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Satellite Observed Groundwater Decline in Southern and Western Iraq

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Abstract

Over the past 20 years rainfall deficits in Iraq and the Middle East have directly depleted groundwater reserves relied upon for drinking water, Industry and Agricultural irrigation. In this research we used the satellite data collected from the satellite of Gravity Recovery and Climate Experiment (GRACE) and GRACE-FO mission to assess fresh water storage depletion in southern-western of Iraq covering parts from Tigris-Euphrates river basins as well as the western desert from(January 2010 to January 2025). GRACE/GRACE-FO satellite data reveal a significant and alarming decline in total groundwater reserves at a rate of approximately -28.6 ± 0.9 mm/year in water equivalent representing a total loss of 279 km³ over the 15-year study period. By integrating additional information from remote sensing satellite data analysis and Earth surface model outputs the analysis identifies groundwater depletion as the primary contributor to this depletion. This methodology represents the "best possible options" for regions like southern and western Iraq where data access is often extremely limited due to the complexity of the calculations. The results show a groundwater level decline of 19.4 ± 2.5 mm per year or the equivalent of 126.8 ± 16.3 cubic kilometers in volume during the study period.

Keywords: Digital Image Processing, Remote Sensing, GRACE, Tigris and Euphrates, Ground Water Reserves

انخفاض مناسيب المياه الجوفية المرصود عبر الأقمار الصناعية في جنوب وغرب العراق

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الخلاصة

على مدى العشرين عامًا الماضية، أدى نقص تساقط الأمطار في العراق ومنطقة الشرق الأوسط إلى استنزاف مباشر لمخزونات المياه الجوفية التي يُعتمد عليها في مياه الشرب والصناعة الزراعة. في هذا البحث، استخدمنا بيانات الأقمار الصناعية التي جُمعت من القمر الصناعي (GRACE) و القمر GRACE-FO لتقييم استنزاف مخزون المياه في جنوب غرب العراق، والتي تغطي أجزاءً من أحواض نهري دجلة والفرات، بالإضافة إلى الصحراء الغربية، وذلك خلال الفترة من يناير 2010 إلى يناير 2025. حيث تكشف بيانات الأقمار الصناعية GRACE/GRACE-FO عن انخفاض كبير ومقلق في إجمالي احتياطيات المياه الجوفية بمعدل يقارب -28.6 ± 0.9 ملم/سنة من منسوب الماء، وهوما يمثل خسارة إجمالية قدرها 279 كيلومترًا مكعبًا خلال فترة الدراسة التي امتدت 15 عامًا. ومن خلال دمج معلومات إضافية من تحليل بيانات الأقمار الصناعية للاستشعار عن بُعد ومخرجات نموذج سطح الأرض، يُحدد التحليل استنزاف المياه الجوفية باعتباره المساهم الرئيسي في هذا الاستنزاف. تمثل هذه المنهجية "أفضل الخيارات المتاحة" لمناطق مثل جنوب وغرب العراق، حيث يكون الوصول إلى البيانات محدودًا للغاية في كثير من الأحيان نظرًا لتعقيد الحسابات. تُظهر النتائج انخفاضًا في مستوى المياه الجوفية بمقدار 19.4 ± 2.5 ملم سنويًا، أو ما يعادل 126.8 ± 16.3 كيلومترًا مكعبًا من حيث الحجم، خلال فترة الدراسة.

