Analysis of the changes and driving force of the water area in the Ulungur Lake over the past 40 years

Fan Gao, Bing He, Zhenglon Yan, Songsong Xue and Yizhen Li

ABSTRACT

The inland lakes in arid regions, especially the terminal lakes, are highly sensitive to the influence of human activities and climate change. In order to analyze the evolution of the area of water in Ulungur Lake (Buluntuohai Lake, Jili Lake) and the main causes of those changes, 3S technology, satellite data preprocessing, water extraction and database construction methods are combined with consideration of climatic changes and human activity in this study. The data in this study include 11 phases of remote sensing image data, field mapping data and relevant attribute data of the study area from 1977 to 2017. The results demonstrated the following. (1) Over the past 40 years, the change in Ulungur Lake's area was characterized by natural expansion, fluctuation stability, and recovery increase. Significant changes were mainly concentrated in the waters of Zhonghaizi, Xiaohaizi, Camel's Neck, and the waters near Akekule. (2) The period from 1977 to 1995 was the expansion period of the lake water area, and human activities were the main driving factors. The period from 2000–2017 was a smaller period of expansion of the lake water area, with warmer and more humid climate trends combined with human activities driving the change. (3) The water area that was extracted based on the *MNDWI* water index method can increase the contrast between bodies of water and buildings, which can aid in interpreting and extracting water element information from flat terrain and single types of surface features. This can provide an effective technical means for quantitative and dynamic analysis of the temporal and spatial changes in lake water area.

Key words | climate change, human activities, remote sensing monitoring, Ulungur Lake, water area

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HIGHLIGHTS

- The inland lakes in arid regions of China.
- Remote sensing monitoring of lake area.
- Climate change and the impact of human activities.
- Modified normalized difference water index.
- Spatial data processing.

INTRODUCTION

The IPCC (Intergovernmental Panel on Climate Change) Fifth Assessment Report has pointed out that lakes, as a land surface water resource, are an important indicator of the regional responses of global climate change. Lakes are particularly sensitive to climate and environmental changes, and in inland arid areas with little precipitation they can record and superimpose climate change signals and human activities at different time scales (Christopher 2014; Tao *et al.* 2015; Wang *et al.* 2018; Laba *et al.* 2019). Therefore, timely and accurate monitoring of changes in lake water resources has important reference significance for understanding regional (basin-scale) and global climate, as well

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as evolution of environmental systems (Zhu *et al.* 2015). With the development and application of remote sensing (RS) and geographic information technology (GIS, GPS), there is an effective technical means for monitoring the dynamic changes of lake water area in large spatial areas. Recent research has used long-term, multi-temporal, and multi-band remote sensing image data to monitor the dynamic change in water area to make a series of achievements in monitoring, extraction methods, and water quality index inversion (Yin *et al.* 2008; Liu *et al.* 2013; Zhu *et al.* 2015; Wu 2016; Zhao *et al.* 2016; Du *et al.* 2018). Zhao *et al.* (2016) analyzed the changes in water area, water quality index, and the surrounding vegetation of Hongjiannao Lake from 1973 to 2013 based on Landsat MSS, TM, ETM+, and OLI remote sensing images using the normalized vegetation index (*NDVI*). Guirguis *et al.* (1996) used principal component analysis (PCA) to dynamically monitor the water area of Brullus Lake in Egypt from 1983 to 1991 using multi-period pseudo-color synthetic images, and found that the lake area shrank significantly due to reclamation and other reasons. Zhang *et al.* (2011) used ICESat (Ice, Cloud, and Land Elevation Satellite) satellite to study 74 lakes in the Qinghai-Tibet Plateau, and found that the area of saline lakes in the region expanded from 2003 to 2009 with an annual growth rate of about 0.27 km^2.

Ulungur Lake is one of the ten largest fresh water lakes in China, and is a typical inland arid lake. It is also an important natural barrier between the Altai mountain oasis and Gurbantunggut in Western China. Ulungur Lake serves a key function of ecological security (Cheng *et al.* 2016). In recent years, impacts from intense human activities and dramatic changes in climate resulted in a series of ecological and environmental problems in the freshwater ecosystem such as the shrinking of the lake surface, declining water level, deteriorating water quality, and impaired ecological functions (Nuerlan *et al.* 2014; Cheng *et al.* 2016) that have seriously affected and threatened the ecological security of the Ulungur Lake basin. Therefore, it is of both theoretical and practical significance to monitor the temporal and spatial dynamic changes of the area of Ulungur Lake and to analyze the forces driving these changes in order to ensure regional water ecological security and promote rational development, utilization, and protection of water resources. At present, research on the dynamic changes in the water area of Lake Ulungur includes: Wang & Zhang (1991) analyzed the change in the water area of Buluntuohai Lake from 1950 to 1980 based on topographic maps and Landsat remote sensing images and found that the lake area gradually decreased. Dilinuer & Aikebaer (2010) selected Landsat satellite remote sensing images from 1989 and 2002 and found an increasing trend in water area in Buluntuohai Lake. Liu *et al.* (2018) analyzed changes in the water area of Ulungur Lake from 1970 to 2015 and its relationship with climate change through Landsat series remote sensing images. Li *et al.* (2015) studied the change trend and forces driving those changes in water area of Ulungur Lake in spring and summer from 2000 to 2014 using MODIS remote sensing data.

