Urban black-odor water body dynamic analysis with high-resolution remote sensing image

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Abstract. The black-odor water has significant negative impacts on the sustainable development of society and survival of mankind. The paper presents a new Urban Black-Odor Water (UBOW) model to identify the urban black-odor water body from high-resolution remote sensing image Gaofen-2(GF-2), to help monitor and control urban black-odor water bodies. The new UBOW model is derived from the analysis of the in-situ observation data and the spectral characteristics of GF-2. It takes advantage of the spectral difference at the blue band, the green band and the red band and has certain theoretical ground. The UBOW model can effectively identify the severe black-odor water and the mild black-odor water. The model is validated by the observation and the overall accuracy can be up to 81%. The UBOW model is used to analyze the dynamics of the urban black-odor water bodies of Beijing China, with monthly GF-2 images from March 2017 to October 2018. Results show that the urban black-odor water bodies, whether it is mild black-odor water bodies or severe black-odor water bodies, have been reduced significantly, which is consistent with the governmental report. This confirms that the Beijing government takes effective measurements to remedy the urban black-odor water bodies.

1. Introduction

The black-odor water is the water who shows black and emits odorous gas and has lost its ecological function. It is caused due to the pollution, and has severely threatened the sustainable development of society and survival of mankind. The development of black-odor water has close relation with the urban landscape and daily life of citizens and so on. The growing urbanization is increasingly turning the urban river, which provides many kinds of ecological services to city dwellers, into the black-odor water body clusters. In China, more than 80% of urban river is contaminated, most of which has changed to black-odor rivers [1-4].

Owing to the significant negative impacts of black-odor water, it is important to examine the location, shape and size of black-odor water bodies. Due to the seasonal and dispersive characteristics of the black-odor water bodies, the ground monitoring methods have rather limited ability to quickly obtain the situation of black-odor water bodies. Since the spectral and textural characteristics of black-odor water body differ from those of clean water body [5], the introduction of remote sensing to assist the identification and remediation of black-odor water bodies is reasonable and has a range of benefits, such as quickly and cost-effectively [6]. Wang et al [7] and Duan et al [8] investigate the black-odor mechanism of water and the spectral characteristics. On the basis of measured remote sensing
reflectance, Cao [9] develops two methods (recognition saturation method and spectral index method) to identify the urban black-odor water bodies in Beijing, and quantitatively analyzes the correlation between the quality parameters of black-odor water and the black-odor water index. Wen et al [6] analyze the spectral characteristics of black-odor water and then developed three methods to identify the urban black-odor water in Nanjing, China from high-resolution remote sensing image Gaofen-2 (GF-2).

The flying development of high-resolution remote sensing technology has already provided a large volume of high-resolution remote sensing image for monitoring the urban black-odor water bodies. Its benefits to identify the black-odor water bodies, however, is still locked, especially when the black-odor water bodies is further classified into more detail level, such as severe black-odor water and mild black-odor water. The monitoring and remediation of black-odor water bodies need the detail information of black-odor water bodies. Therefore, it necessitates the development of identification model for black-odor water bodies with high-resolution remote sensing data which can distinguish the severe black-odor water and mild black-odor water. The paper develops a new model, which is based on the in-situ observation data and the spectral characteristics of Gaofen-2 (GF-2) and is validated by observations, to identify the severe black-odor water and the mild black-odor water.

2. Material

2.1. Study area

![Figure 1. The Beijing layout.](image-url)
Beijing is the capital of China. It is situated at the northern tip of the roughly triangular North China Plain. Beijing has 16 districts, as depicted by figure 1, and its area is 16411 km². The total population is around 20 million in 2010, among whom most lives in the urban area, accounting for 86%. Major rivers flowing through Beijing, including the Chaobai, Yongding, Juma, are all tributaries in the Hai River system, and flow in a southeasterly direction. The Miyun Reservoir, on the upper reaches of the Chaobai River, is the largest reservoir within the municipality.

Beijing has a monsoon-influenced humid continental climate, characterized by hot, humid summers due to the East Asian monsoon, and cold, windy, dry winters that reflect the influence of the vast Siberian anticyclone. Precipitation averages around 570 mm (22 in) annually, with close to three-fourths of that total falling from June to August.

