Seasonal Variation of Water Color at 30m Spatial Resolution in 42 Urban Lakes

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Abstract. Eutrophication has been a serious problem in China’s urban lakes. In this study, to monitor 42 lakes trophic state in Wuhan city, a Forel-Ule index (FUI) method based on Landsat 8 OLI data was proposed among different seasons. The result shown that the FUI calculated from Landsat 8 OLI reflectance spectral (Rrs) can substantially represent the lakes TSI, with accuracy of 79.37% for in situ experiment TSI dataset. And the TSI in urban lakes can be divided into 3 categories by a decision tree (oligotrophic, FUI 1-6; mesotrophic, FUI 7-9; trophic, FUI 10-21). Seasonal dynamics show that the trophic state of 42 lakes in summer is significant higher than other seasons, while 99.65% lakes are under the state of trophic. And the order of average FUI is summer (19) > spring (18) > fall (11) > winter (10). Our results can serve as an example for other lakes lie in Yangtze River basin, and support the formulation of effective strategies to reduce seasonal eutrophication.

Introduction

Urban lakes have played a key role in the development of the national economy, with functions of regulating regional climate, maintaining regional ecosystem and balance the diversity of traditional derivatives. In recent decades, urban lakes suffering serious problem of water eutrophication due to the anthropogenic pollution (Le et al. 2010). This process often accompanied with the rapid increase in the number of harmful algae, especially for the chlorella, cyanobacteria (Wang et al. 2019b), diatom, which would threaten other aquatic life and change the color or odor of the water body, and finally causing drinking water crisis.

Therefore, the trophic state evaluation and monitoring of inland water have been a research hotspot in water ecology community for decades (Chao Rodriguez et al. 2014; Smith and Schindler 2009), Carlson (Carlson 1977) creatively invented a widely adopted numerical trophic state index (TSI) based on 5 water quality parameter, chemical oxygen demand (COD), Secchi depth (SD), total phosphorus (TN), total phosphorus (TP) and chlorophyll-a (Chl-a). And then the trophic state of inland water is divided into three categories, Oligotrophy (TSI: 0-30), Mesotrophy (TSI: 30-50), and Eutrophy (TSI>50).

Satellite sensors for worldwide observations of natural waters, such as the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) (Woerd and Wernand 2015), the Medium Resolution Imaging Spectrometer (MERIS) (Woerd and Wernand 2015), the Moderate Resolution Imaging Spectroradiometer (MODIS) (Chen and Quan 2013), and Landsat 8 Operational Land Imager (OLI) (Pahlevan et al. 2014), gradually developed into a new way of water environment monitoring. These spectrometers are specifically designed for water quality monitoring which only contains narrow (≈10 nm) spectral bands, mostly in the visual domain (380 – 780 nm), to establish empirical formulas for water quality parameters and bands reflectances and detecting the physical and chemical composition in water, like total suspend matters (TSM), chlorophyll-a and other colored component. (Li et al. 2018; Zhang et al. 2014)

The Forel-Ule index (FUI) is a traditional investigations of water color that commonly used in coastal waters, oceans, and regional seas. Based on the principle of FUI, water 21 FUI-classes numbered from 1 to 21 which represent the water color vary from dark blue to yellowish brown (van der Woerd and Wernand 2018). Studies have illustrated that water color is positively related with the
water inherent optical properties (IOPs) (incorporating Chl-a and TSM), and able to express the comprehensive properties of water quality, not just a separated water quality parameter (Wang et al. 2018). Besides, the FUI can be calculated by the satellite reflectances according to the band setting among different spectrometers (Woerd and Wernand 2015).

Wuhan is the largest city in the central of China possessing 166 lakes with different level of eutrophication problem (Chen et al. 2019). Despite of a series of protection and research works these years, water alga bloom occurred repeatedly, the situation of water eutrophication is still serious even with a tendency of deterioration. In this study, a FUI based water trophic state method was proposed and validated by in situ experiment data. And then the FUI in different lakes were calculated from Landsat 8 OLI images reflectance after radiation calibration and atmospheric correction, to assess the lakes trophic state dynamic in different season. And this paper can surely benefit the prevention and control of eutrophication of urban lakes in China.