A review of the existing research on the Buluntuohai Lake area of Ulungur Lake shows that the data sources are different, the technology is uneven, timeseries are generally short, and the monitoring periods are different. Moreover, the whole area of Ulungur Lake is not dynamically monitored, so the monitoring and data are not comprehensive and there is a lack of systematic study and overall analysis of the longer timeseries. On the basis of previous studies, 11 phases of Landsat series remote sensing images of Ulungur Lake from 1977 to 2017 were selected for this study to monitor and analyze spatio-temporal variations and the evolutionary trend of the water area. Additionally, the main drivers of the spatio-temporal variations of water area in the study area were discussed by comprehensively utilizing RS, GIS, GPS, and other technologies such as spatial data processing, information extraction and interpretation, massive data database building, and integrated management and analysis (Yan *et al.* 2004; Gao *et al.* 2011). Results from this work could be significant in helping guide the rational development and utilization of water resources in and around Ulungur Lake, the protection of oases and ecological functions around the lake, and provide a decision-making basis for formulating policies that protect lake resources and promote sustainable economic and social development.

MATERIALS AND METHODS

Ulungur Lake (46°51′~47°25′N, 86°59′~87°34′E) is a fault lake between the Irtysh and Ulungur Rivers in Junggar basin, Xinjiang Uygur Autonomous Region. It is also the second largest lake in Xinjiang, located near Fuhai County, Altay area, Xinjiang (Figure 1). Ulungur Lake is a typical semi-closed lake in the inland arid area; and is composed of two smaller connected lakes, Buluntuohai and Jili Lake, which have capacities of $95.47 \times 10^8\,m^3$ and $17.20 \times 10^8\,m^3$ respectively, an average water level of about 479.1 m and an average depth of about 8 m. Buluntuohai and Jili Lakes are connected by the 7 km long Kuyierga River (Xie 2009; Wu *et al.* 2013a, 2013b; Cheng *et al.* 2016). According to meteorological data from Fuhai County, the annual average temperature of the area is 3.4 °C, the annual average precipitation is 121.9 mm, and the annual average evaporation is 1,830 mm. About 132 million m^3 of water enters the lake annually, the main sources of which are the Ulungur and Irtysh Rivers, which basically maintains a hydrodynamic balance (Wu *et al.* 2013a, 2013b). In recent years, both climate change and human activities have caused the lake area to shrink, water level to change, salinity to increase, water pollution to worsen, and the ecosystem services of the lake to weaken, which directly threatens the ecological security of the river basin.

Satellite data acquisition and preprocessing

Satellite data acquisition

Landsat series satellite remote sensing image data were selected as the source for extracting lake area and basic geographic, meteorological, social, and economic data were used for comparative analysis in this study. Among them, the basic geographic data is the 1:100,000 digital line plot (DLG) provided by the Shaanxi surveying and mapping data archive of the State Bureau of Surveying and mapping geographic information, which was used for the overall control, geometric correction, and registration of the map. The remote sensing image data were from the US Geological Survey website (http://www.usgs.gov/). The image phase

