Integrating *in-situ* field measurements and satellite remote sensing to monitor harmful algae blooms in Oklahoma lakes

[Research]

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Abstract

Lake and reservoir water quality is important to fisheries, wildlife, and humans. Excessive nutrient inputs into freshwater lakes and reservoirs have led to increased frequency and magnitude of harmful algal blooms (HABs), particularly toxic cyanobacteria (blue-green algae). Blooms of cyanobacteria can produce a variety of harmful toxins (hepatotoxins, neurotoxins, or dermatoxins) that may be harmful or lethal to animals and humans. Active monitoring and prediction of water quality and harmful algal blooms is a critical component of public water supply management, the maintenance of touristic value, and the protection of animal and human health associated with publicly accessible lake and reservoir ecosystems. During the summer 2012, the Plankton Ecology and Limnology Laboratory (PEL Lab; led by Dr. Hambright) and the Earth Observation and Modeling Facility (EOMF, http://www.eomf.ou.edu; led by Dr. Xiao) at the University of Oklahoma have worked together and carried out a pilot study that explored the potential of integrating *in-situ* water measurements and satellite remote sensing for cost-effective monitoring of water quality and HABs.

I. The history and current situation of harmful algal blooms in Oklahoma

According to the Oklahoma Water Atlas, Oklahoma has 146 major water reservoirs that were impounded between 1902 and 1997 by the US Army Corps of Engineers (USACE), the Bureau of Reclamation, the Grand River Dam Authority (GRDA), Natural Resources Conservation Service, and various municipalities, private corporations, and others. Most reservoirs serve multiple purposes including flood control, municipal, industrial, and agricultural water supply, power generation, navigation, hydroelectric power production, and conservation, and most reservoirs support fish and wildlife habitat and recreation as ancillary benefits. All reservoirs play a significant role in the economic and social wellbeing of the state, providing rich fisheries, abundant recreational activities, and a general, high-value aesthetic quality to the state. Many large lakes, such as Texoma, Eufaula, and Grand Lakes also serve as critical economic engines for communities around those lakes.

Since 1998, the Oklahoma Water Resources Board has been monitoring water quality of 130 of these reservoirs through the Beneficial Use Monitoring Program (BUMP) (Oklahoma Water Resources Board 2010). Generally, this program includes rotational sampling of 30-40 reservoirs each year on a quarterly basis, with all reservoirs included at least once ~every four years; some systems are monitored more frequently. The stated goal of BUMP is "to detect and quantify water quality trends, document and quantify impairments of assigned beneficial uses, and identify pollution problems before they become a pollution crisis." (p. 9, Oklahoma Water Resources Board 2010). Sample collection and analyses used in BUMP are based on standard limnological protocols and have provided good, though relatively limited, insight into developing trends in water quality across the state.

Most reservoirs in Oklahoma are very productive, classified as either eutrophic or hypereutrophic (aka hypertrophic). Such high productivity is not surprising given the large watershed area to lake surface area ratios that are typical for reservoirs, leading to a strong influence of the watershed on nutrient loading (Thornton et al. 1990). As such, a large proportion of Oklahoma's lakes have been designated as "not fully supporting" one or more of the beneficial uses (defined as fish and wildlife propagation, agriculture, aesthetics, and primary body contact recreation). Nevertheless, general water quality in the state's reservoirs had not been a primary issue of concern for the general public until the extremely warm and dry summer of 2011.

During summer 2011, many of Oklahoma's lakes experienced what many other lakes around the globe have been experiencing in recent years—harmful algal blooms (HABs). Cyanobacteria, also known as blue-green algae, have been common in many of Oklahoma's reservoirs for the past decade, and while they represent an unsightly nuisance during late summer blooms, they have not been a serious and widespread deterrent to those wishing to enjoy the abundant recreational opportunities afforded by our state's lakes. Nor have such blooms caused great concern for municipal water supplies. Unfortunately, as seen in 2011, continued hypertrophy and increased temperature in the near future will likely bring more frequent and more severe blooms of these harmful algae.

To compound the problem, many HAB species are also toxigenic, producing a variety of chemical compounds that are believed to function evolutionarily as grazing deterrents or allelochemicals against competitors, but for humans and wildlife are very potent neurotoxins, hepatotoxins, and dermatotoxins.

