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Changes in the area of inland lakes in arid regions of central Asia during the past 30 years

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Abstract Inland lakes are major surface water resource in arid regions of Central Asia. The area changes in these lakes have been proved to be the results of regional climate changes and recent human activities. This study aimed at investigating the area variations of the nine major lakes in Central Asia over the last 30 years. Firstly, multitemporal Landsat imagery in 1975, 1990, 1999, and 2007 were used to delineate lake extents automatically based on Normalized Difference Water Index (NDWI) threshold segmentation, then lake area variations were detailed in three decades and the mechanism of these changes was analyzed with meteorological data and hydrological data. The results indicated that the total surface areas of these nine lakes had decreased from 91,402.06 km^2 to 46,049.23 km^2 during 1975–2007, accounting for 49.62% of their original area of 1975. Tail-end lakes in flat areas had shrunk dramatically as they were induced by both climate changes and human impacts, while alpine lakes remained relatively stable due to the small precipitation variations. With different water usage of river outlets, the variations of open lakes were more flexible than those of other two types. According to comprehensive analyses, different types of inland lakes presented different trends of area changes under the background of global warming effects in Central Asia, which showed that the increased human activities had broken the balance of water cycles in this region.

Keywords Arid region · Central Asia · Inland lake · Lake variations · Climate change · Human activities

Introduction

Lakes act as the essential components of the hydrological cycle, which would have affected on many aspects of ecosystems and human activities. Lakes remain sensitive to the natural changes, so as to serve as an important proxy of global climate change and regional environment variations (Mason et al. 1994). Especially for the lakes in the arid areas of Central Asia, which provide sparse but valuable water resources for the fragile environments and human beings. Mapping high-precision lakes and detecting their changes are of great significance to understand the relevance of lake variations to climate changes, and they are also crucial to evaluate the impacts of the economic development to ecological balances.

"Middle Asia" was defined as Turkmenistan, Uzbekistan, Tajikistan, and Kyrgyzstan by Russian

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researchers. While the term “Central Asia” included not only the four “Middle Asia” countries, but also Kazakhstan, northwest part of China and Mongolia as well (Cowan 2007; Lioubimtseva and Henebry 2009). However, in majority of Chinese research, Central Asia was defined as the four “Middle Asia” republics, Kazakhstan and Xinjiang of China (Chen 2008), and this definition was used in this paper. Central Asia covers one-third of the arid area of the world (Chen 2008), where the rivers and lakes are the major sources of surface water resources and supply most of the water for human use in the oasis of Central Asia. There are more than 6,000 lakes with a total surface area of 12,300 km^2 (Savvaitova and Petr 1992), and most of them are endorheic lakes. These inland lakes are highly responsive to climatic variations and human activities (Friedrich and Oberhänsli 2004).

The supplied rivers, where headwaters originated from snow melting in the mountains, provided water for upstream storages to support agricultural irrigation, and downstream water flowed into the terminal lowland lakes. With the increase in population, expansion of agricultural land in the basin and increased water diversion, more water in the plains of arid regions had been used for agricultural irrigation, and less water had drained into the terminal lakes. Since the 1960s, a lot of inland lakes in this region had been drying up (e.g., Aral Sea, Issyk-Kul, Ebinur, and Bosten), and some of them even had been disappeared (e.g., Lop Nur, Manas and Taitema; Micklin 1988; Savvaitova and Petr 1992; Boomer et al. 2000; Saiko and Zonn 2000; Kezer and Matsuyama 2006). The decline of lake levels and shrinkage of lake extents had been proven to cause serious environmental issues (Tatyana and Igor 2000; Lioubimtseva et al. 2005; Lioubimtseva and Henebry 2009). Accurate lake mapping and lake dynamics in spatial–temporal variability were vital to the assessment of water resource management and regional environment changes (Lehner and Doll 2004; Ouma-and-Tateishi 2007; Alejandra et al. 2008).

