Monitoring dynamics and driving forces of lake changes in different seasons in Xinjiang using multi-source remote sensing

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\textbf{ABSTRACT}

Lakes are important for ensuring the development of the regional economy and ecological security. Based on MODIS and Landsat TM/OLI remote sensing images captured in 2005-2015 and a Combined Water Index (CWI), this paper extracted information on changes in the temporal and spatial characteristics and driving forces for lake areas in Xinjiang during past 11 years in different seasons (April, July and September). The results showed that over this time period, the area of the lakes exhibited an increasing trend. The largest surface area usually occurred in April, and the lowest value was measured in September. The lake shrinkage area in Xinjiang occurred mainly in Northern Xinjiang and the northeastern region of Southern Xinjiang, whereas the lake expansion area was concentrated in Eastern Xinjiang. Seasonal changes in Manas, Kanas, Barkol, Arkatag, Arik and Ebinur Lakes showed higher trends. Extracted the lake area based on the MODIS and TM/OLI image were analyzed, and both had a good corresponding relationship. The minimum $R^2$ was 0.548, and maximum RMSE was 44.1km$^2$. Therefore, it was feasible to use MODIS to extract lake area. These changes in lake area resulted from both natural factors and human activities, and coupled effects greatly accelerated local environmental changes.

\textbf{INTRODUCTION}

As an important repository of water resources in arid areas, lakes are important components of the water cycle in these areas, which require a balance between the fragile ecosystem and the demand for human economic and social development (Oki and Kanae, 2006; Kaplan & Avdan, 2017; Revelles and Geel, 2016; Song, Huang, & Ke, 2013; Wang, Liu, Zhang, Zhou, & Wang, 2000). Lakes are one of the most sensitive geographical units that respond to global climate change, and they are also affected by human activities. Therefore, changes in lakes will further affect the natural and social economic structure (Li, Liu, & Wang, 2014). As a special kind of water body, a lake is closely related to the atmosphere, biology, soil and other factors, and it is very sensitive to changes in the climate and environmental system (Ba, Bazhuoma, & Tao, 2011; Li, Xia, Li, & Zhang, 2015).

In recent years, with the development and application of remote sensing technology and geographic information technology, many scholars have used remote sensing images to obtain information on dynamic changes in lakes and to analyze the natural and human factors that lead to changes in lake area (Feng et al., 2012; Haas et al., 2011; Li, Gao, Li, Yan, & Xu, 2017; Li, Liu, & Wang, 2014; Wang, Shi, & Tang, 2011; Yang, Huang, Wu, & Jia, 2014). Li, Liu, & Wang, (2014) studied the dynamic changes in lakes in Northeast China; the results showed that the lake changes were influenced by natural factors and human activities, and the natural factors had a greater influence on the lakes. Yan and Zheng (2014) analyzed the effects of climate and human activities on lake changes. Cheng, Fu, Hu, and Li (2015) revealed that alpine lakes were more strongly influenced by climate, whereas open lakes were significantly affected by human activities. Song et al. (2014) used Landsat and MODIS imagery to extract water bodies using the object-oriented classification approach to study the distribution pattern of African surface water. Yang et al. (2014) predicted the future lake area under different water use levels. Many authors have studied changes in lakes in Xinjiang using satellite imagery, such as Landsat (Bai, Chen, Li, Yang, & Fang, 2011; Ma et al., 2010; Ma, Wang, Veroustraete, & Dong, 2007; Zhao et al., 2014), MODIS (Bai, Hua, & Lu, 2012; Chipman & Lillesand, 2007) and SPOT VEGETATION (Yang et al., 2014). Landsat TM imagery was used to analyze changes in the lake area in Xinjiang over the period 1975–2007, but only selected lakes were analyzed in spring and autumn (Bai, Chen, Li, Yang, & Fang, 2011). The above research was mainly concentrated on water areas and quantities.
in a specific region to interpret changes in the dynamic characteristics of lakes and their driving factors, as well as other scientific issues, and usually reflected long-term changes in the climate, geology, ecological environment and other related factors. By contrast, short-term lake changes have rarely been studied, and there is a lack of research on lakes in a specific geographic area division. One of the familiar image processing methods in extracting water area is based on a threshold of a water detection index. Modified Normalized Difference Water Index (MNDWI) (Xu, 2006), Normalized Difference Pond Index (NDPI) and Normalized Difference Water Index (NDWI) (McFEETERS, 1996) have been developed for water detection using remote sensing. NDWI uses green band and near-infrared (NIR) band to distinguish water from vegetation and soil. In order to enhance the ability of water detection, especially for areas with built-up land in the background, the middle infrared band was integrated into MNDWI and NDPI instead of NIR band in NDWI (Lacaux, Tourre, Vignolles, Ndione, & Lafaye, 2007). The result from NDWI shows an obvious underestimation of the lake surface area. An overestimation of lake surface area is observed from the MNDWI results (Li, Xia, Li, & Zhang, 2015). A Combined Water Index (CWI) combining short wavelength infrared (SWIR)’s and Normalized Differential Vegetation Index (NDVI)’s ability to represent vegetation information was proposed for water body identification using MODIS data.

