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The Spatiotemporal Change of Xiao Qaidam Lake from 1990 to 2020 and Its Potential Hazards

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Abstract: In the climatic context of warming and humidification in Northwest China, most lakes in Qinghai Province experienced a rising water level and expanding area, inundating grassland and infrastructure around lakes, and even extreme events such as lake outburst floods. Based on Landsat TM/ETM+/OLI and GF PMS images, lake water level data, SRTM digital elevation model (DEM), GlobeLand30 and meteorological data used in this study, we analyzed the area change of Xiao Qaidam Lake in Qaidam Basin with its causes, factors and potential hazards. The results show that the area of Xiao Qaidam Lake increased by 60.42 km² (85.43%) from 1990 to 2020, which can be roughly divided into three stages: fluctuation decline in 1990–2001 (−1.89 km²/a); relatively stable in 2002–2014; and rapid expansion in 2015–2020 (8.54 km²/a). In 2020, the water level and water volume of Xiao Qaidam Lake increased by 3.62 m and 0.39 km³, respectively, compared with 2015, resulting in the inundation of an area of 54.55 km² of grassland around the lake and a direct threat to the Liuge and Dexiao Expressways. Both the increase in annual precipitation (12.63 mm/10a) and the decrease in potential evapotranspiration (−13.38 mm/10a) since 1990 are the main reasons for the rapid expansion of Xiao Qaidam Lake, and the increasing trend of climate warming and humidification will lead to the continuous expansion of Xiao Qaidam Lake in the next decades. According to the water volume growth rate from 2015 to 2020, it is predicted that by 2024 the area and water level of Xiao Qaidam Lake will reach 154 km² and 3180 m, respectively, and part of Liuge and Dexiao Expressways will be submerged. Therefore, it is urgent to strengthen the monitoring of Xiao Qaidam Lake and formulate corresponding disaster prevention and reduction measures.

Keywords: Xiao Qaidam Lake; spatiotemporal variation; potential hazards; Qaidam Basin; Qinghai Province



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1. Introduction

As an integral part of the terrestrial hydrosphere, lakes are not only an important link in the process of surface water convergence and evaporation, but also an indicator and regulator of climate change [1,2]. The changes in lake area and water level can objectively reflect the water balance process in the basin and have an important impact on the regional ecological environment and socio-economic development [3,4]. The Qinghai–Tibet Plateau lakes are less disturbed by human activities, which can objectively reflect the interaction mechanism between the natural environment and lake evolution [5]. Since the 1960s, the temperature and precipitation on the Qinghai–Tibet Plateau have shown a relatively significant upward (increasing) trend, with the change rates of 0.36 °C/10a (hereafter, /10a refers to per 10 years) and 10.4 mm/10a, respectively [6], and this trend will continue in the future [7,8]. Research shows that most glaciers on the Qinghai–Tibet Plateau have retreated and thinned [9–11] and permafrost has degraded [12] due to climate warming. At the same time, the number, water level and size of lakes have shown a significant increasing trend [13–15]. The rapid rise of lake water level and the continuous increase in water

reserves in the Qinghai–Tibet Plateau not only change its own characteristics (such as lake shoreline outline [16], lake salinity [17], etc.), but also may lead to the reconstruction of river system in the basin [18,19] and even cause natural disasters such as lake outburst flood (or debris flow) [20–22]. The expansion or even collapse of some lakes will inundate large areas of grassland and traffic trunk lines, seriously affecting the surrounding environment and traffic and further affecting the production and life of local residents [23,24]. Therefore, the response mechanism of lakes on the Qinghai–Tibet Plateau to climate change and its impact on the natural and social environment have attracted much attention.

The Qaidam Basin is one of the four major basins in China and located in the northeast of Qinghai–Tibet Plateau and the northwest of Qinghai Province. It is a huge closed intermountain faulted basin, including 47 lakes with an area of $\geq 1 \text{ km}^2$ and with a total area of 2058.6 km^2 , and mostly distributed in the west and north of the basin [25]. In the last half century, the Qaidam Basin has shown a trend of rising temperature, increasing precipitation, and significantly weakened evaporation capacity [26,27]. The average change rate of lake area in the basin is as high as 70.9%, ranking first in the Qinghai–Tibet Plateau [25]. The continuous expansion of the lake water area is bound to change the characteristics of the underlying surface around the lake, and even cause local microclimatic changes. At present, the research on lakes in Qaidam Basin mainly focuses on the production of lake data sets or lake changes [28–31], while the research on the potential impact of lake change is relatively limited. Xiao Qaidam Lake is located in north-central Qaidam Basin, and there are several traffic trunk lines passing around the lake including Delingha–Xiao Qaidam Expressway (also known as Dexiao Expressway, S20), and Liuyuan–Golmud Expressway (also known as Liuge Expressway, G3011) passing along the south and west sides of the lake, respectively. The continuous expansion of Xiao Qaidam Lake has posed a direct threat to both Dexiao Expressway and Liuge Expressway, affecting the production and life of local residents. At present, the research on Xiao Qaidam Lake mainly focuses on the study of its chemical composition [32], surface sediments [33] and the development of mineral resources [27] but does not pay attention to the impact of the expansion of Xiao Qaidam Lake on G3011 and S20. Therefore, long-term monitoring of Xiao Qaidam Lake is very important for disaster prevention.

In this study, we used NDWI and Triangular threshold methods to define the lake boundary of Xiao Qaidam Lake over the last 30 years based on Landsat TM/ETM+/OLI and GF-1/6 PMS remote sensing images. Then we analyzed the spatial-temporal change characteristics and causal factors of Xiao Qaidam Lake combined with the lake water level data and meteorological observation data. Finally, the potential impact of the evolution of Xiao Qaidam Lake was evaluated by combining with digital elevation model (SRTM DEM) and land use data (GlobeLand30). The above work is intended to provide a scientific basis for understanding lake change patterns and lake flood prevention in Qaidam Basin.

