تقييم 38 عامًا من تغير المياه السطحية في البحيرات والسدود العراقية باستخدام مؤشر فرق المياه الطبيعي وصور لاندسات

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عمر ، دابان كاظم ، محمد طيب رؤوف ، مصطفى صالح إسماعيل ، تقييم 38 عامًا من تغير المياه السطحية في البحيرات والسدود العراقية باستخدام مؤشر فرق المياه الطبيعي وصور لاندسات،مجلة مركز بابل للدراسات الانسانية، أيلول 2026،المجلد:16، العدد:9.

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Evaluating 38 Years of Surface Water Change in Iraqi Lakes and Dams Using Landsat-Derived Normalized Difference Water Index (NDWI)

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ملخص

تتعرض الموارد المائية السطحية في العراق لضغوط متزايدة نتيجة لتغير المناخ، والجفاف طويل الأمد، وممارسات إدارة المياه في الدول الواقعة أعلى مجرى النهر. تهدف هذه الدراسة إلى تقييم التغيرات طويلة الأمد في امتداد المياه السطحية عبر البحيرات والسدود الرئيسية في العراق، لفهم الاتجاهات الهيدرولوجية خلال العقود الأربعة الماضية. لهذا الغرض استخدمنا

صور الأقمار الصناعية (لاندسات) ومؤشر الفرق المائي المطبع (NDWI) لتحليل ديناميكيات المياه السطحية من عام (1986 حتى عام 2024)، وذلك في ستة مسطحات مائية رئيسية (سد الموصل، سد دوكان، سد دربندخان، سد حديثة، بحيرة الرزازة، وبحيرة الثرثار). وقد أجريت جميع التحليلات باستخدام منصة (**Google Earth Engine**)، من خلال إنشاء تراكيب سنوية لمؤشر (NDWI) واستخدام عتبات تصنيف مائي ثابتة. تكشف النتائج عن انخفاض كبير في المياه السطحية في بحيرة الرزازة والتي أظهرت اتجاها تنازليا قويا ومستقرا ($R^2 = 0.86$)، إلى جانب انخفاضات ملحوظة في بحيرتَي (الثرثار وحديثة). وأظهر سد (الموصل) اتجاها تنازليا أقل وضوحا، لكنه يبقى ملحوظا، في حين بقي كل من سد (دوكان) وسد (دربندخان) مستقرين نسبيا. تظهر خرائط التغيرات المكانية فقدانا واسع النطاق للمياه في (الرزازة وحديثة والثرثار)، مع تغيرات طفيفة فقط في سد (الموصل).تبرز هذه النتائج شدة الضغوط الهيدرولوجية في وسط وغرب العراق وتؤكد الحاجة الملحة إلى إدارة مستدامة للمياه لا سيما في ظل التحديات العابرة للحدود والتغيرات المناخية المتسارعة.

Abstract :

Iraq's surface water resources are under increasing pressure due to climate change, prolonged droughts, and upstream water management practices. This study aims to evaluate long-term changes in surface water extent across major Iraqi lakes and dams to understand hydrological trends over the past four decades. Using Landsat satellite imagery and the Normalised Difference Water Index (NDWI), we assessed surface water dynamics from 1986 to 2024 across six major water bodies: Mosul, Dokan, Darbandikhan, Hadithah, Razazza, and Tharthar. All analyses were performed in Google Earth Engine (GEE) using annual NDWI composites and fixed water classification thresholds. Findings reveal significant surface water decline in Lake Razazza, which showed a strong and consistent decrease ($R^2 = 0.86$), and notable reductions in Tharthar and Hadithah. Mosul Dam experienced a smaller but clear downward trend, while Dokan and Darbandikhan remained relatively stable ($R^2 = 0.05$). Spatial change detection maps show extensive water loss in Razazza, Hadithah, and Tharthar, with minimal change in Mosul Dam. These results highlight the severity of hydrological stress in central and western Iraq and underscore the urgent need for sustainable water management, particularly under transboundary water constraints and shifting climatic conditions.

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1. Introduction

In recent decades, the global climate system has been undergoing profound changes, with warming trends becoming increasingly evident across all continents. This global warming, primarily driven by the accumulation of greenhouse gases in the atmosphere, has led to shifting weather patterns and more frequent and intense climatic extremes (Intergovernmental Panel on Climate Change 2021). One of the most sensitive indicators of these climatic shifts is the hydrological cycle, which governs the distribution and availability of surface water resources. Particularly in semi-arid regions like Iraq, changes in precipitation regimes, increased evapotranspiration rates, and prolonged droughts have all contributed to a significant alteration in water body dynamics (Al-Ansari, 2013).

Iraq, situated in the heart of the Middle East, has historically relied on a limited number of major water sources, most notably the Tigris and Euphrates rivers and their tributaries. However, the combined effects of climate change and regional geopolitical developments have placed these water bodies under increasing stress (Al-Ansari 2013). In recent years, fluctuations in rainfall intensity and duration have been observed, with more frequent periods of drought interspersed with short bursts of heavy rainfall. These changing patterns have disrupted the replenishment cycles of lakes, dams, and reservoirs, many of which serve as critical sources for irrigation, drinking water, and hydroelectric power (Issa et al.,2014).