II. An *in-situ* harmful algal bloom monitoring system in Oklahoma lakes

Under the support of the Oklahoma Office of the Secretary of Environment, a group of experts and end users from several state agencies and municipalities in Oklahoma developed and relased the Protocols for Harmful Algae Bloom Monitoring in Oklahoma Lakes in April 2012 (Smithee et al. 2012). The authors briefly reviewed the current status of HAB monitoring activities in Oklahoma lakes. At present, Oklahoma does not have a sufficient monitoring program in place for protecting the health of the public visiting, swimming, boating, and fishing in the state's many large lakes. The authors also outlined a comprehensive *in-situ* HAB monitoring system in Oklahoma lakes consisting the following components: (1) visual assessment, (2) water sampling, and (3) laboratory analysis. In addition, the authors of the report examined the financial and logistical constraints of a statewide *in-situ* HAB monitoring protocol. The authors estimated that approximately $3.5 – $4.5 million per year would be required in order to monitor the largest 100 lakes only once a month each year. More frequent and broader spatial coverage, which is needed to provide the necessary coverage of Oklahoma's lakes sufficient for safeguarding public health, would require twice or more of this amount of funding.

More importantly, experience gained from other states faced with similar HAB problems indicates that even the most basic (= insufficient) statewide monitoring program for HABs is not economically sustainable (K. Loftin, USGS, Lawrence, KS, pers. comm.). With little effort and monies being directed to mitigation of nutrient pollution from agriculture, urban areas, and industry, the issues of HABs are forecasted to worsen with time. Increased temperature, as part of climate change, could also have additional impacts of HABs. As such, Oklahoma is in dire need of a solution for dealing with the threat of HABs – one that is low in cost, sustainable, and offers near or real-time risk management and public protection.

The Protocol document (Smithee et al., 2012) provides several recommendations on how to reduce the cost of an HAB monitoring system, including targeted water samples and laboratory analyses in those lakes that have received public complaints or show initial signs of HABs from visual observations. Here, we highlight two complementary approaches that could potentially reduce the cost of an HAB monitoring system and broaden both the spatial and temporal coverage of an HAB monitoring system. Thefirst approach is based on development of a web-based tool and system that would engage and empower the community and citizens for their participation in visual assessment of HABs (see Section III). The second approach is based on integration of remote sensing with *in-situ* observations that would allow for enhanced tracking and prediction of the dynamics of water quality and HABs (see Section IV and V). Development and implementation of these tools would substantially strengthen risk management and communication among researchers, stakeholders and the public.

III. Geo-referenced field photos of water body for assessment of harmful algal blooms in Oklahoma Lakes

III.1. Geo-referenced field photos of lakes using GPS cameras and smartphones

We envisage a system whereby professionals, and ordinary citizens alike, could contribute to a statewide water quality monitoring program simply by taking GPS-stamped digital photographs of the water's surface anytime they are out on a lake and then uploading those photographs into a web-accessible library in which water quality is assessed using various models relating water quality to water color (i.e., reflectance of solar radiation).

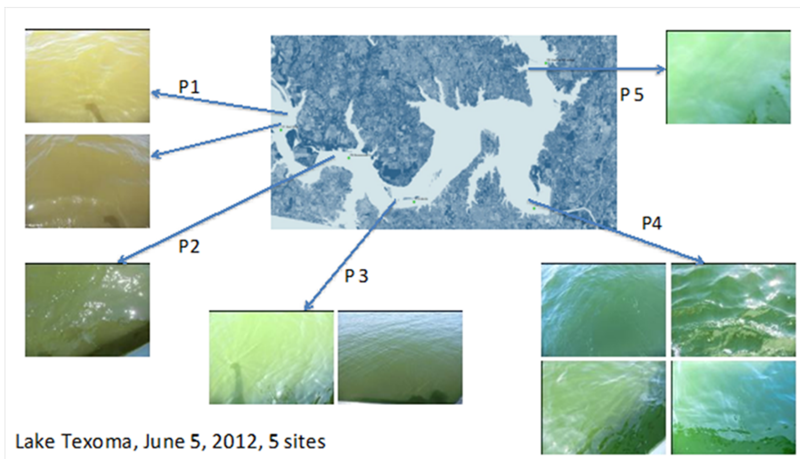

Figure 1. A sample of geo-referenced field photos at five sites in Lake Texoma, June 5, 2012.

III.2. Geo-referenced field photos for visual assessment of harmful algal blooms

Basically, anyone can make simple visual observations of a water body, and provide qualitative assessments of water quality. For example, one could note observations such as a visible green sheen to the water or the presence of a surface scum. We suggest here that such observations could be greatly enhanced if they were accompanied by photographs of the water and surrounding landscapes and a few written comments describing the conditions pertaining to the observations being made.

