Monitoring seasonal variations of colored dissolved organic matter for the Saginaw River based on Landsat-8 data

Jiang Chen, Weining Zhu, Yuhan Zheng, Yong Q. Tian and Qian Yu

ABSTRACT

Remote sensing is an effective tool for studying CDOM (colored dissolved organic matter) variations and its relevant environmental factors. Monitoring CDOM distribution and dynamics in small water is often limited by the coarse spatial resolution of traditional ocean color sensors. In this study, because of its high spatial resolution of 30 m, Landsat-8 data were used to assess seasonal variations of CDOM in the Saginaw River, by using an empirical statistic model. Pearson correlation analysis between CDOM variations and other environmental factors, such as temperature, discharge, and dissolved oxygen, shows that temperature was negatively correlated to CDOM variations and discharge played a positive role. We also calculated the monthly mean $a_{CDOM}(440)$ (the absorption coefficient of CDOM at 440 nm) for the Saginaw River between April and November from 2013 to 2016. This study demonstrates a good example for future applications in small waters: observing CDOM variations and other relevant environmental factors change by using Landsat remote sensing, so that we can know more about water quality and ecosystem health of small waters as well as the climate change impact on regional watersheds.

Key words | colored dissolved organic matter (CDOM), environmental factors, remote sensing, Saginaw River, water quality

Jiang Chen
Weining Zhu (corresponding author)
Yuhan Zheng
Ocean College,
Zhejiang University,
Zhoushan,
China
E-mail: *zhuwn@zju.edu.cn*

Yong Q. Tian
Department of Geography and Institute for Great Lakes Research,
Central Michigan University,
Mount Pleasant,
Michigan,
USA

Qian Yu
Department of Geosciences,
University of Massachusetts – Amherst,
Amherst,
Massachusetts,
USA

INTRODUCTION

CDOM (colored dissolved organic matter) usually serves as a useful indicator for assessing the relative abundance and spatial pattern of DOC (dissolved organic carbon) in aquatic ecosystems (Mannino *et al.* 2008). CDOM is also a part of DOM (dissolved organic matter) which plays a significant role in the carbon cycle and climate change (Coble 2007). Called the yellow substance, CDOM is an optically active matter absorbing UV and visible light (Coble 1996), and hence can be remotely sensed by satellites (Brezonik *et al.* 2015). It is known that remote sensing is an effective method for observing CDOM variations and couplings between CDOM and its ambient environments (Griffin *et al.* 2011).

doi: 10.2166/ws.2018.077

Monitoring CDOM for small waters is often limited by coarse spatial resolutions of traditional ocean color sensors (Wu *et al.* 2015), including SeaWiFS (Sea-viewing Wide Field-of-view), MODIS (Moderate-resolution imaging spectroradiometer), MERIS (Medium Resolution Imaging Spectrometer), and GOCI (Geostationary Ocean Color Imager) – these sensors, with resolutions about 1 km, are typically designed for oceanic water observation. Because of its good spatial resolution (30 m), Landsat-8 OLI (operational land imager) has been widely used for water quality assessment in small aquatic environments, such as Chl-a (chlorophyll-a) (Masocha *et al.* 2017), $K_d(490)$ (diffuse attenuation coefficient of water at 490 nm) (Zheng *et al.* 2016), TN (total nitrogen) and TP (total phosphorus) (Li *et al.* 2017), in which Zheng *et al.* (2016) applied 23 Landsat-8 images to derive monthly mean $K_d(490)$ patterns between 2013 and 2016 in Dongting Lake, and found that temporal variation of $K_d(490)$ were influenced by surface-runoff changes. Li *et al.* (2017) used 25 Landsat-8 images to monitor spatiotemporal variations of TN and TP, and they discovered TN was sensitive to wind speed and temperature change and TP was affected by fishery and agricultural activities.

