Investigation of dynamic lake changes in Zhuonai Lake–Salt Lake Basin, Hoh Xil, using remote sensing images in response to climate change (1989–2018)

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ABSTRACT

The area covered by the four lakes in the Zhuonai Lake–Salt Lake Basin in Hoh Xil (Zhuonai Lake, Kusai Lake, Heidinor Lake, and Salt Lake) has changed significantly over the past 30 years. In this study, remote sensing image data gathered via the Landsat thematic mapper, enhanced thematic mapper plus, and operational land imager from 1989 to 2018 were used to extract the areal parameters of four lakes. The total area of the four lakes had increased by 18% in the past 30 years due to climate change. Interpolated results based on the meteorological data from 28 meteorological stations in the basin were used for trend analysis. A single-layer lake evaporation model was utilized to study the changes in the annual lake evaporation in the basin. The annual lake evaporation slightly increased from 1989 to 1995, followed by a sharp decrease from 1995 to 2018. From 1989 to 2018, the annual evaporation in the basin ranged between 615.37 and 921.66 mm, with a mean of 769.73 mm. A mass balance model was developed to estimate the changes in the lake volumes due to precipitation and evaporation. The increase in precipitation and the decrease in the annual lake evaporation promote the expansion of the four lakes. Lake evaporation is the main factor inducing changes in the lake areas.

Key words | climate change, Hoh Xil, lake area, remote sensing

HIGHLIGHTS

- A study of the evolution of ecological environment in the Tibetan Plateau was proposed.
- Meteorological data from 28 meteorological stations were subjected to trend analysis.
- A lake evaporation model was used to study the changes in annual lake evaporation.
- Precipitation and evaporation were the main factors resulting in lake area changes.

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INTRODUCTION

Lakes in the Tibetan Plateau (TP) can act as indicators of global climate change (Li et al. 2019a). The average elevation of TP is over 4,000 m and contains more than 1,200 lakes (>1 km²; Zhang et al. 2017). In the past 30 years, the total number of lakes and their surface areas have increased significantly (Li et al. 2019a). Due to minimal human activities, the water balance of these endorheic basins is mainly controlled by the regional climate (Sheng & Yao 2013; Haas et al. 2014). Climate change has been an important factor affecting the evolution of high-altitude lakes (Lei et al. 2014) because sustained warming has resulted in the retreat of permafrost and glaciers, supplying water to the lakes. In addition, the general increase in precipitation and the decrease in evaporation contribute water to alpine lakes (Yang et al. 2017). Therefore, long-term monitoring of the lake dynamics can be used to uncover the effects of climate change on water resources and the environment in the TP (Beniston et al. 1997; Li et al. 2019a).

Due to the harsh conditions in the TP, satellite remote sensing is the most feasible method for studying the dynamics of alpine lakes (Song et al. 2014a; Cui et al. 2017; Yang et al. 2017; Sun et al. 2018; Li et al. 2019a). The Landsat series have provided nearly continuous, medium-resolution monitoring data for alpine lakes (Yang et al. 2017; Li et al. 2019a). Landsat imagery has been utilized in many studies regarding the distribution and spatiotemporal changes of lakes in the TP (Liu et al. 2009; Wang et al. 2011, 2013; Lei et al. 2013; Liao et al. 2013; Zhang et al. 2015) and its sub-basins such as the Changtang Plateau (Yang et al. 2017), Qaidam Basin (QB; Li et al. 2019a), Paiku Co Basin (Lei et al. 2018), and Zhuonai Lake–Salt Lake Basin (Yao et al. 2012; Liu et al. 2016; Hwang et al. 2019; Li et al. 2019b). These investigations revealed the strong spatiotemporal variability of the TP lakes in the last few decades (Li & Sheng 2013; Cui et al. 2017; Yang et al. 2017; Sun et al. 2018; Li et al. 2019a). From 1977 to 2015, the total number of lakes (area >0.5 km²) in the QB increased by 18, while the total area expanded by 29.8%, from 1,761.5 ± 88.1 to 2,285.9 ± 91.4 km² (Li et al. 2019a). Between 2009 and 2014, the lakes in the Changtang Plateau continued to expand at a rapid rate of 340.79 km² yr⁻¹ (1.06% yr⁻¹, p < 0.05; Yang et al. 2017).

