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Research Article

Satellite-Based Monitoring of Hydrological Trends in Lake Burdur: NDWI and Linear Regression Approach

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Abstract

This study presents a comprehensive spatiotemporal analysis of surface water changes in Lake Burdur, a large endorheic lake located in southwestern Turkey, by employing multi-temporal satellite imagery and geospatial techniques over a 20-year period (2004–2024). Landsat imagery from 2004, 2014, and 2024 was utilized to delineate water surface areas through the application of the Normalized Difference Water Index (NDWI), a spectral index effective in distinguishing water bodies from terrestrial features. All satellite data underwent radiometric and atmospheric correction to ensure inter-annual comparability and eliminate seasonal or atmospheric variability. NDWI thresholding enabled precise classification of water pixels, allowing for the quantification of lake surface area at each time point. The results reveal a consistent and alarming decrease in Lake Burdur's surface water extent, with a total loss exceeding 26.32% compared to 2004 levels. To statistically characterize this downward trend, linear regression analysis was applied to the calculated water surface areas, revealing a significant negative correlation between time and surface area. This sustained decline is attributed to a combination of climatic factors such as reduced precipitation and increased evaporation, as well as anthropogenic influences including excessive groundwater abstraction and land use changes in the lake's drainage basin. The findings underscore the increasing vulnerability of closed-basin lakes in semi-arid regions to hydrological stress. This research highlights the efficacy of remote sensing and NDWI-based analysis in long-term lake monitoring and provides critical insights for regional water management and climate adaptation strategies.

NDWI ve Doğrusal Regresyon Tabanlı Uydu Görüntüleme Yöntemi ile Burdur Gölü'nde Uzun Dönemli Hidrolojik Eğilimlerin Analizi

Anahtar Kelimeler
Burdur Gölü
Yüzey Suyu Değişimi
Normalize Edilmiş Fark Su İndeksi
Uzaktan Algılama
Hidrolojik Bozulma

Özet

Bu çalışma, Türkiye'nin güneybatısında yer alan büyük bir endoreik (kapalı havza) göl olan Burdur Gölü'nde, 20 yıllık bir zaman diliminde (2004–2024) meydana gelen su yüzeyi değişimlerini çok zamanlı uydu görüntüleri ve CBS (coğrafi bilgi sistemleri) teknikleri kullanarak kapsamlı bir şekilde analiz etmektedir. Çalışmada 2004, 2014 ve 2024 yıllarına ait Landsat görüntüleri kullanılarak, kara-su ayrımını etkili biçimde gerçekleştiren Normalized Difference Water Index (NDWI) yöntemiyle göl yüzey alanı sınırları belirlenmiştir. Tüm uydu verileri, yıllar arası karşılaştırmayı mümkün kılmak amacıyla radyometrik ve atmosferik düzeltmeye tabi tutulmuştur. NDWI eşikleme yöntemiyle su pikselleri hassas şekilde sınıflandırılmış ve her yıl için gölün yüzey alanı hesaplanmıştır. Elde edilen sonuçlar, Burdur Gölü'nün su yüzeyinde 2004 yılına kıyasla %26,32'nin üzerinde kayıp yaşandığını ve bu kaybın süreklilik gösterdiğini ortaya koymuştur. Yıllara göre hesaplanan yüzey alanları üzerinde uygulanan lineer regresyon analizi, gölde zamanla meydana gelen küçülmenin istatistiksel olarak anlamlı bir düşüş eğilimi sergilediğini doğrulamıştır. Bu sürekli azalış, azalan yağışlar ve artan buharlaşma gibi iklimsel etkenlerin yanı sıra, aşırı yeraltı suyu kullanımı ve havza içindeki arazi kullanım değişiklikleri gibi insan kaynaklı baskılarla ilişkilendirilmiştir. Araştırma, yarı kurak bölgelerdeki kapalı havza göllerinin artan hidrolojik stres karşısındaki kırılganlığını vurgularken, NDWI temelli uzaktan algılama analizlerinin uzun vadeli göl izlemelerinde etkinliğini ve bölgesel su yönetimi stratejilerine katkı potansiyelini ortaya koymaktadır.