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1. Introduction

It is widely known that Iraq and its neighboring countries suffer from water scarcity low rainfall and frequent disputes over limited water resources [1]. The prolonged drought from 2010 to 2025 exacerbated the pressure on the region's already scarce water resources with its most severe effects appearing after 2015 [2]. Meteorological reports in Iraq and the Middle East indicate a continuous decline in the average annual rainfall which has left Agricultural fields fallow and directly impacted wetland ecosystems. This has driven hundreds of thousands of farmers to migrate from agricultural areas to urban centers in search of work [3]. These drought conditions are often compounded by water controlling decisions in the up-stream regions south Turkey for Tigris and Euphrates rivers as any water storage or diversion measure can significantly alter water availability in the rivers system with possibly dire significances for water users in down-stream regions of Iraq [2], [4]. Water management in Tigris and Euphrates river basin presents significant challenges [4]. As a transboundary river system Tigris & Euphrates mutual by Turkey, Syria, and Iraq with a minor extent Iran. The two rivers have extensive water controlling infrastructure and their surface waters are vital for region's Agricultural and industrial economies [5]. The region's water policies are largely influenced by tensions between management decisions made by Turkey as an up-stream user and the down-stream claims for Syria and Iraq [6]. The "Turkey's Greater Anatolia Project (GAP)" has exacerbated tensions across three countries with Turkey separately constructing more than 22 dams on the two rivers many of which were completed between 2010 and 2020 [7]. This infrastructure expansion have fundamentally transformed the Tigris and Euphrates basin in several ways. Water managers in Turkey Syria and Iraq regulate river flows by scheduling water releases from reservoirs. Beneath this complex surface water system lies a network of transboundary aquifers [5]. Although these aquifers represent a dynamic source for the area particularly when water is scarce or un-available, they lack monitoring and regulation at both the local and international levels [8]. Water controlling in the Tigris and Euphrates basin faces two fundamental problems. The first is the absence of formal distribution rights for surface-water and ground-water. This problem is rooted in substantially differing views on international water law especially regarding its extension to groundwater and the dynamic interdependence of surface and groundwater resources [9]. These divergent interpretations significantly undermine the possibility of reaching any contract on legal water allocations or management guidelines for Tigris and Euphrates [10]. This data deficiency and limited access lead to a fragmented water understanding availability and use in the region. While other studies have been carried out in the region public available measurements of streamflow precipitation with evaporation are either very scarce or entirely absent where data does exist it is often incomplete [4].

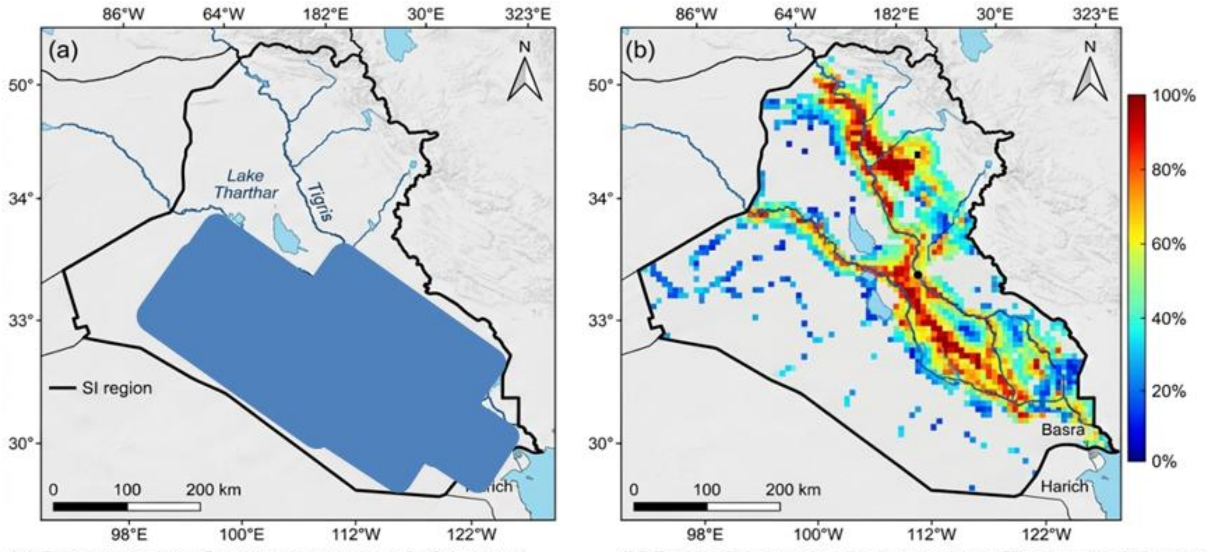
Satellite observations of time-variable gravity from GRACE (2010-2017) and GRACE-FO (2018-present) offer a valuable new tool for addressing these cracks in data availability and water monitoring [11]. When combined these satellite missions deliver a global record of total terrestrial water storage changes including surface water, soil moisture and ground-water [12].Research in recent years has shown that GRACE data can infer variations in water storage at resolutions and accuracy levels sufficient to support water management decisions. GRACE-based estimates have been applied for instance to quantify groundwater depletion assess flood risk monitor drought conditions and track reservoir storage fluctuations.

