POTENTIAL HARMFUL ALGAL BLOOMS ON THE FLATHEAD INDIAN RESERVATION AND WATER QUALITY PARAMETERS AS EARLY WARNING INDICATORS

by

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DEDICATION

This work serves as a permanent reminder of my devoted family members, I dedicate this work to them. To my Mom and Dad, as the pursuit of my higher education comes to an end, I am flooded with memories of your unwavering support and encouragement. Thank you for all that you sacrificed so that I may succeed. Through you, I have the perseverance, patience, and discipline to pursue my dreams.

To my brother, Kekaimalu, for teaching me through his example, that we as Native Hawaiians are more than what is written in the history books. Thank you for connecting me to our ancestors and showing me that we walk the same path, despite our foreign surroundings. I know now that I will never walk alone, our ancestors are always with me.

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ABSTRACT

Half of Montana's lakes and reservoirs are classified as not fully supporting drinking water, and 41% are classified as not fully supporting aquatic life. Cyanobacteria harmful algal blooms are defined as a rapid growth of algae that produce cyanobacteria and cyanotoxins and thrive in low water quality environments. These toxins have the potential to cause mass die-offs in aquatic biota and illness or death in humans and other terrestrial animals. Tribal communities, like the Flathead Indian Reservation (FIR), are at a greater risk of exposure to these toxins because of multiple cultural uses centered on waterways. My research goal is to develop effective and practicable methods to determine potential areas where cHABs occur, and identify water quality parameters that indicate favorable conditions for cHABS on the FIR. I accomplished this by conducting a literature review, identifying which water quality parameters can be used as indicators of favorable environments for cHABs. Remotely sensed false color composite and the Normalized Difference Vegetation Index (NDVI) indices were used to determine if high priority waterbodies on the reservation have potential experienced cHABs in the past. And lastly, I developed a report and advisory tool for reservation community members in Survey123 and ArcDashboard. An outcome of this research also includes the construction of a cHAB advisory tool for at-risk tribal communities. Many physical and chemical water quality parameters were uncovered as early warning indicators of cHABs and should be used as a framework for future cHAB monitoring efforts on the FIR. Remotely sensed spectral indices were successful in detecting cHAB events at a reference site but failed to detect cHAB events (confirmed and suspected) within the study area, likely due to waterbody size and localized nature of blooms in reservation waters. To understand the extent and frequency of cHABs on the FIR, future efforts should be devoted to gathering more on-the-ground observations of confirmed cHABs paired with water quality sampling at the time of occurrence. Once this is achieved, managers can develop a more synthesized framework for cHAB detection using remote sensing and routine monitoring.

INTRODUCTION

Cyanobacterial Harmful Algal Blooms

Algal blooms in lakes and reservoirs are naturally occurring, but an increase in the frequency, duration, and intensity of blooms have been linked to climate change, warming water temperatures, and excessive nutrient loading (Xiao et al., 2019). Algal blooms become harmful when colonies of microscopic algae grow out of control (NOAA, 2016). Some of these blooms can create high biologic oxygen demand as they decay, causing fish to die, while other blooms produce cyanobacteria (blue-green algae) that can be toxic to animals and humans (CDC, 2022). These cyanobacterial harmful algal blooms (cHABs) have the potential to negatively affect humans and the environment by degrading water quality in the waterbodies they occur in (Chapra et al., 2017). Cyanobacteria harmful algal blooms, the focus of this paper, are mostly recognized by their blue-green paint-like appearance that forms in foam or scum mats across the water's surface. Cyanobacteria harmful alga blooms are important to monitor as they have severe risks; depending on severity, they can potentially cause mass die-offs in aquatic biota and illness or death in humans and other terrestrial animals (CDC, 2022).

