in 2015 after more than thirty years (Miller magazine, 2016).

3.4. Groundwater storage anomalies (GWSA) by GRACE and GRACE-Follow on

Our study area is predominantly arid and semi-arid, with minimal surface water inputs. The observed TWS over Wajid, Umm Er Radhuma, and Wasia aquifers systems are connected to changes in soil moisture and groundwater storage. The GWS is quantified based on two parameters: the TWSA from GRACE and GRACE-FO observations, and the SMSA outputs from the GLDAS Noah model. The following equation represents groundwater storage:

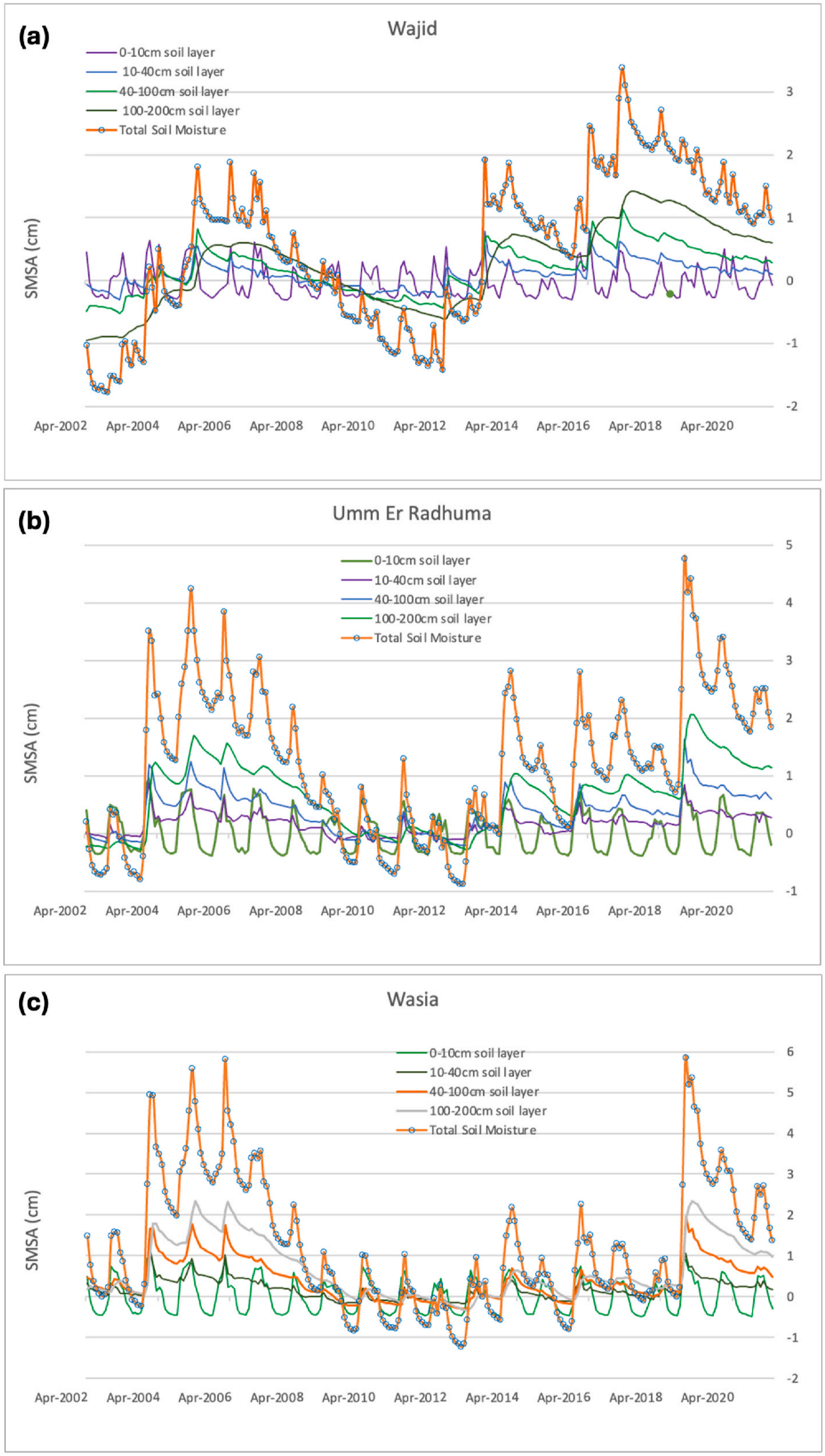

Fig. 5. Temporal variations in SMS anomaly over the (a) Wajid, (b) Umm Er Radhuma, and (c) Wasia Aquifer systems, for four layers extracted from GLDAS during April 2002–May 2021.

$$GWSA = TWSA - SMSA \quad (2)$$

Where GWSA: is groundwater storage anomalies, TWSA: is terrestrial water storage anomalies, SMSA: is soil moisture storage anomalies.

