Postprint Study on Lake Changes in the Hulunbuir Grassland, Inner Mongolia

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Abstract

The Hulunbuir region of Inner Mongolia is characterized by numerous lakes with extensive areas, accounting for 58% of the total lake area in Inner Mongolia. In recent years, lakes in this region have exhibited a shrinking trend; however, existing research has primarily focused on large lakes, with a lack of comprehensive studies on the entire lake population in the region, particularly small lakes (<1 km^2). By employing Landsat series (TM, ETM+, OLI) satellite data, in conjunction with regional lake atlases, lake inventories, and high-resolution Google Earth imagery, we analyzed changes in lake number and area in the Hulunbuir grassland region from 1986 to 2017. Building upon this analysis and integrating climate and human activity data, we discussed the factors influencing lake changes. The results indicate that lakes in the Hulunbuir region have significantly shrunk over the past 30 years, with small lakes experiencing the most dramatic changes: 5 new lakes emerged while 19 dried up, and the total area decreased by over 30%. Prior to 2000, all lake types exhibited area increases; precipitation reached its maximum in 1998, with lake area peaking correspondingly. From 2000 to 2010, lake area displayed a shrinking trend, followed by a slight recovery after 2010. Correlation analysis between lake area and climatic conditions (temperature, precipitation, potential evapotranspiration) and anthropogenic activity factors (grazing intensity, raw coal production, effective irrigation area) demonstrates that lake area changes are predominantly influenced by human activities, whereas the impact of climate change is relatively minor.

Full Text

Changes in Lakes of the Hulun Buir Grasslands, Inner Mongolia

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Abstract: Lakes are important water reservoirs that play a crucial role in water supply and climate regulation, especially in arid regions. A large number of lakes are distributed across the Hulun Buir grasslands, which account for as high as 58% of the total lake area in Inner Mongolia, China. Subjected to significant climate change and intensive anthropogenic activities, lakes in the Hulun Buir grasslands have shrunk significantly. Shrinkage of the lakes in this region may accelerate grassland degradation and reduce the lakes' ecosystem services. However, long-term changes in the number and area of these lakes, especially the small ones (<1 km^2), are poorly understood. Using Landsat data (TM, ETM+, and OLI), in this study, we assess the changes in the number and area of lakes and their drivers in Hulun Buir between 1986 and 2017. The assessment especially focuses on small lakes because they are more sensitive to environmental changes and have more widespread influences on livestock production compared to large lakes. We first used Google Earth Engine to analyze the Landsat surface reflectance data and extract the water body coverage of the lakes based on the normalized differential water index. Then, we explored the changes in the lakes and their possible driving forces over the past three decades. The results showed a significant shrinkage in the lake area during the last three decades with the most dramatic change occurring in small lakes. Specifically, the number and area of small and large lakes showed a significant decrease, whereas the decline in the area of medium-sized lakes was insignificant. The temporal change in the area of the lakes was nonlinear, showing an increase before 2000 and a decrease after 2000. A correlation analysis of the regional changes in the lake area with climatic factors (temperature, precipitation, and potential evapotranspiration) and human factors (grazing, mining, and irrigation) indicated that the areal shrinkage of small lakes was mainly due to an increase in the cropland area and water consumption by irrigation and that the impacts of climate change are relatively minor. The decrease in the area of large lakes was mainly caused by water consumption because of coal mining. In addition, the warmer and drier climate contributes to the shrinkage in the lakes' area. Due to an increase in the area of agricultural land and exploitation of groundwater for coal mining, water consumption in this region stayed at a high level. The findings of this study recommend the optimization of industrial structure, upgrading of irrigation systems, and improvement of coal mining technology to protect lakes from further shrinkage and achieve a sustainable supply of water resources.

Keywords: Lakes; Landsat; Area change; Number change; Hulun Buir

Introduction

Hulun Buir City is located in eastern Inner Mongolia, between 115°31 ~126°04 E and 47°05 ~53°20 N, covering a total area of approximately 25×10^{4} km^2. Lakes are scattered throughout the region and serve as important intermediaries for water and gas exchange between groundwater, surface water, land, and atmosphere. They play vital roles in maintaining soil water retention, preserving vegetation diversity, and improving local microclimate conditions. The Hulun Buir grasslands constitute a major pastoral area in China. However, influenced by human activities and climate warming and drying, significant grassland degradation has occurred. Previous research indicates that lake shrinkage in this region has accelerated grassland ecosystem degradation and threatened the livelihoods of herders. Therefore, monitoring the distribution and changes of lakes in the Hulun Buir grasslands is essential.