CDOM-related water quality assessment has been studied using some hyperspectral images. We have used Hyperion imagery to monitor spatiotemporal CDOM variations for estuarine and coastal waters (Zhu *et al.* 2013), but a Hyperion image only covers a narrow area (<10 km) which usually does not work for waters that span widely, and the sensor also stopped operation a couple of years ago. Landsat-series satellites have continuously served for earth observing over 40 years, and Landsat-8 is the latest one, which has demonstrated tremendous potential for water quality monitoring and environment assessment. There are several previous studies on observing CDOM in high spatial resolution remote sensing for small rivers, and some Landsat-8-based CDOM models have been proposed (Alcântara *et al.* 2016; Slonecker *et al.* 2016). These previous studies, however, only established the CDOM remote sensing model but they have not been well applied to observe seasonal time-series CDOM variations, and tried to connect them to some hydrological and meteorological variables, such as the discharge, temperature, and precipitation.

We also developed a CDOM Landsat-8 model by using a model-ranking method (Chen *et al.* 2017), and the best model has been applied to two Landsat-8 images of the estuary of Saginaw River as well as the Saginaw Bay of Lake Huron. The model-derived images illustrate accurate and reasonable CDOM distributions for small waters, and hence can be used for further assessment of CDOM and its temporal changes coupled with other environmental factors by using Landsat-8 series images. Therefore, the main objective of this study is using remote sensing and Landsat-8 imagery to monitor variations in CDOM and its relevant environmental factors for small waters such as the Saginaw River. CDOM distributions and dynamics in these small rivers can be used as indicators for assessing the water quality of the regional environment and ecosystems.

DATA AND METHODS

Study site

Saginaw River, with a main stream length of 36 km and watershed area of 22,260 km^2, belongs to the water basin of the Great Lakes, flowing into Lake Huron and crossing over the Midland, Saginaw and Bay City in Michigan. Figure 1 shows the watershed and system map of the Saginaw River and related meteorological and hydrologic stations. The local government has paid more attention on the Saginaw River since its water quality worsened according to a recent report (Hoard *et al.* 2012). The EPA (Environmental Protection Agency) of the United States also states the Saginaw Bay, a part of Lake Huron and to which the Saginaw River flows, is an 'Area of Concern' due to the high-concentration nutrients and sediments discharged by the Saginaw River. Based on our field measurements, CDOM concentrations in Saginaw River and Bay area are usually in a large range, but its interannual variation has not been well investigated.

Field and laboratory measurement

Our field measurements were conducted on 10 May, 2012, 18 October, 2012, and 7 May, 2013, respectively, and 41 water samples were collected in dark bottles. The *in situ* R_{rs} (remote sensing reflectance) was measured by a HyperSAS (Hyperspectral Surface Acquisition System) with a range of 350–800 nm. At each sampling point, 20 spectra were measured to minimize the spectral uncertainty caused by water surface waves and ambient light field, and the median one of the 20 spectra was selected for remote sensing modeling.

In the laboratory, water samples were filtered by 0.70 μm GF/F glass microfiber membrane. The filtrate was obtained to measure a_{CDOM} (the absorption coefficient of CDOM, unit m^{-1}) using a Cray-60 spectroradiometer with a range of 200–800 nm. Because of the biochemical complexity of CDOM, its concentration is usually characterized by using its absorption coefficient at a specific wavelength, for example, 355 nm, 375 nm or 440 nm. In this study, a_{CDOM} at 440 nm, namely $a_{CDOM}(440)$, was used, since it has been widely

