Lake Area Changes and the main causes in the hinterland of Badain Jaran Desert during 1973–2010, China

ZhenYu Zhang, NaiAng Wang *, Ning Ma, Yue Wu

College of Earth and Environmental Science/Center for Climate Change and Hydrologic Cycle in Arid Region, Lanzhou University, Lanzhou, Gansu 730000, China

*Correspondence to: Dr. NaiAng Wang, Professor of College of Earth and Environmental Science, Lanzhou University. No. 222, South Tianshui Road, Lanzhou, Gansu 730000, China. E-mail: wangna@lzu.edu.cn

Received: March 13, 2013   Accepted: July 1, 2013

ABSTRACT

Lake area information in the Badain Jaran Desert in 1973, 1990, 2000, and 2010 was obtained by visual interpretation and water index analysis of remote sensing images, based on the spatial and temporal characteristics of lake area changes during 37 years. Results indicated that the number of lakes declined from 94 to 82 and the total surface area was reduced by 3.69 km² during 1973–2010. The desert lake area reduced by different degrees in different periods, but this occurred most rapidly during 1973–1990. According to the statistics of lake area changes, lake area decreases mainly occurred in the lakes with areas less than 0.2 km², while the areas of lakes greater than 0.9 km² only fluctuated. The changes of lake areas were probably due to changes in the quantity of underground water supplies rather than the effects of local climate change or human factors.

Keywords: Badain Jaran Desert; lake; area change; remote sensing; climate change; groundwater recharge change

1 Introduction

Lakes constitute an important component of the terrestrial hydrosphere and are highly sensitive to climate change. They are affected by both climate change and anthropogenic activities, making them significant indicators of global drivers and regional responses (Ma RH et al., 2011). Located in the margin of the monsoon region and spanning the provinces of Gansu, Ningxia, and Inner Mongolia, the Badain Jaran Desert has many lakes widely distributed in its southeastern area (Zhu et al., 1980). Because they are located in a hyper-arid zone, these lakes are important environmental resources and are highly significant in maintaining the regional biodiversity, preventing desertification of the surroundings, improving the regional ecological environment, and promoting the local people’s living standard. For these reasons, many scholars have focused on the water resources in this desert (e.g., Yang and Martin, 2003; Yang et al., 2003; Chen et al., 2004; Dong et al., 2004; Ma et al., 2004; Chen et al., 2006; Yang, 2006; Ding and Wang, 2009; Yang et al., 2010; Ma JZ et al., 2011; Chen et al., 2012; Dong et al., 2013). Because these desert lakes have changed frequently with the background of global warming in recent years, it is necessary to accurately understand the dynamic process of desert lake changes.

Remote sensing data is fast and easy to obtain, so this technology has been widely used in lake surveys and lake changes researches. Xiong et al. (2009) extracted lake information in the Badain Jaran Desert by supervised classification and visual interpretation, and pointed out that the desert lake area decreased during 1973–2007; they affirmed that human factors were the main reasons for the lake changes. From the special spectral characteristics of desert lakes, we were able to use the water index method to obtain lake information automatically and more precisely.
Many scholars have researched the causes of lake changes in China. The lakes in cold and arid regions are especially sensitive to climate change. Lakes in arid areas are affected mainly by precipitation (Ding et al., 2006), while lakes in the Tibetan Plateau are affected by air temperature and changes in recharge resources (e.g., precipitation, glacier meltwater), which are also affected by temperature on a regional scale (Ding et al., 2006; Li et al., 2011). The lakes in the mid-lower region of the Yangtze River are more controlled by human activities (Liu et al., 2006; Yang et al., 2011). Against the background of global warming in recent decades, are the changes in the sizes of lakes located in the hyper-arid region associated with regional climate change or anthropogenic factors, or any other factors? By revealing the change characteristic of desert lakes, not only from the standpoint of clarifying the main factors that change desert lakes, but also for further research on desert lake water balance, can provide some references on water supply sources and other scientific issues.

2 Materials and methods

2.1 Regional setting

The Badain Jaran Desert is located in the center of Alxa Plateau in western Inner Mongolia, a part of the Alxa Desert region, covering an area of 52,162 km²; it is the second largest desert in China (Zhu et al., 2010). The Badain Jaran Desert is bounded to the south by the Heli Mountains, the Beida Mountains, and the Heishantou Mountains that separate it from the Hexi Corridor. To the southeast, it is bounded by the Yabra salt lake and the Yabra Mountains, which separate it from the Tengger Desert. To the north and the west, it is bounded by the Guazihu wetland and the Gurinai grassland.

