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RESEARCH ARTICLE

Application and practice of remote sensing technology in analysis of water environment change and ecological effect

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With the intensification of global environmental changes, the changes of water environment and ecosystem have brought profound impacts on human society and natural ecology. In order to monitor and evaluate these changes more accurately and in real time, this study explored the application of remote sensing technology in the analysis of water environment changes and ecological effects and compared it with traditional ground observation technology. The results showed that remote sensing technology had obvious advantages in spatial and temporal resolution, large-scale continuous monitoring, and so on, and could provide more comprehensive and timely information for decision makers and researchers. Especially in the monitoring of water area, water quality, ecosystem structure and ecological service function, remote sensing data and ground observation data were highly consistent. On the whole, remote sensing technology would play an increasingly important role in the study of water environment and ecological effects in the future and was expected to provide strong support for global environmental protection and ecological restoration.

Keywords: remote sensing technology; water environment change; ecological effect; ground observation; ecological service function.

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Introduction

As global climate change and human activities intensify, the alterations in water environments and their impacts on ecosystems have become a focal point of global concern. In recent years, the frequent occurrence of extreme climatic events, such as persistent droughts and floods, have not only caused significant impacts on human socio-economic activities but also inflicted severe damage on ecosystems. Furthermore, due to the acceleration of industrialization and urbanization, water pollution issues have become increasingly prominent, affecting the health and stability of aquatic ecosystems. Therefore, accurate, rapid, and extensive monitoring and analysis of changes in water environments and their ecological effects are of utmost importance. Traditional ground-based observation methods, although accurate, are limited by time, space, and cost constraints, and often fail to meet the needs for extensive, real-time, and continuous monitoring, which necessitates the need for a new and efficient technology to address this challenge.

Remote sensing technology, as a rapidly developing technique, offers researchers a new perspective and tool. With sensors mounted on satellites or aircraft, it enables remote, extensive, and continuous monitoring of various terrestrial changes, including the dynamics of water environments. Simultaneously, remote sensing technology can capture subtle changes that are difficult to detect with traditional methods, such as minor changes in water temperature or color. These subtle variations are often closely linked to ecological effects. Thus, exploring the application and practice of remote sensing technology in this field is both vital and urgent. The core of remote sensing technology lies in its sensors and corresponding detection mechanisms. These sensors, typically mounted on satellites or aircraft, are responsible for receiving electromagnetic radiation reflected or emitted from the earth's surface. Based on their working principles and application scope, these sensors can be broadly classified into two types of active and passive. Active sensors, such as Synthetic Aperture Radar (SAR), emit radiation themselves and receive the radiation reflected back from the target objects, allowing for detection under all weather conditions. In contrast, passive sensors mainly rely on the sun as a light source, capturing solar radiation reflected off the earth’s surface. The detection mechanism of sensors is based on the absorption, scattering, and reflection characteristics of objects to electromagnetic waves. For instance, clear water bodies and polluted ones exhibit different reflective characteristics at certain specific wavelengths. By utilizing these subtle spectral differences, remote sensing technology can accurately detect changes in water environments and their ecological effects over large areas, providing precise environmental information.

Remote sensing technology has become a key tool to study and monitor water environment change, and it has shown remarkable potential and efficiency in water quality assessment, pollution source location, ecological environment monitoring and so on. Rink *et al*. demonstrated the application of remote sensing technology in environmental monitoring by developing virtual geographic environment to promote water pollution control [1]. In addition, Bi *et al*. stressed the importance of considering water quality trends when conducting water environment assessment, which was also an area where remote sensing data could provide support [2]. Sun *et al*. discussed the method of environmental adaptive deployment of water quality sensor network, which relied on remote sensing technology to determine the best location of monitoring points [3]. Liu investigated water environment monitoring and assessment based on water ecological function zoning in his research, which highlighted the application of remote sensing data in regional water environment management [4]. Wang *et al*. focused on the use of camera sensors to detect pollution in water environment, which indicated the potential of remote sensing technology in real-time monitoring [5]. Liang applied deep belief network to big data of water environment monitoring, demonstrating the prospect of combining remote sensing technology with artificial intelligence [6]. Wang *et al*. used a novel Bayesian method to carry out overloading risk assessment of water environment and water resource carrying capacity, which once again proved the effectiveness of remote sensing data in complex environmental analysis [7]. The application of remote sensing technology is not only limited to water quality monitoring and assessment, but also extends to the evaluation of ecological environment quality. Jiao *et al*. proposed an ecological index based on water benefits for the assessment of urban ecological environment quality. This method could also be combined with remote sensing technology to improve the accuracy and efficiency of assessment [8]. Remote sensing technology is widely used in water environment change and ecological effect analysis, from water quality monitoring, pollution source tracking to ecological environment assessment, showing its unique value. These past studies not only proved the effectiveness of remote sensing technology, but also provided new perspectives and methods for water environment monitoring and management in the future.