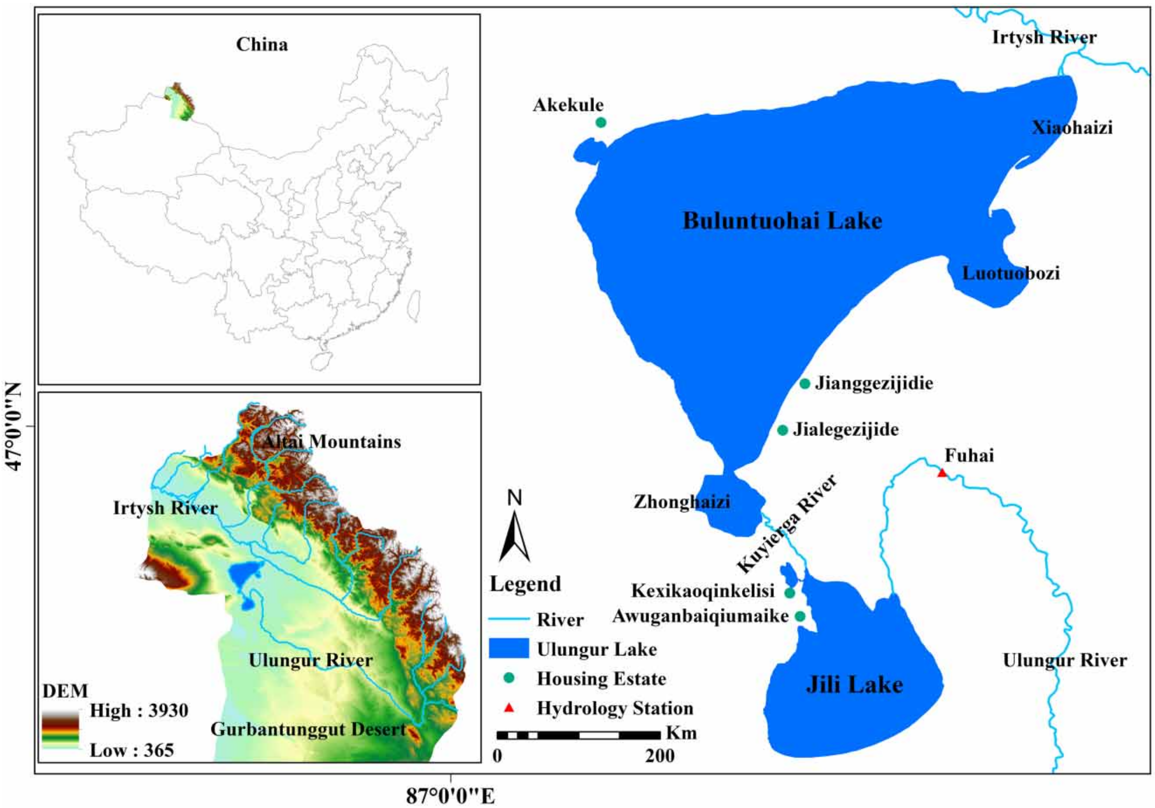

Figure 1 | Geographical location of the study area: Ulungur Lake.

was from August to September, and the cloud amount was less than 10%. As remote sensing data from the 1970s, 1980s and 1990s are very limited from that source, the Landsat 2/MSS remote sensing image from August 16, 1977, the Landsat 4/TM remote sensing image from August 18, 1989, and the Landsat 5/TM remote sensing image from August 25, 1995 were selected to represent images from the 1970s, 1980s and 1990s, respectively. After the 2000s, the remote sensing image data is relatively rich, but the results of inter-annual data extraction showed little change, so a total of 11 phases of image data series from Landsat 7/ETM$^+$ (2000, 2002, 2008, 2010), Landsat 7/ETM (2005), and Landsat 8/OLI (2013, 2015, 2017) were selected for analysis. Among them, the spatial resolution of the data in 1977 and 1989 was 80 m $\times$ 80 m, while the spatial resolution of the other nine periods was 30 $\times$ 30 m. The image coordinate system used was WGS1984, and the orbit number was 143/27 or 144/27. All the above remote sensing image data were processed by geometric correction of control points and digital elevation models from the Shaanxi surveying and mapping data archive of the National Bureau of Surveying and mapping geographic information. All data quality was good, which met the requirements for high-precision registration and extraction of water information in the study area.

Monthly precipitation and temperature data from 1977 to 2017 from the National Meteorological Station (Fuhai station) near the entrance of Ulungur Lake were selected, with data from the China Meteorological Data Sharing Network (http://cdc.cma.gov.cn/). The monthly measured evaporation data from the Fuhai hydrological station from 1977 to 2015 was selected, with data from the Xinjiang Altay Hydrological and Water Resources Survey and Design Institute. Economics, population, and other social data were from the Xinjiang Statistical Yearbook from 1978 to 2018.

Satellite data preprocessing

First, the false color synthesis from multiple-source images were carried out according to the spectral characteristics of the water body. In addition to Band 1 (0.45–0.52 μm, 0.43–0.52 μm), Bands 2–6 were the same wavelength in the TM image, so Bands 2–4, which were the most consistent with the actual water extraction effect, were selected for false color synthesis. Secondly, by removing the strip (individual period image), radiometric correction, geometric correction registration, image fusion and clipping, and other processing means, the image was made into a GeoTIFF remote sensing image stored in a unified coordinate system. Simultaneously, according to the actual application and analysis requirements of the project, a principle of two pixels using the point mean square error and small edge error were used to integrate and process the multi-source remote sensing image, so as to lay a foundation for the extraction of water information. Finally, through the field survey and rearrangement of control points, the field verification and correction processing of multi-source image data were carried out to ensure that the water system information in the study area matched the thematic map collection accuracy of 1:10,000.

Water extraction and database construction

There are many mature methods for extracting water information from remote sensing image data, such as the single band threshold method, multi-band spectral relationship method, normalized difference water index (*NDWI*), modified normalized difference water index (*MNDWI*) and HIS transformation method – among which *NDWI* is the most commonly used method (Yu *et al.* 2008; Wang & Ma 2009; Wu *et al.* 2013a, 2013b). As *NDWI* only considers vegetation and ignores the impact of surface soil and buildings, when using this index model to extract water, many buildings' backgrounds will be mistakenly classified as water bodies, failing to achieve satisfactory results (Nie 2018). Therefore, considering that the study area is located in the transitional area between Fuhai County and the Gurbantunggut Desert with flat terrain and single types of features, and involves TM and OLI images, the *MNDWI* was used for more accurate extraction of water information after comparative analysis. This index can increase the contrast between a water body and buildings, reduce the probability they are confused, and facilitate the interpretation and extraction of water element information (Yan *et al.* 2015; Nie 2018). The formula by which it is calculated is as follows:

$$MNDWI = (Green - MIR)/(Green + MIR) \tag{1}$$

where, *Green* is the green band, which corresponds to Band2 of the TM image or Band 1 (SWIR1) of the short wave infrared in the OLI image. *MIR* is the mid infrared band, which corresponds to Band 5 of the TM image or Band 6 of the OLI image.