In this study, using Remote Sensing, Geographical information System and Global Positioning System, we applied a CWI to extract the area of lakes. Changes in the temporal and spatial dynamics of lakes in Xinjiang were analyzed over the past 11 years in April, July and September, and the driving factors of the changes (e.g. climate change and human activities) were studied. The results of this study will help to improve the understanding of the spatial variation characteristics of lakes in the Xinjiang area, which is of great significance for climate change and lake early warning studies.

The purpose of the present study was (1) to estimate the change in the lake area of Xinjiang from 2005 to 2015 based on MODIS time series data, (2) to explore the causes of the changes in the lake area and (3) to examine the driving factors of the changes in the lakes in Xinjiang.

**Study area**

Xinjiang is located between 34°22' and 49°33'N and 73°32' and 96°21'E. It is a vast territory with an area of 1.66 × 10^6 km², comprising 1/6 of China (Figure 1). 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. Customarily, the area south of the Tianshan Mountains is called Southern Xinjiang, whereas the north part is called Northern Xinjiang.

Xinjiang’s climate is arid, with a mean annual precipitation of 100–200 mm. Most of the precipitation falls during the summer. In winter, the snow cover is shallow and persists until late February or early March. The average annual temperature is 9–12°C, and the annual accumulated temperature (≥10°C) is 2500–3500°C. The annual precipitation in this region normally ranges from 100 to 200 mm in the north and from 16 to 85 mm in the south. In general, the northern part of the region is wetter than the southern part. The evaporation capacity ranges from 1500 to 2300 mm in the north and from 2100 to 3400 mm in the south. The frost-free season lasts 180–220 days. The surface runoff derived from rainfall in the mountains and meltwater from glaciers and snow runs into the desert areas. Forests are sparsely distributed on high mountains and along rivers, and wide areas of arid land have a low vegetation cover. A total of 13 lakes were studied in this paper (Table 1).

**Materials and methods**

**Remote sensing datasets**

Terra MODIS images were selected as the main data source to monitor the dynamic changes in the lakes in Xinjiang. The MODIS surface reflectance (MOD09A1) dataset was used from 2000 to 2015 (Table 2). The study area was completely covered by six tiles (h23v04, h23v05, h24v04, h24v05, h25v04 and h25v05). The lake area of Xinjiang is relatively stable in spring and autumn. The lake area is mainly influenced by agricultural irrigation and higher evaporation in summer. Some lakes are frozen in winter, which may cause high uncertainty in lake area extent extraction. Therefore, images from April, July and September were used in this research. The maximum value composite was used to maximize the 8 days of the four phases of each month to obtain the maximum monthly value for the lake area.

Landsat data with 30-m resolution were used to verify the accuracy of the remote sensing products of 250-m (Carroll, Townshend, DiMiceli, Noojipady, & Sohlberg, 2009) resolution. A total of 29 Landsat image scenes (including Landsat 5 TM and Landsat 8 OLI) were processed for the validation (Table 3).
Lake extraction method

Large areas of deserts and bare rocks in Xinjiang have high sensitivity in the SWIR band (Lu et al., 2014). The spectral reflectance of water is low. In this study, water bodies from MODIS data were detected to calculate CWI. The calculation formula of CWI is as follows (Mo et al., 2007):

\[
\text{CWI} = (\text{NDVI} + \text{SWIR} + A) \times C
\]

\[
\text{NDVI} = \frac{b2 - b1}{b2 + b1}
\]

where b1, b2 and b7 represent the Red band (620–670 nm), NIR band (871–876 nm) and SWIR band (2105–2155 nm) of the MOD09 data, respectively. A and C are correction factors to adjust the data ranges of the CWI values. They are empirically determined by comparing CWI values between water pixels and the background of the study area. We set A as 0.4 and C as 100 in our study according to Mo et al. (2007). In addition, Li, Lu, et al., (2015) also set A as 0.4 and C as 100 to study lake change in Xinjiang. Because C and A can magnify CWI, which can make CWI positive value, and it is easy to analyze and compare. Figure 2 illustrates the procedure for extracting the lake area from the MODIS data.