HABs-Related Illness Cases

Cyanobacterial harmful algal blooms have been a significant problem in United States coastal and inland waters for hundreds of years. Some of the first European explorers and settlers were poisoned from what we now know to be toxins in the seafood they consumed (Anderson et al., 2021). With increased concern for the public, the National Center for Environmental Health, U.S. Centers for Disease Control (CDC), as well as state partners developed the Harmful Algal Bloom-related Illness Surveillance System (HABISS). The goals of this system are to describe the geographic and temporal distribution of algae blooms and cyanobacteria, and to gain an understanding of the suspected human and animal morbidity and mortality associated with toxic bloom events. State partners reported 175 animal and 458 human (suspected and confirmed) cases of morbidity and mortality to HABISS for bloom-related illnesses between 2007 and 2011 (Backer et al., 2015). Exposure to these toxins is normally through direct contact or ingestion of contaminated water. Exposure also occurs through inhalation of contaminative aerosol or from eating contaminated fish. Of the human cases, 273 reported that food was the source of exposure, and 183 reported water-related exposure (Backer et al., 2015). Among the animal cases, domestic animals, wildlife, birds, and fish were vulnerable to cHAB-related illness, with fish and domestic dogs being the most vulnerable (Backer et al., 2015).

The CDC found 368 cHAB events were reported across 16 states, with 330 occurring in lakes and reservoirs from January 1, 2021 to December 31, 2021(CDC, 2021). During the study period 117 human illness cases were reported. These cases were mainly in June (CDC, 2021), and the majority of illnesses were within the 18 to 45 age group. Illnesses included gastrointestinal, generalized, and dermatologic symptoms. Additionally, there were 2715 animal illness cases that occurred in wildlife, domestic pets, and livestock. Of the 2715 animal cases, 2489 were fatal, 2000 of which were bats. The remaining illnesses occurred in dogs, cattle, and fish (CDC, 2021).

HABs-Related Drinking Water Cases

In June through November 2021, there were multiple reports of cHABs in Clear Lake, California (CDC, 2022). The recreational health advisory has a cyanobacteria threshold of 20 μg/L, and the maximum level detected in Clear Lake that summer was over 160,000 μg/L. There are 17 public drinking intakes located at this lake, all of which are monitored and treated to the Environmental Protection Agency (EPA) drinking water health advisory level of 0.3 μg/L (CDC,2022). Since there are an unknown number of homes around Clear Lake that rely on private water sources, experts conducted a study on private wells around Clear Lake. They found that cyanobacteria was detected in 22 out of 31 homes with lake water intake, 18 of those being above the EPA drinking water advisory level (0.3 μg/L), despite water filtration systems in place (CDC,2022).

HABs in Montana

Increased human impacts, wildfires, climate change, and pollution have increased Montana's susceptibility to cHABs. Cyanobacteria harmful algal bloom events predominantly occur in the summer months, peaking in July or August in Montana (Montana Department of Environmental Quality, 2023). Areas of confirmed positive cHAB events in Montana consist of Clark Canyon Reservoir, Delmoe Lake, Nilan Reservoir, Canyon Ferry Reservoir, Holter Lake, Houser Lake, Beaver Creek Reservoir, and Bighorn Reservoir (Puckett, 2018). The Montana Department of Environmental Quality (DEQ) has been raising public awareness statewide through education and outreach. They have also implemented an advisory map viewer on their website where the public can report potential sightings of cHABs. Once they receive a report, they can assess if the site needs further investigation, or a posted advisory based on the photos provided and test strips used to determine if the water body is positive for cyanobacteria.

Even though these reporting tools are usually effective, public awareness efforts may not be as effective within tribal communities, like the Flathead Indian Reservation. Out of all the ethnic groups in the Unites States, Native Americans are the most at risk of toxic exposure. Health conditions in indigenous communities are attributed to poverty, genetics, and inadequate health care delivery systems, and in many cases are compounded by exposure to environmental contaminants and phenomena (Manjeshwar, 2021). These exposures not only affect current indigenous communities, but also future generations.