The results of the time series analysis revealed that groundwater storage declined in all aquifers from April 2002 to May 2021 is shown in Fig. 6. The Wasia shows greatest decline in groundwater storage at an

Table 4
SMSA of underneath layers over the study area.

SMSA Layer/Aquifer	Wajid (Unit)	Umm Er Radhuma (Unit)	Wasia (Unit)
10–40 cm	0.99 mm/yr	1.76 mm/yr	1.71 mm/yr
40–100 cm	1.82 mm/yr	3.68 mm/yr	3.95 mm/yr
100–200 cm	2.62 mm/yr	6.40 mm/yr	6.61 mm/yr
Total	5.43 mm/yr	11.84 mm/yr	12.27 mm/yr

average rate of −4.34 cm/year, which is equivalent to about $-2.92\ km^3/year$, while Umm Er Radhuma declined at the rate of approximately −3.18 cm/year ($-3.13\ km^3/year$), and Wajid at −2.65 cm/year ($-1.08\ km^3/year$) (Table 5). The spatial distribution of the GWSA results show minimal depletion in the southern border region of Saudi Arabia with Oman and Yemen, and the northwest border with Jordan and Syria (Fig. 7). However, rapid groundwater storage depletion can be seen in central Saudi Arabia (near the capital region of Riyadh) and in the northern border areas with Iraq and Kuwait. Our results thus show strong spatiotemporal variations in all three transboundary aquifer systems across Saudi Arabia and in regions shared with most of its neighboring countries in the Arabian Peninsula.

4. Discussion and conclusions

Groundwater is a critical freshwater source in the arid and semi-arid regions of the Arabian Peninsula countries. Most groundwater sources in this region are transboundary aquifers, which have no groundwater sharing or management treaty governing them. As the region is undergoing rapid population growth, unilateral agricultural and urban development projects have drastically increased the demand and usage for groundwater in recent decades. Sustainable management of this critical resource and efficient usage of major aquifer systems are thus key concerns for the region.

In this study, we develop and apply an integrated approach using remote sensing and geophysical observations to quantify the groundwater depletion rates of major transboundary aquifers and examine the natural and anthropogenic drivers of water storage variations over a two-decade period – April 2002 to May 2021 – in the Arabian Peninsula region. We combine earth observations such as Gravity Recovery and Climate Experiment (GRACE) and GRACE-FO (Follow-On), land surface hydrological modeling using the Global Land Data Assimilation Systems (GLDAS), and local water resources infrastructure and usage information to investigate the spatiotemporal variations in the groundwater resources over the Wajid, Umm Er Radhuma, and Wasia transboundary aquifer systems shared between Saudi Arabia, Iraq, Yemen, Oman, and Syria.

Our results show extensive and consistent groundwater depletion in central and northern Saudi Arabia bordering Iraq, while improvements in groundwater storage in the south near the borders with Yemen and Oman. All three aquifers are witnessing significant Total Water Storage (TWS) and Ground Water Storage (GWS) depletion. The largest declines of TWS and GWS were in Wasia aquifer at −3.11 cm per year and −4.34 cm per year, respectively. Umm Er Radhuma is witnessing significant negative variations of −1.98 cm per year and −3.18 cm per year. In contrast, Wajid is experiencing the least negative variations of TWS and GWS at −2.14 cm per year and −2.65 cm per year, respectively. During the same time period of time, the total average rainfall over Wasia received the highest quantity of rainfall of 7.47 mm/month, Wajid received an amount of rainfall of 5.78 mm/month, while Umm Er Radhuma received the lowest annual average rainfall of 5.34 mm/month.

The observed negative trend anomalies over the study area are being influenced by natural factors, such as overall climate change and associated changes in precipitation rate, and anthropogenic factors, such as increased groundwater extraction for urbanization and irrigation activities. In this study, the field data on agricultural and water resources infrastructure collected from KSA (Fig. 1) are used to validate the earth observations since most of the study area is located inside KSA (Fig. 3). Based on our estimation, approximately 8665 Km^2 of irrigation is distributed over the three focus aquifers, primarily located in the northern parts of the KSA. As GRACE data indicates, there is intensive use of TWS in the northern part of the Wajid aquifer, presumably due to large scale agriculture. Within the Umm Er Radhuma Aquifer, approximately 2162 Km^2 of irrigation is located, where groundwater is withdrawn, mostly from the center part of the aquifer. Analysis of satellite

Table 5
GWSA over the study area.

