Impacts of climate change and human activities on water resources in the Ebinur Lake Basin, Northwest China: Postprint

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Abstract

Changing climatic conditions and extensive human activities have influenced the global water cycle. In recent years, significant changes in climate and land use have degraded the watershed ecosystem of the Ebinur Lake Basin in Xinjiang, Northwest China. In this paper, variations of runoff, temperature, precipitation, reference evapotranspiration, lake area, socio-economic water usage, groundwater level and water quality in the Ebinur Lake Basin from 1961 to 2015 were systematically analyzed by the Mann-Kendall test methods (M-K) mutation test, the cumulative levelling method, the climate-sensitive method and land-use change index. In addition, we evaluated the effects of human activities on land use change and water quality. The results reveal that there was a significant increase in temperature and precipitation from 1961 to 2015, despite a decrease in reference evapotranspiration. The Wenquan station was not significantly affected by human activities as it is situated at a higher altitude. Runoff at this station increased significantly with climate warming. In contrast, runoff at the Jinghe station was severely affected by numerous human activities. Runoff decreased without obvious fluctuations. The contributions of climate change to runoff variation at the Jinghe and Wenquan stations were 46.87% and 58.94%, respectively; and the contributions of human activities were 53.13% and 41.06%, respectively. Land-use patterns in the basin have changed significantly between 1990 and 2015: urban and rural constructed lands, saline-alkali land, bare land, cultivated land, and forest land have expanded, while areas under grassland, lake, ice/snow and river/channel have declined. Human activities have dramatically intensified land degradation and desertification. From 1961 to 2015, both the inflow into the Ebinur Lake and the area of the lake have declined year by year; groundwater levels have dropped significantly, and the water quality has deteriorated during the study period. In the oasis irrigation area below the runoff pass, human activities mainly influenced the utilization mode and quantity of water resources. Changes in the hydrology and quantity of water resources were driven primarily by the continuous expansion of cultivated land and oasis, as well as the growth of population and the construction of hydraulic engineering projects. After 2015, the effects of some ecological protection projects were observed. However, there was no obvious sign of ecological improvement in the basin, and some environmental problems continue to persist. On this basis, this study recommends that the expansion of oasis should be limited according to the carrying capacity of the local water bodies. Moreover, in order to ensure the ecological security of the basin, it is necessary to determine the optimal oasis area for sustainable development and improve the efficiency of water resources exploitation and utilization.

Full Text

Preamble

Impacts of Climate Change and Human Activities on Water Resources in the Ebinur Lake Basin, Northwest China

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Abstract: Changing climatic conditions and extensive human activities have profoundly influenced the global water cycle. In recent years, significant alterations in climate and land use have degraded the watershed ecosystem of the Ebinur Lake Basin in Xinjiang, Northwest China. This paper systematically analyzed variations in runoff, temperature, precipitation, reference evapotranspiration, lake area, socio-economic water usage, groundwater level, and water quality in the Ebinur Lake Basin from 1961 to 2015 using the Mann-Kendall (M-K) mutation test, cumulative leveling method, climate-sensitive method, and land-use change index. Additionally, we evaluated the effects of human activities on land-use change and water quality. The results reveal that temperature and precipitation increased significantly from 1961 to 2015, despite a decrease in reference evapotranspiration. The Wenquan station, situated at a higher altitude, was not significantly affected by human activities, and its runoff increased significantly with climate warming. In contrast, runoff at the Jinghe station was severely impacted by numerous human activities and decreased without obvious fluctuations. The contributions of climate change to runoff variation at the Jinghe and Wenquan stations were 46.87% and 58.94%, respectively, while the contributions of human activities were 53.13% and 41.06%, respectively. Land-use patterns in the basin changed significantly between 1990 and 2015: urban and rural construction lands, saline-alkali land, bare land, cultivated land, and forest land expanded, while areas under grassland, lake, ice/snow, and river/channel declined. Human activities have dramatically intensified land degradation and desertification. From 1961 to 2015, both inflow into Ebinur Lake and the lake area declined year by year, groundwater levels dropped significantly, and water quality deteriorated. In the oasis irrigation area below the runoff pass, human activities mainly influenced the utilization mode and quantity of water resources. Changes in hydrology and water resources were driven primarily by the continuous expansion of cultivated land and oasis, as well as population growth and the construction of hydraulic engineering projects. After 2015, the effects of some ecological protection projects were observed. However, there was no obvious sign of ecological improvement in the basin, and some environmental problems persist. On this basis, this study recommends that oasis expansion should be limited according to the carrying capacity of local water bodies. Moreover, to ensure the ecological security of the basin, it is necessary to determine the optimal oasis area for sustainable development and improve the efficiency of water resources exploitation and utilization.

