

Time-Series Analysis of Lake Desiccation and Groundwater Storage Changes Using Google Earth Engine: The Case of Demirköprü Dam Reservoir, Türkiye

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Abstract

Lake desiccation and groundwater depletion are increasingly interconnected manifestations of hydrological stress in semi-arid and regulated basins. This study investigates the relationship between surface water loss and groundwater storage changes at the Demirköprü Dam Reservoir (western Türkiye) during the period 2016–2025 using cloud-based remote sensing analysis. Sentinel-2 multispectral imagery was processed in Google Earth Engine (GEE) to delineate annual reservoir extents using the Normalized Difference Water Index (NDWI), while groundwater storage dynamics were derived from the Global Land Data Assimilation System (GLDAS) Version 2.2 groundwater storage product. Post-processing and spatial analysis were conducted to extract shoreline boundaries and quantify surface area changes. The results reveal a persistent contraction of reservoir surface area accompanied by a declining trend in groundwater storage at both national and local scales. The integrated analysis demonstrates a clear temporal correspondence between lake desiccation and groundwater depletion, highlighting the value of combining satellite-based surface water mapping with land data assimilation products for hydrological monitoring.

Keywords: Lake desiccation, Groundwater storage, Sentinel-2, GLDAS 2.2, Google Earth Engine, NDWI.

Introduction

Surface water bodies and groundwater systems form a hydraulically connected continuum, particularly in regulated basins where reservoirs depend on both surface inflow and subsurface contributions (Winter et al., 1998). Globally, increasing water demand, climatic variability, and intensive groundwater abstraction have led to widespread groundwater depletion, posing a major challenge for sustainable water resource management (Famiglietti, 2014; Wada et al., 2010). Climate-driven shifts in precipitation regimes further exacerbate this problem by altering recharge processes and increasing pressure on subsurface water resources (Taylor et al., 2013).

Remote sensing has become an essential tool for monitoring hydrological change, particularly in data-scarce regions. Optical and Synthetic Aperture Radar (SAR) satellite imagery have been widely applied to quantify lake and reservoir surface dynamics, enabling long-term assessment of surface water variability (Pekel et al., 2016; Donchyts et al., 2016; Nasirzadehdizaji et al., 2017; Yao et al., 2019). Recent studies further demonstrate the increasing capability of multi-sensor satellite observations and advanced computational approaches for monitoring reservoir dynamics and inland water systems at regional and global scales (Xu et al., 2024; Bocchino et al., 2023; Zhou et al., 2025). In parallel, land data assimilation systems such as the Global Land Data Assimilation System (GLDAS) provide spatially consistent estimates of groundwater storage variability at regional to global scales (Rodell et al., 2004; Li et al., 2015). The emergence of cloud-based platforms, particularly Google Earth Engine (GEE), has further

facilitated integrated, multi-temporal hydrological analyses by enabling efficient processing of large satellite archives (Gorelick et al., 2017).

Despite these advances, many studies investigate surface water and groundwater changes independently, limiting the interpretation of lake desiccation as a process-based indicator of subsurface hydrological stress. This study evaluates the relationship between reservoir surface area dynamics and groundwater storage variability by integrating Sentinel-2–derived lake desiccation mapping with GLDAS 2.2 groundwater storage estimates. Focusing on the Demirköprü Dam Reservoir in western Türkiye, the study analyzes synchronous surface–subsurface hydrological changes between 2016 and 2025, providing a reproducible framework for assessing coupled hydrological degradation in data-scarce regions.

Study Area

The Demirköprü Dam Reservoir is located in Manisa Province, western Türkiye, and serves important irrigation and regional water management functions. The basin is characterized by a Mediterranean climate with pronounced seasonal variability in precipitation and evaporation, making it particularly sensitive to prolonged drought conditions and groundwater abstraction pressures. The geographic setting of the study area and its spatial context within Türkiye are shown in Fig. 1.



Fig. 1. Location of the Demirköprü Dam Reservoir in Türkiye, showing the spatial extent of the study area used for lake desiccation and groundwater storage analyses.

