U.S. Army Corps of Engineers
Remote Sensing Software Tools to Assist with Inland Water Quality Monitoring and the Detection of Cyanobacterial Harmful Algal Blooms

The U.S. Army Corps of Engineers (USACE) is challenged by the need to monitor hundreds of lakes and reservoirs that cover vast geographic areas and is further hindered by limited resources, often leading to reactionary responses to Harmful Algal Bloom (HAB) outbreaks. Recent innovations in remote sensing technology, such as readily available high resolution satellite imagery, offer advantages to help shift towards a more proactive stance in HAB response and management. The primary strength of remote sensing includes the ability to provide a synoptic view of water quality conditions for more effective, near-real time monitoring of spatial and temporal variation across an entire waterbody or multiple waterbodies over a large region at one time. Though remote sensing cannot assess toxicity directly, it can help reduce costs and labor by minimizing and prioritizing the location and timing of field samples and serve as an early warning system for potential HAB outbreaks.

The USACE has been conducting research and development to better understand and help advance the role of remote sensing in inland water quality monitoring for over a decade. Initial efforts included a review of the state-of-the-science (Reif 2011) and fundamental research with partners from the University of Cincinnati, the U.S. EPA Office of Research and Development, the ERDC Environmental Laboratory, the USACE Great Lakes & Ohio River Division, the USACE Louisville and Huntington Districts, the Joint Airborne Lidar Bathymetry Technical Center of Expertise, and the Kentucky Division of Water. Pilot experiments were conducted to evaluate existing and new remote sensing methods for the detection and estimation of three water quality indicators of HABs: 1) chlorophyll-*a* (Beck et al., 2016), 2) phycocyanin, a proxy for cyanobacterial or blue-green algal biomass (Beck et al., 2017), and 3) turbidity (Beck et al., 2019). This work included a comprehensive review of available satellite sensors (including those appropriate for small, inland waterbodies) and numerous established and new algorithms (focusing on simple or ratio-based indices that can be easily transferred) to characterize water quality parameters. The work by Beck et al. (2016, 2017, and 2019) produced a vetted array of algorithms that were statistically analyzed and compared to a comprehensive suite of in-situ measurements and water samples in lakes in Ohio and Kentucky. Furthermore, the initial research set the stage for on-going follow-up studies:

- Evaluating the portability of algorithms to other inland waterbodies (Johansen et al., 2018),
- Adapting the findings in concert with low-cost drone technology to assess CubeSat satellite technology for HAB detection (miniaturized satellites that are more affordable and faster to develop than larger counterparts [Beck et al., 2018; Johansen et al., 2019a]),
- Developing sophisticated ensemble and regional approaches to maximize algorithm accuracy (Xu et al., 2019a; Xu et al., 2019b; Xu et al., 2021), and
- Integrating multi-sensor methods with Google Earth Engine for large, regional scale water quality mapping (Wang et al., 2020).

Ultimately, the body of research has helped address and overcome a variety of technical barriers for incorporating remote sensing technology into USACE water quality management and monitoring as follows:

- ✓ Remote sensing approaches to HAB monitoring have been limited by the number of satellites appropriate for estimating water quality parameters due to limitations with revisit frequency, spatial resolution, and most importantly, spectral resolution, since specific spectral bands are needed to characterize select water quality parameters.
- ✓ Most remote sensing and algorithm investigations to detect HAB indicators represent a locally specific "one-off" that cannot be transferred to other waterbodies.
- ✓ While select satellite sensors are specific for water quality monitoring, they typically have coarse spatial resolution, making them unsuitable for small, inland lakes and reservoirs, which comprises most water quality monitoring needs for the USACE.
- ✓ Although research and methods are working to keep pace with new sensor technology, they are often not well translated into usable tools. Thus, important findings that could benefit USACE are not currently user-friendly for field staff.