To explore the main factors inducing the dramatic changes in the lake areas, the variations in meteorological factors in the basin, such as precipitation, temperature, and evaporation, need to be examined. Note that the forces driving the variations of lake surface area due to climate change have been explored in several studies (Wang et al. 2015; Sun et al. 2018). The results showed that the expansion of most lakes in the TP is caused by significant glacier retreat and permafrost thawing due to sustained warming (Ersi et al. 2010; Yang et al. 2010; Zhang et al. 2011a; Lei et al. 2012). Based on modern mass balance data, glacial meltwater contributed 22.2 and 39.8% to the increased water storage in the central and northern TP from 2000 to 2013, respectively (Sun et al. 2018).
to glacial meltwater, the increase in precipitation and the decrease in evaporation are crucial for the expansion of the lakes in central TP (Bian et al. 2010; Zhu et al. 2010; Song & Sheng 2016) and northwestern TP (Qiao & Zhu 2017). During the past few decades, the amount of precipitation has increased, especially in the central TP. This increase correlates with observed lake changes and is considered to be the main reason for these changes (Liu et al. 2009; Lei et al. 2013; Song et al. 2014a, 2014b). Hydrological modeling results indicate that precipitation is also the main factor driving lake expansion (Biskop et al. 2016; Zhou et al. 2016; Yang et al. 2018). It has been suggested that the significant decrease in lake evaporation from 1998 to 2008 contributed to approximately 4% of lake expansion (Ma et al. 2016). The changes in the TP lakes are heterogeneous in both time and space, and the variations in the lake areas differ in different regions based on various influencing factors.

Lake evaporation in the TP has been simulated in many studies. A single-layer lake evaporation model has been widely used; the results agree well with the measured lake evaporation (Xu et al. 2009; Yu et al. 2011; Guo et al. 2019). The single-layer lake evaporation model, which is based on the surface heat and water balances, has been employed to simulate the evaporation over Yamdrok Yumco Lake during 1961–2005 (Kondo & Xu 1997) and Siling Co Lake during 1961–2015 (Guo et al. 2019). The results of the simulations agree well with those of the eddy covariance system. In addition, the primary advantage of the single-layer model is that it explicitly considers the heat storage in the water using the output water temperature (Xu et al. 2009). Therefore, it may be preferable to simulate the long-term evaporation of the TP lakes using the single-layer model.

In 2011, Zhuonai Lake burst and a large amount of lake water spilled into three lakes downstream (Yao et al. 2012; Liu et al. 2016; Hwang et al. 2019; Li et al. 2019b). Many researchers studied the cause of the collapse of Zhuonai Lake. Yao et al. (2012) and Liu et al. (2016) suggested that an increased amount of precipitation was the main reason. Based on Hwang et al. (2019), the collapse was due to the combined action of heavy rainfall and two earthquakes. Liu et al. (2019) suggested that the accelerated melting of glaciers contributed to the event. Although these studies were conducted to determine the cause of the collapse of Zhuonai Lake, they provided insights into the dynamic changes of the four lakes before and after the collapse. Before Zhuonai Lake collapsed, all four lakes experienced different degrees of expansion. In previous studies, the effects of lake evaporation and rainfall on lake expansion were not quantified. Therefore, the aims of this study are to analyze the dynamic changes of the four lakes from 1989 to 2018 and their response to climate change and to quantify the contribution of lake evaporation and precipitation to lake expansion.

### STUDY AREA AND DATASETS

#### Study area

The Zhuonai Lake–Salt Lake Basin (35°19′–35°54′N, 91°21′–93°39′E) is located in the hinterland of Hoh Xil and comprises a series of basins including Zhuonai Lake, Kusai Lake, Heidinor Lake, and Salt Lake (Figure 1). Based on data recorded at the Wudaoliang meteorological station, the multiyear average temperature, annual mean precipitation, average wind speed, and annual average sunshine duration in this area are −4.86 °C, 313.8 mm, 4.2 m s⁻¹, and 2,792.6 h, respectively. The total area of the Zhuonai Lake–Salt Lake Basin is 8,728.78 km², accounting for 25.37% of the Hoh Xil Heritage Area (Hu 1992). Details about the four lakes in the Zhuonai Lake–Salt Lake Basin, Hoh Xil, are presented in Table 1.

The Zhuonai Lake–Salt Lake Basin is located at the northern margin of the Qinghai–Tibet Plateau climate zone. The basin is characterized by distinct cold and hot seasons, relatively high temperature, ample precipitation, long winters, short summers, small annual but large daily temperature differences, long sunshine hours, and strong solar radiation. The plant growth period in the basin is short and lacks a frost-free stage. The average temperature is low, and the cold season lasts up to 7 months. The area is characterized by semi-arid climate, with evaporation exceeding precipitation. The main source of water recharge is snow and ice meltwater, followed by spring water and atmospheric precipitation. The regional precipitation gradually decreases from the southeast to the northwest. Snow
disasters comprise the major meteorological disasters in the region (Hu 1992).

The Zhuonai Lake–Salt Lake Basin is surrounded by mountains on three sides, i.e., the Kunlun Mountains in the north, Haoriarijiu and Yueba mountains in the south, and Wuxuefeng, Dakanding, and Heishi mountains in the west (Hu 1992). The Hudong and Pingding mountains are within the basin. Zhuonai Lake, also known as Huotongnuoer, is located in the west of the series of lakes, in the uppermost reaches. Kusai Lake is the sixth largest lake in the Hoh Xil Nature Reserve and forms an important saline wetland area together with the nearby Heidinor Lake and Salt Lake in the northeast of the reserve (Hu 1994).

