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PII: S0022-1694(24)00382-2
DOI: https://doi.org/10.1016/j.jhydrol.2024.130988
Reference: HYDROL 130988

To appear in: Journal of Hydrology

Received Date: 18 July 2023
Revised Date: 30 December 2023
Accepted Date: 31 December 2023

Please cite this article as: Lai, Y., Zhang, J., Li, W., Song, Y., Water quality monitoring of large reservoirs in China based on water color change from 1999 to 2021, Journal of Hydrology (2024), doi: https://doi.org/10.1016/j.jhydrol.2024.130988

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Water quality monitoring of large reservoirs in China based on water color change from 1999 to 2021

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Abstract: Water color is an essential indicator of water quality, and research methods of water color based on remote sensing have become a trend in large-scale water quality monitoring. Large reservoirs are important for regional development. However, large-scale research into the quality of the water is lacking. Accordingly, to study the spatiotemporal water quality conditions of large reservoirs in China, this study conducted an inversion of water color over the past 23 years. Using Landsat series images, the Dynamic Surface Water Extent (DSWE) algorithm, and the Forel-Ule index (FUI), the water surface of 746 large reservoirs in China was sampled and the water color was inverted using the Google Earth Engine (GEE) platform. The FUI local change index was established to analyze changes over time. The results showed that the annual average FUI value of large reservoirs in China was less than 11, showing mesotrophic and green water bodies. From the water color analysis of 91 large Type I reservoirs, it was found that the water quality of the reservoirs in the Northeast region was poor (FUI greater than 12), with many aquatic plants and algae or highly turbid and greenish-brown waters, mainly for flood control and irrigation. In southern China, there were primarily
mesotrophic and oligotrophic reservoirs (FUI not greater than 8) with green or greenish-blue water color, which were mainly used for water supply and power generation. The construction of the southern reservoirs reduced the FUI values by an average of five levels, apparently changing the water color. The FUI local change index revealed that the FUI values of large reservoirs in China showed an overall decreasing trend from 1999 to 2007, stabilized after 2007, and then fluctuated after 2013. This study also found that the water color index of large reservoirs in China is positively correlated with the trophic status and turbidity of water bodies to some extent. Therefore, this study can compensate for the lack of water color remote sensing in large-scale reservoir water quality studies and support large-scale reservoir monitoring and management.

**Keywords:** DSWE algorithm; water color; FUI; Large reservoirs; FUI local variation index; GEE

1. Introduction

Reservoirs are natural bodies of water with human intervention, and their capacity and water levels determine their regulatory roles and service value. Large reservoirs are arguably more significant in regional development than smaller ones, due to their increased contribution to water supplies (He and Song, 2020). Reservoir operation affects the regional water environment (Mansouri et al., 2023), including the water flow rate of water and aquatic ecology. Hence research on the water quality of reservoirs has also become a focus. The monitored water quality data is the basis for water quality testing and operation of reservoirs, providing support for the comprehensive evaluation of water quality, water ecological environmental protection, and supervision (Wang et al., 2017). Several researchers have studied the ecological safety and environmental safety and benefits of reservoirs (Gao et al., 2023; Lopes et al., 2021; Toller et al., 2022; Yu et al., 2023). However, these studies relied extensively on expensive field monitoring data or water sampling data, providing challenges for rapid generalization to large-scale reservoir water quality inversion efforts.

Water color is a water quality parameter. The water color index was derived from the traditional Forel-Ule index (FUI) in oceanography. It reflects the combined state of water color and water quality through multispectral data (Novoa et al., 2013; Wang et al., 2018; Woerd and Wernand, 2015). The FUI takes discrete values (1-21) and achieves full coverage from blue to brown water color, and can be effectively used in water bodies of different turbidity levels (Novoa et al., 2013). The extraction of FUI based on remote sensing images began in 2012. Wernand et al. (2013b) established a relationship between the FUI and chlorophyll concentration in oceanic waters based on water color field measurement data and analyzed the changes in chlorophyll concentration in oceanic waters between 1889 and 2000. Wernand et al. (2013a) proposed an FUI extraction algorithm for water bodies based on MERIS remote sensing images. In China, Li et al. (2016) developed the FUI inversion algorithm based on MODIS surface reflectance products and applied it to the monitoring of water color and nutrient status in ten major lakes in China. Chen et al. (2020a) used the Landsat-8-based FUI inversion algorithm to extract FUI water colors and analyzed the changes in eutrophic status in the Yangtze River basin from 2013 to 2018. To date, although water color studies based on remote sensing have been applied to natural water bodies such as large lakes and oceans (Chen et al., 2021a; Zhang et al., 2021), there is still a lack of studies on reservoir water bodies.

Google Earth Engine (GEE) is a free remote-sensing cloud-computing platform. It integrates massive volumes of geospatial data, as well as having the corresponding visualization, analysis, and computation capabilities. Its huge cloud storage saves much time for data downloading and pre-processing for monitoring (Li and Demir, 2023; Sherjah et al., 2023; Wang et al., 2021a). Therefore, GEE can be used as an analytical
In this study, based on the GEE platform with atmospherically corrected Landsat 7 Enhanced Thematic Mapper Plus (ETM+) and Landsat 8 Operational Land Imager (OLI) images, the water color inversion of large reservoirs in China was performed by applying the reservoir water surface extracted by the Dynamic Surface Water Extent (DSWE) algorithm as a mask range. The distribution, water quality conditions, and functions of large reservoirs in China were discussed, and the process of spatial and temporal changes in water color in these reservoirs was explored. The main purpose of the study was as follows: 1) Application of the DSWE algorithm for water surface extraction based on the GEE platform to obtain the distribution and area of large reservoirs in China. 2) Remote sensing inversion based on the FUI was used to obtain water quality changes in large reservoirs over a long time series (1999 to 2021). 3) By creating the FUI local change index, the water color stage could be quantitatively throughout the evolution process, exploring both local and overall changes. This study can remedy the lack of water color remote sensing in reservoir water quality studies on a large scale. Water quality research based on GEE cloud-computing capabilities can provide timely water quality feedback to support the environmental monitoring and management of large reservoirs nationwide.

2. Materials and methods

2.1. Study area

China is located east of the Eurasian continent and on the west coast of the Pacific Ocean, with a remarkable eastern monsoon climate. The surface landscape of mainland China (18° ~ 53°33’ N, 73°33’ ~ 135°05’ E) is highly varied. Mountainous areas consisting of mountains, hills, and plateaus account for 2/3 of the country's area, and the abundance of water and steep terrain provide the basis for the development of hydroelectric resources (Fig. 1). Basins and plains, which account for 1/3 of the country's area, are mainly located in the eastern coastal areas. The high quantity and quality of water resources required for living, irrigation, and industrial production have resulted in the construction of a large number of reservoirs for irrigation and other cited water sources. As a result, China has become one of the countries with the largest number of reservoirs in the world. In 2019, China built 98,112 reservoirs of various types, with a total reservoir capacity of 898.3 billion m$^3$. Among them, there are 744 large reservoirs (reservoir capacity greater than 100 million m$^3$) with a total capacity of 715 billion cubic meters (National Water Development Statistics Bulletin 2019). By 2020, China has built 774 large reservoirs (National Water Development Statistics Bulletin 2020). Among them, reservoirs with a storage capacity greater than 1 billion m$^3$ are classified as large Type I reservoirs, while reservoirs with a storage capacity between 100 million m$^3$ and 1 billion m$^3$ are classified as large Type II reservoirs. Considering that the construction of reservoirs takes a long time, this study counted a total of 746 large reservoirs in China based on data from 2019.
2.2. Methods

Data on the names, capacities, and locations of large reservoirs were obtained from the National Water Information Network, the national list of persons responsible for the safety of large reservoir dams, and the websites of China's provincial water departments (Table 1). The geographic locations of the reservoirs were determined using both Google Maps and Baidu Maps.

