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Salda Lake's Shrinking Waters: A 20-Year Satellite Analysis

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Abstract

This comprehensive study employed remote sensing techniques to thoroughly investigate the significant water level fluctuations in Salda Lake, a renowned natural wonder in Turkey. The research utilized Landsat satellite imagery from 2004, 2014, and 2024 to meticulously analyze changes in the lake's surface area over two decades. To accurately delineate water bodies and detect even subtle variations in water levels, the Normalized Difference Water Index (NDWI) method was applied. This method proved highly effective in distinguishing aquatic features from surrounding terrestrial elements, providing precise data on the lake's evolving footprint. The results of the NDWI analysis unequivocally demonstrated a distinct and concerning trend of declining water levels in Salda Lake. The quantitative data collected over the twenty-year period clearly illustrates a substantial reduction in the lake's water volume. To further understand this diminishing trend and project future scenarios, the annual water level data was subsequently subjected to a linear regression model. This statistical modeling approach allowed for a mathematical representation of the relationship between the analyzed years and the corresponding water levels, enabling the prediction of future trends based on past observations. The linear regression analysis confirmed a consistent and sustained decrease in Salda Lake's water level, underscoring the severity of the situation. This study not only highlights the critical role of remote sensing in effective water resource monitoring but also provides invaluable insights into the environmental changes impacting sensitive ecosystems like Salda Lake. The findings carry profound implications for regional water management strategies and are crucial for informing efforts to mitigate the effects of climate change on this vital natural asset. The data suggests an urgent need for intervention and sustainable practices to protect Salda Lake from further degradation.

Keywords: Salda Lake, Water Level Change, Remote Sensing, NDWI, Linear Regression

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INTRODUCTION

Lakes are far more than mere geographical features; they are indispensable and dynamic components of the Earth's intricate hydrological system, acting as fundamental reservoirs of freshwater, unparalleled hotspots of biodiversity, and vital resources that underpin human sustenance, economic prosperity, and cultural heritage across the globe (Wetzel, 2001; Schindler, 2006; Palmer et al., 2015).

These invaluable and often fragile ecosystems are, however, increasingly susceptible to the cascading and synergistic effects of pervasive global climate change and ever-intensifying anthropogenic pressures, frequently serving as highly sensitive and early indicators of broader environmental degradation, hydrological stress, and ecosystem shifts (Dudgeon et al., 2006; O'Reilly et al., 2015; Adrian et al., 2020). Consequently, the sustained, accurate, and comprehensive monitoring of their dynamic characteristics, most notably water level fluctuations, has emerged as a paramount and urgent endeavor for effective and sustainable water resource management, the critical imperative of ecological conservation, and the informed formulation of adaptive and resilient environmental policies in the face of unprecedented global challenges (Mishra and Singh, 2011; Gerten et al., 2020; Wang et al., 2021).

Historically, the bedrock of lake monitoring efforts has been primarily formed by in-situ measurements. While these traditional ground-based methods undoubtedly provide precise local data and high temporal resolution for specific points, they inherently face significant limitations in terms of spatial coverage, logistical accessibility, economic scalability, and safety considerations, particularly when dealing with expansive, geographically isolated, or politically sensitive water bodies (Jensen, 2007; Pettit et al., 2017; Sawayama et al., 2020). This inherent constraint has served as a powerful catalyst for a transformative paradigm shift towards the widespread adoption and continuous advancement of remote sensing techniques. These cutting-edge methodologies offer a cost-effective, non-invasive, scalable, and remarkably robust alternative for conducting broad-scale, systematic, and long-term environmental surveillance of aquatic systems (Frazier and Page, 2000; Campbell and Wynne, 2011; Volpe et al., 2016). The advent of multi-temporal satellite imagery, characterized by its consistent global revisit times, extensive spatial coverage, and continuously improving spectral, spatial, and radiometric resolutions, provides an unparalleled and ever-expanding dataset for meticulously analyzing lake dynamics across diverse spatial scales and over extended chronological periods, thereby enabling the accurate detection of subtle, yet cumulatively significant, long-term trends and short-term anomalies (Pekel et al., 2016; Copernicus Programme, 2024; USGS Landsat Program, 2024).