2.2. In-situ observation data

12 consecutive monthly sampling campaigns were conducted during March 2017-February 2018 and 282 sites were surveyed across the rivers of Beijing. At each site, water sample is collected from surface water of rivers, and restored in sealed bottles in 4°C and then used for tests. According to “The Modification Guidance of Urban Black-Odor Water Body” released by The Ministry of Housing and Urban-Rural Development of RPR China in August 2015, the water clarity, the dissolved oxygen (DO), the oxidation-reduction potential and the ammonium-N(NH3-N) were measured, and the river sections were accordingly classified into normal, mild black-odor water and severe black-odor water. The criteria used is documented in table 1.

| Table 1. Classification criteria for the degree of urban black-odor water [10]. |
|---------------------------------|-----------------|-----------------|-----------------|
|                                | normal          | mild black-odor water | severe black-odor water |
| water clarity(cm)              | >25             | 10-25cm          | <10             |
| dissolved oxygen (DO) (mg/L)   | >2              | 0.2-2.00         | <0.2            |
| oxidation-reduction potential (mV) | >50.0          | -200-50.0        | <200            |
| ammonium-N (NH3-N) (mg/L)      | >15             | 8.00-15          | >15             |

2.3. Remote sensing data

The high-resolution remote sensing data used is from Gaofen-2(GF-2) satellite which is launched on August 19, 2014. It is configured with two identical cameras with 0.8m panchromatic and 3.2 m multispectral bands on a swath of 45 km. Table 2 documents the sensor specifications.

| Table 2. GF-2 sensor specification [11]. |
|---------------------------------|-----------------|-----------------|-----------------|
| Spectral Range (µm)             | Panchromatic    | Multispectral   |                |
|                                 | 0.45-0.89       | Band01 - 0.45-0.52 |                |
|                                 |                 | Band02 - 0.52-0.59 |                |
|                                 |                 | Band03 - 0.62-0.69 |                |
|                                 |                 | Band04 - 0.77-0.89 |                |
| Swath Width (2 camera)          | 45km            | 45km            |                |
| Viewing Angle                   | 0° - 25°        | 0° - 25°        |                |
| Repetition Cycle (days)         | 5               | 5               |                |
| Spatial Resolution (m)          | 0.8             | 3.2             |                |

The monthly GF-2 images were collected from March 2017 to October 2018, so totally it has 20 time point data. Preprocessing for the GF-2 image was conducted, which includes radiometric calibration, atmospheric correction, geometric correction, and ortho-rectification, to convert digital value to surface reflectance through commercial remote sensing image processing software Pixel Information Expert (PIE) (Beijing PIESAT Information Technology Co., Ltd.). Finally, Gram-Schmidt transform method was realized to fuse for the panchromatic and multi-spectral images. The
fusion images not only keep the spectral information of multi-spectral images, but also have the high spatial resolution of panchromatic images.

3. Methods
In this paper, we first describe the study area and the observation and remote sensing data. Then we develop the new model. We validate the new model and apply it to identify the black-odor water in Beijing. We then provide the results and conduct the discussion. Finally, we will draw conclusions.

The development of new model has two stages. The first stage is to project the sampling sites to the GF-2 image, and the second stage is to develop the UBOW model of black-odor water body. At the first stage, when projecting the sampling site to the GF-2 image, it will occur that the matching pixel is not the pure water pixel. That is, the matching pixel is the mixed pixel containing other entities in real ground. In order to eliminate the influence of other entities caused by the narrow urban river, we need get the pure water pixel before projecting the sampling site to GF-2 image, and then project it to GF-2 image. In order to get the pure water pixel, we identify the central line of urban river which ensures to the great extent the pixels of the central line are the pure water pixels. Figure 2 shows the extracted central line of urban river. We then project the sampling sites to the nearest pure water pixels.