Climatically, the area is an extreme continental desert type (Dong et al., 2004), incurring extreme drought, strong sunshine, and relatively little precipitation (Ma et al., 2014). The mean annual precipitation decreases from southeast (about 120 mm) to the northwest (less than 40 mm) (Ma JZ et al., 2011). The mean annual air temperature ranges from 9.5 to 10.3 °C, and the temperatures increase from the south to the north as the elevation decreases (Dong et al., 2013).

More than 50% of the sand sea is covered by mega-dunes 200 to 300 m tall (Zhu et al., 1980), with the tallest mega-dune up to 430 m measured by field measurements. Lying among the tallest mega-dunes in the southeast are many permanent lakes that occur in low-lying areas throughout the desert with different sizes, shapes, and salinity levels. Besides, there are many fresh springs for human and animal to drink in some desert basins. These mega-dunes and inland lakes form a unique desert landscape that has potential value for tourism development.

In early September, 2010 and at the beginning of May, 2011, our research team surveyed all the lakes in the Badain Jaran Desert by fieldwork investigation. We defined each individual enclosed water body as a lake cell. Currently, there are 146 lakes in the Badain Jaran Desert, including 119 perennial lakes and 27 seasonal lakes. Nuoertu, the largest lake in the Badain Jaran Desert hinterland, can exceed 16 m in depth. In order to concentrate our lake change research, we selected the region in the southeast of desert as our study area, between longitudes 101°40'E and 102°40'E and between latitudes 39°30'N and 40°05'N, where more than 100 lakes are concentrated within this area of approximately 4,000 km² (Figure 1).

2.2 Methods

In the Badain Jaran Desert, each lake may be supplied in a different way, and within a given lake the areal size may fluctuate greatly within one year (Zhu et al., 2011). In spring, most lake levels are highest but decline dramatically in summer, and most of them remain relatively stable in autumn. Considering these periodic seasonal lake changes, we used only remote sensing images taken in autumn and we avoided the lakes recharged by glacier and snowmelt water coming from the Qilian Mountains or the Tibetan Plateau in spring (Chen et al., 2004, 2006), those that evaporated heavily in summer, and those where the lake surface froze in winter. Our image data were from October 7, 1973 (MSS), September 17, 1990 (TM), September 20, 2000 (ETM+), and August 23, 2010 (TM). All the images were provided by the U.S. Geological Survey’s web site; the quality of the images was fine and the cloud cover was always below 1%. The images were preprocessed by geometrical correction, image mosaicking, and subsets, and the map projection was Albers-Equal-Area conical projection.

The precipitation data (1971–2010) came from the Alxa Right Banner meteorological station (101°41'E, 39°13'N) and the Yabra meteorological station (102°42'E, 39°18'N), located on the southern fringe of the Badain Jaran Desert.

Remote sensing images record the reflection of electromagnetic waves by ground objects and its own outside radiation information. Compared with other objects, water bodies show a weak reflectivity (about 4%–5%), manifested in the visible wavelength range. As wavelengths increase, water body reflectivity decreases to 2%–3% at 580 nm. When the wavelengths are longer than 740 nm, the water body has the feature of strong absorption (McFeeters, 1996). Thus, this wavelength range can be used to distinguish water from soil, vegetation, buildings, and other ground objects (Jensen, 1996). For multi-spectral images, the ratio-based water index is effective for defining the scope of water bodies (Wang and Ma, 2009), such as NDWI (McFeeters, 1996),
MNDWI (Xu, 2005), EWI (Yan et al., 2007), and NWI (Ding, 2009). These water index models are suited to distinguishing background ground objects with soil, shadow, vegetation, buildings, and other descriptive information, but it is necessary to specify the desert lakes through the sand, vegetation and saline information. Taking this into consideration, Zhu et al. (2011) proposed a desert lake water index (DLWI):

\[
DLWI = \frac{b_{\text{blue}} - b_{\text{mir}}}{b_{\text{blue}} + b_{\text{mir}}} C
\]

In the Landsat TM and ETM+, \(b_{\text{blue}}\) is band 1, \(b_{\text{mir}}\) is band 5, and \(C\) is a constant to stretch the value of DLWI. Then, using threshold segmentation based on histograms, it is possible to extract the desert lakes information accurately.

Liu (1989) and Xiong et al. (2009), respectively, used the ratio method and supervised classification to extract lake information from MSS. However, those methods are not exact with desert lakes, especially the shadow information. In addition, MSS has a relatively low resolution; therefore, we used the visual interpretation method, first using image enhancement by LUT Stretch, and then taking into account the topography, solar altitude, lake survey results, and other factors to interpret lake borders to at least three pixels.

