Water Quantity and Quality of Six Lakes in the Arid Xinjiang Region, NW China

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Abstract Xinjiang arid region is situated in the hinterland of Asia, characterized by very low precipitation and high evaporation. Most lakes in the region have evolved naturally to salt lakes and lagoons over the long term. In recent decades, driven by continuous climate warming and human activities, the water quantity and quality of lakes have fluctuated frequently, which has had significant impacts on regional resources and the environment. In this article, the water quantity and quality of six lakes, from saline to fresh, were studied. They are located at different geomorphologic regions (e.g., mountains and plains) in Xinjiang, China. Mountain Lakes Kanasi and Sailimu have expanded slightly, but their water quantity and quality have not changed significantly over the past decade. Oasis lakes, such as Lake Bositeng and Lake Chaiwopu, and tail-end lakes, such as Lake Wulungu and Lake Ebinur, have reduced in area, and in general, the water has become saline. Lake changes were mainly responses to the regional climate change, although factors like human activities and basin morphological characteristics have led to individual differences in lake evolution. Changes in water quality and quantity are clearly linked. Where water quantity increased, water became less salty and vice versa. Over the past decade, water quality of the mountain lakes (Sailimu and Kanasi) were relatively stable, but oasis lakes (i.e., Bositeng and Chaiwopu) continue to deteriorate, whereas water quality of the tail-end lakes (Wulungu and Ebinur) display unstable hydrochemistry.

Keywords Xinjiang arid region · Lake variations · Human activities · Climate change

1 Introduction

In arid regions, water resources are particularly vulnerable and sensitive to climate change (Piao et al. 2010; Jia et al. 2004; Micklin 1988). Lakes in arid regions are important parts of the hydrologic cycle

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(Leng et al. 2012; Williams 1999). Lake evolution reflects changes in water resources in the lake drainage areas, as a result of climatic changes and anthropogenic impacts (Tranvik et al. 2009; Gikas et al. 2006; Battarbee 1999; Smol 1992). In inland northwest China, the climate became warmer in the 20th century (Ding et al. 2006). From the middle to the end of the last century, the annual average temperature increased by ~ 0.6 to 0.8 °C (Sha et al. 2002; Zhai et al. 1999), but the annual precipitation was variable and did not show a discernible trend. Compared to the 1950s, precipitation in the Xinjiang region in the 1980s has declined (Chen et al. 1991). Following the decreases in precipitation, there was a measurable reduction in river runoff in the arid region (Lai and Ye 1995; Ren et al. 2002). Combined with human exploitation of water resources, the warm and dry climate caused many inland lakes to reduce in size or nearly completely dry, with a consequent loss of riparian swamps and forests, and desertification. In the 1970s, the Lop Nur and Lake Taitema dried completely and became saline playas (Yuan and Yuan 1998). Consequently, the Taklimakan Desert expanded eastward and united with the Kumtag Desert. Since then, there have been irreversible environmental disasters. From the late 1980s to the beginning of the 20th century, Lake Ebinur and Manasi expanded, providing a sign of climate change in the Xinjiang region (Guo et al. 2003; Shi et al. 2007). Although this finding requires confirmation, Xinjiang lakes have apparently displayed a large expansion of surface area, corresponding to the wetter climate (Ma and Wu 2009; Wu and Ma 2011; Ma et al. 2013). Because of uncertainties about future human activities and climate changes, the fate of the lakes in the future remains unknown.

Using a survey of water quality and quantity in different types of lakes in Xinjiang, along with climate data from the drainage basins, the evolution of lakes in this arid region was studied. This study was designed to help understand the current conditions and future trends of the lakes in this arid zone. The insights it provides could also provide the scientific basis to prevent or solve current problems associated with the exploitation of the lake resources.

