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Spectral Monitoring Online System for Water Quality Assessment Based on Satellite–Ground Data Integration

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Abstract: With urbanization and economic growth, water pollution has become a key factor that restricts the sustainable development of cities. Traditional water quality monitoring methods are time-consuming and can easily cause secondary pollution. Online water quality monitoring can automatically and rapidly display water quality in place and in real time, and satellite data can provide sources for large-scale and long-term water quality monitoring assessments. Based on the demand for real-time online monitoring of inland water in China, this study combined a water quality spectral monitoring online system with multisource remote sensing data to research and assess the application of a satellite–ground integrated water quality monitoring system and improve the accuracy and stability of water quality parameter inversion over a long duration and on a large scale by data cross-validation with real-time ground monitoring data.

Keywords: satellite–ground data integration; water quality; hyperspectral; online assessment

1 Introduction

Water quality is directly related to human life. With urbanization and rapid economic growth, the demand for water resources in China is increasing, but the water environment is deteriorating in some areas[1]. Water pollution has become a key factor restricting the sustainable development of cities[2]. The China government proposed adherence to the basic national policy of environmental protection, and thus high-tech methods must be used to carry out research regarding water pollution of lakes and rivers to rapidly and comprehensively perceive the water environment and water pollution status[3].

The traditional method for water quality monitoring involves collection of water samples on-site and transport to the laboratory for analysis using appropriate instruments, or the con-

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struction of a fixed monitoring station[4]. Although traditional methods have great accuracy, there are several problems. First, the cost is high. Manpower and material resources are required for field sampling and transportation to the laboratory, the construction and maintenance costs of fixed stations are high, and chemical reagents must be consumed. Second, secondary pollution can be problematic. Traditional water quality monitoring is based on chemical methods that produce considerable waste during the detection process, which is difficult to manage. Third, monitoring limitations exist. Traditional water quality monitoring involves ex situ detection. Water quality can only be monitored at a specific time and at limited sampling points; therefore, it is difficult to acquire data regarding the temporal and spatial distributions and changes in water quality for a large range of waters.

Spectral online monitoring of water quality can obtain water quality parameter information rapidly, continuously, without pollution, and in real time, thereby avoiding the shortcomings of traditional water quality monitoring. However, it is difficult to perform rapid and efficient monitoring of water quality in large areas because of spatial uncertainty. Satellite remote sensing compensates for the lack of point monitoring through its advantages of wide-range, high-speed, long-term, and dynamic monitoring[5], thus providing a new method for large-scale and long-term water quality monitoring[6]. Therefore, a new approach for dynamic monitoring of the spatiotemporal inland water quality in China involves the combination of satellite remote sensing with a ground-spectra online monitoring system. The key aspect of this research involves establishment of a method for coordinating observations between the spectral monitoring system and the satellite data. To satisfy the demand for inland water quality monitoring in China, this paper proposes a water quality spectral monitoring method based on satellite data, aviation data, and ground data, as well as the project and key technologies of a satellite–ground integrated water quality spectral monitoring online system.

2 Spectral Monitoring of Water Quality

The current data sources of water quality monitoring include mainly satellite data, aviation data, and ground data. Satellite data include multispectral and hyperspectral data, aviation data include mainly manned aircraft and unmanned aerial vehicle data, and ground data are obtained mainly by field portable spectrometers.

2.1 Satellite Data

Multispectral satellite data, such as TM, ETM+, and OLI data in the United States, HRVR data in France, and GF series data in China, were used in the early stages of water quality monitoring, and the TM data were most widely used[7]. Multispectral remote sensing has the advantage of rich data, but its spectral range is concentrated mainly in the visible to near-infrared bands. Moreover, the spectral resolution is usually 20–70 nm and only 4–8 bands can be analyzed; therefore, it is difficult to capture the small spectral characteristics of water. Hyperspectral satellites provide a new data source for inland water quality monitoring because of their rich spectral resolution. For example, GF-5[8] and OHS[9] have been used widely in water quality monitoring.

During the inversion of water quality parameters from satellite data, there is generally a requirement for radiometric correction, atmospheric correction, geometric correction, and filtering to obtain remote sensing images of the study area with suitable quality. An empirical model or a semi-empirical model is established and combined with the measured water quality parameters. Because the band combination is usually determined by enumeration comparison, the inversion results of the model are typically unstable and lack sufficient robustness[10]. The process of retrieving water quality parameters from satellite data is illustrated in Figure 1.

