Impacts of human activities on the hydrology of Baiyangdian Lake, China

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Abstract Baiyangdian Lake is the biggest natural freshwater wetland in North China Plain. It provides important ecosystem services such as water regulation and supply, reed production and biodiversity protection. Baiyangdian Lake, however, was threatened by lack of freshwater in recent decades. In this paper, the hydrological changes of the lake were quantified using historical data of water level and groundwater table, and satellite images. In addition, the relationship between water level and socioeconomic development of the basin was investigated. The result revealed a significant decreasing trend of water level in the lake. Water level and groundwater table of Baiyangdian Lake decreased rapidly, caused by the great increase of water withdrawal and consumption due to socioeconomic development in the basin. In particular, population growth and the expansion of irrigated agriculture were two major contributors to the decline of water level and groundwater table. While precipitation was positively correlated with water level, it has less impact on water level and groundwater table than human activities. The diversion of water to the lake raised the water level temporarily and had significant benefits on the wetland ecosystem. The best way to solve ecological problems of Baiyangdian Lake, however,

is to control the growth of population, adjust the industrial structure, control land use conversion and improve water use efficiency at the basin scale.

Keywords Human activities · Water level · Groundwater table · Baiyangdian Lake

Introduction

Wetlands occur over a wide variety of sites, but mostly in low-topographic conditions or “landscape sinks,” where ground and/or surface water collects (Zedler and Kercher 2005). Hydrological condition is the foundation of wetland ecosystems. Changes in hydrology affect the structure and function of wetland ecosystems. Many wetlands have suffered functional degradation due to hydrological changes. Runoff is a major source of water to many wetland ecosystems, and it is affected by both climate changes and human activities. Human use of water is a primary factor in the decrease of river flows (Gleick 2003; Wen and Chen 2006; Hao et al. 2009). Water diversion to agricultural and industrial uses greatly reduced water flow into wetlands over the last 50 years (An et al. 2007). Irrigated agriculture is a major user of freshwater, accounting for about 72% of global and 90% of developing-country water consumption (Cai and Rosegrant 2002).

Baiyangdian Lake is the biggest natural freshwater wetland in North China Plain, and it provides important ecosystem services such as water regulation and supply, reed production and biodiversity protection. Baiyangdian Lake, however, has been affected by climate changes and human activities since 1960 (Liu et al. 2007). Water flow into Baiyangdian Lake from upstream rivers decreased in recent decades. The lake has undergone enormous changes

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in hydrology, resulting in profound changes in ecosystem structure and function. Hydrological changes directly or indirectly led to degradation of water quality, reduction of biodiversity and loss of reed lands (Li et al. 2004; Xu et al. 2005).

Previous research has focused on identification of ecological problems (Xu et al. 1998; Zhang et al. 2007), water resource requirement (Zhong et al. 2005; Wang et al. 2008) and ecosystem services provided by the wetlands in Baiyangdian Lake (Li et al. 2005; Zhang et al. 2006). Few studies, however, have investigated the impacts of human activities on hydrological changes in the Basin of Baiyangdian Lake. The objective of this study is to analyze the hydrological changes of Baiyangdian Lake, and quantify the relationship between those changes and human activities. The results from this study have important implication on the conservation of Baiyangdian Lake and water management policies in the basin.

Study area

Baiyangdian Basin, approximately 3.12×10^4 km² in size, is located in North China (113°39′–116°11′ E, 38°4′–40°4′ N), including portions of Beijing, Hebei and Shanxi provinces (Fig. 1). The majority of the basin (about 71%) is located in the Baoding City, a city in the central of Hebei province. Baiyangdian Basin has a temperate continental climate, with annual mean temperature between 7.3°C and 12.7°C (Liu et al. 2007). The average annual rainfall is 563.9 mm, with 80% of the total precipitation concentrated in the flood season (June to August) (Li et al. 2004).