Beyond climate change, anthropogenic pressures are further compounding Iraq's water security challenges. Rapid population growth, urban expansion, industrialisation, and increased agricultural demand have all intensified the strain on existing water resources (Al-Falahi and Al-Azzawi 2021). The expanding population not only requires more direct water consumption but also indirectly drives water demand through increased food production and energy consumption (UNESCO and FAO 2018) . This growing pressure has, in many cases, led to unsustainable water withdrawal rates and deteriorating water quality.

Complicating matters further is the transboundary nature of Iraq's principal rivers. A significant portion of the Tigris and Euphrates river flow originates outside of Iraq, primarily from neighbouring countries such as Turkey and Iran (Mazlum, 2009). In recent decades, these upstream nations have undertaken extensive dam construction and water diversion projects. Turkey's Southeastern Anatolia Project (GAP), for example, includes the development of numerous dams and irrigation schemes, which have significantly reduced downstream flow into Iraq *(Altinbilek 2004)*. Similarly, Iran has redirected tributaries of the Tigris, affecting the water balance in eastern and southern Iraq. These upstream activities not only limit Iraq's access to freshwater but also alter the seasonal flow regimes that many ecosystems and human systems depend on (ORSAM.,2012).

Given these overlapping challenges, it is more important than ever to monitor the spatial and temporal dynamics of surface water in Iraq. Understanding how lakes and reservoirs have changed over time is essential for crafting informed water management strategies and for ensuring the sustainability of water supplies in the face of growing uncertainty. Long-term monitoring allows stakeholders to detect trends in water availability, anticipate future shortages, and evaluate the impacts of both natural and anthropogenic influences.

One of the most effective tools for monitoring surface water dynamics is satellite remote sensing *(Pekel et al. 2016)*. Satellite data offers a cost-effective, repeatable, and large-scale method for observing environmental changes over time, especially in regions where in situ data collection is limited or infeasible due to political, economic, or logistical constraints. Among the many satellite programs available, the Landsat series has been instrumental in long-term Earth observation (Roy et al., 2014). Since its inception in the early 1970s, Landsat has provided consistent, high-resolution imagery suitable for tracking changes in land and water surfaces across decades. The continuity of the Landsat program, along with its free and open-access data policy, makes it particularly valuable for studying environmental change in developing and data-scarce countries like Iraq.

In this context, spectral water indices such as the Normalised Difference Water Index (NDWI) have proven useful for detecting and delineating water bodies using satellite imagery *(McFeeters 1996)*. The NDWI, which contrasts reflectance in the green and near-infrared (NIR) bands, enhances water features while suppressing non-water elements such as vegetation and soil. When applied to long-term Landsat data, the NDWI allows for the detection of interannual variability and persistent trends in surface water coverage.

Before the advent and widespread accessibility of satellite remote sensing, surface water extent was commonly estimated through ground-based hydrological surveys, manual field measurements, and aerial photography *(Alsdorf et al. 2007)*. While these traditional approaches provided valuable local insights, they were often labour-intensive, time-consuming, and limited in spatial and temporal scope. In situ gauging stations, for instance, were commonly used to monitor river discharge and reservoir levels, but their coverage was sparse and often restricted to

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specific, accessible locations (Vörösmarty et al., 2000). Aerial photography offered broader perspectives, yet required favourable weather conditions and was costly to repeat over time.

Hydrological models have also been employed to estimate surface water dynamics by simulating runoff, infiltration, and reservoir storage based on meteorological and land surface data. While these models can be powerful predictive tools, their accuracy heavily depends on the quality and resolution of input data, something often lacking in regions like Iraq. Moreover, such models require regular calibration and validation against observational data, which may be scarce or outdated.

In contrast, modern remote sensing approaches overcome many of these limitations by enabling consistent, synoptic, and objective monitoring across large spatial extents and over multiple decades. In addition to Landsat, other satellite platforms such as MODIS, Sentinel-1, Sentinel-2, and, more recently, commercial high-resolution satellites have further expanded the ability to observe surface water dynamics at various spatial and temporal resolutions. Radar-based sensors like those aboard Sentinel-1 offer the advantage of cloud-penetrating capabilities, which is particularly useful during the rainy season or in persistently cloudy conditions. Meanwhile, MODIS offers higher temporal resolution, making it suitable for monitoring rapid surface water changes, albeit at a coarser spatial scale.

Furthermore, data fusion and machine learning approaches are increasingly being integrated with remote sensing to enhance surface water detection, reduce classification errors, and fill observational gaps. These advancements have significantly broadened the toolkit available for water resource monitoring, allowing researchers to explore surface water dynamics with unprecedented detail and continuity.

This study aims to evaluate 38 years of surface water dynamics in six major Iraqi lakes and dams using Landsat imagery and the NDWI. Specifically, the research focuses on identifying patterns of surface water gain and loss over time, quantifying annual water extent, and detecting long-term changes in water body configurations. By utilising the computational capabilities of Google Earth Engine and the full historical archive of Landsat surface reflectance data from 1986 to 2024, this research provides a comprehensive assessment of how surface water resources have evolved in Iraq over nearly four decades. The results offer insights not only into the environmental changes affecting Iraqi water bodies but also into the broader implications of climate stress, regional geopolitics, and water governance in transboundary river basins.