Aquifer/GWSA	Average	1st sharp decline	2nd sharp decline
Wajid	−2.65 cm/yr ($-1.08\ km^3/year$)	2003–2008 0.12 cm/yr	2010–2021 −4.63 cm/yr
Umm Er Radhuma	−3.18 cm/yr ($-3.13\ km^3/year$)	2002–2012 −1.28 cm/yr	2013–2019 −6.83 cm/yr
Wasia	−4.34 cm/yr ($-2.92\ km^3/year$)	2003–2009 −1.51 cm/yr	2010–2020 −6.14 cm/yr

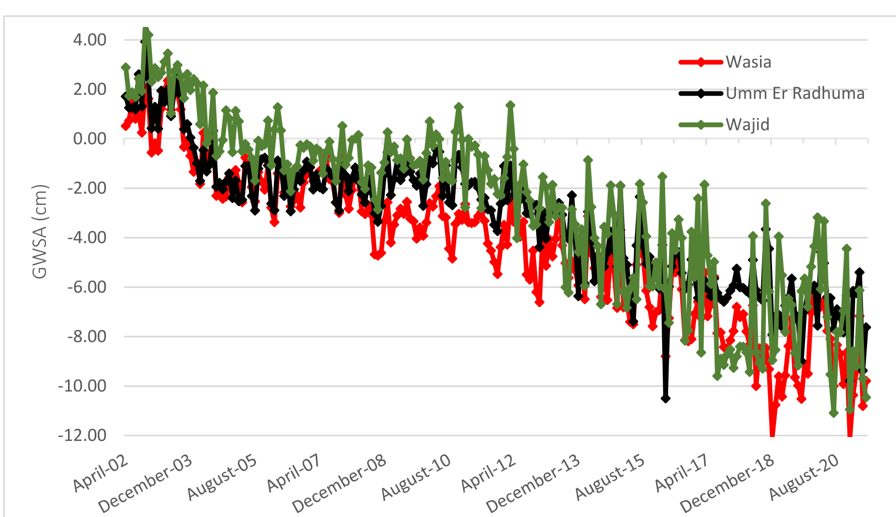

Fig. 6. Groundwater storage anomalies for the study area, showing the variability from April 2002–May 2021.