Many studies about the lake variation in Central Asia had been reported (Micklin 1988; Savvaitova and Petr 1992; Boomer et al. 2000; Saiko and Zonn 2000; Stanev et al. 2004; Kezer and Matsuyama 2006; Ma et al. 2007), while most of them just focused on lakes in local basin and lake changes over the wide region were relatively few. As the inland lakes in Central Asia were numerous and some lakes are hindered by remote locations and difficult terrains, it was a great challenge for mapping and detecting the lakes with field survey and manual digitization. Remote sensing provided a feasible tool to analyze the status and variations over a long-term time period (Harris 1994; Ma et al. 2007). Lake delineation with remote sensing imagery had been studied widely such as threshold segmentation method (Braud and Feng 1998), water indices method (McFeeters 1996; Xu 2006; Ouma and Tateishi 2006), variants of component analysis method (Lira 2006), and step-wise iterative classification algorithm (Luo et al. 2009). These studies had made the lake mapping more effective and efficient.

There were three different types of inland lakes (closed lake, open lake, and alpine lake), as showed in Table 1. The objective of this paper

Table 1 The main lakes in Central Asia

Lake	Country	Elevation (m)	Type	Depth (m)	
				Maximum	Average
Aral Sea	Kazakhstan and Uzbekistan	53	Closed	67	16.1
Balkhash	Kazakhstan	342	Closed	26.5	5.8
Alakol	Kazakhstan	348	Closed	54	22.1
Ebinur	China	189	Closed	2.8	1.4
Issyk-Kul	Kyrgyzstan	1,608	Alpine	702	278
Sayram	China	2,073	Alpine	92	46.1
Zaysan	Kazakhstan	386	Open	13	7
Bosten	China	1,048	Open	16.5	8.15
Sasykkol	Kazakhstan	347	Open	4.7	3.32

is to mapping the dynamics of lake area of nine typical inland lakes in Central Asia using Landsat satellite imagery, and their spatio-temporal changes are also analyzed with related meteorological data.

Materials and methods

Study area

The spatial extents of study area was from N55°25′, E46°29′ to N34°20′, E46°29′ (Fig. 1). Locating in the mid-latitudes of the north-western hemisphere, this area is under the control of continental climate, with a cold winter and a hot dry summer. Water resources in this area have inhomogeneous distribution, and most areas are severe drought. The annual precipitation is about 1,000 mm in mountainous regions, while less than 100 mm in low-lying desert regions. Though the precipitation is less, the potential evaporation is more than 900–1,500 mm per year (Qin 1999), forming an extensive semi-arid and arid region in the world. Most of lakes are concentrated on the northwest grassland of Kazakhstan and the southern mountain regions, and mainly are separated into three types, closed lake, alpine lake and open lake. About 20 larger closed lakes with total areas more than 1,000 km^2 are distributed in the basins of Aral Sea, Ili River and Irtysh River, whose water supplies mainly come from snowmelt water and precipitation, and their area are approximately 50% of total lake area in