Keywords: climate change; human activities; runoff; water resources; groundwater level; climate-sensitive method; Ebinur Lake Basin

1 Introduction

Water resources strongly influence social and economic development in arid regions (Boehmer et al., 2000; Wang et al., 2017). Moreover, water systems are highly sensitive to climate change (Patz et al., 2000). According to the Fifth Assessment Report of the Intergovernmental Panel for Climate Change, the global mean air temperature rose by 0.85°C between 1880 and 2012 (Carraro et al., 2015). Over the past 60 years, the mean annual temperature in Northwest China has been rising at a rate of 0.039°C/a (2.78 times the global average), while precipitation has been increasing at a rate of 1.00 mm/a (1.39 times the Chinese average rate). This indicates that Northwest China is highly sensitive to global climate change (Ohmura and Wild, 2002; Mora et al., 2013). In the future, climate warming will aggravate water shortages in Northwest China, thereby posing more apparent threats to ecological security (Chen et al., 2010; Chen et al., 2012).

Large-scale agriculture, economic restructuring through reclamation of unusable land, population growth, urban development, and land-use changes are the most evident examples of human activities affecting Earth' s natural ecosystems (Yang et al., 2017, 2019, 2020; Gu et al., 2020). Land-use management for sustainable development is an important research field for both global and regional environmental change (Alvarenga et al., 2015; Priess et al., 2015; Madhusoodhanan et al., 2016). In 1995, the International Geosphere-Biosphere Program and the International Human Dimensions Program on Global Environmental Change instituted the Land-Use and Land-Cover Change (LUCC) research program. The impacts of LUCC on hydrology and water resources attracted the attention of scholars in geography, ecology, biochemistry, and environmental geology (Huang et al., 2014; Liu et al., 2016; Mirzaei et al., 2016). Land-use change in a drainage basin not only influences local surface runoff but also affects evaporation, water quality, water volume, and groundwater levels. Moreover, it has far-reaching impacts on the hydrological cycle and the distribution of water resources (Narsimlu et al., 2013; Harrison et al., 2015; Hammouri et al., 2017). In recent years, extensive research has revealed that the impacts of LUCC on hydrological processes in a drainage basin vary based on different geographical features (Lee and Biggs, 2015). Therefore, empirical studies on representative regions are required to establish a generalized theoretical system to account for the impacts of LUCC on hydrological processes in a drainage basin (Tamene et al., 2014; Buysse et al., 2016; Tzabiras et al., 2016).