2. Research Area

Xiao Qaidam Lake ($37^{\circ}26'–37^{\circ}31' \text{ N}$, $95^{\circ}25'–95^{\circ}35' \text{ E}$) is located in the north-central Qaidam Basin, belonging to the Da Qaidam administrative region of Haixi Mongolian and Tibetan Autonomous Prefecture in Qinghai Province, and about 55 km away from its administrative center, Da Qaidam Town (Figure 1). Xiao Qaidam Lake region has typical arid desert and extremely arid climate characteristics. The average annual temperature is 1.10°C , the annual temperature range is as high as 30°C , and the annual precipitation is about 82.8 mm which is mainly concentrated in May to September, and the evaporation is much higher than the precipitation. Xiao Qaidam Lake is mainly recharged by Tataleng River, spring ice, snow melt water and groundwater with about 6154 km^2 catchment area. In 2020, the lake water area was about 130 km^2 , and the lake surface elevation was about 3178 m. According to the Records of Chinese Lakes [1], Xiao Qaidam Lake is a sodium sulfate subtype lake with high content of B^{2+} and Li^{+} , the pH value of 7.80 and the mineralization degree of 339.07 g/L. On the north side of the lake are Lvliang Mountain and Daken Daban Mountain, and the Tataleng River runs through them and flows into

Xiao Qaidam Lake. On the south side of the lake is Xitie Mountain, which constitutes the natural barrier of Xiao Qaidam Lake. There are several traffic trunk lines passing around the lake, among which Dexiao Expressway and Liuge Expressway pass along the south and west sides of the lake, respectively, and provincial highway S314 and Dunhuang–Golmud Railway line pass through the northeast of the lake region.

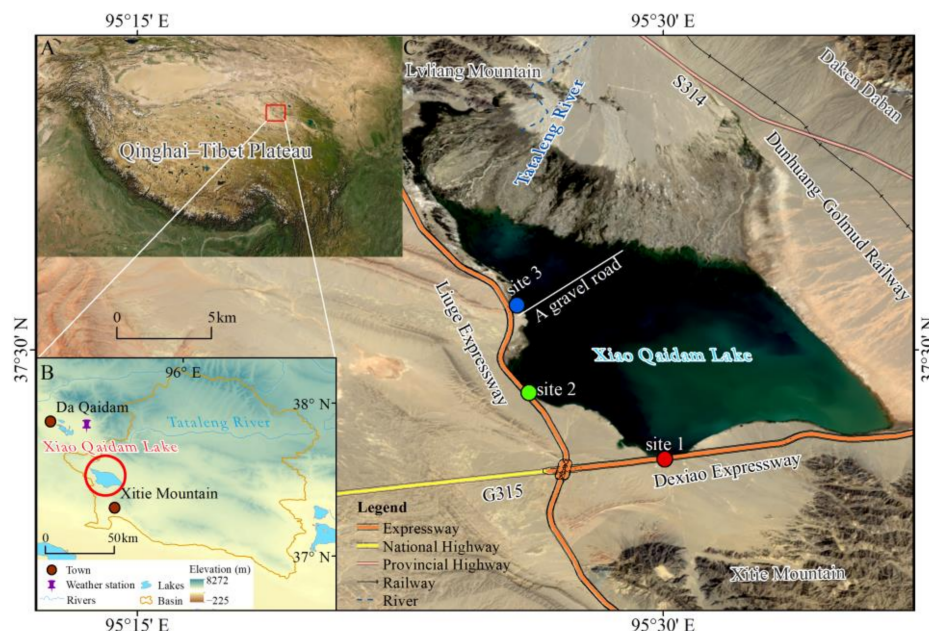


Figure 1. Overview of study area ((A): Location of Xiao Qaidam Lake in the Qinghai–Tibet Plateau. (B): Location of Xiao Qaidam Lake in the Tataleng River Basin. (C): A scene of Landsat OLI image showing the surroundings of Xiao Qaidam Lake, acquired on 15 September 2020, in which sites 1, 2 and 3 are the field investigation sites.).

3. Materials and Methods

3.1. Data

To obtain information on changes in the water area of Xiao Qaidam Lake from 1990 to 2020, a total of 324 scenes of Landsat TM/ETM+/OLI images were downloaded from the website of the United States Geological Survey (USGS, <https://earthexplorer.usgs.gov>, accessed on 20 January 2021) (Figure 2). Monthly images with cloud cover less than 5% were selected, and images close to the water level data date of Xiao Qaidam Lake were supplemented. Among them, there are 178 scenes of Landsat TM images (1990–2011) with a spatial resolution of 30 m, 84 scenes of Landsat ETM+ images (2001–2020), and 62 scenes of Landsat OLI images (2013–2020). The bad band of Landsat ETM+ images after 2003 was fixed in the ENVI 5.3 software with Landsat_gapfill plug-in component. The spatial resolution is 15 m of Landsat ETM+/OLI images after fusing the visible band and the panchromatic band. At the same time, we downloaded 13 GF-1/6 PMS images from 2013 to 2020 from the website of China National Space Administration’s Earth Observation and Data Center (<https://www.cheosgrid.org.cn>, accessed on 20 March 2021); the spatial resolution of the images after fusion processing is 2 m, and they were used for the verification of lake interpretation results of Landsat TM/ETM+/OLI images and the extraction of road information around the lake.

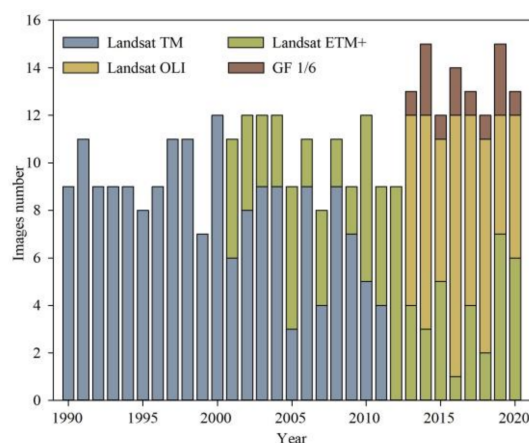


Figure 2. Quantity statistics of Landsat TM/ETM+/OLI and GF-1/6 PMS images.

