Postprint: Characteristics of Wuliangsuhai Lake Area Changes Under Dual Forcing of Climate Change and Human Activities in the Watershed Over the Past 40 Years

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Abstract

Lake area change serves as an indicator of climate change and human activities in watersheds, and clarifying the spatiotemporal dynamics of lake area is fundamental to assessing changes in lake ecological environments and their impacts. Based on Landsat series satellite imagery, the supervised classification method was used to extract the area of Wuliangsuhai Lake from 1986 to 2021; univariate linear regression, Mann-Kendall (M-K) trend test, and change-point detection were employed to analyze trends and abrupt changes in temperature, precipitation, relative humidity, and potential evapotranspiration in the Wuliangsuhai watershed; human activity data for the watershed were collected, and correlation analysis and multiple linear regression were applied to analyze the impacts of climate change and human activities on lake area variation. The results show: (1) The area of Wuliangsuhai Lake fluctuated and increased from 316.19 km^2 to 332.34 km^2, representing an increase of 5.11%; temperature in the watershed increased significantly, precipitation showed a small and non-significant increase, while relative humidity and potential evapotranspiration exhibited increasing trends, indicating overall warming of the watershed climate. (2) Lake area was positively correlated with temperature and precipitation, negatively correlated with relative humidity and potential evapotranspiration, and showed significant positive correlations with watershed population, gross domestic product (GDP), and crop sowing area. (3) From 2002 to 2021, the lake area expanded, with contribution rates of 76.83% from GDP, 18.37% from population, and 7.73% from potential evapotranspiration, indicating that lake area change was more strongly influenced by human activities.

Full Text

Preamble

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Characteristics of Wuliangsuhai Lake Area Changes Under Dual Drivers of Climate Change and Human Activities in the Basin Over the Past 40 Years

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Abstract: Lake area variation serves as an indicator of climate change and human activities within a basin. Clarifying the spatiotemporal dynamics of lake area is fundamental for assessing changes in the lake' s ecological environment and their impacts. Based on Landsat satellite imagery series, this study extracts the area of Wuliangsuhai Lake using supervised classification; employs univariate linear regression and trend analysis to examine trends and abrupt changes in temperature, precipitation, relative humidity, and potential evapotranspiration in the Wuliangsuhai basin; collects human activity data for the basin, and uses correlation and multiple linear regression analysis to investigate the impacts of climate change and human activities on lake area variation. The results show: (1) The area of Wuliangsuhai Lake increased from 316.19 km^2 to 332.34 km^2, an increase of 5.11%; basin temperature rose significantly, precipitation increased slightly and insignificantly, while relative humidity and potential evapotranspiration showed increasing trends, indicating overall warming in the basin. (2) Lake area is positively correlated with temperature and precipitation, and negatively correlated with relative humidity and potential evapotranspiration; population, GDP, and crop sown area in the basin are all significantly positively correlated with lake area. (3) During the lake area expansion period from 2002-2021, GDP contributed 76.83%, population contributed 18.37%, and potential evapotranspiration contributed 7.73%, indicating that human activities have a greater impact on lake area changes.

Keywords: lake area; water index; climate change; human activities; driving factors

Introduction

Lakes serve multiple ecological functions, including flood regulation, water supply, and biodiversity conservation, forming an indispensable barrier for ensuring water ecological security in river basins [1]. Rapid social development, population growth, and increasing industrial proportion have caused severe water shortages, with many lakes facing rapid area reduction and water volume decline. Liu Yekun [2] found that meteorological factors such as temperature, short-term evaporation, and precipitation significantly influence water area changes, while human activities—including increased industrial and agricultural water consumption, water supply sources, and channel blockages—alter lake evolution trajectories. Zhang Lu et al. [3] analyzed the main factors affecting Hulun Lake water volume using the water balance method and concluded that inflow runoff is the primary controlling factor. Li Junli et al. [4] indicated that climate fluctuations affect lake area changes over long time scales. Lake area variation results from the trade-off between precipitation, evaporation, and terrestrial water storage changes, influenced by both climate change and human activities. Understanding lake dynamics is crucial for regional ecological environment and socio-economic development.