Our post-processing included: (1) eliminating the mistakes caused by lower solar altitude creating some "foreign bodies within the spectrum" between mega-dune shadows and lakes; (2) correcting redundancies where some dry saline lakes had DLWI values close to those of actual lakes; and (3) because some lakes shrank and divided in autumn, we unified the divided lakes into one lake in the same basin for improved statistical significance.

Finally, we used ArcGIS tools to compute the area and perimeter of each lake, and then formed four lake spatial databases. Figure 2 shows the distribution of the lakes at each time period.

3 Results

3.1 Characteristics of lake area changes

The number and areas of the lakes showed differences in each period. We interpreted 94 lakes larger than 0.0192 km², with a total area of 20.61 km² in 1973; in 1990, 2000, and 2010 there were 87, 98, and 82 lakes with total areas of 17.96 km², 17.41 km², and 16.92 km², respectively (Table 1).

During 1973–2010, the number of lakes showed a fluctuating trend that decreased, increased, and decreased again (Table 2). During that time period the total number of lakes was reduced by 12, with an annual average of −0.32. The number of lakes decreased by 7 during 1973–1990, with an annual average of −0.41, increased by 11 from 1990 to 2000, and decreased significantly from 2000 to 2010, with an annual rate of −1.6. The lake area changes showed a continuously decreasing trend in all of the lakes. During 1973–2010, the total lake area decreased by 3.69 km², with an annual change rate of −0.48%. The total lake area significantly decreased in
1973–1990, and the mean annual rate was −0.76%, greater than the rate of −0.31% in 1990–2000 and −0.28% in 2000–2010. This descending trend of the annual rate of lake area change indicates that the lakes shrank greatly during 1973–1990, but they have been shrinking slowly since the 1990s.

Table 1 Statistical results of lakes interpreted from remote sensing images

<table>
<thead>
<tr>
<th>Year</th>
<th>Number of lakes</th>
<th>Area (km²)</th>
<th>Perimeter (km)</th>
<th>Smallest lake area (km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1973</td>
<td>94</td>
<td>20.61</td>
<td>166.57</td>
<td>0.0192</td>
</tr>
<tr>
<td>1990</td>
<td>87</td>
<td>17.96</td>
<td>150.30</td>
<td>0.0036</td>
</tr>
<tr>
<td>2000</td>
<td>98</td>
<td>17.41</td>
<td>156.04</td>
<td>0.0036</td>
</tr>
<tr>
<td>2010</td>
<td>82</td>
<td>16.92</td>
<td>138.61</td>
<td>0.0036</td>
</tr>
</tbody>
</table>

Table 2 Statistics for long-term lake changes and annual rates of lake changes

<table>
<thead>
<tr>
<th>Years of period</th>
<th>Change in number of lakes</th>
<th>Total area change (km²)</th>
<th>Annual rate of change in lake numbers (/a)</th>
<th>Annual rate of total lake area change (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1973–1990</td>
<td>−7</td>
<td>−2.65</td>
<td>−0.41</td>
<td>−0.76</td>
</tr>
<tr>
<td>1990–2000</td>
<td>11</td>
<td>−0.55</td>
<td>1.10</td>
<td>−0.31</td>
</tr>
<tr>
<td>2000–2010</td>
<td>−16</td>
<td>−0.49</td>
<td>−1.60</td>
<td>−0.28</td>
</tr>
<tr>
<td>1973–2010</td>
<td>−12</td>
<td>−3.69</td>
<td>−0.32</td>
<td>−0.48</td>
</tr>
</tbody>
</table>

3.2 Characteristics of lake changes at different sizes

In our four lake databases, the largest lake area was more than 1.460 km², while the smallest area was only 0.0036 km². Counting the number of lakes in 0.1-km² increments, all the lakes were distributed in two area intervals: 0–0.6 km² and 0.9–1.5 km²; only six lakes were 0.9–1.5 km², and the other lakes area were less than 0.6 km², mostly between 0–0.1 km² and 0.2–0.3 km². Overall, the larger the lake area was, the fewer the lakes in the interval (Figure 3).

According to the distribution characteristics represented by figure 3, we classified the lakes into three classes based on their area sizes: larger than 0.9 km²,
between 0.2 and 0.9 km², and less than 0.2 km². We believed that this classification could avoid the effects of lake area changes on area intervals. Table 3 summarizes the statistics for lake information in the three size classifications.