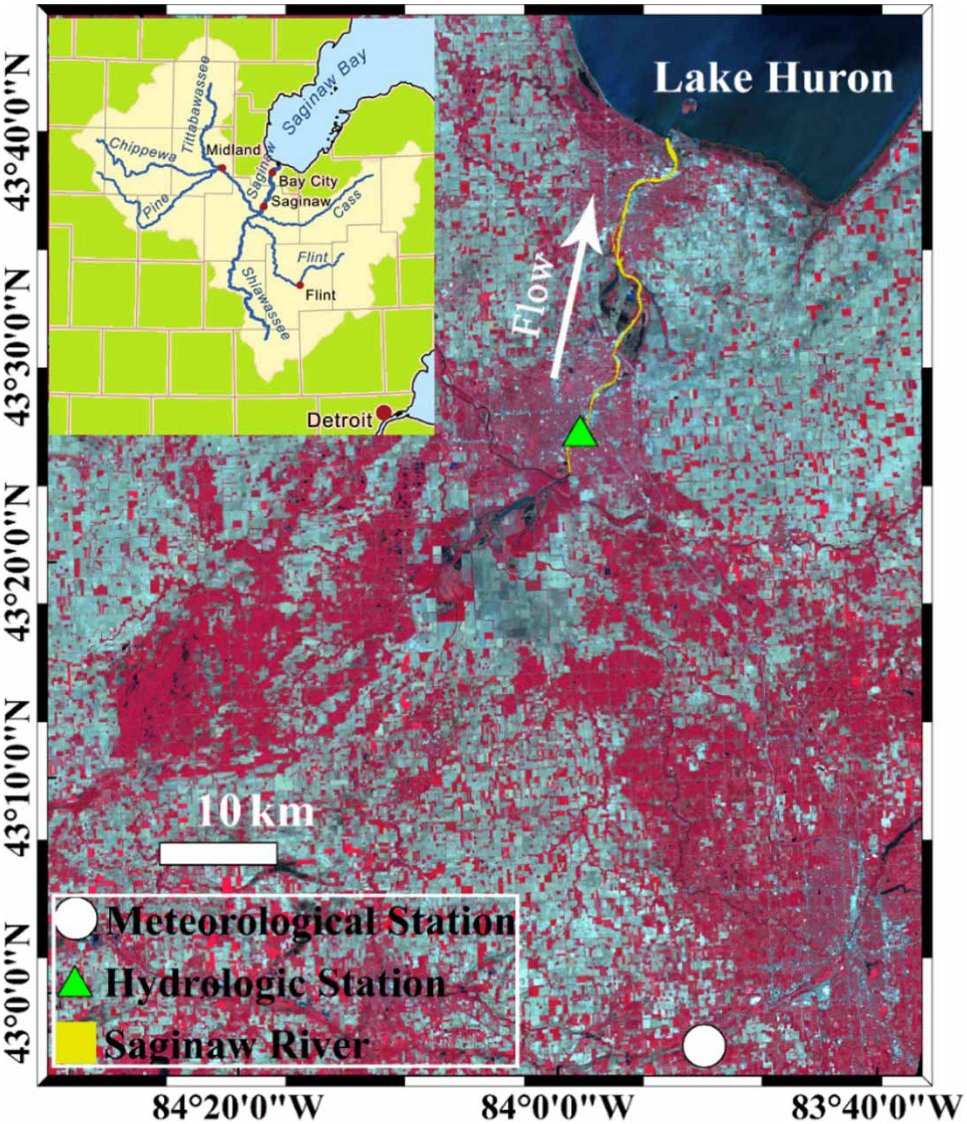

Figure 1 | Site map of the Saginaw River and its watershed, river systems, and two meteorological and hydrologic stations. The base map is a Landsat-8 image presented by a standard false color composite.

accepted as the typical wavelength of CDOM. The measured $a_{CDOM}(440)$ of all samples were in a range 0.11–8.46 m^{-1} and the mean value was 2.61 m^{-1}. More information on our field and laboratory measurements can be found in our previous studies (Zhu *et al.* 2014; Chen *et al.* 2017).

CDOM model development and validation

The CDOM remote sensing model used in this study was developed in our previous study (Chen *et al.* 2017). We used a model ranking method and tested different band-ratio combinations, model functions, and model input spectral variables. As a result, we obtained the best model for Landsat-8-based CDOM retrieval in the Saginaw River, which is a green-red band-ratio exponential model using R_{rs} as the input. The model function is $a_{CDOM}(440) = 40.75e^{-2.463x}$, where $x = R_{rs}(B3)/R_{rs}(B4)$, and B3 and B4 are the green and red bands of Landsat-8. The model was validated with accuracy $R^2 = 0.949$ and RMSE (root-mean-squared error) $= 0.504\ m^{-1}$. RMSE is defined by the formula $RMSE = \sqrt{\frac{\sum_{i=1}^{N}(x_i^{estimated} - x_i^{measured})^2}{N}}$, where $x_i^{estimated}$ and

$x_i^{measured}$ refer to the estimated and measured $a_{CDOM}(440)$ for the ith sample, respectively.

Landsat-8 data acquisition and preprocessing

Thirty-two cloud-free Landsat-8 L1T images downloaded from the USGS (United States Geological Survey) website https://earthexplorer.usgs.gov/, from April 2013 to November 2016, were used to estimate seasonal CDOM variations of the study site. Due to the frozen water of the river in winter, images in December, January, February, and March do not work for CDOM observation. Therefore, the monthly remote sensing CDOM estimations were only conducted from April to November in each year.