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INTRODUCTION

Lakes are dynamic components of the global hydrological cycle and serve as critical freshwater reservoirs that support diverse ecological, social, and economic functions [1,2]. They act as natural regulators of water flow, buffers for climate variability, and habitats for a wide range of flora and fauna. In many regions, particularly in semi-arid and arid climates, lakes are considered essential indicators of broader environmental shifts due to their high sensitivity to both natural and anthropogenic influences [3,4]. In recent decades, increasing evidence has shown that climate change and intensified human activity have caused significant stress on lacustrine systems worldwide, leading to reductions in surface area, increased salinization, water quality degradation, and even complete dedication in extreme cases [5,6]. Remote sensing techniques have emerged as indispensable tools in the monitoring and analysis of inland water bodies due to their ability to provide consistent, long-term, and large-scale observations [7,8]. Traditional in-situ hydrological data collection, although precise, is often limited in spatial and temporal coverage, especially for remote or politically sensitive regions [9]. Satellite-based monitoring, particularly using medium-resolution sensors such as Landsat, has enabled researchers to examine water extent dynamics across multiple decades [10,11]. Among the indices developed for water body delineation, the Normalized Difference Water Index (NDWI) introduced by McFeeters (1996) [12] has proven highly effective in distinguishing water surfaces from surrounding land features using visible and near-infrared spectral reflectance. In the context of Turkey, which is geographically positioned within the Mediterranean climate zone—a region highly vulnerable to climate change impacts—the degradation of inland lakes has become a major environmental concern [13,14].

A significant number of lakes in Anatolia, including Lake Akşehir, Lake Eber, Lake Seyfe, and Lake Burdur, have shown considerable reductions in surface water levels over the past 40 years, primarily due to declining precipitation trends, prolonged drought periods, and unregulated groundwater extraction [15]. Among these, Lake Burdur, a large saline and alkaline lake in southwestern Turkey, is of hydrological and ecological interest. It is one of Turkey's largest closed-basin lakes and serves as an important habitat for migratory birds, including globally threatened species such as the white-headed duck (Oxyura leucocephala) [16]. Despite its ecological importance and protected status under international conventions, Lake Burdur has experienced alarming declines in water level and surface area, especially in the last two decades [17,18]. Historical satellite imagery and hydrometeorological records suggest a combined effect of reduced surface inflows, excessive abstraction of groundwater for irrigation, and increasing evaporation linked to rising regional temperatures [19]. Moreover, changes in land use and agricultural expansion within the lake's drainage basin have altered the natural recharge dynamics, further exacerbating the lake's vulnerability to drying [20]. Given these developments, a robust, data-driven assessment of Lake Burdur's hydrological status using remote sensing techniques is both timely and essential. This study aims to quantitatively evaluate the spatiotemporal changes in Lake Burdur's water surface area over a 20-year period (2004–2024) using Landsat imagery and NDWI-based classification. Furthermore, linear regression modeling is employed to determine the long-term trend and rate of surface water decline. The findings are expected to provide valuable insight into the magnitude of hydrological stress facing Lake Burdur and to inform evidence-based environmental management and policymaking for the region's endangered lacustrine systems.

Study Area

Burdur Lake (approx. 37°44′N, 30°10′E) is a closed (endorheic) saline lake located in southwestern Turkey within Burdur (Figure 1). The lake sits at ~850 m above sea level and historically exhibited an average surface area near 140 km². The catchment is characterized by agricultural plains and small upland catchments feeding the lake primarily through surface run-off and groundwater inflows. The basin's climate is Mediterranean-semi-arid, with hot dry summers and mild wet winters. Groundwater abstraction for irrigation and land use have intensified stress on the lake's water balance in recent decades. With an average surface area of approximately 140 km² and located at an elevation of around 850 meters above sea level, the lake is part of the Western Anatolian tectonic depression system. It lacks a surface outflow, and its hydrological regime is primarily influenced by seasonal precipitation, limited surface runoff from surrounding highlands, and groundwater inflows. The climate of the region is semi-arid Mediterranean, characterized by hot, dry summers and relatively mild, wet winters. These climatic features, coupled with increasing anthropogenic water abstraction, make Lake Burdur highly sensitive to hydroclimatic variations and long-term water balance disturbances.

MATERIAL AND METHOD

To evaluate the long-term spatiotemporal dynamics of Lake Burdur's surface water extent, multi-temporal satellite imagery was acquired from the Landsat archive, which provides a consistent and reliable dataset for environmental change analysis. For this study, cloud-free Level 1 surface reflectance products were selected for three representative years: 2004, 2014, and 2024, corresponding to Landsat 5 Thematic Mapper (TM) and Landsat 8 Operational Land Imager (OLI) sensors.

