



Long-Term Changes in Lake Marmara (Western Türkiye) Based on Remote Sensing and Climate Indicators [†]

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Abstract

This study investigates recent changes in the surface area of Lake Marmara, a shallow lake located in western Türkiye under Mediterranean climate conditions, and their relationship with hydrometeorological variability. Lake surface area dynamics were quantified using the Modified Normalized Difference Water Index (MNDWI) derived from Landsat satellite imagery processed on the Google Earth Engine (GEE) platform. Climatic conditions were characterized by using precipitation, air temperature, and potential evapotranspiration data obtained from the ERA5-Land reanalysis dataset, from which drought indices including the Standardized Precipitation Index (SPI) and the Standardized Precipitation Evapotranspiration Index (SPEI) were derived. Temporal analyses covering the period 2000–2025 were conducted to identify long-term tendencies and seasonal variability in lake area and climatic indicators. The results indicate that the rapid post-2015 lake desiccation cannot be explained by a statistically significant monotonic meteorological drought trend alone, highlighting the likely contribution of basin-scale hydrological pressures.

Keywords: Lake Marmara; remote sensing; MNDWI; climate indicators; drought analysis

1. Introduction

Lakes and wetlands are highly sensitive components of the hydrological system, responding rapidly to climatic variability and water-use pressures. In Mediterranean and semi-arid regions, rising air temperatures, shifting precipitation regimes, and increasing atmospheric evaporative demand have intensified hydrometeorological drought conditions, leading to significant declines in lake levels and surface extents [1,2].

Remote sensing has become a fundamental tool for monitoring long-term lake dynamics, enabling consistent observations of surface water changes across broad spatial and temporal scales [3]. Multispectral imagery combined with water extraction indices such as the Normalized Difference Water Index (NDWI) [4,5] and Modified NDWI (MNDWI) [6,7] has been widely applied to delineate water bodies and quantify surface area variations. The emergence of cloud-based platforms, particularly Google Earth Engine (GEE), has further facilitated efficient analysis of multi-decadal satellite archives and systematic assessment of lake responses to climatic and anthropogenic drivers [8,9]. Climate reanalysis datasets complement satellite observations by providing spatially consistent meteorological variables, especially in regions with limited in situ measurements. ERA5-Land data offer precipitation, temperature, and potential evapotranspiration (PET) records suitable for deriving drought indices such as the Standardized Precipitation Index (SPI) and the Standardized



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Precipitation Evapotranspiration Index (SPEI) [10,11], which integrate precipitation deficits and temperature-driven atmospheric water demand.

Lake Marmara, located in the Gediz Basin of western Türkiye, represents a shallow lake increasingly exposed to climatic stress and intensive water use. Previous remote sensing studies have documented substantial surface area reductions, particularly after the early 2010s [8], while land use change, agricultural expansion, and rising water demand have further increased system vulnerability [9,12]. Hydrological analyses indicate strong groundwater–surface water interactions and reduced basin inflows [13]. The lake’s shrinkage reflects the combined effects of prolonged drought, intensive withdrawals, and water management pressures rather than climate variability alone [14]. Regional climate studies reveal a long-term shift toward drier conditions characterized by decreasing precipitation and increasing temperatures [15], and future projections suggest further reductions in surface water availability under warming scenarios [15,16].

Despite extensive research, most studies examine lake dynamics or climatic variability separately and often focus on relatively short periods. Long-term integrative analyses remain limited. This study addresses this gap by investigating changes in Lake Marmara’s surface area over 2000–2025 and evaluating their relationship with hydrometeorological variability. By integrating MNDWI-based lake surface extraction from Landsat imagery processed in GEE with SPI and SPEI derived from ERA5-Land data, the study provides a comprehensive framework for assessing climate-driven lake evolution under Mediterranean conditions.