![Figure 2. The extracted central line of urban river.](image)

At the second stage, we divide the matched pure water pixels (thereafter called sampling pixels) into two parts: 3000 sampling pixels are used to develop the UBOW model and the rest is used to validate the UBOW model. We directly analyze the spectral characteristics for severe black-odor water body, mild black-odor water body and normal water body for sampling pixels, and find that the black-odor water, whether it is severe or mild, has apparent difference in spectral curve with normal water, as demonstrated by figure 3. At the wavelength of 555 nm (i.e. the green band), the normal water has the largest reflectance (0.085), followed by the mild black-odor water (0.08) and the severe...
black-odor water (0.069). At the wavelength of 665 nm (i.e. the red band), the mild black-odor water has the largest reflectance (0.072), followed by the normal water (0.069) and the severe black-odor water (0.062). From the wavelength of 555 nm to the wavelength of 665 nm, the reflectance of normal water shows deep decline, whereas the reflectance of both severe and mild black-odor water has relatively slow decline. As some studies point out that the reflectance of black-odor water show slow increase from the wavelength of 480 nm (i.e. the blue band) to wavelength of 555 nm (i.e. the green band), while the reflectance of the normal water demonstrates the sharp increase [6], we also find the same observation (figure 3). In order to take advantage of all these observations and similar with Normalized Difference Vegetation Index (NDVI), we propose the UBOW model as

$$UBOW = \frac{R(Green) - R(\text{Red})}{R(Green) + R(\text{Red}) + R(\text{Blue})}$$

where $R(Green)$ is the reflectance at the green band. $R(\text{Red})$ is the reflectance at the red band. $R(\text{Blue})$ is the reflectance at the blue band.

![Figure 3. The spectral curve of normal water, mild black-odor water and severe black odor water.](image)

When using UBOW model to identify the normal water body, mild black-odor water body and severe black-odor water body from GF-2 image, we need determine two critical thresholds $I_1$ and $I_2$ with $I_1 \leq I_2$. For the sampling pixels, these two values of critical thresholds are 0.04 and 0.07, respectively. So if the values of UBOW for one sampling pixel is larger than 0.07, then the sampling pixel will be normal water. If the value of UBOW for one sampling pixel is within [0.04, 0.07], then the sampling pixel will be mild black-odor water. If the value of UBOW for one sampling pixel is smaller than 0.04, then the sampling pixel will be severe black-odor water.

4. Results

4.1. Validation of UBOW model

To validate the UBOW model using the sampling pixels, table 3 documents the confusion matrix, and table 4 documents the errors of commission and omission, and the Producer’s Accuracy (PA) and the User’s Accuracy (UA). In terms of table 3, the UBOW model can effectively identify the normal water, mild black-odor water and severe black-odor water. The overall accuracy is 81.15%. The errors of commission are small (table 4), implying that only a small fraction of features is incorrectly assigned to the underlying classes. The errors of omission are small (table 4), indicating that only a very small fraction of features is left out of the underlying classes. Consequently, the UBOW model works stably when identifying the normal water, mild black-odor water and severe black-odor water.
Table 3. The confusion matrix of UBOW model.

| Observation of UBOW model | normal   | mild black-odor water | severe black-odor water |
|---------------------------|----------|------------------------|-------------------------|
| normal                    | 81.73%   | 9.67%                  | 8.25%                   |
| mild black-odor water     | 10.38%   | 79.27%                 | 9.29%                   |
| severe black-odor water   | 7.89%    | 11.06%                 | 82.46%                  |

Table 4. Errors of commission and omission, producer’s accuracy and user’s accuracy.

|                      | Commission | Omission | PA      | UA      |
|----------------------|------------|----------|---------|---------|
| normal               | 17.98%     | 18.27%   | 81.73%  | 82.02%  |
| mild black-odor water| 19.88%     | 20.73%   | 79.27%  | 80.12%  |
| severe black-odor water | 18.69%   | 17.54%   | 82.46%  | 81.31%  |

Figure 4. The spatial distribution of urban black-odor water bodies in March 2017.

Figure 5. The spatial distribution of urban black-odor water bodies in August 2017.