All spatial water information from the study area was extracted using ENVI 5.3 software, supplemented by basic surveying and mapping corrections. First, according to the workflow of the water sample area selection, the *MNDWI* calculation, threshold adjustment, plaque removal, area calculation, field survey, and the multi-stage water vector element data set which met all accuracy requirements and the unified spatial reference were extracted by human-computer interactive interpretation. During interpretation, the beach distributed around the lake and the small lake water areas which were not directly related to the lake water body were not included in the lake area (Figure 2). Second, through the field survey using GPS positioning and Google Earth high-resolution images to obtain the sample points, the results were interpreted, corrected, and evaluated. According to the statistics, the overall classification accuracy of this method is as high as 95%, which meets the requirements of project research accuracy. Third, based on the ArcGIS 10.4.1 platform, the multi-stage water vector data set was analyzed, and 11 phases of lake area and change information were obtained from 1977 to 2017. Finally, according to the status of data acquisition, the database naming standards of data table space, data set, feature class, and grid catalog were designed considering the unified mathematical basis, i.e., the 2000 national geodetic coordinate system and the 1985 National elevation datum. Five databases of basic geography, remote sensing images, water topic, meteorology, and social economy were constructed separately. Among them, spatial data such as basic geography, remote sensing images, and water topic were input using the SDE command from the ESRI Company. Meteorological, socio-economic, and other attribute data were imported through self-made programs, and spatial and attribute data were associated with spatial geographic information through geographic code or keywords so as to realize the unified integrated management of water data in the research area from multiple periods.

RESULTS

Dynamic changes in the water area of Ulungur Lake

Using the ArcGIS 10.4.1 platform, statistical analysis of changes in the 11 phases' water area in Ulungur Lake was carried out, and the results are shown in Table 1 and

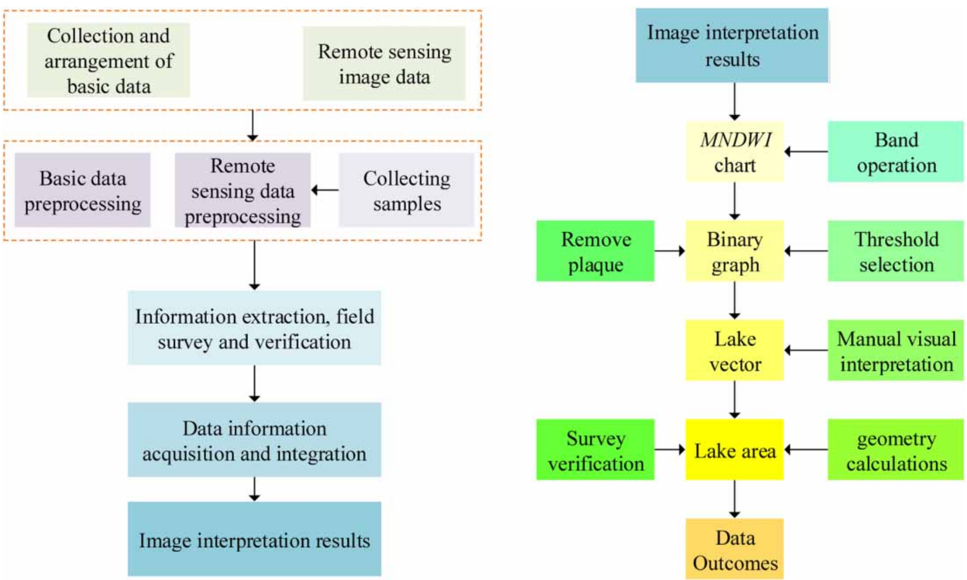

Figure 2 | Flowchart for processing satellite data.

Table 1 | The change in the water area of Ulungur Lake from 1977 to 2017

	Area/km^2		Inter-annual area change/km^2		Inter-annual area change rate/%	
Year	Buluntuohai Lake	Jili Lake	Buluntuohai Lake	Jili Lake	Buluntuohai Lake	Jili Lake
1977	790.09	164.53	/	/	/	/
1989	841.49	168.6	51.4	4.07	0.54	0.21
1995	857.75	169.81	16.26	1.21	0.32	0.12
2000	843.73	167.44	−14.02	−2.37	−0.33	−0.28
2002	845.99	168.42	2.26	0.98	0.13	0.29
2005	841.18	167.13	−4.81	−1.29	−0.19	−0.26
2008	841.75	165.66	0.57	−1.47	0.02	−0.29
2010	841.11	169.31	−0.07	3.65	0.00	1.10
2013	844.91	168.16	3.16	−1.15	0.13	−0.23
2015	846.76	168.82	5.65	0.66	0.33	0.20
2017	862.4	172.1	15.64	3.28	0.92	0.97