Although experts know many factors that contribute to cHABs, several unanswered questions remain, including their environmental triggers, duration, timing, and how they come to form blooms that are toxic. The ability to predict and forecast cHAB events to limit exposure coupled with education and outreach can potentially reduce tribal communities' risk of exposure. Then, water managers can develop a methodology to refine a forecasting tool using remotely sensed data, which will determine high-risk waterbodies and water quality indicators favorable for cHABs. Therefore, the research goal of my project is to develop effective and practicable methods to determine potential areas cHABs occur, and the water quality parameters that indicate favorable conditions for cHABS on the Flathead Indian Reservation.

BACKGROUND

The Confederated Salish & Kootenai Tribes (CSKT)

Western Montana's Flathead Indian Reservation (FIR) (Figure 1) is home to the confederation of three tribes, the Seli'š (Salish), Ksanka (Kootenai), and Qlispe' (Pend d'

Oreille), collectively called the Confederated Salish & Kootenai Tribes (CSKT). The territories of these three tribes once encompassed western Montana, parts of Idaho, British Columbia, and Wyoming. The Hellgate Treaty of 1855 established the Reservation, reestablishing the tribes exclusive use of approximately 1.3 million acres by its people (Confederated Salish & Kootenai Tribes, 2015). Although it was only a tiny portion of their aboriginal territories, almost 500,000 acres once more passed out of Tribal ownership due to the Flathead Allotment Act of 1904 (Confederated Salish & Kootenai Tribes, 2015). What remains today is a cherished home for the tribes' people.

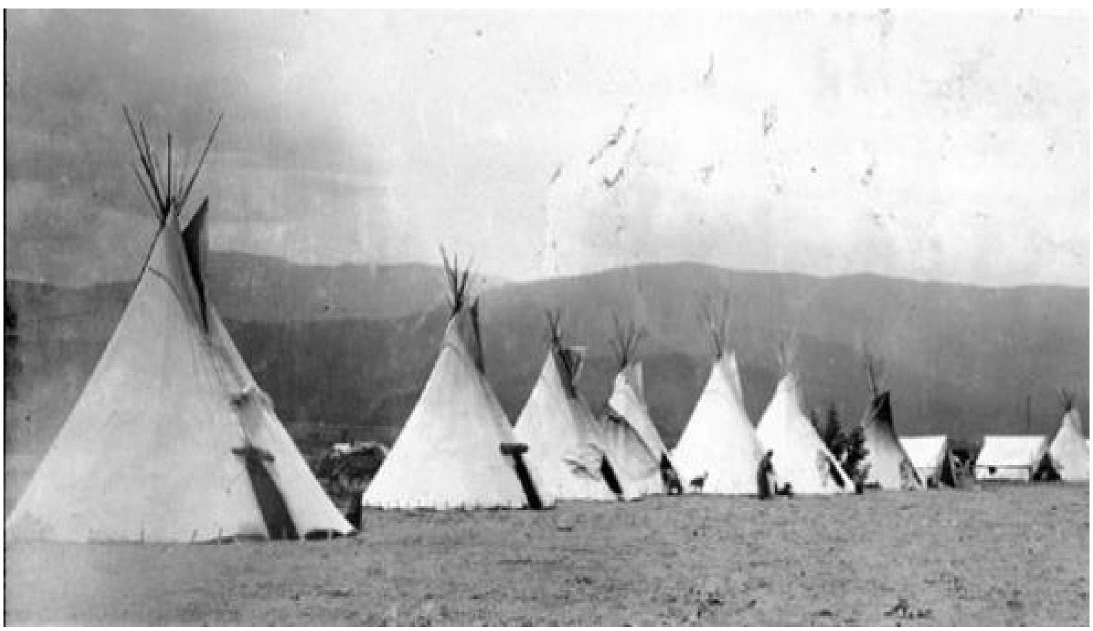

Figure 1. Salish teepees and tents, Dixon, Montana.
Flathead Indian Reservation Historical Archive: Salish teepees and tents, Dixon, Montana, Frances Gilbert Hamblen. American Indians of the Pacific Northwest Images, [Salish tepees and tents, Dixon, Montana - American Indians of the Pacific Northwest -- Image Portion - University of Washington Digital Collections]

