Application of Satellite Remote Sensing Technology in Lake Monitoring

Jiahuan HE *

Hulunbuir Meteorological Bureau, Hulunbuir 021008, China

Abstract Hulun Lake, which is an important carrier of water resources in Hulunbuir Grassland and also a significant barrier in the northern ecosystems, plays a crucial role in supporting regional ecological environment, climate, and biodiversity conservation. In this paper, the application of satellite remote sensing technology in the monitoring and early warning of water dynamics, water quality and water environment, lake ice phenology, and ecosystem in Hulun Lake was studied, and high-resolution and comprehensive lake information can be obtained. It can provide strong technical support for lake supervision, maintenance and management.

Key words Satellite remote sensing; Monitoring; Lake

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The traditional methods of monitoring lakes mainly rely on measurement by ground stations and manual patrols for protection. This method has significant limitations such as high cost, low efficiency, and limited coverage. Especially for large lakes located in remote areas, the traditional monitoring methods cannot achieve comprehensive, rapid, and continuous observation. Satellite remote sensing technology is a modern scientific technology that uses artificial satellites as the platform, utilizes sensors to collect electromagnetic wave information of the target objects, and then processes and analyzes the data to identify the geometric, physical characteristics, interrelationships, and change patterns of the target objects. Satellite remote sensing technology has efficient, macroscopic, and economical characteristics, and can quickly obtain spatial and temporal change information within large areas such as rivers, lakes, and grasslands. It has a short observation period, a large amount of information obtained, and wide coverage, so it has become an indispensable technical means. The application of satellite remote sensing technology to the monitoring of lake ecological environment can achieve intelligent, all-weather and all-round supervision of lakes. Hulun Lake is the fifth largest freshwater lake in China and the largest lake in the north. It is an ecological barrier in the north. In this paper, based on the current status of the ecosystem of Hulun Lake, the application status of satellite remote sensing technology in the monitoring of Hulun Lake was discussed to strengthen the dynamic monitoring of the water area, water quality parameters, lake ice phenology, and ecosystem health of Hulun Lake, and provide technical support for the ecological protection and management of Hulun Lake.

1 General situation of Hulun Lake

Hulun Lake is located between New Barag Right Banner, New Barag Left Banner and Jalainur District of Manzhouli City in Inner Mongolia Autonomous Region. It is situated in the west of Hulunbuir Grassland and is a typical cold and arid inland lake. It has an area of 2 339 km^2, a maximum depth of 8 m, an average depth of 5.7 m, and a water storage capacity of 13.85 billion m^3. The area of its waters and surrounding wetlands reaches 7 680 km^2. Its water system spans across China, Mongolia and Russia. Its special geographical location determines its irreplaceable position in regional ecological environment protection and economic development. It plays an important role in maintaining the water balance, regulating the climate, protecting the biodiversity, and enriching animal and plant resources in Hulunbeir Grassland.

In recent years, due to global warming and intensified human activities, the ecosystem of Hulun Lake has been facing severe challenges. Since the 21st century, obvious natural changes, such as an increase in temperature, a decrease in precipitation, and an increase in evaporation, have occurred in Hulun Lake. At the same time, under the influence of social and economic factors such as population growth and long-term overgrazing, a series of ecological and environmental problems have emerged in Hulun Lake, *e.g.* a rapid reduction in wetland area, continuous degradation of water ecological functions, and a decline in biodiversity. According to relevant studies, the water area of Hulun Lake decreased by 22.7%, and the area of tidal wetlands dropped by 25.9% from 1975 to 2011. Since the 21st century, due to the decline in the water level of Hulun Lake, the biomass of carnivorous fish has sharply decreased, while the proportion of low-nutrient organisms such as blue-green algae and benthic crustaceans has increased, and the energy transfer efficiency of the system has reduced, leading to an overall evolution towards an immature state.

2 Application of satellite remote sensing technology in the monitoring of Hulun Lake

In order to minimize the interference and impact of human

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* Corresponding author.

activities on the natural ecological environment and better maintain the safety of the growth, survival and reproduction environment of wild animals and plants, Hulunbuir City has strengthened the scientific research monitoring and law enforcement management of Hulun Lake, constructed a modern information platform of "Internet + video monitoring, ecological scientific monitoring, cloud computing processing of big data", fully utilized the complementary advantages of satellite remote sensing and ground monitoring, and carried out regular, detailed and dynamic monitoring and assessment around the protection and governance of the ecological environment in Hulun Lake, thereby providing important decision-making basis for all levels of government departments to conduct ecological protection and restoration.