Figure 3, which demonstrate that in the most recent 40 years, the water area of Ulungur Lake has changed, and the areas of Buluntuohai and Jili Lakes have increased. The characteristics of the water area change in Buluntuohai Lake area were as follows. (1) From 1977 to 1995, the water area increased continuously, with a total increase of 67.66 km^2 in 18 years and an average annual change rate of 0.48%. From 1977 to 1989, the water area increased significantly (increased by 51.4 km^2). (2) From 1995 to 2010, the water area decreased slightly, the inter-annual area changes from 1995–2000, 2000–2002, 2000–2005, 2005–2008 and 2008–2010 were 16.26, −14.02, 2.26, −4.81, 0.57, and −0.07 km^2 respectively. The most obvious reduction period was from 1995 to 2000. (3) From 2010 to 2017, the water area showed a slight increasing trend, with an increase of 21.29 km^2 in seven years, of which the largest increase was from 2015 to 2017 (15.64 km^2). In general, from 1977 to 2017, the water area of Buluntuohai Lake showed the dynamic characteristics of natural expansion (1977–1995) followed by atrophic decline (1995–2010), and finally restorative expansion (2010–2017).

The characteristics of changes in the water area in Jili Lake were as follows. (1) From 1977 to 1995, the water area showed a small continuously increasing trend, which increased by 5.31 km^2 in 18 years, with an average annual change rate of 0.18%. The water area increased significantly

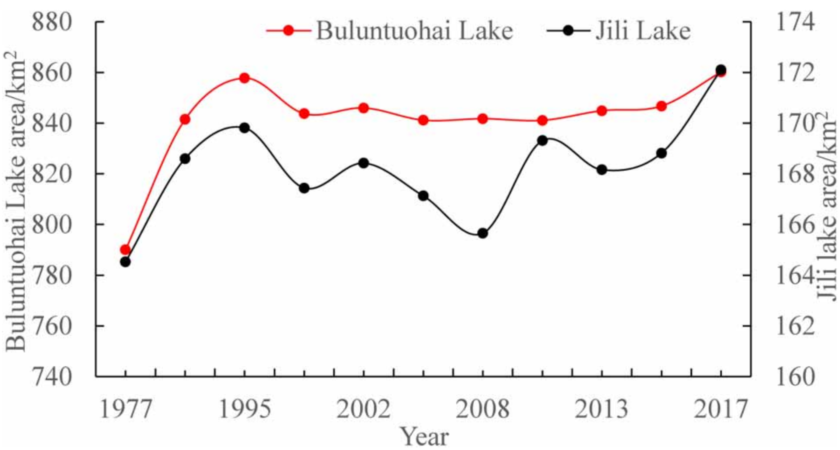

Figure 3 | Timeseries of the change in water area of Ulungur Lake from 1959 to 2017.

(by 4.07 km^2) from 1977 to 1989. (2) From 1995 to 2015, the water area showed a small fluctuation between 167.13 and 169.82 km^2, and then reached a stable state which was manifested in a small reduction of the water area from 1995 to 2008 (by 4.15 km^2), and a small increase in water area from 2008 to 2015 (by 3.16 km^2). (3) From 2015 to 2017, the water area increased slightly, by 3.28 km^2 in two years, with an annual change rate of 0.97%. In general, from 1977 to 2017, the water area of Jili Lake showed the dynamic characteristics of natural expansion (1977–1995) followed by stable volatility (1995–2015, the water area has both increased and decreased changes), and then increased recovery (2015–2017).

Using the ArcGIS 10.4.1 software platform, the 11 phases of remote sensing images and vector data from Ulungur Lake were analyzed, and the results are shown in Figures 4 and 6. As seen in Figure 4, the water area in the study area showed a continuously increasing trend from 1977 to 1995, and the increased areas were mainly concentrated in the Zhonghaizi, Xiaohaizi, Camel's Neck, Akekule, and Jianggezijidi areas, among which the newly increased water area of Zhonghaizi was the largest. As seen in Figure 5, from 2000 to 2008, the change in water area in the study area was very small and were mainly concentrated in Zhonghaizi, Akekule, and Camel's Neck. Figure 6 shows that from 2010 to 2017, the water area of the study area had a continuously increasing trend, concentrated in Zhonghaizi, Xiaohaizi, the lake entrance of the Ulungur River, and near the Akekule, among which the newly increased water area of Zhonghaizi was the largest. Changes in the water area of Ulungur Lake over the past 40 years was characterized by natural expansion – stable volatility – increasing recovery.

Analysis of the variables driving changes in lake area

Climatic factors

The timeseries of annual precipitation and annual average temperature (Figure 7) from the Fuhai Meteorological Station from 1977 to 2017 shows that the annual precipitation in the Ulungur Lake area showed a slight increasing trend of 0.50 mm/a. The maximum annual precipitation occurred in 1984 (215 mm), and the annual precipitation in other years (especially after 1995) fluctuated around 127.92 mm.