The selected Landsat-8 images were preprocessed by radiation correction, atmospheric correction, and water surface reflectance correction. The FLAASH (Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubus) module assembled in ENVI® was used to derive the total water reflectance. Study has demonstrated that FLAASH is an effective method for atmospheric correction of waters (Tebbs *et al.* 2013). Our studies have also shown that FLAASH is accurate to correct water spectra for Landsat-8 in Saginaw River region (Chen *et al.* 2017). The output of FLAASH is the total water reflectance (R_t), which contains not only the water-leaving radiance, but also the surface reflected radiance. The R_t needs to be corrected to water's remote sensing reflectance (R_{rs}), which is widely used for water color remote sensing. The details of water surface reflectance correction are shown in our previous study (Chen *et al.* 2017).

Meteorological and hydrological data

The environmental data related to our study site were obtained from two USGS field stations: one is a hydrological station (Figure 1) which measures the discharge of the river, and also measures various water quality parameters such as temperature, dissolved oxygen, and turbidity, and the other is a meteorological station which provides daily precipitation. The locations of the two stations are shown in Figure 1, and their data can be downloaded from the USGS (https://waterdata.usgs.gov/nwis). Two types of data were used for the CDOM-environment analysis: (1) temperature, dissolved oxygen, turbidity, discharge, and precipitation data that matched the Landsat-8 acquisition date, namely, the intraday data, and (2) the same environmental data but averaged for 3 days, 5 days, 7 days, 15 days, and 30 days prior to the Landsat-8 acquisition date. Then the Pearson correlation analysis was used to study the relations between these factors and CDOM variations seen from the satellite images.

RESULTS AND DISCUSSION

Remotely sensed seasonal CDOM patterns

Monthly mean CDOM patterns between April and November from 2013 to 2016 derived from Landsat-8 data in Saginaw River are shown in Figure 2. The descriptive statistics of monthly estimated $a_{CDOM}(440)$ are shown in Table 1. The distribution of $a_{CDOM}(440)$ displays a significant seasonal variations, with a range of 1.13–5.5 m^{-1} (Figure 2). Overall, the CDOM concentration was relatively higher from April to June, and reached the highest value ($3.23 \pm 0.35\ m^{-1}$) in May. It was relatively lower from July to September, and reached the lowest value ($1.27 \pm 0.29\ m^{-1}$) in August. From September to November, the CDOM concentration started to slowly increase to the level of June. Although CDOM data during November and April are not available due to the river icing, it is reasonable to expect that it may keep increasing to the higher level of April. The seasonal variations of $a_{CDOM}(440)$, see Figure 3, show a clear temporal cycle between April and November from 2013 to 2016, and the monthly mean variation can be expressed as a quadratic function $y = 0.1047x^2 – 1.7285x + 8.7984$, with $R^2 = 0.82$ ($N = 8$, $p < 0.05$). This phenomenon was found for the first time in the Saginaw River by remote sensing, and it needs to be validated by more field data in future to prove CDOM's seasonal fluctuations.

Factors affecting daily CDOM variations

Pearson correlation analysis was carried out between the 32-image derived mean CDOM and meteorological and hydrological factors within different time intervals (intraday/3-day/5-day/7-day/15-day/30-day, see Table 2).