The MODIS data in sinusoidal projection were mosaicked and re-projected, subjected to the maximum likelihood method, and saved in a GeoTIFF format using the MODIS reprojection tool.
The water and land boundary value is determined according to the threshold method; the man-machine interactive method is selected, with band7, band2, and band1 false color images used as references to extract the water area to achieve values that are in line with the actual water area. Finally, the threshold value of the water body is determined. However, there may be some areas that do not agree with the actual situation. Therefore, human computer interaction and visual interpretation should be adopted to correct the threshold value to ensure a satisfactory result. In addition, the atmosphere condition, water depth and chlorophyll content all have influence on the spectral features of water on remote sensing images. A single threshold value derived for one image might not be suitable for another. Since there is no standard threshold for the whole study period, an optimized threshold must be identified for each scene or each month (Li, Lu, et al., 2015). In this study, we set a different threshold for each time step and extracted water pixels. For the threshold selection, the training datasets that pixels were covered by water for all time steps were collected manually from MODIS data in July. The statistics of CWI values were calculated based on training samples. We choose two standard deviations of the mean CWI value as the threshold value and classify pixels within it as water and vice versa.

**Data sources of climate and human activities**

The possible drivers of lake area variations in Xinjiang were analyzed. Specifically, annual precipitation, annual mean temperature and evaporation were used as indicators of regional climate. Cultivated land and built-up areas were used as indicators of human activities. The monthly temperatures and precipitation in Xinjiang were obtained from 67 meteorological stations (National Meteorological Information Center of China Meteorological Administration; http://cdc.nmic.cn/home.do). Monthly values were averaged or summed (for precipitation, temperature and evaporation, respectively) to acquire annual values. For each variable, annual time series graphs were plotted for the 10-year study period, i.e. 2005–2015.

**Gravity center transfer model**

Temporal trends of the lake area can be depicted by the gravity center transfer model. The equations for calculating the center of gravity are given as follows (Duan, Wang, Xue, Liu, & Guo, 2014; Wang et al., 2000; Zhang et al. 2015): The movement of spatial distribution of the lake area was defined as the difference center of gravity in different periods. This application of the gravity center allowed us to quantify the direction and distance of change by
representing the shifts as vectors linking the gravity center from different periods.

\[ X_t = \frac{\sum_{i=1}^{N} (C_{ti} \times X_i)}{\sum_{i=1}^{N} C_{ti}} \]  

\[ Y_t = \frac{\sum_{i=1}^{N} (C_{ti} \times Y_i)}{\sum_{i=1}^{N} C_{ti}} \]  

where \( X_t \) and \( Y_t \) are the latitude and longitude coordinates of the gravity center of the lake in year \( t \), respectively; \( C_{ti} \) is the area of the lake in region \( i \) in year \( t \); and \( X_i \) and \( Y_i \) are the latitude and longitude coordinates of the gravity center in region \( i \), respectively. Comparing the gravity center at the start date and at the end date of the monitoring period, the temporal trends of the lake area could be traced (Wang et al., 2000).

**Results**

**Intra- and interannual lake dynamics**

The total area of 13 lakes in Xinjiang was calculated, and their intra- and interannual changes were analyzed (Figure 3). The total lake surface area showed an increasing trend for all 3 months from 2005 to 2015. In April, July and September, the trend was similar. The largest surface area usually occurred in April, and the smallest value was measured in September. The growth rate of the lake area in April was the fastest, followed by September. The largest surface area in April was measured in 2011, which was 5184.745 km\(^2\). The smallest surface area in April was measured in 2010, which was 4767.076 km\(^2\). The largest surface area in July was measured in 2009, which was 4513.458 km\(^2\). The largest surface area in September was measured in 2012, which was 4982.14 km\(^2\). The smallest surface area in September was measured in 2010, which was 4471.917 km\(^2\). Based on the above analysis, the temperature and evaporation in Xinjiang was lower from 2005 to 2015 than in other years, but there was higher precipitation than in other years. Therefore, the lake area was larger in 2011. For lakes located in high elevation areas, they were frozen and cannot be detected in winter and spring months. For lakes located in arid and semi-arid areas, some of them dried up in the summer months.