The annual average temperature showed an increasing trend of 0.06 °C/a. The perennial mean temperature was

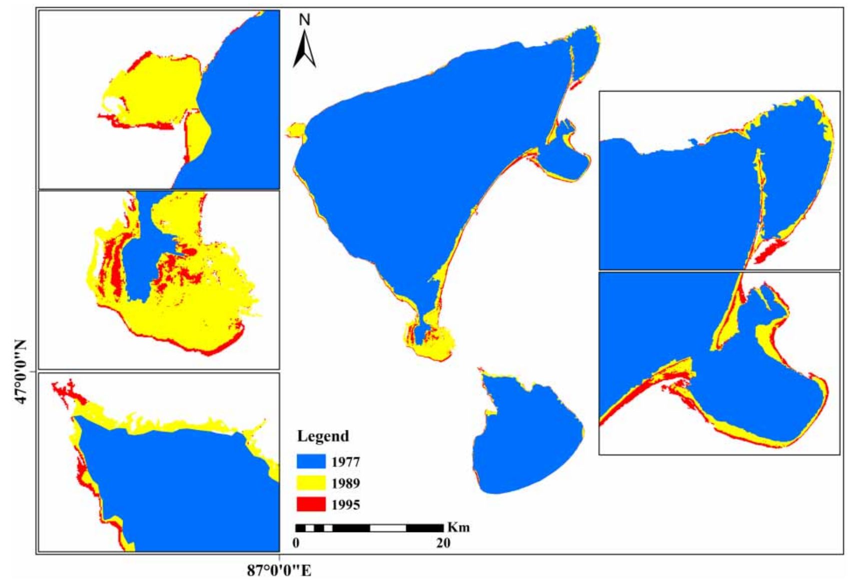

Figure 4 | Map showing superimposed variations in water area in the study area from 1977 to 1995.

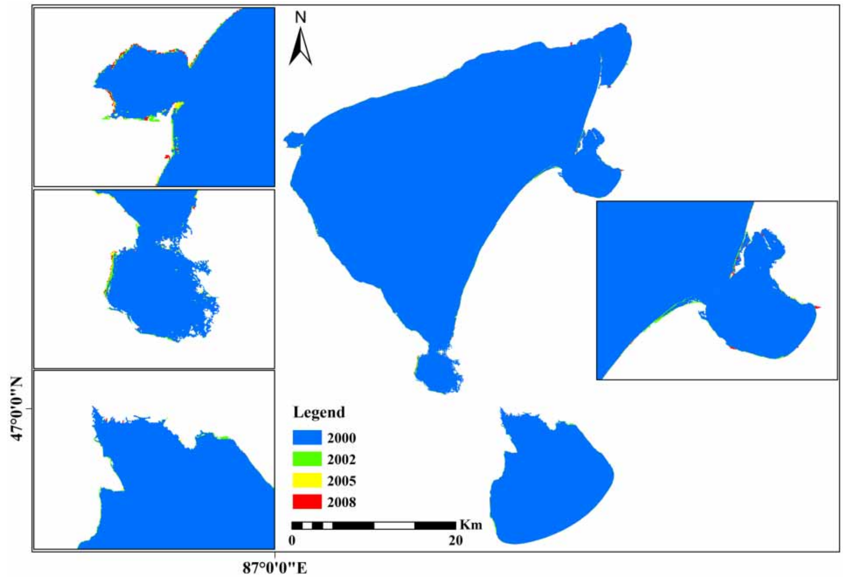

Figure 5 | Map showing superimposed variations in water area in the study area from 2000 to 2008.

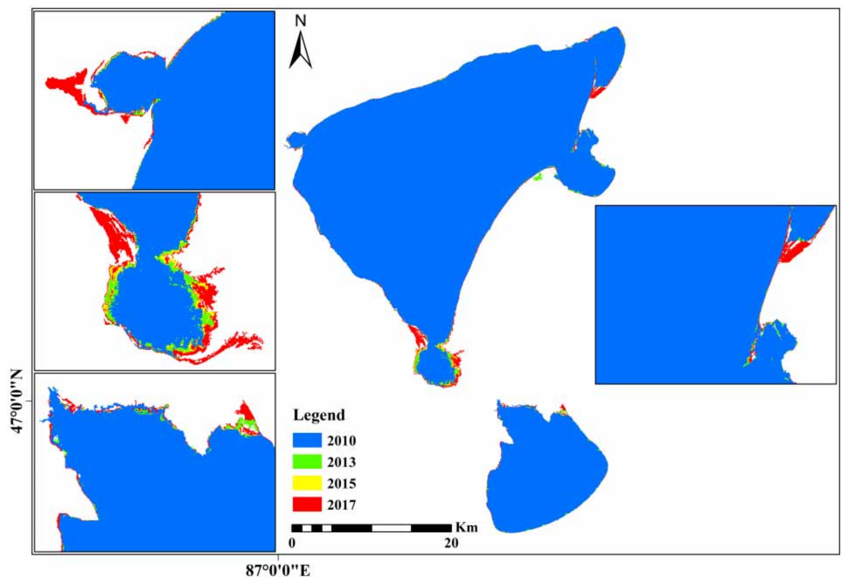

Figure 6 | Map showing superimposed variations in water area in the study area from 2010 to 2017.