The application of remote sensing technology in the analysis of water environment changes and ecological effects has opened a new dimension of research [9]. This study primarily utilized publicly available remote sensing data to monitor and analyze the changes in the aquatic environment and their impact on ecological effects through remote sensing technology and evaluate the accuracy and effectiveness of remote sensing technology in capturing changes in the water environment and related ecological effects. Additionally, the traditional aerial remote sensing sensor data published by local government surveying and mapping departments were also collected in this study. The research team employed drones equipped with multispectral sensors for multiple flights over selected areas to directly collect high-resolution aerial data. Moreover, the collection of water samples, sediments, or biological specimens were sent back to the laboratory for various physical, chemical, and biological tests. The results of this study would not only provide reference data for future water environment and ecological monitoring but also offer practical and significant reference value for governments, enterprises, and the public in the field of environmental protection and sustainable development. For the scientific community, this study would provide a detailed empirical framework for the detection and analysis of the water environment and its ecological impacts using remote sensing technology, which would contribute to the advancement of in-depth research in remote sensing science and offer a reliable technical reference for researchers in related fields, enabling extensive and continuous environmental monitoring. For policymakers and environmental management departments, the results of this study could provide more precise and timely data support. When facing urgent issues such as water resource crises and water pollution, real-time data analysis based on remote sensing could significantly accelerate response times, aiding in the more effective formulation and implementation of relevant policies and measures [10, 11].

Materials and Methods

Data sources and collection methods

1. Remote sensing data

(1) Satellite data

To analyze changes in the water environment and its ecological effects, this study selected two types of satellite data sources including high-resolution WorldView-3 satellite data (https://worldview3.digitalglobe.com/) and medium-resolution Moderate Resolution Imaging Spectroradiometer (MODIS) data (https://modis.gsfc.nasa.gov/). High-resolution satellites offering images with a spatial resolution of 0.31 meters per pixel are particularly suited for detailed water boundary detection and analysis of intra-water body feature changes [12]. MODIS data, while having a coarser spatial resolution of 250 meters compared to WorldView-3, provides a broader coverage area and higher temporal resolution, making it more effective in capturing large-scale water environment change trends [13, 14]. To ensure the accuracy of the analysis, the study selected data with a cloud cover of less than 15%. Additionally, the chosen data were required to cover the same geographical area to facilitate time series analysis and comparison.

(2) Aerial data

Aerial remote sensing data was collected using sensors mounted on airplanes or Unmanned Aerial Vehicles (UAVs) [15]. Due to their much lower flight altitude compared to satellites, these platforms generally provide data with higher spatial resolution, making them particularly suitable for detailed and rich site-specific studies. In this study, UAVs equipped with multispectral sensors were utilized for multiple flights over selected areas, yielding high-resolution aerial data. This approach greatly aided in the detailed investigation of small-scale changes in the aquatic environment and ecological characteristics. Remote sensing sensors mounted on traditional aircraft can cover a larger geographical area and provide relatively stable data quality, which constituted an important data source of this study. In selecting aerial data, this study primarily considered the spatial resolution, coverage area, and collection time of the data to ensure quality and accuracy of the study. By integrating satellite data with aerial data, a comprehensive and in-depth analysis of water environment changes and their ecological effects was possible.

2. Ground observation data

(1) Direct measurement method

The direct measurement method relies on ground equipment and tools to collect physical, chemical, and biological parameters of the water environment on-site. The advantage of this method lies in the high precision and specificity of the data, which is commonly used to validate and supplement remote sensing data [16]. In this study, professional devices such as hydrological sonars, pH meters, and dissolved oxygen meters were used for data collection. These data provided an in-depth understanding of the water environment and served as key benchmarks for validating and calibrating remote sensing data.