GRACE/GRACE-FO satellite data were collected and process over a 15-year period (January 2010 to January 2025) to study groundwater storage patterns in southern and western Iraq. This region encompassing most of Iraq suffers from groundwater depletion and is part of Tigris and Euphrates rivers basin as well as western desert. To help identify the causes of observed depletion and changes we collected complementary datasets including rainfall, evaporation, river flow, reservoir levels and soil moisture [12]

2. Methodology

2.1 Study Area Description

Figure 1(a, b) shows the specific study area in southern and western Iraq was selected based on an Analysis of water depletion zones within the GRACE/GRACE-FO global satellite dataset. This area shown in figure 1(a), exhibits a clear negative depletion and a decrease in total water stock covering an area of approximately 170,000 to 220,000 square kilometers. It is includes most of Iraqi portion the basin of Tigris river the middle and lower parts of Euphrates river basin within Iraq western desert. Therefore, in study we referring to the blue area in figure 1(a) the study area (southern and western Iraq) or simply the study area .The study area covers Iraqi governorates Al-Anbar, Baghdad, Karbala, Najaf, Babylon, Wasit, Al- Qadisiyah, Al-Muthanna, Thi-Qar, Basra and Maysan. The surface water bodies in the region include Lake Tharthar, Lake Habbaniyah, Lake Razzaza, the Qadisiyah Reservoir, and the Marshes of southern Iraq. In addition to these surface water bodies a complex groundwater system lies beneath the study area, comprising the Western Desert Aquifer System, the Mesopotamian Aquifer System, and the Umm ar-Radouma Aquifer System [5].Studying surface and groundwater together is crucial to understanding the dynamics of fresh water storage throughout the study area.



(a) Representation of selected study area in South and West Iraq (2010–2024)

(b) Small grid squares display percent of land under irrigation in the study region (2020 data)

Figure -1 (a) Study area in South and West Iraq (2010–2025). (b) The grid squares display the percentage of irrigated land in the study area. The color gradient from blue - red represent irrigation intensity on scale of 0% to 100%, respectively

Another important factor is land use near broader area surrounding. This larger area covers southeast Turkey and northeast Syria where the bulk by water control structures which includes reservoirs, dams, lakes and canals belonging to the GAP Project are localize with major expansion finalized between 2010 and 2020. Widespread Agricultural irrigation also exists in both the study region and the surrounding broader area [5].

2.2 Water Data Derivative from GRACE and GRACE-FO

ArcGIS program was employed to process 15 years (180 months) of GRACE mission (2010-2017) and GRACE-FO mission (2018–2025) data spanning January 2010 to January 2025. Gaps in the data record between the two missions (June 2017 to May 2018) were addressed using linear interpolation and machine learning techniques, consistent with the methodology of Swenson and Wahr (2002,2006). GRACE and GRACE-FO data were processed to produce monthly anomalies for the full water storage reported as equivalent water height (mm) relative to the study period mean for the region illustrated in Figure 1b. Filtering and scaling were applied to the data to reduce noise and restore lost signals necessitating a scale factor of 1.14 for estimating regional mass changes [12]. Following removal of the annual signal of full water storage depletion (mm/yr) is calculated. The influence of the Arabian Gulf situated to the southeast of the study region was determined to be minor contributing less than 2% to the overall full water storage depletion [11].