2. Methods

2.1 Study Area and Data Sources

To assess long-term surface water dynamics in the lake system, we used a polygon shapefile delineating the lake boundaries. This shapefile was created based on the lake extent observed in Landsat imagery from 1986 and uploaded as a custom asset to Google Earth Engine (GEE). In total, six lakes and dams were included in this study (Table 1 and Figure 1). The analysis spans the period from 1986 to 2024 and relies on optical satellite data from the Landsat program. Specifically, we used four Level-2 surface reflectance datasets: Landsat 5 TM (LANDSAT/LT05/C02/T1_L2), Landsat 7 ETM+ (LANDSAT/LE07/C02/T1_L2), Landsat 8 OLI (LANDSAT/LC08/C02/T1_L2), and Landsat 9 OLI-2 (LANDSAT/LC09/C02/T1_L2). These datasets provide atmospherically corrected surface reflectance and include pixel-level quality assurance (QA) bands, which are essential for filtering cloud and shadow artefacts.

Table 1: Overview of major dams and artificial lakes included in this study, detailing their construction periods, anthropogenic origin, associated river systems, and corresponding references.

Name	**Built / Created**	**Human-made?**	**River (Location)**	**Reference**
Mosul Dam	Construction: 1981–1986; commissioned July 1986	Dam	Tigris River	(Annunziato et al. 2016)
Dukan Dam	Built 1954–1959; power station operational ~1979	Dam	Little Zab River	Ali, Rawshan 2019
Darbandikhan Dam	Constructed 1956–1961; inaugurated Nov 1961	Dam	Sirwan/Diyala River	Othman 2023
Lake Razzaza (Milh)	Late 1970s (flood-control lake)	Artificial lake	Euphrates (via Habbaniyah)	(Jumaah et al. 2022)

Haditha Dam	Built 1977–1988; completed 1988	Dam	Euphrates River	(Li et al. 2018)
Lake Tharthar	Created 1956 (reservoir)	Artificial lake/reservoir	Inlet from Tigris; connects to Euphrates	Sissakian 2011