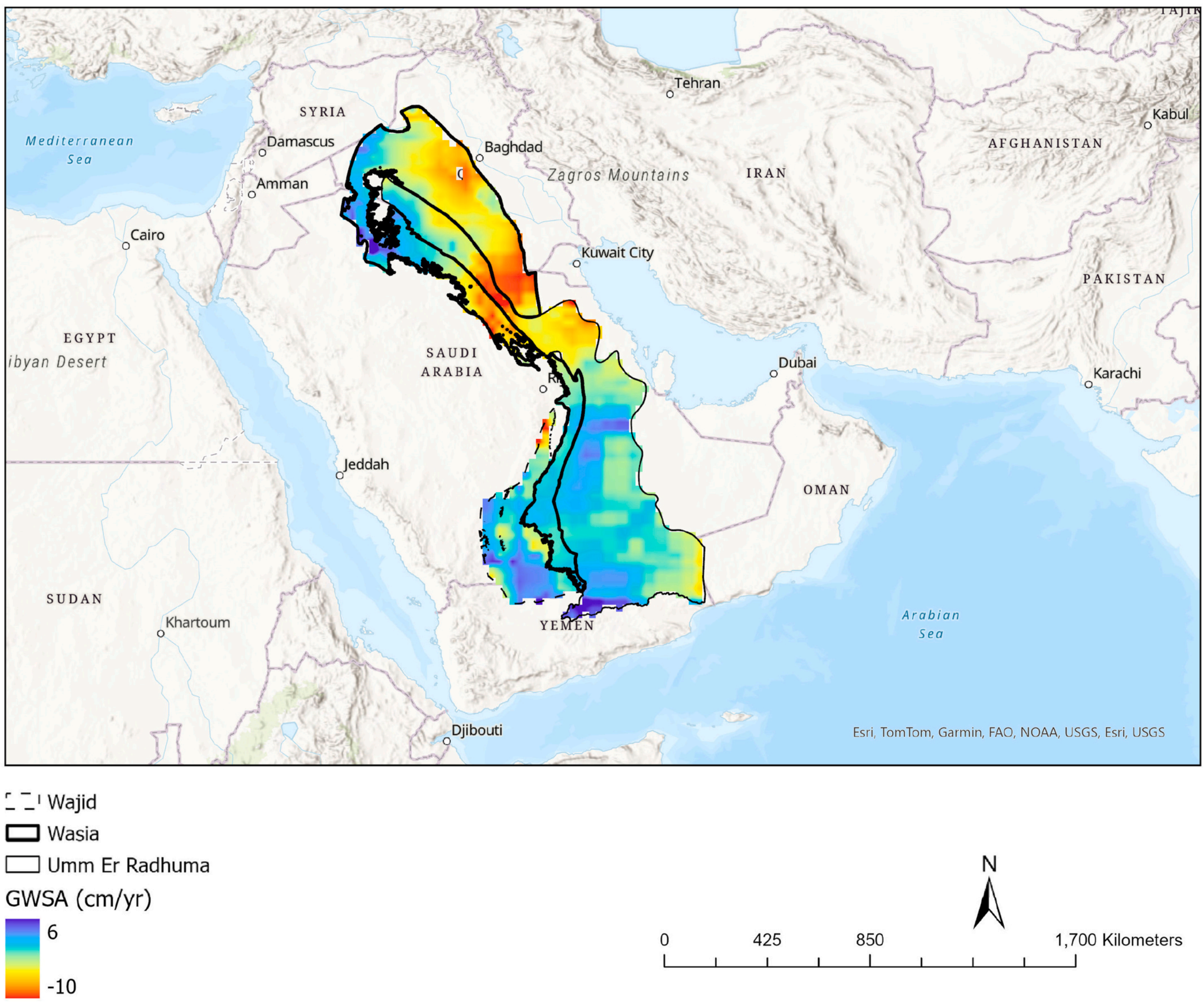

Fig. 7. Calculated Groundwater storage anomaly trends from GRACE and GRACE-FO and GLDAS variables.

data confirms that the central parts of this aquifer are experiencing the highest depletion during the study period (Fig. 7). The figure also shows a significant amount of depletion around Baghdad, the capital city of Iraq – confirming the robustness of this approach for monitoring groundwater storage over large areas as the importance of information exchange and cooperation over these transboundary aquifers.

The findings of this study illustrated the potential of using remote sensing earth observations in conjunction with ground-based datasets and modeling outputs to monitor past and present changes in water storage depletion, time-series patterns, and long-term trends in the vital groundwater resources of this region. However, there are two limitations that should be understood along with the merits of this approach. One, the spatial resolution of the GRACE and GRACE-FO data sources are of coarse nature by design and provide a large-scale picture of total water storage of an area. Thus, it should be interpreted and understood along with more detailed information on local scale variations, demands, and withdrawals of water resources. Two, the downscaling processes employed by research institutions to use the GRACE and GRACE-FO gravity datasets add uncertainty to the mass concentration solutions and increase the room for error. However, the 0.25^{o} x 0.25^{o} solution prepared by CSR are known to be the most accurate and highest resolution dataset appropriate for this study.

Saudi Arabia has launched a 2030 vision and roadmap for economic, social, and institutional reforms to alter the country into a lively and sustainable society. The vision seeks to enhance the quality of life for Saudi citizens and residents, attract investments, and assemble new job opportunities (CEDA, 2016). This huge project is expected to significantly increase water demand and might cause extreme groundwater depletion unless Saudi Arabia and the neighboring countries sharing these transboundary aquifers make collaborative policies to preserve the groundwater resources. This study will help ensure that the Wajid, Umm Er Radhuma, and Wasia aquifers' water resources are monitored and utilized effectively and efficiently, and to support the sustainable development and management of the Arabian Peninsula's natural resources.

CRediT authorship contribution statement

Mohammed O. Altayyar: Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Resources, Project administration, Methodology, Data curation, Conceptualization. **Shoaib Ali:** Writing – review & editing, Validation, Software, Methodology, Investigation. **Albert E. Larson:** Software, Methodology, Data curation. **Thomas Boving:** Writing – review & editing. **Leon Thiem:** Writing –

review & editing. **Ali S. Akanda:** Writing – review & editing, Investigation, Funding acquisition.

Declaration of competing interest

The authors declare no competing interests.

Data availability

Data will be made available on request.

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