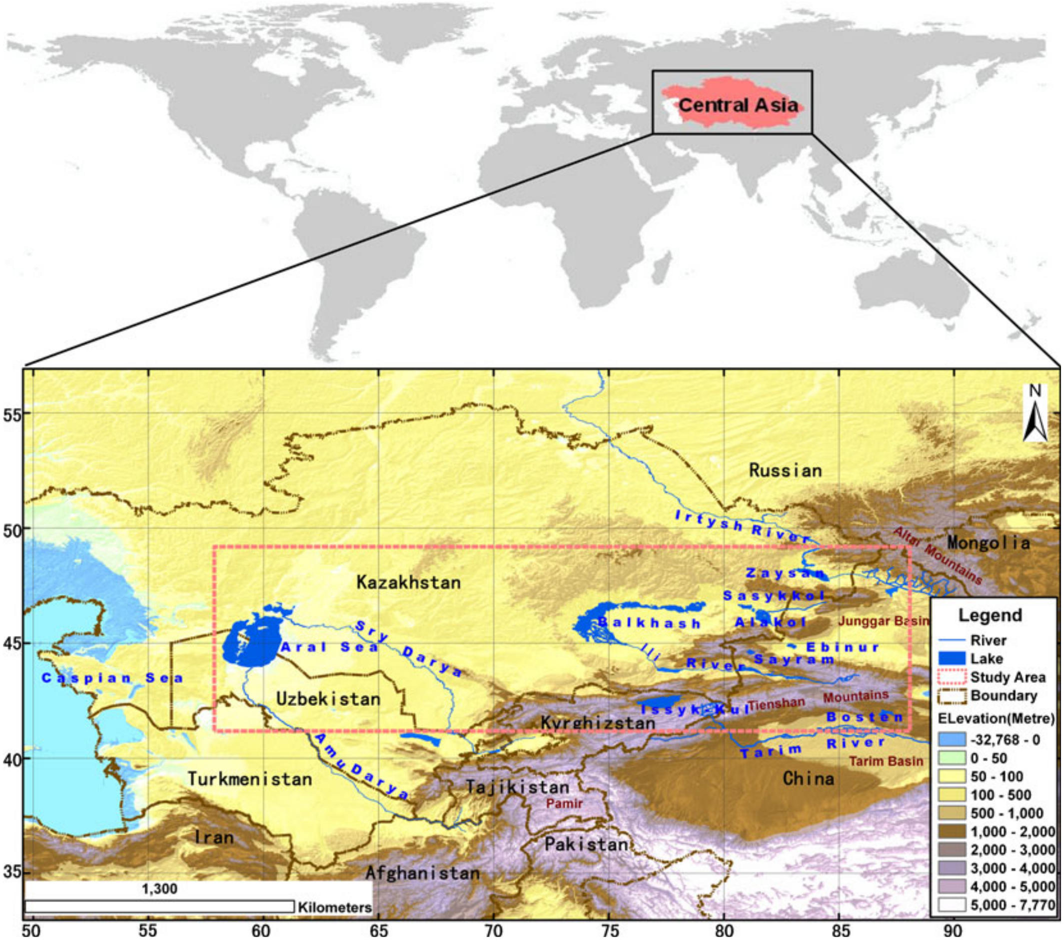

Fig. 1 Location of the study region, Central Asia

Central Asia. Alpine lake is mainly located at the Tienshan Mountains and the Altai Mountains with average elevation more than 1,500 m, and most of them are supplied with the glaciers and snowmelt water during the dry seasons.

Satellite imagery and precipitation data

Landsat MSS, TM, ETM+ imagery during 1975–2007 were used as remote sensing data source for investigating lake extent variations in the study area. The Landsat data was downloaded from USGS GLOVIS, and date preprocessing was proceeded with ENVI software. According to the previous studies, lakes in Central Asia were comparatively stable in spring and autumn seasons as they were less affected by glacier melting water and agricultural irrigation, so 102 scenes of the cloud-free satellite images were acquired in these two seasons. Most of selected images were cloud-free or nearly cloud-free and had been georeferenced with the topographic maps (as shown in Fig. 2). The Shuttle Radar Topographic Mission (SRTM) DEM data with a spatial resolution of 90 m was used (Jarvis et al. 2008).

In order to analyze the relationships between lake area variations and climate changes. Annual precipitation data during 1970–2000 were collected from the Asian Precipitation-Highly-Resolved Observational Data Integration Towards Evaluation (APHRODITE) of the Water Resources, which had a raster format and its spatial resolution of 0.25° × 0.25° (Xie et al. 2007; Yatagai et al. 2009; http://www.chikyu.ac.jp/precip/).

Methods of delineating lake features

In the electromagnetic spectrum, water absorbs almost all of incident radiations in the near- and mid-infrared bands, while shows a strong reflectance in visible bands. Based on the spectral analysis, NDWI is used to extract the water body by McFeeters (1996). It is a band ratio index