In the Ebinur Lake Basin of Northwest China, humans have intensively exploited land and water resources over the past six decades (Viola et al., 2014; Leng et al., 2015; Shrestha and Htut, 2016). A series of hydraulic engineering projects (e.g., the construction of barrages, reservoirs, and canal systems) have also been undertaken (Hu et al., 2002; Abuduwaili et al., 2007; Xia et al., 2011). In addition, there has been a significant increase in cultivated land and population, and land-use patterns have changed considerably (Mu et al., 2007). A combination of these factors has considerably influenced the hydrological cycle of the basin. Significant changes in runoff distribution, surface evaporation, soil water regime, vegetation coverage interception, water quality, and water volume have also been observed (Hu et al., 2002). Lake surface area has remarkably decreased, accompanied by a drop in groundwater level, water quality deterioration, cut-off in the Kuytun River, reduced inflows, and severe degradation of natural vegetation. The lake ecosystem in the Ebinur Lake Basin has undergone retrogressive evolution, thus triggering conspicuous ecological degradation (Yao et al., 2014). Furthermore, such changes have had considerable negative impacts on industrial and agricultural production, transportation, and the physical and psychological health of residents. In addition, environmental changes can pose threats to social and economic development activities and to regional ecological security on the northern slopes of the Tianshan Mountains and even in Xinjiang of Northwest China (Hu et al., 2002; Abuduwaili et al., 2007; Xia et al., 2011). Therefore, by exploring land use and focusing on water resources utilization, the present study investigated the facilitation of efficient exploitation of local water resources and promotion of ecological restoration through sustainable land use in the Ebinur Lake Basin, particularly with regard to hydrology and water resources. In addition, the results of the present study can offer theoretical guidance and reference information on the improvement of inland river ecology and conservation of water resources in arid regions.

Many scholars have provided key recommendations for the sustainable development of the Ebinur Lake Basin based on data collected from the basin (e.g., runoff measurements from gage stations, groundwater level quantity and quality, evaporation, socio-economic data, and remote sensing data) (Li et al., 2007; Mu et al., 2007; Dong et al., 2009; Qiao et al., 2010; Liu et al., 2011; Bai et al., 2012; Meng et al., 2015). The present study differs from previous studies as it established a hydrological process variation analysis method based on climate change and human activity responses. Thus, this study comprehensively evaluated the impacts of climate change and human activities on hydrology and water resources in the Ebinur Lake Basin during 1961–2015, containing an analysis of changes in surface runoff, water resources distribution, lake area, and lake volume. Furthermore, the effects of land use, including water conservancy projects, on total utilization of water resources, groundwater levels, and water quality in the Ebinur Lake Basin are also determined and analyzed.

2.1 Study Area

The Ebinur Lake Basin lies between 43°38 N and 45°52 N and between 79°53 E and 85°02 E (Fig. 1 [Figure 1: see original paper]) in Xinjiang Uygur Autonomous Region, Northwest China. It includes Jinghe County, Bole City, Wenquan County, and Ala Pass City in Bortala Mongolian Autonomous Prefecture of Xinjiang, covering an area of 2.7×10^{4} km^2. Given the large-scale agricultural reclamation and water diversion projects that have been undertaken in the Kuytun River Basin since the 1950s, the surface runoff connection between the basin and Ebinur Lake has been nearly severed; therefore, only a limited amount of water enters Ebinur Lake during the flood season (Qiao et al., 2010; Liu et al., 2011). Moreover, the Jinghe River and Bohe River are the major rivers influencing the hydrology of the Ebinur Lake Basin. In this study, the Ebinur Lake Basin refers mainly to the Jinghe River Basin and Bohe River Basin.

The Ebinur Lake Basin lies in the mid-latitude region of the Eurasian hinterland and is relatively distant from the ocean. There are high mountains to its north, west, and south, resulting in a typical temperate arid continental climate characterized by low precipitation, high evaporation, abundant sunlight, and extreme weather patterns. Such climatic characteristics, coupled with the unique landform, generate abundant and strong gusts of wind as well as frequent sand storms and dust movements in the basin.

In 2019, the total water resources of the Ebinur Lake Basin were 23.93×10^{8} m^3, among which the water resources of Jinghe County, Bole City, Wenquan County, and Ala Pass City were 10.15×10^{8}, 5.97×10^{8}, 7.76×10^{8}, and 0.05×10^{8} m^3, respectively. There is an uneven distribution of precipitation throughout the year. Specifically, in the plain and mountainous areas, precipitation is mainly concentrated in spring and summer, accounting for 68.5%–85.0% of the annual precipitation, while it is less in winter, only accounting for 1.6%–12.1%. The maximum amount of four-month precipitation occurs between April and

July in the plains and between May and August in the mountainous areas.