Data and Method

This study is based entirely on satellite remote sensing and geospatial analysis to investigate the relationship between lake desiccation and groundwater storage dynamics at the Demirköprü Dam Reservoir. Two complementary datasets were employed: Sentinel-2 multispectral optical imagery for surface water mapping and Global Land Data Assimilation System (GLDAS) Version 2.2 data for groundwater storage analysis. All large-scale satellite processing was conducted within the Google Earth Engine (GEE) cloud-computing platform, while spatial post-processing and visualization were performed using QGIS (QGIS Development Team, 2026).

a) Lake Desiccation Mapping and Surface Water Dynamics

Surface water dynamics of the Demirköprü Dam Reservoir were analysed using Sentinel-2 Level-2A multispectral imagery for the period 2016–2025. All processing was conducted within the GEE platform to ensure temporal consistency and efficient handling of multi-year datasets. To minimize the influence of cloud contamination and seasonal noise, annual image composites were generated for each year using median reflectance values from cloud-filtered observations, with scenes restricted to a cloud cover threshold of less than 10%. Water bodies were delineated using the Normalized Difference Water Index (NDWI), defined as:

$$NDWI = \frac{(Green - NIR)}{(Green + NIR)} \quad (1)$$

where *Green* corresponds to Sentinel-2 Band 3 (560 nm) and *NIR* corresponds to Band 8 (842 nm). The NDWI was originally proposed to enhance sensitivity to liquid water content and has been widely applied for delineating open water features in satellite imagery (McFeeters, 2007). Studies on NDWI-based water mapping indicate that although a threshold of 0 is commonly used as a baseline for separating water from non-water surfaces, optimal threshold values may vary depending on sensor characteristics, spectral response, and surrounding land cover conditions. In practice, thresholds ranging between 0 and 0.1 have been applied in surface water studies, often determined through histogram analysis rather than fixed assumptions. In this study, pixels with NDWI values greater than 0.1 were classified as open water, consistent with previous applications for effective water delineation (Du et al., 2016). The resulting binary water masks were generated at a spatial resolution of 10 m. Due to the absence of in situ shoreline observations or reservoir boundary measurements for the study period, a formal quantitative accuracy assessment of the extracted water masks was not conducted. However, NDWI-based water delineation has been widely validated in previous remote sensing studies for mapping surface water bodies from optical satellite imagery (McFeeters, 1996; Pekel et al., 2016). The applied threshold-based approach therefore follows established methodologies commonly used for surface water extraction in multi-temporal satellite analyses. To improve the reliability of water delineation, morphological filtering was applied to remove isolated noise and small artifacts. Annual water masks were subsequently converted to vector polygons to extract lake boundaries and compute reservoir surface areas. Shoreline positions were approximated using inward buffering to reduce mixed-pixel effects along the land–water interface. Post-processing steps, including boundary smoothing and area statistics, were carried out in QGIS to ensure spatial consistency across years.

b) Groundwater Storage Analysis

Groundwater dynamics were analysed using the Global Land Data Assimilation System (GLDAS) Version 2.2, a land surface modelling framework developed by NASA that integrates satellite- and ground-based observations with advanced land surface models to simulate terrestrial water and energy fluxes. GLDAS v2.2 provides physically consistent

estimates of hydrological variables, including soil moisture, evapotranspiration, runoff, and groundwater storage, by assimilating meteorological forcing data and land surface parameters. In this study, the Groundwater Storage (GWS_tavg) variable was used, representing 24-hour averaged groundwater storage anomalies expressed in millimetres (Rodell et al., 2004). The dataset is available at a spatial resolution of 0.25° with monthly temporal resolution and was processed within the GEE platform for the period 2016–2025. It should be noted that GLDAS data have a considerably coarser spatial resolution (0.25° , approximately 25 km) compared to the 10 m spatial resolution of Sentinel-2 imagery used for lake surface mapping. Consequently, the groundwater storage estimates represent regional-scale hydrological conditions rather than localized variations directly at the reservoir shoreline. The comparison between the two datasets therefore focuses on temporal trends and regional hydrological responses rather than pixel-level spatial correspondence. GLDAS-based groundwater storage estimates have been widely applied for large-scale groundwater monitoring, drought assessment, and hydroclimatic trend analysis, particularly in regions where in situ groundwater observations are sparse or unavailable.