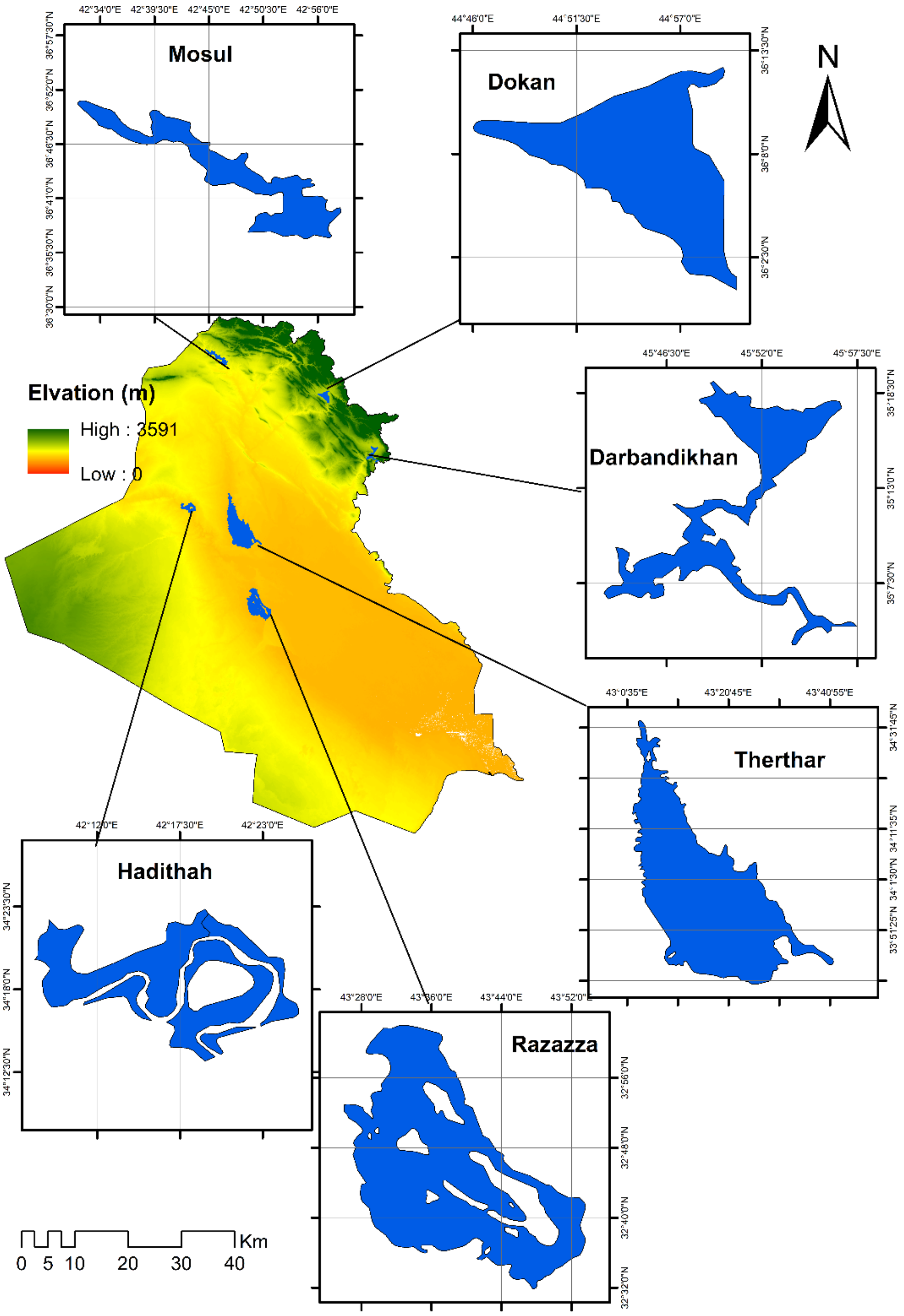

Figure 1. Location and spatial extent of the six major lakes and dams analyzed in this study across Iraq: Mosul, Dokan, Darbandikhan, Hadithah, Razazza, and Tharthar. The background map shows the elevation gradient across Iraq, ranging from low-lying areas (0 m) in the south to mountainous regions (up to 3591 m) in the northeast. Insets display the shape and surface water boundaries of each lake or reservoir, as derived from Landsat imagery.

2.2 Data Preprocessing

Preprocessing steps were applied to ensure consistency and comparability across sensors (Landsat 4–5, 7, 8, and 9) and over time. All images were spatially subset using the lake boundary polygon and temporally filtered to cover the full calendar year (1 January–31 December) for each year within the study period. To reduce the impact of cloud and cloud-shadow contamination, we used the QA_PIXEL band and applied bitmask operations targeting clouds (bit 5) and cloud shadows (bit 3). Surface reflectance values from the SR_Bx bands were then rescaled using the coefficients provided by USGS (scale factor 0.0000275 and offset −0.2). After preprocessing, all reflectance data were harmonised to a common 30 m spatial resolution, resulting in a consistent time series suitable for subsequent analysis.

2.3 NDWI Computation and Water Classification

To understand how the surface water extent of the studied lakes and dams has changed over the period considered in this study, we used the Normalised Difference Water Index (NDWI). The NDWI was calculated using the green and near-infrared (NIR) bands. Specifically, bands SR_B2 and SR_B4 were used for Landsat 5 and 7, while SR_B3 and SR_B5 were used for Landsat 8 and 9. The NDWI was computed as:

NDWI= (Green + NIR) \ (Green−NIR) …………………………. Eq.1

Annual NDWI composites were generated using the median of all NDWI images for each year. A fixed NDWI threshold of 0.1 was used to classify water pixels, as commonly applied in similar studies, although this value can be adjusted depending on lake characteristics.

Moreover, to quantify the surface water extent annually, we applied the binary water masks to pixel area (30 m resolution), and calculated the total water-covered area using ee.Reducer.sum(). The resulting water area was then normalized by the total lake polygon area to estimate the percentage of surface water for each year.

Finally, to assess long-term surface water change, we created a change detection map by subtracting the binary water mask of the first year (1986) from that of the last year (2024). The resulting difference image highlights areas of water gain (positive values), water loss (negative values), and no change (value = 0). This change map was visualized using a diverging color palette and exported as a GeoTIFF for further use and interpretation.

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2.4 Precipitation Data

To assess the potential influence of precipitation variability on lake surface water area, we integrated long-term precipitation data from the NASA Prediction of Worldwide Energy Resources (POWER) project. Specifically, we used monthly corrected precipitation totals (PRECTOTCORR) derived from the MERRA-2 reanalysis dataset, accessed via the NASA POWER Data Access Viewer. The dataset provides consistent, gridded climate variables with a spatial resolution of 0.5° × 0.5° (approximately 50 km × 50 km at mid-latitudes), suitable for regional-scale environmental analysis.

For each lake included in this study, precipitation data were extracted for the grid cell encompassing the lake centroid. The data spans the same temporal range as the Landsat imagery (1986–2024), allowing for annual aggregation and direct comparison with surface water extent metrics. In addition to supporting long-term trend analysis, this precipitation data was also used to assess statistical correlations between annual rainfall and surface water coverage for each water body considered in the study. By incorporating precipitation as a climatic driver, we aimed to better understand how interannual and decadal rainfall variability may have contributed to the observed changes in surface water coverage. This is particularly important for semi-arid and arid regions like Iraq, where lake water budgets are strongly influenced by both direct rainfall and upstream inflow regulated by dam operations and seasonal precipitation dynamics.

3 . Results

3.1 Temporal Surface Water Trends (1986–2024)

The long-term analysis of surface water area changes reveals notable temporal fluctuations across all six lakes and dams (Figure 2). Among them, Lake Razazza exhibited the most dramatic and consistent decline in surface water coverage over the 38-year period. The lake experienced a strong negative trend with an R^2 of 0.86, indicating a substantial and steady decrease in water extent. Similarly, Tharthar and Hadithah lakes showed persistent downward trends in water body surface area. The regression analysis for Tharthar revealed an R^2 of 0.49, suggesting a moderate to strong decline, while Hadithah showed a weaker trend (R^2 = 0.22), but with high interannual variability (Figure 2).

Mosul Dam also experienced a general decline, although with relatively smaller annual fluctuations and a lower R^2 value (0.18). In contrast, both Dokan and Darbandikhan reservoirs showed the least pronounced trends. Dokan displayed minimal variation over time, and the regression line yielded a very low R^2 (0.02), indicating little to no long-term trend.

Darbandikhan also showed weak correlation (R^2 = 0.06), but with irregular year-to-year changes rather than a clear directional trend.