In the past, the Ebinur Lake Basin consisted of 47 rivers of various sizes. The plain area experiences low precipitation and produces virtually no runoff. Precipitation is the main source of river runoff in the mountainous area. However, most of the river runoff penetrates the soil and is lost at the alluvial fan outside the mountain pass. As a result, water enters Ebinur Lake indirectly as an undercurrent or river supplement. Only a few rivers supply water directly to Ebinur Lake during the flood season. Rivers with annual runoff exceeding 1.00$×10^{8}$ m^3/a include the Jinghe, Daheyanzi, Wuerdakesai, and Bohe rivers (Bai et al., 2012; Meng et al., 2015). The Ebinur Lake Basin can be divided into two drainage basins on the basis of the associated river systems: the Jinghe River Basin in the east, which mainly contains the Tuotuo, Aqiale, and Jinghe rivers, and the Bohe River Basin in the west, which mainly incorporates the Daheyanzi, Wuerdakesai, and Bohe rivers.

2.2 Data Collection and Management

Meteorological data were obtained from the National Meteorological Information Center (NMIC) of the China Meteorological Administration (CMA; http://data.cma.cn). The data included monthly temperature, monthly precipitation, and monthly evapotranspiration from ground-based meteorological stations covering the period from 1961 to 2015.

The hydrological data used in this study are as follows: (1) daily, monthly, and annual runoff values of four hydrological stations (Jinghe, Bole, Wenquan, and Ala Pass) in the Ebinur Lake Basin from 1961 to 2015; (2) daily, monthly, and annual runoff values of four inlets in the Ebinur Lake Basin from 1989 to 2019; (3) groundwater level, water quality, and lake area of the Ebinur Lake Basin; and (4) irrigation data and water resources data from the Hydrographic and Water Resources Survey Bureau of Bortala Mongolia Autonomous Prefecture, Xinjiang Uygur Autonomous Region, China.

Land-use data were obtained from the NASA website (https://www.nasa.gov/) (Luo et al., 2003; Li et al., 2005). The data included mainly Landsat TM/ETM images for 1990, 2000, 2005, 2010, and 2015. To ensure the reliability of the data, we concentrated the five selected phases of remote sensing images in the 8–9 months of the corresponding years, because more accurate vegetation interpretations can be obtained in the study area that had few clouds. Cloud pixels were removed using geometric rough corrections, radiometric calibrations, geometric fine corrections, and band-fusing. The Ecognition v 8.7 remote sensing classification software (Trimble Inc., Sunnyvale, CA, USA) was used to perform multi-scale segmentation and feature extraction of the generated remote sensing images. We performed a visual interpretation relative to high-resolution images from Google Earth and corrected the interpretation results by a field investigation based on the interpretation and vectorization of five phases of remote sensing images. Eleven land-use types were studied: river/channel, reservoir/pond, lake, saline-alkali land, bare land, sandy land, cultivated land, forest land, grassland, urban and rural construction land, and land covered with ice/snow. The Kappa coefficient of the data was more than 0.89, and the accuracy was greater than 85%, indicating high data accuracy that met the research requirements.

The social and economic statistical data used in this study included population, land use, district information introduction, economic indicators, etc. These data were mainly from the statistical yearbooks of the Natural Resources Bureau and Family Planning Committee of Bortala Mongolia Autonomous Prefecture for 1961–2015 (Resources Bureau and Family Planning Committee of Bortala Mongolia Autonomous Prefecture, 1961–2015).

2.3 Methods

In arid basins, the impacts of climate change (including temperature, precipitation, and evaporation) on water resources are significantly reflected in upstream runoff. Human activities affect all aspects of water resources, particularly in the middle and downstream regions below the runoff pass. Thus, human activities alter the water resource characteristics and distribution patterns. In the present study, the following methods were applied.