(2) Sample collection and analysis

In addition to direct measurements, this study also conducted laboratory analyses on various substances in the water body through collected samples. This approach involved collecting water samples, sediments, or biological specimens and conducting various physical, chemical, and biological tests in the laboratory to obtain more detailed and specific data. All samples were collected at fixed times and locations and were immediately refrigerated to maintain their stability. During laboratory analyses, mass spectrometry, spectroscopy, and microscopy were employed to ensure the accuracy and reliability of the data. These ground-based observational experimental data provided complementary information to the remote sensing data, enhancing the depth and detail of the analysis of the water environment and its ecological effects.

Sampling regions, data collection time, and data arrangements

Three sampling areas including Hangzhou, Zhejiang, China (area A), Shanghai, China (area B); and Suzhou, Jiangsu, China (area C) were included in this study with their unique research purpose. In area A (120.50 E, 30.25 N), the study period spanned from June 10 to June 30, 2023. Having recently experienced a flood, this study aimed to investigate changes in the water environment post-flooding. The data sources included satellite data obtained from the "High-resolution Earth Observation System (Gaofen)" and aerial data collected using multispectral sensors mounted on the "DJI Phantom 4" UAV (DJI, Shenzhen, China). In area B (121.10 E, 30.75 N), the study period was from July 1 to July 20, 2023. Located in a relatively dry area, this study planned to investigate water resource dynamics during drought periods. Data sources comprised resource satellite data downloaded from the "China Centre for Resources Satellite Data and Application (CRESDA)" and ground observation data, the latter using the economical "Lohand LH-TDS" water quality testing pen (Lohand Biological Technology Co., Ltd., Hangzhou, Zhejiang, China). In area C (120.75 E, 30.50 N), the study was conducted from June 15 to July 10, 2023. Area C, being a typical lake area, was chosen for an in-depth exploration of the interrelationship between ecological effects and changes in the water body. The data sources included remote sensing data acquired from the "Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences" and ground water quality analysis using the economical "Lohand LH-TDS" water quality testing pen (Lohand Biological Technology Co., Ltd., Hangzhou, Zhejiang, China). The selection of these three areas was intended to provide researchers with a comprehensive and multi-perspective view, enabling a thorough assessment of the application of remote sensing technology in analyzing changes in the water environment and its ecological effects.

For remote sensing data, this study used a variety of open remote sensing data centers and databases to download. In particular, WorldView-3, MODIS, and the aerial remote sensing data selected in this study all have corresponding data download platforms, which not only provide the original image data, but also a series of metadata, such as acquisition time, cloud coverage, *etc*., to help researchers screen and select appropriate data. In order to ensure the continuity and integrity of the data, continuous time periods were selected, and the spatial coverage of the data was consistent. For ground observation data, the team in this study conducted continuous sample collection in selected areas and times. Each collection was carried out in accordance with strict standards and procedures to ensure data consistency and reliability. After collection, all samples were labeled and stored in dedicated storage containers before being sent to the laboratory for analysis. Data collation was the next step after collection. For a large number of remote sensing image data, this study adopted professional remote sensing software for preliminary processing, such as radiation correction, atmospheric correction, and geographic calibration. The ground data were organized using spreadsheets and database tools to ensure that each data point corresponded to its corresponding time and place. In the process of collation, preliminary data screening was carried out to remove those data with low quality or inconsistent with the research objectives to ensure the quality and efficiency of subsequent analysis.

Data processing and analysis

1. Data preprocessing

Data preprocessing is the initial correction and adjustment of original remote sensing and ground observation data to prepare for subsequent analysis and model building. The goal of this phase is to ensure the quality, accuracy, and spatial and temporal consistency of the data.

(1) Radiation correction

To obtain the true reflectance of the ground, radiation correction was first performed in this study, which involved converting the digital number into radiant brightness using Formulation (1).

$$L = G \times DN + B \tag{1}$$

where L was the radiation brightness. DN was the original numeric number. *G* and *B* were the gain and offset, respectively, and their values could usually be found in the metadata of remote sensing data.