Remote sensing data

In this study, Landsat images (Table 2) were used to study the interannual changes of major lakes in the Zhuonai Lake–Salt Lake Basin from 1989 to 2018. Corrected Level 1 Precision Terrain ground data with a spatial resolution of 30 m were retrieved from the United States Geological Survey (USGS, https://earthexplorer.usgs.gov/). The path/

![Image of the study area and distribution of the four lakes in the catchment.](Image)

**Figure 1** | Location of the study area and distribution of the four lakes in the catchment.

| Lake name | Lake area (km²) | Catchment area (km²) | Supply coefficient |
|-----------|----------------|---------------------|-------------------|
| Zhuonai   | 269.76         | 1,784.22            | 6.61              |
| Kusai     | 289.49         | 4,132.45            | 14.27             |
| Heidinor  | 53.74          | 1,393.10            | 25.92             |
| Salt      | 48.45          | 1,419.01            | 29.29             |

**Table 1** | Details about the four lakes in the Zhuonai Lake–Salt Lake Basin, Hoh Xil
row values of the images for the study area were 137/35 and 138/35. The data included Landsat Thematic Mapper (5TM), Landsat Enhanced Thematic Mapper Plus (7ETM+), and Landsat Operational Land Imager (8OLI) images. The operation periods of 5TM, 7ETM+ and 8OLI are from 1982 to present, 1999 to present, and 2013 to present, respectively (Song et al. 2014a). Considering the failure of Landsat7 ETM+ sensors after 2003, this series of images was mostly excluded. Sixty images covering the four lakes were selected to identify the lake area.

### Meteorological data

Meteorological stations are mainly distributed in the east of the TP, and there are no meteorological stations in the Zhuonai Lake–Salt Lake Basin in Hoh Xil. Although the Wudaoliang meteorological station is the closest to the study area, it is far from the basin. Therefore, for this study, we selected 28 national meteorological stations in the basin, including Wudaoliang, Xinghai, and Dari (Figure 1). After retrieving daily mean data from 28 meteorological stations, we used the inverse distance weighting method to obtain the daily mean temperature, wind speed, sunshine hours, and precipitation. The meteorological data were retrieved from the China Meteorological Data Service Center (http://data.cma.cn/).

### METHODS

#### Image preprocessing

In this study, 60 Landsat images were used to extract the areas of the four lakes in the basin from 1989 to 2018. Owing to the abundant annual precipitation in the basin from May to early October and the long freezing period of the lakes (December to early May), images from mid-October to end of November without cloud cover over the lakes were selected to extract the lake areas to reduce the effects of precipitation and lake freezing. The Landsat images obtained for the four lakes during the study period are shown in Figure 2. Because the Landsat 7 ETM+ images contained stripes, they were visually interpreted after removing the stripes. Other images were visually inspected after the automatic extraction of waterbodies. Because it is difficult to collect images of the entire basin in the same time period, the seasonal changes of the lake areas were not considered in this study. Geometric correction and calibration were applied to the images to accurately reflect the Earth’s surface. Image pixel values were converted to spectral radiance, and an atmospheric correction was applied to radiation image data to obtain spectral reflectance images.

### Table 2

| Lake          | Data type | Acquisition time (year/month/day) | Resolution (m) |
|---------------|-----------|----------------------------------|----------------|
| Zhuonai       | Landsat 5 | 1989/10/10; 1990/11/14; 1991/11/01; 1992/11/03; 1993/11/22; 1994/11/09; 1995/11/22; 1996/11/14; 1997/11/01; 1998/12/06; 1999/11/23; 2000/10/08; 2001/10/27; 2002/12/30; 2003/10/17; 2004/11/04; 2005/11/07; 2006/11/10; 2009/11/02; 2010/11/05; 2011/11/08; 2012/11/18; 2013/12/15; 2014/11/16; 2015/11/03; 2016/11/21; 2017/11/08; 2018/11/11; | 30 |
| Kusai         | Landsat 5 | 1989/10/10; 1990/11/14; 1991/11/01; 1992/11/03; 1993/11/22; 1994/11/09; 1995/11/22; 1996/11/14; 1997/11/01; 1998/12/06; 1999/11/23; 2000/10/08; 2001/10/27; 2002/12/30; 2003/10/17; 2004/11/04; 2005/11/07; 2006/11/10; 2009/11/02; 2010/11/05; 2011/11/08; 2012/11/18; 2013/12/15; 2014/11/16; 2015/11/03; 2016/11/21; 2017/11/08; 2018/11/11; | 30 |
| Heidinor      | Landsat 5 | 1989/10/10; 1990/11/14; 1991/11/01; 1992/11/03; 1993/11/22; 1994/11/09; 1995/11/22; 1996/11/14; 1997/11/01; 1998/12/06; 1999/11/23; 2000/10/08; 2001/10/27; 2002/12/30; 2003/10/17; 2004/11/04; 2005/11/07; 2006/11/10; 2009/11/02; 2010/11/05; 2011/11/08; 2012/11/18; 2013/12/15; 2014/11/16; 2015/11/03; 2016/11/21; 2017/11/08; 2018/11/11; | 30 |
| Salt          | Landsat 5 | 1989/10/10; 1990/11/14; 1991/11/01; 1992/11/03; 1993/11/22; 1994/11/09; 1995/11/22; 1996/11/14; 1997/11/01; 1998/12/06; 1999/11/23; 2000/10/08; 2001/10/27; 2002/12/30; 2003/10/17; 2004/11/04; 2005/11/07; 2006/11/10; 2009/11/02; 2010/11/05; 2011/11/08; 2012/11/18; 2013/12/15; 2014/11/16; 2015/11/03; 2016/11/21; 2017/11/08; 2018/11/11; | 30 |
|               | Landsat 7 | 2007/11/05; 2008/10/22; 2012/11/18; | 30 |
|               | Landsat 8 | 2013/12/15; 2014/11/16; 2015/11/03; 2016/11/21; 2017/11/08; 2018/11/11; | 30 |
|               | Landsat 8 | 2008/11/16; 2011/11/09; 2012/11/11; | 30 |
|               | Landsat 8 | 2013/11/06; 2014/11/09; 2015/10/27; 2016/11/14; 2017/11/01; 2018/12/06 | 30 |
Lake extent mapping