Results

Annual water extent maps of the Demirköprü Dam Reservoir derived from NDWI-based water masks are shown in Fig. 2. These maps provide a synoptic visualization of interannual variations in lake surface extent between 2016 and 2025, clearly illustrating progressive contraction of the reservoir over time. The largest surface extent is observed in 2016, followed by visibly reduced lake areas in subsequent years.

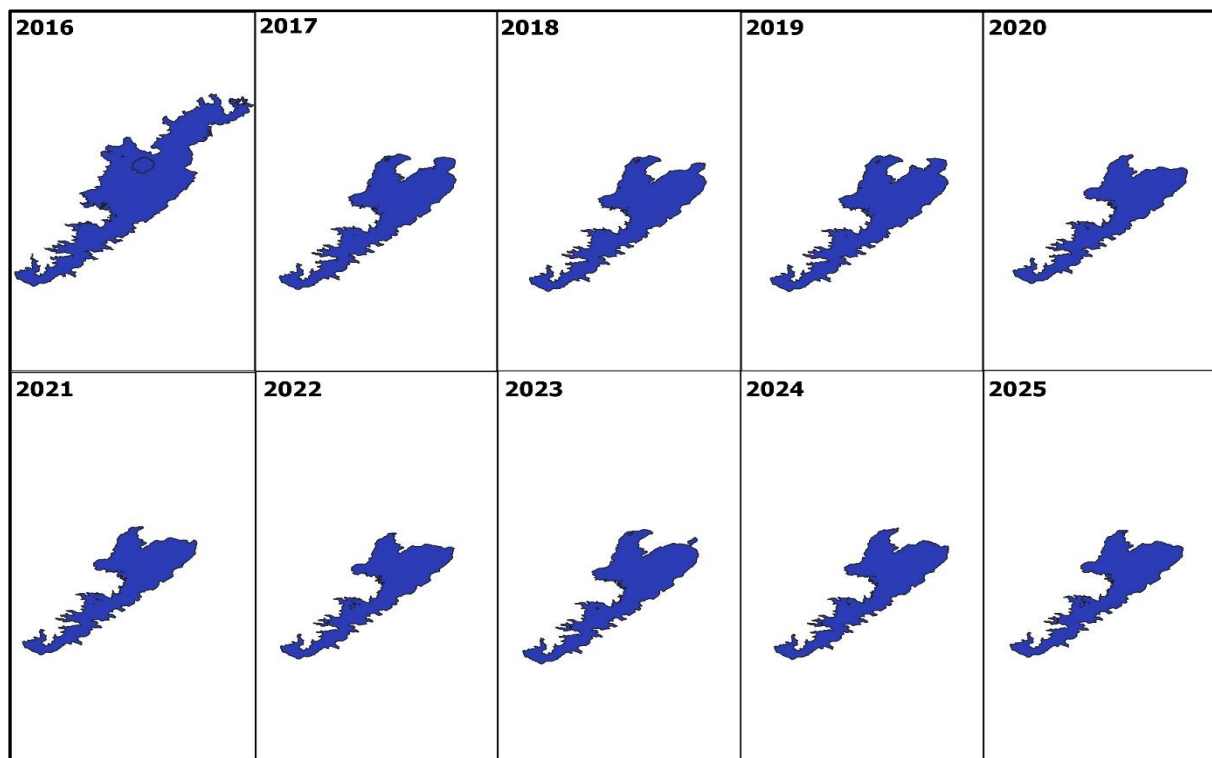


Fig. 2. Annual lake surface extent of the Demirköprü Dam Reservoir derived from Sentinel-2 NDWI for the period 2016–2025.

To explicitly assess spatial patterns of shoreline migration, annual water boundaries were extracted and overlaid for the entire study period (Fig. 3). The superimposed shoreline positions reveal consistent inward retreat of the reservoir margins, particularly along shallow peripheral zones, indicating sustained lake desiccation rather than localized or short-term fluctuations.