**Temporal variations of the lakes**

The spatial distribution characteristics of the area changes were closely related to the geographical location and climate of the lakes. Therefore, the spatial distribution characteristics of the lakes were studied, which can allow full understanding of the change trends of the lake and provide a more concrete basis for the factors driving the changes in the lake.

The interannual variation in the surface area of each lake is presented for April, July and September (Figure 4). We can observe that the area of Bosten Lake showed a decreasing trend in April, July and September, but the area of Ayakkum, Aqqikkol and Aksayquin Lakes showed an increasing trend in April, July and September. The other lakes remained relatively stable during the entire period. The surface area of Kanas Lake in April was typically greater than that in July and September. The seasonal variation in the lake area decreased. In April and July, the lake exhibited the same trends, but the trend in September was mostly the opposite. The largest surface area in April was measured in 2007, which was 56 km\(^2\). The

![Figure 3. Interannual variation in the total area of major lakes in Xinjiang in April (a), July (b), and September (c) from 2005 to 2015.](image-url)
smallest surface area in July was measured in 2009, which was 17.141 km$^2$. The surface area of Ulungur Lake in April was typically greater than that in July and September. The surface area in July and September indicated fewer changes than in April. The largest surface area in April was measured in 2011, which was 1018 km$^2$. The smallest surface area in July was measured in 2009, which was 955 km$^2$. There was a slight variation in the surface area of Jili Lake between July and September, and the interannual change in the lake area was relatively stable. The largest surface area in April was measured in 2011, which was 203.36 km$^2$. The smallest surface area in July was measured in 2009, which was 156.766 km$^2$. There was a slight variation in the surface area of Arik Lake between July and September, and the interannual change in the lake area was relatively stable. The largest surface area in April was measured in 2014, which was 70.408 km$^2$. The smallest surface area in July was measured in 2005, which was 48.322 km$^2$. The surface area of the Manas Lake showed a shrinking trend from 2005 to 2010. The smallest surface area of the lake was measured in September, which was 44 km$^2$. The surface area exhibited a significant expanding trend from 2010 to 2011. The largest surface area of the lake was measured in April, which was 281 km$^2$. The surface area of the Manas Lake showed a decreasing trend from 2011 to 2015. The surface area of Ebinur Lake, ranked in decreasing order, was April, July and September. The interannual change in lake area in April showed a slight variation, whereas the interannual change in lake area in July and September was higher. The largest surface area in April was measured in 2008, which was 940 km$^2$. The smallest surface area in September was measured in 2010, which was 520 km$^2$. The surface area of Sayram Lake was greater in April and July than in September. The surface area of Sayram Lake showed a slight decreasing trend. The largest surface area in April was measured in 2011, which was 421 km$^2$. The smallest surface area in July was measured in 2015, which

Figure 4. Interannual variation in the lake surface area of Xinjiang in April, July and September, from 2005 to 2015.
was 390 km². The interannual change in Barkol Lake was relatively high for April and September compared with July. The largest surface area in April was measured in 2008, which was 102 km². The smallest surface area in April was measured in 2010, which was 61 km². The seasonal difference in the area of Bosten Lake decreased gradually. The largest surface area in April was measured in 2005, which was 890 km². The smallest surface area in July was measured in 2012, which was 800 km². The surface area of Arkatag Lake in September was greater than that in April and July. The interannual change in the lake area in April and September was relatively stable, whereas that in July was higher. The largest surface area in September was measured in 2015, which was 223 km². The smallest surface area in July was measured in 2013, which was 153 km². The surface area of Aksayquin Lake, ranked in decreasing order, was September, July and April. The largest surface area in September was measured in 2014, which was 187 km². The smallest surface area in April was measured in 2005, which was 135 km². The interannual change in the area of Aqqikkol Lake exhibited significant expanding trends. The largest surface area in September was measured in 2012, which was 388 km². The smallest surface area in July was measured in 2007, which was 338 km². The interannual change in the area of Ayakkum Lake exhibited significant expanding trends, and the seasonal variation was low. The largest surface area in September was measured in 2015, which was 636 km². The smallest surface area in July was measured in 2007, which was 556 km². Plain lakes heavily influenced by human activities. This may indicate that human activities cause the lake to shrink, since most human settlements and agricultural lands are distributed along the Tianshan Mountains. Lakes where there is less human influence exhibited expanding trends, mainly due to changes in climate variables.