2.3.1 Cumulative Levelling

Cumulative levelling was determined as the difference between each original value and the mean value, that is, the anomaly value. Additionally, the sum of the anomaly values was the cumulative anomaly sequence:

$$LP_i = \sum_{i=1}^{n} (R_i - \bar{R})$$

where LP_i, R_i, and $\bar{R}$ are the cumulative values of the anomaly, annual value, and annual mean value, respectively.

2.3.2 Mann-Kendall (M-K) Trend Test

The M-K trend test is an effective method for testing trends and abrupt time-series changes (Kadioglu, 1997). This study used the M-K monotonic trend test (Ling et al., 2012), which is a non-parametric test, to analyze the change trends and possible transition points of runoff in the Ebinur Lake Basin.

2.3.3 Trend Analysis of Reference Evapotranspiration (ET_0)

Based on the Penman-Monteith model, we estimated the change in annual ET_0 in the basin from 1961 to 2015. The model is expressed as:

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

where ET_0 is the annual reference evapotranspiration (mm) accumulated from daily ET_0; Δ is the slope of the vapor pressure curve (kPa/°C); R_n is the net radiation (MJ/(m$^2 \cdot$ d)); G is the soil heat flux density (MJ/(m$^2 \cdot$ d)); γ is the psychrometric constant (kPa/°C); T is the daily average temperature (°C); e_s is the vapor pressure of air at saturation (kPa); e_a is the actual vapor pressure (kPa); and u_2 is the wind speed at a height of 2 m (m/s).

2.3.4 Land-Use Change Index

The dynamic degree (K) of land-use changes and land-use transfer matrix analysis (Wang and Bao, 1999; Liu et al., 2000) were mainly used in the present study, as follows:

$$K = \frac{U_b - U_a}{U_a} \times \frac{1}{t} \times 100\%$$

where U_a and U_b are the land-use data of two different periods; t is the time; and P_{nn} is the land-use type.

2.3.5 Quantitative Discrimination of Runoff Change Attribution

In this study, the proposed climate-sensitive method (i.e., hydrologic sensitivity analysis method (HSAM); Dooge et al., 1999) was used to characterize the total change in runoff:

$$\Delta Q_{total} = \Delta Q_{human} + \Delta Q_{climate}$$

where ΔQ_{total} is the total annual runoff variation (mm); and ΔQ_{human} and $\Delta Q_{climate}$ represent the runoff variation caused by human activities and climate change (mm), respectively. The formula can also be expressed as:

$$\Delta Q_{climate} = \frac{\partial Q}{\partial P}\Delta P + \frac{\partial Q}{\partial PET}\Delta PET$$

where $\partial Q/\partial P$ is the contribution rate of precipitation change to runoff change; $\partial Q/\partial PET$ is the contribution rate of potential evaporation to runoff change; ΔPET is the change in annual potential evapotranspiration (mm); and ΔP is the change in annual precipitation (mm). The quantitative effects of potential evapotranspiration and precipitation on runoff change can be expressed as:

$$\frac{\partial Q}{\partial P} = \frac{1 + 0.5S}{1 + S + \omega S}$$

$$\frac{\partial Q}{\partial PET} = -\frac{0.5 + \omega S}{1 + S + \omega S}$$

where S is the aridity index; and ω is a model parameter that is related to vegetation type, hydraulic properties of the soil, and topography (Yao and Chen, 2014).