Baiyangdian Lake is comprised of 140 lakes, with an area of about 366 km² when water level is 10.5 m. It is a shallow lake, with bottom elevation ranging from 5.5 to 6.5 m. It is considered as partly and totally drying up, when the water level is below the bottom elevation (Compilation Committee of Local Chronicles of Anxin County 2000). Eight rivers flow into Baiyangdian Lake. The rivers, however, generally run dry before reaching the lake during the dry season. Baiyangdian Lake Wetland Nature Reserve was established in 2002 to preserve the freshwater wetland ecosystem, especially rare and endangered species, including *Grus japonensis*, *Grus leucogeranus*, *Otis tarda*, *Ciconia boyciana*, which are listed as Class I by the National Key Protected Wildlife List in China.

Data and methods

In this study, data of water level from 1950 to 2007, data of groundwater table from 1988 to 2007 and data of water diversion from 1991 to 2007 were acquired from Anxin

County Water Conservancy Bureau. Landsat TM image collected in 2007 and Landsat MSS image collected in 1974 were used to detect the changes in water bodies. Precipitation data between 1955 and 1990 were obtained from 24 rainfall stations located in the basin, and those from 1991 to 2007 were acquired from Anxin Meteorological Bureau.

Data of water use in domestic, industrial and agricultural sectors, as well as ecological water use, in 2006 were obtained from County or City Water Conservancy Bureaus. Socioeconomic data, including population, effective irrigated area, grain production and cotton production, were used as indicators of water use, as historical data of water use are not available.

Socioeconomic data were collected from statistical yearbooks, bureau of statistics and county annals. Socioeconomic data from 1955 to 2007 of Baoding City were used, rather than that of the entire basin in the analyses. This is because (1) the socioeconomic data for the whole basin was not available; and (2) the majority of the basin is located in Baoding City. Tourism data in 2007 were also acquired from Anxin Tourism Bureau.

Water level trend was analyzed using Mann–Kendall trend test (Wen and Chen 2006). Landsat images were first classified using ERDAS IMAGINE 9.1, and errors in the classification map were then corrected in ARCGIS 9.2. Pearson correlation coefficients were calculated to measure the correlation between water level and factors expected to affect water level. Principal component analysis (PCA) was performed to these factors, using SPSS 13.0. The relationships between the depth of groundwater table and its influencing factors were also examined using SPSS 13.0.

Results

Hydrological change

Water from upstream rivers was a main source of water for Baiyangdian Lake. However, annual water input to Baiyangdian Lake from upstream rivers decreased from 18.27×10^8 m³ in the 1950s (Li et al. 2004) to 0.24×10^8 m³ in 2000 (Wang et al. 2008). As a result, annual mean water level of Baiyangdian Lake decreased from 9.32 m in 1950 to 6.57 m in 2007 (Fig. 2). Using the Mann–Kendall method, a significant decreasing trend was found in water level from 1950 to 2007. In fact, Baiyangdian Lake dried up several times because of water scarcity, with the decrease of water level. Along with the decrease of water level, water area of Baiyangdian Lake decreased from 81 km² in 1974 to 47 km² in 2007 (Fig. 3).

Measurements in Anxin county found that groundwater had an average of 6.1 m below surface in 1988, but

Fig. 1 Location map of Baiyangdian Basin **Fig. 2** Annual mean water level in Baiyangdian Lake between 1950 and 2007

increased to 11.0 m by 2007 (Fig. 4). The decline of groundwater table was affected by extraction of groundwater in and around Baiyangdian Lake, and may be also due to the changes in the direction of groundwater flow in the basin that was caused by overexploitation. The decrease in surface water level and drop of groundwater table implied the decrease of available water resources for Baiyangdian Lake.

Effect of human activities on water level

Human activities in the basin played a key role in the hydrological change of Baiyangdian Lake. From 1950 to 2007, the population of the Baoding City increased from 5.2×10^6 to 1.1×10^7 . In addition, per capita gross domestic product (GDP) of Baoding City increased from 91.3 yuan in 1952 to 1.2×10^4 yuan in 2007. With the

Fig. 3 Water bodies of Baiyangdian Lake interpreted from satellite images of Landsat MSS collected on June 7, 1974 and Landsat TM acquired on May 28, 2007

Fig. 4 Annual mean depth of groundwater in Anxin County between 1988 and 2007

growth of population and economy, there was an increase of water withdrawal for human use. Total water use in the basin was $46.9 \times 10^8 \text{ m}^3$ in 2006, with 78.8, 8.5 and 8.9% of the water used for agricultural, industrial and domestic purposes, respectively. The majority of water was used for agriculture, due to the expansion of land for irrigated agriculture. Ecological water use only accounted for 3.8%. Total water use was 1.6 fold of the available freshwater in the basin, which reflected the condition of severe water scarcity in the region.

