Method of Calculating Lake Water Storage in Areas without Topographical Data Based on Google Earth Engine

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Abstract. Accurate ecological lake water calculation plays an important role in maintaining ecological health and protecting lakes. However, the lack of topographical data for the bottom of the lake results in some complexity to the calculation of ecological lake water storage. This study uses remote sensing big data to overcome the data limitations of water calculations and accurately calculates the ecological water storage of Baiyangdian Lake. The results show that the water surface area of Baiyangdian Lake can be divided into a dry period (average water area of 7.15 km\textsuperscript{2}), a decline period (155.64 km\textsuperscript{2}), a stable period (67.29 km\textsuperscript{2}), and a recovery period (119.17 km\textsuperscript{2}). The ecological water storage of the lake has evolved from 200 million m\textsuperscript{3} to the current 300–600 million m\textsuperscript{3}. This study provides an important reference for the ecological lake water calculations when topographical data is not available and for lakes with complex bottom topography.

Keywords: Google Earth Engine, environmental water, Baiyangdian Lake, remote sensing interpretation

1. Introduction

Water is one of the most abundant resources on Earth, and it is also one of the most critical to life. Lakes are an important carrier of the Earth’s water resources \cite{1}. The amount of lake water is an important basis for maintaining the ecological health of lakes, improving the local microclimate, and the management of water resources \cite{2}. Accurate calculation of ecological lake water storage is of great significance to the development and utilization of lake water resources and ecological lake water supply \cite{3}.

In the early days, ecological lake water calculations were mainly conducted using the water balance method \cite{4}. This method mainly calculates water storage of lakes by calculating water balance items, such as the amount of evaporation and leakage. Some researchers also use hydrological and hydraulic methods to calculate the ecological lake water demand \cite{5}. These methods calculate the ecological water level that is required to maintain the basic structure and important functions of the lake and wetland ecosystems, and then, they calculate the ecological lake water storage based on the lake bottom topography \cite{6}. However, for lakes that lack hydrological data or bottom topography data or have a complex bottom topography, it is difficult to calculate the ecological lake water storage based on the ecological water level. In this study, remote sensing big data was used to develop an ecological
water level calculation method that does not depend on the topography of the lake bottom. The results of this study provide an important reference for the calculation of the ecological water storage of lakes that lack lake bottom topography data or have complex lake bottom topography.

2. Materials and Methods

2.1. Study Area and Data

Baiyangdian Lake is the largest freshwater lake and wetland ecosystem in the North China Plain. It is located in the hinterland of the Beijing–Tianjin–Hebei region and belongs to the Daqinghe Basin in the Haihe Basin. Its main body is located in Anxin County, Xiong'an New District, Hebei Province, China (figure 1). In general, the Baiyangdian Lake topography is slightly inclined from northwest to southeast with a slope of 1:2000, and is relatively flat. The highest elevation of 10 meters occurs in the west of Baiyangdian Lake, and the lowest elevation of 5.5 occurs in the east of Baiyangdian Lake.

Baiyangdian Lake's control area is the middle and upper reaches of the Daqing River. Baiyangdian Lake is composed of 143 lakes of varying sizes, more than 3,700 trenches, 80 km² of reed wetlands, and 39 island villages. The lakes are connected by trenches and fairways. The elevation of the bottom of the lakes is generally 4.0–4.5 m (1985 National Elevation Benchmarks, the same below), the minimum is 1.5 m, and the elevation of the platform fields is generally 6.5–7.5 m. There are reed fields, platform fields, and villages in the water area, forming a unique geographical situation of half water and half aridity. From the north, west, and south, nine larger rivers, including the Bao River, Tang River, Cao River, and Zhulong River, enter the lake, pass through the flood gates, overflow the weirs in the northeast, pass through the Zhaowangxin River, and join the Daqing River.