2. Materials and Methods

2.1. Study Area

Lake Marmara is a shallow inland lake located in western Türkiye within the Gediz River Basin, in Manisa Province (Figure 1). Geomorphologically, it is an alluvial barrier lake formed within the tectonically controlled Gediz Graben system [17]. With an average depth of approximately 3–5 m, the lake is highly sensitive to hydroclimatic variability, and its surface area exhibits pronounced seasonal and interannual fluctuations. Originally a natural wetland, Lake Marmara was embanked and hydraulically regulated in the mid-twentieth century and has since functioned as an irrigation reservoir serving the Lower Gediz agricultural scheme [14]. The lake is fed by precipitation, local runoff, diversion structures, and groundwater discharge, while groundwater–surface water interactions constitute an important component of its hydrological balance [13].

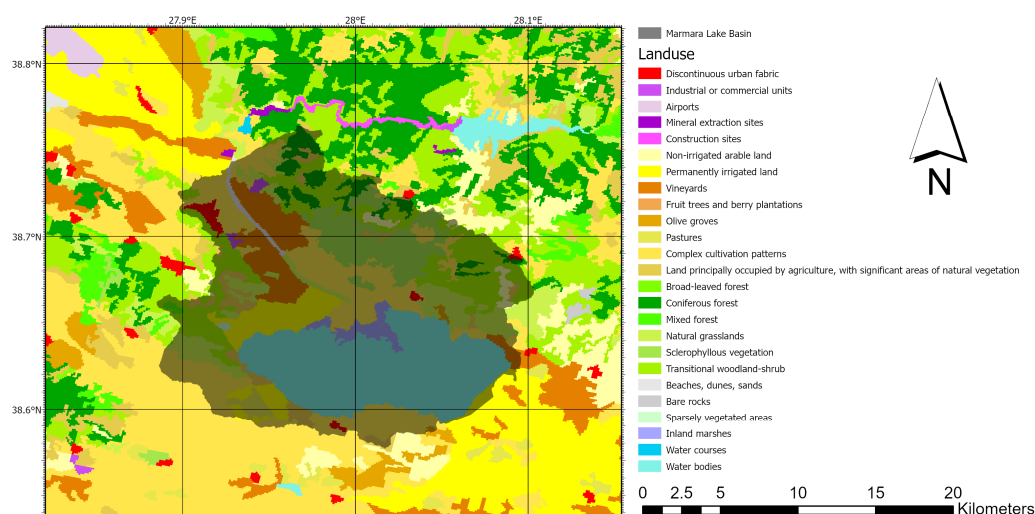


Figure 1. Study area: Lake Marmara basin and land use distribution [18].

In recent decades, upstream hydraulic regulation, increasing groundwater abstraction, and prolonged drought conditions have substantially altered the natural inflow regime, leading to severe shrinkage and periodic drying of the lake [12,15]. These characteristics make Lake Marmara a representative case for investigating long-term lake surface dynamics and their relationship with hydrometeorological variability under Mediterranean climate conditions.

2.2. Lake Area Calculation with MNDWI

Temporal variations in lake surface area were quantified using the MNDWI [19], selected for its improved performance in distinguishing open water from built-up surfaces and moist soils. Seasonal analyses were conducted for the 2000–2025 period, defining winter (December–February), spring (March–May), summer (June–August), and autumn (September–November). Surface reflectance products from USGS Landsat 5 TM, Landsat 7 ETM+, and Landsat 8/9 OLI sensors were processed within the GEE platform at 30 m spatial resolution. To ensure inter-sensor consistency across the multi-decadal archive, spectral harmonization procedures were applied. MNDWI-derived water masks were generated using Otsu’s automatic thresholding method, and lake surface areas were calculated from classified water pixels and converted to square kilometers. Seasonal time series were subsequently analyzed to evaluate temporal variability in lake extent.

2.3. Precipitation and Drought Analysis

To evaluate precipitation variability and drought conditions at the basin scale, the SPI and the SPEI were computed. SPI, developed by [20], is a probabilistic drought indicator based solely on precipitation anomalies, whereas SPEI incorporates both precipitation and PET within a climatic water balance framework [11]. By jointly employing these indices, drought conditions driven exclusively by precipitation deficits and those amplified by atmospheric evaporative demand were assessed. PET was estimated using the FAO Penman–Monteith approach [21]. SPI and SPEI calculations were conducted in the Python environment using the spei v0.5.0 library. Meteorological variables were obtained from the ERA5-Land monthly aggregated dataset [22] via the GEE platform. ERA5-Land data ($\sim 0.1^\circ$ spatial resolution) were spatially averaged over grid cells intersecting the basin boundary to represent basin-scale conditions. Both indices were calculated at 3-, 6-, and 12-month time scales to capture short-, medium-, and long-term drought variability.