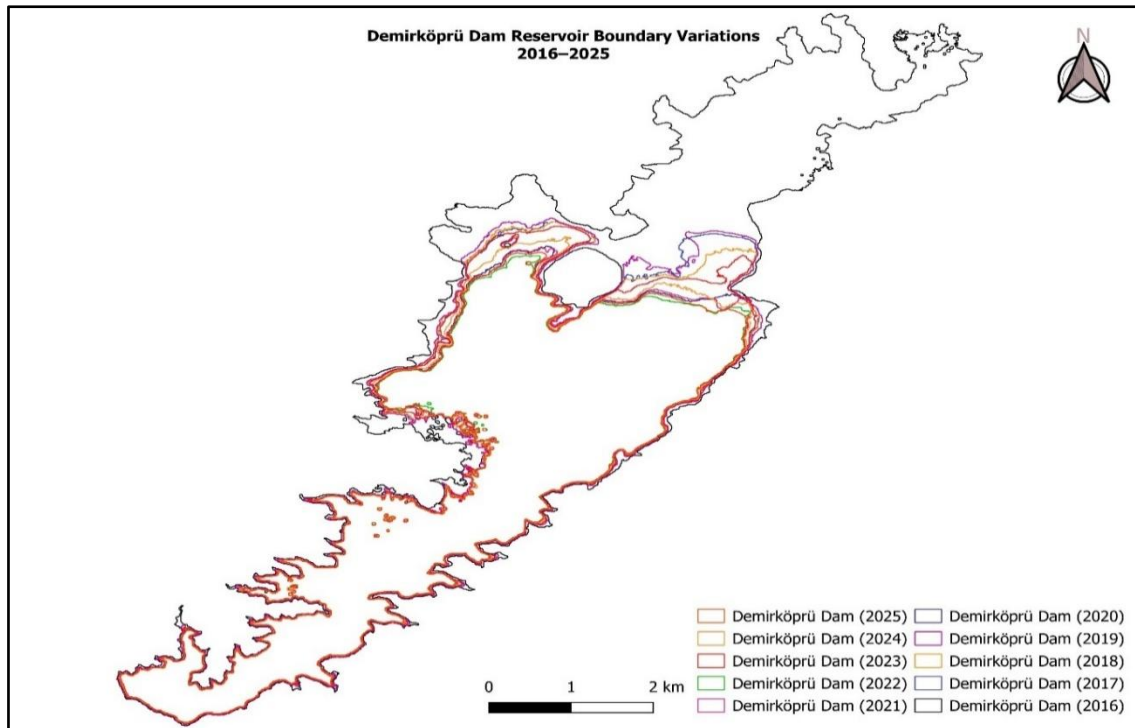


Fig. 3. Overlaid annual shoreline positions of the Demirköprü Dam Reservoir (2016–2025), illustrating spatial patterns of boundary retreat and localized stability.

Changes in lake surface area were quantified from annual NDWI-derived water masks to evaluate temporal trends in reservoir extent (Fig. 4). The resulting time series indicates a pronounced overall decline in surface area throughout the study period, with interannual fluctuations reflecting short-term hydrological variability superimposed on a clear long-term decreasing trend.