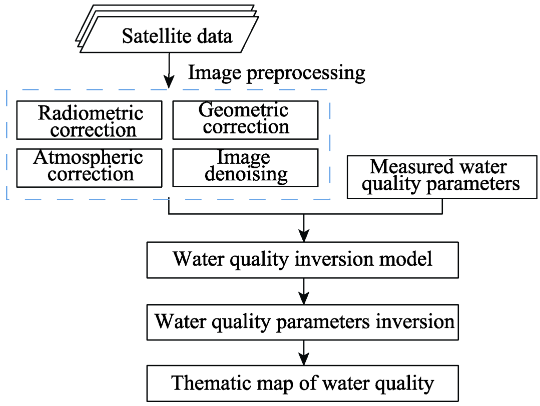

Figure 1 Flow chart of water quality parameter inversion based on satellite remote sensing data

2.2 Aviation Data

Due to the influences of return period, spatial resolution, and weather, the acquisition and post-processing of satellite data are difficult, especially for areas with frequent rain. However, the miniaturization of hyperspectral hardware has permitted the application of hyperspectral remote sensing data based on platforms on manned aircraft and unmanned aerial vehicles in the field of water quality monitoring[11]. In contrast to satellite remote sensing, aerial remote sensing allows the selection of flight time and route as necessary for specific tasks. Because the aerial remote sensing flight altitude is much lower than satellite altitude, aerial remote sensing can obtain higher spatial resolution image data, which can better reflect the spectral and spatial information of water and thus improve the accuracy of water quality monitoring. At present, the main manned aircraft hyperspectral systems include HyMAP-C in Australia, the Prob series in the United States, CASI/SASI/TASI in Canada, AISA+ in Finland, and PHI in China. Hyperspectral equipment based on the unmanned aerial vehicle platform includes mainly OCI in the United States, SPECIM in Finland, HySpex in Norway, and small hyperspectral imaging systems developed by CIOMP, SITP, and AIR of the Chinese Academy of Sciences.

In 2017, the author's team completed aerial hyperspectral remote sensing monitoring of water quality (Figure 2) in Baiyang Lake, Xiongan New Area, Hebei Province[12], using the Yun-5 fixed wing flight platform carrying a self-developed, full-spectra, and multimode imaging spectrometer. In 2018, the author's team used a six-rotor unmanned aerial vehicle platform carrying a small push-broom hyperspectral spectrometer to obtain hyperspectral images of the Maozhou River in Shenzhen, completed the water quality parameter inversion in accordance with the established model based on the chemical values of water parameters, and finally produced a water quality thematic map of the entire area (Figure 3).

In contrast to satellite data, the coverage of aerial data is limited, and both geometric correction and mosaic preprocessing are needed. Both geometric and spectral consistencies of the image should be considered to avoid capturing the same object using different spectra.