III.3. Geo-referenced field photos for quantitative asssessment of harmful algal blooms

As a pilot study we used the Casio EX-H20G Hybrid-GPS camera to take field photos of the water's surface in Lake Texoma at the same time water samples were collected and hyperspectral reflectance was measured with an ASD FieldSpec@3 spectroradiometer (Fig. 1). Our hypothesis was that these geo-referenced field photos could be used not only for qualitative assessment of water quality, but for quantitative assessment of water quality. Specifically, we

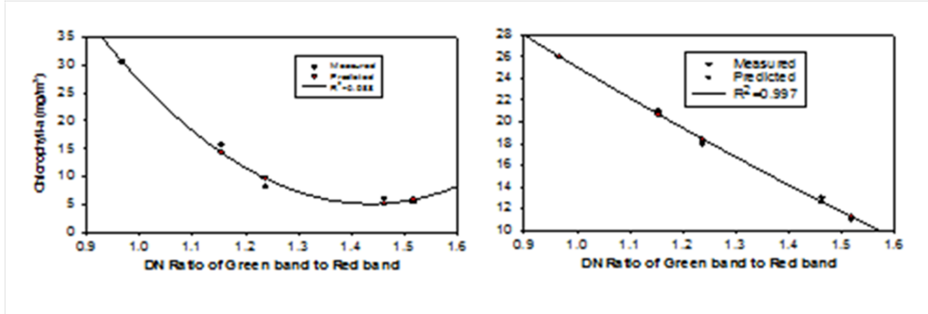

Figure 2. The quantitative relationship between DN ratio of green/red bands from the Casio digital camera and the concentration of chlorophyll-a and phycocyanin pigments at the five sites in Lake Texomas, on July 5, 2012.

hypothesized that these photos could be used to make quantitative estimates of chlorophyll and phycocyanin concentrations, two algal pigments commonly used to assess algal and cyanobacterial abundances, in the water.

We processed the digital photos using the ENVI software. We first calculated the ratio of the green band to the red band for individual photos at each sampling site, and then calculated the means and standard deviations of the ratios for all images within a site. This DN ratio of green/red bands in the *in-situ* digital photos were then related to actual water quality data. Figure 2 shows that there are strong correlations between the DN ratios and the concentrations of chlorophyll-a and phycocyanin pigments in upper mixed surface waters (0 – 1 m depth) at these five sites, and the quadratic polynomial regression models ($y = ax^2 + bx + c$) gave a high degree fit between measured and predicted concentrations of chlorophyll-a and phycocyanin pigments.

III.4. The Global Geo-Referenced Field Photo Library (http://www.eomf.ou.edu/photos/)

The Earth Observation and Modeling Facility (EOMF) at the University of Oklahoma has developed the Global Geo-Referenced Field Photo Library, which is a citizen-science tool for people to share, visualize, and archive geo-referenced field photos around the globe (Xiao et al. 2011). Figure 3 shows an example of geo-referenced field photos available for Lake Texoma, which were collected during a field trip on June 5, 2012. These field photos can be used for

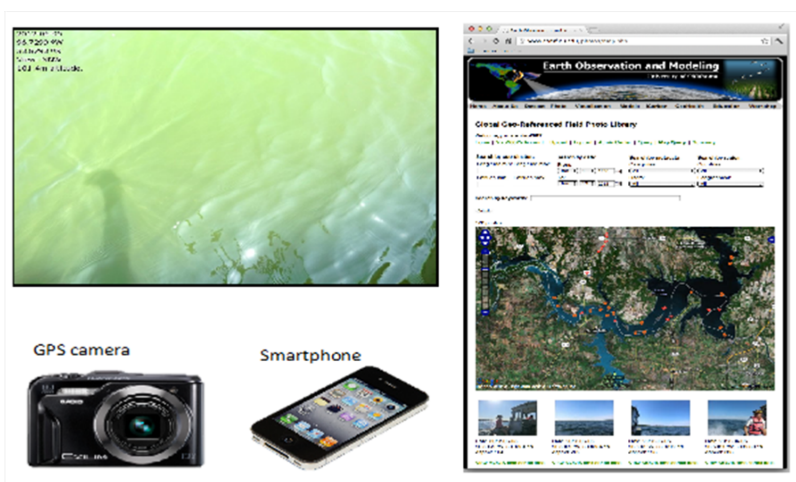

Figure 3. An introduction on the Global Geo-Referenced Field Photo Library. (a) a geo-referenced field photo, and (b) GPS camera and smartphone, and (c) a screenshot of the Field Photo Library at the EOMF website (http://www.eomf.ou.edu/photos).

