ESTIMATION OF MORPHOMETRIC PARAMETERS IN LAKES BASED ON SATELLITE IMAGERY DATA: IMPLICATIONS OF RELATIONSHIPS BETWEEN LAKES IN THE ARID REGION OF WESTERN MONGOLIA, CENTRAL ASIA

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Abstract: The relationship between reservoirs and naturally formed lakes in Mongolia has not been previously studied. This research explores potential future environmental impacts, both positive and negative, in western Mongolia. The study employs morphological analysis (MA), normalised difference water index (NDWI), volume analysis and statistical analysis of water. In the case of Airag Lake and an artificially created lake, temporal changes in lake surface area and volume exhibit inverse trends. The correlation between changes in lake area over time is highly negative ($R = -0.96$, $p < 0.01$ for the surface area), which is attributed to a decrease in Airag Lake's area and volume during the lake water accumulation period from 2007 to 2011 and countered by an increase in Gegeen Lake's area and volume. Conversely, the surface area of Khyargas Lake shows a strong positive correlation ($R = 0.94$, $p < 0.0001$) with Airag Lake's area and a strong negative correlation ($R = -0.88$, $p < 0.0001$) with Gegeen Lake's area during the period from 2007 to 2021. Based on satellite data, our findings suggest a negative relationship between changes in lake surface area and volume, indicating recent significant human impacts on lake water balance. This research explores the implications of hydropower dams and reservoirs in the region, as well as environmental concerns within the context of power production.

Keywords: satellite image, hydropower plant, lake morphometric changes, artificial lake, environmental effect, Khyargas Lake basin

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Introduction

Object-based satellite image classification to identify pre- and post-event changes is the primary method for quickly retrieving evaluation information (Valeyev et al. 2019, Liu et al. 2020). While remote sensing technology has advanced significantly with the development of modern technology, its accessibility remains relatively limited in less developed countries (Sheffield et al. 2018). However, the demand and requirements for research areas using remote sensing technology and research using satellite image data are essential for those countries (Lebedev et al. 2020). Using satellite image data with various spatial resolutions, modelling of lake area changes, monitoring of shoreline dynamics, monitoring of water depth changes, analysis of water index and calculations of water evaporation are performed (Busker et al. 2019, Valeyev et al. 2019, Liu et al. 2020, Luo et al. 2020, Emami, Zarei 2021, Şerban et al. 2022, Xu et al. 2022). Integrating spatial and temporal data from space imagery provides key evidence for detailing lake area changes and interrelationships (Valeyev et al. 2019, Liu et al. 2020, Lehner et al. 2022, Xu et al. 2022). Based on satellite imagery, the study analyses the various changes occurring in the lake and determines the dominant factors (Melesse et al. 2007, Dörnhöfer, Oppelt 2016, Shen et al. 2022). Variations in lake volume, area, their interactions and human activities could exert future influence on the area's climate and environment.

Morphometric changes in the lakes have the potential to trigger a series of ecological and environmental effects, both positive and negative, making it imperative to investigate these transformations. The area of lakes has significantly changed in modern times due to human activities (Seyoum et al. 2015, Qi et al. 2020). Also, due to global climate change, surface water resources and distribution are changing over time (Wang, Qin 2017, Dorjsuren et al. 2018); based on human and natural activities, the lake area is shrinking and increasing, and even new artificial lakes are being created (Zhang et al. 2019). The impact of the processes on both natural ecosystems and human activities associated with the lake has been manifested. The importance of providing reservoirs and ponds in arid climatic regions has been well-proved in numerous studies (Busker et al. 2019, Chen et al. 2020, Mady et al. 2020, Stringer et al. 2021, Lehner et al. 2022, Pi et al. 2022, Shen et al. 2022, Rousta et al. 2023). A synthesis of this research emphasises that developing reservoirs and ponds is crucial for the region's climate, environment, biodiversity, agriculture, and economy.

In recent years, lakes in arid regions have shown a tendency to shrink due to climate change and global environmental shifts (Chen et al. 2020, Stringer et al. 2021). Air temperature plays a significant role in reducing lake volume (Yu et al. 2021). The increase in average annual air temperature has led to greater surface evaporation, resulting in smaller size of the lakes across Central Asia (Sumiya et al. 2020, Enkhbold et al. 2024). Additionally, the trend of decreasing precipitation in recent years has a direct impact on lake volumes in arid regions (Rousta et al. 2023). However, human-driven actions to create reservoirs and ponds help counter this trend by increasing the number of lakes (Pi et al. 2022).

As the scientific and practical challenges of utilising lakes as a primary natural resource are highly crucial, conducting in-depth research on human impacts on lakes is of paramount importance. Mongolia, where nearly 90% of its surface water is stored in lakes (Tserensodnom 2000, Sato et al. 2007), emphasises the significance of investigating lakes to address water resource management and environmental and socioeconomic development concerns (Oyunbaatar et al. 2017). In the future, the results of this research may serve as a foundational model for studying the chemical composition, water characteristics, biological resources, ecosystems and biodiversity of lakes in arid regions. Despite its significance, few studies have previously evaluated the relationship between reservoirs and naturally formed lakes in Mongolia (Sukhbaatar et al. 2020, Baterdene et al. 2022). This research is necessary to raise new questions, introduce them to the scientific community and advance the study of Mongolian lakes.

Mongolia's geographical landscape, located in Central Asia, is defined by a transition zone extending from the southern Siberian Mountains to the Central Asian steppes (Tserensodnom 1971, Yembuu 2021). This region experiences a gradual shift from a cold, humid northern climate to an arid southern one (Lehmkuhl et al. 2016, Yembuu 2021). Most of Mongolia's lakes are situated in dry and arid areas, primarily in the southern and western parts of the country (Tserensodnom 2000, Enkhbold et al. 2021, 2022, Dorjsuren et al. 2024). This arid region is a focal point for changes in surface water, heavily influenced by both natural and human activities.

In Mongolia, the utilisation of hydropower plants (HPPs) requires careful planning to balance hydropower generation, water supply, pasture irrigation and agricultural needs. Gegeen Lake was created in 2007 by constructing a hydropower dam 50 m deep, 75 m wide and 190 m long in the Ulaan Boom Canyon of the Zavkhan River (Oyunbaatar et al. 2011, Mendsaihan et al. 2016). In 2018, it was registered as part of an international satellite imagery database under the name Gegeen Lake (Saint Lake in English). The Taishir HPP generates 12 MW of electricity annually and serves 8–10 towns in the Zavkhan and Govi-Altai provinces (Mendsaihan et al. 2016). Unlike fossil fuel power, HPPs do not emit harmful waste or CO_2, playing a key role in reducing greenhouse gas emissions (Kumar et al. 2019). However, the construction of the HPP and the creation of Gegeen Lake have caused a notable reduction in the wetland area around Airag Lake, a Ramsar Convention site (Purevdorj et al. 2019, 2023). This case represents how human activities can negatively impact the environment. The area surrounding Airag Lake hosts 183 species of waterfowl, whose habitat is now at risk due to the shrinking wetland area (Purevdorj et al. 2019, 2023).

This research aims to calculate morphometric changes in the lakes based on satellite imagery data and to assess its effect on the hydrological relationships among lakes in Mongolia's arid regions.

Study area

The catchment area in the Zavkhan River–Khyargas Lake (Fig. 1) belongs to the closed basin

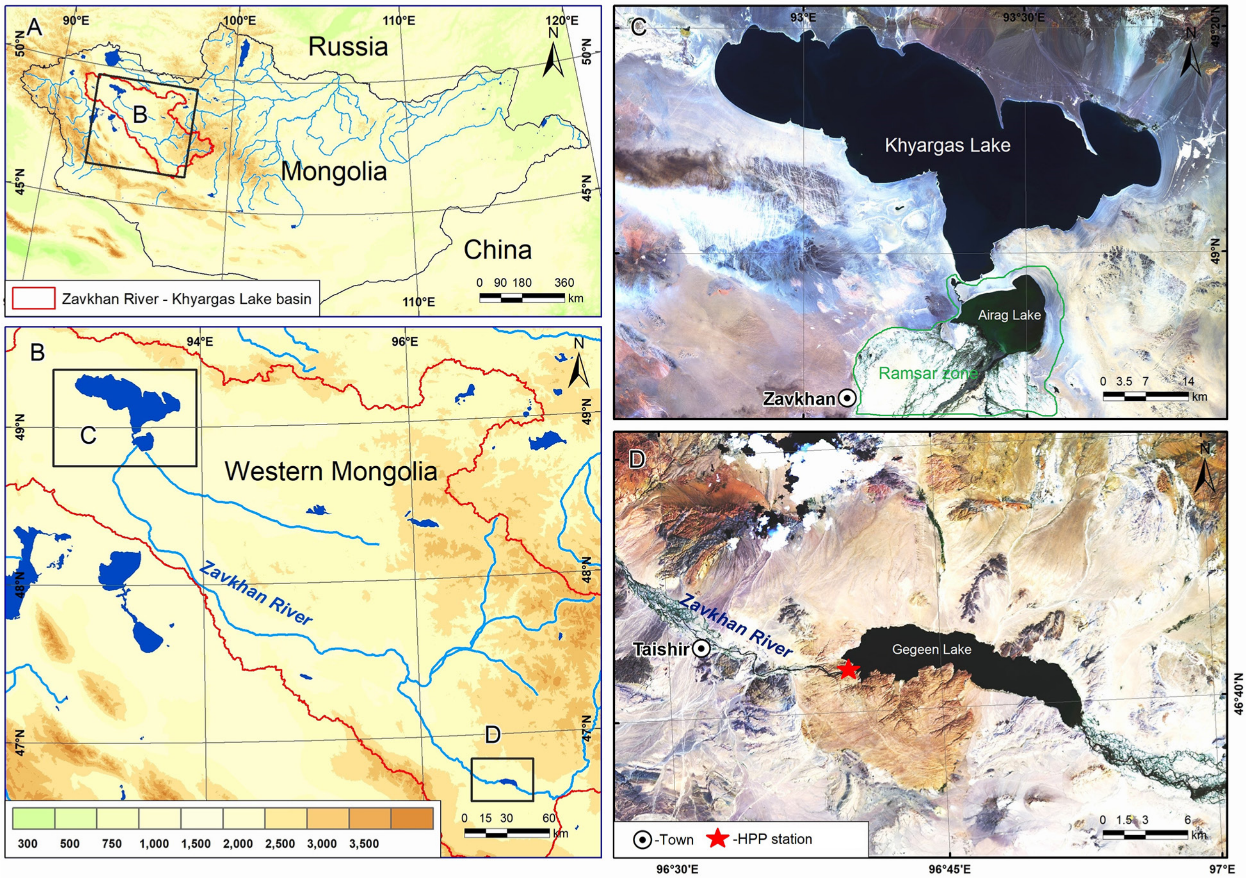

Fig. 1. A – The geographical location of the study area. B – Topographic map of Mongolia and the Zavkhan River–Khyargas Lake basin in western Mongolia. C – Satellite images of the Airag and Khyargas lakes. D – Gegeen Lake.