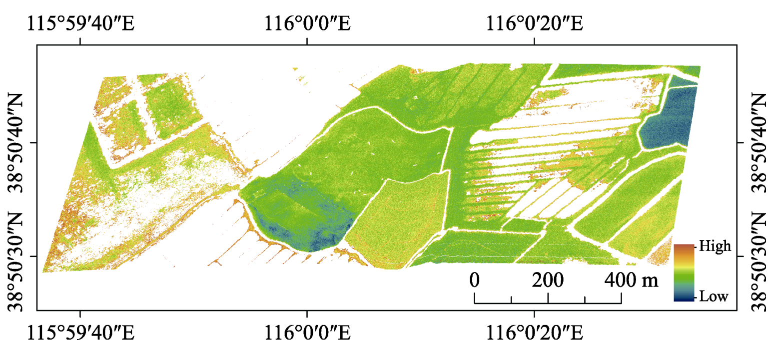

Figure 2 Thematic map of suspended matter inversion of Baiyang Lake

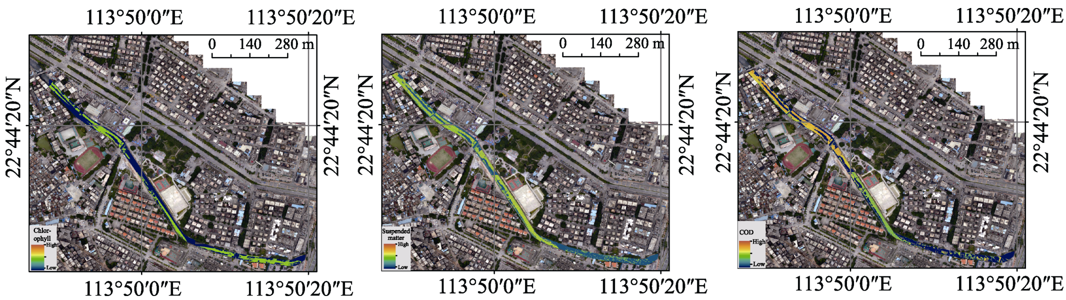

Figure 3 Thematic map of water quality inversion of Maozhou River

The process of retrieving water quality parameters through aerial remote sensing data is shown in Figure 4.

2.3 Ground Data

When no satellite data are accessible, spectral data can be obtained flexibly by field portable spectrometer at low cost. At present, the main manufacturers of field spectrometers include Ocean Optics, ASD, and Avantes. The FieldSpec-4 field portable spectrometer by ASD and the USB4000 and Torus-series microspectrometers by Ocean Optics are used widely in China. Although a microspectrometer cannot compare with the large-scale spectrometer in terms of resolution or spectral measurement range, it has advantages with respect to portability, intelligence, and integration; it can also display field data in real time[13].

When using a field spectrometer to obtain water spectra, water, sky light, and standard plate must be measured, and the remote sensing reflectance of the water must be calculated according to the formula. Hence, the surface reflectance of gas and water, direct solar reflection of the capillary wave, and integration time affect the quality of the data obtained, as well as the inversion accuracy of the water quality parameters[14]. The process of monitoring water quality parameters by ground data is shown in Figure 5.

A spectral monitoring online system of water quality can realize automatic, rapid, and in situ measurement in a stable external environment without chemical reagents and secondary

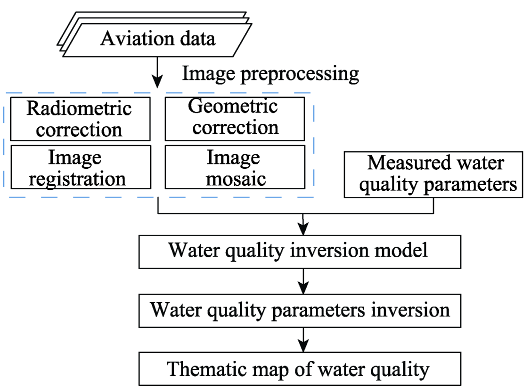

Figure 4 Flow chart of water quality parameter inversion based on aerial remote sensing data

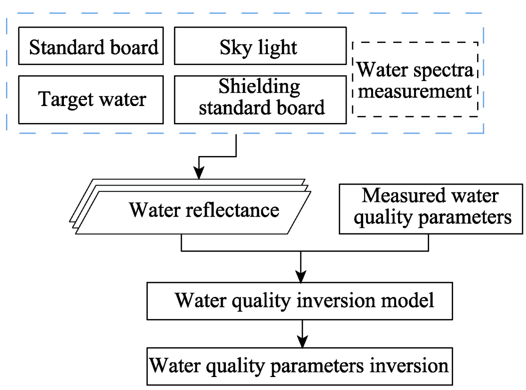

Figure 5 Flow chart of water quality parameter inversion based on ground data

pollution. It can meet the need for real-time online water quality monitoring, a focus of current research. The author's team developed a portable, intelligent, water quality spectrometer, as well as a fixed, intelligent, water quality spectrometer. The device can obtain real-time water spectral data and realize in situ, rapid, real-time, and pollution-free water quality monitoring based on the established multiparameter inversion model. This approach produces high-quality inversion results in many cases.

2.3.1 Portable, Intelligent, Water Quality Spectrometer

The author's team developed the innovative portable, hyperspectral, intelligent water quality spectrometer in China, known as Water Color (Figure 6). The system can rapidly detect water quality in the field using spectral analysis technology. It consists of a portable, intelligent water quality spectrometer, APP operation software (i.e., Water Color), and a water quality, big-data cloud service platform[15].