The Flathead Reservation's water resources encompass seven major watersheds: Camas, Crow, Flathead Lake, Lower Flathead River, Jocko, Little Bitterroot, and Mission. The tribes also own about 26,304 hectares of the southern half of Flathead Lake. Additionally, they own more than 1931 kilometers of irrigation canals, 17 reservoirs, over 10,000 pothole wetlands, 6437 kilometers of streams, and 41,736 national wetland inventory hectares (including the lower portion of Flathead Lake) (Huck, 2021) (Figure 2).

Water Quality on the Flathead Indian Reservation

No natural resource is more vital to the Seli'š, Ksanka, and Qlispe' than water. Rivers and waterways were highways for the tribes before the arrival of horses, and for thousands of years, the tribes relied on the fish native to their homelands for nutritional and cultural subsistence (Confederated Salish & Kootenai Tribes, 2015). High quality waters support drinking, bathing, swimming, recreation, wildlife, salmonids, agriculture, and most importantly, cultural practices on the reservation (Confederated Salish & Kootenai Tribes, 2015). CSKT has demonstrated a long-term commitment to the protection and conservation of the tribes' natural resources.

The mission of CSKTs Water Quality Program is "to preserve, protect, restore, and maintain the physical, chemical, and biological integrity of all surface waters, ground waters, and wetlands of the Flathead Reservation" (Confederated Salish & Kootenai Tribes, 2015). The tribes received "treatment as a state" (TAS) status under section 106 of the Clean Water Act (CWA) in 1989, as well as section 303 in 1992. Federally recognized tribes were given the authority by TAS to implement and manage certain environmental programs and functions and access to grant funding. In 1996 CSKT implemented their first set of water quality standards. Today, the program also conducts CWA Section 401 certifications across the FIR. The program currently monitors seven core sampling sites spread across six watersheds, three non-point source project monitoring locations, and three Flathead Lake monitoring sites. Tribal staff report that water quality in mountainous areas is high quality until it encounters numerous human impacts as it moves across the valley floor (Confederated Salish & Kootenai Tribes, 2015).

Figure 2. Confederated Salish and Kootenai Tribes Flathead Indian Reservation.
Partnerships with Native Americans, 2023. Map of Flathead Indian Reservation. Montana Flathead Reservation, Montana: Flathead Reservation | PWNA Resources - Partnership With Native Americans (nativepartnership.org)

HABs on the Flathead Indian Reservation

CSKT's water quality program does not currently monitor for cHABs nor do they possess any historical data for cHAB indicators. However, there have been three reports of cHABs (confirmed and suspected) on the Flathead Indian Reservation. Of the three cases, only one was confirmed as cyanobacteria. The bloom occurred on June 28, 2021 at Lower Crow Reservoir and persisted past July 29, 2021 (Figure 3). The reservoir is over 115 hectares with an elevation over

883 meters, located in Lake County, Montana. There is only one species of fish in this reservoir, introduced rainbow trout (Oncorhynchus mykiss). No human, animal, or fish related illnesses were reported during this bloom. Reports of water related human and animal illness on the southern end of Flathead Lake occurred in July 2023. Symptoms included severe diarrhea and vomiting and required medical attention. On further investigation, algae experts determined there was no cyanobacteria present in the bloom they investigated (personal communication, Laurel Genzoli, August 3, 2023). Lastly, I discovered a potential cHAB while exploring Google Earth images taken of Lower Crow Reservoir; the images identified another potential bloom event on the date the satellite image was taken, October 12, 2023 (Figure 4).

Figure 3. Lower Crow Confirmed Harmful Algal Bloom July 2021.
Bras, Trevor. 2021. CSKT Complaint Form.