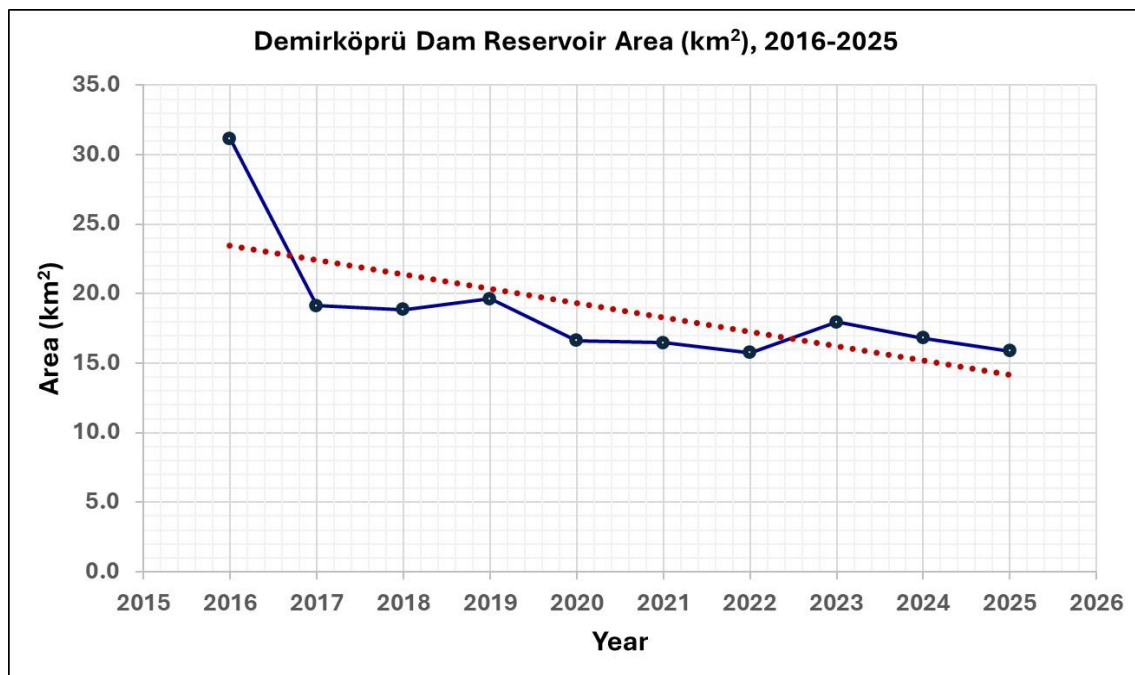


Fig. 4. Temporal variation of Demirköprü Dam Reservoir surface area (km²) between 2016 and 2025, showing an overall declining trend.

To support the graphical trend analysis, the annual reservoir surface areas calculated from Sentinel-2 NDWI products are summarized numerically in Table 1. These values provide a quantitative basis for assessing the magnitude of lake desiccation and allow direct comparison between individual years.

Table 1. Annual surface area of the Demirköprü Dam Reservoir derived from Sentinel-2 NDWI analysis (2016–2025).

Year	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Area (km ²)	31.2	19.1	18.9	19.6	16.6	16.5	15.8	18.0	16.8	15.9

The numerical results confirm a substantial net reduction in reservoir surface area, decreasing from 31.2 km² in 2016 to 15.9 km² in 2025, corresponding to an approximate loss of 49%. Temporary increases observed in 2019 and 2023 suggest episodic recovery linked to short-term hydrological inputs; however, these do not offset the long-term declining trend. The observed contraction of the reservoir is consistent with prolonged dry conditions and decreasing groundwater storage, suggesting a coupled response between surface water availability and subsurface hydrological processes.

To provide a national-scale context for groundwater variability, spatially continuous groundwater storage maps were first generated for Türkiye for representative years within the study period. To establish baseline groundwater conditions, a national-scale groundwater storage map for Türkiye was generated for the year 2016 (Fig. 5), representing the initial state of groundwater availability at the beginning of the analysis period.