Figure 6 Portable intelligent water quality spectrometer

The device is connected with a smart phone via Bluetooth, and spectra are collected by controlling the spectra acquisition device. The spectral data are transmitted to the big-data cloud service platform through a 4G/5G network, and the analysis results are displayed on the smart phone terminal in real time. The device parameters are shown in Table 1.

Table 1 Parameters of portable, intelligent, water quality spectrometer

Index	Parameters
Weight	<0.58 kg
Size	20 cm × 10 cm × 4 cm
Wavelength	350–1,050 nm
Spectral resolution	Better than 5 nm, up to 3 nm
Number of spectral channel	303
Connector	Bluetooth
Continuous working hours	2 to 4 hours (single battery)

The portable, intelligent, water quality spectrometer has the advantages of small volume, all-weather capability, high sensitivity, high resolution, low power consumption, and high cost performance. The device can simultaneously detect more than 10 water quality parameters (e.g., total phosphorus, dissolved oxygen, and ammonia nitrogen) with robust expansibility. When compared with traditional water quality analysis in the laboratory, the greatest technical breakthrough of the system is rapid, real-time, and intelligent monitoring, which can meet the need for rapid, real-time detection of water quality for environmental protection and water departments, as well as other departments. Figure 7 shows the inversion results of total phosphorus and total nitrogen in the city of Ningbo. The overall trend of the predicted value is consistent with the trend of the actual value, and the inversion accuracy is high.

2.3.2 Fixed, Intelligent, Water Quality Spectrometer

The fixed, intelligent, water quality spectrometer developed by the author's team is a non-mobile, fixed-point, water quality detection system that can be applied to rivers, lakes, ponds, and other bodies of water. It consists of a HySan micro-intelligent spectrometer, fixed buoy, and water quality big-data cloud service platform, as shown in Figure 8. The parameters are shown in Table 2.

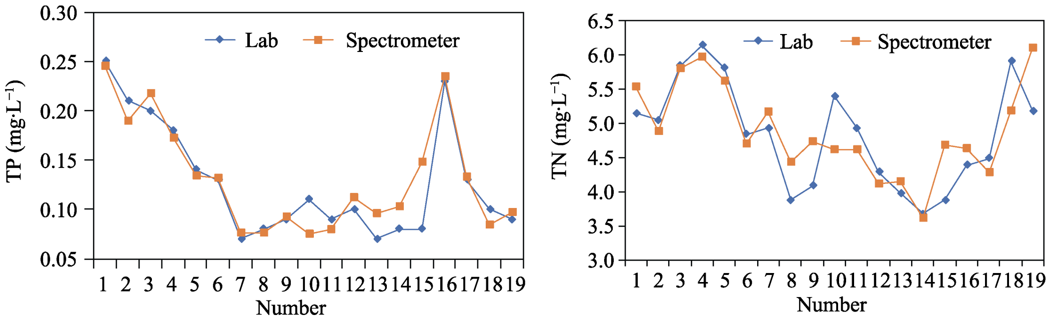

Figure 7 Accuracy comparison chart between the inversion value from the portable, intelligent, water quality spectrometer and the laboratory value

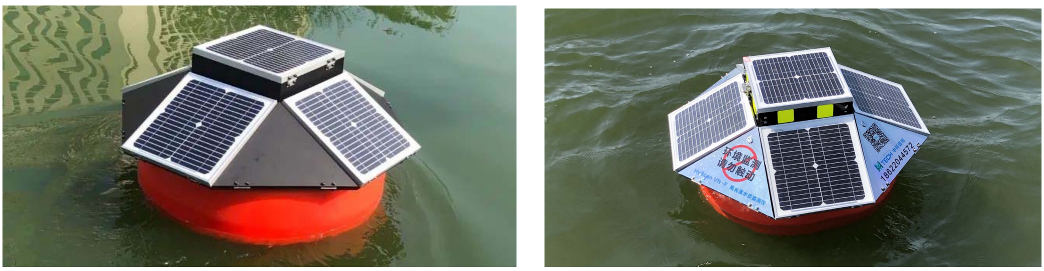

Figure 8 Fixed, intelligent, water quality spectrometer

Table 2 Parameters of fixed, intelligent, water quality spectrometer

Index	Parameters
Wavelength	400–1,000 nm
Power supply	Micro USB/Solar/Rechargeable battery pack
Weight	20 kg
Size	<80 cm × 80 cm × 50 cm
Sampling frequency	Every 30 minutes, 10 groups of data each time