Table 1. Morphometric parameters of the study area (Modified after Tserensodnom 2000; Davaa 2018; Enkhbold et al. 2022; Dorjsuren et al. 2023, 2024).

Description	Unit	Khyargas Lake	Airag Lake	Gegeen Lake
Location	DMS	49°11'05"N, 93°16'16"E	48°53'12"N, 93°26'09"E	46°41'02"N, 96°46'17"E
Elevation (m a.s.l.)	m	1028	1030	1727
Average area	ha	138,306	15,179	3794
Shape	Direction	W–E	W–E	NW–SE
Average length	km	75	18	17.2
Average width	km	19	13	3.1
Depth (max)	m	78.7	10.2	31.5
Origin	–	Tectonic	Tectonic	Human
Chemistry	–	Salt	Fresh	Fresh
Water source	–	Surface	Surface	Surface

of Central Asia (Ochir et al. 2013). The Zavkhan River originates in the Khangay Mountains and flows 808 km into Airag Lake (Fig. 1A, B). The total area of the catchment is 98822–99040 km^2 (Ochir et al. 2013, Dorjsuren et al. 2023), the average annual flow is 0.4 km^3, the average runoff is 1.3 m $\cdot$ s^{-1} and the flow modulus is 1.13 m $\cdot$ s^{-1} (Oyunbaatar et al. 2011, Davaa 2015, Dorjsuren et al. 2023). The three lakes included in this study are situated in the Zavkhan River–Khyargas Lake basin (Fig. 1C, D and Table 1).

The study area is surrounded by Tagna Mountains in the north, Khangai Mountains in the east, Gobi Altai Mountains in the south, and Mongolian Altai Mountains in the west (Fig. 1). Elevations in this area range from 760 to 1800 m a.s.l. Hydrologically, a network of rivers originates from the Altai and Khangai mountain ranges in Mongolia. Extreme weather conditions in the region include low precipitation, resulting in arid and desert landscapes (Lehmkuhl et al. 2016, Yembuu 2021, Dorjsuren et al. 2023).

Data and methods

Satellite data

The relationships between various parameters were determined by analysing spatial image data. We obtained Landsat 5 TM, Landsat 7 +ETM and Landsat 8 OLI/TIRS satellite imagery data with a 30-m resolution from USGS (2023). These data sources were used to calculate the surface area of Airag and Khyargas Lake water over 30 years from 1991 to 2021, as well as the surface area of Gegeen Lake water over 15 years from 2007 to 2021. The volume of the lakes is updated using three-dimensional bathymetric mapping (Tserensodnom 2000, Davaa 2018). In 2021, field measurements were conducted to assess changes in the lakes' shorelines.

Climate data

The climate data of the Khyargas Lake basin in western Mongolia from 1991 to 2021 were provided by the Database Center at the National Agency of Meteorology and Environment of Mongolia. The monthly air temperature and precipitation data, measured at the Taishir (Gegeen Lake) and Zavkhan (Airag Lake and Khyargas Lake) weather stations, were used to estimate the impact of climate factors on lake volume changes.

Morphological analysis

Morphological analysis (MA) is a method of detecting the external signs and changes in various surface elements and determining their shape (Finkl et al. 2005, Harmar et al. 2005). The method is unique in its ability to identify changes in surface shapes and the external processes that influence them. This study will show how the morphology of the lake's water surface changes in response to alternations in the lake's surface using satellite imagery results (Soille, Pesaresi 2002, Shang 2013). MA offers the advantage of quantifying average morphological change by measuring surface alternations. This study is used to determine the average size of the area change of the lake.

If the area of the lake changes according to the satellite map calculations, the average graphical change in the lake area, as determined by MA, is calculated using Eq. (1):

$$Sa = \frac{SF + SL}{tn} \quad (1)$$

where:
- Sa is the average change in the area of the lake,
- SF is the amount of the first estimated area of the lake,
- SL is the amount of the area of the lake calculated in the last period,
- tn is the sum of the time series.

This is essentially the linear regression coefficient of the time series.

Delineation of water surface from multispectral images

Several extracting techniques can be applied to identify and highlight water surface in multispectral images. These methods include approaches that utilise (1) reflected solar radiation, (2) emitted thermal radiation and (3) active microwave emissions. Among these, techniques relying on reflected solar radiation have the longest history of use. In this approach, researchers have either used a single spectral band or ratio of two bands to distinguish and enhance open water features in the imagery. Normalised difference water index (NDWI) is one of the most commonly used water indices to calculate changes in the lake shape and water surface area. It was first introduced by McFeeters (1996), utilising the green (GREEN) and near-infrared (NIR) spectral bands of Landsat TM. The wavelengths in challenges were selected for the following reasons: (1) to achieve the greatest possible reflectance of water features using GREEN wavelengths; (2) to reduce the typically low reflectance of water features in the NIR wavelengths and (3) to utilise the high NIR reflectance characteristic of vegetation and soil. The method is used to distinguish not only water features but also man-made structures that produce light reflections of the same colour as water (Gao 1996, McFeeters 2013, Bijeesh, Narasimhamurthy 2020, Luo et al. 2021). The NDWI on multispectral images is determined using the following Eq. (2):

$$NDWI = \frac{GREEN - NIR}{GREEN + NIR} \quad (2)$$

where:
- $NDWI$ is the normalised difference water index,
- $GREEN$ is the green wavelength (0.52–0.60 µm) in the visible spectrum and
- NIR (0.76–0.90 µm) is NIR wavelengths in the infrared spectrum.

The central wavelengths of the GREEN bands on Landsat 5, 7 and 8 are similar at 0.56 µm, while those of the NIR bands are quite different at 0.83, 0.84 and 0.86 µm. Spatial resolution of the GREEN and NIR bands is 30 m. NDWI is dimensionless and varies between −1 and +1, depending on the leaf water content, vegetation type and surface cover characteristics. The NDWI values > 0.5 usually correspond to water bodies. Vegetation usually corresponds to much smaller values, and built-up areas correspond to values between 0 and 0.2. NDWI estimation of satellite images was performed by ENVI 5.0 (Exelis Visual Information Solutions, Boulder, Colorado), and comparison maps were applied on qGIS 3.18 .

Statistical analysis

We examined the volume fluctuations in the three lakes and computed them using a one-factor regression equation. The linear regression equation for one factor is defined as shown in Eq. (3):

$$y = p_1 x + p_0 \quad (3)$$

The fluctuations in lake volume over time are determined by climate trends (Sumiya et al. 2020, Dorjsuren et al. 2024).

The regression parameter a and the regression coefficient b were determined using the least square method and computed according to Eq. (4):

$$b = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=1}^{n}(x_i - \bar{x})} \quad (4)$$

Here, $x = \frac{1}{N}\sum_{i=0}^{n} x_i$, $y = \frac{1}{N}\sum_{i=1}^{n} y_i$, $b > 0$ indicates an increase in climate factors and $b < 0$ indicates a decreasing trend.

The influence of climate on the changes in the volume of the lakes under study was determined, and the correlation coefficient was calculated using Eq. (5):

$$r_{xy} = \frac{\sum_{i=0}^{n}[(x_i - \bar{x})(y_i - \bar{y})]}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 + \sum_{i=1}^{n}(y_i - \bar{y})^2}} \quad (5)$$

where:
- $r_{x,y}$ is the correlation coefficient,
- x_i is the independent variable,
- $\bar{x}$ is the mean of independent variables,
- y_i is the dependent variable,
- $\bar{y}_i$ is the mean of dependent variables,
- $r_{xy} > 0$ indicates a positive correlation and $r_{xy} < 0$ indicates a negative relationship.

The one-factor linear regression equation for the factor was calculated using the 'polyfit' command in the MATLAB software. Correlation and regression analysis confirmed the relationship between changes in area and volume in the Gegeen, Airag and Khyargas lakes.

Volume analysis

The non-parametric analysis was used to find significant differences between water areas and volumes validated by on-site field measurements (Lu et al. 2013, Chipman 2019, Ahmed et al. 2021). The water volume in the lake is calculated by combining data on water-level variations with accurate bathymetry lakes (Duan, Bastiaanssen 2013, Lin et al. 2020). A water volume change was calculated (Yue, Liu 2019, Zhang et al. 2021, Qi et al. 2022) by the following basic Eq. (6):

$$\Delta V = \frac{1}{3}(h_2 - h_1)(A_1 + A_2 + \sqrt{A_1} \times A_2) \qquad (6)$$

where:
- h_1, A_1 and h_2, A_2 are lake-level areas at the beginning and end of 2 years.

Saberioon et al. (2020) noted that utilising the R software represents the most convenient approach for integrating numerical data into mapping. In this study, the R software was employed to map the volume of lakes.

Figure 2 shows an outline of the study's methodology.

Results and discussion

Lakes' water surface area MA

The water surface area of the Khyargas Lake basin, influenced directly by the Zavkhan River's flow, has experienced significant fluctuations in recent years. These variations are depicted in Table 2.