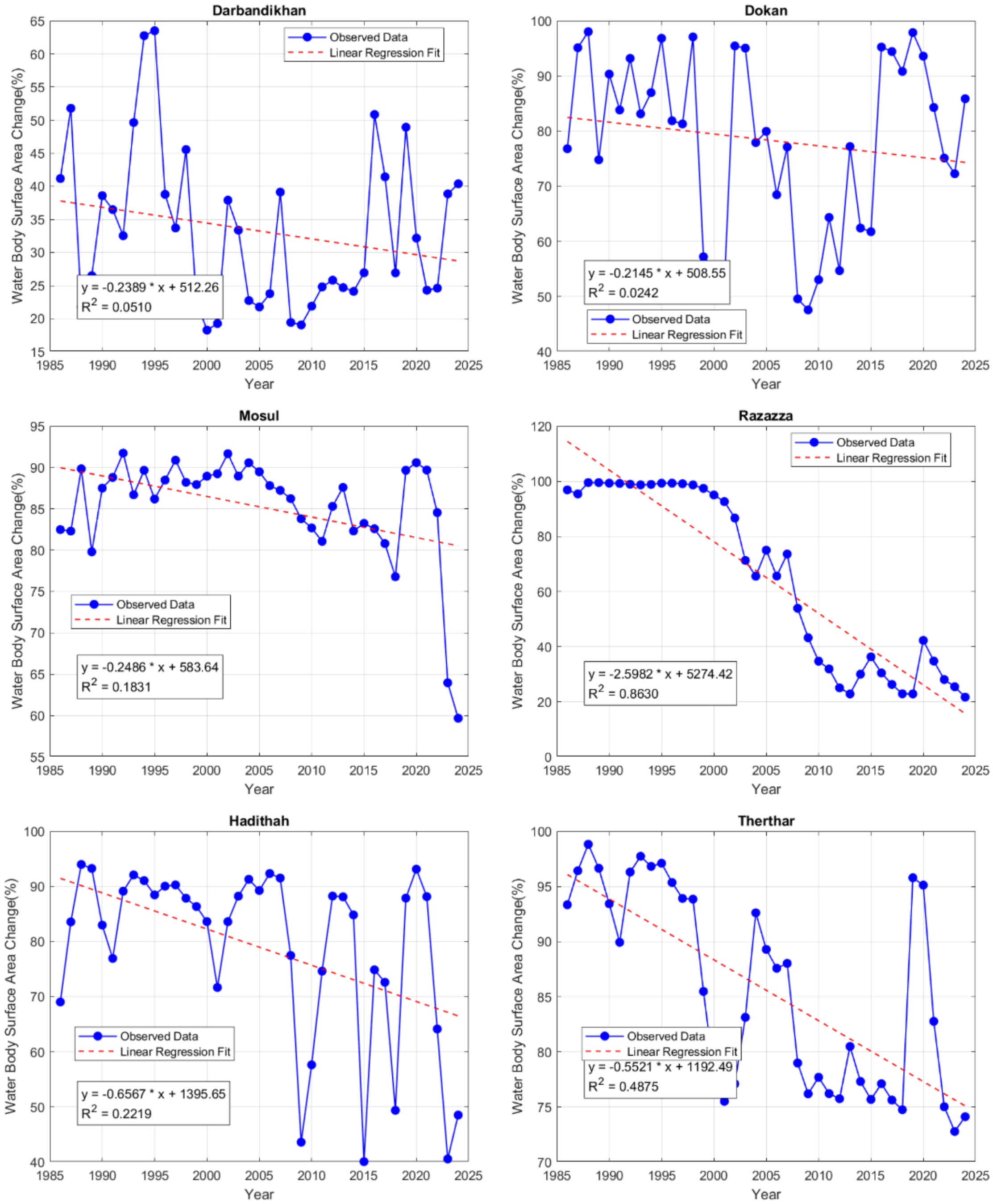

Figure 2. Trends in surface water area change (%) for six major lakes and dams in Iraq from 1986 to 2024, derived using Landsat-based NDWI. Each panel shows observed annual surface water extent (blue dots), a fitted linear regression trend (dashed red line), and the corresponding regression equation and R^2 value. The figure highlights varying degrees

of long-term water surface decline across the water bodies, with significant negative trends particularly evident in Razzaza, Tharthar, and Mosul.

3.2 Spatial Change Detection (1986 vs. 2024)

The spatial change detection analysis between 1986 and 2024 reveals notable surface water loss across several lakes (Figure 3). Lake Razazza experienced the most pronounced shrinkage, with extensive areas along its perimeter showing complete water loss. Hadithah also showed considerable retreat, particularly along its southern and central zones. In contrast, Tharthar retained a more compact core water body but exhibited widespread contraction along its northern and western edges. Dokan and Darbandikhan displayed more localised reductions, primarily along the narrow fringes of their reservoirs. Among all six sites, Mosul Dam exhibited the least spatial change, with the majority of its surface water extent remaining stable, aside from minor localised reductions in the southern section (Figure3).

