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# Factors influencing surface water changes in the Khar-Us Lake basin, western Mongolia

Tsolmonbayar Galbadrakh[1,2,*], Yanjindulam Ganbold[1], Li Dingjun[1], Altanbold Enkhbold[1]

[1]*School of Arts & Sciences, National University of Mongolia, Ulaanbaatar 210646, Mongolia*
[2]*Institute of Geography and Geoecology, Mongolian Academy of Sciences, Ulaanbaatar 15170, Mongolia*

***CORRESPONDING AUTHOR**
Tsolmonbayar Galbadrakh
tsolmonbayrg@mas.ac.mn

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## ABSTRACT
This study investigates the spatiotemporal variability in the surface areas of Khar-Us, Khar, and Durgun Lakes in western Mongolia between 1992 and 2022 using Landsat imagery and climatic datasets. The Normalized Difference Water Index (NDWI) was employed to extract lake extents, and trend analyses such as the Mann–Kendall test, Sen's Slope Estimator, and Innovative Trend Analysis Method were used to examine the influence of climate variables - precipitation and air temperature. Results show a statistically significant decline in lake surface area, particularly for Khar-Us Lake, which decreased by approximately 0.43 km² annually. Over the past 30 years, a strong climatic influence has been observed, as indicated by the Mann Kendall (MK) trend (Z = -2 to -6). Air temperature has exhibited a gradual warming MK trend (Z = 0.68), whereas precipitation has shown a declining trend (Z = -0.781). Climatic factors, including reduced precipitation and increasing temperatures, were identified as the dominant drivers. While surface changes in Khar and Durgun Lakes between 2006 and 2010 appear temporally aligned with the operational period of the Durgun Hydropower Plant (HPP), the current study does not include hydrological or operational data to quantitatively confirm causation. Hence, the potential influence of anthropogenic factors is discussed as a hypothesis requiring further research. These findings contribute to understanding the impacts of climatic variability on lake ecosystems in semi-arid regions.

**KEYWORDS**
Climate change, Lake water surface, Trend analysis, NDWI, Climatic factors

## 1. INTRODUCTION

Recent studies have demonstrated that climate change has profoundly affected surface water resources in the semi-arid regions of Central Asia, particularly in Mongolia, where variations in lake surface areas and shifts in their distribution are closely associated with climatic fluctuations [1–4]. Mongolia's harsh continental climate, marked by pronounced seasonal and interannual variability in temperature and precipitation, renders its lakes especially sensitive to even minor climatic perturbations [5–6]. These climatic factors drive significant changes in hydrological regimes, influencing lake hydrodynamics, water balance, and ecological conditions across the region. Despite the ecological and socio-environmental importance of these lakes, there remains a limited understanding of how specific climatic variables such as precipitation patterns, temperature anomalies, and evapotranspiration rates interact to govern long-term lake surface area dynamics.

Previous studies have investigated changes in lake area and volume in relation to climate and other factors at regional and national scales. This study is particularly significant because it elucidates the relationships among three hydrologically connected lakes within a localized setting [6-9].

In particular, the influence of seasonal shifts and extreme weather events on lake hydrology requires further detailed investigation to inform adaptive management strategies. Advances in remote sensing technologies now provide unprecedented opportunities to monitor lake surface changes over extended periods with high spatial and temporal resolution. Such approaches enable the integration of climatic datasets to improve our understanding of hydrological responses in semi-arid landscapes.

This study targets three major lakes - Khar-Us, Khar, and Durgun Lake - within the Khar-Us Lake Basin of western Mongolia, an area of critical ecological significance protected under the Ramsar Convention. The research aims to quantify spatial and temporal variations in lake surface areas over a 30-year period from 1992 to 2022 and to analyze their correlations with key climatic drivers including precipitation and temperature. By employing Landsat satellite imagery combined with meteorological data, this study seeks to elucidate the underlying mechanisms governing lake dynamics and to contribute to improved water resource management and conservation policies in the face of ongoing climate change.

## 2. RESEARCH AREA AND METHODS

The study focused on the Khar-Us Lake Basin, which encompasses three major lakes: Khar-Us Lake, Khar Lake, and Durgun Lake. The research area is geographically located between 47°33′–48°49′ N latitude and 91°43′–93°20′ E longitude (Figure 1).