**Study Area and Dataset**

**Study Area**

Wuhan possess the largest number of lakes in China located in Hubei Province (30°33'33.0"N, 114°24'38.5"E), which is a north subtropical monsoon humid climate with abundant rainfall, abundant sunshine. Generally, the lakes water level begins to rise after March each year, and keep the relatively high water level period started from May to August, then drops after September, and keep the relatively low water level period started from September to March. The monthly average temperature distribution shows obvious characteristics of seasonal changes. The average temperature is 28.8 °C in July and 4.5 °C in January. The characteristics of the inter-annual variability of temperature indicate the obvious continental climatic characteristics, that is, the average temperature gradually increases from January to July and decreases from August to December month by month.

**Landsat 8 OLI Dataset**

Landsat 8 images are download on website of United States Geological Survey (https://earthexplorer.usgs.gov). All the 42 selected lakes in Wuhan city is at the row 39 and path 123. Four images were preprocessed with ENVI 5.3 software, and then the DNs values of these images were transformed to the top-of-atmosphere (TOA) reflectances $\rho_{\lambda}$ as described by the following equation:

$$\rho_{\lambda} = \pi \cdot L_{\lambda} \cdot d^2 / (S_{\lambda} \cdot \sin \theta)$$

Where $S_{\lambda}$ is solar irradiance (W/m² • sr • μm), $L_{\lambda}$ represent radiance (W/m² • sr • μm) at wavelength $\lambda$, $\theta$ is the sun elevation angle (°) and $d$ is Earth-Sun distance in astronomical units. The $\sin \theta$ is a correction according to the reflectance offsets and gains of the OLI sensor. A 6SV atmosphere correction was used to convert the top of atmosphere (TOA) reflectance into the water surface reflectance (Rrs) (Wang et al. 2019a).

**Method**

**Trophic State Assessment**

Carlson (1977) proposed a TSI to determine the eutrophication condition in lakes, which composed of SD, Chl-a and TP. Many scientists have improved and revised the trophic state index (TSI) calculation formula by adding some items, such as the dissolved reactive manganese, DOC, water color and TN, etc. The TSI in this paper was then calculated by five water quality indices: Chl-a, TN, TP, COD and SD (Wang et al. 2019a). And TSI can be divided into three categories levels: oligotrophy, mesotrophy, eutrophy.

Four in-situ experiments were conducted in 8 April 2018, 27 June 2018, 15 September 2018 and 17 December 2017, respectively. And the five water parameters (Chl-a, TN, TP, COD and SD) were collected to calculate the in situ TSI and test the relationship with in situ FUI dataset.
FUI Derivation from Landsat 8 OLI

The description of Chromaticity is firstly put forward by the International Commission on Illumination (CIE, 1931), according to human color vision.

Where the human perceptible wavelength range from 390 to 740 nm, and the CIE's color matching functions x(\(\lambda\)), y(\(\lambda\)) and z(\(\lambda\)) are the numerical description of the chromatic response of the observer dependence of human vision for red, green, and blue light, respectively.

The chromaticity coordinates x, y and z are normalized tristimulus values, calculated by Equation (2):

\[
x = \frac{x}{X+Y+Z}, \quad y = \frac{y}{X+Y+Z}, \quad z = \frac{z}{X+Y+Z}
\]  

For Landsat 8 OLI instrument (van der Woerd and Wernand 2018), four bands are set in the visible spectrum part that are centered at 443 nm, 482 nm, 562 nm and 655 nm. And the formula to calculate the tristimulus values X, Y, Z by Landsat 8 OLI spectral reflectance is described by Equation (3):

\[
X = 11.053 \cdot R(443) + 6.950 \cdot R(482) + 51.135 \cdot R(561) + 34.457 \cdot R(655)
\]

\[
Y = 1.320 \cdot R(443) + 21.053 \cdot R(482) + 66.023 \cdot R(561) + 18.034 \cdot R(655)
\]

\[
Z = 58.038 \cdot R(443) + 34.931 \cdot R(482) + 2.606 \cdot R(561) + 0.016 \cdot R(655)
\]  