The Airag Lake basin is interconnected with Khyargas Lake through the Khomiin Khooloi, and surplus water from Airag Lake contributes to the water level of Khyargas Lake. This hydrological pattern is expected to decline further, leading to a significant reduction in the size of the Khyargas Lake. Over the past three decades, the area of Khyargas Lake has decreased with an R^2 value of 0.5174. Particularly since 2007, there

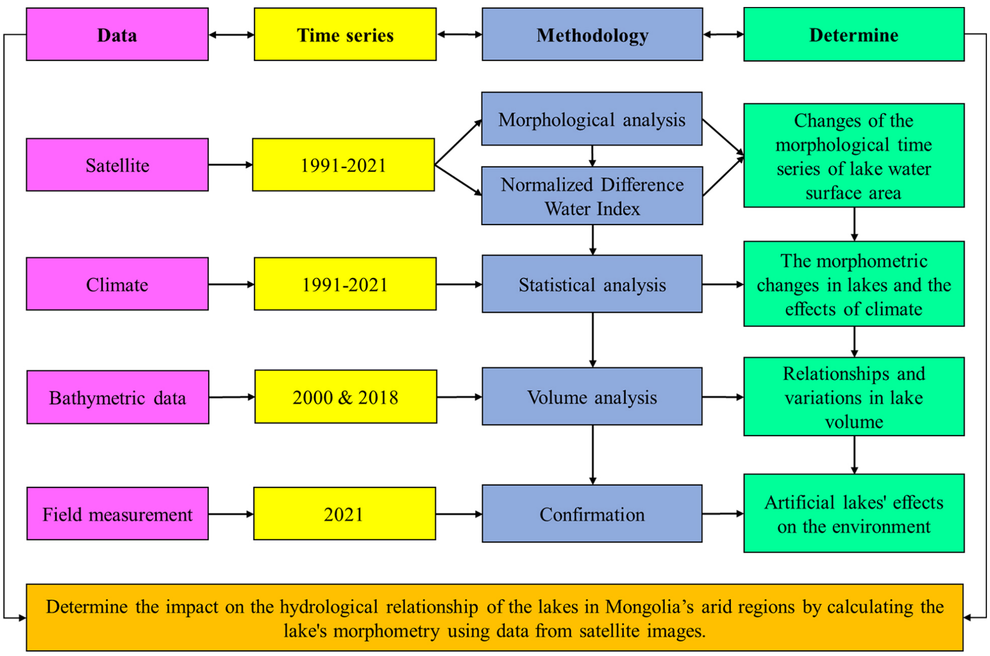

Fig. 2. Methodology flow chart.

Table 2. Estimation of water surface area in the Khyargas Lake basin.

Year	Khyargas Lake area	Airag Lake area	Gegeen Lake area	Satellite imagery considered in the analysis
	[ha]			
1991	137,482	13,190	0.00	LT05_L1TP_140026_19910811_20170125_01_T1
1992	137,726	13,419	0.00	LT05_L1TP_140026_19920813_20170122_01_T1
1993	138,084	16,501	0.00	LT05_L1TP_140026_19930816_20170117_01_T1
1994	139,201	17,811	0.00	LT05_L1TP_140026_19940718_20170114_01_T1
1995	139,913	19,295	0.00	LT05_L1TP_140026_19950822_20170107_01_T1
1996	140,011	19,319	0.00	LT05_L1TP_140026_19960621_20170104_01_T1
1997	139,967	19,039	0.00	LT05_L1TP_140026_19970827_20161230_01_T1
1998	140,105	19,064	0.00	LT05_L1TP_140026_19980611_20161224_01_T1
1999	140,317	18,266	0.00	LT05_L1TP_140026_19990716_20161217_01_T1
2000	139,728	18,023	0.00	LE07_L1TP_140026_20000827_20170210_01_T1
2001	140,007	17,859	0.00	LT05_L1TP_140026_20010806_20161210_01_T1
2002	139,699	17,562	0.00	LT05_L1TP_140026_20020809_20161207_01_T1
2003	139,697	17,392	0.00	LT05_L1TP_140026_20030727_20161205_01_T1
2004	139,629	17,272	0.00	LT05_L1TP_140026_20040713_20161130_01_T1
2005	139,349	16,901	0.00	LT05_L1TP_140026_20050817_20161124_01_T1
2006	139,347	16,545	0.00	LT05_L1TP_140026_20060719_20161120_01_T1
				*LT05_L1TP_138027_20060619_20161121_01_T1
2007	139,124	15,923	89	LT05_L1TP_140026_20070823_20161112_01_T1
				*LT05_L1TP_138027_20070825_20161111_01_T1
2008	138,609	15,125	1521	LT05_L1TP_140026_20080809_20161030_01_T1
				*LT05_L1TP_138027_20080811_20161030_01_T1
2009	138,144	14,331	1801	LT05_L1TP_140026_20090711_20161024_01_T1
				*LT05_L1TP_138027_20090713_20161023_01_T1
2010	138,167	13,808	3235	LT05_L1TP_140026_20100730_20161014_01_T1
				*LT05_L1TP_138027_20100716_20161014_01_T1
2011	137,571	13,314	4749	LT05_L1TP_140026_20110818_20161007_01_T1
				*LT05_L1TP_137028_20110728_20161008_01_T1
2012	137,453	13,096	4540	LE07_L1TP_140026_20120711_20161130_01_T1
				*LE07_L1TP_138027_20120814_20161129_01_T1
2013	136,661	12,429	4431	LC08_L1TP_140026_20130823_20170502_01_T1
				*LC08_L1TP_137028_20130701_20170503_01_T1
2014	136,428	11,992	4729	LC08_L1TP_140026_20140826_20170420_01_T1
				*LC08_L1TP_138027_20140812_20170420_01_T1
2015	136,130	11,524	4363	LC08_L1TP_140026_20150813_20170406_01_T1
				*LC08_L1TP_137028_20150808_20180524_01_T1
2016	136,300	12,108	5297	LC08_L1TP_140026_20160714_20170323_01_T1
				*LC08_L1TP_137028_20160810_20170322_01_T1
2017	136,477	11,877	4715	LC08_L1TP_140026_20170717_20170727_01_T1
				*LC08_L1TP_137028_20170712_20170726_01_T1
2018	136,298	11,585	4251	LC08_L1TP_140026_20180821_20180829_01_T1
				*LC08_L1TP_137028_20180816_20180829_01_T1
2019	136,263	11,556	4710	LC08_L1TP_140026_20190824_20190903_01_T1
				*LC08_L1TP_138027_20190826_20190903_01_T1
2020	137,064	11,529	3797	LE07_L1TP_140026_20200818_20200913_01_T1
				*LC08_L1TP_138027_20200727_20200807_01_T1
2021	136,545	12,904	4686	LC08_L1TP_140026_20210813_20210819_01_T1
				*LC08_L1TP_137028_20210824_20210831_01_T1

* Gegeen Lake sources.

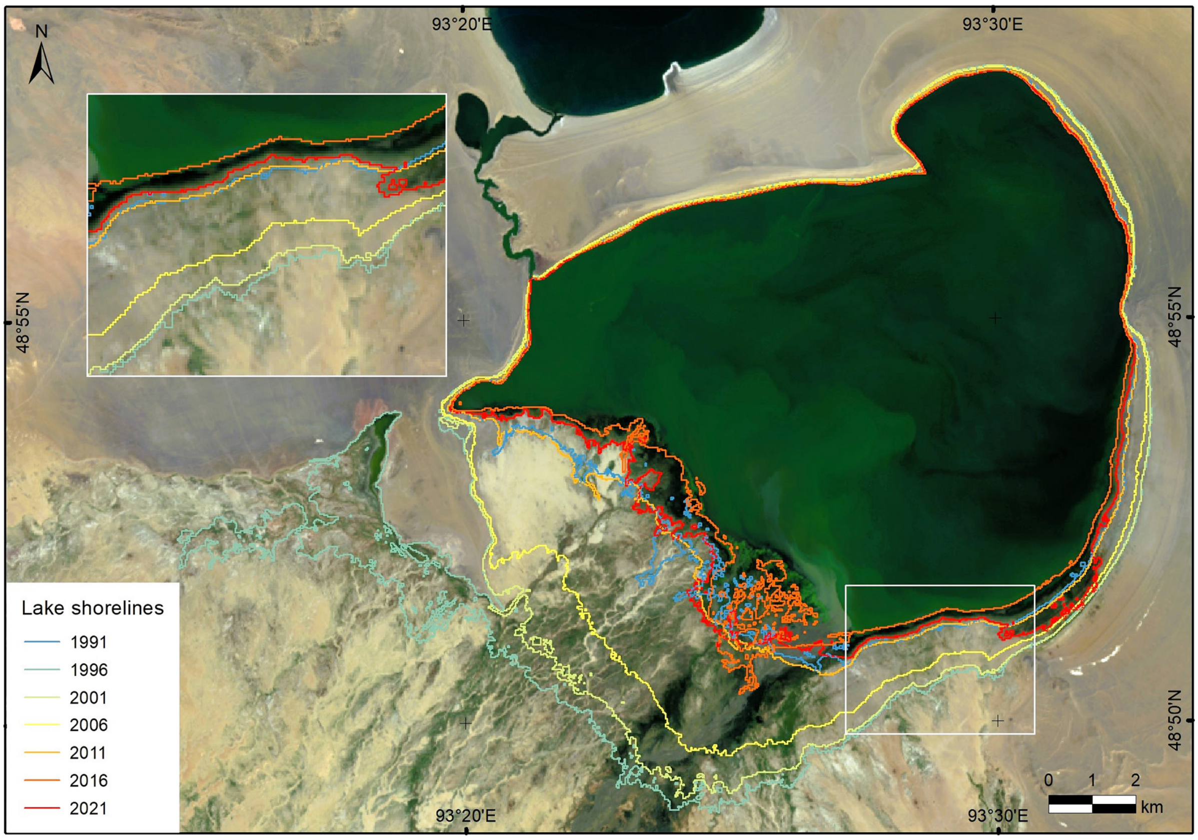

Fig. 3. Morphological changes in the area of Airag Lake (1991–2021).