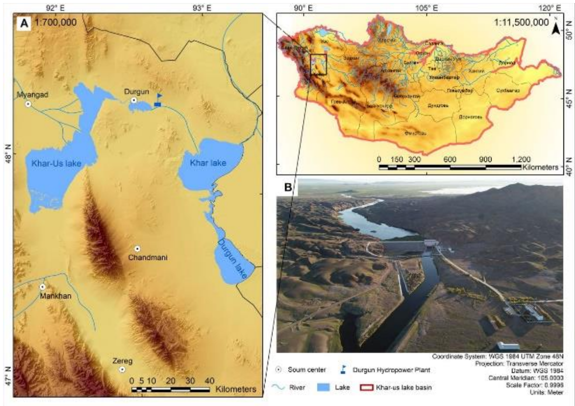


**Figure 1.** (A) Geographical location of the study area; (B) Aerial photograph of the Durgun HPP. Photo by Batbayar Ochirbat

Landsat satellite imagery was downloaded and processed from the USGS EarthExplorer platform (https://earthexplorer.usgs.gov/), and climatic data from 1992 to 2022 were utilized for statistical analysis. The study employed the Trend analysis along with other statistical methods to assess temporal variations and their significance.

**Normalized Difference Water Index (NDWI)**

The changes in lake surface area were assessed using Landsat satellite imagery by calculating the NDWI. NDWI was computed using the following equation [1-3, 10].

$$NDWI = \frac{\rho green - \rho nir}{\rho green + \rho nir} \quad (1)$$

Where ρ_Green is the green band, $\rho\_NIR$ is the near-infrared band.

The NDWI values range from –1 to +1, and areas with NDWI values greater than or equal to 0.1 are classified as water surfaces. The NDWI is a robust method for delineating seasonal and interannual variations in lake extent, and it has proven effective in monitoring lakes across Mongolia [1–3].

**Trend Analysis**

Mann Kendall (MK): The MK analysis is considered particularly suitable for identifying trends in indicators such as climate variables, water resources, and lake surface areas [1–3,11]. The MK test statistic is defined by the following equation:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn\left(x_j - x_i\right) \quad (2)$$

The trend test is applied to $x_i$ data values $(i = 1,2, \dots n-1)$ and $x_j\,(j = i+1, 2, \dots n)$. The data value of each $x_i$ is used as a reference point to compare with the data value of $x_j$ which is given as:

$$sgn\left(x_j - x_i\right) = \begin{cases} +1 & \left(x_j - x_i\right) > 0 \\ 0 & \left(x_j - x_i\right) = 0 \\ -1 & \left(x_j - x_i\right) < 0 \end{cases} \quad (3)$$

Where $x_j$ and $x_i$ are the values in period $j$ and $i$. When the number of data series is greater than or equal to ten $(n \geq 10)$, the MK test is then characterized by a normal distribution with the mean $E(S) = 0$ and variance $Var\,(S)$ is equated as:

$$E(S) = 0 \quad (4)$$

$$Var(S) = \frac{n(n-1)(2n+5) - \sum_{k=1}^{m} t_k(t_k-1)(2t_k+5)}{18} \quad (5)$$

Where $m$ is the number of the tied groups in the time series, and $t_k$ is the number of ties in the $k$th tied group. The test statistics $Z$ is as follows

$$Z = \begin{cases} \frac{s-1}{\delta} & S > 0 \\ 0, & S = 0 \\ \frac{s+1}{\delta} & S < 0 \end{cases} \quad (6)$$

When $Z$ is greater than zero, it indicates an increasing trend, and when $Z$ is less than zero, it is a decreasing trend.

To detect abrupt changes in temporal trends, it is possible to calculate the forward (UF) and backward (UB) statistics. These are defined by the following equations:

$$UF_k = \frac{d_k - E(d_k)}{\sqrt{var(d_k)}} \quad (7)$$

$$UB_k = -UF_k \quad (8)$$

Where $UB_k$ and $UF_k$ are used to represent the time series in both forward and reverse chronological order, which serves to validate the results. The statistical value α (or 0) in the Mann–Kendall test represents the mean level or the confidence threshold. The UF curve reflects the overall trend direction. When the UF trend line crosses above or below the confidence limit, it indicates a statistically significant change. A trend line exceeding the upper threshold denotes an increasing trend, while one falling below indicates a decreasing trend. The use of both forward and reverse time sequences ensures more robust identification of trend reversals or potential turning points in the time series data [1, 12].