Due to the lack of long-time series of measured data of the lake water level, we extracted the water level data of Xiao Qaidam Lake from Lake-level over the Tibetan Plateau using multi-sensor satellite altimetry data (2010–2020) [34]. The data set is based on CryoSat-2 L1B Baseline D data product, which is retrained and obtained with an accuracy of a centimeter [35–37], and the time range is from December 2010 to July 2020. The data set can be obtained from the website of the National Tibetan Plateau Data Center (<https://data.tpdc.ac.cn/zh-hans/>, accessed on 5 January 2022). We downloaded observation data including temperature, precipitation, relative humidity, wind speed, daily sunshine hours and air pressure of Da Qaidam meteorological station from the China Meteorological Data Network (<http://data.cma.cn/>, accessed on 5 June 2021) from 1990 to 2020 to study meteorological changes in Xiao Qaidam Lake region. In addition, SRTM DEM V3.0 and GlobeLand30 products were used to analyze the terrain and the ground features around Xiao Qaidam Lake, both of which have a spatial resolution of 30 m and were downloaded from the USGS website and the Global Land Cover Data website (<http://www.globallandcover.com>, accessed on 10 February 2021), respectively. The former reflects the elevation information of Xiao Qaidam Lake and its surroundings in 2000, and the latter includes three phases of surface coverage data around the lake in 2000, 2010 and 2020.

3.2. Methods

3.2.1. Extraction of Lake Water Area

There are many automatic or semi-automatic water extraction methods applicable to optical remote sensing images, most of which are based on the characteristics of low absorption of water in blue–green light bands and high absorption in other bands, especially in the infrared band, such as the normalized difference water index (NDWI) [38], the modified normalized difference water index (MNDWI) [39], the enhanced water index (EWI) [40], the new water index (NWI) [41], and the automated water extraction index (AWEI) [42]. Among them, NDWI is a normalized ratio index based on green band and near-infrared band, which can effectively suppress non-water information such as soil and vegetation while enhancing water information and has been successfully used to extract all kinds of water body data [38]. In this study, NDWI was used to extract the lake boundary, and its calculation formula is as follows:

$$NDWI = (R_{Green} - R_{NIR}) / (R_{Green} + R_{NIR}), \quad (1)$$

where R_{Green} is the reflectance of green band, corresponding to band 2 in Landsat TM/ETM+ imagery and band 3 in Landsat OLI imagery, and R_{NIR} represents that of near-infrared band, corresponding to band 4 in Landsat TM/ETM+ imagery and band 5 in Landsat OLI imagery.

The result of NDWI calculation is a float value, and determining the optimal threshold is the key to obtaining an accurate water area. In this study, the automatic threshold determination method of triangle algorithm was adopted. To verify the accuracy of the automatic extraction method, we selected three scenes of remote sensing images covering Xiao Qaidam Lake, which were Landsat TM image acquired on 12 August 1990, Landsat ETM+ image acquired on 4 July 2002, and Landsat OLI image acquired on 28 August 2019. We extracted the area of Xiao Qaidam Lake in these three images by visual interpretation method (V) and automatic extraction method (T), respectively (Figure 3). The results show that the area error of the automatic extraction results in 1990, 2002 and 2019 were -2.46% , 1.07% and 0.56% compared with the visual interpretation results, respectively, all within 2.5% .

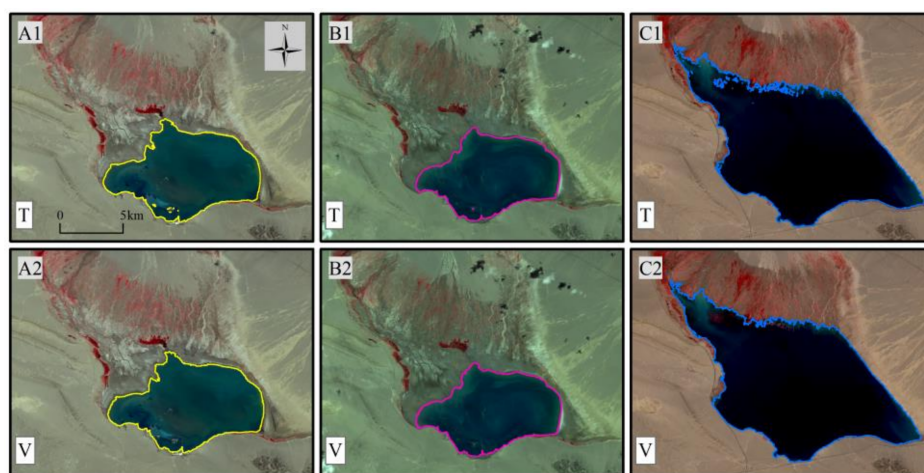


Figure 3. Comparisons on water boundary of Xiao Qaidam Lake based on NDWI method with automatic threshold (T) and visual interpretation (V) (The backgrounds are Landsat TM image acquired on 12 August 1990 (A1,A2), Landsat ETM+ image acquired on 4 July 2002 (B1,B2), and Landsat OLI image acquired on 28 August 2019 (C1,C2), respectively).

Furthermore, to verify the accuracy of area extraction, we selected 13 GF-1/6 PMS images with spatial resolution of 2 m from 2013 to 2020 and Landsat images with spatial resolution of 15 m on similar dates. Based on GF-1/6 PMS images, the water area was extracted by visual interpretation method, and the water area of Landsat images was extracted by automatic extraction method. The result shows that the maximum error of area is 3.29% , the minimum is 0.03% , and most of them are less than 2% (Table 1). In conclusion, the triangle automatic threshold method based on NDWI is suitable for extracting the area of Xiao Qaidam Lake.