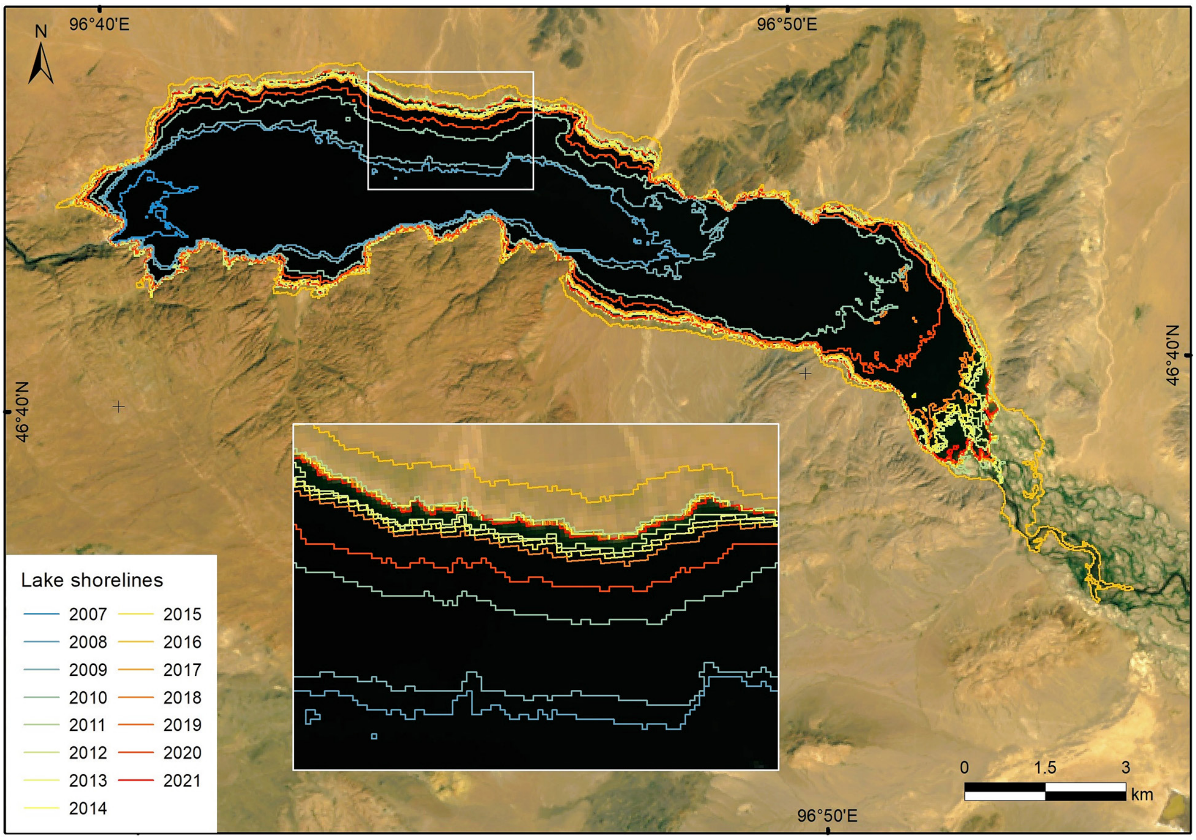

Fig. 4. Morphological changes in the area of Gegeen Lake (2007–2021).

has been an even greater reduction in the area of Khyargas Lake, with an R^2 = 0.7434, a phenomenon closely associated with the formation of Gegeen Lake.

We have conducted lake water surface area mapping at 5-year intervals since 1991. This specific interval was chosen to clarify and align the trends in the water areas of Airag and Khyargas lakes with meteorological parameters, considering the unit of time. Since 2007, the annual lake area has been calculated based on the commencement of water accumulation in Gegeen Lake which began due to the construction of a dam for the Taishir HPP (Figs 3–5).

According to the satellite mapping analysis of the Airag and Khyargas lake areas and their morphological changes, the lake area remained relatively stable from 1990 to 2006. This stability can be attributed to the climate conditions during those years and variations in river inflow, which, in some years, contributed to an increase in the water surface area of the lake. However, between 2007 and 2011, the area of the lakes declined sharply, while since 2012, the water surface area has been relatively stable. This stability may be attributed to the intensive accumulation of water in Gegeen Lake from 2007 to 2011 and the subsequent maintenance of a stable water flow balance. MA of the lake area and satellite mapping changes revealed significant decreases in the lake area, particularly in the south and southwest of the Zavkhan River delta lakes, which are the primary sources of water for Airag Lake. Changes in the area of Gegeen Lake indicate a steady increase each year since August 2007 when water began to accumulate (Fig. 4). The increase in the area of Gegeen Lake since 2007 is remarkably similar in both size and duration to the decrease in the surface area of Airag and Khyargas lakes (Figs 3–5). Based on our measurements using the Landsat TM satellite data, the initial recorded area in 2007 was 8.9 km². By 2021, this area had expanded to 46.85 km², resulting in a 5.3-fold increase in the lake's area.

Analysis of lake water surface area time series

Estimating the relationship between lake water surface areas is crucial in detecting changes

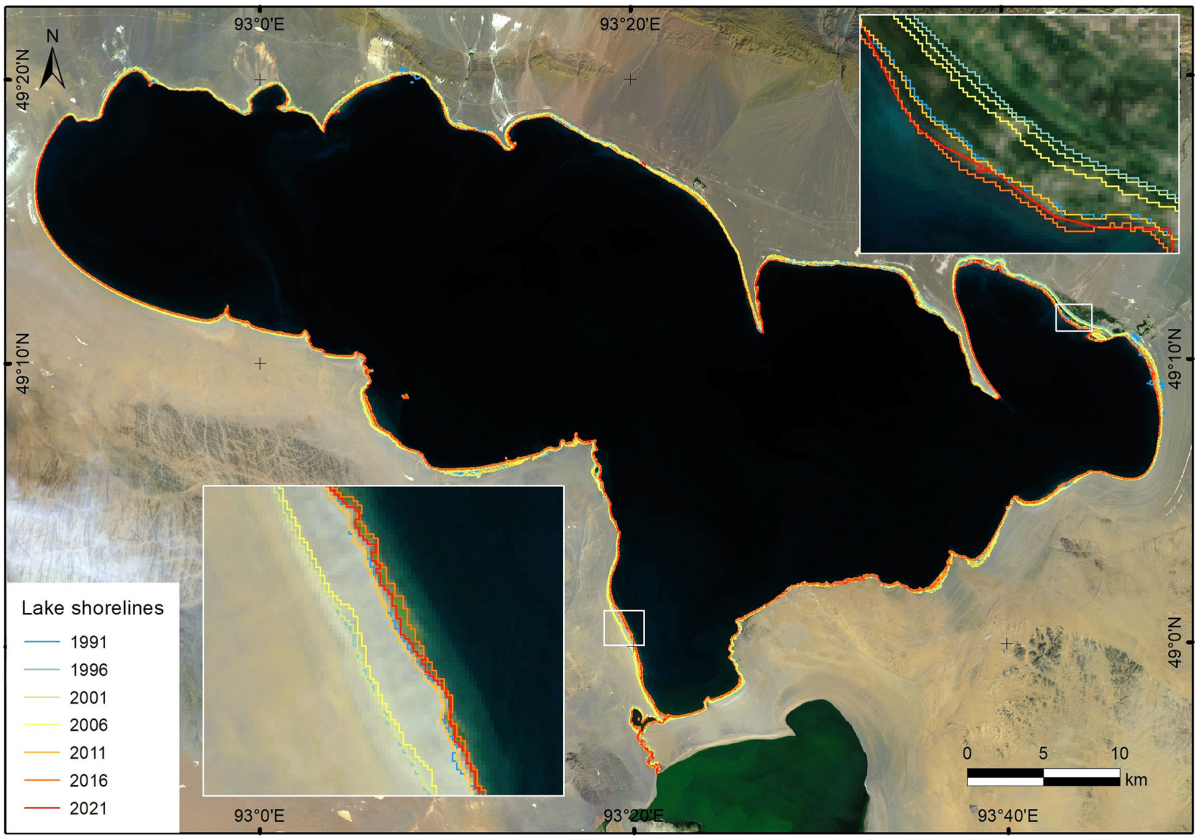

Fig. 5. Morphological changes in the area of Khyargas Lake (1991–2021).

over time. The time series of the water surface area of Airag, Khyargas and Gegeen lakes are calculated using NDWI (Fig. 6).

The decrease in the area of Airag and Khyargas lakes and the increase in the area of Gegeen Lake can be attributed to changes in the average reduction and growth of the lake areas. These changes are calculated using the method of determining the regression coefficient, which reflects the temporal trends in the MA of specific parameters.

According to these estimations, over the last 15 years, the Airag and Khyargas lakes have been steadily declining in the area by an average of approximately 1.72 to 3.54 km² per year. This is directly related to the reduction in the Zavkhan River, which has been the main source of the lake's water since 2007 and its accumulation in Gegeen Lake. However, the area of Gegeen Lake has been increasing by an average of approximately 3.22 km² per year (Fig. 6).

The coefficients of determination of the linear regression equation of the surface water area of the lakes in the time series from 1990 to 2021 and from 2007 to 2021 for Airag Lake were $R^2 = 0.455$ and $R^2 = 0.694$, and for Khyargas Lake, they were $R^2 = 0.517$ and $R^2 = 0.688$. The Gegeen Lake area time series had a coefficient of determination of $R^2 = 0.495$. These values of the coefficient of determination exceed the average, suggesting that the linear approach to these parameters is plausible. Furthermore, this indicates a strong correlation between river flows in the lake area.

Examining the water accumulation period (2007–2011) and the period after accumulation (2011–2021) of Gegeen Lake in the Taishir HPP, we observed that during the lake water accumulation period, the lake area has decreased significantly for Airag Lake ($R^2 = 0.986$) and increased for Gegeen lake ($R^2 = 0.965$) (Fig. 6). However, the water area for all three lakes gradually decreased after the lake water accumulation. The annual

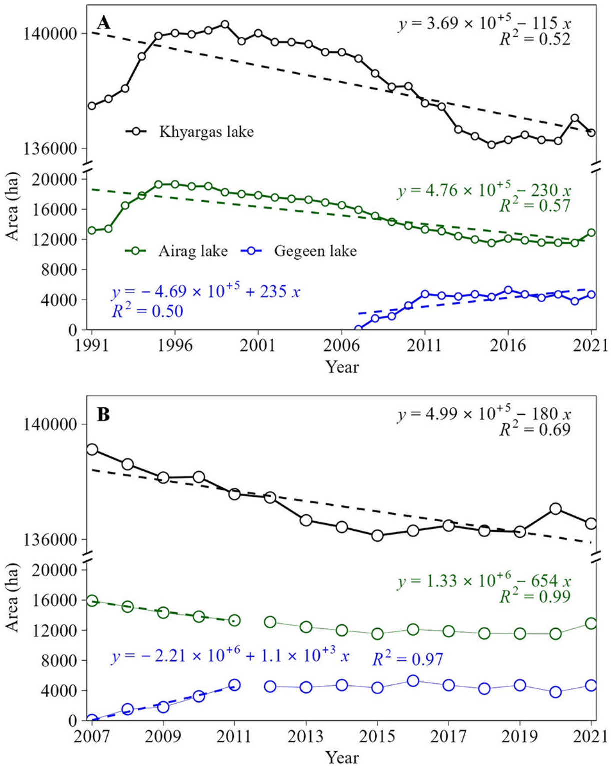

Fig. 6. A – Temporal changes in the water surface area of the Khyargas Lake basin. B – Surface area trends for the water accumulation (2007–2011) and after the accumulation period of Gegeen Lake (2011–2021).