*Innovative Trend analysis Method (ITAM):* ITAM has been used in many studies to detect the hydro-meteorological observations, and its accuracy was compared with the results of MK method [3]. The trend indicator is given as:

$$\varphi = \frac{1}{n}\sum_{i=1}^{n} \frac{10\,(x_j - x_i)}{\mu} \quad (9)$$

where: φ-is the trend indicator, n-is the number of observations in the subseries, $x_i$-is the data series in the first half subseries class, $x_j$-is the data series in the second half subseries class, and μ-is the mean of data series in the first half subseries class [13].

*Sen's Slope Estimator Test (SSET):* The SSET is a non-parametric statistical method used to calculate the rate of increase or decrease in a time series trend, and it is commonly used in combination with the MK test. The slope Qi between two data points is given by the following equation:

$$Q_i = \frac{x_j - x_k}{j-k}, \ i = 1,2, \dots N \quad (10)$$

where $x_j$ and $x_k$ are data points at times $j$ and $(j > k$, respectively. When there is an only single datum in each time, then $N = \frac{n(n-1)}{2}$; n is a number of time periods. However, if the number of data in each year is more than 1, then $N < \frac{n(n-1)}{2}$; n is the number of total observations. The N values of slope estimator are arranged from smallest to biggest. Then, the median of slope (β) is computed as:

$$\beta = \begin{cases} Q[(N+1)/2] & when\ N\ is\ odd \\ Q[(N/2) + Q(N+2)/(2)/(2)] & when\ N\ is\ even \end{cases} \quad (11)$$

The sign of β shows whether the trend is increasing or decreasing[3].

**Statistical Analysis**

The regression parameter $a$ and the regression coefficient $b$ were estimated using the least squares method, as defined by the following equation [1, 14].

$$b = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=1}^{n}(x_i - \bar{x})^2} \quad (12)$$

Where $x = \frac{1}{N}\sum_{i=0}^{n} x_i$, $y = \frac{1}{N}\sum_{i=1}^{n} y_i$ When b>0 it indicates an increasing trend in the climatic variable, while $b < 0$ suggests a decreasing trend.

In this study, the influence of climatic factors on the surface area changes of the selected lakes was evaluated using this method. The Pearson correlation coefficient was calculated using the following equation [1, 15].

$$r_{xy} = \frac{\sum_{i=0}^{n}[(x_i - \bar{x})(y_i - \bar{y})]}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 + \sum_{i=1}^{n}(y_i - \bar{y})^2}} \quad (13)$$

where $y_i$ – correlation coefficient, $x_i$ - is the independent variable, $\overline{x}$ - is the mean of the independent variable, $y_i$ - is the dependent variable, $\overline{y}_i$ - is the mean of the dependent variable. In this equation $\overline{x}$ and $\overline{y}$ the mean of the sample values of two factors, $r_{xy} > 0$ indicates a positive correlation, $r_{xy} < 0$ indicates a negative correlation between the variables.

## 3. RESULT AND DISCUSSION

The 30-year trends in lake surface area and climatic variables within the study area were analyzed using the Mann–Kendall (MK) trend test and linear regression analysis (Figure 2).

The surface area of Khar-Us Lake began to decline after 1995 and has consistently decreased below the confidence threshold of –1.96 since 2000. Khar Lake exhibited a decreasing trend between 1995 and 2010, followed by a shift to a slight increasing tendency after 2010. Durgun Lake showed a marked decline between 1997 and 2010, with a gradual recovery observed from 2011 onwards.

The trend of air temperature, according to the Mann-Kendall (MK) test, has shown a consistent increasing trend since 1992. However, the trend of precipitation shows a decreasing pattern since 1992, according to the statistical values. The precipitation amounts from 2005 to 2022 approached values between 0 and -2, indicating levels below the long-term average.

The surface area of Khar-Us Lake has decreased by an average of 0.43 km² per year. Over the past 30 years, a strong decreasing trend has been observed, as confirmed by the MK (Z = −6.021), ITAM (ϕ = −0.0008), and SSET (β = −1.148) results (Table 1). The surface areas of Khar and Durgun Lakes also show decreasing trends according to the MK (Z = −4.215, −2.651). However, the results from the ITAM (ϕ = 0.001, 0.008) indicate a positive trend, showing a decline from 1992 to 2011 followed by an increasing trend since 2012. These changes are likely related to flow regulation in the Chono kharaikh River and the operational dynamics of the Durgun Hydropower Plant [1,2]. These findings are in line with previous research and reflect the reduction in the surface area of lakes in Mongolia over the last three decades [1,6,16].