2 Regional Features and Lake Distribution

The Xinjiang Uygur Autonomous Region is situated in the northwest of the People's Republic of China. It is a vast territory with an area of 1.66×10^6 km². It is a hinterland and is the land area most distant from the sea in the world. It is dry, receives little rainfall, and belongs to the typical temperate continental arid climate, with an average annual precipitation of only 171 mm. From northeast to southwest, it is bounded by eight countries including Mongolia, Russia, Kazakhstan, Kyrgyzstan, Tajikistan, Afghanistan, Pakistan and India. The topography of Xinjiang can be summarized as “three mountains surrounding two basins.” In the north are the Altai Mountains, in the south are the Kunlun Mountains, and in the middle are the Tianshan Mountains, which divide Xinjiang into north and south parts. Customarily, the area south of the Tianshan Mountains is called Southern Xinjiang, whereas the north part is called Northern Xinjiang. The Tarim Basin in Southern Xinjiang covers an area of 530,000 km² and is the largest inland basin in China. The Taklimakan Desert, located in the middle of the Tarim Basin, with an area of about 330,000 km², is China's largest and world's second largest “mobile” desert. Currently, the number of lakes with an area >1 km² in Xinjiang is 108. Their total area is about 6236 km², accounting for approximately 7.7 % of the total area of the lakes in China (Ma et al. 2011). Lakes in the arid region can be classified into four types on the basis of salinity: (1) freshwater, (2) semi-saltwater, (3) salt water, and (4) dry salt. The lakes are important water resources in the region, playing an important role in the ecological integrity of the watershed and the sustainable development of the region and its economy. In this article, we report analysis of some typical lakes of the region, such as Lakes Sailimu, Ebinur, Bositeng, and Chaiwopu in the Tianshan recharge area, and Lakes Wulungu and Kanasi in the Altai Mountains recharge area (Fig. 1).

Fig. 1 Map showing the location of studied lakes in Xinjiang. Map A showing the location of Xinjiang (B) in China, map C is enlarged part B with numbered locations of studied lakes (1 Lake Kanas, 2 Lake Wulungu, 3 Lake Ebinur, 4 Lake Sailimu, 5 Lake Chaiwopu, 6 Lake Bositeng)

3 Field and Experimental Methods

From 2008 to 2009, the quantity and quality of water in Xinjiang lakes were investigated. A Southern Spirit boat SDE-28 echo sounder and Ling Rui S80 GPS positioning satellite system, produced by South Surveying & Mapping Instrument Co., Ltd., were used to survey the bathymetry of the lakes. The measuring accuracy of the instrument is 0.05 m. In the laboratory, isobath maps of selected lakes were created in ARCGIS 9.3 using data interpolation. A Multi-parameter YSI 6500 water quality analyzer was used to measure total dissolved solids, salinity, pH and conductivity. Water samples for anions and cations were filtered using 0.45- μm Whatman glass fiber filters, and then HNO_3 was added to adjust the sample pH to <2 for preservation. After transport to the laboratory, K^+ , Na^+ , Ca^{2+} and Mg^{2+} were measured by ICP-MS and Cl^- and SO_4^{2-} were measured by Ion Chromatography. Statistical analysis of the data was conducted using SPSS 13.0.

4 Water Quantity and Quality of Lakes in the Past Decade

4.1 Water Quantity

Oval-shaped Lake Sailimu is located in the western part of the Tianshan Mountains (Fig. 2). It is the largest mountain lake in Xinjiang. The present water elevation is 2071 m above sea level (asl), the maximum length is 28 km, the greatest width is 21 km, and the area is about 462 km^2 .