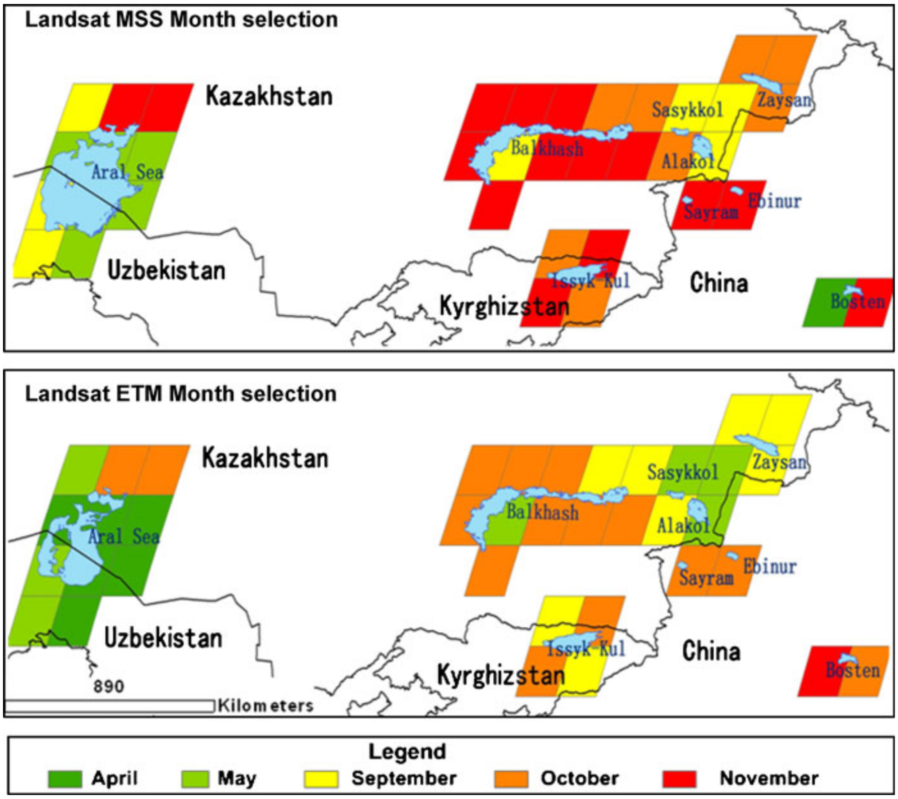

Fig. 2 Landsat images selection at best month

between the green and near infrared (NIR) spectral bands, which would not only enhance water features, but also depress vegetation, bare lands and other environmental information (Xu 2006). NDWI is defined as

$$\mathrm{NDWI} = \frac{R_{\mathrm{Green}} - R_{\mathrm{Nir}}}{R_{\mathrm{Green}} + R_{\mathrm{Nir}}} \tag{1}$$

Where R_{Green} is the top of atmospheric reflectance of the green band, and R_{Nir} represents that of the near-infrared band, which are corresponding to band 2 and band 4, respectively, in Landsat TM/ETM+ imagery.

After the geometric correction and atmospheric correction, the images were used to extract the lake extents with a segmentation algorithm of step-wise iterative based on NDWI (Luo et al. 2009). The algorithm firstly segmented the satellite image into lake pixels and background pixels with global segmentation of NDWI map. Secondly, the results of global lake were processed with the method of regional label, so as to take each lake element as an individual object. Thirdly, each lake was segmented locally with their surrounding background pixels. A buffer was built on each lake and its size was approximately equal to that of the lake, and the threshold was easily determined within the buffer through local histogram analyses. If the change in lake extents was greater than 5% after the local segmentation, iterations of the local segmentation were made to get the best segmentation threshold. As different lake elements were processed with different thresholds, this algorithm made the lake delineation more accurate and more efficient. The method above gave a minor modification of the algorithm based on Luo et al. (2009) and the NDWI was applied to threshold segmentation instead of global classification. The flow diagram showing data processing was in Fig. 3.

The main advantage of this method was that different segmentation thresholds were applied on different types of lakes, so it made the results more reasonable. The raster results of lakes were converted to vector layers with the ArcGIS software, and the analyses of lake change were based on vector processing. As lake areas were concerned, a uniform projection was important to lake mapping in large regions. Here Lambert Azimuthal Equal Area Projection was used to make the lake areas of projected lake layers equal to those of original layers. Then lake layers of the same time period were merged and duplicate lakes in the overlapped regions were removed, so as to form an integrated lake layer over the whole study area. At last, lake area between two time periods were compared and the attributes of area changes were counted with lake-related spatial analyses. In this paper, the mapping accuracy was evaluated by overlaying NDWI map with vector layer, and it was found that they were matched