Air temperature has shown a gradual warming trend over the past 30 years (Z = 0.68). In contrast, the MK indicates a decreasing trend in precipitation (Z = -0.781). These changes clearly have a significant impact on the lake's surface area.

To analyze changes in the lake's surface area in relation to temporal cycles and key climate variables (such as annual air temperature and precipitation), the study was divided into two periods, 1992–2001 and 2002–2022, for comparative analysis (Figure 3).

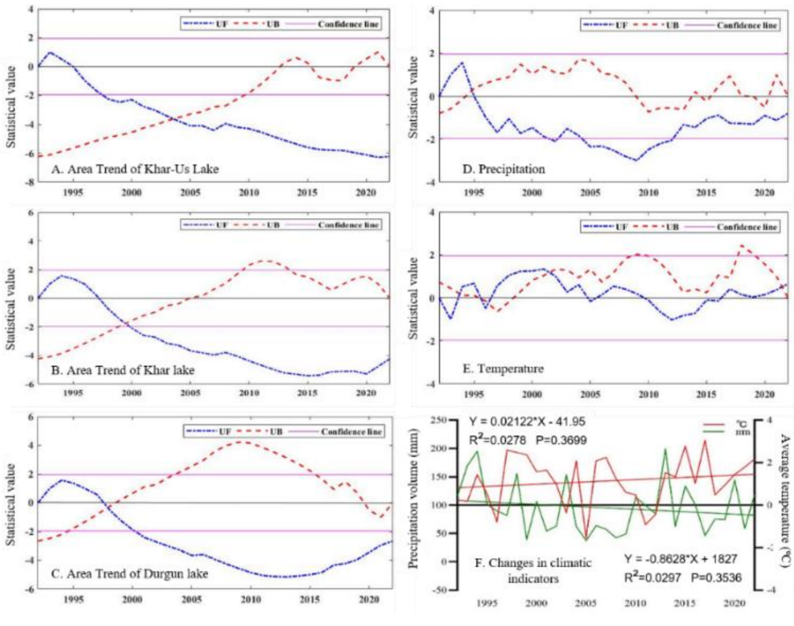


**Figure 2.** Spatiotemporal changes in surface area for the three major lakes in the Khar-Us Basin (A–B), trends in air temperature and precipitation (C–D), and linear climatic trends (E) during the period 1992–2022 (where UF and UB are parameters of the change, UB = −UF)

**Table 1.** Trends in Water Surface Area Changes in the Khar-Us Lake Basin: A Comparison of Results from the Mann-Kendall (MK) Test, Innovative Trend Analysis Method (ITAM), and Sen's Slope Estimator (SSE)

| № | Parameters | MK | ITAM | SSET |
|---|---|---|---|---|
| 1 | Khar-Us Lake | -6.221 | -0.0008 | -1.148 |
| 2 | Khar Lake | -4.215 | 0.001 | -0.217 |
| 3 | Durgun Lake | -2.651 | 0.008 | -0.588 |
| 4 | Trend of total annual precipitation | 0.68 | -0.017 | 0.021 |
| 5 | Trend of annual average air temperature | -0.781 | 0.203 | -0.655 |

** 0.1 trend with low variation; ** 0.05 trend with relative changes; *** 0.01 trend with high variation.*

During the 1992–2001 period, a positive correlation ($R^2$=0.35, p=0.07) was observed between the surface area of Khar-Us Lake and precipitation, indicating that increased precipitation was associated with lake expansion.

Although precipitation increased during the period from 2002 to 2022, the continued decline in lake area indicates that other factors—such as reduced surface runoff and anthropogenic constraints—have had a strong influence on the lake's hydrological regime.

In the 1992–2001 interval, a strong negative correlation ($R^2$=0.33, p=0.09) was identified between the lake area and air temperature. The observed decrease in lake area in response to rising temperatures suggests that increased evaporation associated with warming has disrupted the lake's water balance. Despite the negative trend observed between 2002 and 2022, the correlation remains weak, indicating that temperature variability may not exert a direct influence and that other factors are playing a more significant role.