In summary, Kanas, Ulungur, Jili, Arik, Manas, Ebinur, Sayram, Barkol and Bosten Lakes had the largest surface areas in April. By contrast, Arkatag, Aksayquin, Aqqikkol and Ayakkum Lakes had the largest surface areas in September. Barkol and Aksayquin Lakes had the smallest surface areas in April. By contrast, Kanas, Ulungur, Jili, Arik, Sayram, Bosten, Arkatag, Aqqikkol and Ayakkum Lakes had the smallest surface areas in July, and Manas and Ebinur Lakes had the smallest surface areas in September. The largest lake surface area was measured in April, and the smallest lake surface area was measured in July.

Changes in the surface area of each lake were calculated for April, July and September (Figure 5). In April, the lake areas in mid-Northern Xinjiang and the northeastern part of Southern Xinjiang decreased whereas those in the northern and western parts of Northern Xinjiang, Eastern Xinjiang and the southern part of Southern Xinjiang tended to expand. In July, the lake areas in Northern Xinjiang and the northeastern and southeastern parts of Southern Xinjiang decreased whereas those in Eastern Xinjiang and the southern part of Southern Xinjiang tended to expand. In September, the lake areas in the northern and southwestern parts of Northern Xinjiang and the northeastern and southeastern parts of Southern Xinjiang decreased whereas those in the middle part of Northern Xinjiang, Eastern Xinjiang and the southern part of Xinjiang expanded. Overall, the lake areas in Northern Xinjiang and the middle part of Xinjiang decreased, whereas those in Eastern Xinjiang tended to expand.

Figure 4 and Figure 5 indicate that the lake surface area of Northern Xinjiang in April was greater than that in July and September, and the variation in the lake area remained relatively stable. The interannual change in lake area in Eastern Xinjiang was greater than in other areas. The lake surface area of Southern Xinjiang in September was typically greater than that in April and July, and the lake surface area exhibited an expanding trend.

The statistical results of the interannual variations in the surface area of each lake are listed in Table 4 (Feng et al., 2012). Seasonal changes in Manas, Kanas, Barkole, Arkatag, Arik and Ebinur Lakes were greater than in other lakes. Seasonal changes in Sayram, Ulungur, Jili, Bosten, Ayakkum and Aqqikkol Lakes were lower than in other lakes. The seasonal dynamics of Ebinur, Manas and Arik, Barkol, Kanas and Aksayquin Lakes are illustrated in Figure 6; these lakes have the highest seasonality. The pixel number, which was used to classify water, was calculated for April, July and September from 2005 to 2015. Different seasonal changes were observed for six lakes (Manas, Arik, Kanas, Barkol, Arkatag and Ebinur). Seasonal changes in Ebinur and Arkatag Lakes were greater than in other lakes. The surface area of Ebinur Lake was greatest in April and lowest in September. The surface area of Arkatag lake was greatest in September and lowest in July.

**Accuracy assessment**

In this paper, five lakes were selected to verify the extracted lake area of MODIS. The MODIS and TM/OLI extracted lake areas were significantly correlated (Figure 7). The smallest value of $R^2$ was obtained for Sayram Lake, which was 0.548. The largest RMSE was obtained for Ebinur Lake, which was 44.1km². The area of Ebinur Lake was very sensitive to inflow water, therefore, the seasonal distribution of water caused considerable differences in the area of Ebinur Lake during the year. Therefore, there was a greater difference in the extracted lake area of MODIS and that of TM/OLI.
In this study, we set a different threshold for each time step and extracted water pixels. We choose two standard deviations of the mean CWI value as the threshold value and classify pixels within it as water and vice versa. Due to the high concentration of salts and other dissolved minerals, the spectral feature of water in Manas Lake is different from other water bodies. Therefore, the identification of water pixels using a general threshold for all of the water bodies in the study area may lead to misclassifications. The atmosphere condition, water depth, water quality and chlorophyll content can also lead to lower accuracies. In summary, the extracted lake area may have had some errors, but these were within permissible limits. It was therefore feasible to use MODIS to extract the lake area. Mixed pixels of wetland and small water bodies can be misclassified as non-water bodies in Ebinur Lake due to the coarse resolution of MODIS data. The lake ice and snow can also lead to lower accuracies for plateau lakes like Ayakkum.