Previous studies on lakes in the Hulun Buir region have primarily focused on large lakes such as Hulun Lake, while changes in small and medium-sized lake groups have received little attention. Related research shows that these widely distributed lake groups are significant for developing local grassland animal husbandry and industrial and agricultural production. Consequently, this study employs Landsat TM data, combined with climate and yearbook data, to analyze changes in lakes and their driving factors in the Hulun Buir region over the past three decades (1986–2017), with particular emphasis on small and medium-sized lakes. These smaller lakes respond more sensitively to environmental changes and have more widespread impacts on grassland animal husbandry. Since lakes in Hulun Buir are mainly distributed in the southwestern grassland area, this study selects six banners/cities in southwestern Hulun Buir (Xin Barag Right Banner, Xin Barag Left Banner, Chen Barag Banner, Hailar City, Evenk Autonomous Banner, and Manzhouli City) as the study area [Figure 1: see original paper].

1. Data and Methods

1.1 Data Sources

1.1.1 Landsat Satellite Data The Landsat series of remote sensing satellites provides data with a spatial resolution of 30 m. Since the successful launch of Landsat 1 in 1972, a total of eight satellites have been launched. Landsat 5 (Thematic Mapper, TM) data covers the period 1984–2013. Landsat 7 (Enhanced Thematic Mapper-plus, ETM+) data covers 1999–present (though data after 2003 has striping issues and cannot be used). Landsat 8 (Operational Land Imager, OLI) data covers 2013–present. For the specific study area, we utilized Google Earth Engine (GEE), a new platform for online visualization, computation, and analysis of various global-scale geoscience data, especially satellite data. GEE provides convenient data access, with archives of satellite data from the past 40 years, including Landsat and MODIS, and can quickly and batch-process target remote sensing images using cloud computing services, greatly reducing analysis time.

Considering that water area changes seasonally, lake area studies should select imagery from the same season. Based on the climate characteristics of Hulun Buir, we selected imagery from July to September, with cloud cover less than

10% for each image. All preliminary data processing was conducted on GEE. The Landsat data used were Surface Reflectance Tier 1 data, which have undergone atmospheric correction.

1.1.2 Meteorological and Yearbook Statistical Data Climate data were obtained from the China Meteorological Administration (http://data.cma.cn/data/cdcindex.html), including annual precipitation and mean annual temperature data from 8 meteorological stations in Hulun Buir, Inner Mongolia, from 1986 to 2017. Potential evapotranspiration was calculated using the Thornthwaite method. Data on raw coal production, grazing intensity (total year-end numbers of large livestock, sheep, and pigs), and effective irrigation area for Hulun Buir City were obtained from the *Inner Mongolia Statistical Yearbook*.

1.2 Analysis Methods

Various water body extraction methods have been developed in recent years, including single-band threshold methods, multi-band spectral relationship methods, water index methods, and other approaches such as neural networks and wavelet analysis. Water bodies have strong reflectance in blue and green bands, low reflectance in other bands, and near-zero reflectance in near-infrared bands. This characteristic makes water bodies significantly different from other land features in remote sensing imagery. The water index method is based on the reflection spectral characteristics of water bodies to construct an enhanced water information index model and uses thresholds to directly extract water bodies. Among these, the Normalized Difference Water Index (NDWI) has achieved ideal results in water body dynamic monitoring studies and is currently the most commonly used and widely recognized analysis method. Therefore, this study used the NDWI index to extract lake coverage.

The NDWI is calculated as:

$$NDWI = \frac{G - NIR}{G + NIR}$$

where G represents the green band: band 2 for Landsat 5 TM and band 3 for Landsat 8 OLI; NIR represents the near-infrared band: band 4 for Landsat 5 TM and band 5 for Landsat 8 OLI.

Since the baseline values of lake areas differ, to reflect the overall trend of lake area changes in a region, this study used the Relative Water Area (RWA) index to describe the relative area changes of all lakes in a certain region across different years. The calculation method is as follows:

$$RWA(\%) = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{A_i}{A_{si}}\right) \times 100$$

where n represents the number of lakes; A represents the average area of the ith lake in a certain period (km^2); A represents the area of the ith lake in the baseline year s (km^2). The baseline year in this study is the starting year of the data series.

1.3 Data Processing and Analysis

1.3.1 Image Data Processing We used GEE to process Landsat 5 TM, Landsat 7 ETM+, and Landsat 8 OLI data, and used matching pixel quality assessment data to remove non-clear-sky target pixels such as clouds, cloud shadows, and snow/ice. Spatial overlay and mosaicking were performed to obtain annual image data. The mosaicked image data were then subjected to overall quality assessment (checking whether the pixel missing rate was below 10% in the maximum cumulative water body area), and images with poor overall quality were removed.