(2) Atmospheric correction

Since aerosols and moisture in the atmosphere can absorb and scatter sunlight, causing biases in remote sensing images, atmospheric correction is required. The method used in this study was Dark Object Subtraction (DOS) method with assuming that the reflectivity of the darkest object in the image was 0.

$$\rho = \frac{L - L_{\min}}{L_{\max} - L_{\min}} \tag{2}$$

where ρ was the reflectivity of the ground. L was the radiant brightness. $L_{\min}$ and $L_{\max}$ were the minimum and maximum radiant brightness in the image, respectively.

(3) Geometric correction

Remote sensing images may have shape biases due to the curvature of the Earth and the Angle changes of satellite sensors. In order to correct these deviations, geometric correction was performed using known ground control points and points on remote sensing images by Formula (3) and (4).

$$x' = ax + by + c \tag{3}$$

$$y' = dx + ey + f \tag{4}$$

where (x', y') was the corrected image coordinate. (x, y) was the original image coordinate. a, b, c, d, e, and f were the transformation parameters.

The above pre-processing steps ensured that the obtained remote sensing data was consistent with the real situation on the ground and provided a solid foundation for subsequent analysis and verification.

2. Data matching and fusion

Data matching and fusion is designed to integrate data from different sources to achieve higher spatial, temporal, or spectral resolution to provide richer and more accurate information for in-depth analysis.

(1) Data matching

Since the collection time and space range of remote sensing satellite and ground observation data might be different, data matching was first carried out in this study, which included ensuring that all data covered the same geographic range and time period. Specifically, if you had A remote sensing image $I(x,y,t)$ and a ground observation data $D(x',y',t')$, you needed to ensure $x=x'$, $y=y'$, and $t=t'$.

(2) Data fusion

Data fusion is the combining of data from different resolutions or sources, usually using weighted averages or other methods. Assuming that there were high-resolution remote sensing images $H(x,y)$ and low-resolution images $L(x,y)$, the fusion method was shown in formulation (5).

$$F(x,y)=\alpha\times H(x,y)+(1-\alpha)\times L(x,y) \tag{5}$$

where, $F(x,y)$ was the fused image. α was a weight coefficient between 0 and 1, which determined the degree of contribution of the two kinds of data.

(3) Spectrum matching

When remote sensing data from multiple spectral bands were available, spectral matching might be required to ensure that the data from each spectral band was on the same physical scale. Suppose there were reflectance ρ_1 and ρ_2 of two spectral bands, and their matching relationship was shown in formulation (6).

$$\rho_2=k\times\rho_1+b \tag{6}$$

where k was the slope, representing the proportional relationship between the two spectral bands. b was the intercept, representing the baseline difference.

Through the above data matching and fusion steps, this study successfully integrated data from different sources to form a continuous and consistent data set, which provided a solid foundation for the subsequent analysis of water environment change and ecological effects.

3. Quantitative analysis of data

(1) Mean square error evaluation (MSE)

In this study, MSE was used to assess the difference between remote sensing data and terrestrial data as shown in formulation (7).

$$MSE=\frac{1}{n}\sum_{i=1}^{n}\left(O_i-P_i\right)^2 \tag{7}$$

where O_i was ground observation data. P_i was remote sensing data. n was the number of data points.

(2) Application of relative error (RE)

In this study, the formulation of Relative Error (RE) was selected to describe the difference between the data observed by the two methods as shown in formulation (8).

$$RE=\frac{\left|O_i-P_i\right|}{O_i}\times 100\% \tag{8}$$

where O_i was ground observation data and P_i was remote sensing data.

(3) Calculation of water body area change rate

In this study, the change rate calculation method was selected to calculate the observed water area change as a key ecological environment indicator to evaluate and quantify the dynamic change and ecological effect in the water environment as shown in formulation (9).

$$Rateofchange = \frac{Waterbodyarea_{2023-07-01} - Waterbodyarea_{2023-06-15}}{Waterbodyarea_{2023-06-15}} \times 100\% \quad (9)$$

Through these quantitative analysis methods, the research had laid a solid data foundation for the following in-depth research and discussion.