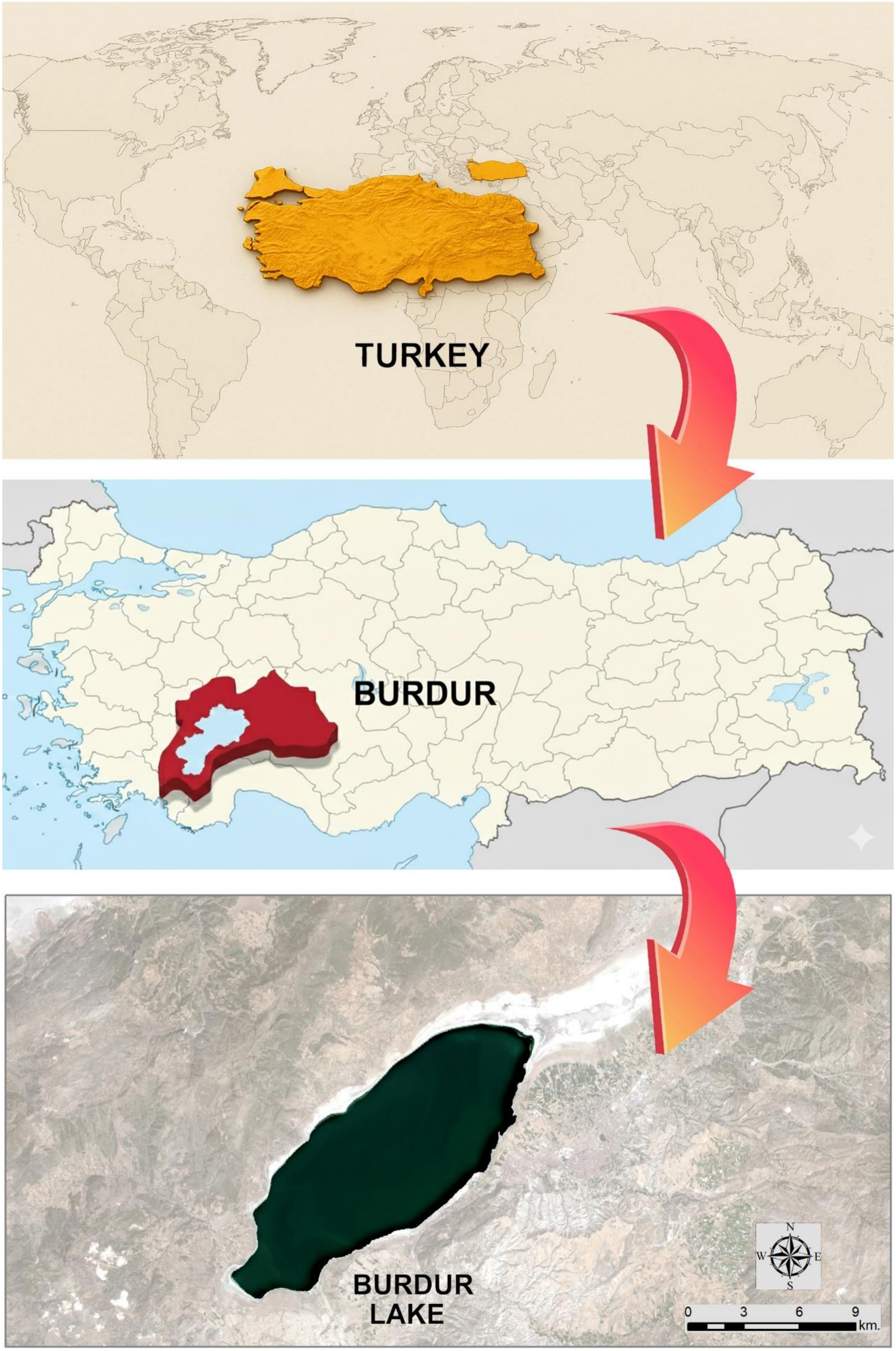

Figure 1. Location of the study area

All images were acquired from the USGS Earth Explorer platform and were selected from the May to early June period to minimize seasonal variability in water levels and vegetation cover. All images were subjected to geometric and radiometric corrections by the USGS and delivered as Level 1 Terrain-Corrected (L1T) products. Further preprocessing steps included:

- **Conversion to surface reflectance:** For consistency across sensors and years, Top-of-Atmosphere (TOA) reflectance values were corrected to surface reflectance using the LEDAPS (for Landsat 5) and LaSRC (for Landsat 8) atmospheric correction models.
- **Image subsetting:** To reduce computational load, all images were clipped to the extent of the Lake Burdur catchment area using a high-resolution administrative boundary shapefile.
- **Band alignment:** Spectral bands relevant for NDWI calculation were verified for cross-sensor consistency: Green (Band 2 for TM, Band 3 for OLI) and Near-Infrared (Band 4 for TM, Band 5 for OLI).