According to the calculated value of x, y by equation (2), we can obtain the perceived color in chromaticity coordinates. The horseshoe-shaped envelope (locus) encompass all possible chromaticity values, which is composed of the x and y values calculated from monochromatic light at each wavelength. The center coordinates of the chromaticity diagram is at the point with the value of x = y = z = 1/3. Any pair of x, y coordinates of an upwelling radiance spectrum can be identified by the hue angle (\(\alpha\)), which is calculated using the four quadrant arctangent function atan2, as described in Equation (4), and it refers to the counterclockwise rotated angle between the vector to point and the x'-axis in the converted coordinate system (y=1/3):

\[
\alpha = \frac{\text{Arctan2} \left( \frac{y-\frac{1}{2}}{x-\frac{1}{2}} \right)}{180/\pi}
\]  

Particularly, van der Woerd and Wernand (2018) have found that an offset (-5°-20°) caused by the spectral bandpass for the hue angle (\(\alpha\)) derived from sensor spectral reflectance. However, the hue angle offset (\(\Delta \alpha\)) is not completely random, which can be approximately described by a specific one-element fifth-order equation for different satellite sensors. As for OLI (van der Woerd and Wernand 2018), the \(\Delta \alpha\) can be approximately calculated by equation (5):
\[ \Delta \alpha = -52.16a^5 + 373.81a^5 - 981.83a^5 + 1134.19a^5 - 533.61a^5 + 76.72 \]  \hspace{1cm} (5)

Where the parameter \( a \) is one hundredth of the value of hue angle (\( \alpha \)).

**Result and Discussion**

**Relationship between Landsat 8 Retrieved FUI and TSI**

The Hydrolight simulated dataset (LEE 2006) has displayed the relationship between FUI and TSI were, based on 500 in situ Chl-a concentrations. And as shown in Figure 2a, the FUI positively increased with TSI in an exponential trend \( (R^2 = 0.9358) \). And in the in situ dataset shown in Figure 2b, the calculated FUI value derived from Landsat 8 Rrs also increased with TSI \( (R^2 = 0.6464, \text{N}=155) \).

![Figure 2](image)

Comparing the results of the relationship between TSI and FUI, we found that our in situ dataset \( (\text{N}=155) \) has a similar trend with the Hydrolight simulated dataset \( (\text{N}=500) \), which has proved the effectiveness of the FUI method for indicating trophic states in different lakes.

**Seasonal Variation**

Seasonal variation of FUI values were obtained by calculating the FUI value of all pixels from each Landsat image in different season. As shown in Figure 3, significant difference has been detected among different seasons for lakes. Overall, the highest value of FUI appeared in summer season (27 June 2018), while 99.65% lakes are under the state of eutrophication with an average FUI value of 19. And winter season (17 December 2017) appeared the relatively lower water trophic state with the average FUI of 10, and the TSI percentage of eutrophic, mesotrophic and oligotrophic is 64.01%, 23.50% and 12.48%, respectively. In spring and fall season, the average FUI value in 42 lakes is 11 and 18, respectively.

![Figure 3](image)

Figure 3. The FUI level of study lakes in different season (Spring, 8 April 2018; Summer, 27 June 2018; Fall, 15 September 2018; Winter, 17 December 2017).
Conclusions

To develop the remote sensing monitoring technology for water eutrophication, we investigate a FUI derived method to monitor the TSI in 42 urban lakes of Wuhan city. This method was validated by developing the relationship between FUI derived from Landsat 8 OLI Rrs and in situ measured TSI data (N=155), which contain a wide range of water trophic state from oligotrophy to eutrophy. A decision tree was use to classified the trophic state in 42 urban lakes that FUI <7 represent the oligotrophic state, 7<FUI<10 represent a mesotrophic state and FUI≥10 represent a trophic state. And an obvious seasonal variation was found, that the average TSI value is highest in summer and lowest in winter.

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