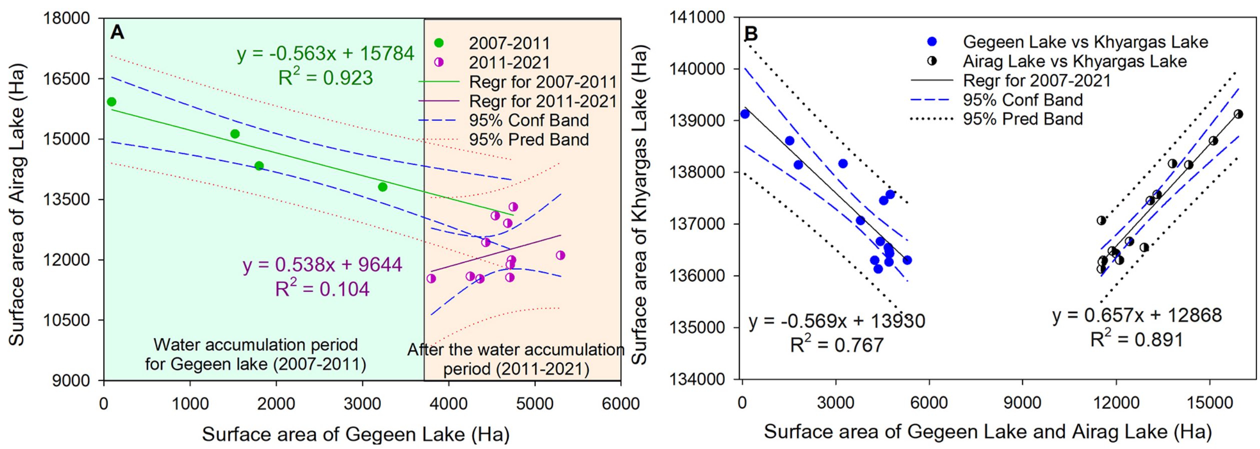

Fig. 7. A – Relationship of surface area changes between the Gegeen and Airag lakes. The light green background represents the water accumulation period for Gegeen Lake, while the light orange background corresponds to the water accumulation period of the lake. B – Relationship of surface area changes for Khargas Lake with the Gegeen and Airag lakes.

areas of Airag and Gegeen lakes are graphically plotted in Figure 7A.

The correlation between the temporal changes in the area of these lakes is highly negative ($R = -0.96$, $p < 0.01$), indicating that approximately 92% of the causes for the decrease in the area of Airag Lake can be attributed to the increase in the area of Gegeen Lake during the period from 2007 to 2011, which corresponds to the water accumulation period of the artificial lake. However, from 2011 to 2021, the relationship between the lake areas weakened and became positive ($R^2 = 0.104$, $p = 0.36$) under the influence of recent climate change conditions. In other words, the changes in the lake area of Airag Lake after the water accumulation period cannot be explained by the changes in the area of Gegeen Lake.

As shown in Figure 7B, the decrease in the surface area of Khyargas Lake exhibits a highly positive correlation ($R = 0.94$, $p < 0.0001$) with the decrease in the surface area of Airag Lake, while it demonstrates a strong negative correlation ($R = -0.88$, $p < 0.0001$) with an increase in the surface area of Gegeen Lake during the period from 2007 to 2021.

Relationship between volumes of lakes

The changes in the volume of the lakes were compared for the period from 2007 to 2021. In August 2007, water was initially stored in the HPP. The Khyargas Lake basin (2007–2021) shows changes in the water volume of lakes (Table 3, Fig. 8).

Similar to the area comparison, there is a highly negative correlation between the changes in the volume of these lakes ($R = -0.85$ to -0.86, $p = 0.06$). This means that approximately 73% to 74% of the decrease in the volume of Airag and Khyargas lakes can be explained by the increase in the volume of Gegeen Lake during the water accumulation period of Gegeen Lake. Another contributing factor to the decrease in the water volume of Airag and Khyargas lakes is the influence of climate.

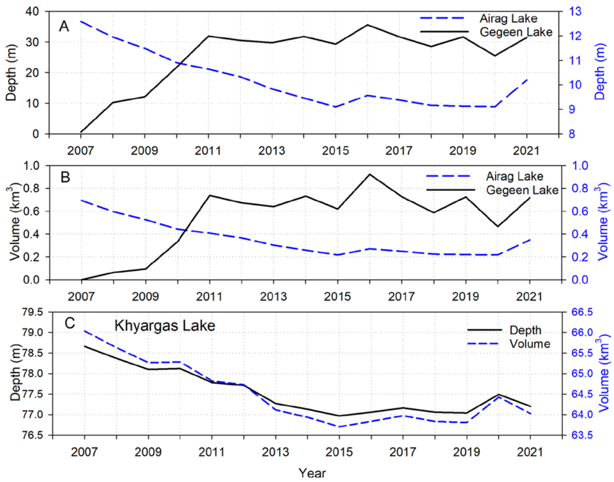

Fig. 8. Variations in morphometric changes in the lakes. A – Depth change; B – volume change of the Airag and Gegeen lakes and C – depth and volume changes of Khyargas Lake.

Table 3. Changes in the depth and volume of the Khyargas Lake basin (2007–2021).

Serial No.	Year	Airag Lake		Gegeen Lake		Khyargas Lake	
		Depth [m]	Volume [km³]	Depth [m]	Volume [km³]	Depth [m]	Volume [km³]
1	2007	12.587	0.694	0.598	0.001	78.66	66.034
2	2008	11.956	0.596	10.224	0.064	78.37	65.630
3	2009	11.491	0.527	12.107	0.095	78.10	65.266
4	2010	10.905	0.444	21.746	0.335	78.12	65.283
5	2011	10.643	0.408	31.923	0.738	77.78	64.819
6	2012	10.333	0.367	30.519	0.673	77.71	64.727
7	2013	9.834	0.304	29.786	0.640	77.27	64.113
8	2014	9.465	0.259	31.789	0.732	77.13	63.934
9	2015	9.107	0.216	29.329	0.620	76.97	63.704
10	2016	9.572	0.271	35.607	0.923	77.06	63.835
11	2017	9.385	0.249	31.695	0.727	77.16	63.972
12	2018	9.169	0.224	28.576	0.588	77.06	63.833
13	2019	9.136	0.220	31.661	0.726	77.04	63.806
14	2020	9.113	0.217	25.524	0.465	77.49	64.426
15	2021	10.200	0.350	31.500	0.718	77.20	64.024

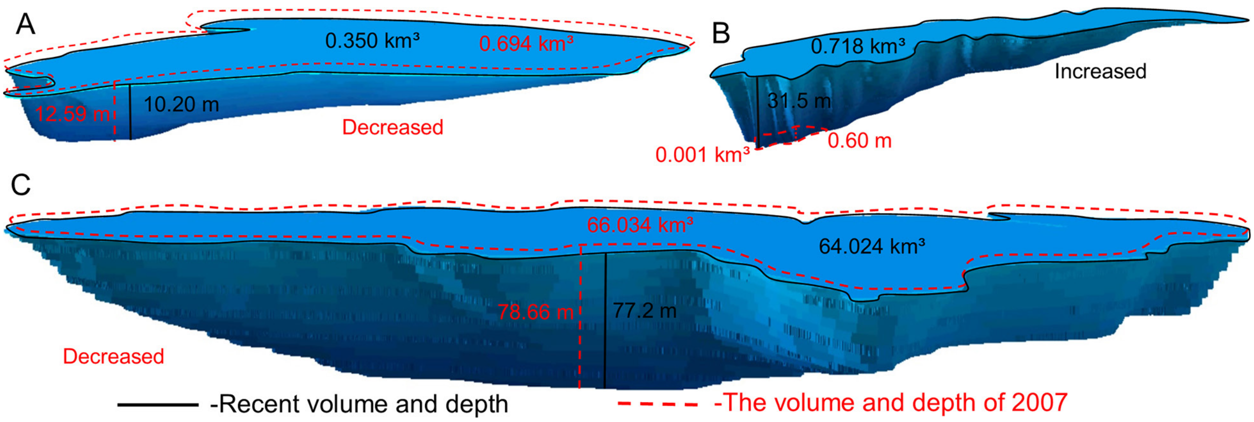

Fig. 9. Three-dimensional model of water volume changes in lakes. Morphometric changes in A – Airag Lake, B – Gegeen Lake and C – Khyargas Lake.

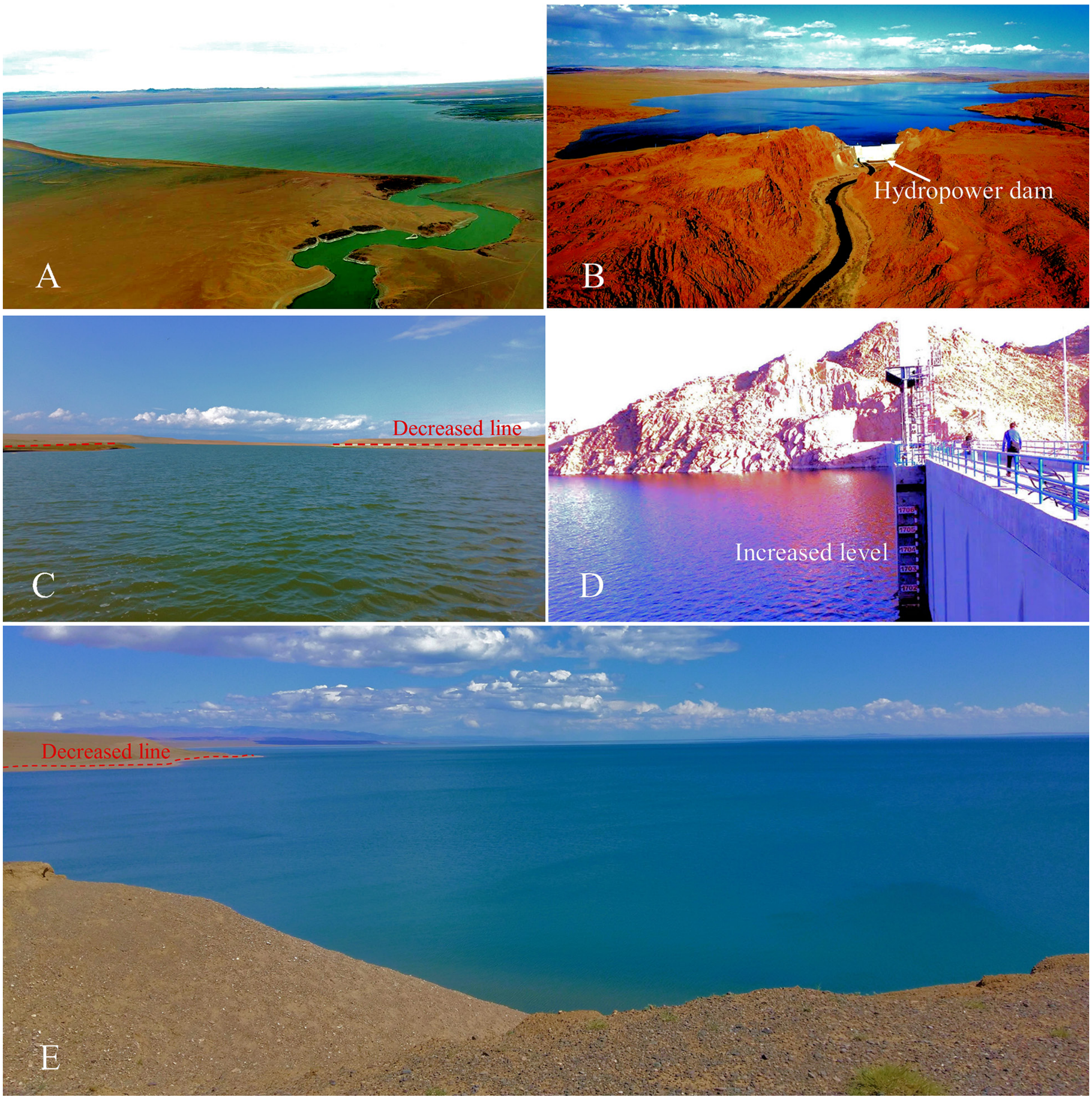

Fig. 10. Photograph of the lakes. A – Airag Lake aerial photo, photo by Batbold Dorj; B – Gegeen Lake aerial photo, photo by Dorjzovd Enkhtur; C – Airag Lake water level decline; D – The level of water increase in the Gegeen Lake and E – Khyargas Lake water level decline, photo by Altanbold Enkhbold.