The GEE stores two global-scale terrestrial resource satellites: TOA products (Top of Atmosphere Albedo or Realized Albedo products) and SR products (Surface Albedo products). This study applied Landsat's SR series products, which were atmospherically and geometrically corrected for high product quality. A total of 63,077 images of 91 large Type I reservoirs (with a capacity greater than 1 billion m$^3$) were taken between 1999 and 2021 using mainly Landsat 7 ETM+ and Landsat 8 OLI images. To ensure the accuracy of this time-series dataset, the mean values of the de-clouded images were obtained for each quarter. In addition, the presence of valid data within each region in each quarter was counted, and missing image elements accounting for 10% of the region were excluded from subsequent processing. In addition, we applied the DEM 30 m data provided by the GEE to obtain reservoir elevations and global surface water data, facilitating that calculation of the multi-year maximum water surface of the reservoir. The SR images were masked by the maximum water surface vector range and the water color was inverted. Finally, A brief analysis of the...
drivers of FUI changes was conducted based on the monitoring values of eight water quality parameters (pH, dissolved oxygen, potassium permanganate, ammonia nitrogen, total phosphorus, total nitrogen, conductivity, and turbidity) in 10 reservoirs from April 2020 to October 2021. Ten reservoirs are the Miyun Reservoir, Gangnan Reservoir, Sanmenxia Reservoir, Xiaolangdi Reservoir, Zheli Reservoir, Zhanghe Reservoir, Huanglongtan Reservoir, Geheyuan Reservoir, Fushu Reservoir, and Danjiangkou Reservoir.

Table 1. Image data and reservoir information sources were used in this study.

<table>
<thead>
<tr>
<th>Data</th>
<th>Source</th>
<th>Reference path</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global Surface Water</td>
<td>Google Earth Engine</td>
<td>JRC/GSW1_1/GlobalSurfaceWater</td>
</tr>
<tr>
<td>DEM</td>
<td>Google Earth Engine</td>
<td>CGIAR/SRTM90_V4</td>
</tr>
<tr>
<td>Image data</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Landsat 7</td>
<td>Google Earth Engine</td>
<td>LANDSAT/LE07/C01/T1_SR</td>
</tr>
<tr>
<td>Landsat 8</td>
<td>Google Earth Engine</td>
<td>LANDSAT/LC08/C01/T1_SR</td>
</tr>
<tr>
<td>Reservoir capacity and location</td>
<td>Ministry of Water Resources of the People's Republic of China</td>
<td><a href="http://www.mwr.gov.cn/">http://www.mwr.gov.cn/</a></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Department of Water Resources of Hubei Province</td>
<td><a href="http://113.57.190.228:8001/web/Report/BigMSKReport">http://113.57.190.228:8001/web/Report/BigMSKReport</a></td>
</tr>
</tbody>
</table>
Based on the GEE platform, we downloaded the multi-year maximum water surface data from the Global Surface Water dataset (only part of mainland China). Combined with location information of the statistical reservoir, we extracted the multi-year maximum water surface extent of the large reservoirs in China counted in this study in the ArcGIS 10.6 tool. Vector files of each reservoir were finally obtained. A 1000-m buffer zone was created as the study area extent for each of the above reservoir vector files through the GEE platform. Using the DSWE algorithm, the quarterly water surface coverage of large reservoirs in China from 2020-2021 (large Type I reservoirs: 1999-2021) was extracted individually, and the water surface area of each reservoir at the corresponding time was also counted. The images of each quarter were fused using the average value and then passed through a water surface mask to obtain images of the water coverage of the reservoir. The chroma angle $\alpha$ was then calculated based on the off-water reflectance ($R_{os}$) of the image, and the FUI value was obtained based on the FUI look-up table. As the information on large reservoirs was based on 2019, we only performed water surface extraction and water color inversion for 2020-2021. Because some reservoirs in the northern region are covered with ice for extended periods in winter. The imaging time was primarily considered from March to November each year (only summer and autumn were considered in the northeastern region), and the third quarter (July, August and September) of each year was selected for the focused analysis. Finally, the change in water color was analyzed using the FUI local change index. Details of the methodology are given below.

2.2.1. DSWE water surface extraction algorithm

DSWE algorithm is derived directly from investigations carried out by Jones (2015 and 2019). In this study, only the extent to which the reservoir was covered by water was considered. The extraction area was restricted based on the product of the maximum water surfaces, and then the DSWE algorithm was used to obtain the water surface of the reservoir for each period. DSWE utilized five indices (Modified Normalized Difference Wetness Index (MNDWI), Multi-band Spectral Relationship visible (MBSRV), Multi-Band Spectral Relationship Near-Infrared (MBSRC), Normalized Difference Vegetation Index (NDVI), and Automated Water Extent Shadow (AWEsh)) and two single bands (NIR and SWIR1) to set up five identification conditions for water body pixels. In addition, further water body pixel identification was performed based on the slope percentage ($S_p$) and hillshade data obtained from DEM images. The algorithms for the five indices are shown in Equations 1-5:
\[ M_{\text{NDWI}} = \frac{(\text{Green} - \text{Red})}{(\text{NIR} + \text{SWIR1})} \]

\[ M_{\text{BSRV}} = \text{Green} + \text{Red} \]  \hspace{1cm} (2)

\[ M_{\text{BSRN}} = \text{NIR} + \text{SWIR1} \]  \hspace{1cm} (3)

\[ AWEIsh = \text{Blue} + 2.5 \times \text{Green} - 1.5 \times (\text{NIR} + \text{SWIR1}) - 0.25 \times \text{SWIR2} \]  \hspace{1cm} (4)

\[ \text{NDVI} = \frac{(\text{NIR} - \text{Red})}{(\text{NIR} + \text{Red})} \]  \hspace{1cm} (5)

Where \( \text{Green} \), \( \text{Red} \), \( \text{NIR} \), \( \text{SWIR1} \), and \( \text{SWIR2} \) represent bands 3, 4, 5, 6, and 7 when applied to Landsat 8, and bands 2, 3, 4, 5, and 7 when applied to Landsat 7, respectively. The test conditions are shown in Table 2. An image pixel that satisfies any four or more of test conditions 1 to 5 and satisfies test condition 6 is classified as a water body.