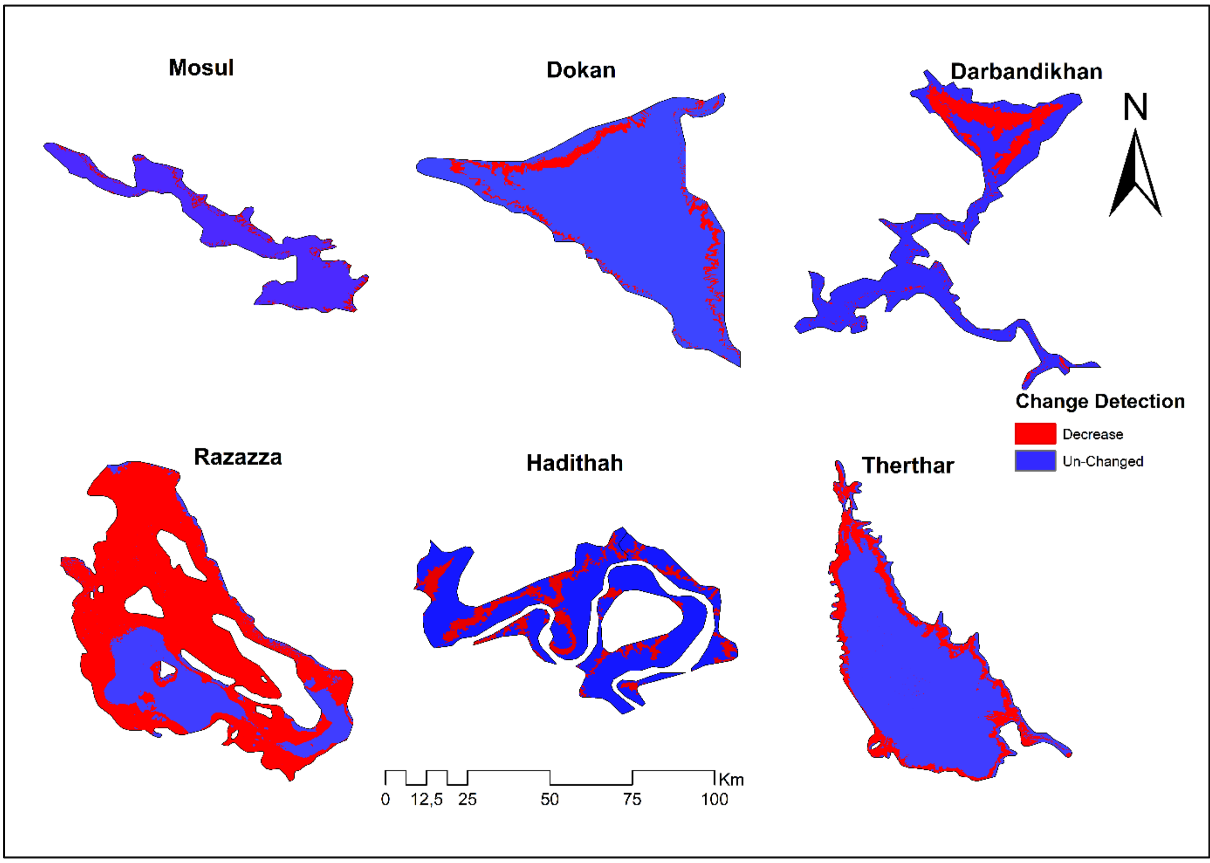

Figure 3. Spatial change detection of surface water extent in six major Iraqi lakes and reservoirs between 1986 and 2024. Areas in red indicate surface water loss, while blue areas represent unchanged water surfaces. The maps highlight the most significant contractions in Razazza, Hadithah, and Tharthar lakes, with relatively stable conditions observed in Mosul Dam.

3.3 Precipitation Trends and Climate Correlations

To better understand the role of climatic drivers in shaping long-term water surface dynamics, we examined the temporal trends in annual precipitation (Figure 4) and assessed their statistical relationships with surface water coverage across all six lakes and reservoirs (Figure 5). The precipitation data, obtained from the NASA POWER/MERRA-2 dataset, covers the full study period from 1986 to 2024 and was aggregated annually for each lake based on the corresponding grid cell at the lake centroid.

The time series plots (Figure 4) reveal considerable interannual variability in precipitation across all sites, with no clear long-term trend in most locations. Dokan and Darbandikhan reservoirs received relatively higher annual rainfall totals, frequently exceeding 300 mm, with notable peaks observed in 2015 and 2019. Conversely, arid-region lakes such as Hadithah, Razazza, and Tharthar recorded substantially lower annual rainfall, typically below 200 mm, with more erratic fluctuations.

Despite the expectation that precipitation might play a primary role in driving surface water changes, correlation analyses (Figure 5) showed only weak to moderate relationships between annual precipitation and surface water coverage. The highest positive correlations were observed for Dokan ($R = 0.29$) and Darbandikhan ($R = 0.23$), suggesting a partial influence of rainfall on water levels. However, several lakes showed negligible or even negative correlations. Notably, Lake Razazza exhibited a moderate negative correlation ($R = -0.37$), indicating that precipitation alone cannot explain its persistent surface water loss. Mosul and Tharthar had weak correlations ($R = -0.14$ and $R = 0.11$, respectively), while Hadithah showed virtually no correlation ($R = -0.01$), underscoring the dominance of other hydrological factors such as dam operations, inflow variability, and water extraction in shaping surface water dynamics.