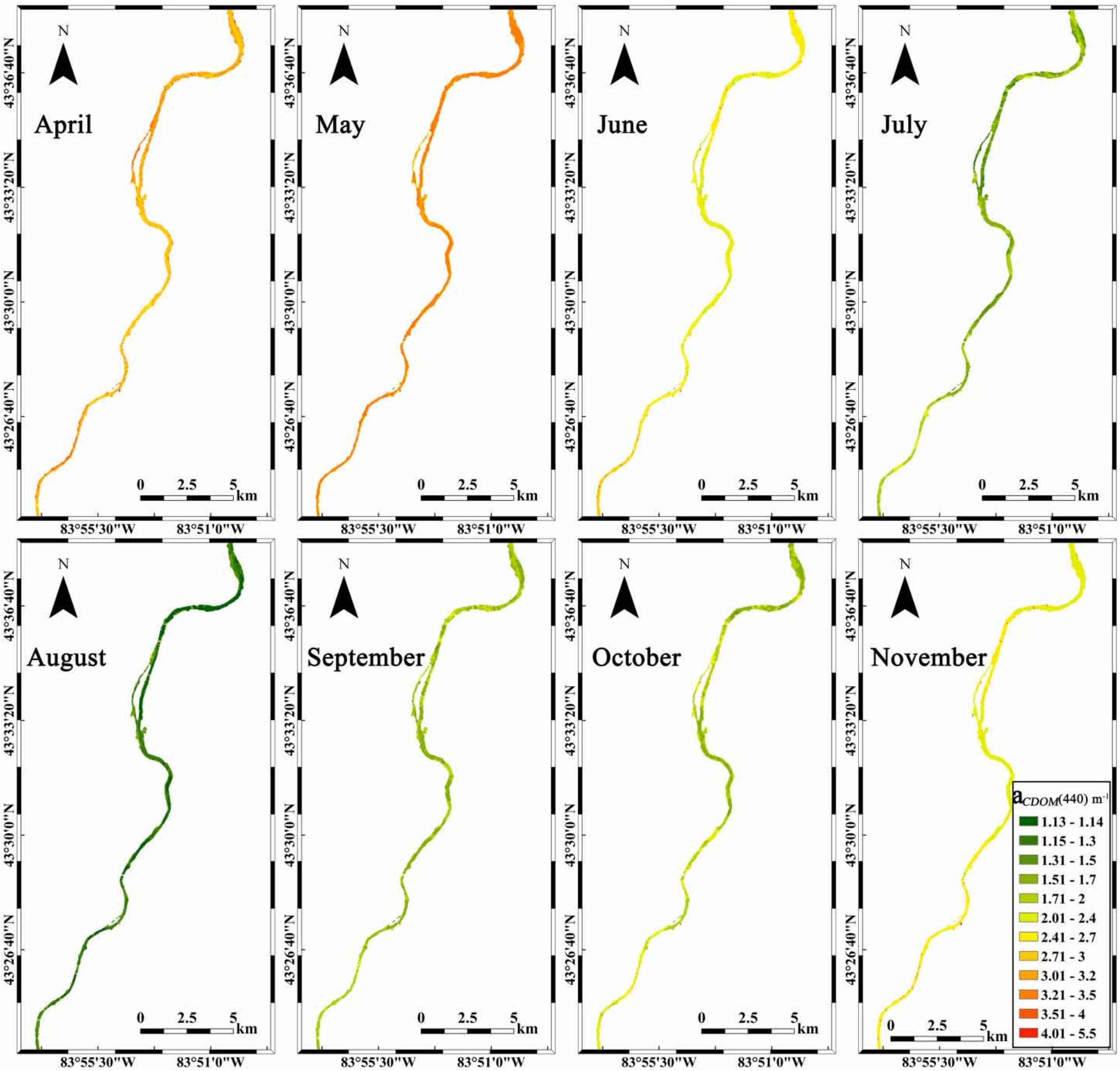

Figure 2 | Monthly mean a_{CDOM}(440) derived from Landsat-8 in the Saginaw River between April and November from 2013 to 2016.

The goal is to evaluate the time duration which each factor takes effect on CDOM variations. The results show that temperature was negatively correlated with daily CDOM variations at any time intervals ($r > -0.419$, $p < 0.05$), meaning that higher temperature brought about lower CDOM concentration. Temperature changes are mainly caused by seasonal changes and hence insolation duration. The photo-bleaching caused by intensive insolation makes CDOM disappear rapidly, and high temperature also provides a good condition for microorganism activities consuming CDOM in water. Some previous studies also found that there are negative correlations between CDOM and temperature (Coble 2007). Discharge was positively correlated to daily CDOM variations ($r > 0.655$, $p < 0.05$), indicating that larger discharge usually bring more CDOM, which has been reported in some previous studies (Griffin *et al.* 2011; Zhu *et al.* 2013). Precipitation is the major factor changing the river's discharge, and surface run-off and

Table 1 | Descriptive statistics of the monthly remote-sensing estimated a_{CDOM} (440) from April to November, 2013–2016