3. Results

3.1. Changes in Lake Surfaces

MNDWI-based calculations (Figure 2a) indicate that the lake surface area was approximately 6000 ha in the early 2000s and remained relatively stable until the mid-2010s. However, a sharp and persistent decline occurred after 2015, leading to near-complete desiccation during 2020–2025. Following 2021, lake area values dropped to nearly zero across all seasons (Figure 2a). For the full 2000–2025 period, a statistically significant decreasing trend was detected (Kendall’s $\tau = -0.47$, $p < 0.001$), with Sen’s slope indicating an average decline of 35.6 ha yr^{-1} . When divided into sub-periods, no significant trend was observed for 2000–2015 ($p = 0.71$), confirming relative stability during this interval. In contrast, the 2015–2025 period exhibited a very strong and significant decline (Kendall’s $\tau = -0.77$, $p < 0.001$), demonstrating that the desiccation process was concentrated in the last decade (Figure 2b,c). Seasonal patterns (Figure 2d) show higher lake areas in winter and spring and lower values in autumn. Nevertheless, significant decreasing trends were detected across all seasons after 2015 (τ between -0.71 and -0.87 , $p < 0.01$), indicating that the decline has been persistent and year-round rather than seasonally restricted. Overall, Figure 2

demonstrates that the lake remained relatively stable until 2015, after which rapid and systematic hydrological degradation led to near-total surface loss within a decade.