Remote sensing interpretation for lake water information extraction has become a widespread trend. Optical remote sensing image water automatic extraction methods include threshold methods based on pixel classification and target classification methods [5], which are further divided into single-band threshold and multi-band methods. Liu et al. [6] proposed a "global-local" adaptive threshold segmentation method for water surface extraction using the normalized difference water index. Qi Changxian et al. [7] utilized the Google Earth Engine (GEE) remote sensing cloud computing platform to calculate modified normalized difference water index (MNDWI), normalized difference vegetation index (NDVI), and enhanced vegetation index (EVI) from satellite imagery data, classifying pixels as water when MNDWI>NDVI and MNDWI>EVI<0.1 to extract lake areas in the Three-River Headwaters region. Peng Yanfei et al. [8] calculated the normalized difference water index (NDWI) from Landsat and MODIS data, employing threshold segmentation to reclassify and extract Bosten Lake area from 2000 to 2019.

Previous studies have extensively investigated climate change characteristics [9], water environment evolution and assessment [10-11], nutrient migration and transformation mechanisms during ice-bound and non-ice-bound periods [12], plant community structure and distribution [13], and water balance [14] in the Wuliangsuhai basin. However, research on the coupled impacts of climate change and human activities on lake hydrological elements remains limited. Based on Landsat satellite remote sensing imagery, this study obtains long-term sequences of Wuliangsuhai Lake area, analyzes climate change characteristics in the basin, quantifies the impacts of human activities and climate change on lake area variation, explores the coupled driving mechanisms of climate change and human activities on Wuliangsuhai Lake area, and provides a basis for ecological restoration and management of Wuliangsuhai Lake.

1.1 Study Area Overview

Wuliangsuhai Lake is located in Urad Front Banner, Bayannur City, Inner Mongolia, at the eastern end of the Hetao Plain, bordered by the Yellow River to the west and south, the alluvial plain of the northern bank of the Yellow River to the east, and the alluvial plain at the southern foot of the Langshan Mountains to the north. Geographically, it is situated between 40°36 -41°03 N and 108°43 -108°57 E. The basin lies in an arid and semi-arid region of northern China, characterized by a mid-temperate continental climate with strong solar radiation and intense evaporation. The multi-year average temperature is 7.6°C, and the average annual precipitation is 100-200 mm. Wuliangsuhai Lake is an important component of the Hetao Plain irrigation water conservancy project, with water supply sources including drainage from main canals, precipitation, and groundwater recharge, while water losses primarily consist of surface evaporation, underground seepage, and discharge through the Wumaoji Drainage Gate [15].

[Figure 1: see original paper] Schematic diagram of the Wuliangsuhai Basin

1.2 Data Sources

Elevation data for extracting lake basin boundaries were obtained from the Geospatial Data Cloud (http://www.gscloud.cn). ASTER GDEM imagery was selected from the Geospatial Data Cloud. Landsat images from the flood season (July-September) were chosen; if data quality during this period could not meet requirements, images from other similar timeframes were used. Sentinel-2A imagery was sourced from the United States Geological Survey (https://earthexplorer.usgs.gov/). Meteorological data with a temporal resolution of 10 days were obtained from the China Meteorological Data Network (http://data.cma.cn), including daily-scale temperature, precipitation, and relative humidity data from meteorological stations around Wuliangsuhai Lake from 1980-2021. Hydrological data, including annual inflow volumes from the Eight, Nine, Ten, and Main drainage canals from 1986-2021, as well as outflow volumes through the Wumaoji Gate, were provided by the Bayannur Hydrology Bureau. As the basin largely overlaps with Bayannur City, socio-economic data—including population, gross domestic product (GDP), and crop sown area for Bayannur City from 1986-2021—were sourced from the *Inner Mongolia Statistical Yearbook*.