Table 1. Comparison of the area of Xiao Qaidam Lake based on GF-1/6 PMS images and Landsat images on similar dates.

Image Type	Date	Area/km ²	Image Type	Date	Area/km ²	Area Error (%)
GF1	2013/10/29(29 October 2013)	93.83	LC8	14 October 2013	92.18	1.79
GF1	4 March 2014	92.2	LC8	23 March 2014	91.46	0.81
GF1	25 September 2014	87.31	LE7	7 September 2014	85.55	2.06
GF1	5 November 2014	85.07	LC8	2 November 2014	84.00	1.27
GF1	29 September 2015	88.81	LC8	18 September 2015	88.43	0.43
GF1	30 January 2016	86.26	LC8	24 January 2016	86.36	-0.12
GF1	11 March 2016	86.36	LC8	28 March 2016	83.61	3.29
GF1	27 December 2017	105.03	LC8	12 December 2017	105.00	0.03
GF1	4 January 2018	105.45	LC8	13 January 2018	104.16	1.24
GF1	10 February 2019	125.05	LE7	25 February 2019	124.88	0.14
GF6	12 October 2019	132.47	LE7	7 October 2019	130.72	1.34
GF6	26 November 2019	132.06	LE7	24 November 2019	130.63	1.09
GF6	19 October 2020	128.5	LC8	17 October 2020	128.37	0.10

3.2.2. Calculation of Lake Water Volume Change and Simulation of Inundation Range

The change in lake water volume is the comprehensive embodiment of its water level and area change [43–45]. Compared with lake area, lake water level is traditionally obtained by manual recording of water gauge or automatic water level gauge. With the rapid development of satellite altimetry technology, a variety of lake water volume change calculation methods were proposed based on lake water level and lake area data [19,44,46]. This paper adopts the lake water volume change calculation method proposed by Yao et al. [19]:

$$\Delta V = (S_i \times H_j - H_i) + (S_j - S_i) \times (H_j - H_{DEM}) / 1000, \quad (2)$$

where ΔV is the change in lake water volume (km^3); S_i and S_j are the lake area at time i and j , respectively (km^2); H_i and H_j are the lake water levels at times i and j , respectively (m); and H_{DEM} is the surface elevation not submerged at time i (m).

When the water volume of the lake changes to a positive balance, the inundation range of the lake in the future can be simulated based on the digital elevation model (DEM) data of the lake area [19]. Essentially, this method solves H_j according to Formula (2), extracts the range below the contour line corresponding to DEM according to H_j , and eliminates the pixels that are not connected with the lake. The result is the range of lake water area when the water level elevation is H_j . Referring to the area and water level of Xiao Qaidam Lake in 2020, we utilized the contour tool in the 3D analysis tools module in ArcGIS software (version 10.6, founded by ERSI, a company headquartered in Redlands, California, USA) to calculate the corresponding relationship between elevation value and area in the step of 1 m, simulate the inundation range of Xiao Qaidam Lake at different altitudes and correct the lake range by eliminating the unconnected area in consideration of the connectivity of lake expansion [23]. Finally, the water reserve increment of Xiao Qaidam Lake at different altitudes can be obtained by using Formula (2). By calculating the change rate of water volume and the change in the simulation results at different altitudes relative to the lake water storage in 2020, we can obtain the time required for Xiao Qaidam Lake to reach different simulation ranges, and then conduct risk assessment on the surrounding grassland, roads, power poles and other infrastructures.

3.2.3. Potential Evapotranspiration Calculation

Xiao Qaidam Lake is a closed endorheic lake, and evaporation is the principal way to consume its water. In order to calculate the water loss of Xiao Qaidam Lake, the modified Penman–Monteith (PM) equation [47] recommended by the Food and Agriculture Organization of the United Nations (FAO) is used to calculate the potential evapotranspiration of the lake, which has been used to obtain the evaporation of lakes [48–50]. The calculation formula is as follows:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1+0.34u_2)}, \quad (3)$$

where ET_0 is the potential evapotranspiration (mm); Δ is the slope of saturated water vapor pressure curve at a certain temperature ($\text{kPa}/^\circ\text{C}$); R_n is the net radiation of the reference crop surface [$\text{MJ}/(\text{m}^2 \cdot \text{d})$]; G is soil heat flux [$\text{MJ}/(\text{m}^2 \cdot \text{d})$]; γ is the constant of dry and wet meter, taking $0.067 \text{ kPa}/^\circ\text{C}$; T is the daily average temperature ($^\circ\text{C}$), taking the arithmetic mean of the daily maximum temperature and the daily minimum temperature; u_2 is the wind speed at a height of 2 m above the ground (m/s); e_s is the average saturated water vapor pressure (kPa); e_a is the actual vapor pressure; $e_s - e_a$ is the differential pressure of saturated water vapor (kPa).

We used the ET_0 calculator provided by FAO (<https://www.fao.org/land-water/databases-and-software/eto-calculator/en/>, accessed on 25 June 2021) to calculate the potential evapotranspiration. The input data include daily sunshine hours, average temperature, maximum temperature, minimum temperature, average wind speed, average

air pressure, relative humidity, and finally the daily potential evapotranspiration value was obtained.