Figure 4. Lower Crow Suspected Harmful Algal Bloom October 2023

Project Importance

Cyanobacteria harmful algal blooms in tribal waters make tribal communities especially vulnerable due to the use of waterways for cultural, recreational, and subsistence use. Despite the growing concern for cHAB occurrence on the reservation, the tribe's water quality program does not have the resources necessary to routinely monitor cHABs in FIR waterbodies, and must utilize their funding for core monitoring efforts. It is essential to recognize the parameters that indicate a viable environment for cHABs to flourish in, warn community members of potential blooms on the reservation, and potentially locate causes and sources for preventative actions and measures. Adding these monitoring frameworks and advisory map to CSKT's water quality program could also provide the opportunity for further research into locating and mitigating the sources that exacerbate cHABs on the Reservation.

METHODS

To meet the needs of the research goal, I accomplished three objectives in developing an effective and practicable method to determine potential areas of cHAB occurrence: 1) determine which water quality parameters can be used as indicators of favorable environments for cHABs, 2) use remote sensing applications and methods to determine if high priority waterbodies on the reservation have potentially experienced cHABs in the past, and 3) develop a report and advisory tool for community members to report cHAB sightings and observations.

Objective 1-Determine water quality parameters favorable for cyanobacteria growth.

To determine the water quality parameters that are favorable for cyanobacterial harmful algal bloom occurrence, I conducted a literature review of current studies and predictive modeling efforts by other researchers. I conducted a keyword search for harmful algal bloom indicators in Google Scholar and Science Direct, limiting the search to contemporary papers from 2003 to 2023 and summarizing the findings into a table.

Objective 2- Use remote sensing applications to determine which high priority FIR waterbodies have potentially experienced cHABs

Image Acquisition & Analysis

I used Landsat 8 Collection 2 Level 1 Operational Land Imager (L8/OLI) images to detect potential areas cHABs have occurred in FIR waterbodies. The Landsat 8 mission is a collaboration between the United States Geological Survey (USGS) and National Aeronautics and Space Administration (NASA). Landsat 8 OLI produces multispectral 30-meter spatial resolution images and has complete global coverage of the earth every 16 days. The OLI sensor operates using the visible, near infrared, short wave infrared, and thermal infrared spectrums. Images were selected using the following criteria: tier 1 image availability, limited cloud cover (less than 30%), and within the analysis timeline for each site.

Spectral Indices

Spectral indices are commonly used in remote sensing for the quantification of specific properties of vegetation, water and land cover. In some cases, spectral indices are used to detect physical cHAB indicators and determine presence of cHABs. Many algorithms and remote sensing experts use chlorophyll-a (greenness) as an indicator of photosynthetic activity in water, which can be used to determine presence and absence of blooms (Rodríguez-López et al., 2023). I conducted image analysis which included measuring greenness and density of past potential cHABs in waterbodies of interest. False color (FC) composite images were used to help visualize wavelengths the human eye cannot see in the visual spectrum (RGB), using false color images often helps increase spectral separation and increases the interpretability of images. The bands I used to create false color images were near-infrared, red, and green. Near-infrared was displayed as red, red was displayed as green, and green was displayed as blue. This color combination visually renders green vegetation and algae as red in false color images.

The Normalized Difference Vegetation Index (NDVI) is used to indicate greenness, density, and health of vegetation. Cyanobacteria blooms are distinct based on their physical appearance because they create changes in color, density, and transparency. However, spectral characteristics of cyanobacteria blooms and terrestrial vegetation are similar. The index (ranging from -1.0 to +1.0) (Equation 1) is based on near infrared and red reflectance. Although the NDVI is not a direct indicator of cHABs, it is an indicator of chlorophyll-a and photosynthetic activity. Therefore, we can assume that high NDVI values in waterbodies represent presence of chlorophyll-a, which can potentially be related to cHABs.

$$NDVI = \frac{Near\ Infrared\ Band - Red\ Band}{Near\ Infrared\ Band + Red\ Band} \qquad \text{Equation 1.}$$

<u>Reference Site</u>

A reference site was selected to test the capability of the remote sensing methods and their effectiveness in detecting photosynthetic activity in waterbodies. I selected Montana's Canyon Ferry Reservoir as the reference site because it has documented cHAB presence according to the MT-DEQ (Montana Department of Environmental Quality, 2020).