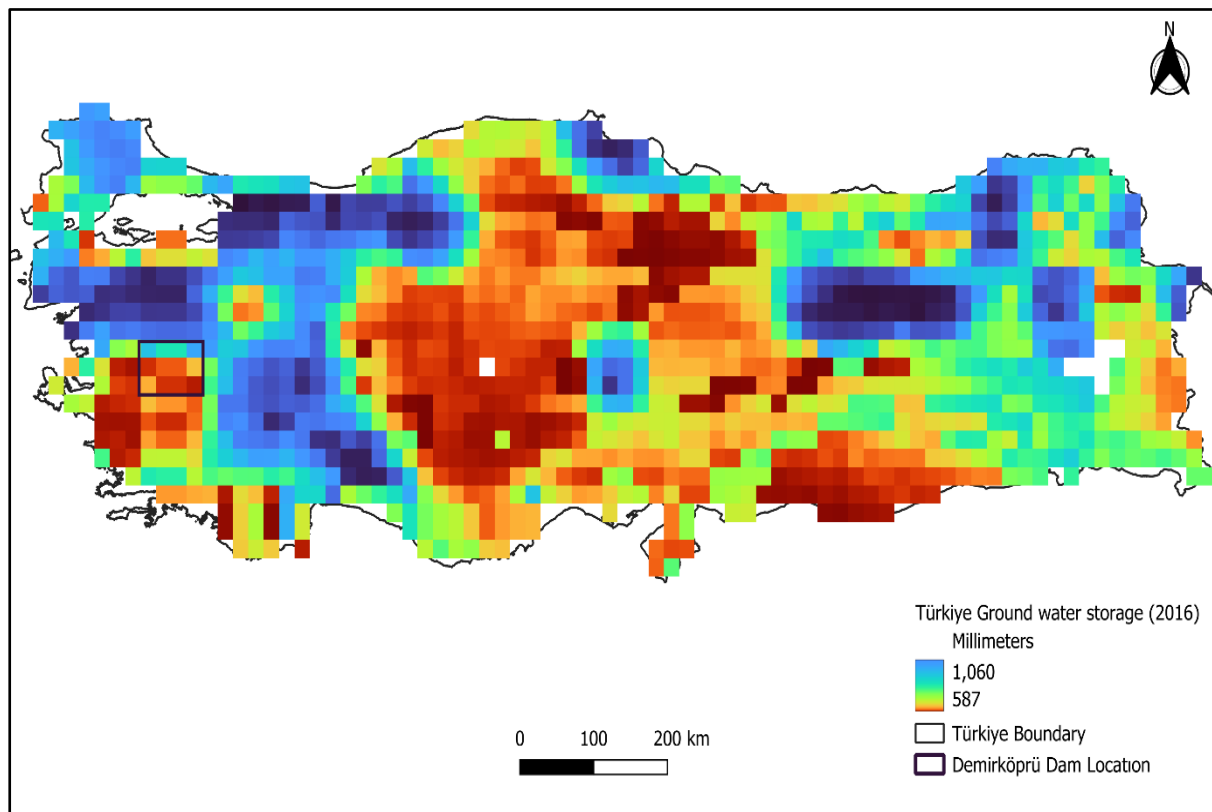


Fig. 5. Spatial distribution of groundwater storage across Türkiye in 2016 derived from GLDAS v2.2 GWS_tavg data. The location of the Demirköprü Dam Reservoir is highlighted for spatial reference.

A corresponding groundwater storage map for 2025 (Fig. 6) was produced to evaluate decadal-scale changes in groundwater conditions and to identify regions experiencing persistent groundwater depletion.