The lake areas were obtained from Landsat satellite images. The spectral water index was derived from arithmetic operations applied to two or more spectral bands (e.g., the ratio, difference, and normalized difference). Although the images used in this study had the same spatial resolution, different spectral and radiation resolutions were generated during the segmentation process. The spectral water index is based on the fact that water absorbs radiation energy in the near-infrared (NIR) and short-wave infrared wavelength ranges (Phiri & Morgenroth 2011). In this study, the lake area was extracted using the normalized differential water index, which is defined as follows (McFeeters 1996):

\[
\text{NDWI} = \frac{\rho_{\text{GREEN}} - \rho_{\text{NIR}}}{\rho_{\text{GREEN}} + \rho_{\text{NIR}}}
\]

where GREEN denotes the green band and NIR denotes the NIR band. In this method, after band operations, the spectral curves are analyzed to set reasonable thresholds, the number of pixels within the thresholds is counted, and the lake area is calculated according to the resolution of the satellite image.

Climate change is an important factor affecting the lake surface area. To examine the effect of climate change on the changes of lake areas, the inverse distance weighting method was used in this study to interpolate monthly average and annual average meteorological data (temperature, wind speed, sunshine hours, and precipitation) recorded at 28 stations and to obtain meteorological basin data in raster format.

Single-layer lake evaporation model

The single-layer lake evaporation model (Xu et al. 2009; Yu et al. 2011; Guo et al. 2019) was used to calculate the lake evaporation of the basin from 1989 to 2018. The input data of this model include air temperature, wind speed, relative humidity, and sunshine duration. The main outputs are net radiation, sensible heat flux, latent heat flux, lake evaporation, and lake heat storage changes. The input and output data are based on daily scales. The basic principle of this model is to provide the initial lake surface temperature and iterate the lake surface temperature with the energy balance of the lake surface as the boundary condition. The input data of the model were recorded at the Wudaoliang
meteorological station. The lake surface temperature and measured evaporation were used to validate the model. The coefficient of determination ($R^2$), Nash–Sutcliffe coefficient (NSE), root-mean-square deviation (RMSD), and mean bias error (MBE) were used to evaluate the model.

$$R^2 = \frac{\sum_{i=1}^{n} (X_i - \bar{X})(X'_i - \bar{X'})}{\sqrt{\sum_{i=1}^{n} (X_i - \bar{X})^2 \sum_{i=1}^{n} (X'_i - \bar{X'})^2}},$$ (2)

$$\text{NSE} = 1 - \frac{\sum_{i=1}^{n} (X_i - X'_i)^2}{\sum_{i=1}^{n} (X_i - \bar{X})^2},$$ (3)

$$\text{RMSD} = \frac{1}{n} \sum_{i=1}^{n} (X'_i - X_i)^2,$$ (4)

$$\text{MBE} = \frac{1}{n} \sum_{i=1}^{n} (X'_i - X_i),$$ (5)

where $n$ is the number of data, and $X_i$, $X'_i$, $\bar{X}$, and $\bar{X'}$ are the measured value, model output, mean of the measured value, and mean model output, respectively.

**Change in the lake mass balance**

The variation in the lake water quantity depends on the inflow of land runoff (including glaciers), lake evaporation, and precipitation. In the TP, glacier mass loss may contribute to the lake water balance. Therefore, the lake water balance equation can be written as (Yang et al. 2018):

$$\frac{dV_1}{dt} = (P - E_1)A_1 + R(A_b - A_1) + \frac{d(G - S)}{dt},$$ (6)

where $A_1$, $A_b$, $V_1$, $G$, and $S$ are the lake area ($m^2$), basin area ($m^2$), lake water volume ($m^3$), glacier volume ($m^3$), and groundwater storage ($m^3$), respectively; $R$ (m s$^{-1}$) is the precipitation-generated land runoff; $E_1$ (m s$^{-1}$) is the lake evaporation; and $P$ (m s$^{-1}$) is the precipitation.