2.3 Output from the (GLDAS)

After a general investigation of hydrological in the area it became evident that no publicly accessible in-situ measurements were available for the study period. To gain a clearer understanding of the study area's water balance dynamics we therefore drew upon data from the NASA Global Land Data Assimilation System(GLDAS) which supplies modeled estimates for precipitation, evapotranspiration snow water equivalent streamflow and soil moisture [11]. GLDAS is land surface model framework merges the satellite based observations with advanced modeling capabilities to support climate and hydrologic research. To minimize the bias associated with any single model, we used outputs from three GLDAS land surface models VIC, Noah and CLM2 in this study [11]. GLDAS forcing and model outputs constitute a practical means of overcoming data inaccessibility in regions like Iraq and they are expected to serve as the best available proxy datasets for analogous areas characterized by limited or elusive observational records [12]. Precipitation from observations and evapotranspiration and streamflow from model outputs were integrated into the water balance calculation.

$$dS/dt = P - E - Q$$

dS/dt = water storage change with time, P = precipitation, E= evapotranspiration. Q = stream-flow.to validate our results, the dS/dt model was compared with the corresponding model obtained from GRACE. To determine the individual contributions of snow water equivalent, soil moisture and lake/reservoir elevations against total water storage anomalies detected by GRACE/GRACE-FO satellite we combined GLDAS outputs for the two former variables with satellite altimetry measurements of the latter. All datasets were expressed as monthly anomalies relative to the research period mean in(mm)and as depletion in(mm/yr) after removing the annual signals.

2.4 Acquisition of Surface Water level Data

Remote Sensing data on satellite water levels were obtained from two databases (French Hydro-web and German DAHITI) to track how water storage in lakes and rivers changed over time were used to compute variation of water storage from surface-bodies. The full data time series for main surface-water bodies lake Habbaniyah, the Qadisiyah Reservoir, and Haditha Reservoir were obtainable for study period (2010-2025). That water bodies rank between the largest in the study area by surface extent collectively representing roughly 60% of the region's full surface water. Monthly altimetry-derived water elevations were changed into monthly volumetric water change using the known mean exterior area of each water-body. The resulting volume changes were then summed and separated by the full area of the region to obtain surface water storage anomalies in (mm) relative to the study period . After removing the signal we also calculated the depletion in surface water storage in mm/yr. These data were ultimately used to infer how much surface water variations contributed to the full water storage changes detected through the GRACE/GRACE-FO [12].

2.5 Estimating Storage Changes of Groundwater

The research has shown that it is possible to extract groundwater from the full water storage data obtained through GRACE/GRACE-FO. Using this approach monthly groundwater storage variation is predictable as the residual of the water storage budget stability calculated by subtracting changes in snow water equivalent surface water and soil moisture storage from full water storage changes calculated by GRACE/GRACE-FO.

$$G = S - SWE - SW - SM$$

G denote ground water storage, S denote full water storage, SWE denote snow water equivalent. SW denote surface water storage and SM indicates soil moisture. The primes signify anomalies relative to the mean of each respective component over the study period [12].

2.6 Analysis of Error

To calculate error for other components the depletion error of GW was estimated using the equation:

$$\sigma\_aGW = \{[(\sigma\_aS)^2 + (\sigma\_aSW)^2 + (\sigma\_aSM)^2 + (\sigma\_aSWE)^2]\}^{0.5}$$

σ_aS is the associated one-sigma depletion error for full water storage from GRACE /GRACE-FO (0.9 mm/yr). σ_aSW is the associated one-sigma depletion error from the altimetry-derived surface water (0.6 mm/yr) σ_aSM and σ_aSWE are the depletion errors for GLDAS computed soil moisture (2.3 mm/yr) and snow water equivalent (0.4 mm/yr) separately. The depletion and depletion error for each component of water budget are calculated after annual signal is removed [12].