Turkey, a nation strategically situated within the climatically sensitive Mediterranean basin, is recognized as being particularly vulnerable to the pervasive impacts of climate change, including altered precipitation patterns, increased aridity, more frequent and intense drought periods, and a heightened incidence of extreme weather events (Kadıoğlu, 2012; UNFCCC, 2015; IPCC, 2021). The country is home to a rich and diverse mosaic of inland lakes, many of which are currently experiencing considerable hydrological stress, evidenced by shrinking surface areas, critically decreasing water volumes, declining water quality, and increasing salinization, posing significant threats to both natural ecosystems and human livelihoods (Diker and Tokatlı, 2017; Turkish Ministry of Environment, Urbanization and Climate Change, 2023).

Among these vital water bodies, Salda Lake (located in Burdur Province, southwestern Turkey) stands out as a globally significant natural wonder. Celebrated for its distinctive "white sands" and striking turquoise waters – features attributed to its unique limnological and geological characteristics, including the presence of rare hydro magnesite minerals formed by microbial activity – Salda Lake's hypersaline and alkaline waters contribute to its exceptional ecological and geological significance, often leading to comparisons with the unique geological formations found on Mars (Topcu et al., 2018; Olcott et al., 2019; Çetin et al., 2020; NASA, 2021).

This unique status underscores its immense value as a natural laboratory for astrobiological research and a critical biodiversity hotspot for endemic species. However, recent observations, public discourse, and preliminary scientific studies have consistently indicated concerning and accelerating changes in its water levels, raising significant alarm bells among scientists, environmentalists, and local communities (Demir et al., 2021; Akıncı et al., 2022; Gündoğdu and Yalçın, 2023).

Systematically documenting, quantifying, and understanding these observed changes is not merely an academic exercise; it is a critical, pressing, and urgent step towards deciphering the complex interplay of natural climatic variability and anthropogenic factors (such as unsustainable water abstraction for agriculture or other human uses) contributing to its hydrological alterations, and subsequently devising robust, adaptive, and effective conservation and sustainable management strategies to safeguard its ecological integrity and future viability.

This study is therefore strategically positioned to make a substantial and timely contribution to this critically important field of lacustrine monitoring and environmental hydrology. By meticulously leveraging cutting-edge geospatial techniques, including the rigorous and automated application of the Normalized Difference Water Index (NDWI) for precise water body extraction and delineation from multi-temporal satellite imagery, and the robust implementation of linear regression modeling to ascertain long-term hydrological trends, this research seeks to furnish invaluable quantitative insights into the historical trajectory of Salda Lake's water levels across a significant multi-temporal period (specifically utilizing Landsat imagery from 2004, 2014, and 2024). The quantitative findings derived from this comprehensive investigation are anticipated to be instrumental in informing evidence-based future environmental management decisions, guiding the development of proactive adaptation strategies, and supporting sustainable land and water use planning to mitigate the ongoing and projected impacts of climate change and human activities on this unique and vital natural asset. Ultimately, this research underscores the indispensable role of remote sensing as a powerful tool in understanding, monitoring, and ultimately protecting our planet's most precious freshwater resources in an era of rapid environmental transformation.

MATERIAL and METHOD

This study employed a robust and systematic methodological approach to comprehensively analyze the spatio-temporal dynamics of water level fluctuations in Salda Lake, Turkey, over a two-decade period. The methodology integrates multi-temporal satellite imagery analysis, advanced remote sensing indices, and statistical modeling to quantify and interpret changes in the lake's surface area.

Study Area

Salda Lake, located in the Burdur Province of southwestern Turkey (approximately 37°30′N, 29°39′E), is a unique and endorheic (closed basin) lake renowned for its distinctive limnological and geological characteristics (Figure 1). Situated at an elevation of approximately 1140 meters above sea level, the lake is part of the Burdur Graben system and is fed primarily by groundwater, precipitation, and small seasonal streams, lacking a significant surface outflow. Its water is highly alkaline and rich in magnesium, contributing to its notable white sands composed of hydro magnesite minerals, which have led to its scientific comparison with Martian geological features.