The Griewank model, as utilised by Bacanin et al. (2020), was used to map the nonlinear volume of the lake depression. The volume change of the lake was estimated using both field data (Tserensodnom 2000, Davaa 2018) and satellite image data. The most recent three-dimensional changes were computed to determine changes in lake volume, as depicted in Figure 9.

The findings demonstrated a clear correlation between the variations in lake volume. It was observed that the volumes of Airag and Khyargas lakes tended to decrease, while Gegeen Lake showed an upward trend in volume. Additionally, the shoreline changes resulting from lake water level fluctuations were observed through field measurements (Fig. 10).

Morphometric changes in the lakes and the effects of climate

Over the past three decades, almost all of the lake areas in the Mongolian arid region have been shrinking or even drying up, as documented by Amgalan et al. (2020), Sumiya et al. (2020), Enkhbold et al. (2021), Dingjun et al. (2023) and Enkhbold et al. (2024). The reasons for the decline in the volume of Khyargas and Airag lakes can be attributed to factors not considered in the regression analysis, such as changes in surface water and climate parameters influenced by global climate change. Currently, the primary factor affecting the lake areas in Mongolian arid regions is the influence of climate (Amgalan et al. 2020, Dingjun et al. 2023, Dorjsuren et al. 2023, Enkhbold et al. 2024).

An analysis of the area and climate trends of the lakes included in the study is depicted in Figure 11.

In the past 30 years, climate trends have had noticeable effects on the regions surrounding Gegeen Lake. The average temperature has risen from 1.1°C to 1.4°C, and precipitation has increased from 84 mm to 105 mm. The slight increase in precipitation could be attributed to the more temperate climate following the water accumulation at Taishir HPP in Gegeen Lake. However, in the vicinity of Airag and Khyargas lakes, the average temperature over the same period has slightly increased from 1.4°C to 1.5°C. Precipitation, on the other hand, has dropped significantly from 79 mm to 61 mm, as shown in Figure 11. Despite a weak correlation with lake surface area, these temperature changes correspond to reductions in lake surface area and volume.

Based on calculations from a satellite data study, it is evident that the volumes of Airag and Khyargas lakes have decreased, while Gegeen Lake has shown an increasing trend in volume. Notably, the air temperature and precipitation in the vicinity of these lakes did not exhibit significant trends. The hydrological changes in the Khyargas Lake basin were caused by dams constructed for hydropower stations rather than by climate change.

Impact of artificial lakes on the environment

In arid regions, it is crucial to monitor changes in lake areas and their impacts on resource availability (Kang et al. 2015, Zhang et al. 2019). One such region is the arid climate around Airag Lake, a remnant of a once vast ancient lake situated in a tectonic depression. Owing to its relatively shallow water, the lake's water level has experienced significant fluctuations due to both modern climate change and human activities. As

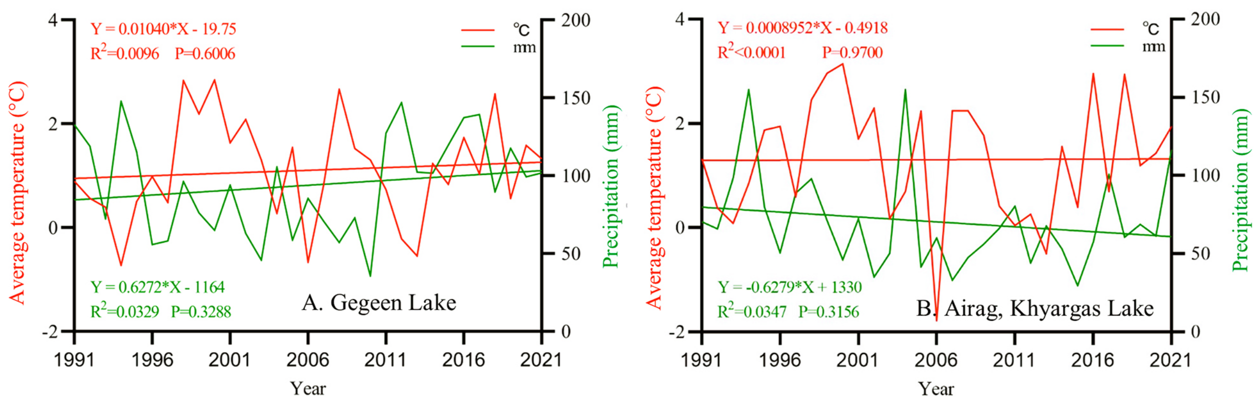

Fig. 11. Climate trends in years 1991–2021.

a consequence, the lake's area and water volume have witnessed a notable decline. In contrast, Gegeen Lake has an artificial origin, formed more than a decade ago through the construction of a hydroelectric dam. Remarkably, both the area and water level of the lake have been on a steady increase year by year. In the arid regions of western Mongolia, the natural flow of rivers experiences fluctuations, and the impact of human activities has brought about a marked transformation in the surface area and appearance of the Airag, Khyargas and Gegeen lakes, as evidenced by satellite imagery. Therefore, it becomes essential not only to consider the morphometric parameters of lake areas but also to delve into various aspects of hydrology, such as changes in water characteristics, the influence of climate, ecological effects, artificial interventions and alternations in the physical properties of lake water. This comprehensive approach helps understand the broader environmental dynamics and challenges faced by these lakes.

The establishment of new artificial lakes has been associated with a significant positive impact on local hydrology, as noted in studies by Gurnell (1998), Wang et al. (2017) and Zhang et al. (2019). However, this practice may also disrupt the natural hydrological system and ecological patterns (Shang 2013, Fang et al. 2015, Mendsaihan et al. 2016, Wang et al. 2021). Our study reveals that a substantial reduction in the area of a natural lake can indeed have adverse implications for the hydrological and ecological environment of the lake. Climate change has led to a notable reduction in the flow of the Zavkhan River, as documented in studies by Oyunbaatar et al. (2011), Ochir et al. (2013) and Dorjsuren et al. (2024). Moreover, the construction of the hydroelectric power station since 2007 has further exacerbated the situation, leading to a 10-fold reduction in water flow downstream of the Zavkhan River compared to the long-term average (Oyunbaatar et al. 2011, Dorjsuren et al. 2024). The consequences within the Zavkhan River basin are dire, including severe drying, sand migration, desertification, a substantial decline in pasture plant growth and notable shifts in species composition.

This phenomenon is substantiated by satellite imagery, which reveals a significant increase in the area of the Zavkhan and Khungui rivers as they flow into the lower reaches of Airag Lake. The reduction in the lake's surface area at the confluence of Airag Lake and rivers may be a primary factor disrupting the lake's ecological balance. The growing disparity between the supply and demand of water resources has become increasingly evident. These rivers are important components of the surface water cycle, serving as a lifeline for maintaining the ecological equilibrium and facilitating social development.

The economic and social development in western Mongolia imposes significant demands on water resources, emphasising the growing disparity between supply and demand. The findings of this research not only address national needs but also represent a collective success vital for the long-term growth and sustainability of local communities.

Taishir HPP has the potential to enhance the region's water supply, ensuring access to clean water for rural residents and livestock farming. This transformation can lead to a shift from Mongolia's traditional nomadic way of life to a semi-settled one, facilitating the construction of urban houses and farms with necessary engineering infrastructure. Additionally, the associated increase in employment offers substantial benefits from social, economic and ecological standpoints. This study provides a model for identifying, analysing and categorising issues that may influence future changes in the lake region using satellite mapping technologies. A notable feature and novelty of our study is its estimation of relationships within the Khyargas Lake basin, addressing a significant gap in the research on natural and artificial lakes in western Mongolia. By examining temporal variations in satellite data, this study determines the relationships between lake volume, water surface area and morphological changes.

Conclusions

Variations in the area of lakes in Mongolia's arid regions were illuminated using satellite imagery. Estimates derived from satellite data indicate the significant impact of recent human activity on lake water balance, primarily due to the observed adverse correlation between changes in lake surface area and volume.

Over a relatively short 15-year period, the Khyargas Lake basin has undergone substantial changes in its field and volume. This transformation is primarily attributed to the accumulation of water in the Taishir HPP dam, initiated in 2007 (within Gegeen Lake). Satellite imagery reveals a rapid expansion of the lake area, originating at the confluence of Airag and Gegeen lakes, and extending downstream along the Zavkhan River and its valley.

A strong correlation exists between changes in morphometric parameters of the lakes over time, particularly in the case of Airag Lake ($R = -0.96$, $p < 0.01$) and Khyargas Lake ($R = 0.94$, $p < 0.0001$). Volume changes are significantly explained by the growth of Gegeen Lake in area and volume ($R = -0.88$, $p < 0.0001$).

The Taishir HPP, with its annual capacity to generate 12 MW of power, plays a vital role in supplying electricity to nearby towns, driving employment, reducing greenhouse gas emissions and developing tourism. Nonetheless, the decline in the water area and volume of Airag Lake, a Ramsar Convention-registered site, has led to significant degradation of the wetland ecosystem. These factors pose significant constraints on environmental changes, as well as on economic and social development in western Mongolia.

This study's distinctive focus lies in examining how artificial and naturally formed lakes in arid regions are related to one another and to the natural hydrological network, ultimately contributing to the formation of artificial reservoirs and lakes.