2.1 Dynamic monitoring of the waters Dynamic monitoring of the waters is the most fundamental and mature application area of satellite remote sensing in Hulun Lake. Researchers analyzed the long-term sequence of satellite images of Hulun Lake, and revealed the significant changes in the water area of Hulun Lake[1]. During 1975 – 2011, the water area and the area of tidal flats and wetlands in Hulun Lake showed a clear decreasing trend, which was particularly obvious from 2000 to 2005. The lake area declined by approximately 18.9% (about 440 km^2), and the water level continuously dropped by 1.8 m within the 5 years. In recent years, with the increase in governance efforts, the condition of the waters of Hulun Lake has improved. Based on the altimetry data from ICESat-2 satellite, it is found that from November 2018 to January 2022, the water level of Hulun Lake showed an overall upward trend, and the annual average increase of water level was up to 0.49 m. From May to August in 2023, the area of Hulun Lake tended to increase slightly, and satellite monitoring reveals that the changes in water level had obvious seasonal characteristics. Additionally, the main driving factors of changes in water level in Hulun Lake have been revealed. There was a decrease from March to June, an increase from July to October, and no change from November to next February. This seasonal changes in the water level were closely related to the distribution of precipitation and the evaporation cycle in the basin. The increase in temperature led to an increase in evaporation, which was the dominant factor causing the decline in the water level of the lake. Temperature and evaporation had a strong negative correlation with changes in the water level. Artificial water injection can replenish the water volume of the lake, and there was a significant increase in the water level during water injection period in 2021. Moreover, the precipitation in the basin directly affects the annual changes in the water level of Hulun Lake by changing the inflow volume of the river into the lake.

The Hulunbuir Meteorological Bureau used the high-resolution satellite to produce monitoring products of monthly water body area of Hulun Lake, and submitted the monitoring products to the relevant management departments of Hulun Lake for analyzing the correlation between changes in the area of Hulun Lake and precipitation. The satellite remote sensing image of Hulun Lake is shown in Fig. 1.

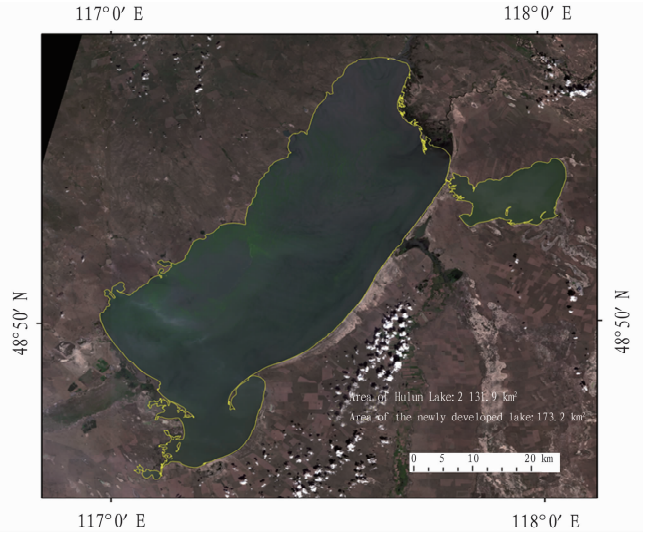

Fig. 1 Satellite Remote Sensing Map of Hulun Lake

2.2 Monitoring of water quality and water environment Hulun Lake is an algal lake, and the water body has been in a moderately eutrophic state for a long time, providing conditions for the proliferation of blue-green algae. The high temperature and strong light in summer further accelerate the growth of blue-green algae, so cyanobacterial bloom becomes a common natural phenomenon in Hulun Lake in summer. It can make the lake water turn green, lead to deteriorating water quality, damage the water landscape, and threaten the health of the ecosystem. For Hulun Lake, monitoring and early warning are combined with small-scale artificial control to deal with cyanobacterial bloom, but the lake area is large, and the number of monitoring stations is small, making the prevention and control difficult. With the development of hyperspectral remote sensing technology, the application of satellite technology in the water quality monitoring of Hulun Lake has become increasingly widespread. The HY-1C/D satellite coastal imaging instrument (CZI) has played an important role in the monitoring of blue-green algae in Hulun Lake. Based on remote sensing data with high spatial and temporal resolution and combining ground verification, a remote sensing identification model for cyanobacterial bloom in Hulun Lake is established to achieving precise monitoring of the spatial distribution, occurrence frequency and intensity of cyanobacterial bloom[2]. In the summer of 2022, Hulun Lake suffered from the most severe cyanobacterial bloom in the past 40 years, and the coverage area of the lake surface reached over 70%. In response to this event, researchers used multi-source remote sensing data and WET model scenario simulation analysis to explore the chain mechanism of the formation of cyanobacterial bloom. Due to the excessive precipitation in 2021, the water level of Hulun Lake rose significantly, and the water surface expanded. As a result, the surrounding fertile soil was submerged, and a large amount of nitrogen and phosphorus nutrients accumulated in the soil entered the water body, ultimately leading to the large-scale outbreak of cyanobacterial bloom. According to the special path of the formation of cyanobacterial bloom in the lake, researchers further developed a satellite remote sens-

ing early warning model for cyanobacterial bloom in Hulun Lake, and predicted the occurrence risk of cyanobacterial bloom by real-time monitoring of the expansion of the lake surface and changes in surrounding soil moisture, thereby providing early warning and intervention time windows for the management departments.