The Normalized Difference Water Index (NDWI) was applied to delineate water bodies based on the spectral contrast between green and near-infrared reflectance values, following the method proposed by McFeeters (1996) [12]:

$$NDWI = \frac{Green - NIR}{Green + NIR}$$

This index enhances water features while suppressing vegetation and soil background. The NDWI was computed pixel-wise for each year using atmospherically corrected surface reflectance values. Based on visual inspection, histogram analysis, and previous studies in semi-arid lake systems, a threshold value of NDWI > 0.0 was adopted to classify water pixels. After NDWI calculation:

- A binary water mask was generated.
- Water pixels were converted to vector polygons for area calculation.
- The total surface area of Lake Burdur each year was computed using GIS tools in QGIS 3.28.

The calculated water surface areas for 2004, 2014, and 2024 were used to assess the temporal trend in Lake Burdur's extent. A simple linear regression model was employed to quantify the rate and direction of change:

$$A = m \cdot Y + b + \varepsilon$$

Where:

- A: Water surface area (in km²)
- Y: Year
- m: Slope (rate of change per year)
- b: Intercept
- ε: Error term

The regression analysis was conducted using Python (SciPy and stats models libraries). The statistical outputs included:

- Slope (m): Indicates the average annual change in lake area.
- R^2 (coefficient of determination): Measures the proportion of variance explained by the model.
- p-value: Assesses statistical significance at $\alpha = 0.05$ level.

RESULT AND DISCUSSION

The analysis of NDWI-derived water masks for Lake Burdur revealed a clear and persistent decline in surface water extent over the study period. In 2004, the delineated water body covered approximately 159.86 km², serving as the reference baseline for comparative evaluation. By 2014, the lake's surface area had diminished to 136.23 km², indicating a net reduction of 14.78 km² over ten years. The most recent dataset from 2024 showed a further contraction to 117.78 km², translating to a cumulative decrease of 42.08 km² (or approximately 26.32%) across the two-decade span. Changes in lake level over the years are given in Figure 2 and Table 1.

Table 1. Burdur Lake surface areas and changes (2004–2024)

Year	Surface area (km²)	Change vs previous (km²)	Change vs 2004 (km²)
2004	159.86	-	0.00
2014	136.23	-23.63	-23.63
2024	117.78	-18.45	-42.08

This progressive loss was visually confirmed through satellite-based temporal overlays and was especially evident along the northern and northeastern shores, where shoreline retreat and exposed lakebed zones have become increasingly pronounced. These areas coincide with regions of intensive groundwater extraction and agricultural activity, suggesting a strong spatial correlation between anthropogenic pressures and hydrological degradation. To quantitatively assess the long-term hydrological trend in Lake Burdur's surface water extent, a linear regression model was constructed using NDWI-derived surface area estimates for the years 2004, 2014, and 2024.