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Authors' contribution

A.E., B.V.: conceptualisation and methodology, G.Y., C.N., B.G.: software, B.D., E.S.: formal analysis, S.D., L.D.: investigation and resources, A.E., B.V., Y.G.: writing – original draft preparation and writing – reviewing and editing.

Conflicts of interest

The authors declare that they have no conflicts of interest.

Data availability statement

This study used satellite data that were publicly available from the United States Geological Survey (USGS) Earth Resources Observation. The data that support the findings of this study are available from the first and corresponding author, upon reasonable request.

References

Ahmed I.A., Baig M.R.I., Talukdar S., Asgher M.S., Usmani T.M., Ahmed S., Rahman A., 2021. Lake water volume calculation using time series LANDSAT satellite data: A geospatial analysis of Deepor Beel Lake, Guwahati. *Frontiers in Engineering and Built Environment* 1(1): 107–130. DOI 10.1108/FEBE-02-2021-0009.

Amgalan M., Matsumoto T., Ulaanbaatar T., Nandintsetseg N., Erdenesukh S., Sandelger D., Altanbold E., 2020. Estimation of evaporation from Ogii Lake using the energy budget method. *Journal of Japan Society of Civil Engineers, Ser. G (Environmental Research)* 76(5): 301–309. DOI 10.2208/jscejer.76.5_I_301.

Bacanin N., Bezdan T., Tuba E., Strumberger I., Tuba M., 2020. Optimizing convolutional neural network hyperparameters by enhanced swarm intelligence metaheuristics. *Algorithms* 13(3): 67. DOI 10.3390/a13030067.

Baterdene A., Nagao S., Zorigt B., Ochir A., Fukushi K., Davaasuren D., Gankhurel B., Munkhsuld E., Tsetsgee S., Yunden A., 2022. Seasonal variation and vertical distribution of inorganic nutrients in a small artificial lake, Lake Bulan, in Mongolia. *Water* 14(12): 1916. DOI 10.3390/w14121916.

Bijeesh T.V., Narasimhamurthy K.N., 2020. Surface water detection and delineation using remote sensing images: A review of methods and algorithms. *Sustainable Water Resources Management* 6(4): 68. DOI 10.1007/s40899-020-00425-4.

Busker T., de Roo A., Gelati E., Schwatke C., Adamovic M., Bisselink B., Pekel J.F., Cottam A., 2019. A global lake and reservoir volume analysis using a surface water dataset and satellite altimetry. *Hydrology and Earth System Sciences* 23(2): 669–690. DOI 10.5194/hess-23-669-2019.

Chen Y., Zhang X., Fang G., Li Z., Wang F., Qin J., Sun F., 2020. Potential risks and challenges of climate change in the arid region of northwestern China. *Regional Sustainability* 1(1): 20–30. DOI 10.1016/j.regsus.2020.06.003.

Chipman J.W., 2019. A multisensor approach to satellite monitoring of trends in lake area, water level, and volume. *Remote Sensing* 11(2): 158. DOI 10.3390/rs11020158.

Davaa D., 2015. *Surface water regime and resources in Mongolia*. Admon Printing, Ulaanbaatar: 120–122.

Davaa G., 2018. Assessment of the water resources of Mongolian lakes based on land and satellite data, and a feasibility study for continuous monitoring. Institute of Water, Climate and Environmental Research and Information, Consulting Services Report, Ulaanbaatar: 33–54.

Dingjun L., Altanbold E., Batsuren D., Tuvshin G., Yumchmaa G., Boldbayar R., Gansukh Y., 2023. Changes in the area of lakes in different natural regions of Mongolia and climate effect. *Geographical Issues* 23(01): 4–21. DOI 10.22353/.v23i01.1571.

Dorjsuren B., Yan D., Wang H., Chonokhuu S., Enkhbold A., Davaasuren D., Girma A., Abiyu A., Jing L., Gedefaw M., 2018. Observed trends of climate and land cover changes in Lake Baikal basin. *Environmental Earth Sciences* 77: 1–12. DOI 10.1007/s12665-018-7812-9.

Dorjsuren B., Zemtsov V.A., Batsaikhan N., Demberel O., Yan D., Hongfei Z., Yadamjav O., Chonokhuu S., Enkhbold A., Ganzorig B., Bavuu E., 2024. Trend analysis of hydro-climatic variables in the Great Lakes Depression region of Mongolia. *Journal of Water and Climate Change* 15(3): 940–957. DOI 10.2166/wcc.2024.379.

Dorjsuren B., Zemtsov V.A., Batsaikhan N., Yan D., Zhou H., Dorligjav S., 2023. Hydro-climatic and vegetation dynamics spatial-temporal changes in the great lakes depression region of Mongolia. *Water* 15(21): 3748. DOI 10.3390/w15213748.

Dörnhöfer K., Oppelt N., 2016. Remote sensing for lake research and monitoring – Recent advances. *Ecological Indicators* 64: 105–122. DOI 10.1016/j.ecolind.2015.12.009.

Duan Z., Bastiaanssen W.G.M., 2013. Estimating water volume variations in lakes and reservoirs from four operational satellite altimetry databases and satellite imagery data. *Remote Sensing of Environment* 134: 403–416. DOI 10.1016/j.rse.2013.03.010.

Emami H., Zarei A., 2021. Modelling lake water's surface changes using environmental and remote sensing data: A case study of Lake Urmia. *Remote Sensing Applications: Society and Environment* 23: 100594. DOI 10.1016/j.rsase.2021.100594.

Enkhbold A., Dingjun L., Ganbold B., Yadamsuren G., Tsasanchimeg B., Dorligjav S., Nyamsuren O., Dorjsuren B., Gerelmaa T., Dashpurev B., Boldbayar R., 2024. Changes in morphometric parameters of lakes in different ecological zones of Mongolia: Implications of climate change. *Climate Research* 92: 79–95. DOI 10.3354/cr01734.

Enkhbold A., Khukhuudei U., Doljin D., 2021. Morphological classification and origin of lake depressions in Mongolia. *Proceedings of the Mongolian Academy of Sciences* 61(02): 35–43. DOI 10.5564/pmas.v61i02.1758.

Enkhbold A., Khukhuudei U., Kusky T., Tsermaa B., Doljin D., 2022. Depression morphology of Bayan Lake, Zavkhan province, Western Mongolia: Implications for the origin of lake depression in Mongolia. *Physical Geography* 43(6): 727–752. DOI 10.1080/02723646.2021.1899477.

Fang J., Bai Y., Wu J., 2015. Towards a better understanding of landscape patterns and ecosystem processes of the Mongolian Plateau. *Landscape Ecology* 30: 1573–1578. DOI 10.1007/s10980-015-0277-2.

Finkl C.W., Benedet L., Andrews J.L., 2005. Interpretation of seabed geomorphology based on spatial analysis of high-density airborne laser bathymetry. *Journal of Coastal Research* 21(3): 501–514. DOI 10.2112/05-756A.1.

Gao B.C., 1996. NDWI – A normalized difference water index for remote sensing of vegetation liquid water from space. *Remote Sensing of Environment* 58(3): 257–266. DOI 10.1016/S0034-4257(96)00067-3.

Gurnell A.M., 1998. The hydrogeomorphological effects of beaver dam-building activity. *Progress in Physical Geography* 22(2): 167–189. DOI 10.1177/030913339802200202.

Harmar O.P., Clifford N.J., Thorne C.R., Biedenharn D.S., 2005. Morphological changes of the Lower Mississippi River: Geomorphological response to engineering intervention. *River Research and Applications* 21(10): 1107–1131. DOI 10.1002/rra.887.

Kang S., Lee G., Togtokh C., Jang K., 2015. Characterizing regional precipitation-driven lake area change in Mongolia. *Journal of Arid Land* 7: 146–158. DOI 10.1007/s40333-014-0081-x.

Kumar A., Yang T., Sharma M.P., 2019. Greenhouse gas measurement from Chinese freshwater bodies: A review. *Journal of Cleaner Production* 233: 368–378. DOI 10.1016/j.jclepro.2019.06.052.

Lebedev S.A., Shevyakova O.P., Bedanokov M.K., 2020. Seasonal and Interannual Variability of the Krasnodar Reservoir Water Level Based on Satellite Altimetry Data. In: Bedanokov, M.K., Lebedev, S.A., Kostianoy, A.G. (eds) *The Republic of Adygea Environment*. The Handbook of Environmental Chemistry, vol 106. Springer, Cham. DOI 10.1007/698_2020_588.

Lehmkuhl F., Klinge M., Rother H., Hülle D., 2016. Distribution and timing of Holocene and late Pleistocene glacier fluctuations in western Mongolia. *Annals of Glaciology* 57(71): 169–178. DOI 10.3189/2016AoG71A030.

Lehner B., Messager M.L., Korver M.C., Linke S., 2022. Global hydro-environmental lake characteristics at high spatial resolution. *Scientific Data* 9(1): 351. DOI 10.1038/s41597-022-01425-z.

Lin Y., Li X., Zhang T., Chao N., Yu J., Cai J., Sneeuw N., 2020. Water volume variations estimation and analysis using multisource satellite data: A case study of Lake Victoria. *Remote Sensing* 12(18): 3052. DOI 10.3390/rs12183052.

Liu X., Shi Z., Huang G., Bo Y., Chen G., 2020. Time series remote sensing data-based identification of the dominant factor for inland lake surface area change: Anthropogenic activities or natural events? *Remote Sensing* 12(4): 612. DOI 10.3390/rs12040612.

Lu S., Ouyang N., Wu B., Wei Y., Tesemma Z., 2013. Lake water volume calculation with time series remote-sensing images. *International Journal of Remote Sensing* 34(22): 7962–7973. DOI 10.1080/01431161.2013.827814.

Luo R., Yuan Q., Yue L., Shi X., 2020. Monitoring recent lake variations under climate change around the Altai Mountains using multimission satellite data. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* 14: 1374–1388. DOI 10.1109/JSTARS.2020.3035872.

Luo X., Tong X., Hu Z., 2021. An applicable and automatic method for earth surface water mapping based on multispectral images. *International Journal of Applied Earth Observation and Geoinformation* 103: 102472. DOI 10.1016/j.jag.2021.102472.

Mady B., Lehmann P., Gorelick S.M., Or D., 2020. Distribution of small seasonal reservoirs in semi-arid regions and associated evaporative losses. *Environmental Research Communications* 2(6): 061002. DOI 10.1088/2515-7620/ab92af.