The fixed, intelligent, water quality spectrometer can freely adjust the collection frequency and time to collect spectra at intervals of ≥ 5 s. It can automatically retrieve water quality parameters and realize data transmission, cloud data storage, data display, and statistical analysis in real time. Users can view the results in real time through a terminal, such as a large screen, iPad, or mobile phone. Figure 9 shows an accuracy analysis of the data measured at a station. The predicted values of water quality parameters are consistent with the real values, indicating that changes in water quality can be displayed well.

3 Scheme and Key Technologies of Satellite–Ground Integrated Water Quality Spectra Online Monitoring

3.1 Satellite–Ground Integrated Water Quality Spectral Monitoring Scheme

The establishment of a water quality parameter inversion model in remote sensing depends heavily on observation samples, which can cause instability of the inversion model. The satellite–ground integrated water quality spectra monitoring system can improve the stability and accuracy of water quality parameter inversion to realize a wide range of water quality monitoring and spatiotemporal analyses, thus providing a new method for long-term water quality monitoring in China.

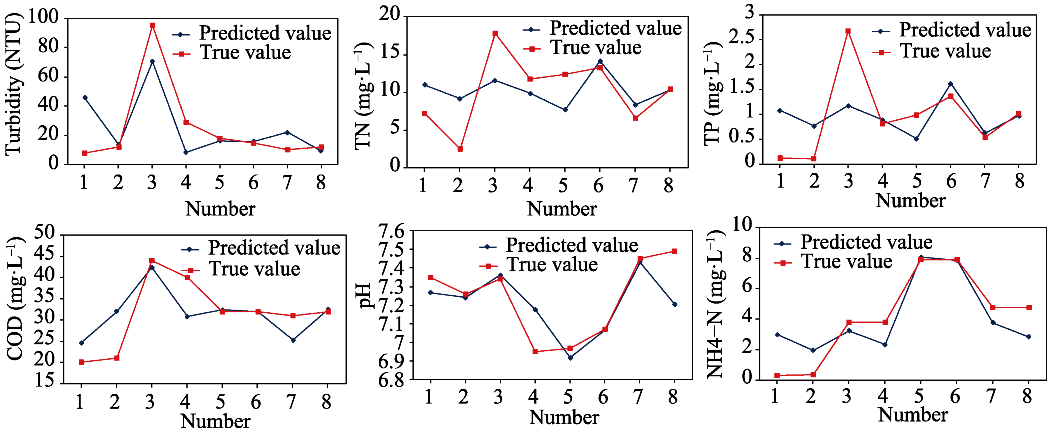

Figure 9 Accuracy analysis chart of data measured at the test station

Figure 10 shows the overall scheme of the satellite–ground integrated, water quality spectra monitoring online system. The satellite data provide the basis for selection of the optimal networking mode, sampling frequency, and observation time. The ground system provides the water quality parameter and measured spectral data. Then, the data are transmitted to the big-data cloud platform. The water quality parameters are retrieved in real-time from the water quality parameter samples, satellite remote sensing data, and inversion model, then stored in the cloud platform. Finally, the real-time monitoring results of the ground network and the water quality inversion products of the satellite data are displayed on the terminal.