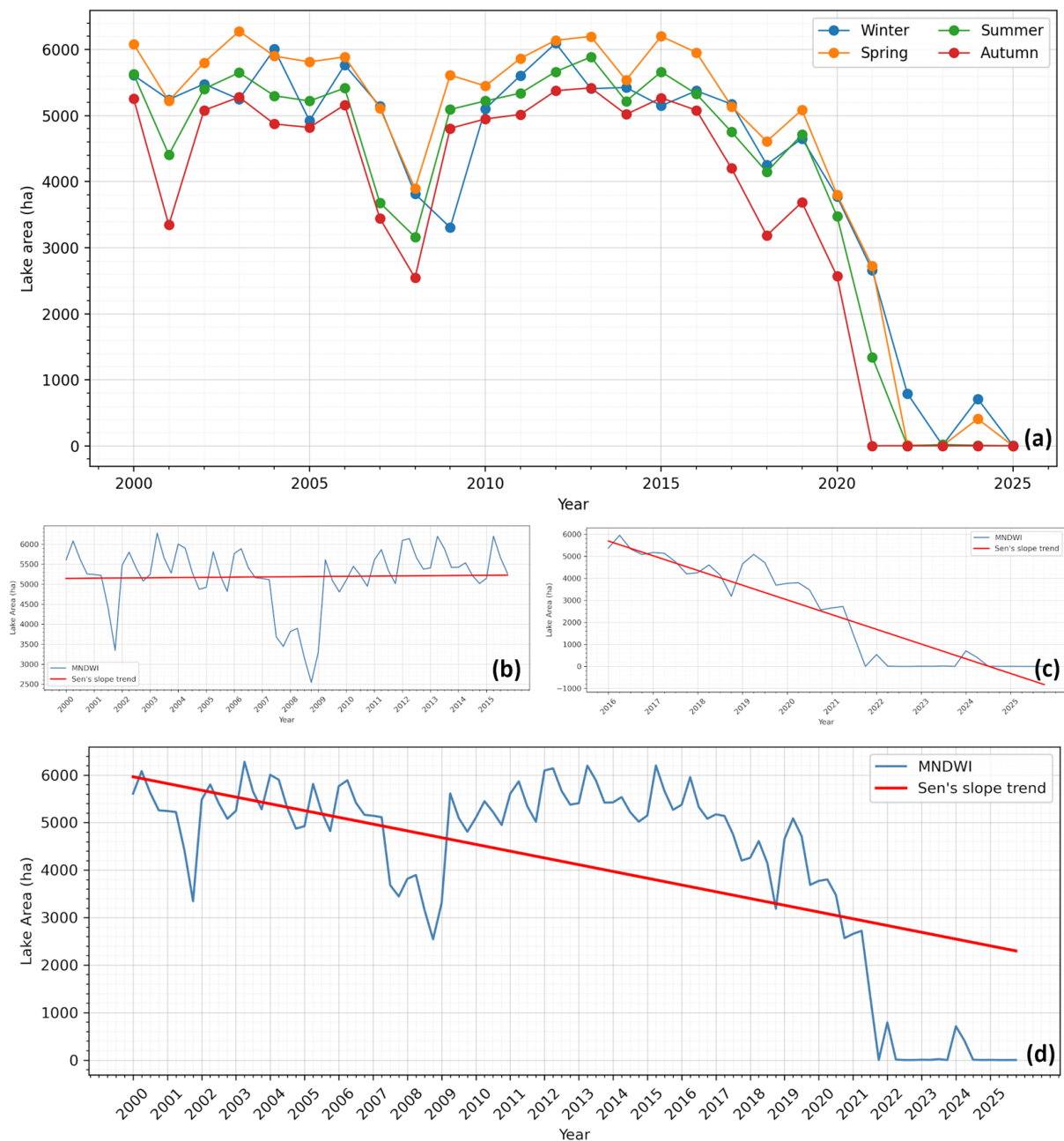


Figure 2. Temporal variations and trend analysis of Lake Marmara surface area derived from satellite imagery. Panel (a) presents the annual lake area time series together with the Sen's slope trend for the entire study period (2000–2025). Panels (b,c) show trend analyses for two sub-periods, 2000–2015 and 2016–2025, respectively, highlighting the shift from relatively stable conditions to a rapid decline in lake surface area. Panel (d) illustrates seasonal variations in lake area (winter, spring, summer, and autumn) throughout the study period.

It should also be noted that lake area estimates derived from MNDWI may contain certain uncertainties related to spectral confusion between water and non-water surfaces. In particular, built-up land and other background features may produce spectral responses similar to water, which can lead to misclassification in index-based water extraction methods [18]. Although such effects may introduce minor errors in the delineation of

lake boundaries, the use of consistent processing procedures and multi-temporal imagery allows reliable identification of long-term lake surface trends.

3.2. Change in SPI and SPEI

The 3-, 6-, and 12-month SPI and SPEI series (Figure 3) show largely synchronous behavior throughout 2000–2025, with most values fluctuating within the -1 to $+1$ range, indicating predominantly near-normal conditions. Extreme wet or dry episodes are limited, short-lived, and lack long-term persistence. Sen's slope lines are nearly horizontal at all time scales (Figure 3), and Mann–Kendall results indicate that no statistically significant monotonic meteorological drought trend was detected for either index ($p > 0.05$). Thus, no monotonic long-term meteorological drought trend is detected during the study period. Although SPEI (particularly at 6- and 12-month scales) shows slightly more frequent negative anomalies than SPI, reflecting additional evaporative demand effects, these differences are not statistically significant. Overall, Figure 3 indicates that the pronounced post-2015 lake area decline cannot be explained by a persistent or intensifying meteorological drought signal alone, suggesting that non-climatic or basin-scale hydrological pressures likely played a dominant role.