Remote sensing data information

1.3 Methods

1.3.1 Lake Surface Extraction Methods

Landsat imagery was preprocessed through radiometric calibration and atmospheric correction. Three methods were employed to extract Wuliangsuhai Lake water area: the normalized difference water index (NDWI), modified normalized difference water index (MNDWI) [21], the interspectral relationship method [22], and maximum likelihood supervised classification (Table 2). Among these, MNDWI could not accurately distinguish between reed-covered water surfaces and land (Figure 2). The interspectral relationship method could not differentiate between vegetation around the lake area and the lake itself, misclassifying vegetation in the northeastern part of the lake area as water. Supervised classification based on maximum likelihood provided better extraction results than MNDWI.

Formula for calculating water index

Note: Green = green band; Red = red band; NIR = near-infrared; MIR = mid-infrared; SWIR1 = shortwave infrared 1; NDWI = normalized difference water index; MNDWI = modified normalized difference water index. Same below.

Among the different water extraction models, NDWI showed the worst overall classification accuracy, Kappa coefficient, and mapping accuracy (Table 3), at only 39.62% and 15.68%, respectively—significantly lower than other methods and unsuitable for water extraction in the study area. Supervised classification achieved an overall classification accuracy of 97.80% with a high Kappa coefficient, and both its mapping accuracy and user accuracy were high, indicating effective extraction performance. Overall, the accuracy ranking of the four water extraction models was: supervised classification > MNDWI > NDWI. Supervised classification was ultimately selected to extract Wuliangsuhai Lake area.

Since 1986, Wuliangsuhai Lake area has shown a significant increasing trend ($Z=3.36$, $p<0.01$). During the study period, the average lake area was 338.36 km^2, with a coefficient of variation of 4.77%, indicating relative stability. The maximum lake area was 371.62 km^2 (in 2012), and the minimum was 303.96 km^2 (in 1986). The M-K mutation test results indicate that Wuliangsuhai Lake water area underwent an abrupt change in 2002. The average area from 1986-2001 was 326.07 km^2, while from 2002-2021 it was 348.20 km^2, representing an increase of 22.13 km^2.

Lake area changes were more pronounced on the western shore and relatively smaller on the eastern shore (Figure 4). The western shore connects sequentially from north to south to the Main Drain, Eight Drain, Tongji Canal, Nine Drain, Changji Canal, Tabu Canal, and Ten Drain, which link to the lake via irrigation and drainage channels. Affected by farmland irrigation return flow and Yellow River ecological water replenishment, the water area experienced significant changes.

[Figure 2: see original paper] Comparison of the results of different methods for identifying water bodies
Verification of water extraction accuracy
[Figure 3: see original paper] Annual changes in lake area from 1986 to 2021
Statistics of water area change from 1986 to 2023
[Figure 4: see original paper] Changes in lake area

1.3.2 Data Analysis Methods

The Penman-Monteith method recommended by the Food and Agriculture Organization (FAO) [23] was used to calculate potential evapotranspiration (ET$_0$):

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

where Δ is the slope of the saturation vapor pressure curve; R is net radiation; G is soil heat flux; γ is the psychrometric constant; T is air temperature at 2 m height; u$_2$ is wind speed at 2 m height; e is saturation vapor pressure; and e is actual vapor pressure.

Linear tendency estimation [24] was used to calculate the rate of change in climatic elements and analyze trends in lake area, temperature, precipitation, relative humidity, and potential evapotranspiration during the study period. The Mann-Kendall trend test and mutation test were employed to analyze the significance and abrupt changes in meteorological elements. Correlation analysis was used to identify the main factors affecting lake area. Multiple linear regression was applied to obtain regression coefficients for each influencing factor and calculate the contribution rate of different factors to lake area changes [25].