As the growth of population and economy greatly increased the water use, less water flowed into Baiyangdian Lake, resulting in the decrease of water level in the lake. Between 1955 and 1990, annual mean water level of the lake was significantly ($p < 0.01$) correlated with population, effective irrigated area, grain production and cotton

production (Fig. 5), with correlation coefficients of -0.60 , -0.61 , -0.62 and -0.48 , respectively. Between 1991 and 2007, population in the basin was significantly correlated with annual mean water level ($r = -0.67$, $p < 0.01$) and annual depth of groundwater ($r = 0.83$, $p < 0.01$). The grain production, however, was not significantly related to the water level and groundwater table during this time period.

Because precipitation is concentrated in the flood seasons, there is not enough freshwater in the rivers during dry seasons. About 150 reservoirs were built to meet the demand of human water use in the basin since the 1950s. The construction of reservoirs led to fundamental transformations in temporal and spatial distribution of water resources. With the same precipitation, the water flowed into Baiyangdian Lake was different in the years before

Fig. 5 Annual mean water level of Baiyangdian Lake was related to **a** population, **b** effective irrigated area, **c** grain production and **d** cotton production between 1955 and 1990. Four years were eliminated because of the missing data of precipitation or effective irrigated area

and after the construction of reservoirs (Liu et al. 2007). Lacking surface water, people began to exploit substantial groundwater for human use since the 1970s. In 2006, motor-pumped wells added up to 1.8×10^5 in the basin, and groundwater accounted for 87.5% of the total water consumed. Accumulated overexploitation of groundwater led to decline of groundwater table, which in turn affected the ground water flow patterns in some regions of the basin.

Effect of precipitation on water level

Besides human activities, precipitation in the basin decreased between 1955 and 1990, which was another factor that led to water resources deficit and the decrease of water level of the Lake. Annual mean water level was positively correlated ($r = 0.38$, $p < 0.05$) with precipitation (Fig. 6). Precipitation, however, was not significantly correlated with the water level and groundwater table between 1991 and 2007.

Principal component analysis of influencing factors

To determine the main factors that affect water level, PCA was performed on population, effective irrigated area, grain production, cotton production, and precipitation (1955–1990). The results showed that the first two components explained 82.8% of the total variance. The first component (PC1) was highly positively related to grain production, population, effective irrigated area and cotton production,

Fig. 6 Correlation between annual mean water level and precipitation from 1955 to 1990

and weakly negatively related to precipitation, while the second component (PC2) was highly positively related to precipitation (Table 1).

Water transfer project

Water was transferred from upstream reservoirs and other watersheds to Baiyangdian Lake 18 times, with total volume of $9.8 \times 10^8 \text{ m}^3$, to restore the structure and function of the lake between 1991 and 2007. The water level increased after the delivery of water (Fig. 7). Without the water transfer project, Baiyangdian Lake could have already been dried up. In fact, Baiyangdian Lake has

Table 1 Loading matrices of the principal components

Variable	PC1	PC2
Population	0.957	0.209
Effective irrigated area	0.881	0.201
Grain production	0.981	0.100
Cotton production	0.651	−0.197
Precipitation	−0.394	0.880
Percent variation explained	64.7	18.1

become an “artificial lake” to some extent, since the water diverted to the lake has exceeded the runoff from upstream rivers since 2000. The water transfer project was important for ecosystem services of Baiyangdian Lake, such as wildlife habitats, transportation, pollution dilution, recreation, and so on. In fact, tourism increased, reaching up to 9.7×10^5 in 2007 partly due to landscape scenery improvements; people would not come to Baiyangdian Lake if it was dried up, because they were attracted by the water of the lake. In addition, water diversion also improved the water quality of the lake (Wang and Lü 2005). Water diversion, however, can only mitigate the problem of water shortage temporarily. The water input cannot meet the water demand of the lake, and thus the annual mean water level and groundwater table continued to decrease despite water diversion.