	Min	Mean	Max	SD
Apr	1.74	3.18	4.59	0.57
May	1.13	3.23	5.5	0.35
Jun	1.24	2.5	3.64	0.32
Jul	0.81	1.7	3.28	0.33
Aug	0.73	1.27	2.83	0.29
Sep	1.11	1.79	3.49	0.3
Oct	1.39	1.97	3.91	0.38
Nov	1.4	2.55	4.93	0.48

SD refers to standard deviation.

ground water caused by precipitation can bring many allochthonous terrestrial dissolved organic matter into rivers and lakes. However, precipitation and CDOM have not shown a strong correlation in our study site. The reason is possibly that the meteorological station, while being the nearest one, is still ~50 km away from the Saginaw River. Therefore, the precipitation data recorded in this station are unable to reflect the precipitation amount of the entire watershed of the Saginaw River.

It is known that CDOM is partly from the autochthonous production of phytoplankton and DO (dissolved oxygen) is the key component for phytoplankton growth; however, based on the results, the correlation between CDOM and DO ($r = 0.383$, $p < 0.05$) was weak within the 30-day interval. Turbidity is an indicator of attenuation of the underwater light field. High turbidity usually leads to strong light attenuation, and as the optically active components absorbing UV and visible light, CDOM also often leads to strong light attenuation; therefore, in some relations, turbidity and CDOM were positively correlated within the 15 day interval ($r = 0.444$, $p < 0.05$).

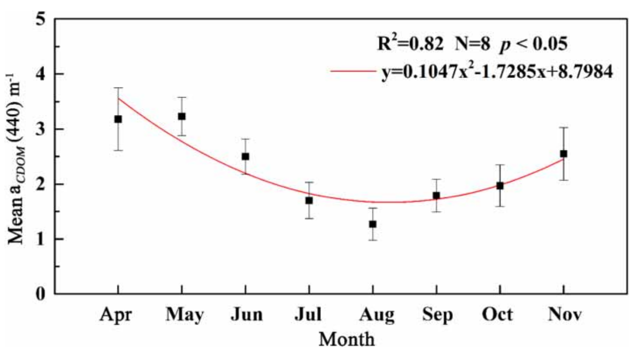

Figure 3 | Monthly mean a_{CDOM}(440) variations between April and November from 2013 to 2016.

Factors affecting monthly mean CDOM variations

The correlation analysis between monthly mean meteorological and hydrologic variables and CDOM has shown that mean a_{CDOM}(440) was negatively correlated to monthly mean temperature with $r = -0.618$, $p < 0.1$, while it was positively correlated to monthly mean discharge with $r = 0.774$, $p < 0.05$, see Table 3. Figure 4 shows daily variations of temperature and discharge in the Saginaw River, which can explain the CDOM variation patterns in Figure 2. During the summer days, temperature is often much higher and the incident solar radiation is usually strong, which makes the photobleaching of CDOM strong. Moreover, hot temperature triggers aquatic microorganisms to be more activated and hence they may consume more CDOM as their nutrition. During the same time, the river's discharge is the lowest, and hence the lowest CDOM occurred in summer during August. Discharge reaches a high level from March to June, and during this time, CDOM concentrations are also at a high level. Starting from September, the temperature drops, making the CDOM concentration also drop correspondingly, but meanwhile the discharge stays almost unchanged with only small fluctuations. Overall, according to the results, we can see that temperature and discharge are the two major environmental factors that have large influences on CDOM variations.

CONCLUSION

A remote sensing model was used to observe CDOM variations coupled with meteorological and hydrological variables, based on time series Landsat-8 images in the Saginaw River, Lake Huron. Results show that the temperature is negatively correlated with daily CDOM variations, and the discharge is positively correlated with routine CDOM variations. Monthly mean a_{CDOM}(440) shows a seasonal fluctuation between April and November from 2013 to 2016, which was relatively higher during April to June,

Table 2 | Correlation analysis results ($N = 32$) between $a_{CDOM}(440)$ and intraday, 3 days prior, 5 days prior, 7 days prior, 15 days prior, and 30 days prior cumulative average meteorological, hydrologic, and water quality conditions

	Intraday	3-day	5-day	7-day	15-day	30-day
Temperature	−0.406*	−0.42*	−0.419*	−0.434*	−0.536*	−0.644*
Dissolved oxygen	0.048	0.006	−0.032	−0.023	0.157	0.383*
Turbidity	0.19	0.257	0.236	0.266	0.444*	0.307
Discharge	0.828*	0.796*	0.751*	0.693*	0.655*	0.665*
Precipitation	–	0.074	−0.037	0.208	0.263	0.243

*indicates $p < 0.05$.