Fig. 2 Bathymetric maps of the studied lakes in the Xinjiang arid region

The maximum depth is 99 m. Lake Kanasi is the third deepest lake in China. The water surface is at 1362 m asl, the greatest length is 24 km, the maximum width is 2.6 km, and the area is 45 km². The maximum depth is 197 m. The lake receives most of its hydrologic input from glacial melt water and precipitation in the Kuitun and Youyi Mountains. Lake Bositeng, the largest lake in Xinjiang, is located in the southeast part of the Yanqi Basin and is surrounded by mountains with elevations of 2,000–3,000 m. The water surface lies at 1,050 m asl, the greatest length is 81 km, the greatest width is 42 km, and the area is 1,005 km². The maximum depth is 14 m. Lake Chaiwopu is situated in the Chaiwopu Basin. The basin is connected with the Junggar Basin to the west, and the Baiyanggou River links it with the Turpan Basin to the southeast. The lake surface is at 1,089 m asl and the lake has a maximum length of 6.8 km and maximum width of 5.6 km. The lake surface area is 29.6 km². The maximum depth is < 4 m. Lake Wulungu is located in the Fuhai Mountain Depression, Junggar-North Tianshan fold system. The lake lies at 482 m asl, with a maximum length and width of 45 and 26 km, respectively. The lake area is about 859 km². The maximum depth is 17.4 m. Lake Ebinur is located in the lowest part of Junggar Basin, and to the northwest is Alataw Pass, which is the second Asia-Europe continental bridge and a gateway to China. The lake surface lies at 194 m asl and it has an area of 527 km². The water body is 163 km long and it has a maximum depth of 1.8 m.

The mountain lakes are the main freshwater storage in the Xinjiang arid region. The area of Lake Sailimu is not large, but because of its great depth, its volume is 261×10^8 m³, equal to half that of the other five lakes combined. Water stored in Lake Kanasi is 43.44×10^8 m³, somewhat smaller than Lake Bositeng, which is 59×10^8 m³. The water volumes of Lake Wulungu and Lake Ebinur are 88.93×10^8 m³, 4.50×10^8 m³, respectively, and the water in Lake Chaiwopu amounts to only 0.63×10^8 m³. The area-volume variation with water depth curves for the six lakes are shown in Fig. 3. Differences between the six lakes are seen from these curves. The curves for Lake Chaiwopu and Lake Wulungu are similar. For depths of Lake Chaiwopu greater than 2 m, and for depths of Lake Wulungu greater than 6 m, as the

Fig. 3 Hypsographic (depth-area) curve and depth-volume curve of studied lakes in Xinjiang

water level increases the volume increases rapidly but the rate of area increase is lower. And when the water level declines, the water area and volume decrease sharply until the lake dries out. The curves for Lakes Ebinur, Sailimu and Kanasi have similar tendency in that the variation rate of area and volume with water depth is inconsistent. However, the changes of area and volume along with water depth is mainly synchronous for Lake Bositeng (Fig. 3). The divergences of the changes basically resulted from the shapes of different lake basins, and in turn, the diversities of lake responses to climate changes and human activities.

4.2 Water Quality

As shown in the Piper diagram of Fig. 4, the water in Lake Kanasi is bicarbonate-calcium-I type, the water in Sailimu Lake is sulfate-magnesium-II type, the waters in Lakes Wulungu, Bositeng and Chaowopu are sulfate-sodium-II type, and the water in Lake Ebinur is chloride-sodium-II type. The major cations in Lakes Wulungu, Bositeng, Chaowopu and Ebinur were K^+ and Na^+ , which accounted for 87 and 81 % of the total cations in Lake Chaowopu and Lake Ebinur, respectively. The major anion in Lake Kanasi was HCO_3^- , and the major anion in Lake Ebinur was Cl^- , which accounted for 54.1 % of the total anions. The major anion of the other lakes was SO_4^{2-} , with highest content (56 %) in Lake Chaowopu. The present water type of Lake Wulungu is SO_4^{2-} , with a concentration a little higher than that of Cl^- .

Overall, ion content in Lake Kanasi was lowest, the contents of Na^+ , K^+ , Ca^{2+} , Mg^{2+} , SO_4^{2-} and Cl^- in Lake Ebinur were the highest, and the content of HCO_3^- was highest in Lakes Chaowopu and Sailimu (Table 1). The water bodies with the highest and lowest pH were Lake Kanasi and Lake Sailimu, respectively. Lake Kanasi was the only freshwater lake and the salinity was 0.04 g/L, Lake Ebinur was a lagoon, and the other lakes were slightly salty lakes (Table 1).