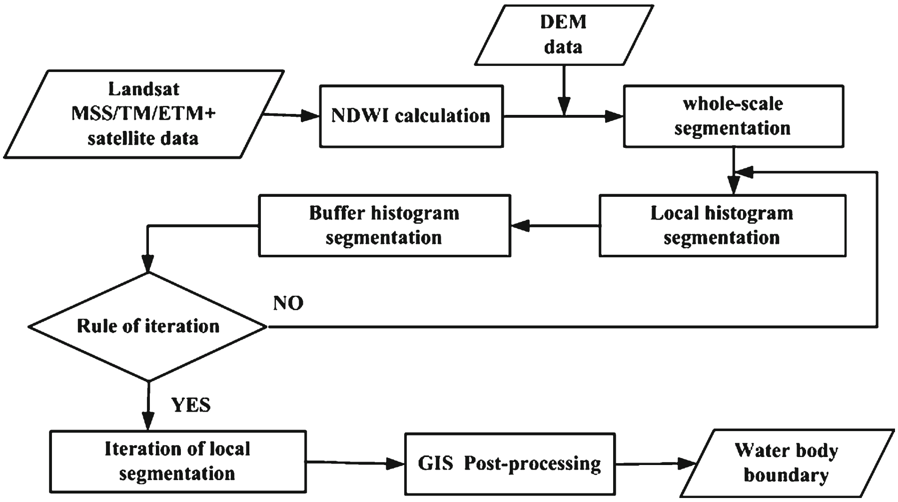

Fig. 3 Flow chart depicting processes involved in extraction of lake areas information

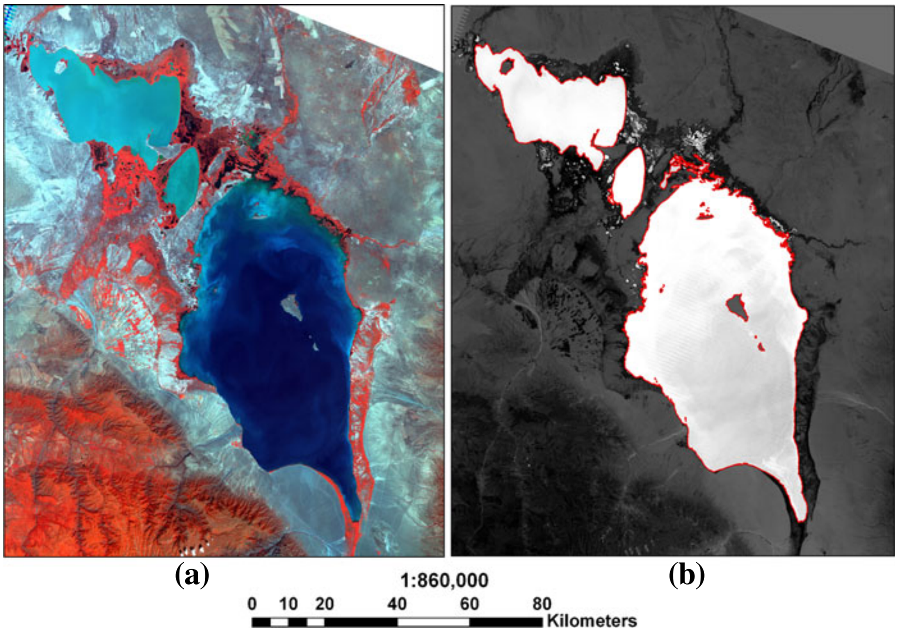

Fig. 4 Selected Landsat TM (**a**), and the extraction results of water information overlying NDWI map in Landsat TM (**b**)

perfectly and the mapping accuracy was less than 1 pixel (Fig. 4).

Results and discussion

Changes in lake surface area

Table 2 showed the dynamic changes in surface area of nine Central Asian lakes during the period from 1975 to 2007. The total surface area of the nine lakes decreased from 91,402.06 km^2 to 46,049.23 km^2, with 49.62% shrinkage compared with the area in 1975. Although the total area of Zaysan, Sayram, and Sasykkol lakes expanded by 4.2%, the other six lakes in this region lost approximately 52.1% of their area from 1975 to 2007. Water boundaries in four periods showed that the surface area of the lakes in the eastern part of Central Asia was larger than that of those in the western part. The trend of decreased lake area had spread from east to west. As the largest inland lake of Central Asia, the endorheic Aral Sea had shrunk by 75% of its surface area, which was the largest loss of surface area among nine lakes. At the beginning of 1990, the Aral Sea split into a small northern sea (named Maly) and a large southern sea (named Bolshoi) as the water