3.2.4. Assumptions and Limitations

Many studies show that the average temperature and precipitation on the Qinghai–Tibet Plateau will increase in the future based on CMIP6 [51–53]. According to the research of Zhang et al. [53], the precipitation of Qaidam Basin from 2031 to 2050 under various scenarios of GCM model shows an increasing trend, of which the SSP370 scenario is the most sensitive to the precipitation change and the precipitation increase can reach 30% compared with the base period. Therefore, we assume that the water volume of Xiao Qaidam Lake will be in a positive balance in the future. In addition, due to the lack of data including lake surface precipitation, evaporation and runoff into the lake, it is impossible to quantify the contribution of precipitation, evaporation and melting water of glacier and frozen soil to lake expansion. Meanwhile, it is difficult to accurately predict the future meteorological conditions of Xiao Qaidam Lake because the area of Xiao Qaidam Lake is much smaller than the spatial resolution of GCM model. Finally, the simulation results of this study are under ideal conditions; that is, without the intervention of the government (filling high subgrade, drainage, etc.), and the results may deviate from the actual situation.

4. Results

4.1. Spatiotemporal Variation Characteristics of Xiao Qaidam Lake

According to the monthly area of Xiao Qaidam Lake from 1990 to 2020 (Figure S1), its annual changes were not consistent. In most years, it was relatively stable from January to March, decreased slightly from April to June, increased rapidly in July or August, and reached the peak area in August or September of the year, and then decreased slightly and remained stable. In particular, the area of Xiao Qaidam Lake remained stable in 2020 without obvious fluctuations.

From 1990 to 2020, Xiao Qaidam Lake showed an overall expansion trend (Figure 4A). According to the maximum water area of each year, the evolution of Xiao Qaidam Lake can be roughly divided into the following three stages: (1) Fluctuant decline period (1990–2001), the change rate of lake area was $-1.89 \text{ km}^2/\text{a}$ (hereafter, /a refers to per year), with an average area of 59.65 km^2 , the area of lake in 1995 was the smallest (42.48 km^2) and decreased by 25.25 km^2 (-40%) than that in 1990, which was also the smallest area in the last 30 years. Although the lake area rebounded in 1996, it remained at a low level from 1996 to 2001 (with an average area of 56.26 km^2). (2) Relatively stable period (2002–2014), the lake area first decreased then increased, and finally remained the same as that in 2002, with an average area of 87.03 km^2 , and an increase of 30.78 km^2 compared with 1990–2001. (3) Rapid expansion period (2015–2020), the change rate of the lake area was $8.54 \text{ km}^2/\text{a}$, and the area reached the maximum value (131.15 km^2) in 2020, which is 1.85 times the lake area in 1990.

The shoreline of Xiao Qaidam Lake has changed significantly in the past 30 years (Figure 4B): the northwest and southeast sides of the lake have expanded significantly, and the length of lake shoreline has increased from 41.45 km to 100 km. Specifically, from 1990 to 2000, the north and east sides of the lake shrank significantly, by about 1.7 km and 1.1 km, respectively, in 1995 compared with 1990. After 2000, Xiao Qaidam Lake continued to expand to the northwest and southeast, and the lake shoreline changed most significantly from 2015 to 2020, with the increased outward expansion distance in these two directions of about 8.5 km and 2.2 km, respectively. According to the Globeland30 data, the expansion of Xiao Qaidam Lake from 2000 to 2010 resulted in the inundation of grassland and wetland around the lake, with an area of 10.72 km^2 and 15.2 km^2 , respectively. From 2010 to 2020, with the rapid expansion of Xiao Qaidam Lake, the submerged grassland area reached 54.55 km^2 and the submerged wetland area was 5.52 km^2 . It is worth noting that although the expansion distance between the west side and the south side of Xiao Qaidam Lake is

relatively small, it is gradually approaching Liuge and Dexiao Expressways, which may pose a potential threat to the safety of these two expressways.

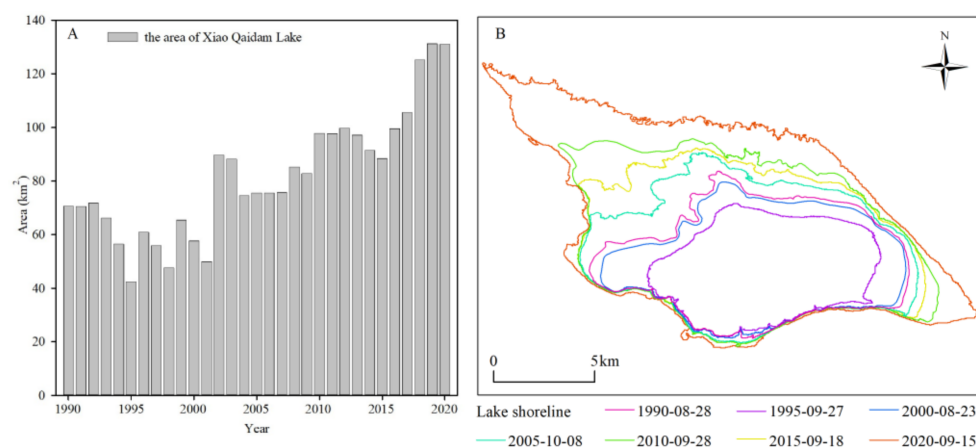


Figure 4. The maximum area of each year from 1990–2020 (A) and changes in shoreline of Xiao Qaidam Lake (B).

4.2. Changes in Water Level and Volume of Xiao Qaidam Lake

A fitting relationship between lake area and water level on similar dates shows that the water level change trend of Xiao Qaidam Lake from 2010 to 2020 is obviously consistent with its area change, with the correlation coefficient R^2 of 0.993 at the 0.01 confidence level test (Figure 5A). The water level change of Xiao Qaidam Lake is roughly bounded by 2015; from 2010 to 2015 the water level of the lake decreased and reached the lowest value in the last 10 years in 2015 (3174 m). After that, the water level of the lake increased year by year and hit the peak in 2020 (3177.62 m), 2.71 m and 3.62 m higher than that in 2010 and 2015, respectively. Accordingly, the water volume of Xiao Qaidam Lake was at a loss from 2010 to 2015, with a decrease of about 0.08 km³. After 2015, the water volume of Xiao Qaidam Lake increased continuously, with a change rate of 0.08 km³/a, of which the water volume increased the most in 2019, with an increment of 0.22 km³ (Figure 5B). Compared with 2010, the water volume of Xiao Qaidam Lake increased by 0.31 km³ by 2020.