McFeeters S.K., 1996. The use of the normalized difference water index (NDWI) in the delineation of open water features. *International Journal of Remote Sensing* 17(7): 1425–1432. DOI 10.1080/01431169608948714.

McFeeters S.K., 2013. Using the normalized difference water index (NDWI) within a geographic information system to detect swimming pools for mosquito abatement: A practical approach. *Remote Sensing* 5(7): 3544–3561. DOI 10.3390/rs5073544.

Melesse A.M., Weng Q., Thenkabail P.S., Senay G.B., 2007. Remote sensing sensors and applications in environmental resources mapping and modelling. *Sensors* 7(12): 3209–3241. DOI 10.3390/s7123209.

Mendsaihan B., Dulmaa A., Krylov A.V., Kosolapov D.B., Slynko Y.V., Prokin A.A., Demidsereeter S., Lebedeva D.L., Altantsetseg B., Dgebuadze Y.Y., 2016. Formation of the lake-type ecosystem in semidesert zone: Tayshir Reservoir in the Zavkhan River (Western Mongolia). *Arid Ecosystems* 6: 213–219. DOI 10.1134/S2079096116030082.

Ochir A., Munkhjargal M., Bat-Erdene A., Tsetsgee S., 2013. Zavkhan river and its catchment area delineation using satellite image. *Journal of Water Resource and Protection* 5(10): 1–11. DOI 10.4236/jwarp.2013.510095.

Oyunbaatar D., Erdenebayar B., Davaa G., Saikhanjargal D., 2017. Recent changes of water regime and resource of the Ganga Lake and related some socio-economic aspects. *Modern Environmental Science and Engineering* 3(7): 482–491. DOI 10.15341/mese(2333-2581)/07.03.2017/008.

Oyunbaatar D., Galbaatar D., Munkhjargal S., 2011. Impact of Zavkhan River Regime Reserve and Ulaanboom hydroelectric power plant on climate change. In: *Conference of Water Resources and Permafrost in Temperate Regions*, Murun City, Khuvsgul Province, Mongolia: 116–122.

Pi X., Luo Q., Feng L., Xu Y., Tang J., Liang X., Ma E., Cheng R., Fensholt R., Brandt M., Cai X., 2022. Mapping global lake dynamics reveals the emerging roles of small lakes. *Nature Communications* 13(1): 5777. DOI 10.1038/s41467-022-33239-3.

Purevdorj Z., Jargal N., Ganbold O., Munkhbayar M., Purevee E., Jargalsaikhan A., Paik I.H., Paek W.K., Lee J.W., 2023. Spatial and temporal variations in waterfowl assemblage structures in Mongolian lakes and the changes linked to the gradient of lake surface areas. *Diversity* 15(3): 334. DOI 10.3390/d15030334.

Purevdorj Z., Paek W.K., Munkhbayar M., Ganbold O., Bing G.C., Jargalsaikhan A., Purevee E., Paik I.H., Choi W.S., Jargal N., Lee J.W., 2019. The avifaunal survey at important bird areas in western Mongolia. *Journal of the Korean Society of Ornithology* 26(1): 7–15. DOI 10.30980/KJO.2019.6.26.1.7.

Qi M., Liu S., Wu K., Zhu Y., Xie F., Jin H., Gao Y., Yao X., 2022. Improving the accuracy of glacial lake volume estimation: A case study in the Poiqu basin, central Himalayas. *Journal of Hydrology* 610: 127973. DOI 10.1016/j.jhydrol.2022.127973.

Qi Y., Lian X., Wang H., Zhang J., Yang R., 2020. Dynamic mechanism between human activities and ecosystem services: A case study of Qinghai lake watershed, China. *Ecological Indicators* 117: 106528. DOI 10.1016/j.ecolind.2020.106528.

Rousta I., Sharif M., Heidari S., Kiani A., Olafsson H., Krzyszczak J., Baranowski P., 2023. Climatic variables impact on inland lakes water levels and area fluctuations in an arid/semi-arid region of Iran, Iraq, and Turkey based on the remote sensing data. *Earth Science Informatics* 16(2): 1611–1635. DOI 10.1007/s12145-023-00995-9.

Saberioon M., Brom J., Nedbal V., Souček P., Císař P., 2020. Chlorophyll-a and total suspended solids retrieval and mapping using Sentinel-2A and machine learning for inland waters. *Ecological Indicators* 113: 106236. DOI 10.1016/j.ecolind.2020.106236.

Sato T., Tsujimura M., Yamanaka T., Iwasaki H., Sugimoto A., Sugita M., Kimura F., Davaa G., Oyunbaatar D., 2007. Water sources in semiarid northeast Asia as revealed by field observations and isotope transport model. *Journal of Geophysical Research: Atmospheres* 1-13D17). DOI 10.1029/2006JD008321.

Şerban C., Maftei C., Dobrică G., 2022. Surface water change detection via water indices and predictive modeling using remote sensing imagery: A case study of Nuntasi-Tuzla Lake, Romania. *Water* 14(4): 556. DOI 10.3390/w14040556.

Seyoum W.M., Milewski A.M., Durham M.C., 2015. Understanding the relative impacts of natural processes and human activities on the hydrology of the Central Rift Valley lakes, East Africa. *Hydrological Processes* 29(19): 4312–4324. DOI 10.1002/hyp.10490.

Shang S., 2013. Lake surface area method to define minimum ecological lake level from level-area-storage curves. *Journal of Arid Land* 5: 133–142. DOI 10.1007/s40333-013-0153-3.

Sheffield J., Wood E.F., Pan M., Beck H., Coccia G., Serrat-Capdevila A., Verbist K.J.W.R.R., 2018. Satellite remote sensing for water resources management: Potential for supporting sustainable development in data-poor regions. *Water Resources Research* 54(12): 9724–9758. DOI 10.1029/2017WR022437.

Shen Y., Liu D., Jiang L., Nielsen K., Yin J., Liu J., Bauer-Gottwein P., 2022. High-resolution water level and storage variation datasets for 338 reservoirs in China during 2010–2021. *Earth System Science Data* 14(12): 5671–5694. DOI 10.5194/essd-14-5671-2022.

Soille P., Pesaresi M., 2002. Advances in mathematical morphology applied to geoscience and remote sensing. *IEEE Transactions on Geoscience and Remote Sensing* 40(9): 2042–2055. DOI 10.1109/TGRS.2002.804618.

Stringer L.C., Mirzabaev A., Benjaminsen T.A., Harris R.M., Jafari M., Lissner T.K., Stevens N., Tirado-von Der Pahlen C., 2021. Climate change impacts on water security in global drylands. *One Earth* 4(6): 851–864. DOI 10.1016/j.oneear.2021.05.010.

Sukhbaatar C., Sodnom T., Hauer C., 2020. Challenges for hydropeaking mitigation in an ice-covered river: A case study of the Eg hydropower plant, Mongolia. *River Research and Applications* 36(8): 1416–1429. DOI 10.1002/rra.3661.

Sumiya E., Dorjsuren B., Yan D., Dorligjav S., Wang H., Enkhbold A., Weng B., Qin T., Wang K., Gerelmaa T., Dambaravjaa O., 2020. Changes in water surface area of the lake in the Steppe Region of Mongolia: A case study of Ugii Nuur Lake, Central Mongolia. *Water* 12(5): 1470. DOI 10.3390/w12051470.

Tserensodnom J., 1971. *Lakes of Mongolia*. Mongolian Academy of Sciences, Institute of Geography and Permafrost, Ulaanbaatar, Mongolia: 56–60.

Tserensodnom J., 2000. *Catalog of lakes of Mongolia*. Mongolian Academy of Sciences, Institute of Geography, Ulaanbaatar, Mongolia: 45–84.

USGS [United States Geological Survey], 2023. USGS Global Visualization Viewer. Online: glovis.usgs.gov (accessed March 2023).

Valeyev A., Karatayev M., Abitbayeva A., Uxukbayeva S., Bektursynova A., Sharapkhanova Z., 2019. Monitoring coastline dynamics of Alakol Lake in Kazakhstan using remote sensing data. *Geosciences* 9(9): 404. DOI 10.3390/geosciences9090404.

Wang G., Zhang J., Li X., Bao Z., Liu Y., Liu C., He R., Luo J., 2017. Investigating causes of changes in runoff using hydrological simulation approach. *Applied Water Science* 7: 2245–2253. DOI 10.1007/s13201-016-0396-1.

Wang Y., Gu X., Yang G., Yao J., Liao N., 2021. Impacts of climate change and human activities on water resources in the Ebinur Lake Basin, Northwest China. *Journal of Arid Land* 13(6): 581–598. DOI 10.1007/s40333-021-0067-4.

Wang Y.J., Qin D.H., 2017. Influence of climate change and human activity on water resources in arid region of Northwest China: An overview. *Advances in Climate Change Research* 8(4): 268–278. DOI 10.1016/j.accre.2017.08.004.

Xu N., Ma Y., Wei Z., Huang C., Li G., Zheng H., Wang X.H., 2022. Satellite observed recent rising water levels of global lakes and reservoirs. *Environmental Research Letters* 17(7): 074013. DOI 10.1088/1748-9326/ac78f8.

Yembuu B., 2021. General Geographical Characteristics of Mongolia. In: Yembuu, B. (eds) *The Physical Geography of Mongolia*. Geography of the Physical Environment. Springer, Cham. DOI 10.1007/978-3-030-61434-8_1.

Yu Y., Chen X., Malik I., Wistuba M., Cao Y., Hou D., Ta Z., He J., Zhang L., Yu R., Zhang H., 2021. Spatiotemporal changes in water, land use, and ecosystem services in Central Asia considering climate changes and human activities. *Journal of Arid Land* 13: 881–890. DOI 10.1007/s40333-021-0084-3.

Yue H., Liu Y., 2019. Variations in the lake area, water level, and water volume of Hongjiannao Lake during 1986–2018 based on Landsat and ASTER GDEM data. *Environmental Monitoring and Assessment* 191: 1–25. DOI 10.1007/s10661-019-7715-6.

Zhang G., Bolch T., Chen W., Crétaux J.F., 2021. Comprehensive estimation of lake volume changes on the Tibetan Plateau during 1976–2019 and basin-wide glacier contribution. *Science of the Total Environment* 772: 145463. DOI 10.1016/j.scitotenv.2021.145463.

Zhang G., Yao T., Chen W., Zheng G., Shum C.K., Yang K., Piao S., Sheng Y., Yi S., Li J., O'Reilly C.M., 2019. Regional differences of lake evolution across China during 1960s–2015 and its natural and anthropogenic causes. *Remote Sensing of Environment* 221: 386–404. DOI 10.1016/j.rse.2018.11.038.