Table 2 The changes in lake area extracted from satellite images in Central Asian during the past 30 years

Lake name	Area in 1975 (km^2)	Change (%)*				Area in 2007 (km^2)
		1975–1990	1990–1999	1999–2007	1975–2007	
Aral Sea	59,262.35	−32.90	−28.18	−49.57	−75.70	14,400.15
Balkhash	17,199.72	−2.18	−0.36	−0.08	−2.61	16,750.22
Ebinur	603.50	−10.59	0.78	1.69	−8.37	553.00
Alakol	2,992.47	−3.48	0.96	1.83	−0.76	2,969.76
Issyk-Kul	6,252.23	−0.61	−0.29	0.24	−0.66	6,211.21
Sayram	458.17	0.48	−0.25	0.50	0.72	461.48
Zaysan	2,832.79	1.79	3.18	0.79	5.85	2,998.60
Bosten	1,055.83	−11.70	15.16	−10.69	−9.18	958.90
Sasykkol	745.00	−0.14	0.04	0.22	0.12	745.91
Total	91,402.06	−22.05	−15.47	−23.54	−49.62	46,049.23

recorded (Nezlin et al. 2004). The water moved 100–150 km away from the original coastline, and a salty bed with area 4,500 km^2 was formed.

In terms of the variations of surface area since 1975, the inland lakes in Central Asia could be classified into three types. The first type was defined as the closed lake, which was mainly located on the low-lying plains of Central Asia (including Aral Sea, Balkhash, Alakol, and Ebinur lakes). Changes in the surface area in this type of lake were consistently decreased. These lakes were located at the base of a great tectonic basin below 500 m elevation, with only water supply from river runoff feeding by the glacial and snow-melting but no outlet. Both the surface area and water level decreased in these inland lakes. As the largest landlocked lake in the eastern part of Central Asia, the Aral Sea accounted for 64.84% of total lake area in 1975, but decreased to 31.27% in 2007, with a sharp decrease of 75.7% (see Fig. 5). Balkhash Lake, in the east of the Aral Sea, covered an area 18.82% of the total lake area in 1975, but shrunk by 2.26% in 2007. Alakol Lake and Ebinur Lake experienced surface area decreases with 3.48% and 10.59% from 1975 to 1990, and then expanded 2.47% and 2.79% from 1990 to 2007. Ebinur Lake had shrunk by 8.37% while Alakol Lake had no obvious changes from 1975 to 2007.

The second type was categorized to alpine lake, which was mainly located above 1,500 m elevation with an average water depth greater than 90 m. With less anthropogenic disturbances, alpine lake was in a natural environment and the changes in