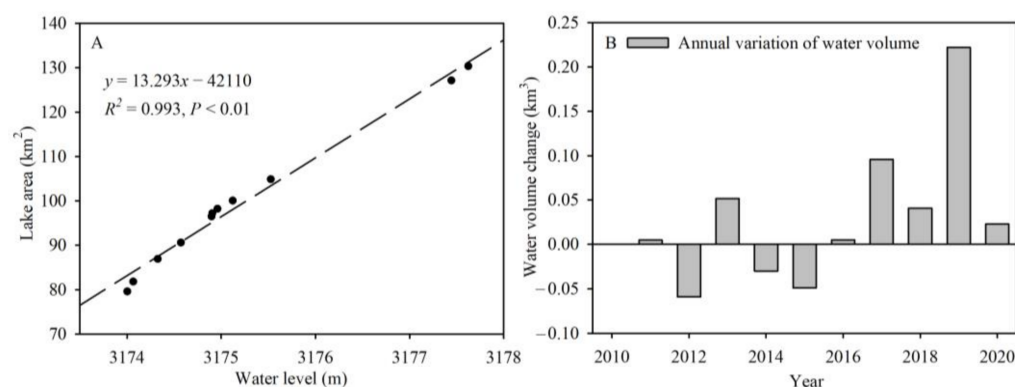


Figure 5. Correlation between water level and area (A) and interannual variations in the water storage (B) of Xiao Qaidam Lake from 2010 to 2020.

4.3. Simulation of the Future Evolution of Xiao Qaidam Lake

Simulations of many climate models show that the warm and humid trend in North-west China may continue for a long time [54,55]. To explore the future evolution scenario of Xiao Qaidam Lake, a simulation of future water level rise was performed based on the 3178 m shoreline elevation of Xiao Qaidam Lake in 2020. The inundation simulations were performed based on the DEM data of Xiao Qaidam Lake basin, and the area corresponding to each elevation value was calculated by combining the same elevation values. According

to the lake area and water level of Xiao Qaidam Lake, the change in water reserves can be estimated by Formula (2) (Figure 6A), and the time to reach different water levels of Xiao Qaidam Lake can be obtained by combining the water volume growth rate ($0.08 \text{ km}^3/\text{a}$) from 2015 to 2020. The simulation results (Figure 6B) show that when the water volume of Xiao Qaidam Lake increases by 0.29 km^3 , the water level of the lake will rise to 3180 m (2024), and the corresponding lake area will increase to 156.5 km^2 . The lake shoreline will mainly expand to the northwest and southeast, with distances of about 1.95 km and 1.1 km, respectively. It is estimated that by 2033, the water level of Xiao Qaidam Lake will rise to 3184 m, and the lake area will be 202.56 km^2 . When the water level of Xiao Qaidam Lake rises to 3187 m, the lake area is 231.5 km^2 , and the lake shoreline expands to the northwest and southeast by 3.9 km and 3.26 km, respectively. By about 2041, the lake water will overflow from the southeast corner of the lake area, and the lake will change from a closed flow lake to an outflow lake.

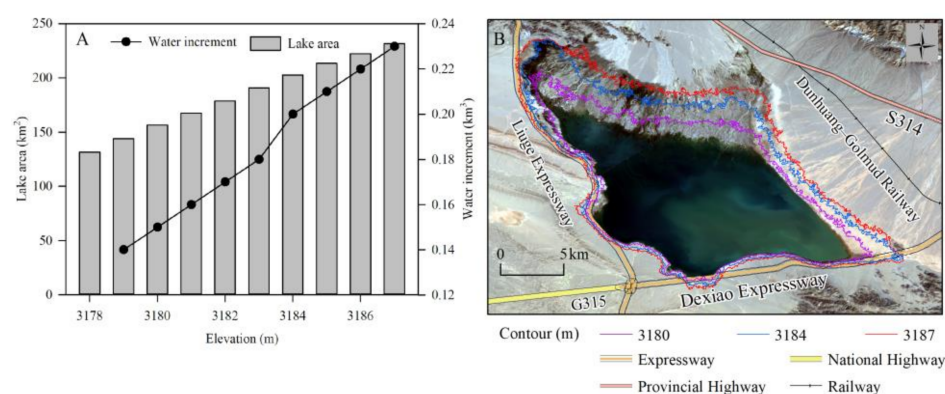


Figure 6. Simulation of area variation corresponding to water volume change (A) and inundation region (B) of Xiao Qaidam Lake (The base image of subfigure B is Landsat OLI image acquired on 15 September 2020).

5. Discussions

5.1. The Causes of Changes in Xiao Qaidam Lake

As a closed endorheic lake in the inland area, Xiao Qaidam Lake is little affected by human activities; its water balance depends on the changes in atmospheric precipitation, surface runoff and evaporation on the lake surface. According to the monthly precipitation and evaporation of Da Qaidam meteorological station from 1990 to 2020, the precipitation mostly occurs from May to September, and the evaporation is approximately normal distribution. The monthly area changes of Xiao Qaidam Lake lag behind the precipitation change, but the sudden increase in area is generally related to the large increase in precipitation, such as August 1991, July 1992, August 2002, August 2008 and July 2015, most of which had a monthly precipitation of more than 60 mm. The intra-annual decreasing trend in lake area then corresponds to relatively low monthly precipitation, which maxes out at about 20 mm. However, it is difficult to fully explain the cause of the annual area change of Xiao Qaidam Lake only from precipitation and evaporation, which may be related to the large catchment area of the lake, the supply of glacial melt water during the melting period, and the release of frozen soil water. From November to March in most years, as the temperature drops to freezing point the lake surface freezes, and the area is in a stable state.