Once foundational research was established, the focus shifted to the development of satellite image-based software tools for estimating the three primary water quality indicators of HABS in support of USACE water quality monitoring needs. A series of three, beta-tested software tools, ranging in complexity and functionality, were developed to accommodate a broad range of skills and needs across USACE. The purposes of the software tools are to: 1) assist water quality managers by serving as a proactive warning system to better monitor and manage HAB outbreaks, 2) reduce costs and labor through optimizing field-based sampling across space and time, and 3) facilitate interagency coordination through communication of HAB potential to managers, leadership, partners, and the public. The software tools and related products include the following:

An open-source R software package, *waterquality* v0.3.0, a University of Cincinnati collaboration, is the most comprehensive option to aggregate a near-comprehensive list of over 40 algorithms and six satellite image types, facilitating comparison across imagers and developing image-based abundance maps of HAB indicators:
Available on GitHub: https://github.com/RAJohansen/waterquality
User-guide report (Johansen et al., 2019b): http://dx.doi.org/10.21079/11681/35053

A Python-based ArcGIS Pro *waterquality* toolbox v1.1, designed for use in and requiring ESRI ArcGIS Pro desktop software 2.7 and greater, uses Sentinel-2 satellite imagery in a sequential workflow with four embedded menus and constrained options to streamline analysis and produce image-based abundance maps of HAB indicators:
Toolbox, Draft Report (Saltus et al., 2022), and Sample Data available on the ERDC Knowledge Core: http://dx.doi.org/10.21079/11681/42240

An online ESRI web application, *HAB Explorer* phase 2, accesses Sentinel-2 satellite imagery through a cloud-based image service to rapidly screen for potential HAB conditions with limited algorithm, visualization, and search filter options (requires internal USACE network access; will be made publicly available in 2023):
Available on the USACE Common Operating Picture: https://arcportal-ucop-corps.usace.army.mil/hab/

New tools require renewed technical skills, time to learn and overcome potential barriers, as well as understanding assumptions behind satellite-based approaches. Therefore, current and future efforts include tool updates and expansion of technical transfer, such as technical training webinars, supporting documentation, and marketing to increase awareness and provide learning opportunities. To date, presentations highlighting tool fundamentals have been provided not only to the USACE water quality community, but also to partner agencies and internal leadership. This includes a quick guide matrix to more readily communicate and compare tool functionality for a brief illustration of ease of access, capabilities, and limitations (Table 1). Additionally, technical training webinars and in-person tool demonstrations have been presented to the USACE water quality community with detailed descriptions of the following:

- Fundamentals of remote sensing for HAB water quality indicators,
- Software requirements and installation,
- Sample datasets from real-world examples to illustrate software mechanics, and
- Product interpretation, statistical analyses, and additional options to explore data products.

Recorded presentations and training webinars can be found on the USACE Natural Resources Management Gateway's Harmful Algal Bloom site (R package and ESRI tools).

Table 1. Water quality and HAB remote sensing software tools quick guide matrix.

Tool Skill/Requirement	*waterquality* for R Advanced (Coding)	*waterquality* for Pro Intermediate (GIS)	HAB Explorer Basic (Google Chrome)
Type	Open-Source R Program	ESRI ArcGIS Pro Toolbox (v. 2.7+)	ESRI Online Web Application
Location	GitHub	ERDC Knowledge Core	uCOP Corpsnet (CAC required)
Price	Free	Free (ArcGIS Pro Advanced license required)	Free
Sensors			
WorldView-2 (<3 meters)	No cost to DoD (licensed)	NO	NO
Sentinel-2 (10-20 meters)	Free	Free	Free
Landsat-8 (30 meters)	Free	NO	NO
MODIS/MERIS/OLCI (>200 meters)	Free	NO	NO
Parameters			
Chlorophyll-a	YES	YES	YES
Phycocyanin	YES	YES	NO
Turbidity	YES	YES	NO
Total Algorithms	40	5	1
Features			
Customizable	YES	NO	NO
Image pre-processing (radiometric correction)	YES	NO	NO
Batch processing	YES	Limited	NO
Statistical evaluation	Multiple	One	NO

Access/Capability
- Maximum
- Limited/Conditional
- Minimum/None

Points of Contact:

Molly Reif (ERDC-EL) Molly.K.Reif@usace.army.mil

Erich Emery (LRD) Erich.B.Emery@usace.army.mil

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