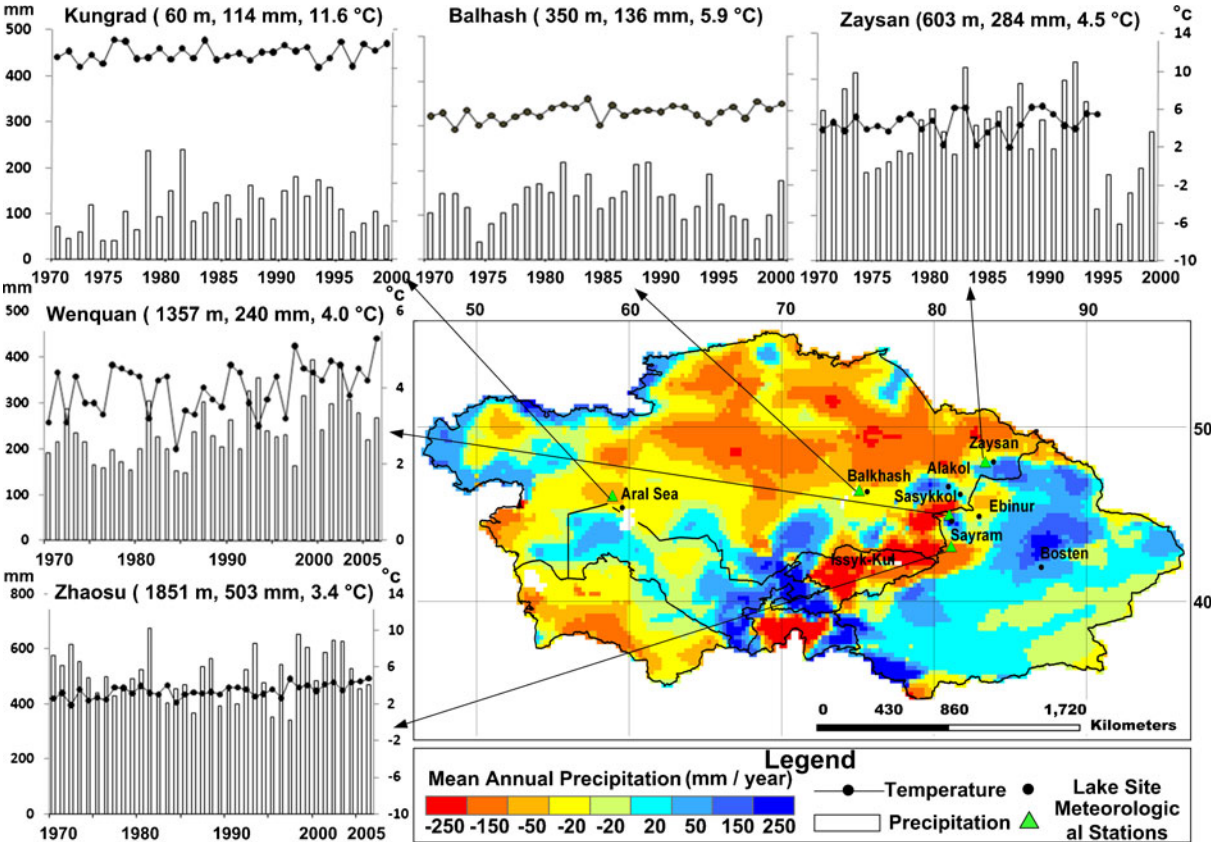

Fig. 5 The spatial changes in mean annual precipitation (mm year^{-1}) in Central Asia during 1970–2000 were defined by gauge-based precipitation analyses. Five meteorological stations at different elevations and precipitation zones were marked on the histograms. Histograms in the vertical direction showed the precipitation distribution at different elevations, and those in the horizontal direction showed the precipitation distribution at different latitudes

surface area were mainly affected by climate variations. The changes in lake surface area in high mountains were smaller than those on the plains. During the period 1975–2007, the high mountain lakes Sayram Lake and Issyk-Kul experienced slight changes in their surface area, with 0.7% and −0.66%, respectively.

The third type of lake was termed open lake (including Zaysan, Bosten, and Sasykkol lakes). As these lakes had outlets, the changes in surface area were much more complicated than those of the other two types. The surface area of Zaysan Lake, in the lower western region of the Altai Mountains, had expanded by 5.85% from 1975 to 2007. The Bosten Lake, located in the central Tienshan Mountains, had fluctuant surface area and decreased by 9.1% during 1975–2007. The surface area of Sasykkol Lake was basically in the constant.

Causes of the changes in inland lake surface area in Central Asia

Climate changes in Central Asia

The climate changes affected the river runoff which supplied the inland lakes, and then influenced the changes in inland lake areas over the long term. Most inland lakes in arid regions were supplied by seasonal snow-melt water and rainfall, so they were sensitive to the volume of water flowing into the lake and evaporation losing from the lake surface.

A rain-gauge-based analysis of annual precipitation had been constructed for Central Asia during 1970 to 2000. Over most of Central Asia, the climate change was featured as decreased precipitation (Fig. 5). About 40% of Central Asia was in the area of decreased precipitation, and 22% was in the area of increased precipitation. The spatial distribution of precipitation became relatively reduced by 20–50% in the eastern part of Central Asia (including Kazakhstan, Uzbekistan and Turkmenistan), while it was going plentiful in the western part from 1970 to 2000. The Aral Sea, Issyk-Kul, Balkhash, and Ebinur basins which were situated at Western Tienshan Mountains had significant decreases in annual precipitation, and the surface area of these lakes had decreased. Despite the general decrease in precipitation in most regions of Central Asia, the opposite trend was found in Tienshan Mountains, Altai Mountains, northern Xinjiang, western Tarim basin and Yanqi basin during the period 1980–2000, and surface area of Boston, Zaysan, Ebinur, and Alakol lakes which were local in these basins showed an increased trend after 1990s.