**Discussions**

**Driving force underlying lake changes in Xinjiang**

The lakes were mainly influenced by precipitation and water consumption, which were driven by climate and human activities. Human activities include the impairment of the water cycle as a result of large tracts of cultivated land and the expansion of construction land, and the natural factors include climate change. The change in the modern lake environment, especially over a short time scale, i.e. tens and hundreds of years, is closely related to human factors, and human factors were the main influential factors of the lake changes in the study area (Wang, Xue, Ji, & Yao, 2009).

**Effects of regional climate on lake changes**

Precipitation is one of the important recharge sources of lakes and has an important influence on lake changes.
The temperature, precipitation and evaporation data for Northern Xinjiang, Southern Xinjiang and Eastern Xinjiang are presented in Figure 8. The results show different trends for temperature and precipitation in these areas over the past 10 years. The change in precipitation can directly affect the area of stored water, whereas temperature indirectly affects evaporation (Liu et al., 2013; Sun, Zhang, Zhu, Pan, & Liu, 2017).

Precipitation initially decreased followed by increase, whereas evaporation increased first and then decreased as temperature increased, reaching the highest value in Northern Xinjiang from 2005 to 2007. The decreased area of water storage was caused by obvious climate change (Figure 8). A decrease in precipitation limits recharge from lakes and rivers, and an increase in temperature accelerates lake evaporation and reduces supplies from rivers, which results in a decreased area of water storage (Huang, Liu, Shao, & Liu, 2011). The temperature showed a decreasing trend from 2007 to 2012. Precipitation from 2007 to 2009 showed an upward trend and reached the lowest value in 2008 and the highest value in 2010. Evaporation reached its highest value in 2008 and its lowest value in 2010. Therefore, the

Figure 6. High seasonal variation lakes in Xinjiang for the months of April, July, and September from 2005 to 2015 (a) Manas and Arik Lakes; (b) Kanas Lake; (c) Barkol Lake; (d) Arkatag Lake; (e) Ebinur Lake.
water storage area decreased in 2008 and increased in 2010 (Figure 4). The temperature was higher in 2013 than in other years, precipitation was at an average level, and evaporation was low; therefore, the water storage area exhibited a decreasing trend (Figure 4).

Precipitation and temperature exhibited an increasing trend from 2005 to 2009 in Southern Xinjiang, and evaporation showed a decreasing trend in 2008. The temperature was lower and the precipitation increased significantly, especially in 2008, which significantly increased the recharge ability of the lakes resulting from precipitation (Yang & Lu, 2014). At the same time, a substantial decline in the temperature reduced lake evaporation and also reduced the evaporation intensity of the sources of the water supply; therefore, the lake area increased significantly (Figure 4). The temperature fluctuated within a certain level, and precipitation decreased from 2009 to 2014; the precipitation change was relatively stable after 2011, and evaporation showed an increasing trend; consequently, there was a decrease in the rate at which the lake area increased (Figure 4).

The temperature showed a decreasing trend, and the precipitation reached its lowest value in 2006 and its maximum in 2007. In addition, evaporation showed a decreasing trend from 2005 to 2008 in Eastern Xinjiang, which resulted in an increase in lake area. From 2008 to 2014, the temperature reached peak values, especially in 2009, 2011 and 2013; precipitation was at a low level, evaporation exhibited a fluctuating decrease, and the lake area was at a low level.

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. The surface area showed an increased trend after 1990s in Tienshan Mountains, Altai Mountains, northern Xinjiang, western Tarim basin and Yanqi basin (Bai, Chen, Li, Yang, & Fang, 2011). Glacial lakes, which form when a glacier retreats or are predominantly supplied by glacier meltwater, are widely distributed in glaciated regions. The trends of change toward a warmer-wetter climate and widespread glacial retreat contributed to the observed lake expansion. In inland river basins, changes in glacier mass balance not only influence glacier meltwater, but can also affect the “close lake”. The great retreat of glaciers provided substantial water for glacial lake

Figure 7. Relationship between the TM/OLI and MODIS lake area (a) Ebinur Lake; (b) Bosten Lake; (c) Ulungur Lake; (d) Ayakekumu Lake; (e) Sayram Lake.
expansion (Wang, Liu, Liu, Wei, & Jiang, 2016). In addition, substantial high-temperature permafrost developed in the glacial lake zone, which is sensitive to climate warming. This leads to lakes getting larger.