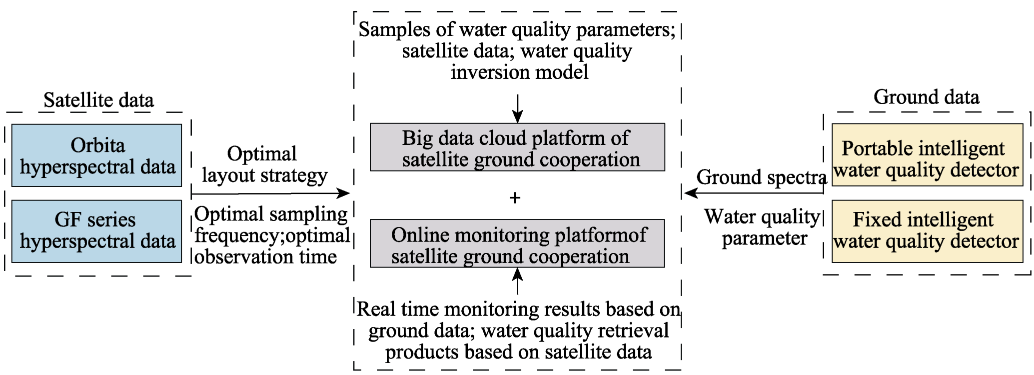

Figure 10 Diagram of satellite–ground integrated water quality spectra online monitoring scheme

3.2 Key Technologies of Satellite–Ground Integrated Water Quality Spectral Monitoring

3.2.1 Intelligent Selection of Inversion Models

Water spectra differ among spatial and temporal distributions; therefore, the water must be classified and an inversion model must be established to improve accuracy. The water quality parameter inversion model is the key to the design of the water quality spectral monitoring online system. The system provides two inversion modes: a geographic proximity model based on geographical coordinates and a similar water-type model based on spectral matching. The inversion process is shown in Figure 11.

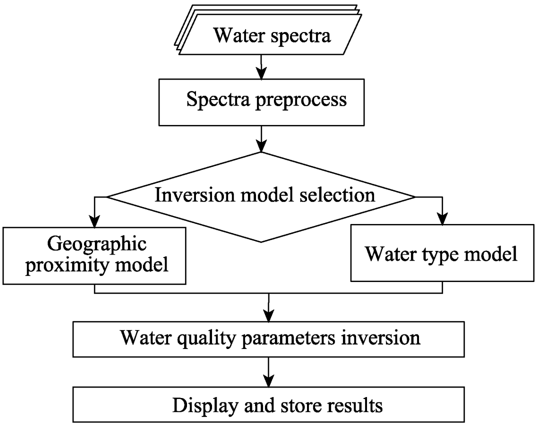

Figure 11 Flow chart of inversion model selection

The basic process of water quality parameter inversion in the system is as follows. The water spectra are measured by the spectrometer and then transmitted to the intelligent analysis cloud platform. After pretreatment of the water spectra, the system retrieves water quality parameters according to the selected inversion model. Then, the inversion results are transmitted to the terminal and stored in the cloud platform. At present, the system provides two water quality inversion models:

(1) Geographic proximity model

According to the GPS positioning information of the survey point, the system automatically identifies and assesses the water quality inversion model adjacent to the survey point and applies it to the survey point. When the satellite passes, the satellite data processing system automatically searches the water near the water to be measured. In combination with the water quality parameters of the ground network provided by the water quality online monitoring equipment, water quality parameters are retrieved in real time through a preset algorithm in the system. The real-time monitoring results and satellite data water quality parameter inversion products are displayed at the terminal.

(2) Water-type model

The water spectra of the point to be measured are automatically matched to all existing water types in the cloud platform, according to the classification method. Then, the water quality parameters are retrieved. The water classification method currently used in the system is the Normalized Trough Depth at 675 nm (NTD675) method. The types of water quality inversion models will be expanded in future research and applications. Users will be able to choose a water quality inversion model according to their actual needs.

3.2.2 Intelligent Matching of Time Scale

Water quality conditions in complex waters may change within a few hours, and daily observations are insufficient for fully assessing the spatiotemporal variation of water quality. Therefore, the optimal observation time and sampling frequency should be studied to achieve optimal observation with the time scale of the ground network (Figure 12). The assessment could provide a basis for establishment of the observation frequency and transit time of hyperspectral water color satellites.

The high-frequency observation data obtained by the fixed, intelligent, water quality spectrometer were resampled. Then, the maximum value, minimum value, mean value, and variance were determined, as were the characteristics of daily, weekly, and monthly changes. Inversion of water quality parameters was performed through the semivariogram.