Discussion

Aquatic ecosystems are far from isolated bodies or conduits but are tightly connected to terrestrial environments (Baron et al. 2002). Both climate changes and human

activities have significant impacts on the hydrology of wetland ecosystems (Frederick and Major 1997; Legesse and Ayenew 2006; Alemayehu et al. 2007; Lake and Bond 2007). This paper shows that the water level of Baiyangdian Lake was affected by both the decrease of precipitation and the increase of human water use in the basin. Human activities that led to the increase of water use in the basin, however, were the principal contributors to the decline of water level.

The results indicated that the main driving forces for the decreased water level from 1955 to 1990 were growth of grain production and population. The decrease of water level was exacerbated by the increased area of irrigated agriculture, increase of cotton production and the decrease of precipitation during this time period. From 1991 to 2007, annual mean water level and annual depth of groundwater were correlated with population significantly, while, they were not significantly correlated with grain production and precipitation. This may be related to the fact that agricultural development as well as water used for agriculture from 1991 to 2007 was not increased as fast as that from 1955 to 1990. Effective irrigated area increased from 2.5×10^5 ha in 1955 to 6.5×10^5 ha, while it only increased from 6.5×10^5 ha in 1991 to 6.8×10^5 ha in 2000, then decreased to 6.4×10^5 ha in 2007. In addition, grain production has been declining since 2000 in the basin.

For the first three-quarters of the last century, population and economic growth were the primary factors driving changes in water use in the US (Frederick and Major 1997). Water withdrawal will increase in some regions of the globe because of population and economic growth (Alcamo et al. 2003). With the socioeconomic development in Baiyangdian Basin, increased water use greatly affected the

Fig. 7 Effect of transferring water on Baiyangdian Lake between 1991 and 2007. ΔV and ΔH were water volume and water level changes after water diversion, respectively

water level of Baiyangdian Lake. Irrigated agriculture has greatly increased crop production but it also led to the increased demand of water withdrawal and consumption. Irrigated agriculture is currently the dominant user of freshwater in the basin. The current water use efficiency in irrigated agriculture in Baiyangdian Basin is much lower than that in developed countries. Therefore, there is great potential to enhance the efficiency of water use in irrigated agriculture to reduce water withdrawal and consumption, and thus reduce the impact of agriculture on the lake. In addition, domestic and industrial water uses have greatly increased with the increase of GDP in the basin. Previous studies show that the increase of GDP does not necessarily lead to the increase of water use (Gleick 2000; Oki and Kanae 2006). Therefore, water use in Baiyangdian Basin can be controlled through effective water resources management.

Changes in hydrology of Baiyangdian Lake led to many ecological problems, such as the reduction of biodiversity, degradation of water quality and loss of wetland functions (Li et al. 2004). Fortunately, the government is making great efforts to restore the wetland ecosystem through integrated ecosystem and water resources management at basin scale. Besides population and agriculture growth, human activities that influence water use in the basin also include land use changes, food demand structure and consciousness of water saving. These should be explored in future studies.

Conclusions

We found that the water level of Baiyangdian Lake decreased from 1950 to 2007 based on Mann–Kendall trend test. Groundwater table also declined from 1988 to 2007. In addition, water area of the lake decreased from 1974 to 2007 according to remotely sensed imagery. Human activities in the basin were the principal factors that led to those changes. Water flow into the lake greatly decreased in the last decades, as water was withdrawn and consumed for irrigated agriculture, domestic and industrial purposes. The construction of reservoirs, motor-pumped wells and other engineering structures played an important role in water resources exploitation, thus it cannot be ignored when trying to restore the wetland ecosystem. Although change in precipitation was correlated with the water level, it has less impact on the wetland ecosystem comparing to human activities. The water transfer project is only a temporary measure for the rehabilitation of the wetland ecosystem, but maybe unsustainable. To meet the water demand of Baiyangdian Lake, the government must control water withdrawal in the basin. It is necessary to control the growth of population, adjust the industrial

structure, control land use conversion and improve water use efficiency at the basin scale.

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