Results and discussion

Validation of remote sensing data accuracy

To validate the accuracy of the remote sensing data, this study used ground observation data as a benchmark for comparison. Taking the water temperature, a physical parameter of the water body, as an example, data from point A was selected for verification. According to the Mean Square Error (MSE, Formula 7) calculation results, the water temperature measured at point A through remote sensing technology was 22.70°C, while ground observation data showed a temperature of 22.45°C. The calculated MSE value was 0.0625. These results indicated that, for the water temperature at point A, the remote sensing data was very close to the ground observation data with a low MSE value. This suggested a high accuracy of remote sensing data, demonstrating good consistency with ground observations. Such accuracy provided strong data support for subsequent analysis of water environment changes and ecological effects.

Comparison between ground data and remote sensing data

To further validate the accuracy and reliability of remote sensing data, this study compared the remote sensing data with ground observation data. The primary parameter examined was water temperature, as it was a key parameter significantly affecting the health and functionality of aquatic ecosystems. This study used the aforementioned Relative Error (RE, Formula 8) to calculate data for points A, B, and C. The results of these calculations were shown in Figure 1. The results showed that, for all three points, the relative error between remote sensing data and ground observation data was small, and the maximum error was no more than 1.11%. This further proved that the remote sensing data used in this study had a high accuracy and a good agreement with the ground observation data, which provided a solid foundation for subsequent analysis and research.

Changes in water area and distribution

To evaluate and compare the effects of remote sensing technology and traditional ground observation technology in the detection of water area and distribution changes, this study conducted a detailed analysis of three previously selected areas. Direct measurements in areas A, B, and C gave water depths of 12.50 m, 8.75 m, and 15.32 m, respectively. Transparency was 1.87 meters, 1.42 meters, and 2.15 meters, respectively. The index of water area and distribution change was selected to compare the detection effect of remote sensing technology and traditional ground observation technology. The water body area test results of the two technologies in the three areas were shown in Figure 2. The change rate of the water body area in the three areas during this period was calculated. According to the calculation method of the change rate in formulation 9, the change rate of the water body area was quantitatively analyzed in this study. The calculation results showed that in area A, the change rate of water area monitored by remote sensing technology was -9.84%, while the change rate obtained by ground observation was -10.00%. In area B, the change rate of water area shown by remote sensing technology was 4.76%, which was slightly different from the change rate of 4.33% obtained by ground observation. In area C, the change rate measured by remote sensing technology was -3.61%, which showed a small difference compared with the ground observation of

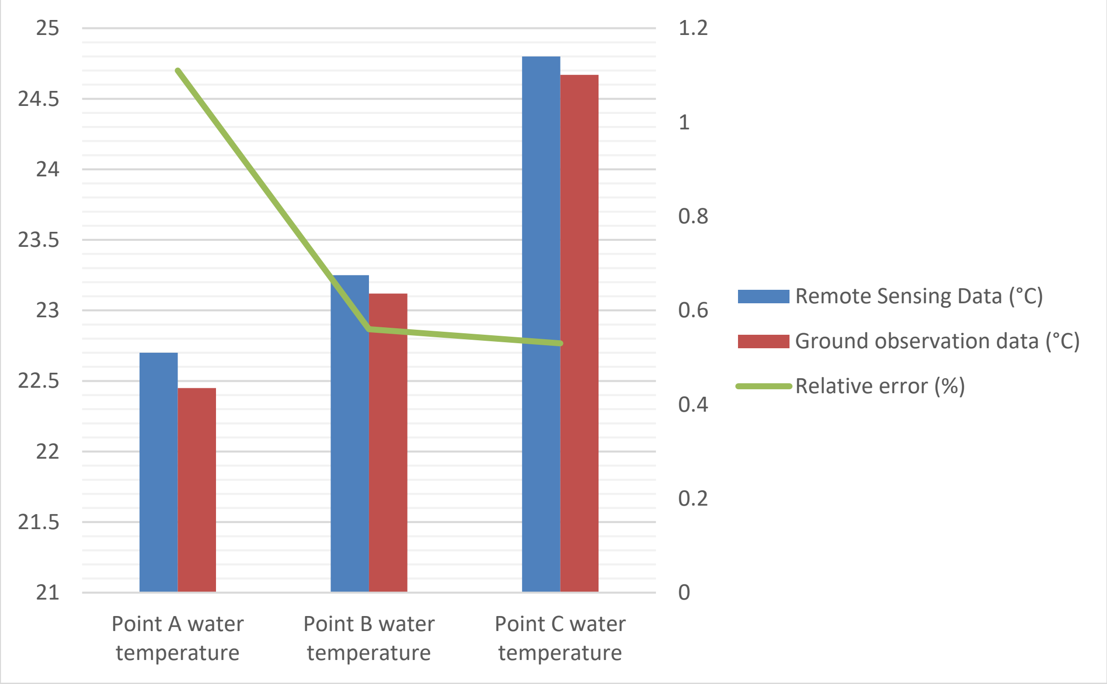

Figure 1. Comparison between ground observation data and remote sensing data.