Based on Equation (6),

$$\frac{dV_1}{dt} = [P \times A_1 + P \times C_R(A_b - A_1)] - (E_1 \times A_1) + \frac{d(G - S)}{dt}.$$ (7)

Let:

$$V_P = P \times A_1 + P \times C_R(A_b - A_1)$$ (8)

and

$$V_E = (E_1 \times A_1)$$ (9)

where $V_P$ ($m^3$) and $V_E$ ($m^3$) are the volumes of water change caused by precipitation and evaporation, respectively, and $C_R$ is the runoff coefficient (Yang et al. 2018).

During a period with stable lake volume (i.e., $dV_1/dt = 0$), $d(G - S)/dt$ is assumed to be zero. Equation (6) may be simplified as follows:

$$C_{R0} = \left(\frac{E_{10}}{P_{01}} - 1\right) \frac{A_{10}}{A_b - A_{10}}.$$ (10)

The solution of $V_P$ and $V_E$ can be obtained using the following procedure.

1. Calculate $C_{R0}$, $V_{P0}$, and $V_{E0}$ for the stable period using Equation (7).
2. Calculate the annual $V_P$ and $V_E$ values of the four lakes.
3. Calculate the cumulative changes based on steps 1 and 2 according to the stable year of the lake as follows:

$$\sum_{i=1}^{n} \Delta V_P = \sum_{i=1}^{n} V_{Pi} - n \times V_{P0}$$ (11)

and

$$\sum_{i=1}^{n} \Delta V_E = \sum_{i=1}^{n} V_{Ei} - n \times V_{E0}$$ (12)

**Standardized precipitation evapotranspiration index**

The standardized precipitation evapotranspiration index (SPEI) is based on precipitation and temperature data and is important because it combines multiscale characteristics with the capacity to include the effects of temperature variability on drought assessment (Vicente-Serrano et al. 2010). The SPEI combines the sensitivity of the Palmer drought
severity index to the change in evaporation demand with the simplicity of calculation, and has the robustness of the multitemporal nature of the standardized precipitation index (Yu et al. 2014). The SPEI calculation includes potential evapotranspiration and deficit or surplus accumulation of a climate water balance at different time scales, normalizing the water balance into a log-logistic probability distribution to obtain the SPEI, as shown in the following equations (Vicente-Serrano et al. 2010):

\[
\text{PET} = 16K \left( \frac{10T}{T} \right)^m 
\]

(13)

\[
D_i = P_i - \text{PET}_i
\]

(14)

\[
X^i_{lj} = \sum_{l=13-k}^{12} D_{I-1, j} + \sum_{l=1}^{j} D_{i, j}, \text{ if } j < k
\]

and

\[
X^i_{lj} = \sum_{l=j-k+1}^{j} D_{i, j}, \text{ if } j \geq k
\]

(15)

\[
F(x) = \left[ 1 + \left( \frac{\alpha}{x-\gamma} \right)^\beta \right]^{-1}
\]

(16)

\[
\text{SPEI} = W - \frac{C_0 + C_1 W + C_2 W^2}{1 - d_1 W + d_2 W^2 + d_3 W^3}
\]

(17)

where \( T \), \( I \), and \( m \) are the monthly mean temperature (°C), heat index, and coefficient depending on \( I \), respectively; \( D_{i, j} \) is the \( P - \text{PET} \) difference in the first month of year \( I \); \( \alpha \), \( \beta \), and \( \gamma \) are the scale, shape, and origin parameters, respectively; \( W = \sqrt{-2 \ln(P)} \) and \( P \) are the probability of exceeding a determination \( D \) value. The constants are \( C_0 = 2.515517 \), \( C_1 = 0.802853 \), \( C_2 = 0.010328 \), \( d_1 = 1.432788 \), \( d_2 = 0.189269 \), and \( d_3 = 0.001308 \).

**Trend analysis**

In this study, the nonparametric Mann–Kendall (MK) test was used to analyze the trends of the climate and lake area changes (Mann 1945; Kendall 1975). Nonparametric tests do not assume data distribution and are useful to detect monotonic trends (Huth & Pokorná 2004; Nepal 2016). In addition, because the MK test is based on a sign difference rather than a value difference, it is insensitive to the effects of extreme values and outliers (Helsel & Hirsch 2002). The MK test is widely used for trend analysis (Zhang et al. 2019b).

In this study, simple linear regression was used to determine long-term linear trends. Simple linear regression includes two steps; the time \( t \) and hydrological variable (i.e., precipitation or lake area in this study) are used as independent and dependent variables, respectively, to fit the linear simple regression equation. The statistical significance of the slope of the regression equation was determined using \( t \)-tests (Xu 2001; Zhang et al. 2009).