3. The Results

3.1 Inter-Comparison of Full Water storage from GRACE/GRCAE-FO & GLDAS

Monthly terrestrial water storage anomalies from GRACE/GRACE-FO satellite observations were compared to GLDAS based anomalies of study area latter calculated as average of three land surface models as shown in figure 2. This evaluation reveals three key subjects that merit additional argument. The first numerous studies have demonstrated by GRACE/GRACE-FO have data capture natural water storage variation very well when compared with observation. A second notable discrepancy is seasonal cycle of full water storage from GRACE/GRACE-FO exhibits greater amplitude than the model simulations as evident in figure 2. Earlier GRACE based studies indicate that this mismatch is typically due to models omitting or poorly representing essential storage components including snow water equivalent surface water bodies reservoirs total soil moisture and groundwater storage a conclusion that holds true for this study as well [10]. Third, in regions where the human water management exert a strong influence on the regional water balance outputs from land surface models differ markedly from GRACE/GRACE-FO observations. As show in Figure 2. GLDAS simulations don't capture anthropogenic response to the prolonged drought from 2010 to 2025 [2]. The models can represent natural variability driven by decreasing precipitation they lack parameterizations for surface and ground water reservoir storage and abstraction irrigation and the human water activates. Therefore, they unable to represent excessive groundwater extraction that happens during drought periods. As a result the models fail to reproduce the declining water storage depletion observed by GRACE/GRACE-FO [8].

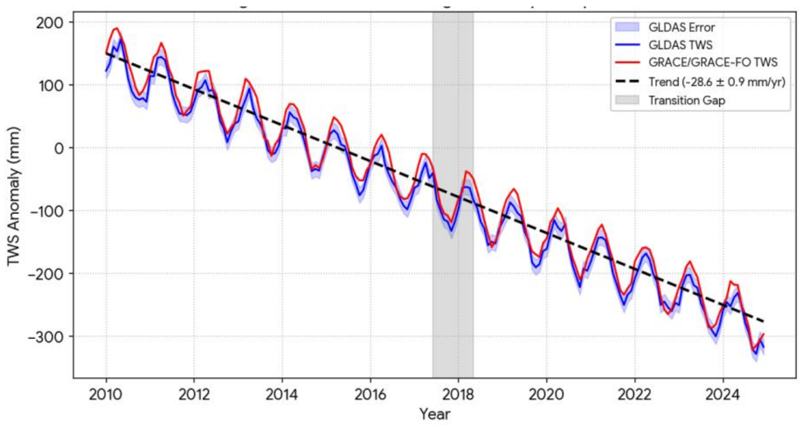


Figure -2 The full water storage anomaly

3.2 Full Terrestrial Water Reserves

Figure (3a) show the GRACE/GRACE-FO-derived depletion in full water reserves for the study region from 2010 to 2025 was −28.6 ± 0.9 mm/yr. This corresponds to an annual water volume loss of 18.6 ± 0.6 km^3 resulting in the total loss approximately 279 ±6.0 km^3 over last 15-year study period . This amount of decline ranks among the biggest losses of liquid fresh water observed at any continent. GRACE/GRACE-FO data reveal a clear downward depletion in regional water storage particularly after 2012 with an accelerated decline after 2015. This accelerated loss coincides with the persistence and intensification of a local drought along with subsequent shift in water use and availability. To contextualize the magnitude of this loss the total 279 km^3 reduction over 15 years is roughly equivalent to 2.325 times the volume of Lake Tharthar which has an average volume of about 120 km^3 [2].