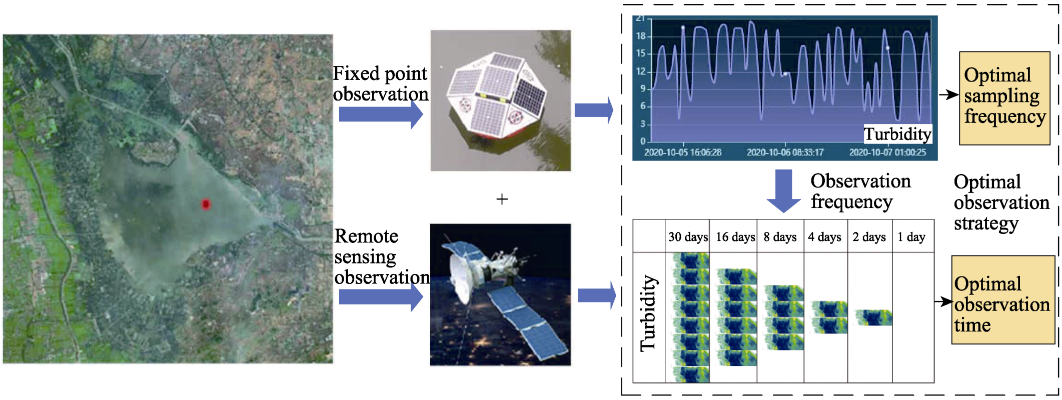

Figure 12 Chart of intelligent matching of time scale

3.2.3 Optimization of Spatial Scale

Water quality monitoring data on the ground are point data, and the water qualities of lakes and rivers vary among locations. The inversion results cannot represent the water quality of the entire region if the layout of sampling points is not representative, and thus an optimal layout strategy of fixed, intelligent, water quality spectrometers must be designed. When the devices are deployed at a large scale, the layout points should be arranged reasonably according to the water types, geographical spatial correlations, and shape characteristics of different lakes and rivers (Figure 13).

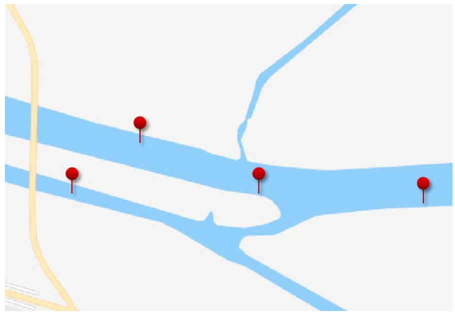

Figure 13 Schematic diagram of optimal locations of fixed water quality spectrometers

4 Discussion and Conclusion

The online monitoring system of water quality spectra can rapidly obtain water quality parameters in real time, but cannot monitor the water quality in a large area. Satellite remote sensing, which can be used to obtain a large range of water quality data in a rapid and timely manner, counterbalances the shortage of point observation data. Based on the demand for inland water quality monitoring in China, this study combined online monitoring data with remote sensing data to carry out research regarding the online monitoring system and the application of water quality data. The research method was able to be used to capitalize on the advantages of ground data and remote sensing data at both temporal and spatial scales, effectively improving the accuracy and stability of large-scale water quality monitoring.

The method of coordinating the acquisition of the ground water quality monitoring data with the hyperspectral satellite data is one of the key problems. Future research should focus on the following aspects: First, a classification model of inland water should be studied; at present, there is no high-precision inversion model suitable for all waters in China and abroad. The spectra of water differ among spatial and temporal distributions. Therefore, water must be classified and different inversion models must be established to improve accuracy. Second, research should be performed to determine the optimal observation frequency for water quality of typical inland waters in China. The inversion model could be evaluated, verified, and corrected through online monitoring data of water quality and satellite transit time to improve the accuracy and stability of the water quality inversion model and provide a basis for transit time design of hyperspectral water-color satellites. Third, research should be performed to establish the fixed-point layout strategy. The spatial scale of typical inland water monitoring in China could be analyzed to develop an optimal network layout strategy of observation points according to the geospatial correlation of observation points, water classification results, and water quality parameter monitoring results.

Author Contributions

Zhang, L. F. designed the research and wrote the original draft; Zhang, L. S collected and processed data, wrote the original draft; Sun, X. J. organized experiments and designed models; Chen, J. did data verification and participated in writing original draft; Wang, S. collected relevant materials; Zhang, H. M. supplemented relevant contents; Tong, Q. X. reviewed and revised the paper.

Conflicts of Interest

The authors declare no conflicts of interest.

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