Therefore, Equation 5 can be expressed as:

$$\Delta Q_{total} = \Delta Q_{human} + \left(\frac{1 + 0.5S}{1 + S + \omega S}\right) \Delta P + \left(-\frac{0.5 + \omega S}{1 + S + \omega S}\right) \Delta PET$$

3.1.1 Temperature and Precipitation Changes in the Ebinur Lake Basin

An analysis of the annual temperature at the main watershed hydrological stations and the Ala Pass meteorological station was conducted for the period from 1961 to 2015 (Fig. 2a [Figure 2: see original paper]). The results indicated obvious differences in annual average temperature change across the watershed. The annual average temperature at the Wenquan station was 4.0°C, with a maximum average temperature of 5.3°C and a minimum average temperature of 2.4°C, yielding a difference of 2.9°C between the annual minimum and maximum temperatures. The annual average temperature at the Bole station was 6.4°C, and the difference between the annual maximum and minimum temperatures was as high as 3.9°C. However, the annual average temperatures at the Ala Pass and Jinghe stations were similar, with values of 8.9°C and 8.0°C, respectively, and both stations exhibited large differences between annual maximum and minimum temperatures. Overall, the annual temperature variation in the Ebinur Lake Basin during 1961–2015 was relatively high. Warming trends and ranges in the mountainous area were relatively low, while trends in the oasis and plain were relatively high, indicating that human activities contributed more to regional climate warming.

The trends in precipitation change at the four stations (Fig. 2b) revealed that the average annual precipitation at the Wenquan station was the highest, reaching 234.1 mm. At this station, the maximum and minimum annual precipitation was 394.3 mm and 77.8 mm, respectively, with a difference of 316.5 mm—much greater than the average annual precipitation. This shows that the range of precipitation change at the Wenquan station during 1961–2015 was high. At the Bole station, the average annual precipitation was 191.9 mm, and the difference between the maximum and minimum annual precipitation was also large (224.5 mm). Furthermore, the average annual precipitation at the Ala Pass station and Jinghe station was low, with values of 113.3 mm and 104.6 mm, respectively. Although the differences between the maximum and minimum annual precipitation at these two stations were lower than those at the Wenquan and Bole stations, the range was still large, indicating considerable precipitation change during the study period. Moreover, precipitation in the mountainous area showed the maximum increase.

The variation trend of precipitation at the four stations was as follows: Wenquan

> Bole > Ala Pass > Jinghe, indicating that the distribution trend of precipitation was: mountain > oasis > desert. Specifically, the Wenquan station is located in a high-altitude mountain area, which receives the maximum amount of precipitation; the Bole station is located in the oasis area, receiving the second highest amount of precipitation; and the Ala Pass and Jinghe stations are in the mountain-desert ecotone, both having similar amounts of precipitation.

3.1.2 Evaporation Change in the Ebinur Lake Basin

Based on the Penman-Monteith model, we estimated the change in annual ET_0 in the basin from 1961 to 2015, with results shown in Figure 3 [Figure 3: see original paper]. The analysis revealed that at the Ala Pass station, the average ET_0 was 1629.4 mm, the maximum value was 1873.3 mm, the minimum value was 1386.0 mm, and the difference between the maximum and minimum annual ET_0 values was 487.3 mm. The average annual ET_0 at the Jinghe station was 993.1 mm, and that at the Wenquan station was 917.1 mm. The average annual ET_0 values at the Wenquan and Jinghe stations also differed greatly, with ranges of 316.6 mm and 407.5 mm, respectively. However, they were lower than the Ala Pass station. Overall, ET_0 exhibited a decreasing trend: desert > oasis > mountain. Given the high temperature throughout the year, ET_0 was high in the desert area, while low temperatures in the mountainous area greatly inhibited evaporation. ET_0 at the Ala Pass station experienced a mutation in 1991. Specifically, before 1991, it showed a positive anomaly with increasing fluctuation amplitude, but after 1991, the declining trend became obvious. ET_0 at the Jinghe and Wenquan stations fluctuated significantly in 1993. Specifically, ET_0 showed an obvious decreasing trend before 1993 and then increased significantly after 1993. The fluctuation time of ET_0 was consistent with the change of ET_0 in Northwest China (Chen et al., 2014), and the fluctuation nodes were the same, but the ET_0 at the

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

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