**RESULTS AND DISCUSSION**

**Temporal and spatial variations of the four lake areas**

The changes in the surface area of the four lakes from 1989 to 2018 are shown in Figure 3. From 1989 to 2018, the Zhuonai Lake area decreased and the areas of the other lakes increased. The changes in the areas of the four lakes during the study period can be divided into three periods: from 1989 to 1995, the lake areas decreased; from 1995 to 2011, the lake areas increased; and from 2011 to 2018, the changes in the areas of the four lakes differed. In 2011, Zhuonai Lake burst and its area decreased by 105.48 km² within 1 year because the lake changed from an endorheic to an exorheic lake characterized by outflow due to the burst event (Liu et al. 2019). The areas of lakes Kusai, Heidinor, and Salt increased sharply. Due to the burst of Zhuonai Lake (Yao et al. 2012; Liu et al. 2016; Hwang et al. 2019), approximately 3.2 km³ of water has leaked into the Salt Lake since 2011 (Li et al. 2019b). After 2011, the areas of lakes Zhuonai, Kusai, and Heidinor gradually decreased. In contrast, the area of Salt Lake continued to rapidly expand by 122.2 km². These phenomena can be explained as follows: after the burst of Zhuonai Lake, the overflow passed through the
Kusai and Heidinor lakes, and flowed into the Salt Lake; however, there was a certain lag (Li et al. 2019b; Liu et al. 2019).

The areas of the four lakes significantly changed in 1995, 2010, and 2011, as shown in Table 3. The fluctuations of the four lakes between 1989 and 2018 are shown in Figure 4.

Climate change trends in the basin during the past 30 years

Precipitation

As shown in Figure 5, the annual precipitation in the basin increased from 1989 to 2018, with a growth rate

### Table 3 | Areas of the four lakes in different years and changes (Δa) between 1989 and 2018

| Lake/year | 1989   | 1995   | 2010   | 2011   | 2018   | Δa/1989-1995 | Δa/1995-2010 | Δa/2010-2011 | Δa/2011-2018 | Δa/1989-2018 |
|-----------|--------|--------|--------|--------|--------|--------------|--------------|--------------|--------------|--------------|
| Zhuonai (km²) | 259.16 | 255.4  | 269.76 | 164.29 | 150.12 | −0.63        | 0.96         | −105.48      | −2.02        | −3.76        |
| Kusai (km²)  | 265.50 | 258.2  | 289.49 | 344.07 | 329.65 | −1.22        | 2.09         | 54.58        | −2.06        | 2.21         |
| Heidinor (km²) | 45.33  | 33.14  | 53.74  | 82.87  | 78.80  | −2.03        | 1.37         | 29.13        | −0.58        | 1.15         |
| Salt (km²)   | 44.83  | 32.48  | 48.45  | 72.86  | 195.06 | −2.06        | 1.06         | 24.41        | 17.46        | 5.18         |

![Figure 3](image-url) | Areal changes of the four lakes between 1989 and 2018.

![Figure 4](image-url) | Climate change trends in the basin during the past 30 years.

![Figure 5](image-url) | Precipitation trends in the basin from 1989 to 2018.
From 1989 to 2018, the mean annual precipitation in the basin ranged from 199.01 to 342.06 mm, with an average of 256.03 mm. The trend of the annual precipitation in the basin is similar to that recorded at the Wudaoliang meteorological station. The annual precipitation in the basin was lower than that recorded at the Wudaoliang meteorological station, but higher than that obtained at the Golmud and Xiaozaohuo stations. Before 2010, the changes of the lake areas correlated with the precipitation (decrease between 1989 and 1995 and increase between 1995 and 2010). The correlations between the precipitation and changes may indicate that the increase in precipitation plays a dominant role in the expansion of most lakes in the TP (Lei et al., 2021).
et al. 2013; Song et al. 2014a, 2014b; Zhang et al. 2017; Yang et al. 2018; Yao et al. 2018).

Temperature

As shown in Figure 6, the annual mean temperature of the basin increased from 1989 to 2018. The annual mean temperature in the basin ranged between -2.08 and 0.22 °C, with an average of -0.77 °C. The annual mean temperature in the basin was lower than that at the Golmud and Xiaozaohuo stations, but higher than that at the Wudaoliang station. The changes in the annual mean temperature do not correlate with the changes in the lake areas (Liu et al. 2019). Note that the effect of the air temperature on the water balance in the lakes is mainly related to glacier retreat and permafrost thawing (Yang et al. 2017). The temperature increase promoted the lake expansion to a certain extent, but it was not the dominant factor.

Wind speed

From 1989 to 2018, the annual mean wind speed in the basin first declined and then increased, as shown in Figure 7. The annual mean wind speed in the basin ranged between 3.18 and 4.01 m s⁻¹, with an average of 3.49 m s⁻¹. The annual mean wind speed of the basin is similar to that recorded at the Xiaozaohuo Station, lower than that obtained at the Wudaoliang Station, and higher than that measured at the Golmud Station. The change in the wind speed does not impact the lake expansion, but it controls the changes in the lake evaporation (Yu et al. 2011; Guo et al. 2019). The increase in the wind speed was the main factor causing the significant increase in the evaporation of Siling Co Lake from 1961 to 1984 (Guo et al. 2019). A decrease in the wind speed can lead to a decrease in the lake evaporation, which indirectly promotes lake expansion.