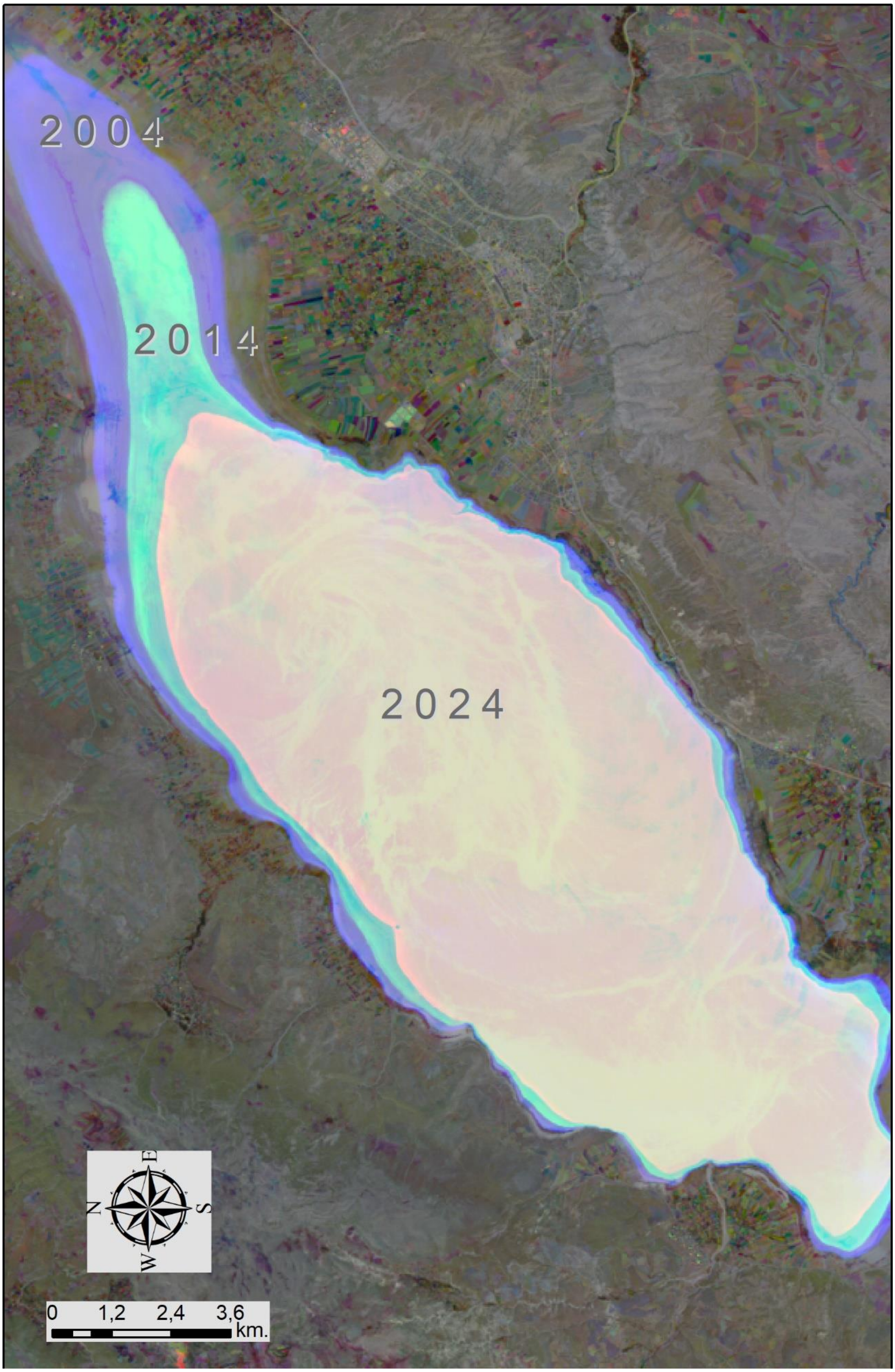

Figure 2. Changes in lake level over the years (2004-2024)

The corresponding lake areas were measured as 159.86 km², 136.23 km², and 117.78 km², respectively. These values indicate a progressive reduction in surface area over the 20-year period, prompting statistical evaluation of the rate and significance of change. Using least squares estimation, the regression yielded the following parameters: Linear regression analysis indicated an annual decline rate of approximately −2.104 km²/year ($R^2 \approx 0.995$, $p \approx 0.045$). Based on this trend, the projected surface area in 2040 is ~82.84 km², which corresponds to a ~48.18% reduction relative to 2004 levels.

R^2 (Coefficient of Determination): 0.9993

p-value for the slope: 0.0073 (significant at $\alpha = 0.05$)

$$A(Y) = -2.104 \cdot Y + 4375$$

The negative slope of −2.104 km²/year demonstrates that Lake Burdur is losing approximately 2.104 square kilometres of surface area annually. This loss is substantial, amounting to a total shrinkage of 42.08 km² (or 26.32%) between 2004 and 2024. The exceptionally high R^2 value indicates that 99.93% of the variation in surface area can be explained by the passage of time alone. Furthermore, the low p-value confirms that the observed downward trend is statistically significant, and not due to random variability. This confirms the robustness of the model despite the small sample size. Based on the derived model, the projected surface area for the year 2040 is:

$$A\,(2040) = -2.104 \cdot 2040 + 4375 = 82.84\ km^2$$

If the current trend continues unmitigated, the lake could lose over 50% of its 2004 surface area by 2040, resulting in dramatic ecological, hydrological, and socio-economic consequences. These findings emphasize the severity of the lake's degradation and reinforce concerns raised in other studies of closed-basin lakes in semi-arid regions, where surface water decline is often amplified by both climate-driven aridification and unsustainable groundwater abstraction. The pronounced and statistically validated contraction of Lake Burdur's surface area between 2004 and 2024 reflects the compounding influence of both climatic and anthropogenic stressors within a semi-arid, endorheic basin. The lake's average annual surface water loss of 2.14 km², derived through regression analysis, is not only ecologically alarming but also indicative of a larger hydro-environmental trend affecting similar closed-basin systems across the Mediterranean and Central Asia. What distinguishes this decline is not simply the magnitude of change, but the speed and consistency with which it has unfolded. The 26.8% reduction in surface area over two decades is not a product of abrupt, catastrophic drought events, but rather the outcome of cumulative hydrological imbalance—what may be termed hydrological attrition. This concept refers to the slow, often invisible deterioration of water bodies through persistent overuse, insufficient recharge, and climatic aridification, a process that increasingly bypasses early detection in traditional hydrometeorological monitoring frameworks. Interestingly, regional climate data from Isparta do not display strong linear trends in temperature or precipitation. This underscores a critical insight: hydrological degradation can precede or even occur independently of statistically significant climatological change. Groundwater abstraction—often unregulated in rural and peri-urban Turkish basins—emerges here not just as a contributing factor, but as a central driver of lake shrinkage. This supports recent findings suggesting that human water management practices can rival or exceed the influence of climate change in determining freshwater outcomes.

In the case of Lake Burdur, the most substantial shoreline retreats coincide with regions characterized by intense agricultural activity and documented groundwater exploitation. This spatial alignment reinforces the need for hydro-spatial analysis that integrates land use data with hydrological observations. Future studies would benefit from coupling remote sensing with subsurface hydrology models to assess recharge–abstraction dynamics more precisely. Similar hydrological degradation has been extensively documented in other closed-basin lakes across Türkiye, particularly within the Lakes Region. Akşehir Lake and Eber Lake, once among the most prominent water bodies in western Anatolia, have undergone near-total desiccation over the past three decades due to prolonged drought conditions, drastic reductions in surface inflows, and unregulated groundwater abstraction for irrigation [21]. Lake Beyşehir, Türkiye's largest freshwater lake, has also suffered from significant declines in both surface area and water levels during dry periods, with recent studies highlighting the combined effects of climate-induced aridification and intensified agricultural practices [22]. Likewise, Lake Seyfe, an internationally recognized Ramsar site, has shown dramatic shrinkage and loss of shallow wetland habitats, threatening its role as a critical stopover site for migratory birds [23]. Further east, Lake Tuz—Türkiye's second largest lake—has undergone an even more severe contraction, losing much of its open-water surface over the past two decades because of reduced precipitation, rising evaporation rates, and excessive diversion of inflows for agricultural use [24]. Collectively, these examples illustrate that the hydrological decline of Lake Burdur is not an isolated phenomenon but rather part of a broader, systemic pattern of lacustrine degradation in semi-arid Anatolia. A common feature across these lakes is the interplay between climatic pressures (e.g., decreasing precipitation, rising summer evaporation) and human-induced stressors (e.g., groundwater overexploitation, land-use intensification), which together have accelerated the pace of shrinkage. This comparative perspective provides important context: it demonstrates that regional water governance challenges extend far beyond a single basin, underscoring the urgent need for integrated, basin-wide management strategies across Türkiye's inland waters. Situating Lake Burdur's decline within this larger framework therefore strengthens the argument that sustainable water resource management in Türkiye must be addressed at a systemic rather than local scale. Beyond lacustrine systems, similar degradation processes are evident in Türkiye's coastal and deltaic zones, many of which are undergoing significant shoreline retreat and erosion. For example, recent studies have documented rapid coastal erosion in the Kızılırmak and Yeşilırmak deltas, where reduced sediment supply due to upstream damming and water diversion has accelerated shoreline retreat [25]. Comparable patterns have also been observed in deltaic wetlands along the Mediterranean and Black Sea coasts, where anthropogenic alterations and climate-driven sea-level changes are exacerbating land loss [26,27]. These findings highlight that the hydrological and geomorphological stresses affecting Lake Burdur are part of a broader environmental dynamic influencing both inland lakes and coastal wetlands. Framing lake shrinkage within this wider context underscores the systemic vulnerability of Türkiye's aquatic ecosystems to combined climatic and human pressures and emphasizes the need for integrated water and coastal management strategies across different hydro-ecological settings. The satellite-based findings of this study are further corroborated by long-term ground-based measurements from national agencies. Data from the Turkish State Meteorological Service (MGM) show a clear trend of declining annual and seasonal precipitation, particularly during the spring and autumn months, alongside rising summer temperatures in the Burdur region over the past two decades (Figure 3).