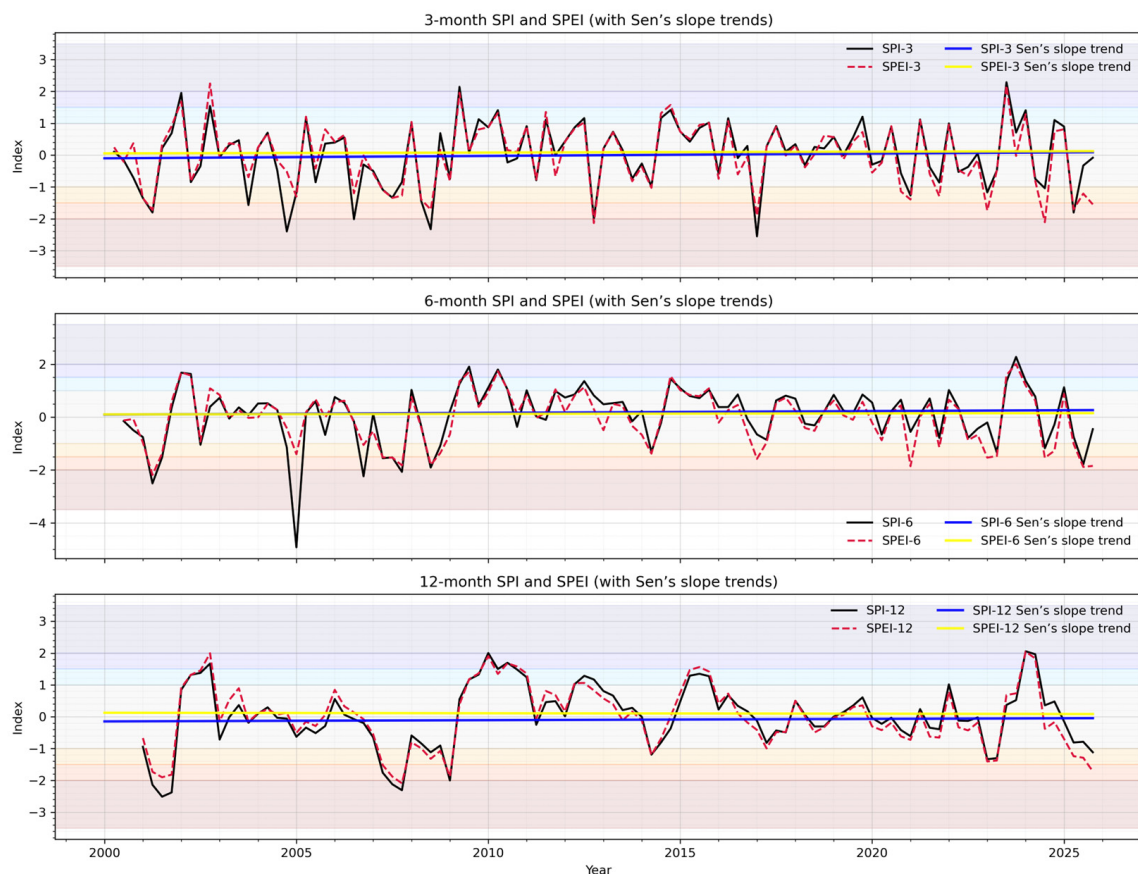


Figure 3. Time series of 3-, 6-, and 12-month SPI and SPEI values with Sen's slope trends. Blue and red shading indicate wet (positive) and dry (negative) periods, respectively.

3.3. Correlation Analysis

Figure 4 shows that correlations between MNDWI and long-term drought indices (SPI-6/12 and SPEI-6/12) are generally moderate and positive, with stronger relationships during summer and weaker ones in winter. This indicates that lake surface area is more sensitive to cumulative climatic water balance conditions during the dry season.

Among meteorological variables, air temperature (t2m), dew point temperature (d2m), and wind speed (ws) exhibit negative correlations with MNDWI, particularly during summer and autumn, whereas precipitation shows weak and inconsistent relationships across seasons (Figure 4). These patterns highlight the dominant role of evaporative demand rather than precipitation alone in controlling lake variability.