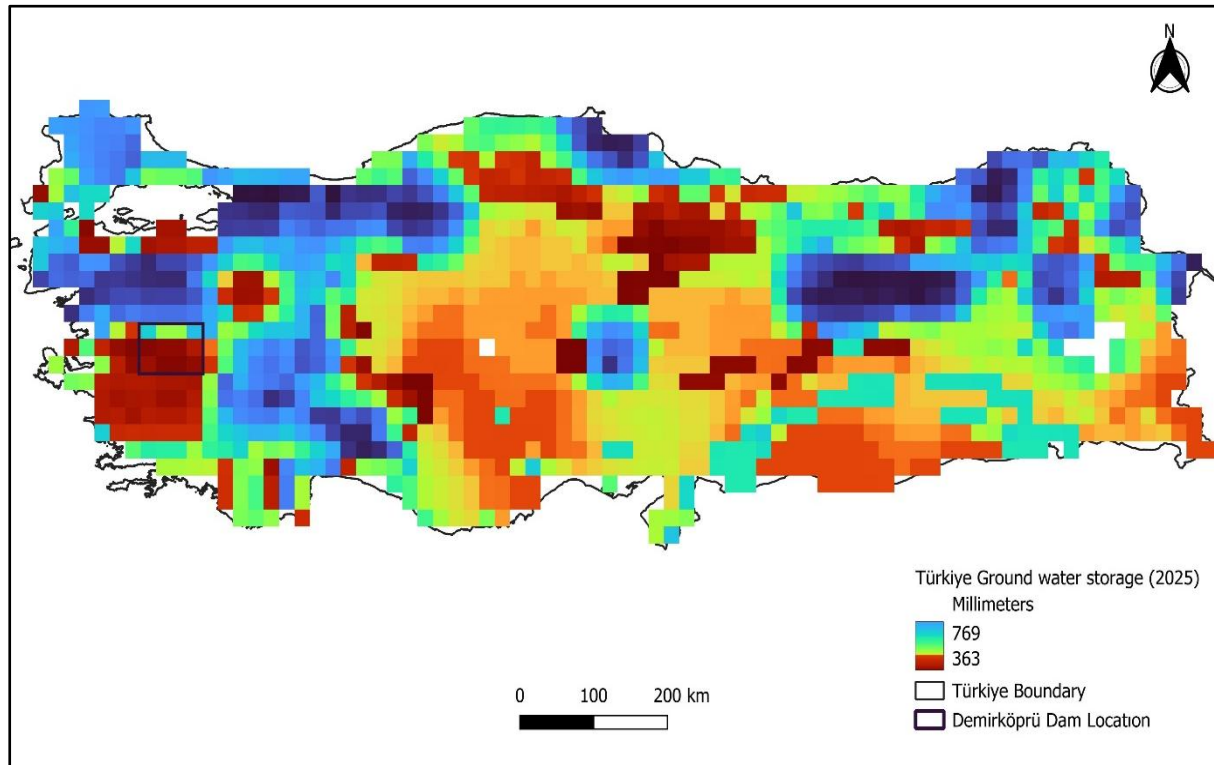


Fig. 6. Spatial distribution of groundwater storage across Türkiye in 2025 derived from GLDAS v2.2 GWS_avg data, illustrating changes relative to 2016 conditions.

Comparison of the national-scale groundwater storage maps reveals widespread spatial variability, with notable declines in several central and western regions of Türkiye. These regional patterns provide important context for interpreting localized groundwater behavior within the Demirköprü Dam Reservoir influence zone. To assess groundwater dynamics at the study-area scale, spatial subsetting was applied to extract groundwater storage time series for the Demirköprü Dam Reservoir location, using a buffer zone of approximately 10 km to represent the surrounding hydrological influence area. Although a full basin-scale analysis could provide additional insight into regional groundwater dynamics, the buffer-based approach allows a more direct comparison between local groundwater variability and observed changes in reservoir surface area. It should also be noted that groundwater dynamics within the broader basin may be influenced by other wetlands or hydrological systems, and therefore the results should be interpreted as indicators of regional hydrological trends rather than direct causal relationships. Temporal variations in groundwater storage within the Demirköprü Dam Reservoir influence zone were evaluated using a time-series analysis derived from GLDAS groundwater storage data. Monthly groundwater storage values were averaged within this buffer to generate a continuous temporal profile for the period 2016–2025 (Fig. 7).