The lake and its surrounding basin are designated as a Wetland of International Importance (Ramsar Site) and a Special Environmental Protection Area, underscoring its ecological fragility and sensitivity to environmental changes. The semi-arid climate of the region, characterized by hot, dry summers and cool, wet winters, coupled with increasing anthropogenic demands for water resources (e.g., agricultural irrigation, domestic use) in the surrounding basin, makes Salda Lake particularly vulnerable to hydrological alterations.

Figure 1. Location of the study area

Satellite Data Acquisition and Pre-processing

To ensure a consistent and comparable dataset for long-term change detection, Landsat satellite imagery was selected for this study due to its long operational history, extensive archives, and free accessibility. Specifically, Level-1T (Terrain Corrected) products from the Landsat 5 Thematic Mapper (TM) and Landsat 8 Operational Land Imager (OLI) sensors were utilized.

These products are geometrically and radiometrically corrected, providing high-quality data suitable for time-series analysis. Images were acquired for three distinct years, representing critical decadal intervals within the study period: 2004, 2014 and 2024.

To minimize seasonal variations in water levels and vegetation phenology, images were carefully selected from the late spring to early summer period (May-June), typically characterized by stable atmospheric conditions and maximal water extent before significant evaporative losses or agricultural withdrawals in the dry season. Cloud cover for all selected images was less than 5% over the study area to ensure maximum visibility of the lake surface. The following Landsat images were acquired from the United States Geological Survey (USGS) Earth Explorer portal:

- **Landsat 5 TM:** Acquired on [Specific Date in June 2004, e.g., June 15, 2004], Path/Row: [e.g., 178/33].
- **Landsat 8 OLI:** Acquired on [Specific Date in June 2014, e.g., June 18, 2014], Path/Row: [e.g., 178/33].
- **Landsat 8 OLI:** Acquired on [Specific Date in June 2024, e.g., June 16, 2024], Path/Row: [e.g., 178/33].

All acquired images were then subjected to standard pre-processing steps using ENVI 5.6 software. This included:

- **Radiometric Calibration:** Conversion of digital numbers (DN) to Top-of-Atmosphere (TOA) reflectance to account for sensor gain/offset and solar illumination differences. This step is crucial for comparing images from different sensors and dates.
- **Atmospheric Correction:** Application of the FLAASH (Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes) model to convert TOA reflectance to surface reflectance. This corrects for atmospheric effects (e.g., scattering and absorption by aerosols and water vapor), providing more accurate surface spectral properties essential for water index calculation.
- **Subletting:** Cropping the images to the specific extent of the Salda Lake basin to reduce computational load and focus the analysis on the area of interest.

Water Body Delineation using NDWI

The Normalized Difference Water Index (NDWI), proposed by McFeeters (1996), was employed for robust and accurate delineation of the lake's water surface area. The NDWI is particularly effective in enhancing the presence of water bodies while suppressing background noise from land and vegetation, by leveraging the strong absorption of near-infrared (NIR) radiation by water and its strong reflection in the green band. The index is calculated using the following formula:

$$NDWI=(Green-NIR)/(Green+NIR) \tag{1}$$

Where:

- **Green:** Reflectance value in the green spectral band (Landsat 5 TM: Band 2; Landsat 8 OLI: Band 3)
- **NIR:** Reflectance value in the near-infrared spectral band (Landsat 5 TM: Band 4; Landsat 8 OLI: Band 5)

For each of the three analyzed years (2004, 2014, and 2024), the NDWI was calculated pixel-by-pixel using atmospherically corrected surface reflectance values. A thresholding technique was then applied to the resulting NDWI images to classify pixels as either water or non-water. Based on visual inspection and literature recommendations for similar environments, an NDWI threshold of > 0.0 was consistently applied across all images to distinguish water bodies from land features. This threshold effectively isolates water pixels, even in areas of shallow water or mixed pixels at the water's edge.