Sunshine duration

As shown in Figure 8, from 1989 to 2018, the annual mean sunshine duration in the basin decreased at a rate of
The annual mean sunshine hours in the basin ranged between 7.21 and 8.51 h, with an average of 7.93 h. The annual mean sunshine duration in the basin was lower than that at the Golmud and Xiaozaohuo stations, but higher than that at the Wudaoliang Station. Similar to the wind speed, the duration of sunshine influences the lake area by affecting the lake evaporation. The longer the sunshine duration, the greater the lake evaporation (Guo et al. 2013). Therefore, a continuous decline in the sunshine hours can promote the lake expansion.

Standardized precipitation evapotranspiration index

The SPEI was used to analyze the effects of precipitation and air temperature on lake expansion. Figure 9 shows the 3-, 12-, and 24-month SPEIs for the basin between 1989 and 2018. Based on the SPEI, the basin was mainly dry, but the drought started to decline in 2007. Before 1996, drought may have led to lake shrinkage. However, in 2007, a humid period occurred, which may have accelerated the lake expansion. According to the trend analysis, the change in SPEI can be divided into two periods: from 1989 to 1995, the SPEI increased (0.097 yr⁻¹); from 1996 to 2018, the SPEI decreased (−0.012 yr⁻¹). As the area of the four lakes changed dramatically after 2010, we compared the Pearson correlation coefficients between the changes in the four lakes before 2010 and the SPEI, as shown in Table 4. There was a negative correlation between the SPEI and lake area change. From 1989 to 1995, owing to the decrease in precipitation and the increase in temperature, the SPEI showed a significant upward trend. From 1996 to 2010, both precipitation and temperature showed an upward trend, while the SPEI showed a downward trend, which was relatively slow. Therefore, the correlation

![Figure 9](https://example.com/figure9.png)  
*Figure 9* | The 3-, 12-, and 24-month SPEIs of the basin (1989–2018).
between the SPEI and lake area change is good during the first period (1989–1995), but poor during the second period (1996–2010).

Long-term variation in the annual lake evaporation in the basin

The surface temperature data measured during June and July 2018 were used to validate the simulated lake surface temperature. The surface temperature is strongly affected by the release of energy stored in the water and by surface water energy exchange processes, such as cooling/warming involving sensible and latent heat, which are affected by meteorological variables (Zhang & Liu 2013). As shown in Figure 10, the simulated daily lake surface temperature agrees well with the measured temperature. The $R^2$, NSE, RMSD, and MBE between the daily simulations and observed lake evaporation data are 0.45, 0.41, 1.12, and 0.26 mm, respectively. Although the correlation between the simulated and measured evaporation is poor, correlation for the temperature data is better. The simulated surface temperature of the lake, which is an important model output (Xu et al. 2013; Yu et al. 2011), agrees with the measured temperature, reflecting the accuracy of the model. Our results are similar to those obtained by Guo et al. (2019) and indicate that the single-layer lake evaporation model can be used to accurately simulate the lake evaporation at a daily scale (Guo et al. 2019). Therefore, the simulated evaporation reflects the long-term variation in the lake evaporation in the basin.

As shown in Figure 11, from 1989 to 2018, the annual lake evaporation in the basin decreased at a rate of $-1.45$ mm yr$^{-1}$. The annual lake evaporation ranged between 615.37 and 921.66 mm, with an average of 769.73 mm. The annual evaporation in the basin differs notably from the values of the other eight lakes in the TP (Guo et al. 2019). It is smaller than the values of six lakes (Siling Co Lake, Qinghai Lake, Zigetang Co Lake, Erhai Lake, Yamdrok Yumco Lake, and the small lake adjacent to Nam Co), but larger than the evaporation of the Nam Co and Ngoring lakes. Guo et al. (2019) compared the evaporation of Siling Co Lake with the values of seven other lakes in the TP and suggested that the latitude and altitude

| Table 4 | Pearson correlation coefficients between the four lakes and SPEI |
|---|---|---|---|---|---|
| Period | Zhuonai Lake | Kusai Lake | Haidinor Lake | Salt Lake | Total area of four lakes |
| 1989–1995 | – 0.74 | – 0.79 | – 0.67 | – 0.63 | – 0.73 |
| 1996–2010 | – 0.30 | – 0.39 | 0.46 | 0.49 | 0.43 |

![Figure 10](image1.png) | Comparison of the simulated and measured lake surface temperatures with the air temperature over Kusai Lake. |

![Figure 11](image2.png) | Variations in the lake evaporation between 1989 and 2018. |
significantly affect the evaporation. The altitudes of the lakes in the basin are close to those of Siling Co, Zigetang Co, and Yamdrok Yumgo lakes. The lower evaporation in the basin may be due to the higher latitude of the basin. However, the latitudes of the lakes in the basin are similar to those of Ngoring and Qinghai lakes. The evaporation of Qinghai Lake at lower altitude is higher than that of the basin, while the evaporation of Ngoring Lake is lower than that of the basin. This might be due to the different climate and atmospheric conditions.

Response of the lake area to climate change

Assessing the impact of climate change on lake area variations is essential for water resource management and ecological protection. The variations in the areas of the four lakes and meteorological data over the past 30 years obtained using the MK method are shown in Table 5.