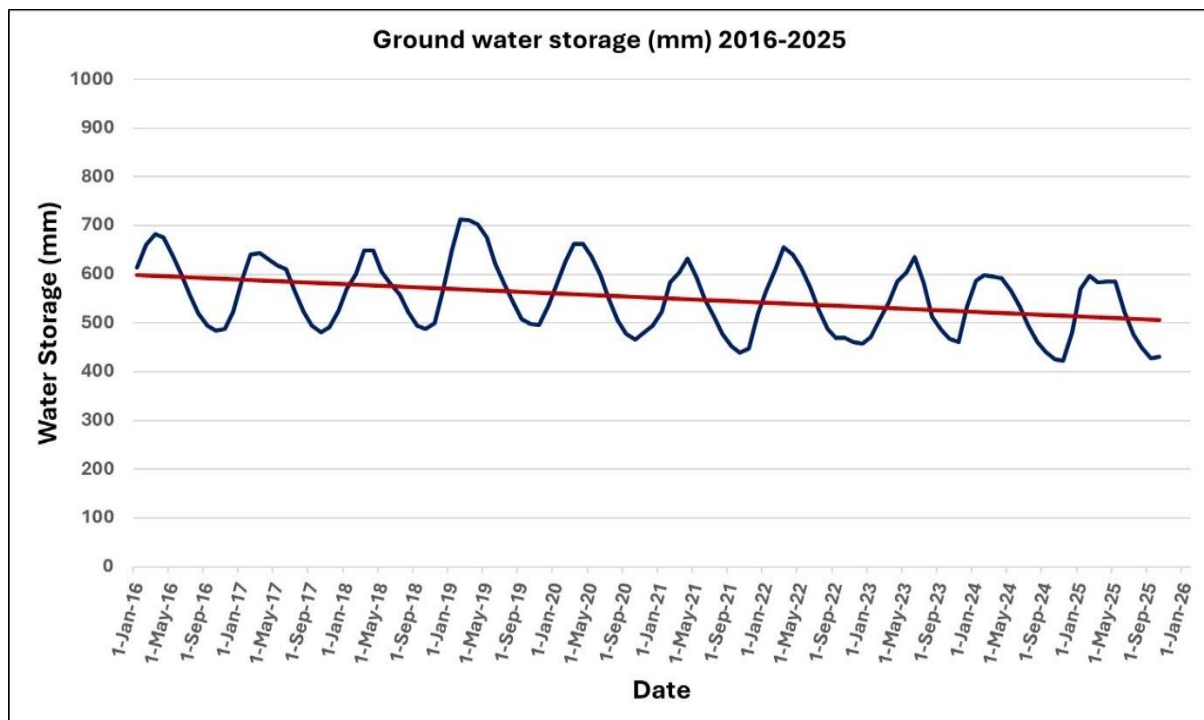


Fig. 7. Time series of groundwater storage (mm) from 2016 to 2025 extracted for the Demirköprü Dam Reservoir location using a ~10 km buffer, showing seasonal variability and long-term trends.

The resulting groundwater storage time series exhibits pronounced seasonal fluctuations superimposed on a clear long-term declining trend (Fig. 7). Over the study period, mean groundwater storage within the Demirköprü Dam Reservoir influence zone decreased from approximately 615 mm in 2016 to ~430 mm in 2025, corresponding to a net decline of about 185 mm. A notable temporary increase in groundwater storage is observed in 2019, reaching values of approximately 715 mm, which may be associated with above-average precipitation, enhanced surface water availability, and increased recharge during that year, as also reflected by the partial recovery in reservoir surface area. In addition to the long-term decline, recurrent short-term increases on the order of approximately 100–150 mm are evident, indicating episodic groundwater recharge associated with seasonal precipitation and surface subsurface hydrological interactions. However, these temporary recoveries do not compensate for the overall downward trend, indicating sustained groundwater depletion throughout the 2016–2025 period.

Sentinel-2–based NDWI analysis reveals a persistent contraction of the Demirköprü Dam Reservoir throughout the study period (Figs. 2–4). Shoreline retreat is spatially heterogeneous, with the most pronounced reductions occurring along shallow peripheral zones that are highly sensitive to declining water levels. Although short-term expansions are visible in certain years, these fluctuations do not alter the overall downward trajectory of reservoir surface extent. Groundwater storage dynamics derived from GLDAS 2.2 data indicate a consistent declining tendency at both national and local scales (Figs. 5–7). National-scale maps highlight widespread groundwater stress across Türkiye, while localized analysis around the Demirköprü Dam Reservoir shows pronounced seasonal variability superimposed on a long-term downward trend. Periodic increases suggest episodic recharge events; however, these remain temporary and do not offset the overall depletion pattern.

Temporal comparison between NDWI-derived lake surface variations and GLDAS-based groundwater storage trends demonstrates a clear correspondence between surface water reduction and subsurface decline. Periods of decreasing groundwater storage generally

coincide with contractions in reservoir extent, indicating a coupled response between subsurface and surface water systems within the basin. Although direct in situ groundwater observations (e.g., well piezometric measurements) were not available for validation, interpretations are based on relative temporal patterns and established physical relationships linking groundwater depletion, surface water availability, and climatic variability.

The analysis relies exclusively on remote sensing and model-assimilated datasets. Future research should incorporate ground-based measurements, including well-level observations and reservoir stage records, to improve quantitative validation and strengthen causal assessment. Nevertheless, the integrated use of Sentinel-2 surface water mapping and GLDAS groundwater storage analysis provides a scalable framework for monitoring hydrological stress in data-limited regions.

Conclusion

The integrated remote sensing framework demonstrates that the joint interpretation of Sentinel-2–derived lake surface dynamics and GLDAS 2.2 groundwater storage estimates offers an effective means of characterizing hydrological stress in reservoir systems. The Demirköprü Dam Reservoir exhibits coherent patterns of surface water contraction and groundwater decline, reflecting interconnected responses within the regional hydrological system.

The proposed framework relies exclusively on open-access satellite observations and model-based datasets, enabling scalable and repeatable assessments across data-scarce regions. While the results provide robust indications of hydrological change, incorporation of in situ groundwater measurements, such as well-based piezometric records, would enhance validation and improve quantitative understanding of lake–groundwater interactions in future studies.

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