Figure 4. Annual total precipitation (mm/year) from 1986 to 2024 for six major lakes and reservoirs in Iraq: Dokan, Darbandikhan, Mosul, Hadithah, Razazza, and Tharthar. The data were derived from the NASA POWER/MERRA-2 reanalysis product at 0.5° spatial resolution. Each panel shows year-to-year variability, highlighting significant fluctuations in rainfall patterns across different climatic zones in the country.

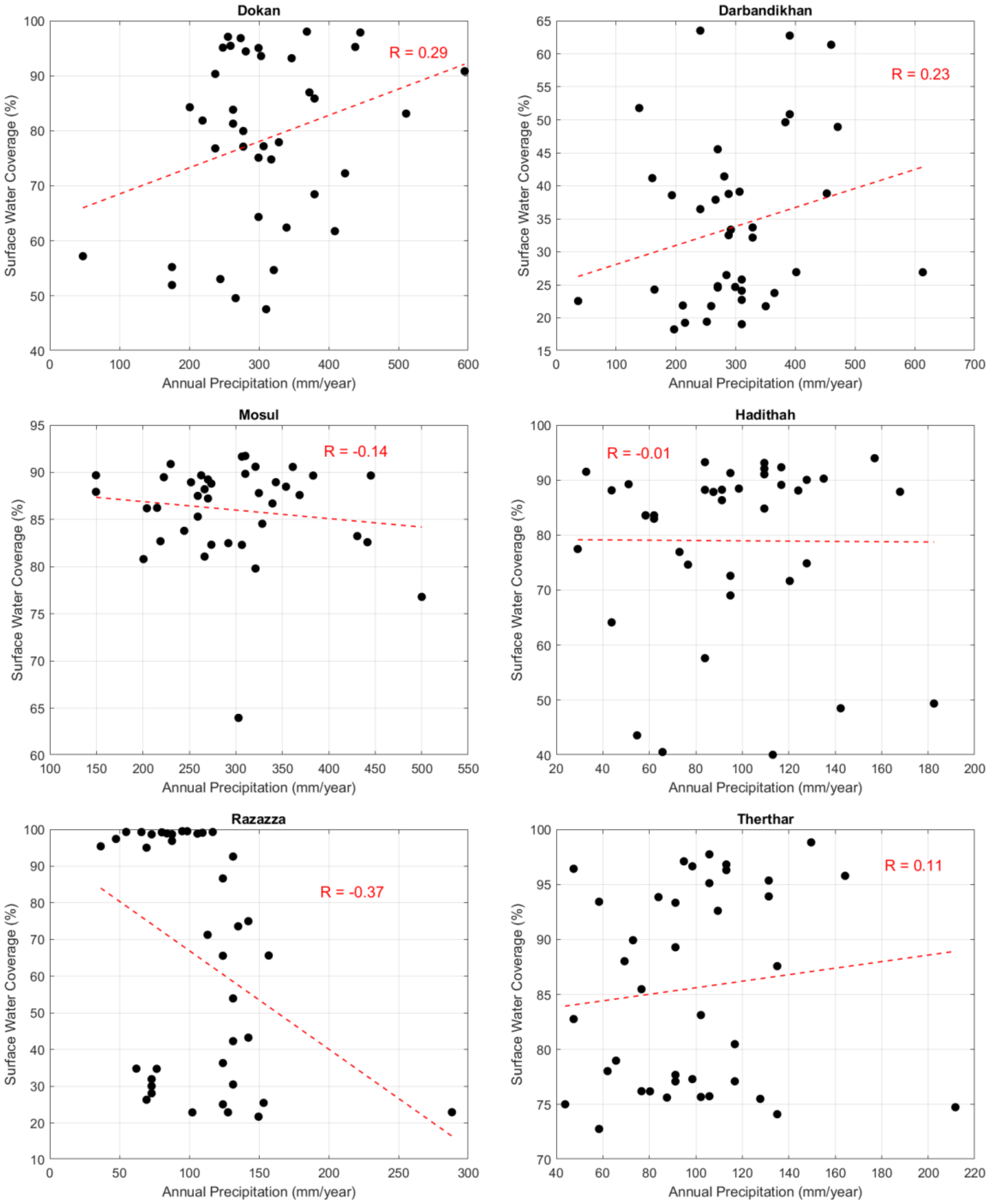

Figure 5. Scatter plots showing the relationship between annual precipitation (mm/year) and surface water coverage (%) for six major Iraqi lakes and reservoirs over the period 1986–2024. Each point represents a yearly observation. Dashed red lines indicate linear

regression fits, and the corresponding Pearson correlation coefficients (R) are shown in each panel.

4. Discussion

The multi-decadal analysis revealed a pronounced and spatially structured pattern of surface water loss across Iraq, particularly in its southern and central regions. Among all water bodies studied, Lake Razazza exhibited the strongest and most consistent negative trend ($R^2 = 0.86$), underscoring an alarming and sustained desiccation. This aligns with previous observations that highlight closed or semi-closed inland lakes as especially vulnerable to long-term climatic shifts and reduced water inflows (Al-Ansari, 2013; (Intergovernmental Panel on Climate Change 2021. The spatial contraction of Razazza's shoreline across its entire perimeter suggests a critical loss of functionality, both as a flood control mechanism and as an ecological habitat, with implications comparable to shrinking terminal lakes in other arid regions globally (e.g., Lake Urmia; (Azizi et al. 2024).