**Effects of regional human activities on lake changes**

Human activity is also an important factor that affects the lake area. Mainly embodied in agricultural and human water use, the lakes have been strongly affected by human activities in Xinjiang, and continued expansion of the cultivated area has increased the demand for water resources (Jiang & Huang, 2004). Therefore, the cultivated area and built-up area were used to represent the changes in regional water in this paper (Figure 9). Water used for agricultural irrigation is an important factor that affects the area of water storage (Piao et al., 2010). From 2005 to 2013, the cultivated area showed an increasing trend. In Xinjiang, the cultivated area was $3.7 \times 10^4$ hm$^2$ in 2005 versus $5.2 \times 10^4$ hm$^2$ in 2013, i.e. a 1.5-fold expansion over 9 years. The average annual cultivated area increased by $2 \times 10^3$ hm$^2$ from 2005 to 2009, and the average annual cultivated area increased by $1 \times 10^3$ hm$^2$ from 2009 to 2013. This shows the average annual increase in the cultivated area had decreased, and the expansion rate slowed down. The decrease in the growth rate of the cultivated area naturally led to a decrease in the water demand. The lakes provided a more secure supply for farmland water compared with recharge from natural precipitation, which led to a slight increase in the lake area as an important source of water supply for cultivated land.

Many lakes and wetlands were transformed into farmland as the population increased. In addition, the demand for food increased and the conflict between humans and land increased, which directly decreased the lake area or even dried up the lakes. The increased rate of the built-up area was higher than that of the cultivated area. The built-up area showed an increasing trend from 2005 to 2013, i.e. 600 km$^2$ in 2005 and 1066 km$^2$ in 2013, a nearly 1.8-fold increase in the built-up area over 9 years. The average annual built-up area increased by 40 km$^2$ from 2005 to 2009, and the average annual built-up area increased by 53.2 km$^2$ from 2009 to 2013, which shows an increase in the average annual built-up area, and the expansion rate was high. The increase in daily water consumption strengthened the demand for land surface and groundwater resources. A decrease in surface runoff, the groundwater level decreased and affected the volume of water flowing into the lakes. In turn, the decline in the groundwater level increased the exchange between groundwater and the water in the lakes; the water in the lakes recharged the groundwater, resulting in a new water balance (Wang & Zhang, 2002). This caused a reduction in the lake area and water salinization. However, the impact of the built-up land on the lakes in Xinjiang was lower than that resulting from the climate (Li, Lu, et al., 2015). Therefore, the lake area showed a slight increasing trend.

Author analyzed the comprehensive correlation between lake area and natural and human factors for

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**Figure 8.** Changes in the climatic factors in Xinjiang (a) Northern Xinjiang; (b) Southern Xinjiang; (c) Eastern Xinjiang.
studying influence factors of lakes in Xinjiang. Many scholars (Cai et al., 2017; Jiang et al., 2017; Zhang et al., 2015) also established a multiple linear regression equation to analyze changes based on natural and anthropogenic factors. In this paper, a multiple linear regression equation was established based on the analysis of the driving mechanism. Lake area was used as the dependent variable, temperature, precipitation, evaporation, cultivated land, and built-up area were used as independent variables. A multiple linear regression equation was established based on the analysis of the driving mechanism.

\[
Y = 1.007 - 0.4X_1 + 0.606X_2 - 0.5X_3
- 1.179X_4 - 1.433X_5
\]

where \(Y\) is lake area, \(X_1\), \(X_2\), \(X_3\), \(X_4\), \(X_5\) represent temperature, precipitation, evaporation, cultivated land, and built-up area, respectively. \(R^2\) was 0.731. Lake area was significantly correlated with temperature, precipitation, evaporation, cultivated land, and built-up area. It shows that the fitting model is better fitted with the data.

**Lake centroid displacement**

To further explore the shifts in the spatial distribution of the lake area in the study area, the movements of the centroids of the lakes were examined (Figure 10). From 2005 to 2015, the gravity center of the lake surface area exhibited varying degrees of migration. The gravity center of Arik and Barkol Lakes exhibited a northerly migration trend. The gravity center of Manas Lake exhibited a northwesterly migration trend. The gravity center of Kanas Lake exhibited a southwesterly migration trend. The gravity center of Arkatag Lake exhibited a northwesterly migration trend. The gravity center of Armatag Lake exhibited a southeasterly migration trend. The migration of the gravity center of Manas and Ebinur Lakes was significant, and the direction was irregular.