qualitative assessment of water quality by water professionals and educated citizens; and they can also be used for quantitative assessment of water quality by remote sensing professionals. The field photos in the Field Photo Library are linked with satellite images (e.g., time series MODIS data

from 2000 to present). Users can upload, edit, query, and download field photos in the library, and use the thematic databases associated with the field photos for various geospatial analyses.
III.5. A web-based tool for visual assessment of freshwater harmful algal blooms

A web-based tool that empowers people to share, visualize, archive and analyze geo-referenced field photos of Oklahoma lakes is needed to engage broader participation of the communities and citizens for visual assessment of freshwater HABs. This web-based tool could be comprised of (1) a standard protocol for taking geo-referenced field photos, (2) a standard questionnaire and entry for field notes, (3) a web site and an application for smartphones and iPads (and similar mobile devices) to support interactive data exchange between field investigators and the web data portal, including data uploading and visualization, (4) a customized geo-referenced field photo library, or an enterprise version of our Geo-Referenced Field Photo Library, and (5) web-based query, reporting and distribution for the public and decision makers. In a cost-effective perspective, we could start with the above-mentioned Field Photo Library at OU and customize and expand it to meet the requirements of HABs monitoring in Oklahoma lakes.

IV. *in-situ* optical remote sensing of harmful algal blooms in Oklahoma lakes

The Plankton Ecology and Limnology Laboratory (PEL Lab) at the University of Oklahoma has monitored water quality in Lake Texoma since the 2004 outbreak and blooms of the harmful alga, *Prymnesium parvum* (Hambright et al. 2010, Zamor et al. 2012). The PEL Lab added sampling for blue-green algae beginning in 2009, and provided bluegreen algae cell counts and cyanotoxin analysis to the US Army Corps of Engineers (USACE) during much of the 2011 bluegreen bloom period in which many areas of Lake Texoma were placed under advisories and warnings due to the risk of exposure to bluegreen algal toxins.

We carried out a pilot study on June 5, 2012 at these five sites in Lake Texoma to explore the potential of *in-situ* hyperspectral remote sensing for estimating chlorophyll-a and phycocyanin concentrations of water body. Water samples at the five sites were taken from different depths at 1-m intervals (0, 1, 2, …). Field measurements using *in-situ* sondes and laboratory analyses of water samples provided estimates of chlorophyll-a and phycocyanin concentrations. We also measured *in-situ* lake surface reflectance at the five sites, using an ASD FieldSpec@3 spectroradiometer.

We investigated the relationship between ASD-based reflectance data and chlorophyll-a and phycocyanin concentrations at different depths of water. Figure 4 shows that there are significant correlations between lake surface reflectance and chlorophyll-a and phycocyanin concentrations in upper mixed surface waters (0 – 1 m depth) at these five sites.

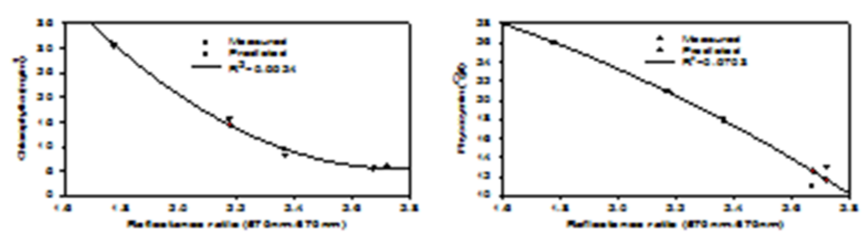

Figure 4. The quantitative relationship between water surface reflectance and the concentrations of chlorophyll-a and phycocyanin pigments at the five sites in Lake Texoma, June 5, 2012.

V. Satellite-based remote sensing of harmful algal blooms in Oklahoma lakes

V.1. Multi-spectral sensors and algorithms

Landsat TM/ETM+ sensors have seven spectral bands and acquire images at a 30-m spatial resolution and a 16-day revisit cycle. As shown in Fig. 3, green and red bands in the Landsat sensors are useful for characterization of water quality with respect to HABs. Landsat images from 1970s to present are freely available to the public, and make it possible to track changes in water quality over the past several decades.