Table 3 | Correlation analysis results ($N = 8$) between mean $a_{CDOM}(440)$ and monthly mean temperature, DO (dissolved oxygen), turbidity, discharge and precipitation of Saginaw River

	Temperature	DO	Turbidity	Discharge	Precipitation
$a_{CDOM}(440)$	−0.618**	0.462	0.362	0.774*	0.268

*indicates $p < 0.05$.
**indicates $p < 0.1$.

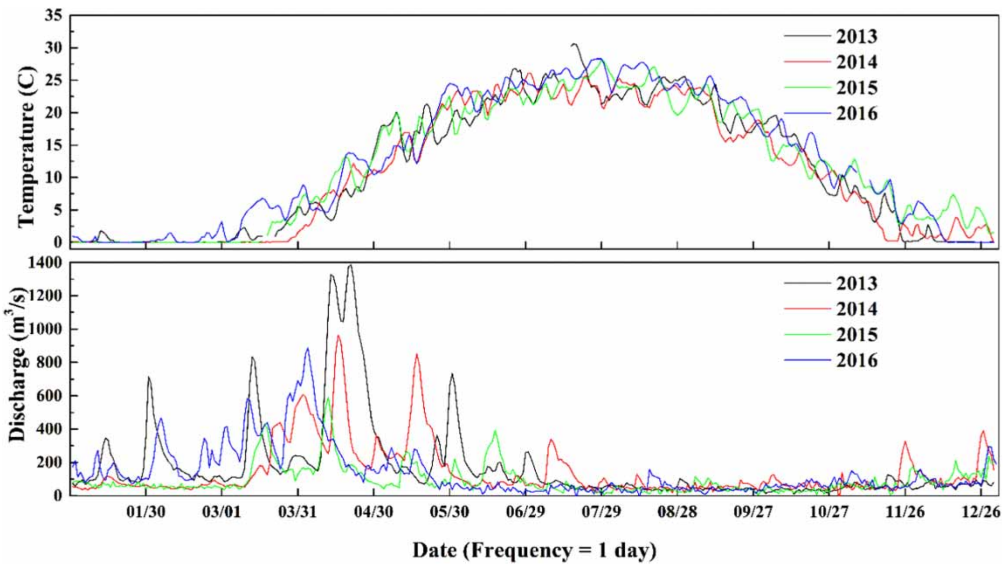

Figure 4 | Daily changes of temperature (°C) and discharge (m^3/s) in Saginaw River from 2013 to 2016.

particularly reached the highest concentration ($3.23 \pm 0.35\ m^{-1}$) in May and was relatively lower during July to September, with the lowest concentration ($1.27 \pm 0.29\ m^{-1}$) in August. Monthly mean $a_{CDOM}(440)$ negatively correlated with monthly average temperature with $r = -0.618$ ($p < 0.1$) and positively correlated with monthly average discharge with $r = 0.774$ ($p < 0.05$). Overall, temperature and discharge both play the important environmental factors to influence monthly CDOM concentrations in the Saginaw River, and hence CDOM is subject to significant variations during the seasons with different temperatures and discharges.

Landsat-8 data have the capability to monitor spatial and temporal CDOM variations for future applications, and we can use Landsat imagery to study CDOM distributions and dynamics for other rivers and lakes by using remote sensing in large scale.

ACKNOWLEDGEMENTS

This research was supported by the National Natural Science Foundation of China (No. 41471346), the Natural Science Foundation of Zhejiang Province (No. LY17D010005), an internal grant from Central Michigan University, and two collaborative grants from the National Science Foundation of USA (Grant Nos 1025547 and 1230261).

REFERENCES

Alcântara, E., Bernardo, N., Watanabe, F., Rodrigues, T., Rotta, L., Carmo, A., Shimabukuro, M., Gonçalves, S. & Imai, N. 2016 Estimating the CDOM absorption coefficient in tropical inland waters using OLI/Landsat-8 images. *Remote Sensing Letters* **7** (7), 661–670.