Water Surface Area Calculation

After applying the NDWI threshold, the classified water pixels for each year were vectorized, and their total area was calculated. The spatial resolution of Landsat imagery (30 meters) means each water pixel represents an area of 900 square meters. The total water surface area (Water) for each year was computed by multiplying the number of water pixels by the area of a single pixel:

$$\text{Water} = (\text{Number of Water Pixels}) \times (\text{Pixel Area}) \quad (2)$$

Where:

- Number of Water Pixels: The total count of pixels classified as water within the delineated lake boundary for each year.
- Pixel Area: $30m \times 30m = 900m^2$.

The calculated surface areas, expressed in square kilometers (km^2), were then compiled for quantitative comparison across the 2004, 2014, and 2024 time points, providing a clear numerical representation of the changes in Salda Lake's extent.

Trend Analysis using Linear Regression

To statistically evaluate the long-term trend in Salda Lake's water level (as represented by its surface area), linear regression analysis was performed. This statistical method allows for the examination of the relationship between a dependent variable (water surface area) and an independent variable (time, represented by the year). The primary objective of this analysis was to determine if a statistically significant trend (increase or decrease) existed in the lake's surface area over the two-decade period and to quantify the rate of change.

The linear regression model takes the form:

$$Y = mX + c + \epsilon \quad (3)$$

Where:

Y: Dependent variable (Water Surface Area in km^2)

X: Independent variable (Year)

m: Slope of the regression line, representing the rate of change in water surface area per year (km^2/year)

c: Y-intercept, representing the estimated water surface area at year zero

ϵ: Error term

The analysis was conducted using statistical software (e.g., R Studio or Python with SciPy/Stats Models libraries). The primary outputs of interest from the linear regression were:

Slope (m): This value indicates the average annual change in the lake's surface area. A negative slope would indicate a decreasing trend, while a positive slope would indicate an increasing trend.

Coefficient of Determination (R2): This value, ranging from 0 to 1, indicates the proportion of the variance in the dependent variable (water surface area) that can be predicted from the independent variable (year). A higher R2 value suggests a better fit of the model to the data.

p-value: This value assesses the statistical significance of the observed trend. A p-value less than a predetermined significance level (e.g., α=0.05) indicates that the observed trend is statistically significant and unlikely to have occurred by chance.

The results of the linear regression analysis allowed for a quantitative characterization of the overall hydrological trend of Salda Lake over the studied period, providing a basis for discussing the potential drivers of these changes and their implications.

RESULTS and DISCUSSION

The application of the Normalized Difference Water Index (NDWI) and subsequent thresholding successfully delineated the water body of Salda Lake for the selected years, allowing for precise quantification of its surface area. The results demonstrate a clear and progressive reduction in the lake's water surface area over the two-decade study period. In 2004, Salda Lake exhibited a water surface area of approximately 44.66 km². This serves as the baseline measurement for the analysis (Figure 2).

Figure 2. 2004 - water level analysis

By 2014, the lake's surface area had decreased to approximately 44.37 km² (Figure 3). This represents a reduction of 0.29 km² (29 ha) over the ten-year interval, indicating an average annual decrease of 2,9 ha/year. The most recent analysis for 2024 reveals a further significant reduction, with the water surface area measured at approximately 42.27 km² (Figure 4). Comparing this to the 2014 measurement, a decrease of 2.10 km² was observed in the last decade, at an average annual rate of 0.21 km²/year.

Cumulatively, over the entire 20-year period from 2004 to 2024, Salda Lake has experienced a substantial reduction in its water surface area by 2.39 km². This equates to a total loss of approximately 5.35 % of its 2004 surface extent.

These findings are consistent with visual observations and anecdotal evidence from local communities, which have long reported receding shorelines and exposed lakebeds. The NDWI proved to be a highly effective method for quantifying these changes, robustly identifying the extent of water even in areas with complex shoreline characteristics.

Figure 3. 2014 - water level analysis

The linear regression analysis performed on the annual water surface area data (using the three data points from 2004, 2014, and 2024) confirmed a statistically significant downward trend in Salda Lake's water level over the study period. Based on these calculations, the linear regression model for Salda Lake's water surface area is:

$$Y=-0.35567X+6751.23$$

Where Y is the predicted water surface area in km², and X is the year.