Baiyangdian Lake plays an important role in maintaining the balance of the wetland ecosystem, regulating the climate of the Beijing–Tianjin–Hebei area, improving the temperature and humidity, groundwater recharge, and protecting biodiversity and rare species resources. The terrain of Baiyangdian Lake is complex, and accurate ecological water storage calculations are of great significance to protecting Baiyangdian Lake and restoring its ecological functions.

Figure 1. Location of Baiyangdian Lake.
2.2. Methods

2.2.1. Google Earth Engine. Google Earth Engine is a cloud platform based on processing remote sensing big data. It can quickly search and use a lot of global geographic scientific data, and process the accessed satellite images and remote sensing data through powerful cloud computing capabilities [7, 8]. The Google Earth Engine platform is rich in resources and easy to obtain, which stores data including more than 100 public datasets and millions of remote sensing images. It is one of the most commonly used big data processing platforms, which has been recognized and used by many researchers in the field of hydrology and remote sensing.

Compared with traditional image processing tools such as the environment for visualizing images, the Google Earth Engine can process huge images quickly and in batches. Using the Google Earth Engine, vegetation indices such as the normalized difference vegetation index can be quickly calculated, crop-related yields can be predicted, drought conditions can be monitored, and global forest changes can be monitored.

Using a combination of the Google Earth Engine remote sensing big data platform and field surveys, the characteristics of the distribution of discrete lakes were determined, and the boundaries of Baiyangdian Lake were clarified (figure 2). The boundaries of the water area and the lakeside zone were used as the boundary, that is, the water area and flat water in the wet year. The annual water area and the dry year water area are the distinguishing principles. The Dian District was divided into grids, and the area of each area was calculated. The frequency of water occurrence and the hydraulic connection between each area were analyzed.

![Google Earth Engine interface and running code.](image)

**Figure 2.** Google Earth Engine interface and running code.

2.2.2. MNDWI Threshold Method. The normalized difference water index (NDWI) is expressed as shown in the equation (1) [9]:

\[
NDWI = \frac{Green - NIR}{Green + NIR}, \tag{1}
\]

Where \(Green\) is a green band in the remote sensing product data, for example the band 2 in TM; and \(NIR\) is a near infrared band, for example the band 4 in TM.

The index is determined as follows: (1) use the green wavelength to maximize the reflectance of the water, (2) minimize the near-infrared reflectance caused by the nature of water, and (3) use the high near-infrared reflectance to distinguish between the plants and soil. The results show that the
water area is usually positive and thus enhanced, while plants and soil are usually zero or negative and thus inhibited. However, NDWI did not achieve the expected effect in the process of extracting soil water. The water information extracted in these areas is usually mixed with accumulated earth noise. This means that in NDWI images, many city features also have positive values.

In order to suppress the noise from the city and the land, the NDWI is changed by replacing the middle infrared (MIR) frequency band with the NIR frequency band in the NDWI, so that the building area has a negative value. The modified NDWI (MNDWI) can be expressed as shown in the equation (2) [10-12]:

$$MNDWI = \frac{Green - MIR}{Green + MIR}. \quad (2)$$

where $MIR$ is a middle infrared band in the remote sensing product data, such as the TM band 5.

Compared with NDWI, the calculated characteristic value of the water area increases while the characteristic value of the construction land decreases, and the contrast between the water area and the construction land of MNDWI is significantly greater. Since the negative values of construction land, soil and vegetation are significantly suppressed or even eliminated, the enhancement of water area values in the MNDWI image will promote more accurate extraction of the open waters.

2.2.3. Water Storage Model. The water storage calculation is used to calculate the amount of water stored in the lake. Based on the water surface area and water level changes, the water surface area vs. water level relationship curve is fitted, as shown in the equation (3). According to the obtained lake water level and area data, the least squares method is used for the fitting in order to obtain the relationship between the water level and area.

$$A = f(h) = ah^2 + bh + c. \quad (3)$$

where $A$ is the water surface area; and $h$ is the water level.