In comparison, Lake Tharthar and Hadithah Dam showed negative trends of lower intensity ($R^2 = 0.49$ and 0.22, respectively), yet the spatial patterns of decline, particularly Tharthar's retreat along northern and western shorelines, mirror those of reservoirs experiencing combined pressure from drought and upstream water abstraction. The correlation between these patterns and regional hydro-political developments is consistent with the findings of *(Kibaroglu*, et al. (2011), who documented the cumulative impact of Turkey's GAP project and Iran's diversion of tributaries such as the Karun and Sirwan on Iraq's water inflow. This study strengthens the evidence that anthropogenic upstream control exacerbates climate-driven reductions in natural recharge, especially for Euphrates-fed systems.

Contrasting these trends, the northern reservoirs of Dokan and Darbandikhan exhibited minimal long-term change ($R^2 = 0.02$ and 0.06). Their relative stability is consistent with their geographic setting in the Zagros region, where orographic precipitation remains more reliable (Othman, 2023) and catchment hydrology is less influenced by transboundary withdrawals. Moreover, local basin morphology and dam management practices may further buffer these systems against hydrological extremes, an effect also observed in high-altitude reservoirs in other semi-arid basins (Mueller et al. 2021).

Mosul Dam presents an intermediate case. Although showing a weak decline ($R^2 = 0.18$), spatial analysis indicates localised shrinkage in the southern reaches. This nuanced pattern may reflect its upstream location on the Tigris and adaptive operational adjustments, as suggested by recent water release policies (Alshami et al.,2020**)** While more stable than southern reservoirs, Mosul's trend points to emerging vulnerabilities that merit close monitoring.

To contextualise these trends, we also examined the role of precipitation variability over the 38-year period using data from the NASA POWER/MERRA-2 dataset. The results showed strong interannual variability across all lakes, but no consistent long-term trends in total rainfall. Northern lakes such as Dokan and Darbandikhan generally received higher annual precipitation, often exceeding 300 mm, while southern lakes like Razazza and Tharthar experienced more erratic and lower precipitation levels, usually below 200 mm. This north-south gradient in rainfall distribution corresponds well with the observed patterns of surface water persistence. However, when directly correlating annual precipitation with surface water extent, the relationships were found to be generally weak. The highest positive correlations were observed in Dokan (R = 0.29) and Darbandikhan (R = 0.23), suggesting that precipitation contributes modestly to interannual water fluctuations in these reservoirs. For other lakes, including Mosul (R = -0.14), Hadithah (R = -0.01), and Tharthar (R = 0.11), the correlations were near zero or negative, indicating that factors other than direct rainfall, such as regulated inflows, dam operations, and groundwater extraction, play a more dominant role in shaping water surface dynamics.

Lake Razazza exhibited a moderate negative correlation (R = -0.37), implying that even during wetter years, surface water did not recover, likely due to sustained anthropogenic extraction or limited upstream contributions. This finding reinforces the idea that precipitation alone is not a sufficient explanatory variable for water surface change, particularly in highly regulated or terminal lake systems.

Together, these results underscore the complex interplay between climatic and non-climatic drivers of surface water variability in Iraq. While rainfall variability contributes to year-to-year fluctuations, the overriding influence of water management policies, upstream withdrawals, and dam operations, especially in downstream and arid-zone lakes, appears to be more decisive. These insights call for a more integrated water governance strategy that accounts for both natural variability and human-induced controls in hydrological planning and climate adaptation frameworks.

5. Study Limitations and Implications

Although this study provides a comprehensive, multi-decadal assessment of surface water dynamics across Iraq using Landsat-derived NDWI, several limitations should be acknowledged. First, the analysis relied

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solely on optical satellite data, which can be affected by cloud contamination and atmospheric conditions despite the applied corrections. Second, the use of a fixed NDWI threshold may introduce classification uncertainties across different water types, turbidity levels, or seasonal conditions. Third, precipitation data were derived from a coarse-resolution reanalysis product, which may not fully capture local rainfall variability or inflow contributions from upstream catchments. Moreover, the absence of in situ hydrological measurements limited the validation of satellite-derived water extent. Despite these limitations, the findings provide valuable long-term insights into Iraq's surface water trends. They underscore the importance of integrating multi-sensor observations (e.g., radar or higher-resolution optical data) and ground measurements in future studies to improve accuracy and support evidence-based water management and policy development in transboundary and climate-stressed regions.

6. Conclusion

This study utilised 38 years of Landsat imagery and NDWI analysis to assess surface water trends across six major lakes and dams in Iraq. The findings reveal a stark reality: Iraq's surface water bodies have undergone significant and uneven transformations, with the most severe contractions occurring in southern and central areas, particularly in Lake Razazza, Tharthar, and Hadithah. In contrast, northern reservoirs like Dokan and Darbandikhan remained largely stable.

The causes of these changes are multifaceted, involving reduced rainfall, intensifying drought, and extensive upstream damming and diversion in Turkey and Iran. These combined pressures are diminishing Iraq's water security and threatening both ecological integrity and socioeconomic stability.

By leveraging satellite remote sensing and long-term NDWI trends, this research provides critical evidence for policymakers, hydrologists, and regional planners. In light of ongoing regional water negotiations and increasing climate volatility, prioritising transboundary water-sharing agreements and adaptive water management strategies is essential for Iraq's future sustainability.

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