Table 2. Test conditions for water body image pixels in the DSWE algorithm.

<table>
<thead>
<tr>
<th>Number</th>
<th>Test conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test 1:</td>
<td>( M_{\text{NDWI}} &gt; 0.124 )</td>
</tr>
<tr>
<td>Test 2:</td>
<td>( M_{\text{BSRV}} &gt; M_{\text{BSRN}} )</td>
</tr>
<tr>
<td>Test 3:</td>
<td>( AWEIsh &gt; 0.0 )</td>
</tr>
<tr>
<td>Test 4:</td>
<td>( (M_{\text{NDWI}} &gt; -0.44) \text{ } \text{ and } \text{ } (\text{SWIR1} &lt; 900) \text{ } \text{ and } \text{ } (\text{NIR} &lt; 1500) \text{ } \text{ and } \text{ } (\text{SWIR1} &lt; 900) \text{ } \text{ and } \text{ } (\text{NDVI} &lt; 0.7) )</td>
</tr>
<tr>
<td>Test 5:</td>
<td>( (M_{\text{NDWI}} &gt; -0.5) \text{ } \text{ and } \text{ } (\text{SWIR1} &lt; 1000) \text{ } \text{ and } \text{ } (\text{NIR} &lt; 3000) \text{ } \text{ and } \text{ } (\text{SWIR1} &lt; 1000) \text{ } \text{ and } \text{ } (\text{NIR} &lt; 2500) )</td>
</tr>
<tr>
<td>Test 6:</td>
<td>( (S_p \geq 30) \text{ } \text{ and } \text{ } (\text{Hillshade} &gt; 90) )</td>
</tr>
</tbody>
</table>

2.2.2. FUI inversion

Color space refers to an objective way to describe the human eye's perception of color, which usually requires first defining three main colors. Then using the color superposition model, various colors can be narrated. For the reservoir water color, the smaller the FUI value, indicating a greenish-blue water color, the
clearer and more transparent (and therefore higher quality) the water is. The larger the FUI value, the more yellowish the water color, and the lower the water transparency, proving the high sand content or a greater possibility of pollution. To represent colors quantitatively, the Commission International De L'Eclairage CIE) developed a CIE-XYZ color system (Smith and Guild, 1931). The CIE-XYZ system replaces R, G, and B with X, Y, and Z, respectively, so that all three stimulus values of the XYZ spectrum in the colorimetric system are positive. The conversion relationship between XYZ-RGB is shown in Equation (6):

\[
\begin{align*}
X &= 2.7689R(645) + 1.7517G(555) + 1.1302B(469) \\
Y &= 1.0000R(645) + 4.5907G(555) + 0.0601B(469) \\
Z &= 0.0000R(645) + 0.0565G(555) + 5.5943B(469)
\end{align*}
\]  

(6)

The three stimulus values in the CIE-XYZ system were calculated as shown in Equation (7):

\[
\begin{align*}
X &= K \int_{380}^{700} S(\lambda) \cdot \rho(\lambda) \cdot \chi(\lambda) d\lambda \\
Y &= K \int_{380}^{700} S(\lambda) \cdot \rho(\lambda) \cdot \psi(\lambda) d\lambda \\
Z &= K \int_{380}^{700} S(\lambda) \cdot \rho(\lambda) \cdot z(\lambda) d\lambda
\end{align*}
\]  

(7)

where K is the adjustment factor; \(S(\lambda)\) is the relative spectral energy distribution of the light source; \(\rho(\lambda)\) is the spectral reflectance of the object; \(\chi(\lambda), \psi(\lambda), z(\lambda)\) are the color matching functions specified by CIE.

The tri-stimulus values in the CIE-XYZ system help define colors but do not visually correspond to different colors in nature. Therefore, in 1931, a two-dimensional chromaticity space map was devised, where the colors on the two-dimensional chromaticity map are independent of luminance. The coordinates x, y, and z on the chromaticity diagram were calculated from the three-stimulus values X, Y, and Z. The formula can be seen in Equation (8):

\[
\begin{align*}
x &= X/(X + Y + Z) \\
y &= Y/(X + Y + Z) \\
z &= Z/(X + Y + Z)
\end{align*}
\]  

(8)

Considering the isoenergetic white light point \(\odot(1/3, 1/3)\) as the coordinate origin, each color can find its corresponding chromaticity coordinate \(p(x_M, y_M)\) in the chromaticity space. The angle \(\alpha_M\) between the vector of the equal-energy white light point and the P-point and the positive direction of the x-axis (at \(y - y_\odot = 0\)) is shown by Equation (9):

\[
\alpha_M = \tan^{-1}\left(\frac{y_M - \frac{1}{3}}{x_M - \frac{1}{3}}\right) \mod 2\pi
\]  

(9)

where \(\alpha_M\) increases gradually by turning counterclockwise from the x positive axis direction. The calculated
\( \alpha_M \) can be found in the FUI index lookup table to determine the FUI value.

In \( R_\text{rs} \)-based water color extraction, solar illumination is considered a constant, so the effect of solar illumination variation on the water color can be ignored. However, most current satellite sensors only have a few discrete bands in the visible range. Therefore, different band settings are required for different sensors to calculate the chromaticity angles \( \alpha_M \) and FUI. To calculate the water color index from remote sensing data in discrete bands, missing bands must first be interpolated. Woerd et al. (2018) addressed this problem by extracting a linear weighted interpolation method. The extraction equations for the Landsat8 OLI and Landsat7 ETM+ can be seen in Equation (10) and (11):

\[
\begin{align*}
X &= 11.053R(443) + 6.950R(482) + 51.135R(561) + 34.457R(655) \\
Y &= 1.320R(443) + 21.053R(482) + 66.023R(561) + 18.034R(655) \\
Z &= 58.083R(443) + 34.931R(482) + 2.606R(561) + 0.016R(655)
\end{align*}
\]

(10)

\[
\begin{align*}
X &= 13.104R(443) + 53.791R(482) + 31.304R(561) \\
Y &= 24.097R(443) + 65.801R(482) + 15.883R(561) \\
Z &= 63.845R(443) + 2.142R(482) + 0.013R(561)
\end{align*}
\]

(11)

As described by Woerd et al. (2018), the chromaticity angle calculated by Landsat 8 OLI will have an offset of between -5 and 20 from the hyperspectral calculated chromaticity angle due to the spectral band shift. A fifth-order polynomial can be used to correct for \( \alpha_M \). The fifth-order polynomial can be seen in Equations (12) and (13):

\[
\Delta \alpha = -52.16a^5 + 373.81a^4 - 981.83a^3 + 1134.19a^2 - 533.61a + 76.72 \quad (12)
\]

\[
\Delta \alpha = -84.94a^5 + 594.17a^4 - 1559.86a^3 + 1852.5a^2 - 918.11a + 151.49 \quad (13)
\]

Where, \( a = \alpha_M / 100 \).