2 Results

2.1 Characteristics of Wuliangsuhai Lake Area Changes

2.2 Climate Change Characteristics in the Wuliangsuhai Basin

Trend analysis of meteorological elements in Wuliangsuhai (Table 5) shows that from 1980-2021, the basin’ s annual average temperature exhibited a significant increasing trend (Z=5.28, p<0.01), with a growth rate of 0.53°C·(10a)$^{-1}$ and a multi-year average temperature of 7.09°C. Annual average precipitation showed an insignificant increasing trend (Z=0.82, p>0.05), with a growth rate of 6.57 mm·(10a)$^{-1}$ and a multi-year average of 197.14 mm. Relative humidity showed a decreasing trend (Z=-1.56, p>0.05), with a decline rate of 0.38%·(10a)$^{-1}$ and a multi-year average of 47.58%. Potential evapotranspiration showed an increasing trend with a rate of 1.17 mm·(10a)$^{-1}$ and a multi-year average of 1144.98 mm. The basin climate is trending toward warming and drying.

Mutation test results (Figure 6) indicate that basin temperature, average relative humidity, and potential evapotranspiration underwent abrupt changes in 1997, 2002, and 2002, respectively, while precipitation showed no obvious abrupt change.

Test values of the change tendency rate and trend of meteorological elements in the Wuliangsuhai Basin from 1980 to 2021 (Z-value)
[Figure 5: see original paper] Trend change of meteorological elements

[Figure 6: see original paper] Analysis of sudden changes in meteorological elements

2.3 Changes in Drainage Water Inflow to the Lake

The Main Drain receives return water from Drains 1-7 in the Hetao Irrigation District and discharges it into Wuliangsuhai Lake via the Honggebu Pumping Station, serving as an important reflection of the irrigation district’ s climate and hydrology. From 1986-2021, the Main Drain discharge showed a fluctuating increasing trend, with a maximum discharge of 9.27$×10^{8}$ m^3 (in 2020) and a minimum of 2.357$×10^{8}$ m^3 (in 1986). The annual average inflow to the lake was 5.14$×10^{8}$ m^3. Total inflow to the lake showed an increasing trend, with a maximum total inflow of 10.31$×10^{8}$ m^3 (in 2020) and a minimum of 3.59$×10^{8}$ m^3 (in 1986). The multi-year average total inflow was 6.15$×10^{8}$ m^3. The average annual discharge through the Wumaoji Gate was 2.84$×10^{8}$ m^3, with a maximum discharge of 6.15$×10^{8}$ m^3 (in 2019) and a minimum of 0.11$×10^{8}$ m^3 (in 2004).

Due to ecological water replenishment in the Yellow River basin, inflow volumes have increased, while lake discharge has gradually decreased, reducing the difference between inflow and outflow (Figure 7). The changing trends of total inflow and discharge are consistent, maintaining the basic ecological water demand of Wuliangsuhai Lake. In recent years, increased water retention and consumption in the lake area have been observed. Lake area increased during the initial ecological water replenishment period but began to decrease later, indicating that human activities in the basin partially offset the area expansion brought by ecological water replenishment.

[Figure 7: see original paper] Water inflow and outflow from Wuliangsuhai Lake from 1986 to 2021

2.4 Human Activity Changes in Wuliangsuhai

Bayannur City’s GDP showed a growth trend from 1986-2021 (Figure 8), increasing from 1.55$×10^{10}$ yuan to 9.82$×10^{10}$ yuan. Population showed a trend of initial increase followed by decrease, growing from 1.45$×10^{6}$ people (in 1986) to 1.79$×10^{6}$ people (in 2015), then declining sharply to 1.52$×10^{6}$ people (in 2021). The crop sown area in Bayannur City showed an overall increasing trend, reaching a maximum of 7.60$×10^{5}$ hm^2 (in 2016) and a minimum of 4.77$×10^{5}$ hm^2 (in 1986), with a stepped decline after 2016. Both GDP and crop sown area showed significant upward trends.