Based on the observation data from 1990 to 2020, the trend rate of each meteorological element combined with the Mann–Kendall test shows the annual precipitation in the region where Xiao Qaidam Lake is located had an increasing trend ($z = 1.73$, $p < 0.05$) in the past 30 years with a change rate of $12.63 \text{ mm}/10\text{a}$. The potential evapotranspiration experienced a decreasing trend ($z = -1.7$, $p < 0.05$) with a change rate of $-13.38 \text{ mm}/10\text{a}$. Precipitation and evaporation are the key input and output components of Xiao Qaidam Lake, and their rise and fall together lead to the increase of the lake scale. There is an obvious corresponding relationship between the area of Xiao Qaidam Lake and the annual

precipitation. For example, the annual precipitation in 1995 was only 44.8 mm, the least precipitation in recent 30 years, which made the smallest area of Xiao Qaidam Lake in that year. On the contrary, the area of Xiao Qaidam Lake increased significantly in the years with more precipitation (such as 1992, 2002 and 2017). Pearson correlation analysis further shows that the area of Xiao Qaidam Lake is positively correlated with annual precipitation, but negatively correlated with evaporation, and the correlation coefficients are 0.377 ($p < 0.05$) and -0.588 ($p < 0.01$), respectively.

In addition to atmospheric precipitation, Xiao Qaidam Lake is mainly recharged by the runoff of Tataleng river. Xiao Qaidam Lake is in seasonal frozen soil zone [56], and the Tataleng River originates from the Turgan Daban Mountains where modern glaciers developed [57] and flows through the sheet frozen soil zone [56]. In the past 30 years, the annual average temperature around Xiao Qaidam Lake has shown a significant upward trend ($z = 4.32$, $p < 0.01$), with the change rate of $0.57\text{ }^{\circ}\text{C}/10\text{a}$. Affected by climate warming, the glaciers in the Tataleng River Basin retreated significantly. From 1987 to 2016, the glacier area decreased by 379.4 km^2 , with a change rate of $-1.6\%/a$ [57,58]. Previous studies have demonstrated that the melting of ice in frozen soil will release a certain amount of water and participate in the regional water cycle [12]. In some inner flow areas of the Qinghai–Tibet Plateau, runoff from the melting of ice in frozen soil caused by rising temperature may be one of the reasons for the rise of lake water level in the basin, and its contribution rate to lake water volume is about 12% [44]. Pearson correlation analysis shows that the area of Xiao Qaidam Lake was positively correlated with the annual average temperature ($p < 0.01$) with the correlation coefficient of 0.524. To sum up, the increase in precipitation and the decrease in evaporation in the area during the past 30 years are the direct reasons for the expansion of Xiao Qaidam Lake while the rise of temperature plays an indirect role by changing the state of glaciers and permafrost in the basin.

5.2. Potential Hazards and Prevention Measures

The expansion of Xiao Qaidam Lake has caused a large area of grassland and wetlands around the lake to be submerged, and if it continues to expand more grassland on the north side of the lake area will be submerged. For example, when the water level of Xiao Qaidam Lake rises to 3180 m, 3184 m and 3187 m, the submerged grassland area will reach 19.85 km^2 , 52.37 km^2 and 70.08 km^2 , respectively (Figure 6B), which may have a direct impact on the production and life of local residents. What is more noteworthy is that the expansion of Xiao Qaidam Lake has posed a direct threat to Dexiao and Liuge Expressways. On 1 February 2021, through the field investigation of Xiao Qaidam Lake, we found that the south bank of the lake has reached the lower part of the Dexiao Expressway, and the vertical distance from the road is 2.1 m (Figure 7A). The shortest horizontal distance from the west bank of the lake to Liuge expressway is 10.73 m (Figure 7B). The gravel road connecting the east and west banks in the northwest of the lake is closed to vehicles because the road surface is close to the water surface (Figure 7C). Due to the freezing period of Xiao Qaidam Lake during the field investigation, it is expected that the water level of the lake will be higher from May to October, and the lake shore will be closer to the two expressways. According to the simulation results of the future evolution of Xiao Qaidam Lake (Figure 6B), by 2024, when the water level of the lake rises to 3180 m, part of Dexiao Expressway and Liuge Expressway will be submerged, with the submerged length of 3.27 km and 1.82 km, respectively, and the gravel road will be fully flooded.

Although the water level of Xiao Qaidam Lake has not risen to the pavement of Dexiao Expressway and Liuge Expressway for the time being, the lake water is alkaline and therefore highly corrosive, coupled with the wave washing and lake ice freezing and thawing, it is likely to cause the instability or damage of the facility foundation. As shown in Figure 8A, some poles of the transmission line parallel to Liuge Expressway have been seriously tilted, which poses a serious threat to local power and signal transmission. Although the Dexiao Expressway on the south bank of Xiao Qaidam Lake was repaved in 2020, the roadbed in contact with the lake surface has changed (Figure 8B), which may

decline the stability of the pavement, and it is very prone to collapse, subsidence and other hazards. Due to the rapid rise of the water level in Xiao Qaidam Lake in recent years, it is very likely to submerge some sections of Dexiao and Liuge Expressways in a short time, and the two are the transportation trunk lines connecting the east and west of Qinghai Province with the central part of Qinghai Province and the west of Gansu Province. They are also key sections connecting Xinjiang–Gansu–Qinghai–Tibet. Hence it is urgent to strengthen the monitoring of Xiao Qaidam Lake and the assessment of disaster losses and take corresponding prevention and control measures for Dexiao and Liuge Expressways, such as filling the subgrade or changing the road, and at the same time the power facilities around the lake should be protected and reinforced.



Figure 7. Status of expressway and road around Xiao Qaidam Lake (Photos (A–C) are corresponding to site 1/2/3 in Figure 1, respectively).