2.2.3 FUI local change index

To characterize the detailed variation in reservoir water color from year to year, the FUI local variation index was created to quantify the local water color evolution process relative to a long time series (Equation (14)).

\[
FUI_x^* = \frac{FUI_x - \sum_{i=1}^{j} FUI_x}{FUI_{\text{max}} - FUI_{\text{min}}} \quad (14)
\]

where \( FUI_x^* \) refers to the FUI local change index in year \( x \), which is used to explore local relative to global changes. This study explored the changes each year for several years. \( FUI_x \) denotes the FUI value for year
3. Results

3.1. Distribution characteristics of reservoirs

Due to natural reasons, there are significant differences between the north and south of China. For the convenience of comparison, we divide the north and south based on 34° N. This latitude line roughly overlaps with the Qinling-Huaihe Line, which is an important geographical boundary in China (Han et al., 2022; Li et al., 2015; Zhong et al., 2023). In this study, a total of 489 large reservoirs were counted in the southern region (Excluding the Xizang region) and 228 large reservoirs in the northern region (Excluding the Xinjiang region). Based on the size and distribution of the reservoir water surface, northeastern China shows high-value clustering of reservoir areas, and the Yangtze River basin shows low-value clustering. Southern China has many large reservoirs with small water surfaces. Large reservoirs with a water surface of less than 10 km² account for 63% of the total in the southern region, of which 55% are in the Yangtze River basin. In the northern region of China, large reservoirs with a water surface larger than 10 km² account for 59% (including 51% in the Northeast region, which is also 71% of the total number of reservoirs in the Northeast region). In terms of quantity, the regions with a higher aggregation of the number of large reservoirs are mainly Hubei Province (the highest degree of aggregation, with a kernel density of 5.37) and Jiangsu Province in the Yangtze River basin, followed by a higher number in Shandong Province and Guangxi Region (Fig. 1). 93% of the large Type II reservoirs range from 1 km² to 50 km², whereas the area of large Type I reservoirs is generally above 10 km², 77% range from 10 km² to 100 km², and 21% are larger than 100 km² (Table 3).

Table 3. Water surface area statistics of 746 large reservoirs (including 91 large Type I reservoirs) in China in 2020.

<table>
<thead>
<tr>
<th>Type</th>
<th>Area (km²)</th>
<th>&lt;1 km²</th>
<th>1~10 km²</th>
<th>10~50km²</th>
<th>50~100 km²</th>
<th>&gt;100 km²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large Type I reservoir</td>
<td>Number</td>
<td>2</td>
<td>39</td>
<td>31</td>
<td>19</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Proportion</td>
<td>0.02</td>
<td>0.43</td>
<td>0.34</td>
<td>0.21</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Number</td>
<td>24</td>
<td>392</td>
<td>218</td>
<td>16</td>
<td>5</td>
</tr>
<tr>
<td>Large Type II reservoir</td>
<td>Proportion</td>
<td>0.04</td>
<td>0.60</td>
<td>0.33</td>
<td>0.02</td>
<td>0.01</td>
</tr>
</tbody>
</table>

3.2. Water color evolution process
Combined with the photographs (Table A.1) taken in the field in Fig. 2a, it is clear that when the FUI value is less than 9, the water color is greenish-blue, and the water is clearer and more transparent. When the FUI value range was between 9 and 12, the water color was greenish-yellow, and water transparency was reduced. When the FUI value was much greater than 12, the water color was brown, the water became turbid, and the visible sand content increased. In terms of the percentage of the annual average FUI for large reservoirs in 2020 and 2021 (Fig. 2b), the range of values was 6 - 17. Less than 16 % of the total number of reservoirs had an average annual FUI of no greater than 8 and had bluish water. 9-12 was the dominant FUI distribution interval, reaching 69 % in 2020 and decreasing to 65 % in 2021, with green or greenish-blue water. Approximately 19 % of the reservoirs had an annual average FUI value greater than 12 and were brownish-green in color. The water color of the reservoirs in Northwest China, Northeast China, and the Yellow River Basin (YRB) is brownish-green. In the Yangtze River Basin (YZRB) and its south, the FUI value is generally small, and the water color is dominated by green and greenish-blue.

Fig. 2. Distribution of annual average Forel-Ule index (FUI) values of large reservoirs in China. a shows the FUI values and spatial distribution of each reservoir in 2021 (The basin names are abbreviated, see Appendix Table A.2 for full names, same as below), the legend shows the corresponding color of FUI values, and the photos on the left and right sides are the photos of reservoir water color taken in the field (The text indicates the reservoir name, shooting time and corresponding FUI values). b is a pie chart showing the percentage of the annual average FUI values of large reservoirs in China in 2020 and 2021, respectively.

From the water surface extraction results, it can be seen that the area of large Type I reservoirs is mainly above 10 km². Meanwhile, considering the importance of large Type I reservoirs in large reservoirs, we selected 91 large Type I reservoirs for further water color analysis to represent the spatial variation of water color more intuitively. The changes in the FUI values of the reservoirs in northern and southern China over the past 23 years are shown in Fig. 3b and Fig. 3c (combined with Fig. 3a). The average value of FUI for large reservoirs in northern China is about 11, while the average value in the south is about 10. The reservoirs in the Northeast (basins: SHRB and LiaoRB) have the highest FUI values (greater than 12 per year), with
brownish-green water color, and some of the reservoirs showed an increasing trend in FUI values, such as Jingpo Reservoir and Lianhuahu Reservoir (Fig. 3b). The overall FUI values in North China (excluding the middle reaches of the Yellow River) ranged from 8 to 12, with greenish water color. The overall FUI values in the south were low (less than 12). Most of the large reservoirs in the Yangtze River Basin (basin: YZRB) had FUI values ranging from 6 to 10, with some showing a decreasing trend and a greenish-blue water color. Meanwhile, the frequency of the annual average FUI values of certain reservoirs from 1999 to 2021 (Fig. 3d and Fig. 3e) show that the areas with higher values are mainly distributed in the Northeast (points A and B in Fig. 3d), middle reaches of the Yellow River (point N in Fig. 3d), and southern part of Guangxi Province and Guangdong Province (points K and L in Fig. 3e). The distribution frequency of the FUI values in most large reservoirs were concentrated, indicating that the water color of these reservoirs has been relatively stable over the years without significant changes. The distribution frequency of FUI values for some reservoirs in the middle reaches of the Yangtze River (basin: YZRB) was scattered (points C-F in Fig. 3e), i.e., the water color varied considerably from year to year. Combined with Fig. 3c, it can be seen that the FUI value decreased significantly.
Fig. 3. Multi-year Forel-Ule index (FUI) distribution of large Type I reservoirs (91) in China (Blank spaces represent missing data); a shows the distribution of annual average FUI values of large Type I reservoirs in 2020 (The color corresponds to the color standard of the International Illuminating Society for FUI values); b and c are the thermal maps of the average annual FUI values (1999-2021) for large reservoirs in northern and southern China, respectively (The color of the legend from blue to red represents the FUI values from small to large); d and e are the frequency distribution of FUI values over 23 years for typical reservoirs selected vertically in northern and southern China, respectively (The reservoirs are arranged from high to low according to the dimensional position).