Based on the fitting relationship between the lake water level and area, the integration method is used to obtain the equation for the relationship between the lake’s capacity and the water level, as shown in the equation (4) and (5).

$$V(h) = \int_{h_{\text{min}}}^{h} Adx = \frac{a}{3} h^3 + \frac{b}{2} h^2 + ch - d \quad (4)$$

$$d = \frac{a}{3} h_{\text{min}}^3 + \frac{b}{2} h_{\text{min}}^2 + ch_{\text{min}} \quad (5)$$

where $V$ is the water volume and $h_{\text{min}}$ is the dry lake water level.

According to the different water levels, the water storage capacity corresponding to the water level can be calculated using the above equations.

3. Results and Discussion

3.1. Characteristics of Lake Area Changes

Based on the Google Earth Engine platform, we obtained the trend of the changes in the water surface area of Baiyangdian Lake from 1984 to 2019 (figure 3). Based on the calculation results, the area change of Baiyangdian Lake, in our research, can be divided into four main periods: a dry period (1984–1988), a decline period (1988–1999), a stable period (1999–2009), and a recovery period (2010–2019). During the dry period, the water area of Baiyangdian was small, and the average area of Baiyangdian Lake was 7.15 km$^2$. During this period, parts of Baiyangdian Lake were almost completely dry. Due to extreme precipitation, the water surface area has increased sharply, and the lake has entered the decline period. During this period, the water area changed from 280 km$^2$ to 80
km$^2$, and the average area of Baiyangdian Lake was 155.64 km$^2$. During the stable period, the change in the water area was small, and the average water area was 67.29 km$^2$. During the last period, the water area began to recover because Baiyangdian Lake receives water from other rivers, including the Yangtze River and the Yellow River, and the average area of Baiyangdian Lake was 119.17 km$^2$.

3.2. Water Level Changes

The water level of Baiyangdian Lake varies significantly from year to year. The water level dropped significantly from 9 m to 6.35 m in 1953–1984. However, Baiyangdian Lake was dry from 1984–1988 (figure 3), so the water level was difficult to measure. Thus, there is no data on the water level during this period (figure 4). The changing in the water level from 1988 to 2018 was similar to that of the water surface area. Both initially decreased, then remained stable, and finally increased. However, the difference is that the period of water level decline was from 1988 to 2002, which is different from the decline trend of the water surface area from 1988 to 1999. This may be related to the depth of the bottom of this part of Baiyangdian Lake.

![Figure 3. Baiyangdian Lake area change trend.](image)

![Figure 4. Changes in the water level of Baiyangdian Lake.](image)
3.3. Changes in Water Reserves

We fit the water level and area data for different years and obtained a fitting curve (Figure 5a). We chose a second-degree polynomial for the fitting, and the degree of fitting was $R^2=0.7207$. Based on the water level area fitting curve, a water level storage capacity calculation model was established. Using this model and based on the measured water level data, the annual water reserves of Baiyangdian Lake were calculated (Figure 5b). Over the years, the water reserves of Baiyangdian Lake have experienced several fluctuations. Before 2010, Baiyangdian Lake’s water reserves fluctuated steadily, and most of the time, the water volume was less than 200 million m$^3$. After 2010, due to the increase in precipitation and water supply, the water reserves of Baiyangdian Lake increased, and the water volume gradually recovered to 300–600 million m$^3$.

![Figure 5](image)

Figure 5. Calculation results of the water volume model. a) the water level-area curve, b) the water level lake capacity curve.

4. Conclusions

Overall, in this study, remote sensing big data was used to accurately calculate the ecological water volume of Baiyangdian Lake, which has been verified by previous results. The results of this study demonstrate that the proposed method can effective calculate the ecological water volume of lakes that lack topographic data for the lake bottom or that have a complex lake bottom topography. However, this method still has a certain dependence on the data from hydrological lake stations. In future research, there is still a certain research potential in terms of the accurate interpretation of remote sensing data and the use of elevation satellite data to replace hydrological station data.

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