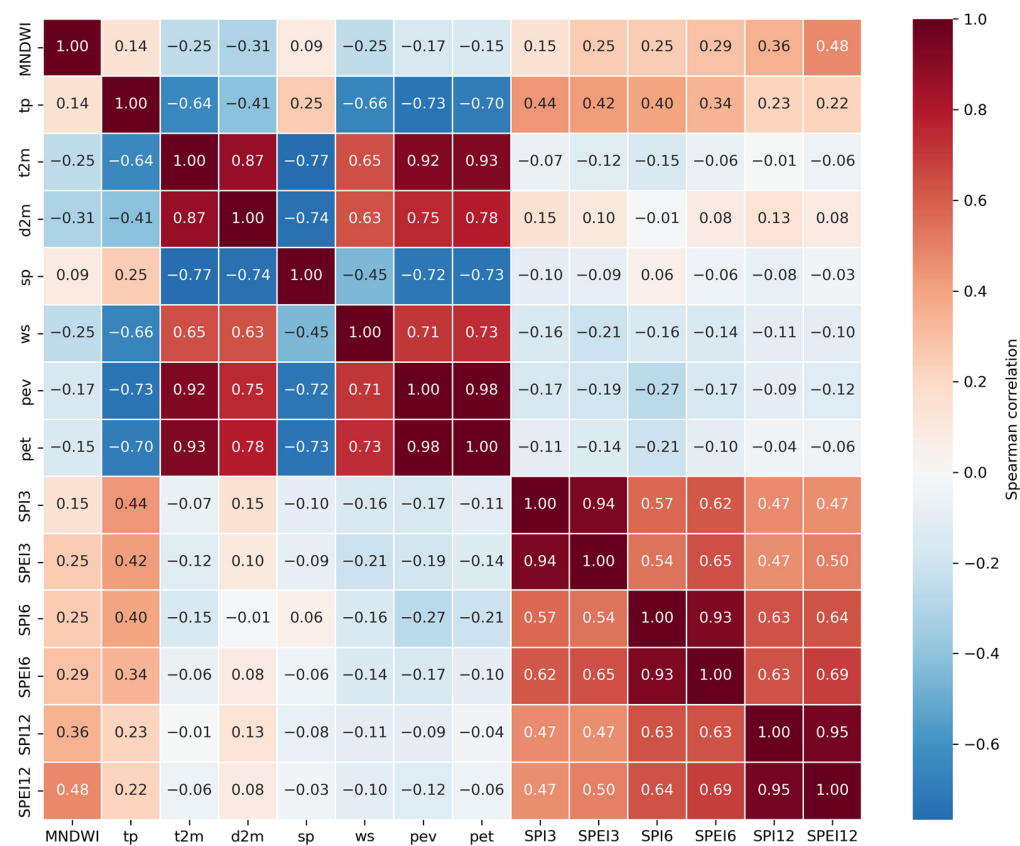


Figure 4. Correlation matrix of variables related with lake area.

Overall, the seasonal correlation structure suggests that the lake system behaves in a water-balance-limited manner, with summer representing the most climatically sensitive period. Thus, lake–climate interactions are seasonally heterogeneous, and annual averages alone are insufficient to explain the observed desiccation dynamics.

4. Conclusions

This study investigated long-term changes in lake surface area and their relationship with meteorological drought conditions at multiple time scales. MNDWI-based analysis revealed that the lake remained relatively stable until 2015, after which a rapid and persistent contraction occurred, leading to near-complete desiccation during 2020–2025. Trend analyses confirmed that the statistically significant long-term decline is largely driven by the post-2015 period.

In contrast, SPI and SPEI time series at 3-, 6-, and 12-month scales did not exhibit a significant monotonic drought trend over 2000–2025. Although SPEI showed slightly stronger negative anomalies than SPI (reflecting evaporative demand effects), these signals were not indicative of an intensifying long-term meteorological drought regime.

Seasonal correlation analyses demonstrated that lake surface area is more sensitive to climatic water balance conditions during summer, when temperature and evapotranspiration exert stronger controls, and is less responsive during winter. However, the absence of

a statistically significant monotonic meteorological drought trend suggests that climatic variability alone cannot fully explain the rapid lake desiccation observed after 2015.

Overall, the findings indicate that the post-2015 collapse of lake surface area reflects increasing hydrological vulnerability amplified by anthropogenic pressures, including basin-scale water use and management practices. Previous studies show that upstream hydraulic regulation, particularly the construction of the G rdes Dam in 2011, significantly altered the natural inflow regime of the lake and created competition between environmental, domestic, and irrigation water demands [15]. In addition, expanding agricultural activities and increasing irrigation demand in the Gediz Basin have intensified regional water stress [12], while excessive groundwater abstraction and the disruption of spring–lake connections have reduced groundwater contributions to the lake system [13]. Together, these basin-scale hydrological alterations highlight the critical role of human pressures in accelerating the degradation of Lake Marmara beyond the effects of climatic variability alone [14].

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