3.3. FUI local change index evolution

Relative to the long-time series variation, there is a similarity in the local year variation of FUI values for each large reservoir in China. During the period 1999-2021, the FUI values of large Type I reservoirs in China show an overall decreasing trend. Combined with Fig. 4a, the local variation in FUI in all large Type I reservoirs was high and decreased between 1999 and 2007. The variation gradually stabilized after 2007 and fluctuated after 2013. Among all reservoirs, the year with the highest value of local variation in FUI was 2000, and the year with the lowest value of local variation was 2015. Combined with Fig. 4b, the value of the local change in FUI for reservoirs in 2000 was positive relative to the maximum change in 23 years (except for some reservoirs in the northeast), and the FUI value is large. Combined with Fig. 4c, in 2015, the FUI values of large Type I reservoirs in the middle reaches of the Yellow River, the upper reaches of the Yangtze River basin, the southern part of the Pearl River basin, and the Hainan Island region (main basins: YRB, YZRB, and QL & SGRB) have a positive contribution relative to the maximum change in 23 years. In the southeast, the upper reaches of the Yellow River, and the northeast (main basins: SCTRB, YRB, LiaoRB, and SHRB), most of the reservoirs have a negative contribution to the maximum change in 23 years. The 2021 distribution was roughly the same as the 2015 distribution (Fig. 4d). However, some reservoirs in the northeast and southeast changed from a relative decrease to a relative increase.
Fig. 4. Distribution of Forel-Ule index (FUI) local change index values in the third quarter of 1999-2021 for large Type I reservoirs in China. a shows a scatter plot of FUI* values for all reservoirs between 1999 and 2021 and a line graph of the median distribution; b, c, and d show the distribution of positive and negative FUI* values for 2000, 2015, and 2021, respectively (Greater than 0 indicates a positive contribution relative to the 23-year change, and less than 0 indicates a negative contribution relative to the 23-year change).

4. Discussion

4.1. Applicability of research methods

Before inverting the water color, this study extracted the water surface of a single reservoir for each year based on the DSWE algorithm (Jones 2015 and 2019), to identify the portion that is only covered by water. This algorithm does not require scenario-based training. The inputs were limited to Landsat surface reflectance products and DEM. Unlike other Landsat-based water products, the DSWE product provided by the USGS
includes pixels that are only partially covered by water, to provide dynamic inundation information. Meanwhile, through the superposition of five indices, it can effectively compensate for the uncertainty of individual water body index threshold settings. The use of 30 m DEM can match the resolution of Landsat images and improve the accuracy of water surface extraction by reducing the effects of steep slopes and terrain shadows through the limitation of slope percentage and hill shading values (Jones, 2019). Moreover, the wetland and water surface are divided, which is convenient for selecting the part covered by water only. We cited the remote sensing water color inversion method of Woerd et al (2018). Their study provides tri-stimulus value calculation coefficients based on Landsat 8 and Landsat 7 imagery, along with correction parameters for Landsat 8 and Landsat 7 relative to MERIS satellites, but does not include Landsat 5. That is, the FUI inversion based on Landsat 8 and Landsat 7 is in good agreement. Landsat 7 data are missing in strips after 2003, but the area of large Type I reservoirs in this study is generally larger than 10 km², the distribution of FUI classes in the same reservoir is continuous and the strips of missing data are evenly distributed. In the end, the location of the existing strips was not calculated, and the mean value was taken to quantify the water color in the reservoir at that time.

GEE-based FUI inversion and water color analysis can quickly and intuitively determine water quality on a large scale (Sherjah et al., 2023). The FUI* created can be used to normalize the data, which is convenient for exploring the overall change pattern of a large range of multiple objects. Its positive and negative values can clearly determine whether each time point is incremental or negative with respect to the total time series, and can also explore the stability of the local relative to the overall change.

4.2. Analysis of reservoir distribution

The distribution of reservoirs is closely related to terrain, climate, and functional requirements (Gu et al., 2021; Sjoberg et al., 2022; Zhou et al., 2016). Scholars analyzed and compared the morphological scale relationships of large lakes and reservoirs (with an area greater than 1 km²) based on global scale data, and found that reservoirs often occur in mid to low latitudes and higher altitudes where lakes are relatively uncommon, and most reservoirs located in high surface roughness terrain (Sjoberg et al., 2022). Meanwhile, China's large reservoirs are mainly located in the monsoon zone. Eastern China receives concentrated rainfall in summer under the influence of the monsoon climate. Because of this seasonal impact, water resource facilities, such as reservoirs, have been developed to accommodate seasonal variations in precipitation (Chang et al., 2019; Duan et al., 2023). Influenced by topographic and climatic factors, Southwest China (including the eastern Qinghai-Tibet Plateau, the Yunnan-Guizhou Plateau, and the Sichuan Basin topographic region) has become the most water-abundant region in China, with the construction of large-depth, small-area river-valley reservoirs. Similarly, many large reservoirs are located at the intersection of the second and third terraces of the Chinese terrain, as well as in the low mountain and hilly areas of the south (Fig. 5). The Yangtze River Basin is the largest in China and is located in the humid zone of China, with an annual precipitation of more than 800 mm (Li et al., 2021). At the same time, it spans the three terrain levels of China (major topographic regions: the Tibetan Plateau, the Sichuan Basin, and the plains of the middle and lower reaches of the Yangtze River), with plenty of ups and downs. As a result, there are a large number of large reservoirs with ample water storage capacity. However, affected by the terrain, most of the middle and upper reaches of the valley-type reservoirs are deep, but the area is significantly smaller than the same level of plains-type reservoirs.

In terms of demand for reservoir construction, a large number of plains reservoirs have been built due to
the high demand for water in eastern China as a result of developed irrigated agriculture and high levels of urbanization. They are mainly distributed in the Middle and Lower Yangtze Plain, the Northeast Plain, and the North China Plain (Zhang et al., 2023). Therefore, the Northeast Plain, as an essential grain-producing region in China (Chen et al., 2021b), has constructed many large reservoirs with ample water surface areas. The average water surface area in the region is about 38 km² and the average elevation is about 225 m, while the average elevation of reservoirs in the southern region is about 404 m. Compared to the monsoon region, Northwest China has fewer reservoirs due to drought. In addition, in the Yunnan-Guizhou Plateau region, where water resources are superior, geological conditions (such as widespread karst landform) make it more challenging to build reservoirs, thus affecting their number (Song et al., 2022).

Fig. 5. Annual average water surface size distribution of 746 large reservoirs in China in 2020 (DEM resolution is 30 m; Green to white represents a gradual increase in altitude; Reservoir area size is divided into 5 categories according to the shape of the points from small to large). Northeast China and the Yangtze River Basin are two typical regions for the distribution of large reservoirs in China.