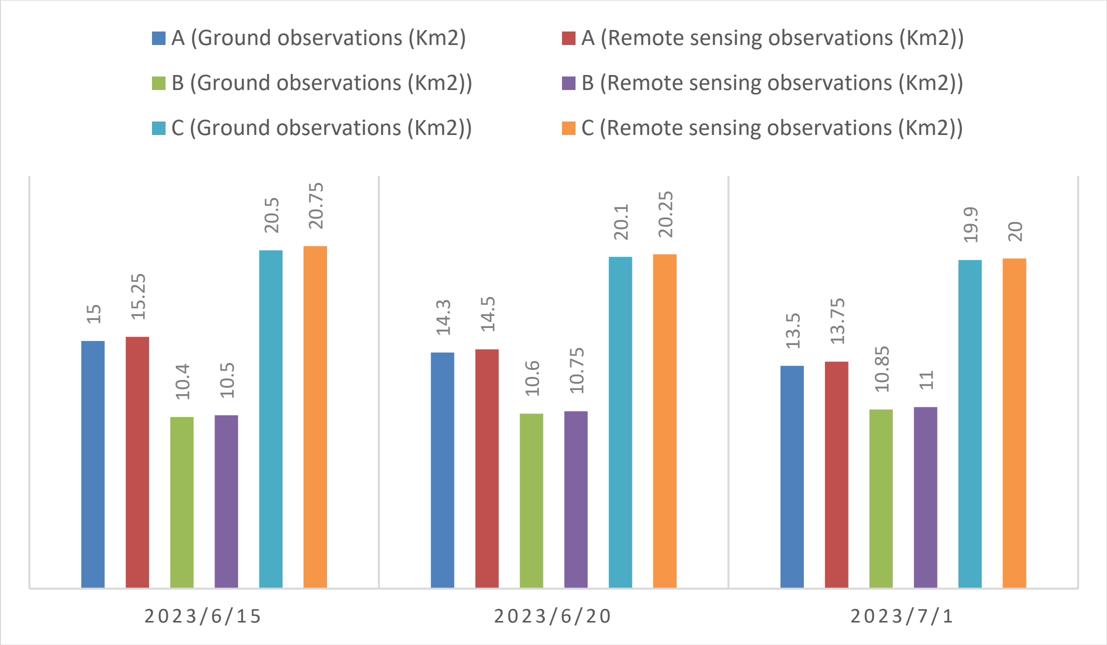

Figure 2. Comparison of observations (Km^2) from the ground-based observation technique with those from the remote sensing technique.

-2.93%. Both techniques had good performance in detecting water area changes, and the results were similar. However, remote sensing techniques showed slightly larger variations in the detection of certain dates and areas, which were likely related to their higher temporal

Table 1. Comparison of water quality testing.

Technique	Date	Turbidity (NTU)	Chlorophyll a (mg/L)	Total Nitrogen (mg/L)
Remote Sensing	2023-06-15	45	12	2.8
Ground Observation	2023-06-15	44	11.5	2.7
Remote Sensing	2023-06-20	42	11	2.6
Ground Observation	2023-06-20	41	11	2.6
Remote Sensing	2023-07-01	38	10	2.5
Ground Observation	2023-07-01	38	9.8	2.4

Table 2. Comparison of ecosystem structure changes in area A.

Technique	Date	Vegetation Cover (%)	Wetland Area (km²)
Remote Sensing	2023/6/15	65	8.5
Ground Observation	2023/6/15	64	8.4
Remote Sensing	2023/6/20	63	8.3
Ground Observation	2023/6/20	62	8.2
Remote Sensing	2023/7/1	61	8.0
Ground Observation	2023/7/1	61	7.9

resolution and continuous monitoring capabilities. Remote sensing technology could provide more comprehensive and continuous data for areas with large areas and complex terrain, while ground-based observations might be affected by practical operations and resource constraints.