4.3 Water Resource Variations in the Past Decade

Changes in lake volume and area over the last decade are different among the six lakes (Fig. 5). The areas of Lakes Bositeng, Ebinur and Chaowopu shrunk markedly, and their water volumes

Fig. 4 A Piper diagram groups the chemical water types of the studied lakes

declined, especially in recent years. But Lake Wulungu, despite shrinking from 2006 to 2008, has expanded since then. Mountain Lakes Sailimu and Kanasi remained relatively unchanged, with Kanasi fluctuating about the mean level, whereas Sailimu displayed a low, steady increase in water level. In 2002, the area and volume of Lake Bositeng reached their highest values of $1,146 \text{ km}^2$ and $72 \times 10^8 \text{ m}^3$, respectively. Values are declining thereafter, falling to the lowest points in 2009, with an area of 928 km^2 and a volume of $55 \times 10^8 \text{ m}^3$. The area declined by 16.7 % and the volume declined by 25.3 % compared to the 2002 values. After 2010, the area and volume remained relatively stable, and slightly increased. The area and volume of Lake Ebinur reached their greatest values from 2002 to 2005, respectively, 893 km^2 and $12 \times 10^8 \text{ m}^3$. The area and volume started sharply declining in 2006, and fell to their lowest values in 2009, respectively, 420 km^2 and $2.93 \times 10^8 \text{ m}^3$. In 2011, the lake area increased slightly, but the area and volume were only 52.9 and 75.5 % of their respective highest values. Changes in area and volume of Lake Ebinur were the greatest of all the lakes. Before 2008, the changes in the area and volume of Lake Chaiwopu were small, fluctuating from 28.9 to 29.5 km^2 and 0.56 to $0.63 \times 10^8 \text{ m}^3$, respectively. From 2002 to 2005, the area and volume were both high, but started declining fast after 2008. The lake area shrunk to 26.5 km^2 and the volume dropped

Table 1 Lake water quality variables

Lake name	pH	Salinity g/L	Cation (mg/L)				Anion (mg/L)			
			K ⁺	Na ⁺	Ca ²⁺	Mg ²⁺	HCO ₃ ⁻	CO ₃ ²⁻	SO ₄ ²⁻	Cl ⁻
Lake Kanasi	8.17	0.04	0.68	0.99	5.28	0.78	23.07	0.00	1.66	0.26
Lake Sailimu	9.17	2.75	31.20	326.25	7.03	383.64	554.01	117.85	1218.24	374.13
Lake Bositeng	8.65	1.48	22.01	263.78	49.61	94.91	177.64	30.45	486.54	286.13
Lake Chaiwopu	9.04	6.22	53.65	2006.5	41.88	129.67	871.71	117.20	3255.3	1216.6
Lake Wulungu	8.99	2.34	72.38	698.13	35.00	74.02	329.09	67.72	893.22	530.96
Lake Ebinur	8.40	102.4	546	27762	229	3215	279.55	29.52	32697	28704

Fig. 5 Lake volume and area changes over the past decade

sharply to $0.36 \times 10^8 \text{ m}^3$. Compared to the highest stage, the area declined by 10.2 %, and the volume declined by 41.8 %. The surface area and volume of Lake Wulungu fluctuated from 2000 to 2006, and dropped at a faster rate from 2006 to 2008, then rapidly increased after 2010, and reached the highest values of the past 12 years, which were 859 km^2 and $89 \times 10^8 \text{ m}^3$, respectively. The changes in area and volume of the mountain lakes were relatively small. The area and volume of Lake Sailimu from 2001 to 2011 were basically stable, fluctuating from 458.6 to 462.2 km^2 and 252.5 to $259.9 \times 10^8 \text{ m}^3$, respectively. Lake Kanasi fluctuated in area from 43.6 to 44.2 km^2 , and the volume varied between 42.4 and $43.0 \times 10^8 \text{ m}^3$. The change in area of Lakes Sailimu and Kanasi was 0.4 and 1.3 %, respectively. And the volume changes in Lakes Sailimu and Kanasi were 1.6 and 2.5 %, respectively. Both lakes were thus relatively stable.