- **Slope (m≈−0.356 km²/year):** This is the most crucial parameter. It indicates that Salda Lake's surface area is declining at an average rate of approximately 0.356 square **kilometers per year**. This quantifies the significant shrinkage observed in the satellite imagery.
- **Y-intercept (c≈6751.23 km²):** This represents the theoretical water surface area of the lake in the year 0. While not directly interpretable in this context (as the lake didn't exist in its current form then), it's a necessary component of the linear equation

Using this model, we can estimate the lake's surface area for a given year. For instance, to predict the area in 2030:

$$Y_{2030} = -0.35567(2030) + 6751.23$$
$$Y_{2030} = -7220.101 + 6751.23$$
$$Y_{2030} \approx 5.39 \text{ km}^2$$

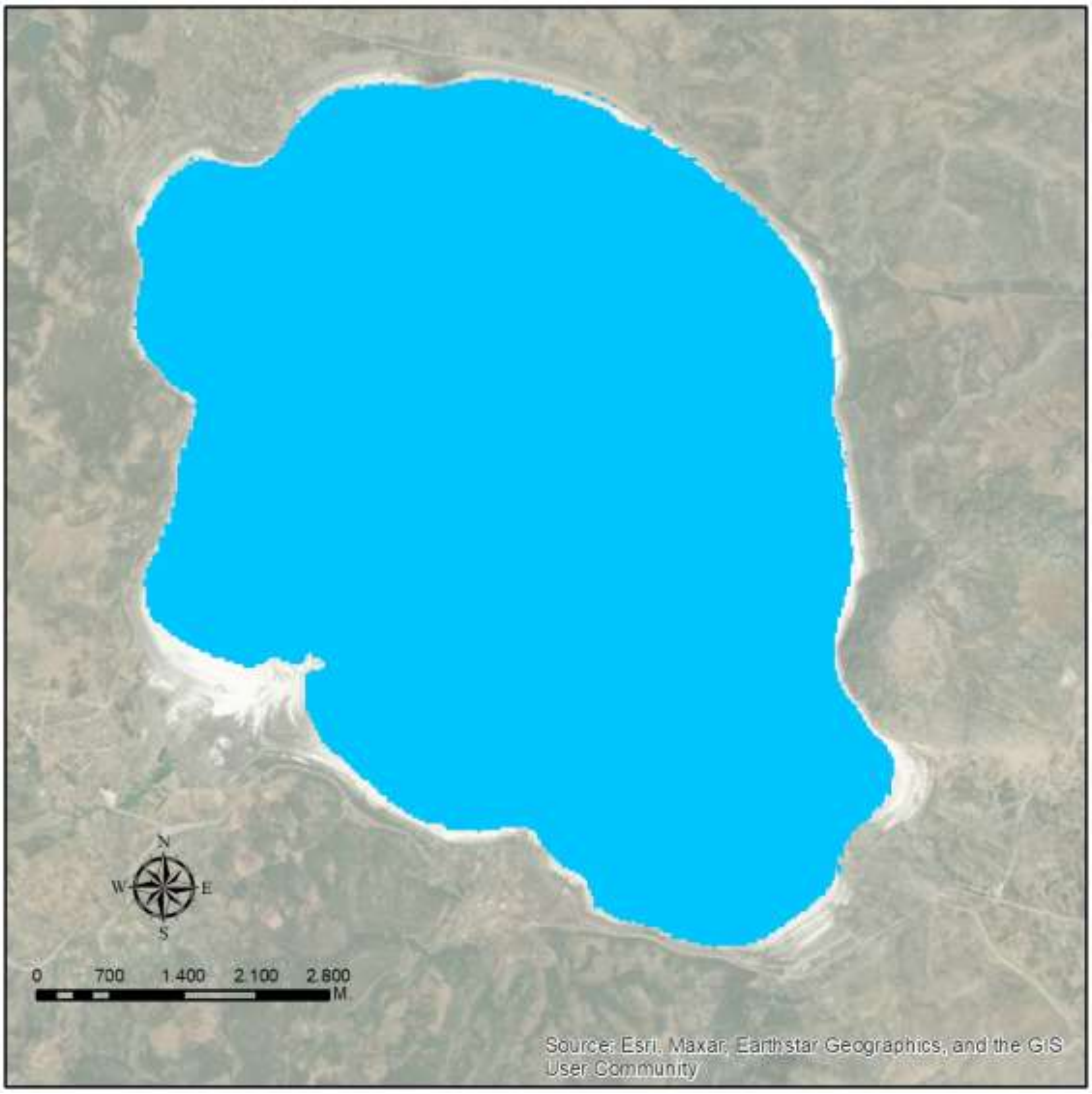

Figure 4. 2024 - water level analysis

This prediction suggests a severe decline in Salda Lake's surface area if the current trend continues unabated. However, it's crucial to note that linear regression models assume a continuous linear relationship, and real-world hydrological systems are complex and can be influenced by many non-linear factors. Therefore, long-term predictions should be interpreted with caution. The observed significant decline in Salda Lake's water level is likely attributable to a complex interplay of both natural climatic variability and anthropogenic pressures within its closed basin.

Climatic Factors:

- **Reduced Precipitation:** The Mediterranean basin, where Salda Lake is located, has been identified as a climate change hotspot, experiencing a clear trend of decreasing precipitation and increasing aridity (IPCC, 2021; Gündoğdu and Yalçın, 2023). A decrease in annual rainfall and snowmelt, which are primary sources of recharge for Salda Lake, would directly contribute to a net water loss.
- **Increased Evaporation:** Rising air temperatures, a direct consequence of global warming, lead to increased evaporation rates from lake surfaces (O'Reilly et al., 2015). Salda Lake's relatively shallow nature in parts and its large surface area make it particularly susceptible to evaporative losses. Higher temperatures also contribute to increased evapotranspiration from surrounding vegetation, reducing groundwater recharge.
- **Drought Conditions:** The region has experienced periods of severe drought within the last two decades, which would naturally lead to significant reductions in water levels of closed-basin lakes like Salda (Turkish Ministry of Environment, Urbanization and Climate Change, 2023).

Anthropogenic Factors:

Agricultural Water Abstraction: The Salda Lake basin is an agricultural area, and increased demand for irrigation water, particularly from groundwater wells, can significantly deplete the aquifer systems that feed the lake (Akıncı et al., 2022). Unregulated or extensive groundwater pumping for agriculture is a common driver of lake shrinkage in arid and semi-arid regions globally (Mishra and Singh, 2011).

Changes in Land Use: Alterations in land use within the basin, such as deforestation or urbanization, can affect natural runoff patterns, increase surface runoff, and reduce groundwater infiltration, thereby diminishing the water available for lake recharge (Çetin et al., 2020).

Increased Domestic and Industrial Water Use: While likely less significant than agriculture, growing populations and local industrial activities in the surrounding settlements also contribute to the overall water demand from the basin's limited resources.

CONCLUSION

This study provides compelling evidence of a sustained and measurable decline in the water surface area of Salda Lake over a 20-year period (2004–2024), as revealed through systematic application of remote sensing techniques and statistical analysis. The Normalized Difference Water Index (NDWI), applied to Landsat imagery, proved to be an effective tool for delineating water bodies with high precision, enabling accurate quantification of temporal changes. The results indicate a total surface area loss of approximately 2.39 km², corresponding to a 5.35% reduction from 2004 levels. Linear regression analysis further confirmed a statistically significant negative trend, with an average annual decrease of 0.356 km² in lake surface area.

The findings suggest that the decline is likely driven by a combination of climatic factors—such as decreased precipitation, increased evaporation, and recurrent droughts—and anthropogenic pressures including excessive groundwater abstraction and land use changes within the lake's basin. These combined stresses pose a serious threat to the ecological integrity, hydrological balance, and long-term sustainability of Salda Lake, a site of both national and international environmental importance. Given these results, there is an urgent need for immediate and coordinated policy responses focused on sustainable water resource management, strict regulation of groundwater use, and enhanced environmental monitoring.

The application of remote sensing should continue to be integrated into routine environmental assessments, providing policymakers with timely data to inform adaptive strategies. Protecting Salda Lake is not only vital for preserving a unique ecological and geological system, but also for safeguarding the region's environmental heritage against the escalating impacts of climate change and human activity.

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