5.43 °C during 1977–1994, while the average annual temperature mostly stayed lower than 5.43 °C. Since 1994, the average annual temperature was generally higher than 5.43 °C. The timeseries of annual evaporation in the Ulungur Lake region from 1977 to 2015 (Figure 8) shows that it decreased from 1977 to 2015 at a rate of 14.1 mm/a, and had an average annual evaporation of 1,673.14 mm. During 1977–1990, the evaporation was generally higher than 1,673.14 mm, and after 1990, the evaporation was generally lower than 1,673.14 mm. Over the past 40 years,

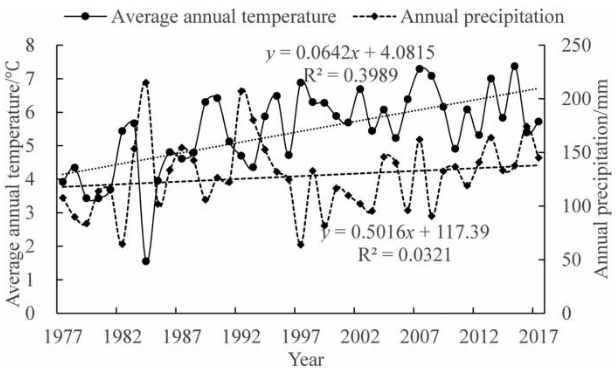

Figure 7 | Timeseries of annual precipitation and annual average temperature in the study area from 1977 to 2017.

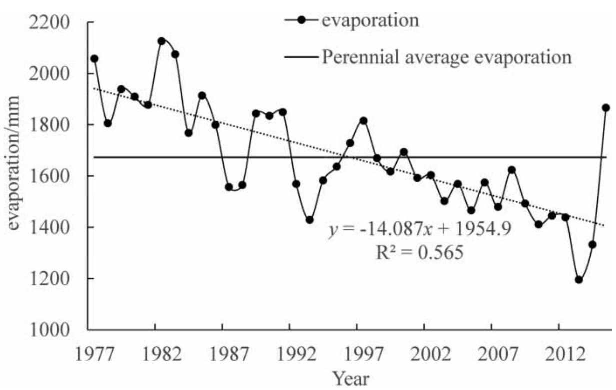

Figure 8 | Timeseries of annual evaporation in the study area from 1977 to 2015.

climatic changes in the Ulungur Lake region showed an increase in annual precipitation and annual average temperature, and a decrease in evaporation, matching global climate trends (Ding & Wang 2001). The change trend towards increasingly warm and humid climates was basically consistent with the dynamic change trend of the overall expansion of lake water area during the same period.

According to Pearson correlation analysis, the correlation coefficients of the Buluntuohai Lake area change with precipitation and temperature were 0.36 and 0.65, respectively. The correlation coefficients between the Jili Lake area change and precipitation and temperature were 0.53 and 0.25, respectively. This showed that there was a positive correlation between precipitation, temperature, and lake water area, and the correlation coefficient between temperature and Buluntuohai Lake water area was relatively large, which is consistent with results from Dilinuer & Aikebaer (2010). Due to the influence of global warming (Wang & Qing 2017), climate change was one of the driving factors that lead to the change in the area in Ulungur Lake in the last 40 years, but the degree of correlation was not high, which showed that global warming was not the key factor.

Human activity factors

Before 1970, the main water supply of Ulungur Lake was Ulungur River, which first flowed into Jili and then Buluntuohai Lake through the Kuyierga River. In November 1970, an open trench of desert hydraulic engineering project was built that diverted water from the Irtysh River into Urumqi, which led to water from the Irtysh River being used to supply the Zhonghaizi, though it was insufficient (Yan *et al.* 2004; Ji *et al.* 2018). In 1972, in order to maintain the water level stability in Jili Lake, a river sluice was built on the Kuyierga River. The water supply from Buluntuohai Lake was limited, and the water area had been decreasing. In 1988, after the completion of the new 'water diversion project from the Irtysh River to Fuhai', 3×10^8–$4\times10^8\,m^3$ of water was introduced into the Xiaohaizi (Ji *et al.* 2018), after which the Buluntuohai Lake area became relatively stable.

According to the Xinjiang Statistical Yearbook from 1978 to 2018 (Figure 9), the population of Fuhai County showed a significant increase (1977–1995) followed by a decrease (1995–2000), then a fluctuating increase (2000–2017). Planted crop area showed a trend of a fluctuation increase (1977–2000) followed by a decrease (2000–2002),

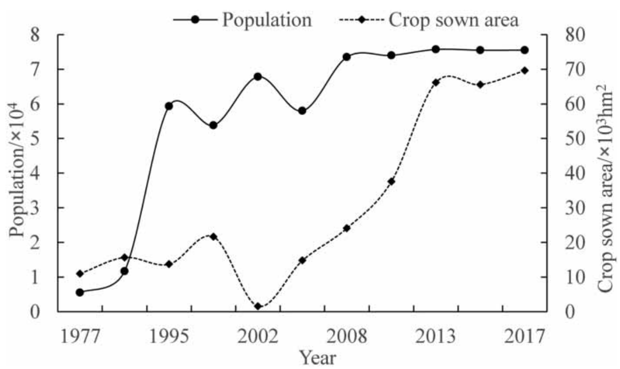

Figure 9 | 1977–2017 timeseries of population and planted crop area in Fuhai County from 1977 to 2017.

then a significant increase (2002–2017). This increasing trend is consistent with changes in the Ulungur Lake area. According to the Report on the Cutoff of the Ulungur River, in the late 1970s, due to a sharp increase in cultivated land area in the lower reaches of the Ulungur River Basin, the volume of diverted water in the region reached 7.04×10^8 m^3. From 1985 to 1995, the water consumption of users in the area increased significantly, but it declined after 2000. However, it was still above 5×10^8 m^3 in most years, and the contradiction between water resource distribution and irrigation water consumption in the middle and lower reaches of the area was very prominent.