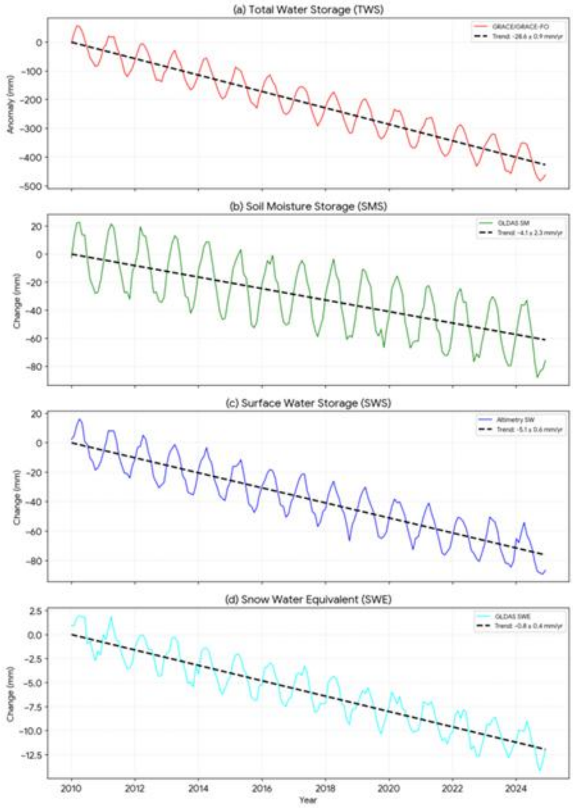


Figure -3 Comparison of monthly storage anomalies and depletion across different water storage components for the study period (2010-2025): (a) GRACE/GRACE FO total water storage b) GLDAS soil moisture (c) altimetry based surface water storage and (d) GLDAS snow water equivalent

3.3 SWE and Soil Moisture Levels

Soil moisture depletion from GLDAS are presented in fig. 3b while fig. 3d show snow water equivalent depletions. The soil moisture depletion was(-4.1 ± 2.3 mm.yr-1) and the snow water equivalent depletion was (-0.8 ± 0.4 mm.yr-1) corresponding to volume losses of (-1.9 ± 1.1 km^3/yr) and (-0.4 ± 0.2 km3/yr) respectively. This negative depletion is largely climate-driven and reflect the regional deficit. Together they account for approximately 17% of the observed full water losses [9]. Figure 3c displays surface water storage anomalies. Over the study period the observed depletion was -5.1 ± 0.6 mm/yr representing loss of -2.3 ± 0.3 km^3/yr equivalent to nearly 18% from the full water volume lost between 2015 and 2025. The study surface water depletion likely underestimates the true depletion for two reasons: first only five water bodies (Lake Tharthar Lake Habbaniyah the Qadisiyah Reservoir and the Haditha Reservoir) were included in the calculation; second, changes in their surface areas were not accounted for. Assuming a constant surface area leads to an overestimation of monthly surface water storage yet this same assumption causes the calculated rate of decrease (depletion) to be underestimated. Therefore, omitting reservoirs and ignoring surface area reduction both cause underestimation of the actual surface water storage depletion. As a result our residual groundwater storage estimates may be overestimated [12].

3.4 Ground Water

Ground-water storage irregularities were calculated as the residual following ground-water estimation equation. The soil moisture and equivalent surface water components of the water budget were subtracted from the GRACE/GRACE-FO observed full water storage anomalies. Figure (4) illustrates monthly ground-water storage anomaly estimate using this approach. Mutually the seasonal cycle with a pure downward depletion in ground water storage after 2012 are apparent with an even sharper decline beginning in 2015. The computed groundwater depletion was (-19.4 ± 2.5 mm/yr) (-12.7 ± 1.6 km^3/yr amounting to -126.8 ± 16.3 km^3) for full study period a significant reduction accounts by 45% form total change in water storage between 2010 and 2025. The declining depletion ground water coincides with the drought that continued from 2010 through 2025 with particularly severe declines after 2015. The depletion in the water storage components is shown in Table 1.