Canyon Ferry Reservoir

Canyon Ferry Reservoir is a popular Montana recreation, camping, and fishing destination, known for its rainbow trout, perch, and walleye. Canyon Ferry contains over 144 shoreline kilometers, and about 13,354 surface hectares of water. Canyon Ferry Reservoir experienced multiple cHAB blooms in the summer of 2023 (Table 1). The reservoir was under a cHAB advisory in at least one section of the reservoir from late June through mid-October, 2023, due to confirmed detection of cyanobacteria by cHAB experts at MT-DEQ, via toxin strip tests or citizen reported photos (Montana DEQ Survey 123, 2023).

Table. 1 Canyon Ferry Reference Site Information

cHAB Advisory Date	Canyon Ferry Location	Landsat Imagery Acquisition Date	Path & Row	Advisory Category
6/26-8/2/2023	Northern End	May 19, 2023	040, 027	No Advisory
7/13-8/31/2023	Silos Campground	July 14, 2023	040, 027	During Advisory
8/8-9/14/2023	Lower Duck Creek	August 15, 2023	040, 027	During Advisory
9/16-10/16	Upper Duck Creek	September 16, 2023 & October 18, 2023	040, 027	During & After Advisory

Image Acquisition

Landsat 8 images (path 40/row 27) were obtained from the United States Geological Survey (USGS) Global Visualization (GloVis) website for Canyon Ferry Reservoir (46.43711, -111.52723). To test NDVI's ability to detect cHABs, I acquired images from confirmed cHAB advisory events. In order to get a complete assessment of the capability of the NDVI index to detect cHABs, the reference site images I selected were based on closeness to 3 advisory categories (see Table 1): No cHAB advisory, During cHAB advisory, and After cHAB advisory, Study Area

I selected Flathead Lake, Ninepipe Reservoir, Lower Crow Reservoir, Pablo Reservoir, Dry Fork Reservoir, Rainbow Lake, and Turtle Lake as study areas for this research (Table 2). Study areas I selected were based on their perceived risk to FIR communities based on water quality and human access categories:

- Suspected cHAB presence
- Recreational access
- Ecological importance
- Proximity to pollution sources

Table 2. cHABs Study Area Information

Satellite	cHAB Study Areas	Coordinates
LANDSAT 8 OLI	Flathead Lake	47.91654 -114.09962
LANDSAT 8 OLI	Rainbow Lake	47.52585 -114.76062
LANDSAT 8 OLI	Turtle Lake	47.6691 -114.07569
LANDSAT 8 OLI	Ninepipe Reservoir	47.44399 -114.11886
LANDSAT 8 OLI	Lower Crow Reservoir	47.50388 -114.2186
LANDSAT 8 OLI	Pablo Reservoir	47.63744 -114.16027
LANDSAT 8 OLI	Dry Fork Reservoir	47.70359 -114.66689

Site Characteristics

Flathead Lake is the biggest recreational destination on the Flathead Indian Reservation. Flathead Lake is also considered the largest freshwater lake in the western U.S. at a size of 51,022 hectares and has an average summer water temperature range of 13°C to 15°C (Flathead Lake Biological Station, 2023). The cultural importance of this waterbody dates back to some of the tribe's origin stories. From time immemorial, the tribes have relied on the "wealth" that Flathead Lake provided, including access to staple food sources like bull trout (*Salvelinus confluentus*) (Smith, 2023).