During the 1992–2001 period, a positive correlation was observed between the surface areas of Khar and Durgun Lakes and precipitation. Although this relationship was not statistically significant, the moderate correlation coefficient suggests that increases in precipitation likely contributed to lake area expansion during this period. However, from 2002 to 2022, the relationship shifted to a negative correlation, which was statistically significant. This indicates that despite increasing precipitation over the past two decades, the lake areas have continued to decline.

Between 1992 and 2001, air temperature and lake surface area showed a negative correlation, although this was not statistically significant. In contrast, during the most recent 20-year period, a statistically significant positive correlation emerged. This situation

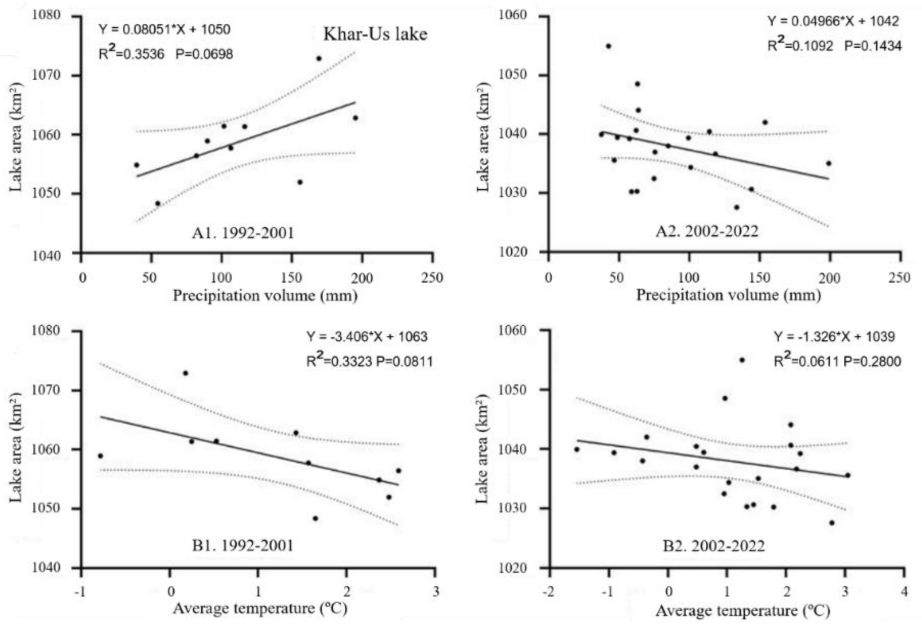


**Figure 3**. Correlation between the Surface Area of Khar-Us Lake and Changes in Climatic Variables. Relationship between Lake Surface Area and Precipitation (A1: 1992–2001; A2: 2002–2022), Relationship between Lake Surface Area and Air Temperature (B1: 1992–2001; B2: 2002–2022)

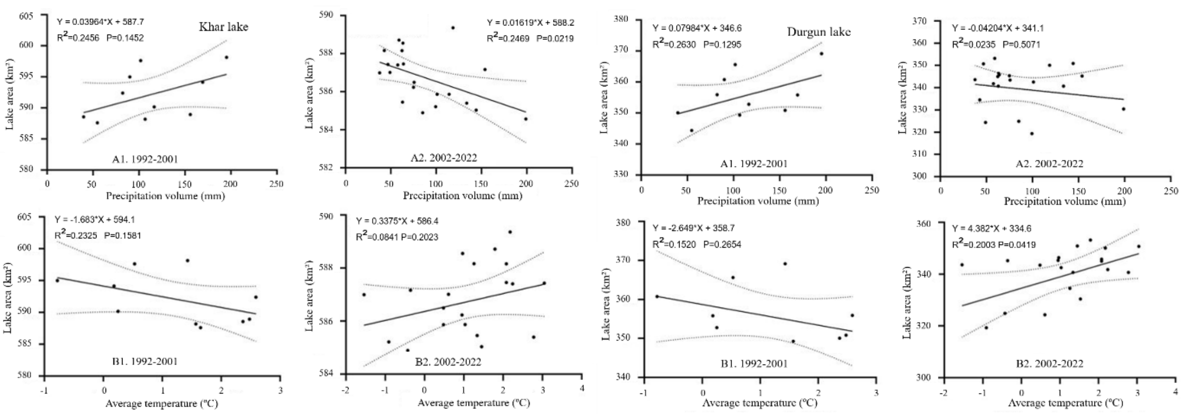


**Figure 4**. Correlation between the Surface Areas of Khar and Durgun Lakes and Changes in Climatic Variables. Relationship between Lake Surface Area and Precipitation (A1: 1992–2001; A2: 2002–2022), Relationship between Lake Surface Area and Air Temperature (B1: 1992–2001; B2: 2002–2022)