4.3. Color characterization analysis of water quality
To explore the correlation between FUI and water quality parameters, we obtained measurements of eight water quality parameters (pH, dissolved oxygen (DO), potassium permanganate, ammonia nitrogen, total phosphorus (TP), total nitrogen (TN), conductivity, and turbidity) for the period April 2020 to October 2021 for analysis (taking the average value monthly to obtain the number of available samples, n = 85). Dimensionality reduction was performed by principal component analysis, and three principal elements were obtained. FUI values based on the inversion of the remote sensing images did not correlate well with the three main elements (Table 4). However, it can be clearly seen that the second principal element has two aggregations. Through a cluster analysis for correlation, it was found that the second principal element less than -20 was significantly correlated with the FUI value of the water body at a 0.01 confidence level (Fig. 6).

Examining the locations of the sampling sites, we found that they were both located in Xiaolangdi Reservoir and Sanmenxia Reservoir in the middle reaches of the Yellow River where turbidity is high in summer and fall (average annual FUI ≥ 11). Therefore, by analyzing the correlation between the turbidity values measured at the automated detection sites of China and the corresponding annual average FUI values for 2021 (Fig. A.1a), the annual average FUI values were nonlinearly correlated with turbidity. Further analysis revealed a significant positive correlation with average annual turbidity when the mean annual FUI value was greater than 12 (N = 30, R = 0.80, P < 0.05). In contrast, the correlation with turbidity was lower when the mean annual FUI value was less than 12 (N = 77, R = 0.37, P < 0.01). That is, when the FUI value is greater than 12, the influence of water turbidity is enhanced. Therefore, pH, DO, TP, and turbidity are the main parameters affecting the coloration of turbid water (Wang et al., 2018). Among them, DO and TP have the greatest impact on water quality (with weights of 0.7 and 0.62, respectively). The higher the DO content, the better the water quality (Liu et al., 2022a). Excessive TP content in water can lead to excessive algae growth and eutrophication of the water body (Savic et al., 2022; Wang et al., 2023). Ultimately, it will be reflected in the water color. An increase in DO concentration decreases the FUI level of the water resulting in a bluish color, while an increase in TP concentration increases the FUI level resulting in a brownish-green color.

Besides, to investigate the effect of turbidity on water color, this study conducted a remote sensing inversion of large Type I reservoirs for each month of 2021 based on the Turbid Water Index (TWI) (Feng et al., 2012; Liang et al., 2017). When FUI is greater than 15, the area of turbid water bodies in the reservoir is greater than 85% (Fig. A.1b). That is, FUI greater than 15 can clearly distinguish turbid water bodies.

Table 4. Principal component analysis of 8 water quality parameters (x1: pH, x2: dissolved oxygen, x3: potassium permanganate, x4: ammonia nitrogen, x5: total phosphorus, x6: total nitrogen, x7: conductivity, x8: turbidity) with FUI values.

<table>
<thead>
<tr>
<th>Main Element</th>
<th>Dimensionality Reduction Formula</th>
<th>Number of Samples</th>
<th>Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>First Principal Component</td>
<td>(Y_1 = 0.59x_1 + 0.33x_2 + 0.3x_3 + 0.76x_4 + 0.52x_5 + 0.89x_6 + 0.87x_7 + 0.55x_8)</td>
<td>85</td>
<td>0.49</td>
</tr>
</tbody>
</table>
Second Principal Component
$Y_2 = 0.56x_1 + 0.7x_2 + 0.01x_3 + 0.16x_4 - 0.62x_5 - 0.07x_6 - 0.05x_7 - 0.46x_8$

Third Principal Component
$Y_3 = 0.31x_1 - 0.45x_2 + 0.8x_3 - 0.31x_4 - 0.06x_5 + 0.12x_6 + 0.09x_7 - 0.36x_8$

**Fig. 6.** Correlation between Forel-Ule index (FUI) values and second principal component (correlation between the two aggregation cases obtained by kernel density analysis)

### 4.3.2. Effects of chlorophyll condition and water body trophic status

Chlorophyll-a (Chl-a) is the primary water quality parameter controlling water color (Brezonik et al., 2019; Wang et al., 2018). Pitarch et al. (2019) discovered that, in oceanic and coastal waters, FUI increases with Chl-a concentration, until a FUI threshold of approximately 17 is reached. That is, when the FUI level is high, the concentration of Chl-a decreases instead. Previous studies have shown that the Cyanobacteria and Macrophytes Index (CMI) (Chen et al., 2020b; Liang et al., 2017) is very sensitive to aquatic plants such as cyanobacteria in the water body, and the Floating Algae Index (FAI) (Hu, 2009) is mainly used for the extraction of floating algal blooms, both of which better reflect the overall chlorophyll content of the water body.

To investigate the effect of chlorophyll conditions on water color, this study conducted a remote sensing
inversion of large Type I reservoirs for each month of 2021 based on FAI and CMI. The distribution of FUI
value classes was found to be nonlinearly correlated with their area size (Fig. 7a and Fig. 7b). The value of
FUI less than or equal to 15 was significantly and positively correlated with the area share of CMI (R = 0.52,
P < 0.01). When FUI was less than 12, the area of CMI accounted for less than 1.5% of the reservoir area.
When FUI was between 13 and 15, the area of CMI had the greatest effect on the FUI of the reservoir, but the
area share was maximally less than 3.5%. When FUI is greater than 15, the area of aquatic plants and floating
algal blooms is tiny.

We obtained monthly monitoring data of the comprehensive trophic level index (TLI(Σ)) (incorporating
SD, Chl-a, CODMn, TN, and TP) of 21 reservoirs (385 samples from October 2012 to December 2016 and
January 2018 to December 2021) through the monthly water quality monitoring reports of the China
Environmental Monitoring General Station (CEMG) (http://www.cnemc.cn/jcbg/qgdbsszyb/), and analyzed
their correlations with the FUI values on annual and monthly (March to November 2021) scales, respectively
(Fig. 7c and Fig. 7d). Then, a significant correlation was found between the TLI(Σ) and the FUI (Liu et al.,
2022b). Accordingly, when the FUI is less than or equal to 8, 83% of large reservoirs are in the oligotrophic
(TLI(Σ) < 30) state. Both floating algal blooms and aquatic plants are smaller in size at this time. When the
FUI is between 8 and 10, 89% of reservoirs are in the mesotrophic (30 \leq TLI(Σ) < 50), while the remaining
11% are in oligotrophic. When the FUI is greater than 10, most of the reservoir is in a mesotrophic state, and
a small portion appears to be eutrophic (TLI(Σ) \geq 50). In eutrophic reservoirs, the highest degree of
eutrophication is observed when the FUI is between 11 and 13. At this time, the area of floating algal blooms
is the largest. The probability of eutrophication is higher when the FUI is between 14 and 15, and the area of
aquatic plants is largest at this time.

When the FUI was between 9 and 15, the aquatic plant area (R = 0.47, P < 0.01) and turbid water area
(R = 0.48, P < 0.01) jointly influenced the FUI values. The geodetic detector (Wang and Xu, 2017; Li et al.,
2024) yielded univariate TWI and CMI q-values of 0.26 and 0.24, respectively, and an interaction detection
value of q (aquatic plant area \cap turbidity area) of 0.56, which was significantly larger than the sum of the
univariate variables, indicating that the interaction between the two was nonlinearly enhanced. It indicates that
the joint effect of the two is more able to influence the change of FUI.