Ninepipe Reservoir has high recreational and ecological value. It is located within the Ninepipe National Wildlife Refuge, which is characterized as the center of a glacial terminal moraine with a high density of complex small wetlands and uplands grasses. There are over 150 bird species that use the Ninepipe area. The reservoir is about 488 hectares and does not contain native fish. However, endangered species of concern like trumpeter swans (Cygnus buccinator) and great blue herons (*Ardea herodias*) frequent these areas (U.S Fish & Wildlife Service, 2023).

I selected Lower Crow Reservoir for this study based on suspected and confirmed cHABs presence. It is the only site that has had a bloom that has resulted in an advisory on the FIR. The reservoir is about 115 hectares, and contains introduced rainbow trout (Montana Fish, WIldlife, & Parks, 2023). It is important that we added this site to our research as we can evaluate the ability to detect the cHAB event that occurred in 2021 and the suspected event in 2023.

Pablo Reservoir is about 667 hectares in size and is a very popular recreational area on the reservation (Montana Fish, WIldlife, & Parks, 2023). The reservoir is also located within the Pablo National Wildlife Refuge and is integral in preserving connectivity of varied habitats and an abundance of wildlife species across the landscape. The public is allowed to fish at this site, however the west and south shores of the reservoir are reserved exclusively for migratory bird habitat (U.S Fish & WIldlife Service, 2023). The site was selected for analysis due to its ecological importance to endangered bird species and recreational access.

Dry Fork Reservoir is about 62 hectares in size and contains many native fish species, including native largescale sucker (*Catostomus macrochelius*), longnose sucker (*Catostomus catostomus*), and northern pike minnow (*Phychocheilus oregonensis*). It was important to add this site because of its ecological importance to native fish species and its proximity to agricultural pollution sources on the western half of the reservoir (U.S Fish & WIldlife Service, 2023).

Rainbow Lake is about 84 hectares in size and a popular recreation and fishing destination on the FIR. Northern pike (*Esox Lucius*), northern pike minnow (*Phychocheilus oregonensis*), pumpkinseed (*Lepomis gibbosus*), rainbow trout (*Oncornhynchus mykiss*), walleye (*Sander viterus*), yellow perch (*Perca flavescens*) and the native species redside shiner (*Richardsonius balteatus*) can be found at this lake (U.S Fish & WIldlife Service, 2023). This site was selected due to its recreational access and ecological importance to native fish species.

Turtle Lake is about 19 hectares in size, surrounded by tribal housing, and a popular recreational area on the FIR. Turtle Lake also seasonally drains north to Flathead Lake (Montana Fish, WIldlife, & Parks, 2023). I selected this site due to its proximity to tribal housing and ecological importance to native fish, like the Westslope Cutthroat Trout (*Oncornhynchus clarkii lewisi*).

Image Acquisition

Cyanobacteria harmful algal blooms are more likely to occur in the early and late summer months, when light availability is at its highest intensity (Bone, 2019). Landsat 8 images used for the study area were captured in the months of June, July, August, September, and October from 2018-2023 in path 041 and row 027 (Table 3).

Table 3. Flathead Indian Reservation image acquisition dates and files used in research