1.3.2 Water Feature Identification Using the above formula, the NDWI was calculated, and areas meeting the threshold range (NDWI $>$ 0) were extracted as water body regions.

1.3.3 Classification Accuracy Assessment The overall accuracy and Kappa coefficient calculated from the error matrix were used to evaluate the accuracy of water body identification results. Taking the 2015 classification result as an example, high-resolution historical imagery data in Google Earth were used to select 200 verification points (the selection method involved uniform sampling at 0.01° intervals within the maximum cumulative water body area). Visual interpretation was used to establish a verification dataset. The statistical classification overall accuracy was 95.51%, and the Kappa coefficient (K) was 90.13%, indicating that the water extraction results have high accuracy and meet analysis requirements. The Kappa coefficient is calculated as:

$$K = \frac{\sum_{i=1}^{r} x_{ii} - \sum_{i=1}^{r}(x_{i+} \times x_{+i})}{N^2 - \sum_{i=1}^{r}(x_{i+} \times x_{+i})}$$

where r is the total number of columns in the error matrix (i.e., total number of classes); x is the number of samples in row i and column i of the error matrix (i.e., correctly classified samples); x and x are the total samples in row i and column i, respectively; and N is the total number of samples used for accuracy assessment .

1.3.4 Lake Change Analysis Since this study focuses on lakes in an open state, we referred to the *Chinese Lake Distribution Atlas* and *Inner Mongolia Lakes* catalog to remove water bodies such as rivers using Google Earth high-resolution imagery. Lakes were classified by area into small lakes (<1 km^2), medium lakes (1-10 km^2), and large lakes (>10 km^2). We first counted the number and area of lakes in each decade to analyze overall lake changes, then examined interannual variations in the number and area of each lake type, focusing on the emergence and disappearance of small and medium lakes, and discussed the driving factors of lake changes.

2. Results

2.1 Lake Distribution

In the study area in the late 1980s, there were 427 lakes with areas greater than 0.5 km^2, with a total area of approximately 2,416 km^2. Xin Barag Left Banner had the most lakes (about 180), accounting for 42% of the total number of lakes; followed by Xin Barag Right Banner with about 120 lakes, accounting for 28% of the total. The largest lake area was in Xin Barag Right Banner (approximately 2,152 km^2), accounting for 89% of the total lake area; followed by Xin Barag Left Banner (about 137 km^2), accounting for 5.7% of the total area.

When classified by lake area, small lakes were most numerous in Xin Barag Right Banner (105), followed by Xin Barag Left Banner (75). Medium lakes were most numerous in Xin Barag Left Banner (45), followed by Xin Barag Right Banner and Chen Barag Banner (both 15). Large lakes were most numerous in Xin Barag Right Banner (3), followed by Xin Barag Left Banner (2). The largest areas for both large and small lakes were in Xin Barag Right Banner (2,150 km^2 and 16 km^2, respectively), while the largest medium lake area was in Xin Barag Left Banner (47 km^2) [Figure 2: see original paper].

2.2 Changes in Lake Number and Area

Between 1986 and 2017, lakes in Hulun Buir showed a shrinking trend, with the most dramatic changes occurring in small lakes [Figure 3: see original paper]. Specifically, 52 small lakes dried up (approximately 12% of the total), with an area reduction of 33.3%; 4 medium lakes dried up (about 5%), but the area change was not significant; 1 large lake dried up (Danaichaolai Lake, an affiliated lake in the northeastern part of Hulun Lake). Regionally, the most dramatic changes occurred in Xin Barag Right Banner and Xin Barag Left Banner. In Xin Barag Right Banner, 30 small lakes dried up, 2 medium lakes dried up, and 1 large lake dried up. In Xin Barag Left Banner, 22 small lakes dried up and 2 medium lakes dried up, with no large lake loss.

2.3 Temporal Variations in Lake Changes

2.3.1 Interannual Changes in Lake Number and Area To examine the characteristics of lake changes in greater detail, we counted the number and area of lakes annually. The results showed that both the total number and total area of lakes decreased significantly between 1986 and 2017. Type-specific results indicated that the number of large lakes decreased by one, showing a significant downward trend in area (-13.2 km^2). The number of small lakes decreased significantly, with an average annual loss of 1.7 lakes, and the total area of small lakes decreased by an average of 4.0 km^2 per year. The number of medium lakes decreased by 0.7 per year, but the area change was not significant.