There were six lakes larger than 0.9 km²: Nuoertu, Barunsumujilin, Cherigele, Yindeertu, Yihejigede, and Huhejilin. These lakes are large, deep, and have rich water resources, so they changed little during the study period. In the four time periods given above, the number of lakes in this classification was always six, the total lake areas ranged from 6.64 to 6.80 km², and the total perimeters of the lakes remained similar: 28.92 km, 29.70 km, 29.35 km, and 28.98 km, respectively. By visually assessing the lake spatial databases, we found that the lake areas of the six separate lakes fluctuated. For example, the area of Cherigele decreased and then increased, and the area of Yihejigede increased first and decreased afterwards. Thus, we can conclude the large lakes only fluctuated but did not shrink.

Lakes with areas between 0.2 and 0.9 km² showed a trend that first decreased and then tended to plateau in terms of their number, areas, and perimeters. During 1973–1990, the number of lakes declined by three and the total lake area declined by 1.027 km². In the period 1990–2010, these lakes were relatively stable: the number of lakes remained at 25 and their total area was larger than 8 km², and each lake changed little. During 1990–2010, the three lakes mentioned above did not disappear but shrank, and they were therefore transferred from the 0.2–0.9 km² class to the class less than 0.2 km².

As shown in table 3, the lakes in the class of area less than 0.2 km² shrank significantly, and the rates were descending. In 1973–1990, these lakes shrank the most rapidly, their total area declined by 1.61 km² (nearly 36%), the number of lakes declined by four (there actually were seven, including the three lakes transferred from the class of 0.2–0.9 km²), and their perimeters reduced by 11.31 km. In the period of 1990–2000, although the number of lakes was increased by 11, the total area still decreased. This shows that the lakes in 1990 shrank hard and the total area of the new lakes was quite small. In 2000–2010, these lakes continued to shrink, their number declined by 16, the total area was reduced by 0.49 km², and the total perimeter changed from 61.14 km in 2000 to 45.20 km in 2010, a reduction of 15.94 km.

We observed and contrasted the lake spatial databases from 2000 and 2010, and found that most of the disappeared lakes were of very small size or had been formed from lake division. This indicates: (1) not all of the lakes in the desert shrank during that time period; the lakes that shrank were mainly in the smaller area-size intervals; (2) there is some relationship between lake changes and their area size: the lakes that were larger than 0.9 km² only fluctuated, whereas those with areas between 0.2 and 0.9 km² decreased slowly and tended to be stable. Significant lake shrinkage mainly occurred in those lakes with areas less than 0.2 km², and its rate descended; and (3) the changes in lakes with areas less than 0.2 km² were complicated: the total number of lakes declined but there were some new lakes added; table 3 is just a statistics for the whole lakes information.

![Figure 3](image)

**Figure 3** Numbers of lakes of different sizes

<table>
<thead>
<tr>
<th></th>
<th>&gt;0.9 km²</th>
<th>0.2–0.9 km²</th>
<th>&lt;0.2 km²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1973</td>
<td>Number</td>
<td>Area (km²)</td>
<td>Perimeter (km)</td>
</tr>
<tr>
<td>1990</td>
<td>6</td>
<td>6.80</td>
<td>28.92</td>
</tr>
<tr>
<td>2000</td>
<td>6</td>
<td>6.78</td>
<td>29.70</td>
</tr>
<tr>
<td>2010</td>
<td>6</td>
<td>6.64</td>
<td>29.35</td>
</tr>
</tbody>
</table>

4 Discussion

In general, lake changes should be a result of both natural factors and human activities. Anthropogenic factors having great influence on lakes include diversion, drainage, lake reclamation, lake pollution, and eutrophication. In desert lake wetlands, the ecosystem is very fragile and vulnerable to human activities. The Badain Jaran Desert is sparsely populated, having less than one family per 10 km². The main activity of the locals is ani-
mal husbandry without farming. One ancillary discovery in our study was that there are rarely long-term lake changes directly caused by human activities. In recent years, as the locals' living standards have improved, more and more people choose to quit livestock grazing and move out of the desert, so they have little effect on desert lake changes. On the other hand, since 2000, tourism resources in the Badain Jaran Desert have been developing gradually. The local government is developing tourism while protecting the ecological environmental of the desert, to avoid irreversible harmful effects on desert lakes caused by tourism development. Therefore, it can be said that long-term changes of lakes in the Badain Jaran Desert are not influenced by anthropogenic factors.

Changes in lake levels are determined by the water balance in the water catchment. Within a given period of time, lake water level change is predicated by the water budget during that time. Without surface water runoff in this region, desert lake water changes only bear on the underground runoff, rainfall, and evaporation from the lake surfaces.