Changes in water quality

To compare the performance of remote sensing technology and traditional ground observation technology in water quality detection, several common water quality parameters were selected in this study including turbidity, chlorophyll a concentration, and total nitrogen. These parameters were important for the health and ecological effects of water environment. Taking area A as an example, the water quality test results of the two technologies in this area were shown in Table 1. The results of the two technologies in detecting water quality parameters were very close. For some dates and areas, there were slight differences between the two sets of data, which might be related to the spectral resolution of remote sensing techniques and the limitations of ground-based observation methods. In general, remote sensing technology had a good consistency with traditional ground observation methods in water quality detection, but provided a more continuous, large-scale monitoring capability.

Changes of ecosystem structure

The change of ecosystem structure mainly involves the change of vegetation cover, wetland distribution, water edge habitat, and so on. Laboratory chemical analysis of water and sediment samples showed that the chemical properties of points A, B, and C were measured, where the heavy metal contents were 0.015 mg/L, 0.020 mg/L, and 0.012 mg/L, and the organic pollutant contents were 1.25 mg/L, 1.10 mg/L, and 1.35 mg/L, respectively. The microbial populations were 320 CFU/mL, 290 CFU/mL, and 310 CFU/mL, respectively. The results of sediment sample analysis showed that the organic matter content of these sites were 4.25%, 3.89%, and 4.55%, and the heavy metal contents were 32.50 mg/kg, 31.75 mg/kg, and 33.00 mg/kg, respectively. Among them, the structural changes of ecosystems were mainly related to the changes of vegetation cover, wetland distribution, water edge habitat, and so on. This study mainly focused on two core indicators of vegetation coverage and wetland area. The test results of ecosystem structure

Table 3. Comparison of ecological service function changes.

Technique	Date	Water Yield (m^3)	Carbon Sequestration (tons)
Remote Sensing	2023-06-15	850	48
Ground Observation	2023-06-15	845	47.5
Remote Sensing	2023-06-20	830	46
Ground Observation	2023-06-20	825	45.5
Remote Sensing	2023-07-01	810	44
Ground Observation	2023-07-01	805	43.5

changes in two technical areas A were shown in Table 2. The results showed that the detection results of remote sensing technology and traditional ground observation technology were very close to each other in terms of ecosystem structure changes. There were small data differences between the two technologies at certain areas and time points, but the overall trend was consistent. Remote sensing technology had shown obvious advantages in large-scale, continuous, and real-time ecological structure monitoring, which could provide valuable information for decision makers and researchers.

Changes of ecological service functions

The ecological service function refers to the direct or indirect economic, social, and cultural value that the ecosystem provides to human beings. Here, this study selected two important ecological service functions of water conservation and carbon sink function. The test results of ecological service function changes of the two technologies in the three regions were shown in Table 3. The results showed that remote sensing technology and traditional ground observation technology gave very similar results in the detection of ecological service function changes. However, remote sensing technology could provide a large range of continuous data, which provided a strong support for the long-term change trend analysis of ecological service functions. In addition, remote sensing technology provided the only source of data for remote or dangerous areas where ground-based observations were difficult, providing the possibility for a comprehensive assessment of ecological service functions.

Conclusion

In this study, the practical application of remote sensing technology in the analysis of water environment change and ecological effect was discussed, and the comparison with the traditional ground observation technology was made in detail. Through the experimental data, this study found that remote sensing technology was significantly superior to traditional methods in large-scale and continuous monitoring. Especially in the detection of water body area, water quality and ecological service function, remote sensing data was highly consistent with ground observation data, which confirmed its accuracy and reliability in actual environmental monitoring. In addition, its unique temporal and spatial resolution advantages allowed remote sensing technology to capture rapid changes in the environment, such as flood and drought events, in a timely manner. With the continuous progress of remote sensing technology, researchers expect that it will play a greater role in environmental and ecological research in the future. Combined with ground observation, remote sensing technology has the potential to provide more accurate and real-time data support for water environment protection and ecological restoration. This integration of technologies will provide environmental scientists and policymakers with more complete information to better address the challenges posed by global change.

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