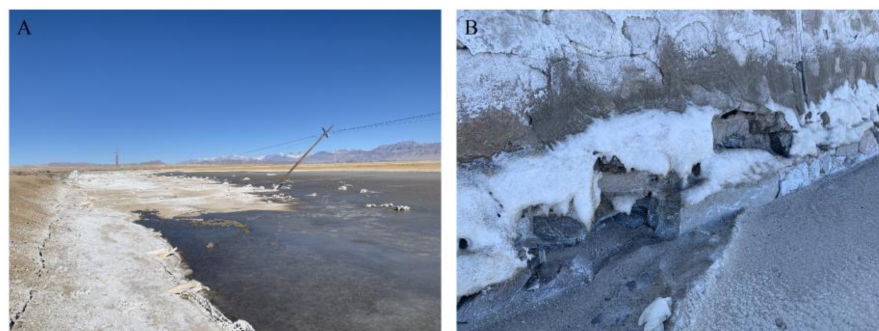


Figure 8. The tilted telegraph pole (A) and the eroded subgrade (B) around Xiao Qaidam Lake.

5.3. Similarities and Differences between Lakes

Studies showed that most lakes in the northwest of the Qinghai–Tibet Plateau have expanded since 2000 [59]. The area of lakes in Hoh Xil region, located in the southwest of Xiao Qaidam Lake, increased rapidly from 1990 to 2011, of which the most obvious increase occurred in 2001–2002 and 2009–2011 [60]. Qinghai Lake, the largest lake on the Qinghai–Tibet Plateau, showed a small decreasing trend from 1986 to 2004; then the water level rose rapidly and the water area continued to expand [16]. Compared with these surrounding lakes, the overall change trend of Xiao Qaidam Lake is consistent; that is, the lake area has generally increased since the beginning of this century. At the same time, due to the differences in the catchment area and the spatial distribution of precipitation and resource endowment of glaciers and frozen soil among these lakes, the temporal variation in lake areas are different. For example, during 2002–2004, the area of Xiao Qaidam Lake continued to increase and then decreased rapidly, while the area of Qinghai Lake continued to decrease.

Similar to the direct threat of Xiao Qaidam Lake to the traffic trunk lines and grasslands around the lake, the evolution of some lakes in this region has caused harm to some critical infrastructure or is rapidly changing the local underlying surface condition and lake ecological environment. For example, in September 2011 the collapse of Zhuonai Lake in Hoh Xil region led to the overflow of lake water from the downstream Kusai Lake and Haidingnuoer Lake [20], causing the sudden increase in the area of Yanhu Lake after 2013 and posing a potential threat to infrastructures in cold regions such as the Qinghai–Tibet

Highway and Qinghai–Tibet Railway [19]. To this end, in 2019, the Department of Water Resources of Qinghai Province completed Yanhu Lake drainage and dredging emergency project, excavated a drainage channel with a width of about 50 m in the southeast of the lake area, and injected it into the Chumar River through the Qingshui River. It fundamentally eliminates the risk of natural overflow from Yanhu Lake, which also turned Yanhu Lake from an inward flow lake into an outward flow lake. However, the potential impact on the local frozen soil environment and the volume and quality of Chumar River still needs continuous attention. In recent years, the continuous expansion of the waters of Qinghai Lake has led to the inundation of roads, wharves, grasslands and residential areas in Tiebuka Bay, Quan Bay and Bird Island [16], and the expansion of *Cladophora* bloom [61]. Therefore, remote sensing monitoring and ground observation of rapidly expanding lakes should be continuously enhanced in the future, to screen potentially dangerous lakes, and carry out comprehensive lake risk assessment in combination with climate models.

6. Conclusions

In this study, we systematically analyzed the spatial-temporal variation characteristics, influencing factors, future evolution and potential hazards of Xiao Qaidam Lake from 1990 to 2020 based on Landsat TM/ETM+/OLI images and GF-1/6 PMS images combined with lake water level data, SRTM DEM, GlobeLand30 and meteorological observation data. The main conclusions are as follows:

(1) In the past 30 years, the area of Xiao Qaidam Lake has experienced a change process of “fluctuation decline–relatively stable–rapid expansion”, and on the whole, it shows an expanding trend. Especially after 2015, the expansion rate of the lake has accelerated significantly and the annual change rate is as high as $8.54 \text{ km}^2/\text{a}$. In 2020, the lake area reached a peak (131.15 km^2), which was 1.85 times the lake area in 1990, when the corresponding lake water volume increased by 0.31 km^3 . With the continuous expansion of Xiao Qaidam Lake, its shoreline has changed significantly, presenting a spatial pattern of “fast in the northwest and slow in the southeast”. In the past 30 years it has expanded about 10 km along the northwest and about 3 km along the southeast;

(2) The increase in precipitation and the decrease in evaporation are the direct reasons for the expansion of Xiao Qaidam Lake. It is expected that by 2024, the water level of Xiao Qaidam Lake will rise to 3180 m, and the lake area will reach 154 km^2 , resulting in a large area of grassland around the lake and part of Dexiao and Liuge Expressways being submerged. The expansion of Xiao Qaidam Lake has posed a direct threat to these two expressways and transmission lines in the lake region. It is urgent to strengthen lake water level monitoring and disaster loss assessment, and take scientific measures to ensure the safety of roads and transmission lines;

(3) The change of Xiao Qaidam Lake has a reference significance for the study of lakes in the Qaidam Basin, and more attention should be paid to the expanding lakes similar to Xiao Qaidam Lake near the traffic trunk lines. The relevant departments shall consider the surrounding environment and its possible changes in the future when planning the roads to minimize the losses. It is hoped that in the future, there will be more open meteorological and hydrological data with higher accuracy to make the prediction of lake changes more accurate; this will be conducive to disaster assessment and help to reduce property losses.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su141811372/s1>, Figure S1. Bar plots of monthly area variation of Xiao Qaidam Lake from 1990 to 2020.

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