Simultaneously, since 2000, the lower reaches of the Ulungur River (which are 49 km from the mouth of Jili Lake) had been cut off in varying degrees for many consecutive years (Menggubieke *et al.* 2014; Nuerlan *et al.* 2014). Due to damage on the Kuyierga River sluice (Cheng *et al.* 2016), when the water level of Jili Lake was insufficient due to decreases in the water supply of the Ulungur River, it was difficult to recover rapidly. Additionally, the original water level potential balance between the Buluntuohai and Jili Lakes was broken, making the water level of Buluntuohai Lake higher than that of Jili Lake, resulting in water being supplied to Jili Lake, which was an important reason for the relative stability in the water area of Jili Lake.

DISCUSSION

Ulungur Lake is a typical inland closed desert lake in the arid region of China. The reasons for the observed changes in water area are complex, and include both climate change and high-intensity human activities. Based on the remote sensing method, the change characteristics in the water area of Ulungur Lake over the last 40 years were monitored and analyzed in this study. Dilinuer & Aikebaer (2010) found that the water area of Buluntuohai Lake increased by 37.2 km^2 from 1980 to 2002. Liu *et al.* (2018) showed that the water area of Ulungur Lake in the 1980s increased sharply, while in the 1990s it decreased slightly, and then increased slightly after 2000. Li *et al.* (2015) studied the change of the area of Ulungur Lake from 2000 to July 2014 and found that the water area showed a trend of increasing fluctuation. The above results are consistent with the results of this study, but the size of the water areas are different, as their study included the Buluntuohai lake, an additional small lake in the northeast corner of the region.

In the last 40 years, the regional climate of Ulungur Lake has changed, showing increased annual precipitation and annual temperature fluctuations and decreasing fluctuations in evaporation. The trend towards an increasingly warm and humid climate in the study area was basically consistent with the dynamic characteristics of the overall expansion of lake water area in the same period, but the correlation was not high. Climate change was one of the driving factors, but not the key factor, that led to the changes in the water area of the lake in the most recent 40 years. From 1977 to 1995, the water area expanded, and human activities such as the water diversion project from the Irtysh River to Fuhai were the main driving factors affecting the temporal and spatial changes of the water area, while climate warming and humidification had little impact. From 2000 to 2017, the lake water area was slower period of expansion. The climatic trend towards greater warming and humidification with superimposed human activities was the key factor for the temporal and spatial dynamic change of water area during this period.

Applying '3S', spatial data processing, data building, and other technologies to constructing the database of lake water area can help planners realize more effective storage and management of multiple data types, improve the speed of data retrieval, browsing, and extraction, and provide basic data support for the unified integrated management of water data information and ecological environment research in the research area. Gao *et al.* (2011) and Yan *et al.* (2004) have studied different regions of China using this method, and their results show that this method can effectively solve the weak integration of '3S' technology and data and the low efficiency of data warehousing in the construction of a water or ecological database.

CONCLUSIONS

RS, GIS, GPS, satellite data preprocessing, and water extraction and database construction were used to monitor and analyze the spatial and temporal variations and driving forces of the water area of near 40a Ulungur Lake. The main conclusions are as follows:

1. The water area of Ulungur Lake has changed significantly over the past 40 years. Composed of several smaller lakes, Buluntuohai Lake showed the dynamic change characteristics of natural expansion (1977–1995), atrophic decline (1995–2010), restorative increase (2010–2017), while the water area of Jili Lake showed the dynamic change characteristics of natural expansion (1977–1995), stable volatility (1995–2015), significant increase (2015–2017).
2. From 1977 to 1995, the water area showed a continuously increasing trend, concentrated mainly in the waters of Zhonghaizi (the largest newly increased water area), Xiaohaizi, Camel's Neck and the waters near Akekule and Jianggezijidi. From 2000 to 2008, the change in water area in the study area was very small, mainly concentrated in the waters of Zhonghaizi. From 2010 to 2017, the water area showed a continuously increasing trend which was mainly concentrated in the waters of Zhonghaizi (the largest newly increased water area), Xiaohaizi, the junction of Ulungur River with the lake, and the waters near Akekule.
3. Climate change is not highly correlated with the water area using the Pearson correlation analytical method. Human activity is the main driving force influencing the spatio-temporal change of water area based on the analysis results of the water conservancy project (the water diversion project from the Irtysh River to Fuhai), population quantity and crop sown area.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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