In addition, satellite remote sensing is also used for the inversion of water quality parameters such as colored soluble organic matter, transparency, and suspended solids in Hulun Lake. By establishing empirical or analytical models between remote sensing reflectance spectra characteristics and water quality parameters, the large-scale and rapid assessment of the water quality of Hulun Lake can be achieved.

2.3 Phenology monitoring of lake ice Hulun Lake freezes in early November each year, and thaws in early May of the following year. The winter freezing period lasts for 170 – 180 d, and the maximum thickness of ice layer can be up to over 1 m. It is one of the lakes with a longer freezing period in China, and has abundant ice and snow resources. Lake ice is a sensitive indicator of climate change. The analysis of the relationship between phenological parameters of lake ice and climatic factors can reveal the rate and magnitude of climate warming in Hulun Lake and the impact of changes in lake ice on the thermal structure, water chemistry, and ecosystem of the lake. Satellite remote sensing provides an effective means for the phenology monitoring of lake ice in Hulun Lake, and the data set of lake ice has been continuously improved. Based on the MODIS global daily snow cover product MOD10A1, the data set for the daily distribution of lake ice in Hulun Lake from 2000 to 2020 was developed, including the phenological periods of lake ice (the beginning day of freezing, the day of complete freezing, the beginning day of melting, and the day of complete melting). According to the latest released LI-CCR data set (2002 – 2024), the deficiency of MODIS observation was filled, and daily lake ice coverage, annual lake ice phenology, and the probability of complete freezing for 32 800 lakes in the global cold climate zones can be provided. These data provide an important basis for studying the response of lake ice in Hulun Lake to climate change.

2.4 Assessment of ecosystem health In recent years, drought has occurred frequently due to climate warming, and along with local human-induced disturbances, the water conditions of Hulun Lake have undergone drastic changes. The wetlands around the lake have sharply decreased, and grasslands have degraded; the aquatic ecosystem has deteriorated, and land desertification has appeared. These problems seriously threaten the local ecological security. The application of change monitoring technology, automatic interpretation technology, and rapid acquisition and processing technology of satellite remote sensing images can significantly shorten the investigation cycle of natural resources, and realize the detailed and emergency monitoring of the ecosystem in Hulun Lake, and ensure the accuracy of the investigation results. At the same time, based on multi-source and multi-period satellite remote sensing data and the analytic hierarchy process (AHP), a comprehensive evaluation indicator system for the health of the wetland ecosystem in Hulun Lake is constructed, consisting of three criterion layers (lake wetland ecological environment, overall function, and external social and economic environment) and 15 evaluation indicators. This provides a multi-dimensional reference for the assessment of the ecosystem health of Hulun Lake[3]. Through the analysis of satellite remote sensing monitoring data, the correlation between the water level, area, volume, and salt content in the water of Hulun Lake are studied, and the main thresholds for maintaining the stability of the ecosystem are determined[4], such as the minimum ecological water requirement value of Hulun Lake (10.201 billion m^3) and the corresponding lake surface area for ecological safe (2 137.87 km^2). Besides, the key threshold for the multi-stable transformation of the ecological structure and function of Hulun Lake (water depth is 2.6 m) are revealed. The discovery and determination of these thresholds provide important management basis for the ecological protection of Hulun Lake.

3 Conclusions

With the continuous advancement of ecological civilization construction, the health status of river and lake ecosystems has become an important indicator for measuring regional sustainable development. The application of satellite remote sensing technology, big data platforms, and artificial intelligence analysis technology marks that the ecological monitoring of Hulun Lake has entered the era of intelligence. Since the introduction of the satellite remote sensing monitoring system, functions such as dynamic monitoring of waters, assessment of ecological restoration, and early warning of water body abnormalities have been realized. It can accurately capture changes in water body, dynamically collect vegetation coverage, and monitor abnormal phenomena such as cyanobacterial bloom in real time, providing strong technical support for the supervision, water resource management, water environmental protection, and water ecological restoration of Hulun Lake. Through timely and effective prevention and control, water quality has been improved significantly, and biodiversity has recovered; the ecosystem has gradually returned to stability, and the intelligent monitoring has significantly decreased the frequency of manual inspections, reduced annual operation and maintenance cost, greatly enhanced the response time for problem discovery and disposal, and truly achieved "early detection, quick response, and precise governance" of problems.

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