Figure 4 shows the precipitation change during last 40 years recorded by the Alxa Right Banner and the Yabra meteorological stations on the southern fringe of the desert. The mean annual precipitations in these two meteorological stations were, respectively, 117.6 mm and 89.7 mm per year—not significantly different. The annual precipitation had a slightly increasing trend (not significant at the 0.05 level), but the total lake area decreased in this period, so it can be inferred that the local precipitation was not the main factor affecting the lake area changes.

Figure 4: Variation of precipitation at Alxa Right Banner (a) and Yabra (b) in the southern Badain Jaran Desert during 1970–2010

Against the background of global warming, Peterson et al. (1995) found that, pan evaporation has tended to decline in the past 50 years. This was called the "evaporation paradox" by Michael and Graham (2002), and it has been confirmed by observations in many parts of the world (Cohen and Stanhill, 2002; Roderick and Farquhar, 2004; Bandyopadhyay et al., 2009). In China, evapotranspiration studies have shown that, in northwestern China and including western Inner Mongolia, pan evaporation and potential evaporation show a significantly decreasing trend (Ren and Guo, 2006; Xie and Wang, 2007; Liu et al., 2009). Although pan evaporation and potential evaporation are not equal to the actual evaporation of lakes, they should be on a coincident trend.

On the other hand, in September, 2010 our research group set up automatic meteorological stations and evaporation stations in the desert hinterland to continuously observe the water surface evaporation. We found that evaporation and wind speed are most closely related (results have not been published), and previous researches also confirmed that evaporation is closely related to wind speed in northwestern China (Zuo et al., 2005; Liu et al., 2009; Yi et al., 2010; Ma et al., 2012). However, climate change research pertaining to the Badain Jaran Desert shows that the wind speed in this area has decreased significantly since 1970 (Ma N et al., 2011). Therefore, in accordance with the above, we believe lakes evaporation in the Badain Jaran Desert has been declining in the last 40 years.

Nevertheless, evaporation in the Badain Jaran Desert is still strong: calculated by the modified Penman Equation approach, annual evaporation is 1,040 mm (Yang et al., 2010); our field observations of annual lake evaporation were also over 1,000 mm. Although the volume of annual precipitation is much lower than the losses caused by evaporation, desert lake water can remain relatively stable, suggesting that one or more stable water supplies (such as deep groundwater, which has not yet been confirmed) should be recharging the lakes. Based on the principle of water balance, if evaporation decreases and precipitation does not increase obviously, decreases in lake area are likely to be due to the decrease of groundwater recharge; in such cases, the volume of the recharge reduction is greater than the volume of the lake evaporation reduction. This also indicates that desert lake changes are not influenced by local (the Badain Jaran Desert) climate change but, rather, by changes in the groundwater recharge.

The problem of water recharge is not clearly understood and is subject to much scholarly dispute. Further research is needed on the contribution of each factor to lake area changes.

5 Conclusions

Based on the water index method and the visual interpretation method, we analyzed four Landsat remote sensing image datasets from 1973, 1990, 2000, and 2010 to study the change of lake areas in the Badain Jaran Desert. We obtained the lake change characteristics and features and combined them with local climate change and human activities analysis to determine the main causes of
the lake area changes. Our conclusions show:

1) The number and total area of the lakes in the desert hinterland changed considerably during 1973–2010: the number of lakes first declined and then increased, and then decreased in the last 10 years. The total number of lakes reduced by 12, by an average of −0.32 per year. The total lake area has declined by 3.69 km² in the past 40 years; the annual area change rate was −0.48%, and the rate of reduction decreased gradually.

2) Not all the desert lakes shrank during the study period: the lakes with areas greater than 0.9 km² only fluctuated, the lakes with areas between 0.2 and 0.9 km² decreased slowly and tended to be stable, and significant lake area decreases mainly occurred in lakes with areas less than 0.2 km², in which the rate changed from fast to slow.

3) Human factors and climate change are not the main factors of desert lake changes, but groundwater recharge is. Lake area decreases are likely due to the decrease of underground water recharge, but it is difficult to give a quantitative interpretation at this time.

Due to the spatial resolution limitations of remote sensors, some small lakes, especially those having a diameter less than 20 m, should be further investigated. Thus, our future work will address physical and chemical characteristics of desert lakes, such as salinity effects of evaporation, to analyze the spatial characteristics of lake area changes.

Acknowledgments:

This work is supported by the National Natural Science Foundation of China (41371114, 41101187), the National Environmental Protection Public Welfare Industry Targeted Research Fund (201209034), and the Ministry of Education, Humanities and Social Science Projects (10YJCH053).

References