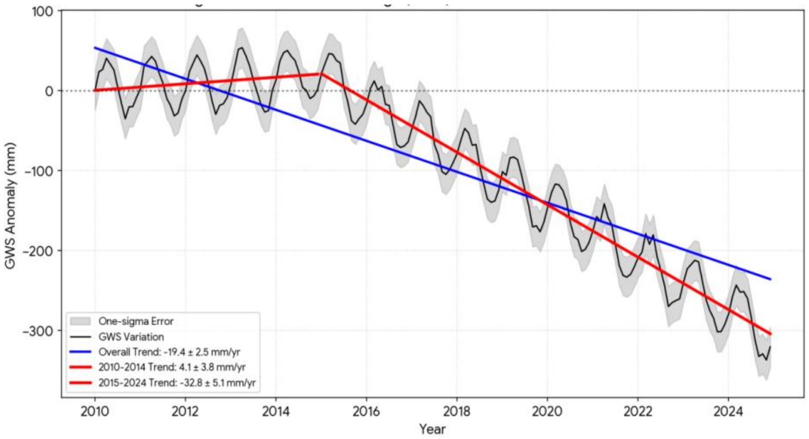


Figure -4 Temporal Variations in Monthly Groundwater-storage

Table 1- Water storage Depletion of Study Area from 2010 to 2025

Module	**Depletion (mm/yr)**	**Lost in Volume (km^3/yr)**	**Average Volume (km^3)**
GRACE/GRACE-FO water-storage	-28.6 ± 0.9	-18 ± 0.6	-279 ± 60
Surface Water	-5.1 v 0.6	-2.3 ± 0.3	-34.5 ± 4.5
Soil Moisture	-4.1 ± 2.3	-1.9 ± 1.1	-28.5 ± 16.5
Snow Water Equivalent	-.08 ± 0.4	-0.4 ± 0.2	-6.0 ± 3.0
Ground Water (GRACE-SW-SM-SWE)	-19.4 ± 2.5	-12.7 ± 1.6	-126 ± 16.3
Ground Water from 2010 to 2014	4.1 ± 3.8	2.7 ± 2.5	13.5 ± 12.5
Ground Water from 2015-2025	-32.8 ± 5.1	-21.4 ± 3.3	-214.0 ± 33.0

4. Discussion

4.1 Hydrologic Depletion in South and West Iraq (2010–2025)

According to GRACE/GRACE-FO data the average volume of water lost over 15-year study period was nearly 279 km^3 a depletion particularly concerning for regions such as South and West Iraq which are already grappling with severe water scarcity. Our analysis indicates that groundwater depletion is the primary driver of this decline accounting for roughly 45% of the full water loss with most of that depletion occurring after 2015. The rate of groundwater depletion more than doubled from a slight gain of 4.1 mm/yr between 2010 and 2014 to a loss of -32.8 mm.yr-1 between 2015 and 2025 reflecting a dramatic acceleration in groundwater extraction. While the lack of in situ data introduces uncertainty which we have attempted to quantify we maintain integrating remotely sensing and in-situ data offers a valuable alternative for considerate hydrological change in data-scarce region such as Iraq. Land subsidence resulting from excessive groundwater extraction near Baghdad, Karbala, and the western desert is a well-documented phenomenon, with subsidence rates accelerating after 2015. Institution information also highlighted the displacement of several thousands of people from northern and central Iraq as a result of water scarcity with further waves of displacement reported after 2018 . In 2022 the United Nations Environment Program ranked Iraq as the fifth most vulnerable country to climate change foreshadowing dire consequences for water availability. During the study period the water use behaviour in Iraq followed a predictable response to the crisis as droughts intensified and surface water dwindled groundwater extraction increased dramatically. Elevation data indicate that the Qadisiyah Reservoir Iraq's main water reservoir on the Euphrates River experienced a sharp decline starting in 2012 reaching its lowest historical levels in 2018 and 2022. In 2021 hydrological statistics confirmed that the flow of the Euphrates river had reduced from around 50% of its standard level when it enters Iraq from Syria. Deprived of surface water from reservoir discharges or river stream. Iraq had no practical option but to rely more heavily on groundwater. The Iraqi government drilled approximately 3000 new ground-water wells between 2010 and 2025. The vast majority after 2015 in areas west of the Euphrates River with intensive extraction of groundwater reserves to compensate for the surface water shortage. It is worth noting that these figures only include wells drilled by the government. It is almost certain that civilians have added countless set apart wells to meet their Agricultural industrial and domestic needs. This swift depletion of ground-water without any significant recharge from rainfall or stream flow appears to be a major factor in the estimated groundwater.