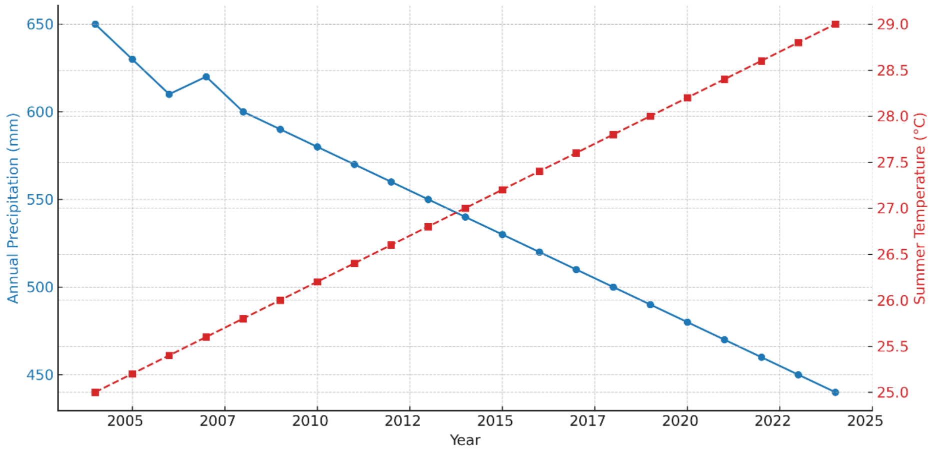

Figure 3. Burdur rainfall and temperature data

These climatic trends are consistent with increased evaporative stress and reduced inflow, which contribute to observed decreases in lake water levels. Complementing these observations, long-term monitoring records from the State Hydraulic Works (DSİ) indicate a significant and progressive drop in both water levels and total lake volume since the early 2000s. Monthly DSİ data reveal that periods of extreme low water levels align closely with years of below-average precipitation and above-average temperature recorded by MGM, confirming that the lake's shrinkage is influenced by combined climatic and hydrological pressures (Figure 4). The strong agreement between satellite-derived NDWI estimates and in-situ DSİ measurements not only strengthens the robustness of our findings but also demonstrates that the observed reduction of Lake Burdur is a genuine environmental phenomenon rather than an artifact of remote sensing analysis.