The RapidEye System (www.rapideye.com) is a constellation of five Earth Observation satellites. Each satellite collects multi-spectral imagery (blue, green, red, red edge and near infrared) at 5-m pixel resolution. This five-satellite constellation could acquire an image of any point on the Earth daily at a low viewing angle (<20 degree). Since its commercial operations began in February 2009, a large number of images have already been acquired for Oklahoma. The green, red and red edge bands in the RapidEye sensors should be useful for characterization of water quality. In comparison to Landsat imagery, the higher temporal frequency (1-2 day revisit time), finer spatial resolution (5 m) and additional red edge band may offer an improved capacity (relaive to Landsat) for monitoring water quality and HABs in lakes and reservoirs.

V.2. Hyperspectral sensors and algorithms

The NASA HyspIRI (hyperspectral Infrared Imager) mission includes an imaging spectrometer that measures reflectance from the visible to shortwave infrared (VSWIR:380 nm – 2500 nm) in 10 nm continguous bands. It will acquire images for the globe at 60-m spatial resolution and 19-day revisit temporal resolution. It will be launched in several years from now and will provide an important source of images for quantifying and monitoring the concentrations of chlorophyll-a and phycocyanin pigments in Oklahoma lakes.

V.3. A pilot study that uses Landsat imagery in Lake Texoma

We recently carried out a pilot study to develop the quantitative relationship between Landsat 5 TM imagery and pigment (chlorophyll-a and phycocyanin) concentrations in Lake Texoma. We downloaded the Landsat 5 TM images acquired on May 24, 2006 (summer season), January 10, 2010 and December 13, 2010 (winter season), corresponding to the dates water samples were taken in Lake Texoma. The digital number (DN) values of the Landsat 5 TM image from those 30-m pixels covering the five water sample sites were extracted and converted to the top-of-the-atmosphere radiance. Atmospheric correction of those pixels was also conducted using the 6S radiative transfer model (http://6s.ltdri.org) (Kotchenova et al. 2006, Kotchenova and Vermote 2007), which generated water surface reflectance data at these five sites.

We evaluated the relationship between water surface reflectance values and the concentrations of chlorophyll-a and phycocyanin pigments at the five water sample sites. For the Landsat TM image in summer (May 22, 2006), there is a very high correlation coefficient

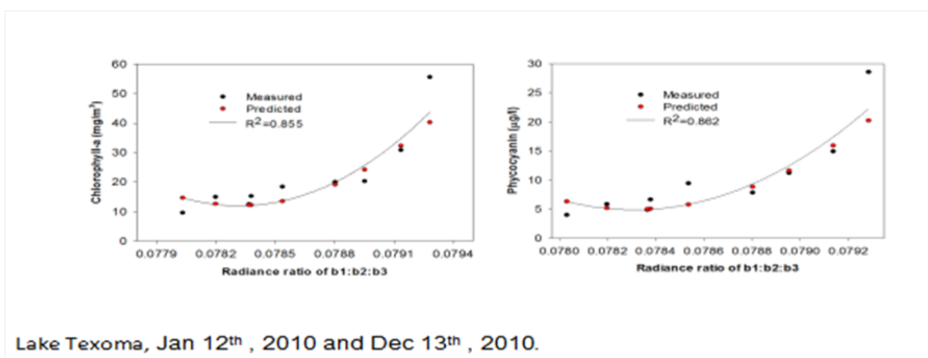

Figure 5. The quantitative relationship between radiance ratio of blue/green/red bands from Landsat 5 TM image (January 12, 2010, December 13, 2010) and chlorophyll-a and phycocyanin concentrations at the five sites in Lake Texoma.

between water quality indicators (chlorophyll-a concentrations) at the mixed 0-10m zone and the

radiance ratio of green/red bands from the Landsat image at these five water sample sites (Fig. 5). For the Landsat TM images in winter (Janurary 12, 2010, December 13, 2010), there are also high correlation coefficients between water quality indicators (chlorophyll-a and phycocyanin concentrations) and the radiance ratio of green/red bands from the Landat images (Figure 8). It clearly demonstrates the potential of using Landsat TM images to estimate the concentrations of chlorophyll-a and phycocyanin pigments in the open-water (pelagic) areas of Lake Texoma.

VI. Summary

The large-scale harmful algal blooms in summer 2011 in Oklahoma has drawn substantial attention from the public, and a great deal of effort was carried out by various state agencies to address the HAB events. A large number of water samples and laboratory analyses were carried out by the Oklahoma Department of Environmental Quality, the US Army Corps of Enginers, and the Oklahoma Water Resources Board (OWRB), and the OU Plankton Ecology and Limnology Lab. The development of the Protocols for Harmful Algae Bloom Monitoring in Oklahoma Lakes (Smithee et al., 2012) represents a significant step in the community for addressing the HABs in Oklahoma lakes.

Acknolwedgements

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