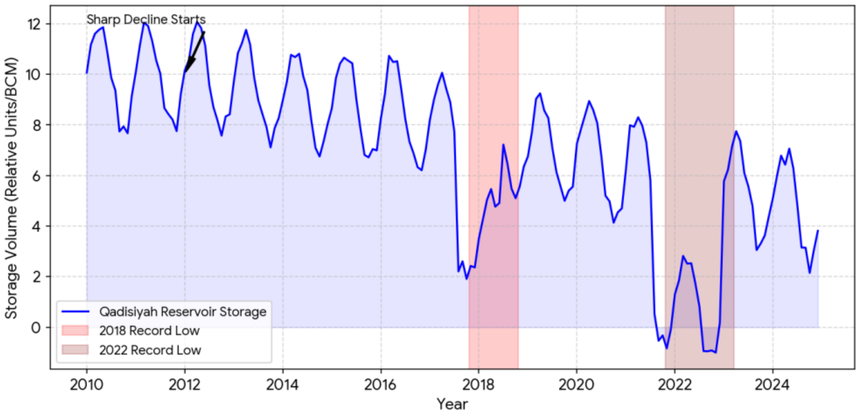


Figure -5 Qadisiyah Reservoir Storage Variations

4.2 Modern Solutions for Joint Water Management

Our analysis highlights the value of GRACE, GRACE-FO and other remote sensing advances as critical tools for transboundary environmental decision-making. Using these data we found that the study region lost nearly 279 km^3 of water from 2010 to 2025 with groundwater accounting for roughly 127 km^3 over the full 15-year period. Notably, most of this groundwater loss (214 km^3) occurred after 2015 reflecting a dramatic acceleration in extraction rates during the second half of the study period. The economic toll of this crisis includes Agricultural losses unemployment forced displacement and profound hardship. Politically it signals a lost chance for collaborative water management. The pronounced increase in the rate of groundwater depletion after 2015 should function as an urgent call for regional cooperation. Though no replacement for in situ measurements exists satellite-based observations offer a unique window into water depletion in data-limited areas. Presented with a shared picture of declining resources nations might find common ground to foster cooperation.

Recent advances in hydrologic remote sensing and hydrological modelling coupled with improved access to observational data suggest that the opportunity to construct an accurate and comprehensive picture of freshwater availability for a specific region or globally is now within reach. The successful continuation of GRACE-FO and planned future gravity missions will enable continued monitoring of this critical region. Science-informed studies are indispensable to more active sustainable and transboundary regions collective water organization.

5. Conclusions

This study demonstrates that GRACE and GRACE-FO satellite data can successfully quantify fresh water storage depletion in data-scarce regions such as South and West Iraq over the15-year period from January 2010 to January 2025. The region lost approximately 279 km^3 of full water storage at a rate of -28.6 mm/yr. Groundwater depletion was the primary driver accounting for 45% of the total loss (127 km^3 at a rate of -19.4 mm/yr). Surface water storage loss contributed 18% while soil moisture and snow water equivalent losses contributed the remaining 17%. The depletion accelerated dramatically after 2015 with groundwater loss rates increasing from near-stable conditions (2010-2014) to -32.8 mm/yr (2015-2025) representing a more than eightfold increase in depletion rate. These results raise serious issues regarding transboundary water organization in Tigris-Euphrates Basin highlighting the urgent need for international water use treaties and cooperative management strategies. For water-scarce Iraq satellite gravimetry offers an invaluable tool for monitoring and managing groundwater resources in the absence of adequate in-situ data particularly as climate change and upstream development continue to pressure the region's water resources.

Ethical Statement

This research did not involve any human participants, animals, or sensitive personal data. All data utilized in this study were derived from publicly available satellite remote sensing products (GRACE, GRACE-FO, GLDAS, Hydro-web, and DAHITI) and processed using standard geophysical and hydrological methods. No ethical approval was required for this type of observational, satellite-based environmental study.

Disclosure and Conflict of Interest

The authors, Alaa Ali Hussein and Adnan Hashim Abdulkadhim, declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. No funding bodies or external organizations influenced the design, analysis, or interpretation of the data. The results and conclusions presented are solely those of the authors.

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