Brezonik, P. L., Olmanson, L. G., Finlay, J. C. & Bauer, M. E. 2015 Factors affecting the measurement of CDOM by remote sensing of optically complex inland waters. *Remote Sensing of Environment* **157**, 199–215.

Chen, J., Zhu, W.-N., Tian, Y. Q. & Yu, Q. 2017 Estimation of colored dissolved organic matter from Landsat-8 imagery for complex inland water: case study of Lake Huron. *IEEE Transactions on Geoscience and Remote Sensing* **55** (4), 2201–2212.

Coble, P. G. 1996 Characterization of marine and terrestrial DOM in seawater using excitation-emission matrix spectroscopy. *Marine Chemistry* **51** (4), 325–346.

Coble, P. G. 2007 Marine optical biogeochemistry: the chemistry of ocean color. *Chemical Reviews* **107** (2), 402–418.

Griffin, C. G., Frey, K. E., Rogan, J. & Holmes, R. M. 2011 Spatial and interannual variability of dissolved organic matter in the Kolyma River, East Siberia, observed using satellite imagery. *Journal of Geophysical Research* **116** (G3), G03018-1–G03018-12.

Hoard, C., Holtschlag, D., Duris, J., James, D. & Obenauer, D. 2012 *Comparison of Streamflow and Water-Quality Data Collection Techniques for the Saginaw River, Michigan*, Report 2328-0328, US Geological Survey.

Li, Y., Zhang, Y., Shi, K., Zhu, G., Zhou, Y., Zhang, Y. & Guo, Y. 2017 Monitoring spatiotemporal variations in nutrients in a large drinking water reservoir and their relationships with hydrological and meteorological conditions based on Landsat 8 imagery. *Science of the Total Environment* **599–600**, 1705–1717.

Mannino, A., Russ, M. E. & Hooker, S. B. 2008 Algorithm development and validation for satellite-derived distributions of DOC and CDOM in the US Middle Atlantic Bight. *Journal of Geophysical Research: Oceans* **113** (C7), C07051-1–C07051-19.

Masocha, M., Dube, T., Nhiwatiwa, T. & Choruma, D. 2017 Testing utility of Landsat 8 for remote assessment of water quality in two subtropical African reservoirs with contrasting trophic states. *Geocarto International* 1–14.

Slonecker, E. T., Jones, D. K. & Pellerin, B. A. 2016 The new Landsat 8 potential for remote sensing of colored dissolved organic matter (CDOM). *Marine Pollution Bulletin* **107**, 518–527.

Tebbs, E. J., Remedios, J. J. & Harper, D. M. 2013 Remote sensing of chlorophyll-*a* as a measure of cyanobacterial biomass in Lake Bogoria, a hypertrophic, saline–alkaline, flamingo lake, using Landsat ETM +. *Remote Sensing of Environment* **135**, 92–106.

Wu, G., Cui, L., Liu, L., Chen, F., Fei, T. & Liu, Y. 2015 Statistical model development and estimation of suspended particulate matter concentrations with Landsat 8 OLI images of Dongting Lake, China. *International Journal of Remote Sensing* **36** (1), 343–360.

Zheng, Z., Ren, J., Li, Y., Huang, C., Liu, G., Du, C. & Lyu, H. 2016 Remote sensing of diffuse attenuation coefficient patterns from Landsat 8 OLI imagery of turbid inland waters: a case study of Dongting Lake. *Science of the Total Environment* **573**, 39–54.

Zhu, W., Tian, Y. Q., Yu, Q. & Becker, B. L. 2013 Using Hyperion imagery to monitor the spatial and temporal distribution of colored dissolved organic matter in estuarine and coastal regions. *Remote Sensing of Environment* **134**, 342–354.

Zhu, W., Yu, Q., Tian, Y. Q., Becker, B. L., Zheng, T. & Carrick, H. J. 2014 An assessment of remote sensing algorithms for colored dissolved organic matter in complex freshwater environments. *Remote Sensing of Environment* **140**, 766–778.

First received 10 October 2017; accepted in revised form 3 April 2018. Available online 13 April 2018