[Figure 8: see original paper] Changes in human activity indicators from 1986 to 2021

2.5 Correlation and Contribution Rate Analysis

2.5.1 Correlation Analysis Pearson correlation analysis was conducted between Wuliangsuhai Lake area changes and temperature, precipitation, relative humidity, potential evapotranspiration, Bayannur City population, GDP, and crop sown area (Table 6). Lake area showed a positive correlation with precipitation ($r>0.05$), as increased rainfall raises basin runoff and inflow to the lake, expanding its area. Lake area showed a positive correlation with temperature ($r<0.05$), because higher temperatures increase crop water consumption in the irrigation district, leading to increased irrigation water use and subsequently more drainage discharge into the lake, further expanding lake area. Relative humidity and potential evapotranspiration showed negative correlations with lake area ($r>0.05$), with correlation coefficients of <0.05. Population, GDP, and crop sown area showed significant positive correlations with Wuliangsuhai Lake area, with correlation coefficients of <0.01, <0.01, and <0.01, respectively. Total inflow showed a negative correlation with lake area ($r>0.05$), with a correlation coefficient of <0.05. Human activities in the Wuliangsuhai basin are complex; expanded crop sown area and land use changes increase potential evapotranspiration, reducing basin water yield and requiring more water for local consumption and vegetation growth, while increased ecological water replenishment enlarges lake area.

Correlation coefficients between lake area and climate and human activity indicators from 1986 to 2021

2.5.2 Contribution Rate Analysis A multiple linear regression model was established between lake area and other indicators. Indicators not significantly correlated with area were sequentially removed, while significantly correlated indicators were gradually introduced to determine the final model equation [26] for analyzing lake area change causes and providing references for area change prediction. The model's goodness-of-fit R^2 value was 0.713, indicating that independent variables could explain approximately 71.3% of the dependent variable variation. Significance tests on regression coefficients for each factor showed that potential evapotranspiration, population, and GDP had significance P values less than 0.05. The regression equation was:

$$y = 0.573 \times \text{GDP} + 0.031 \times \text{Population} + 414.594$$

Lake area simulated values were calculated according to the linear regression equation. A scatter plot was created with remotely sensed extraction values as the x-coordinate and corresponding simulated values as the y-coordinate (Figure 9). Most points were uniformly distributed on both sides of the 1:1 line, indicating good model fit.

Using the lake area mutation year 2002 as a benchmark, the period 1986-2001 was defined as the baseline period to analyze each factor' s contribution to area change during the 2002-2021 expansion period (Table 8). Compared with the baseline period, Wuliangsuhai Lake's average area increased by 22.13 km^2 during 2002-2021. Population increase of 7.10$×10^{4}$ people and GDP increase of 5.49$×10^{10}$ yuan contributed to lake area increases of 4.07 km^2 and 17.00 km^2, respectively. Potential evapotranspiration decrease of 12.21 mm and total inflow increase of 0.68$×10^{8}$ m^3 caused lake area to decrease by 2.34 km^2 and increase by 1.71 km^2, respectively. The contribution rates of population increase, GDP growth, and potential evapotranspiration reduction to lake area change were 18.37%, 76.83%, and 7.73%, respectively. Human activities contributed more to lake area changes than climate factors.

[Figure 9: see original paper] Correspondence between the extracted and simulated area values of Wuliangsuhai Lake
Lake area and hydrometeorology, partial regression coefficients of human activities and their t-test
Influence and contribution rate of influencing factors on lake area change from 1986 to 2001 and from 2002 to 2021

3 Discussion

Meteorological data indicate that the Wuliangsuhai region experienced rising temperatures, minimal precipitation change, and increasing potential evapotranspiration. Ma Long et al. [18] showed that the Hetao region had a significant warming trend and fluctuating decreasing precipitation over the past 50 years. Zhang Baolong et al. [19] analyzed climate change in the Wuliangsuhai basin, reporting increasing trends in both temperature and precipitation, suggesting the basin is undergoing a drying process consistent with global warming trends [27].

