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Original Articles

Satellite monitoring of cyanobacterial harmful algal bloom frequency in recreational waters and drinking water sources

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ABSTRACT

Cyanobacterial harmful algal blooms (cyanoHAB) cause extensive problems in lakes worldwide, including human and ecological health risks, anoxia and fish kills, and taste and odor problems. CyanoHABs are a particular concern in both recreational waters and drinking water sources because of their dense biomass and the risk of exposure to toxins. Successful cyanoHAB assessment using satellites may provide an indicator for human and ecological health protection. In this study, methods were developed to assess the utility of satellite technology for detecting cyanoHAB frequency of occurrence at locations of potential management interest. The European Space Agency's MEdium Resolution Imaging Spectrometer (MERIS) was evaluated to prepare for the equivalent series of Sentinel-3 Ocean and Land Colour Imagers (OLCI) launched in 2016 as part of the Copernicus program. Based on the 2012 National Lakes Assessment site evaluation guidelines and National Hydrography Dataset, the continental United States contains 275,897 lakes and reservoirs > 1 ha in area. Results from this study show that 5.6% of waterbodies were resolvable by satellites with 300 m single-pixel resolution and 0.7% of waterbodies were resolvable when a three by three pixel (3 × 3-pixel) array was applied based on minimum Euclidian distance from shore. Satellite data were spatially joined to U.S. public water surface intake (PWSI) locations, where single-pixel resolution resolved 57% of the PWSI locations and a 3 × 3-pixel array resolved 33% of the PWSI locations. Recreational and drinking water sources in Florida and Ohio were ranked from 2008 through 2011 by cyanoHAB frequency above the World Health Organization's (WHO) high threshold for risk of 100,000 cells mL^{-1}. The ranking identified waterbodies with values above the WHO high threshold, where Lake Apopka, FL (99.1%) and Grand Lake St. Marys, OH (83%) had the highest observed bloom frequencies per region. The method presented here may indicate locations with high exposure to cyanoHABs and therefore can be used to assist in prioritizing management resources and actions for recreational and drinking water sources.

1. Introduction

Harmful algal blooms are environmental events that occur when algal populations achieve sufficiently high density resulting in negative environmental or health consequences (Smayda, 1997). Blooms associated with photosynthetic prokaryotes (cyanobacterial harmful algal blooms [cyanoHAB]) occur worldwide and have been documented across the United States (Loftin et al., 2016). Toxic blooms are a global issue and examples exist on every continent such as the Baltic Sea in Europe (Kahru et al., 2007), Lake Victoria in Africa (Verschuren et al., 2002), Lake Taihu in Asia (Duan et al., 2009), Lake Erie in North America (Stumpf et al., 2012), Murray River in Australia (Al-Tebrineh et al., 2012), several reservoirs in South America (Dörra et al., 2010), and even Antarctica (Hitzfeld et al., 2000). Harke et al. (2016) reported documented events of the freshwater *Microcystis* species in 108 out of 257 countries and territories. Many U.S. states have issued health advisories or closed recreational areas due to potential risks from cyanoHAB exposure (Chorus, 2012; Graham et al., 2009). CyanoHABs typically result from a combination of excess nutrients (Michalak et al., 2013) and other environmental conditions, such as warming tempera-

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tures and water column stratification (Paerl and Huisman, 2008). Alterations in land-use practices, such as urbanization or agricultural practices, can change sediment loading and increase nutrient delivery in watersheds (Lunetta et al., 2010), which is known to influence cyanobacterial growth. CyanoHABs can produce an array of potential toxins and cause nuisance odors, hypoxia, and unappealing surface scums creating a potential for adverse recreational exposure and ecological impact (Codd et al., 2005a). Additional consequences of cyanoHABs may include undesirable finished drinking water, increased drinking water treatment costs, and economic and infrastructure costs such as loss of revenue from recreational systems and from businesses that rely on potable water (Dodds et al., 2009; Steffensen, 2008).

Water quality is a critical consideration in determining water resource availability for human consumption, aquatic life, and recreation (U.S. EPA, 2013b). Despite sufficient water quantity, water availability may be limited if quality does not meet the requirements of intended use. CyanoHAB toxins frequently limit water resource availability by negatively impacting water quality and rendering it unsuitable for multiple uses. Potential short- and long-term human health effects of cyanoHABs and the toxins they produce include dermatitis; gastrointestinal, respiratory, and neurological impairments; and adverse impacts to liver and kidney function. These effects may reduce the availability of drinking water resources and increase treatment costs (Hilborn et al., 2014). CyanoHABs and associated toxins have been identified in drinking water sources throughout the world (Hoeger et al., 2005). Documented events include impaired drinking water resources at Haimen city, Fusui county, China, in 1993 and 1994 (Ueno et al., 1996); Wuxi city, Jiangsu, China in May 2007 (Qin et al., 2010); Caruaru, Brazil, in 1996; and Australia in 1983 (Falconer and Humpage, 2005). Depending on the severity of a cyanoHAB event, municipalities may issue "Do Not Drink" advisories, as they did in Carroll Township, Ohio, in September 2013 (Henry, 2013) and in Toledo, Ohio, in August 2014 (Sonich-Mullin, 2014).