With the rapid development and wide application of remote sensing technology, combined with Remote Sensing, Geographical Information System, and Global Positioning System, there is higher accuracy and real-time data for remote sensing research on the dynamic changes in lakes. MODIS data were used to analyze the dynamic changes in the lakes in Xinjiang in this paper. The MODIS data resolution is 500 m and there may be some errors; however, analysis and comparison with Landsat data allowed the error to be restricted within an allowable range. Therefore, it was feasible to use the MODIS data to analyze the dynamic changes of the lakes. Using the Ebinur Lake area from September 2009 as an example, the area on Landsat TM data was extracted, which was 595 km². In addition, the area based on MODIS was extracted, which was 600 km², and the relative error was 0.91%. NDWI was used to extract the MODIS area of 557.01 km² (Liu, Zhao, Shi, & Fu, 2011). In this case, the relative error was 6.38%; therefore, the CWI can effectively improve the accuracy of the extracted area. In addition, the MODIS-extracted lake area was compared with data from other studies (Bai et al., 2012; Liu et al., 2011), for example, the Sayram Lake extracted area ranged from 402 km² to 416 km² in September 2005–2011, while the extracted lake area reported by Bai et al. (2012) ranged from 400 km² to 420 km² over the same period. The Jili Lake extracted area ranged from 164 km² to 176 km² in September 2005–2011, and the extracted lake area reported by Bai et al. (2012) ranged from 170 km² to 180 km² for the same period. The Barkol Lake extracted area ranged from 63 km² to 99 km² for September 2005–2011, and the extracted lake area reported by Liu et al. (2011) ranged from 50 km² to 90 km² for the same time period. The Sayram Lake extracted area was 408 km² in September 2009, and the extracted lake area reported by Liu et al. (2011) was 425.68 km² for the same time period. Although these data differed, the differences were not large and were within a feasible range.

Many changes occur over long-time series (Li, Xia, Li, & Zhang, 2015; Zhang, Shi, Zhou, Liu, & Qin, 2016), which usually reflect changes in climate, geology, the ecological environment, and other related factors. However, short-term changes are less frequently studied. Therefore, this paper studied the dynamic changes in the lakes in Xinjiang from 2005 to 2015. It mostly focused on the dynamic changes in the lakes over medium to large spatial scales. Due to the limitation of image resolution, sensitive small lakes that were affected by the environment and other factors were less studied.
We can study the dynamic changes in small-scale lakes with the development of high resolution satellite images. Lake change is the result of a variety of factors, and because of the complexity of various factors, the interaction effects also differ. Therefore, it is necessary to strengthen quantitative research on the contribution ratios of the main factors.

Conclusions

This study presented the extracted area using MODIS satellite remote sensing images from April, July and September over the period from 2005 to 2015. The temporal changes in the lake area and the driving factors in Xinjiang were discussed. The area of the lakes showed an expanding trend during the past 11 years. The largest lake area was usually measured in April, and the smallest value was measured in September. The largest surface area in April was measured in 2011, which was 5184.745 km$^2$, and the smallest surface area in September was measured in 2010, which was 4471.917 km$^2$. Lakes with shrinking areas in Xinjiang were mainly located in Northern Xinjiang and the northeastern region in Southern Xinjiang;
lakes with expanding areas were concentrated in Eastern Xinjiang.

In Northern Xinjiang, the lake area in April was typically greater than that in July and September, and the change in the lake area was relatively stable. Interannual variability in Eastern Xinjiang was larger. In addition, the lake area in Southern Xinjiang in September was typically greater than that in April and July, and the lake area showed an increasing trend. Seasonal changes in Manas, Kanas, Barkol, Arkatag, Arik and Ebinur Lakes were higher than in other lakes. In general, the migration of the gravity center of Manas and Ebinur Lakes was significant, and the direction was irregular.

The MODIS- and TM/OLI-extracted lake area was analyzed, which showed good correspondence; the minimum value of $R^2$ was 0.781, and the maximum value of RMSE was 4.4 km$^2$. Therefore, it was feasible to use MODIS data to extract the lake area.

The climate factors were more important for lake changes, while human activities such as the area of cultivated land and the built-up area had obvious effects on the lakes. Therefore, climatic factors and human activities both were important factors that affected the regional lake area.

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**Disclosure statement**

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