4.2. Dynamics of black-odor water bodies

We now analyze the dynamics of urban black-odor water bodies. Figures 4-8 show the dynamics of urban black-odor water bodies from GF-2 image in March 2017, August 2017, January 2018, May 2018 and October 2018 using UBOW model, respectively. We specifically analyze three urban rivers which have received a lot of attention from Beijing Government: Xiaotaihou River, Fenggangjian River and Shengligan Canal. For Xiaotaihou River, the whole Xiaotaihou River, which is 7.8 km, is the mild black-odor water body in March 2017 (figure 4). From March 2017 to October 2018, the mild black-odor water bodies are reduced and are gradually converted into normal water bodies, although in May 2018, the mild black-odor water bodies increase. It has no severe black-odor water bodies from March 2017 to October 2018. For Fenggangjian River, it has the 1.12 km normal water bodies, the 13.88 km mild black-odor water bodies, and the 8.27 km severe black-odor water bodies in March 2017 (figure 4). From March 2017 to October 2018, the mild black-odor water bodies are reduced and are gradually converted into normal water bodies, although in May 2018, the mild black-odor water bodies increase. It has no severe black-odor water bodies from March 2017 to October 2018. For Shengligan Canal, the whole canal is the mild black-odor water bodies in March 2017, which is the same with Xiaotaihou River. From March 2017 to October 2018,
the mild black-odor water bodies are reduced and the whole canal becomes the normal water bodies in October 2018. In contrast to Xiaotaihou River, the Shengligan Canal has severe black-odor water bodies, accounting for merely 0.13 km in length.

5. Discussion
Although it is based on the empirical analysis of the spectral curve among normal water, mild black-odor water and severe black-odor water, the development of UBOW model has certain theoretical ground. The analysis of the absorption characteristics of urban black-odor water bodies shows that the
Colored Dissolved Organic Matter (CDOM) absorption coefficients for urban black-odor water bodies and non-black-odor water bodies differ, and its slope at the characteristic wavelength band of 440 nm, together with other wavelength bands, can be used to distinguish the black-odor water body and normal water body [12,13]. In the UBOW model, we use the spectral different at the wavelength of 480 nm (i.e. the blue band) to enlarge the difference of the ratio of the green band and red band.

Water is one of the vital resources supporting human survival [14,15], and the urban water environment protection concerns vital interests of the urban residences. The development of urbanization worsens the urban water ecology and turns some urban waters into black-odor water bodies. In order to protect the urban water environment, the State Council of China issues the Action Plan for Prevention and Control of Water Pollution. One of the objectives of the Action Plan is to dramatically reduce the heavily polluted water bodies. As the biggest city in China, Beijing invests a lot to monitor and remedy the black-odor water bodies since 2016. The results show that the urban black-odor water bodies, whether it is mild black-odor water bodies or severe black-odor water bodies, have been reduced significantly, and the urban water environment becomes better than before, which is consistent with the governmental report [16][16]. This confirms that the Beijing government takes effective measurements to remedy the urban black-odor water bodies.

The urban black-odor water bodies are caused by various pollutions across cities. The black-odor water bodies in Beijing are caused mainly by industrial waste water and domestic sewage. The black-odor water bodies in Nanjing, China are caused mainly by domestic sewage, industrial waste water and broken river channel [6]. The different pollution sources will result in different black-odor mechanisms of urban water bodies [17], which will present more challenges to remedy the black-odor water bodies. The integration of remote sensing into in-situ observations can not only identify the black-odor water bodies but also track the pollution sources of black-odor water bodies, which can benefit both the monitoring and remediation of urban black-odor water.

6. Conclusion
The UBOW model developed takes advantages of the spectral difference among normal water, mild black-odor water and severe black-odor water. Although it is simple, it is effective to identify the normal water, mild black-odor water and severe black-odor water. The overall accuracy can be up to 81%. Compared to the ratio index [6], the UBOW model takes also account of the spectral difference among normal water, mild black-odor water and severe black-odor water at the blue band.

When developing the UBOW model, we only use the four bands. This is because the GF-2 sensor only has four channels. Actually, the reflectance of urban black-odor water and normal water is continuous, and some important difference in spectral curve may be hidden by these widen band width. In this sense, the hyperspectral satellite may provide better solution, although the idea used to develop the UBOW model is still applicable. In addition, the spectral information of sampling pixel used to develop the UBOW model has no direct relationship with the chemical components of black-odor water body, and therefore the UBOW model can be only used to identify the black-odor water body and has no way to reveal the chemical components of black-odor water body. Furthermore, the UBOW model is developed specially for the urban black-odor water body caused by domestic sewage. For the urban black-odor water body caused by other pollutions such as industrial waste water, it still needs further researches.

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