Before 2010, the four lakes were independent inland lakes (Liu et al. 2019). After the Zhuonai Lake burst in 2011, the changes in the areas of the four lakes were affected by climate change and hydrological processes. Therefore, changes in the lake areas before 2010 better reflect their correlation with climate change. From 1989 to 2010, the precipitation and annual mean temperature significantly increased. They are generally considered to be the most important factors affecting the water budget of inland lakes (Liu et al. 2019). The changes in the lake areas are similar to the variations in the precipitation amount but do not correlate with changes in the annual mean temperature.

Response of the lake water volume to evaporation and precipitation changes

According to the changes in the areas of the four lakes, Zhuonai, Kusai, and Heidinor lakes were relatively stable in 1990 and their areas insignificantly changed, whereas Salt Lake was relatively stable in 1991. Therefore, 1990 was selected as the base year for Zhuonai, Kusai, and Heidinor lakes and 1991 was the base year for Salt Lake to calculate the changes in lake water volumes due to precipitation and evaporation until 2010. The results are shown in Figure 12 and Table 6 (the time range for lakes Zhuonai, Kusai, and Heidinor is 1990–2010 and that of Salt Lake is 1991–2010). Table 6 shows that the water volumes of lakes Zhuonai, Kusai, and Salt increased due to rainfall and that of Heidinor Lake decreased. The lake water volumes of all four lakes decreased due to evaporation. Both the increase in precipitation and decrease in evaporation promote the expansions of the lakes, but the decrease in evaporation is the main control factor.

Table 5 | Variations in the areas of the four lakes and meteorological data of the past 30 years

| Lake/year | 1989–1995 | 1995–2010 | 1995–2011 | 2010–2018 | 2011–2018 | 1989–2018 |
|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| Zhuonai   | −2.70     | 3.92      | −         | −2.40     | −         | −1.89     |
| Kusai     | −2.10     | −         | 4.73      | −         | −0.62     | 5.10      |
| Heidinor  | −2.70     | −         | 5.00      | −         | −0.62     | 5.10      |
| Salt      | −2.70     | −         | 4.64      | −         | 3.34      | 5.92      |
| Total area| −3.00     | −         | 5.07      | −         | 3.34      | 5.67      |
| Annual precipitation | −0.60     | −         | 1.94      | −         | 0.37      | 2.93      |
| Annual mean temperature | 0.30      | −         | 3.01      | −         | 1.61      | 4.89      |
| Sunshine duration | −0.30     | −         | −2.35     | −         | −1.11     | −2.71     |
| Wind speed | −1.20     | −         | −0.12     | −         | 1.24      | −2.09     |
Although this study provides monitoring data with high temporal resolution for four lakes in the basin and indicates that the recent lake dynamics may be mainly driven by lake evaporation, it has a few limitations. First, extracting the surface area of lakes from satellite remote sensing data might lead to misestimates (Sun et al. 2012). Second, we only quantified the contributions of evaporation and precipitation to lake expansion. However, to accurately estimate the effect of different factors on lakes, additional parameters must be considered (Zhu et al. 2010), including precipitation, evaporation, runoff, other sub-basins, groundwater, and the ice mass loss of glaciers. Thus, detailed research on the interactions between these factors and lakes will be conducted in the future.

**CONCLUSIONS**

The areas of the four lakes have significantly changed due to climate change. In 2011, Zhuonai Lake burst, and its area continues to shrink. The areas of Kusai and Heidinor lakes increased gradually, whereas the area of Salt Lake sharply increased. Climate change has caused dramatic changes in the areas of the four lakes and affected the hydrological conditions of the lakes, resulting in their integration. Because the water level of Salt Lake continuously rises, the

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**Table 6** Cumulative changes in the lake water volume due to precipitation and lake evaporation

|           | Zhuonai Lake | Kusai Lake | Heidinor Lake | Salt Lake |
|-----------|--------------|------------|---------------|-----------|
| Precipitation (m³) | 592.64       | 190.86     | −25.66        | 67.14     |
| Evaporation (m³)   | −638.92      | −113.72    | 603.68        | 27.98     |

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*Figure 12* Changes in the lake water volume due to precipitation and lake evaporation.
lake water may overflow, posing great threats to the Qinghai–Tibet Highway and Qinghai–Tibet Railway. Both the increase in precipitation and decrease in lake evaporation promote the expansion of lakes, but the decrease in lake evaporation is the main control factor. Changes in the precipitation and lake evaporation directly affect the lake water volume. The effect of the air temperature on the water balances of the lakes is mainly related to evaporation and glacier processes. The wind speed and sunshine duration mainly affect lake evaporation, but have no direct impact on lake expansion. In this study, the effects of glacier melt and permafrost thawing were not considered; however, they might have significant effects on lake expansion.

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DATA AVAILABILITY STATEMENT

All relevant data are available from United States Geological Survey (USGS, https://earthexplorer.usgs.gov/); China Meteorological Data Service Center (http://data.cma.cn/).

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