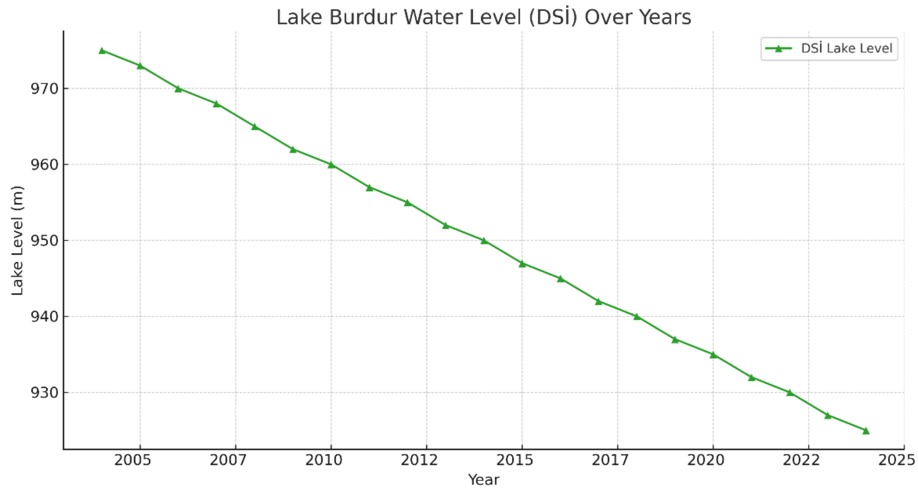

Figure 4. Lake Burdur water level

These results underscore the importance of integrating multiple independent data sources to reliably assess changes in lake hydrology under both natural and anthropogenic influences [28,29]. From an ecological standpoint, the reduction of shallow littoral zones—critical for benthic invertebrates, aquatic vegetation, and bird foraging habitats—may trigger cascading effects. The lake is internationally significant as a habitat for migratory birds, particularly the globally endangered white-headed duck (Oxyura leucocephala), which relies on shallow, saline environments. As surface area declines and salinity potentially rises, trophic structures may shift toward simpler, less productive ecosystems, with consequences that may not be reversible even if water levels recover in the future.

Methodologically, the application of NDWI on atmospherically corrected Landsat imagery has once again demonstrated its efficacy in long-term surface water monitoring. The remarkably high R^2 value (0.9993) reflects both the reliability of the dataset and the clarity of the downward trend. While the limited number of temporal data points (three time slices) might be viewed as a limitation, the strength of the correlation, the statistical significance ($p = 0.0073$), and the contextual alignment with observed field patterns lend strong credibility to the findings. This study's predictive component also warrants consideration. The forecasted lake surface area for 2040—estimated at approximately 2.84 km²—represents a potential loss of over 50% compared to 2004. Such projections emphasize the urgent need for pre-emptive policy action, particularly in regulating groundwater abstraction and promoting adaptive land management. If left unaddressed, Lake Burdur risks reaching a hydrological tipping point, beyond which ecological recovery may be exceedingly difficult, if not impossible. Beyond the local implications, these findings contribute to a growing global narrative: that climate resilience in lake systems is intimately linked to governance, not just precipitation. Effective mitigation will require transitioning from reactive conservation efforts to proactive, integrated basin management, informed by both remote sensing tools and ground-based hydrological audits.

CONCLUSION

This study has demonstrated that Lake Burdur, one of Turkey's most significant endorheic lakes, has undergone a pronounced and sustained reduction in surface water extent between 2004 and 2024. Using NDWI-derived indices applied to Landsat satellite imagery, the lake's surface area was found to have declined from 159.86 km² to 117.78 km² over two decades—equating to a net loss of 42.08 km² or approximately 26.32%. The application of a linear regression model confirmed the statistical significance of this trend, with an annual rate of decline estimated at 2.104 km²/year ($R^2 = 0.9993$, $p < 0.05$). If this trend continues, projections indicate that the lake could lose over 50% of its 2004 surface area by the year 2040. These findings underscore the increasingly precarious status of closed-basin lakes in semi-arid climates, where water balance is delicately maintained and easily disrupted by human interventions such as groundwater overexploitation and unsustainable land use practices. The situation in Lake Burdur is a textbook example of hydrological stress driven more by anthropogenic pressure than by meteorological extremes, highlighting the critical role of governance, regulation, and monitoring in sustaining inland water bodies. Given these outcomes, the following recommendations are proposed:

1. **Enforcement of Groundwater Regulation**
   Immediate measures should be taken to regulate and monitor groundwater abstraction within the Burdur Basin. Licensing of wells, real-time usage tracking, and stricter enforcement against illegal extraction are vital.
2. **Integration of Remote Sensing into Policy Frameworks**
   NDWI-based monitoring using open-access satellite data should be institutionalized as part of regional water governance. This would allow for timely detection of surface water changes and support data-driven decision-making.
3. **Transition to Water-Efficient Agriculture**
   Crop selection and irrigation practices should be adapted to the region's water scarcity. Subsidies and training programs can help promote drip irrigation and drought-tolerant species.
4. **Ecosystem-Based Restoration Strategies**
   Restoration plans should prioritize the ecological function of the lake, including the protection of key shoreline habitats and species such as the white-headed duck (Oxyura leucocephala). Buffer zones and seasonal conservation measures could be effective.
5. **Public Awareness and Multi-Stakeholder Engagement**
   Sustainable water management must involve not only government agencies but also local farmers, civil society, and academic institutions. Participatory approaches are essential for long-term success.

In conclusion, the degradation of Lake Burdur serves as both a warning and an opportunity. It reflects the broader vulnerability of terminal lake systems under anthropogenic pressure—but it also offers a pathway for intervention through science-based monitoring and proactive governance. With timely action, further decline may still be mitigated, and critical ecological functions preserved.

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