An additional route of cyanoHAB toxin exposure is through recreational contact, including dermal and oral contact, with occasional exposure through inhalation of surface waters (Backer et al., 2015; Backer et al., 2010; Codd et al., 2005b). Adverse human health impacts from recreational exposure to cyanoHABs include, but are not limited to, headaches and allergic reactions, including blistering, vomiting, and diarrhea (Falconer, 1999; Stewart et al., 2006b). CyanoHABs also pose risks to non-human populations. Negative impacts include canine illness and death, where the number of reported events and animals affected has increased over the past 50 years (Backer et al., 2013). Wildlife and livestock illness and death have been globally reported in animals ranging from traditional farm stock to fish, birds, and insects (Backer et al., 2015; Hilborn and Beasley, 2015). In birds, cyanobacterial toxins can cause neurological disease leading to brain lesions and death. The documented deaths of over 170 bald eagles, thousands of American coots, the federally endangered Florida snail kite, and other species of wild birds have been caused by cyanoHAB events (Dodd et al., 2016).

Cell counts and microcystin concentrations are most commonly used to evaluate potential human health risk, and many states have customized thresholds based on additional information gathered locally (Graham et al., 2009). The World Health Organization (WHO) has a three-level guideline approach, which describes concentrations of the ubiquitous photosynthetic pigment chlorophyll-a and cyanobacterial cell abundance (cells/mL) to determine the level of associated risk to support a warning or closure. WHO provides estimates of microcystin that could correspond to the cell abundance at each guideline level. The U.S. Environmental Protection Agency (U.S. EPA) also has the drinking water health advisory for cyanobacteria microcystins toxin (U.S. EPA, 2015a).

Many U.S. states have experienced challenges in developing monitoring programs for cyanoHABs because of the need to cover large geographic areas with insufficient resources. The presence of cyanotoxins is a primary indicator of human health risk, but quantifying all forms and derivatives of the related toxins is difficult, expensive, and time-intensive. There are approximately 246 variants of microcystin-LR, 3 variants of cylindrospermopsin, and 7 variants of anatoxins (Loftin et al., 2016; Meriluoto et al., 2017; U.S. EPA, 2014). Loftin et al. (2016) highlights that WHO thresholds agreed in only 27% of cases between all three recreational risk metrics (cyanobacteria abundance, chlorophyll-*a*, and microcystins) when applied against the 2007 National Lakes Data (2007 NLA), clearly demonstrating that the presence of chlorophyll-*a* does not always equate to cyanoHABs and that cyanobacterial abundance can result in over-prediction of microcystin recreational risk. However, microcystin may not be a good predictor of other classes of toxins also produced by cyanoHABs with co-occurrence between cylindrospermopsins, microcystins, and saxitoxins only 0.32% of 2007 NLA samples. Epidemiological studies have reported statistically significant associations between inflammatory and allergenic human health exposure to water containing cyanoHAB cells (Lévesque et al., 2016; Lévesque et al., 2014; Lin et al., 2016; Pilotto et al., 1997). Some adverse health endpoints may not be associated with exposure to known toxins (Stewart et al., 2006a; Stewart et al., 2006b). Thus cyanobacterial abundance is perhaps better suited for assessing nationwide risks depending on the balance between public health and socioeconomics. In consideration of these challenges and uncertainties, new tools and methods are needed to help develop reliable and cost-effective monitoring programs at lake, watershed, state, regional, and national scales with sufficient spatial-temporal resolution to detect change where field monitoring alone may not provide sufficient coverage.

This study explores the possibility of using satellite remote sensing technology to assess cyanoHAB abundance for spatially resolvable inland recreational and public water supply lakes, reservoirs, and ponds using algal pigments as surrogates for HAB and cyanoHAB abundance related human health risk thresholds. The presence of cyanoHAB abundance estimated from satellites can be used to prioritize waterbodies requiring further evaluation for cyanotoxins. Although satellite observations cannot detect toxins (Stumpf et al., 2016), they can be used to quantify cyanoHAB abundance (Kutser, 2009). Previous studies provide a comprehensive review of past, present, and new satellite sensors available for deriving water quality in estuaries and inland waters (Dörnhöfer and Oppelt, 2016; Tyler et al., 2016). The advantages and disadvantages of sensor spatial, spectral, temporal resolution, and other parameters are also discussed in other studies (Mouw et al., 2015), along with recent progress updates (Palmer et al., 2015).

The use of satellites for management involves spatial coverage of both recreational and drinking water lakes and reservoirs. Satellite remote sensing has reportedly detected cyanoHAB abundance in drinking water sources, and most efforts to date have focused primarily on algorithm development, validation, and refinement (Medina-Cobo et al., 2014; Song et al., 2013; Song et al., 2014). Satellites can provide a synoptic survey, but their scope of application is poorly defined. Water quality managers need to understand the number of lakes and reservoirs resolvable by satellite. Once the scope of application is defined, it may be possible to use satellite technology to support management needs such as providing occurrence information relevant to the national Safe Drinking Water Act (SDWA) Contaminant Candidate List (CCL) (U.S. EPA, 2013a, 2016a) and the Unregulated Contaminant Monitoring Rule (UCMR) (U.S. EPA, 2016b). The SDWA's CCL includes drinking water contaminants (such as cyanotoxins) known or anticipated to occur in public water systems not currently subject to regulations. The UCMR includes contaminants suspected to be present in drinking water that do not yet have set standards under the SDWA. Selection of contaminants for the UCMR is largely based on the CCL.

The objectives of this study are to (1) determine the number of surface water bodies on the basis of permissible use as recreational and drinking water sources viewable with existing pixel resolutions (defined as the minimum spatial detection area) measured by satellites licensed