2.3.2 Emergence and Disappearance of Small and Medium Lakes Changes in the number of lakes in Hulun Buir are concentrated in small and medium lakes. Therefore, this study focused on the disappearance and emergence of small and medium lakes. Between 1986 and 2017, the number of small and medium lakes showed a nonlinear change: during the 1990s, the number of small and medium lakes increased significantly (with a cumulative net increase of 20 lakes), but after 2000, the number of disappearing lakes increased sharply, with a net decrease of 52 lakes [Figure 5: see original paper].

2.3.3 Overall Trends in Lake Area Changes Using the lake area in 1986 as the baseline, the RWA index was used to calculate the relative area changes of each lake type. Overall, lake areas shrank rapidly after 2000, with a slight recovery after 2010 [Figure 6: see original paper]. Before 2000, all lake types showed increased areas, with lake areas peaking in 2000 when precipitation was highest. After 2000, lake areas showed a shrinking trend, with some recovery after 2010. The area of large lakes continued to increase slightly after 2010, while the areas of small and medium lakes showed a decreasing trend.

3. Impacts of Natural and Anthropogenic Factors on Lake Area Changes

We analyzed the interannual variations in natural factors (precipitation, temperature, potential evapotranspiration) and anthropogenic factors (raw coal production, grazing intensity, effective irrigation area) in Hulun Buir from 1986 to 2017 [Figure 7: see original paper] and their impacts on changes in each lake type (primarily area changes) . We selected direct factors affecting lake changes to analyze human impacts. Research shows that open-pit coal mining in Hulun Buir destroys shallow aquifers, and coal production consumes large amounts of water (up to 2.5 tons of water per ton of coal), leading to increased irrigation water use and intensifying water resource shortages, which cause lake area reduction. Additionally, cultivated land expansion increases water consumption.

From the perspective of natural factors, precipitation showed no significant overall change, but was relatively low around 2000, when lake area and number also dropped sharply. Mean annual temperature increased slightly but not significantly, while potential evapotranspiration showed a significant increasing trend, indicating obvious warming and drying of the climate in Hulun Buir. From the perspective of anthropogenic factors, industry, agriculture, and animal husbandry in Hulun Buir developed rapidly after 2000, accelerating natural resource consumption and increasing water supply pressure. Raw coal production surged starting in 2002, reaching a maximum in 2011, then decreasing but remaining at high levels. Effective irrigation area and grazing intensity also increased rapidly after 2000 and have remained high despite fluctuations.

Correlation and linear regression analyses were used to quantitatively describe the contributions of these factors to area changes in each lake type . The results show that for small lake area changes, precipitation explained 35.4% of the variance, followed by effective irrigation area (31.2%). For medium lake area changes, effective irrigation area explained 38.5% of the variance, followed by precipitation (34.1%). For large lake area changes, raw coal production explained 33.5% of the variance, followed by effective irrigation area (31.1%). Potential evapotranspiration and temperature explained 6.7-6.8% of the variance for all lake types. Overall, area changes in small and medium lakes are mainly influenced by effective irrigation area and precipitation, while coal mining affects the disappearance of small lakes to some extent but has little impact on medium lake area changes. Large lake area changes are mainly affected by raw coal production and effective irrigation area, and warming has exacerbated lake area reduction to some extent. These findings are consistent with previous studies on large-scale lake changes in Inner Mongolia. Thus, the shrinkage of lake areas in this region is more heavily influenced by human activities, while climate warming and drying trends have intensified these changes.

4. Conclusion

This study analyzed lake area and number changes in Hulun Buir City and found that both the number and area of lakes showed a decreasing trend in recent decades, with the most dramatic changes in small lakes—52 small lakes dried up, with an area reduction exceeding 33.3%. Only one large lake dried up, and although four medium lakes dried up, the area change was not significant. Specifically, all lake types showed increased areas before 2000, with lake areas peaking in 2000 when precipitation was highest. After 2000, lake areas showed a shrinking trend, with some recovery after 2010. Statistical analysis shows that lake area changes are greatly affected by human activities, especially increased agricultural land area and irrigation water use from land use changes, which are the main causes of the decline in small and medium lake numbers and areas. Coal mining also consumes groundwater, causing lake drying. In addition, the overall regional climate warming and drying trend is another important factor causing lake shrinkage. Therefore, adjusting industrial structure, adopting new irrigation methods, and implementing more standardized coal mining practices are important approaches for lake protection in Hulun Buir.

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Note: Figure translations are in progress. See original paper for figures.