Although most of the reservoirs and lakes in China are eutrophic due to the rapid economic development with little control of the nutrient inputs (Wu et al. 2012), the nutritional status of Lakes in Xinjiang is much better (Jiang et al. 2011). Only the northwest of Lake Bositent, among the studied lakes, occasionally reaches slight eutrophic status (Xie et al. 2011). Lakes in the Xinjiang region mainly displayed shifts in salinity and water chemistry. In the past decade, the salinity of each lake in the arid region changed along with the concentration of ions. The salinity of the water in Lake Bositent was about 0.4 g/L from 1958 to 1960, and started rising thereafter. From 1980 to 1991, the salinity stayed at a relatively higher level of 1.60 – 1.87 g/L . After 1992, the salinity began to decline and dropped to the lowest value, 1.17 g/L , in 2002. The salinity of Lake Bositent increased gradually from 2003, and reached 1.48 g/L in 2008. The salinity of Lake Wulungu was 2.72 g/L in 1959, and stayed at high values of 3.35 – 3.87 g/L during 1978 to 1987. In 1988, it declined to 2.74 g/L , and then continued declining year by year. In 2007, the salinity was reduced to 2.46 g/L (Li and Wang 2003), then decreased to 2.34 g/L in 2008 and 2.05 g/L in 2011. During 1988 to 2008, the hydrochemical type of Lake Wulungu changed from chloride-sodium-II type to sulphate-sodium-II type. The salinity of Lake Chaiwopu increased rapidly, from 3.62 g/L in 1996 to 5.16 g/L in 2006, then to 6.22 g/L in 2008, reaching 7.0 g/L in 2010. At the end of the 1940s, the salinity of Lake Ebinur was about 70 g/L . From 1950s to 1980s, washed salt-alkali water was imported into the lake, accelerating the increase in the salinity of Lake Ebinur, and the values reached 100 – 115 g/L at the end of the 1990s. In 2000, the value increased to 131 g/L . In 2002 the lake area expanded and the salinity declined to 92 g/L , and then increased to 102 g/L in 2008.

The salinity of Lake Sailimu was 2.85 g/L in 1988, 2.74 g/L in 2008 and 2.78 g/L in 2011. Thus, salinity changes in Sailimu were small. The salinity of Lake Kanasi in 1988 was 0.05 g/L (Wang and Dou 1998), 0.04 g/L in 2008, 0.05 g/L in 2009 and 2010. Overall, salinity changes across the lakes were comparable. From 2002, the salinity of Lake Bositeng increased rapidly. Salinity in Lake Wulungu fluctuated greatly and began to decline in 2008, whereas salinity values in the mountain lakes, i.e., Lakes Sailimu and Kanasi, were relatively stable.

5 Lakes Response to Precipitation Change

Data for precipitation and relative humidity were collected from 2000 to 2010 at six selected weather stations: (1) Fuhai in the Lake Wulungu area; (2) Dabancheng in the Lake Chaiwopu area; (3) Wenquan in the Lake Sailimu area; (4) Altai near Lake Kanasi; (5) Jinghe in the Lake Ebinur area; and (6) Yanqi in Lake Bositeng area (Fig. 6). Precipitation from 2000 to 2007 in Lake Wulungu did not display an obvious trend, but the lowest value occurred in 2008, and then precipitation began to increase. Relative humidity and precipitation were relatively stable, declined year by year from 2000 to the lowest values in 2008, and then started increasing. The lake areas and volumes changed along with it (Fig. 5). Precipitation and relative humidity in the Lake Chaiwopu area decreased from 2003, but the lake area changed slowly. After 2008, the lake area and water quantity began to change faster, especially in 2011. According to the data from Wenquan weather station, in the past decade, except for the high values around 2002, precipitation changed slightly, and correspondingly the relative humidity slightly fluctuated. The two variables show the same trends. In response to precipitation change, Lake Sailimu began to expand, but not dramatically. Except for the drought of 2008, precipitation and relative humidity fluctuated slightly in the Lake Kanasi area during the past decade, and the lake, correspondingly, did not change much. Precipitation and

Fig. 6 Precipitation and relative humidity changes in different lake regions over the past decade

relative humidity in the Lake Chaiwopu area fluctuated and high values appeared in 2002, but declined thereafter. Changes in precipitation were generally reflected by variations in the lake. Precipitation and relative humidity of the Lake Bositeng area decreased broadly from 2003, and the lowest values occurred in 2009. Changing trends in Lake Bositeng reflect relative shifts in precipitation.