is linked to the regulation of the Chono Kharaikh River—the primary source of inflow to the lake—due to construction activities between 2002 and 2010. Additionally, the stabilization of operations at the Durgun HPP from 2010 onward coincides with this period, suggesting a possible direct influence on changes in lake surface area.

Numerous studies have noted that lake ecosystems in central and western Mongolia are highly sensitive to climate change and increasingly vulnerable to anthropogenic impacts [5, 8, 17]. The present study reinforces these findings through the analysis of lake dynamics in the Khar-Us Lake basin.

Furthermore, lake-specific morphometric and microclimatic factors including evaporation intensity, duration of ice cover, lake depth, and water volume contribute to unique hydrological dynamics for each lake [6].

For instance, the change in the surface area of Durgun Lake had a weak positive correlation with precipitation during 1992–2001 ($R^2 = 0.26$, $p = 0.13$), but became uncorrelated during 2002–2022 ($R^2 = 0.02$, $p = 0.51$). As for temperature, a slight increasing trend in recent years ($R^2 = 0.20$, $p = 0.04$) indicates that the influence of climate has decreased, and human impact has become dominant.

The MK trend analysis provides a robust framework for detecting changes in lake surface area, offering important insights for future ecosystem management and water resource planning in arid and semi-arid environments [18, 19].

Although a noticeable decline in the surface areas of Khar and Durgun Lakes occurred during the period of Durgun HPP construction and early operation (2006–2010), this correlation is observational. The current study did not utilize hydrological inflow/outflow records, reservoir management data, or formal causality modeling. Therefore, while the temporal overlap suggests a possible anthropogenic influence, this remains a hypothesis. Future research should incorporate detailed operational data and hydrological modeling to robustly assess the direct and indirect impacts of the HPP on lake hydrodynamics.

## 4. CONCLUSION

This study assessed changes in the surface areas of Khar-Us, Khar, and Durgun Lakes within the Khar-Us Lake Basin in western Mongolia from 1992 to 2022 and examined their correlations with key climatic variables—precipitation and air temperature—using the Normalized Difference Water Index (NDWI) and trend analysis methods.

Khar-Us Lake exhibited a consistent long-term decreasing trend in surface area, whereas Khar and Durgun Lakes experienced sharp declines up to 2011, followed by increasing trends from 2012 onward. Statistical analysis revealed that during the period 1992–2001, lake surface areas were positively correlated with precipitation (e.g., Khar-Us Lake: $R^2 = 0.35$, $p = 0.07$), suggesting that increased rainfall contributed to lake expansion. However, after 2002, this relationship shifted to negative values (e.g., Khar Lake: $R^2 = 0.25$, $p = 0.02$), indicating changes in the lakes' hydrological responses to precipitation.

Between 1992 and 2001, air temperature was negatively correlated with lake area, implying that higher temperatures contributed to surface area reductions. Since 2002, however, the relationship became positive (e.g., Durgun Lake: $R^2 = 0.20$, $p = 0.04$), possibly reflecting indirect effects such as altered evaporation rates, inflow regimes, or anthropogenic modifications.

Overall, the surface area of the Khar-Us Lake Basin has steadily declined, with an average annual reduction of approximately 0.43 km². Mann–Kendall trend analysis confirms a statistically significant decrease in lake surface area (Z = –2 to –6), alongside a warming trend in air temperature (Z = 0.68) and declining precipitation (Z = –0.781). These climatic factors appear to be the primary drivers of the long-term shrinkage of the lake system.

To ensure the long-term sustainability of these lakes, it is crucial to further investigate the underlying drivers of surface area changes and implement integrated basin management policies that address both climatic and anthropogenic influences.

## DISCLOSURE STATEMENT

No potential conflict of interest was reported by the author(s).

## AUTHOR CONTRIBUTIONS

All authors participated in data analysis and manuscript preparation.

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