Wuliangsuhai is a river-formed lake whose western basin primarily consists of a water circulation system of "Yellow River water diversion → old Yellow River channel water transfer → Wuliangsuhai purification → drainage"[28]. The basin' s dryness degree and runoff magnitude are influenced by water diversion from the Sanshenggong Yellow River diversion point. Ecological water replenishment for Wuliangsuhai began in 2003, but the introduced volume was not substantial. After drainage facility improvements in 2014, water replenishment efforts increased, reaching 2.5$×10^{8}$ m^3 in 2020. The Wuliangsuhai basin is dominated by irrigated farmland. Correlation analysis shows that basin population, GDP, and crop sown area are all significantly positively correlated with lake area. Therefore, the study concludes that during the research period, intense human activities in the basin consumed more water resources while also increasing drainage discharge after production and domestic use, thereby increasing inflow to the lake. This study found that Wuliangsuhai' s area expansion over the past 40 years resulted from Yellow River irrigation return flow and reed planting around the lake.

Previous studies show that Wuliangsuhai Lake area remained relatively stable during the study period, with slight expansion and an abrupt change in 2002. Li Shanyang et al. [29] indicated that the area basically stabilized after 2014, with slow expansion. Li Shuai et al. [30] reported that Wuliangsuhai Lake volume showed an overall declining trend. In basin hydrological cycles, rainfall is the most direct water supply source for lakes, particularly for those in arid and semi-arid regions where precipitation reduction can easily cause river drying and lake disappearance [31]. The insignificant correlation between precipitation and Wuliangsuhai Lake area suggests that most rainfall-generated runoff is artificially intercepted and consumed. The significant positive correlation between lake area and temperature (r=0.351) contrasts with Zhang Na et al. [32], who found that increased evaporation reduced water area and level, causing lake shrinkage. This difference occurs because artificial reed planting maintains lake area at a certain level. Wuliangsuhai' s reed area is 134.243 km^2, water area is 161.092 km^2, with reeds covering approximately 45% of the total lake area. Artificial reed planting began in 2002 and has been expanding, reaching 14.46 km^2 in 2002 and 28.12 km^2 in 2014.

Increased ecological water replenishment is another important factor in Wuliangsuhai area changes. This study found that ecological water replenishment corresponded temporally with the lake area mutation, indicating that ecological water replenishment promoted lake area increase. The contribution rate of potential evapotranspiration was 7.73%, causing lake area to shrink by 2.34 km^2. The contribution rate results demonstrate that human activities have a greater impact on Wuliangsuhai Lake area, though the influencing factors are complex and require further investigation.

4 Conclusions

Based on remote sensing imagery data from 1986-2021, this study analyzed area changes in Wuliangsuhai Lake, a typical arid region lake, and investigated influencing factors using multi-year measured meteorological and human activity data in the basin. The main conclusions are:

(1) During the study period, Wuliangsuhai Lake area showed an increasing trend ($Z=3.36$, $p<0.01$), with an abrupt change in 2002. The minimum lake area was 303.96 km^2 (in 1986) and the maximum was 371.62 km^2 (in 2012), with water surface changes following a pattern of initial increase followed by decrease.

(2) The Wuliangsuhai basin' s annual average temperature showed a significant increasing trend ($Z=5.28$, $p<0.01$), annual precipitation showed an insignificant increasing trend ($Z=0.82$, $p>0.05$), annual average relative humidity showed a decreasing trend ($Z=-1.56$, $p>0.05$), and potential evapotranspiration increased at a rate of 1.17 $mm \cdot (10a)^{-1}$. The basin climate is transitioning toward warming and drying. Basin temperature, average relative humidity, and potential evapotranspiration underwent abrupt changes in 1997, 2002, and 2002, respectively. All human activity

indicators showed increasing trends, indicating continuously strengthening human activities in the basin.

(3) Wuliangsuhai Lake area showed an insignificant positive correlation with precipitation and a significant positive correlation with temperature. Correlation coefficients with relative humidity and potential evapotranspiration were >0.05 and <0.05, respectively. Stepwise multiple linear regression analysis indicated that GDP contributed most to lake area change at 76.83%, followed by population increase at 18.37% and potential evapotranspiration at 7.73%. Complex and varied human activities were the primary drivers of Wuliangsuhai Lake area expansion from 2002-2021.

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