In conclusion, FUI can effectively distinguish between oligotrophic and non-oligotrophic conditions.
When the average annual FUI is less than or equal to 8, the water body is oligotrophic. When the annual
average FUI is between 8 and 10, the water body is stabilizing mesotrophic. FUI can distinguish high turbidity
waters. When the average annual FUI is greater than 15, the water body is highly turbid. This conclusion is
similar to the results of Wang's study (Wang, 2018).
Fig. 7 Correlations of FUI values with chlorophyll-related indices (the Cyanobacteria and Macrophytes Index (CMI), and the Floating Algae Index (FAI)) and the comprehensive trophic level index (TLI(Σ)). a and b are the correlation between the FUI values and the remotely sensed inversion of the reservoir CMI area share and reservoir FAI area share at the monthly scale in 2021, respectively. c is the correlation between the FUI values and TLI(Σ) values on an annual scale from 2012-2021; d is the correlation between the FUI values and TLI(Σ) values on a monthly scale in 2021.

4.3.3. Other factors

Age may be the origin of the high water color obtained for some reservoirs (Geraldes and Boavida, 2003). Because of the decomposition of the terrestrial vegetation, which can take several years, and because of the use of the land before the creation of the reservoir, certainly large amounts of nutrients were and are being released to the water column. The main functions of reservoirs in different regions are different, and differences in the purpose of use can also affect the water color of the reservoir (Lopes et al., 2021; Ma et al., 2023).

As shown in Fig. 8a, reservoirs in northern China are mainly used for water supply, whereas reservoirs in southern China are mainly used for power generation. Large reservoirs for water supply in China are mainly used for domestic and agricultural purposes, and water transfer. However, the “sources” of organic pollutants were agricultural (Ni et al., 2021; Wang et al., 2021b). Therefore, in the agriculturally developed areas of northeastern China, the middle and lower reaches of the Yangtze River, and the southeastern coastal areas (main basin: QL & SGRB), the reservoirs play an important role in water supply and flood control, and its water color is greenish-yellow. In contrast, reservoirs in North China (main basins: LuanRB and HaiRB) with more domestic water supply and water transfer roles have smaller FUI values, green or blue-green water color and relatively good water quality. Reservoirs in the southern region, which are mainly used for power generation, exhibited low FUI values. In particular, the water-rich southwestern region (including the upper Yangtze River (main basin: YZRB)) and southeastern coastal areas (main basin: SCTRB) showed a blue-green color and better water quality.

Simultaneously, the FUI changed significantly after the reservoir was impounded under the sluice gate, with an average decrease of 5-unit values (Fig. 8d). Especially in rivers with high turbidity, the construction
of reservoirs has changed the water color from greenish-brown to green. For example, Sanmenxia (Fig. 8b) and Xiaolangdi (Fig. 8c) are reservoirs located at the middle and lower reaches of the Yellow River, respectively. The middle reaches of the Yellow River flow through the Loess Plateau with a high sand content, after which it first flows through the Sanmenxia Reservoir, which has an average annual FUI value greater than 15 and a yellowish water color. Then the Yellow River flows through the Xiaolangdi Reservoir, whose annual average FUI value is 11-12, and the water is green. In other words, the construction of a reservoir can significantly reduce the river's sand content and enhance water quality. It is also demonstrated that at FUI greater than 12, turbidity may be the influence.

Fig. 8. Main functions of large Type I reservoirs in China (a, the size of the points varies with the magnitude of the annual average Forel-Ule index (FUI) value) and the cumulative change of the FUI value after the reservoir is impounded under the gate (d, the legend is the name of the reservoir, and the time when the reservoir is impounded under the gate is shown in parentheses), b and c are the images of the FUI inversion results of Sanmenxia Reservoir and Xiaolangdi Reservoir in the autumn of 2020, respectively.

4.4. Water quality analysis based on water color

The water color quantified by FUI can determine the nutritional status and turbidity status of reservoirs. The yellower the color of the water, indicates that the water has a higher sand content or is richer in nutrients. Of the 746 large reservoirs in China, 16.38% will be oligotrophic, 32.08% will be stabilizing mesotrophic, and 2.42% will be highly turbid in 2020. By 2021 these three types account for 14.78%, 34.81%, and 2.82%, respectively. It can be shown that large reservoirs in China are mainly in mesotrophic condition, and the number of oligotrophic reservoirs has decreased in both years. In terms of the distribution of large Type I reservoirs, China's highly turbid reservoirs are mainly located in the northeast, the QL & SGRB, and the
middle reaches of the Yellow River. Moreover, the oligotrophic reservoirs are mainly located in the southern part of the country, such as the southwestern region and the Yangtze River Basin. From 1999 to 2021, the average value of FUI for large Type I reservoirs in China was 10, showing a mesotrophic condition. The overall FUI values of the northern reservoirs were higher than those of the southern reservoirs.

The water color changes between the four seasons are not significant (Fig. 9). Generally, the water volume fluctuates in summer due to rainfall in a monsoon climate. Most of the reservoir water bodies are green or greenish-yellow in color and the FUI values of the water bodies are relatively higher compared to other seasons. The spatial variability of the monthly mean FUI values was high, with lower FUI values in the center of the reservoir and areas with greater water depth. Due to the influence of substrate quality, water level fluctuation, and water depth, the FUI value of the water-level-fluctuating zone of the reservoir is the highest in the whole reservoir area (Pei et al., 2018). Therefore, the closer it is to the dam, the bluer the color of the water. As shown in Fig. 9b, the FUI values (14-17) of the Moon Lake Reservoir in the northeast are high, and by combining our results with those of previous studies (Lai et al., 2022; Li et al., 2022; Skandaraja, 2015; Xu, 2020), it can be seen that the water quality has high nutrient levels and a high phytoplankton content, with increased sediment and dissolved organic matter content, making the water greenish-brown in color. The FUI value range of Guanting Reservoir in North China is 10-13. There is a high amount of eutrophication taking place in the water. Therefore, phytoplankton content has increased, and the water contains minerals and dissolved organic substances, which make the water color green to yellow. The FUI values of the Miyun Reservoir in North China range from 6 to 9, with algae dominating the water and increasing dissolved substances, causing the water to be greenish-blue. The overall FUI values of the reservoirs in the southern region were relatively stable and low (Fig. 9c). The differences in water color between reservoirs were minor, mostly greenish-blue.
Fig. 9. Forel-Ule index (FUI) inversion results of three reservoirs in northern China (b: Yuelianghu Reservoir, Guanting Reservoir, Miyun Reservoir) and three reservoirs in southern China (c: Meishan Reservoir, Fushui Reservoir, Hongmen Reservoir) for each season in 2021. a is the location of reservoir distribution.
In this study, the area distribution of large reservoirs in China and the spatial and temporal status of water quality were assessed using a DSWE-based water surface extraction algorithm and a FUI-based remote sensing algorithm. The following conclusions were mainly obtained: 1) Influenced by topography and terrain, climate, and construction demand, the area distribution of large reservoirs in China showed high-value clustering in the northeastern region and low-value clustering in the middle reaches of the Yangtze River region. 2) Water color quantified by FUI can reflect the trophic status and turbidity of water bodies. The FUI level of large reservoirs in China ranges from 6 to 17, with an annual average value of less than 11, showing mesotrophic. The water quality of reservoirs in southern China (except for the southern Pearl River region) is generally better than that in the north. 3) The FUI of large reservoirs is affected by the central service functions. Reservoirs whose primary functions are irrigation and flood control have high nutritional levels or turbidity (FUI >12), such as the plains-type reservoirs in Northeast China, while reservoirs whose main function is power generation have low nutritional levels (FUI <10), such as the valley-type reservoirs in Southwest China. 4) The constructed FUI local change index revealed that the FUI values of large reservoirs in China showed an overall decreasing trend from 1999 to 2007, stabilized after 2007, and then fluctuated after 2013. Meanwhile, the water quality of reservoirs in the northeast has not improved significantly over the past 23 years. 5) The FUI value of Chinese reservoirs in summer is higher than that of other seasons, and the FUI value of the water-level-fluctuating zone of the reservoir is higher than the center of the reservoir.