The distribution of precipitation was different depending on altitude. Five meteorological stations, located at different elevations, showed the variations of annual average temperature and precipitation. The total annual precipitation in mountainous regions was higher than that in low desert regions. Zhaosu meteorological Station, at an elevation of 1,851 m, had an average precipitation of 503 mm year^{-1}, while Kungrad meteorological Station, at an elevation of 60 m, had an average precipitation of 140 mm year^{-1}. Sayram Lake which located in the west Tienshan Mountains was an alpine lake, and supplied by snow-melt water from the mountains. The meteorological data in Wenquan meteorological Station nearby Sayram Lake represented that the annual increscent of temperature was 0.022° and that of precipitation was 2.9 mm (histograms in Fig. 5). With the increases in precipitation and runoff water of snow-melt, the lower evaporation rate of the lake water and less human activities made the surface area of this lake remained steady.

Impact of human activities on changes in lake area

In arid regions, the changes in lake surface area caused by human factors were mainly from agricultural water consumption and construction of reservoirs, which was a significant withdrawal of water which would otherwise flow into the terminal lakes.

The Aral Sea had two transnational supplied rivers of Amu Darya and Syr Darya, and nearly 75% of available water was used for agriculture (Aladin and Plotnikov 1993). The irrigated area in this basin had expanded by 54.17% from 1960 to 1999, and the water flow into this lake had decreased by 67.67% (Saiko and Zonn 2000), which resulted in a great reduction in discharge to the sea and the surface area of lakes shrank significantly. As for the Bosten Lake, its area was controlled by both of the feeding water of Kaidu River and outlet river of Konqi River and Tarim River. The annual discharge of the Kaidu River reduced by 7.04% from 1970s to 1980s, and then increased by 17.80% in the wet periods of 1990s (Gao et al. 2005). With the changes in runoff inputting lake, the lake area grew by 15.16% from 1990 to 1999, and then reduced by 10.69% in the wet seasons as total 22.76×10^8 m^3/yr water redirected to aliment the Konqi River and Tarim River at the downstream from 2000 to 2006.

The construction of reservoirs and dams were two other types of human interference that affected both of the runoff into the lakes and the outlets from them. The key supplied river of Balkhash was Ili River, which accounted for 73% of the total inflow and decreased by 77% of the pre-1969 mean values after Kapchagay Dam construction (Kezer and Matsuyama 2006), causing a sharp reduction in the level and area of lake. Zaysan was the outlet lake of the Irtysh River, and the lake level raised 6 m and the area increased since it became a part of the Buqtyrma Reservoir at the downstream.

Conclusion

The present study showed that more than half of the inland lakes (accounting for 93% of the area of nine lakes) had experienced significant decreases in surface area during the period from 1975 to2007.The total area of nine lakes continuously shrunk from 1975 to 2007. The trend of decreasing lake area extended from the eastern to the western part of the region, and this trend of lake changes was correlated to the variations of the spatial–temporal distribution in precipitation. The amount of precipitation had been showed decreased across the entire region, especially in the western parts of Turkmenistan, Uzbekistan, and Kazakhstan. The Aral Sea, Balkhash, and Ebinur basins were on the plains where precipitation had decreased to a very large extent, and correspondingly the surface area of the lakes had also shrunk significantly.

While lake changes in three different types had different change status due to the morphometic parameters, lake levels and water supplies. The alpine lake was less intervened by human activities and the lake variation was mainly caused by the climate change, and the lake surface area kept stable during the observed period. The terminal end lake at the downstream part of the basin was affected by both of climate changes and human activities, and water area had decreased by 56.7% since 1975. For the open lake at the midstream of basin, the outflow and increased water diversion broke the water balance and the changes in lake area were mainly affected by human activities.

The analysis based on satellite images in this research indicated that both climate change and human activities had importance effects on the changes in lake surface area in Central Asia, but anthropogenic effects are more dominated in plain lakes. The future research would focus on the quantitative analyses of the relationship among the changes in inland lake surface area, climate change and human activities over long time scales and assess the natural and anthropogenic impacts on the changes in the surface area of inland lakes.

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