6 Discussion and Conclusions

The lakes of Xinjiang region can be divided into three types based on their geographic locations: mountain lakes, oasis lakes, and tail-end lakes. In the past few decades, the mountain lakes (e.g., Lake Kanasi and Lake Sailimu) expanded to a certain degree, but the water quality and quantity slightly fluctuated. Oasis Lakes Bositeng and Chaiwopu and tail-end lakes Lake Wulungu and Lake Ebinur decreased significantly in size, but expansion of Lake Wulungu in the last 2 years was related to the large amount of winter precipitation. The lake variations generally reflected the climate changes. Because of local climate characteristics and different patterns of human activity among the lake basins, the evolutionary process has been different for each lake. Mountain Lakes Sailimu and Kanasi lie in rift basins with steep banks, and water nearly filled the basin. The lake areas have been stable and relatively insensitive to climate change. However, because there is little human influence on these lakes, any fluctuations in water level reflect regional climate changes. In the past decade, changes in Lake Sailimu clearly indicate regional climate change. On the other hand, because Lake Kanasi is an open lake, changes in lake area do not reflect periods of continuous wet weather. But because lake level was relatively stable, it indicates a lack of continuous drought in the region. Such a drought would convert the open lake to a closed system, with lake area declining continuously.

The areas of oasis Lakes Bositeng and Chaiwopu declined fairly consistently with the lower precipitation, but displayed some discrepancies in recent years. Precipitation in the Lake Bositeng area declined, accompanied by a drop in lake area. Precipitation at Lake Chaiwopu, however, did not display an obvious decrease, but the lake shrunk slowly anyway. The above phenomenon is attributed to human activities in the drainage area and basin morphology. Among the human activities in the drainage area that affected water quantity is the pumping of well water around the lake. In addition, Lake Bositeng is an open lake, and continuous shrinkage indicated a persistent drought. The water surface of closed Lake Chaiwopu was near the bottom of the basin. In the early stage of drought, the lake area did not change significantly, but the water volume did change, because the water level was low in the basin. Once water level falls considerably, the lake will shrink rapidly or even disappear. Lake Chaiwopu is now at the stage of rapid decline. Lakes Wulungu and Ebinur are tail-end lakes, with water supply coming mainly from mountain precipitation. Human activities along the river, like irrigation, could be used to meet industrial and agricultural needs. In the past decade, changes in the stage of Lake Wulungu have generally reflected climate shifts in the drainage, suggesting that the influence of water pumping is not obvious. In Lake Ebinur, however, changes are evidently influenced by human water consumption, and the lake did not respond to climate. Unlike Lake Ebinur, Lake Wulungu has expanded in the last 2 years, a shift closely related to the increase in precipitation in the Altai Mountains, especially the increase in winter precipitation. Precipitation in winter was in the form of ice and snow, and summer storms led to flooding and rapid expansion of the lake. Therefore, changes in the tail-end lakes depend on precipitation in the drainage area, but reflect the combined effects of precipitation and human activities in the plain parts of the drainage area.

Over the past decade, changes in lake water quantity of Xinjiang lakes were accompanied by shifts in water quality. Following increases in water quantity, lake waters became fresher. Now Lake Kanasi is a freshwater lake with stable water quantity, and the salinity of Lake Sailimu remains around 2.8 g/L. The salinity of oasis Lakes Bositeng and Lake Chaiwopu, increased quickly in recent years. Salinity of tail-end Lake Wulungu fluctuates greatly whereas Lake Ebinur is a salt lake with precipitating sulphate. Currently, nutrient enrichment is not a serious problem for all the studied lakes in arid Xinjiang.

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