This study was based on a large amount of data from a cloud platform for water color inversion, thus allowing for the long-term monitoring of large reservoirs. It provides a new idea for reservoir water-quality detection and research, provides guidance value for timely monitoring of reservoir water quality, and theoretical support for reservoir water-quality prediction. Simultaneously, it has enriched the application of remote sensing in large numbers. However, the use of a single FUI value to determine water quality is still not comprehensive enough, and subsequent research may supplement it by combining multiple water quality parameter inversion, such as turbidity inversion. At the same time, the simple correlation between water color and nutritional level is challenging to explain its internal connection, and subsequent methods such as causal analysis will be used to explore its internal connection.

**CRediT authorship contribution statement**

**Yuequn Lai:** Data curation, Formal analysis, Methodology, Writing - original. **Jing Zhang:** Writing – review & editing, Project administration, Supervision. **Wenwen Li:** Data curation, visualization. **Yongyu Song:** Investigation.

**Declaration of Competing Interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

**Acknowledgments**
This research was funded by the National Natural Science Foundation of China (Grant No. 41271004). The authors thank these funds for their support and special thanks are owed to the anonymous reviewers for their invaluable suggestions for the improvement of the manuscript.

Appendix A. Supplementary Material

Table A.1. Photographs of 5 reservoirs to obtain information.

<table>
<thead>
<tr>
<th>Reservoir</th>
<th>Shooting time</th>
<th>Get URL</th>
</tr>
</thead>
<tbody>
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<td>Qingtongxia</td>
<td>2019.12</td>
<td><a href="http://www.nxnews.net/yj/jrww/201912/t20191203_6504658.html">http://www.nxnews.net/yj/jrww/201912/t20191203_6504658.html</a></td>
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<tr>
<td>Xiaojiang</td>
<td>2020.02</td>
<td><a href="https://www.toutiao.com/article/6834201616048980487/?channel=&amp;source=search_tab">https://www.toutiao.com/article/6834201616048980487/?channel=&amp;source=search_tab</a></td>
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<tr>
<td>Miyun</td>
<td>2021.08</td>
<td><a href="http://swj.beijing.gov.cn/swdt/swyw/202108/t20210825_2476835.html">http://swj.beijing.gov.cn/swdt/swyw/202108/t20210825_2476835.html</a></td>
</tr>
</tbody>
</table>

Table A.2. Abbreviations and full names of the watersheds in this study.

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full name of the basin</th>
</tr>
</thead>
<tbody>
<tr>
<td>STIFA</td>
<td>Inner flow area of southern Tibet</td>
</tr>
<tr>
<td>SCTRB</td>
<td>Southeast Coast and Taiwan River Basin</td>
</tr>
<tr>
<td>DL-IRB</td>
<td>Dulong - Irrawaddy River Basin</td>
</tr>
<tr>
<td>IRB</td>
<td>Irtysh River Basin</td>
</tr>
<tr>
<td>HaiRB</td>
<td>Hai River Basin</td>
</tr>
<tr>
<td>HC-AIFA</td>
<td>Hexi Corridor - Alashan Inner Flow Area</td>
</tr>
<tr>
<td>Code</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>-------------------------------------------------------</td>
</tr>
<tr>
<td>YRB</td>
<td>Yellow River Basin</td>
</tr>
<tr>
<td>LC-MKRB</td>
<td>Lancang-Mekong River Basin</td>
</tr>
<tr>
<td>LDPRB</td>
<td>River basins in the Liaodong Peninsula</td>
</tr>
<tr>
<td>LiaoRB</td>
<td>Liao River Basin</td>
</tr>
<tr>
<td>WLN &amp; HBCRB</td>
<td>West Liaoning and Hebei coastal river basins</td>
</tr>
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<td>Luan River Basin</td>
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<td>IMIRB</td>
<td>Inner River Basin of Inner Mongolia</td>
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<tr>
<td>NJ-SWRB</td>
<td>Nujiang - Salween River Basin</td>
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<tr>
<td>QTPIFA</td>
<td>Inner flow area of the Qiangtang Plateau</td>
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<tr>
<td>QL &amp; SGRB</td>
<td>Qionglei and the coastal river basins in southeastern Guangxi</td>
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<tr>
<td>SGZB-IDRB</td>
<td>Senge Zangbu - Indus River Basin</td>
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<td>SDPRB</td>
<td>River basins in the Shandong Peninsula</td>
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<td>SHR</td>
<td>Songhua River Basin</td>
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<td>SFRB</td>
<td>Suifen River Basin</td>
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<td>TIFA</td>
<td>Tarim inner flow area</td>
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<td>TMRB</td>
<td>Tumen River Basin</td>
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<tr>
<td>YLRB</td>
<td>Yalu River Basin</td>
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</table>
ILRIA Ili River inflow area

YJ-HRB Yuanjiang-Hong River Basin

YZRB Yangtze River Basin

PRB Pearl River Basin

JIFA Inner flow area of Junggar

QDIA Qaidam inflow area

Fig. A.1. Correlation of FUI values with turbidity, composite trophic level index (TLI(∑)) values and Turbid Water Index (TWI) based area share (P < 0.05). a is the correlation between the turbidity values measured at the automated detection site and the corresponding annual average FUI values in 2021 on an annual scale; b is the correlation between the FUI values and the remotely sensed inversion of the reservoir TWI area share at the monthly scale in 2021.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Highlights:

- GEE-based water color inversion for rapid water quality monitoring.
- The FUI local change index was constructed to quantify the water color change.
- The annual average FUI value of large reservoirs in China is 11, with green water.
- Construction of the reservoir reduced the FUI value by an average of 5 levels.
- The FUI of reservoir water is positively correlated with its TLI and turbidity.