Landsat Imagery Date	GLoVis Download File	Path & Row
6/12/2018	LC08_L1TP_041027_20180612_20200831_02_T1	041, 027
7/14/2018	LC08_L1TP_041027_20180714_20200831_02_T1	041, 027
7/30/2018	LC08_L1TP_041027_20180730_20200831_02_T1	041, 027
8/15/2018	LC08_L1TP_041027_20180815_20200831_02_T1	041, 027
10/18/2018	LC08_L1TP_041027_20181018_20200831_02_T1	041, 027
8/18/2019	LC08_L1TP_041027_20190818_20200827_02_T1	041, 027
9/3/2019	LC08_L1TP_041027_20190903_20200826_02_T1	041, 027
7/3/2020	LC08_L1TP_041027_20200703_20200913_02_T1	041, 027
7/19/2020	LC08_L1TP_041027_20200719_20210330_02_T1	041, 027
8/4/2020	LC08_L1TP_041027_20200804_20200914_02_T1	041, 027
10/7/2020	LC08_L1TP_041087_20201007_20201018_02_T1	041, 027
6/4/2021	LC08_L1TP_041027_20210604_20210614_02_T1	041, 027
7/6/2021	LC08_L1TP_041027_20210706_20210713_02_T1	041, 027
7/22/2021	LC08_L1TP_041087_20210722_20210729_02_T1	041, 027
9/24/2021	LC08_L1TP_041027_20210924_20210930_02_T1	041, 027
7/17/2022	LC08_L1TP_041027_20220717_20230407_02_T1	041, 027
8/2/2022	LC08_L1TP_041027_20220802_20230405_02_T1	041, 027
8/18/2022	LC08_L1TP_041027_20220818_20230401_02_T1	041, 027
9/27/2022	LC08_L1TP_041027_20220927_20221004_02_T1	041, 027
10/13/2022	LC08_L1TP_041027_20221013_20221020_02_T1	041, 027
7/20/2023	LC08_L1TP_041027_20230720_20230720_02_T1	041, 027
8/13/2023	LC08_L1TP_041027_20230813_20230819_02_T1	041, 027
8/29/2023	LC08_L1TP_041027_20230829_20230906_02_T1	041, 027
9/14/2023	LC08_L1TP_041027_20230914_20230919_02_T1	041, 027
10/08/2023	LC08_L1TP_041027_20231008_20231008_02_T1	041, 027

Objective 3-Develop a CSKT reporting/advisory tool for water managers and tribal community members for FIR cHABs events.

I constructed a cHABs reporting tool for CSKT water managers using Survey 123 on ArcGIS (https://survey123.arcgis.com). This tool helps create a framework for cHAB actions for CSKT water managers by gathering more data on potential cHAB occurrences and extents on the FIR. Once the tool is finalized, data that will be gathered in the future to help meet CSKT's water quality program data needs (Table 4). Lastly, I used ArcDashboard (https://www.esri.com/en-us/arcgis/products/arcgis-dashboards/overview) to create an FIR cHAB advisory map using data points that will be collected in the reporting tool. Data from the report form is linked to a map viewer that automatically uploads observations as points on a map of the FIR. The data collected from this tool are intended to support the next stages of the cHAB reporting tool, which includes early warning detection and advisory. With data sovereignty in mind, points will be expanded using the expand tool to include select cHAB observation data from the original cHAB report form for the public.

Table 4. cHAB data needs

Cyanobacteria Harmful Algal Bloom Data Needs		
Occurrence	**Risks**	**Monitoring**
How often? • How many cHABs are experienced in one summer *Where?* *Waterbody type?* • River • Stream • Lake • Reservoir *Duration?* *Extent* • Widespread • Localized	*Toxicity* • Human • Wildlife • Fish • Domestic Livestock • Domestic Pets *Accessibility* • Advisories • Closures	*Physical Parameters* • Turbidity • Water Temperature • Flow • Photos • pH • Dissolved Oxygen • Air Temperature *Chemical Parameters* • Total Nitrogen • Total Phosphorus • Ammonia • Chlorophyll-a

RESULTS

Objective 1-Water quality parameters favorable for cyanobacteria growth

There were many physical and chemical parameters that were explored in this research (Table 5). The Congressional Research Service argues that the factors contributing to blooms in freshwater ecosystems include nutrient concentrations, water temperature, light availability, pH, and water circulation (Gatz, 2019). Nutrient enrichment is among the highest contributors to cHAB events, specifically nitrogen and phosphorus. Sources of this type of pollution include municipal wastewater discharges, failing septic systems, fertilizer, and agricultural and urban runoff (Gatz, 2019). Some indicators of excessive nutrient enrichment in water include depletion of dissolved oxygen, increased turbidity, native species depletion, and odor or scum (Gatz, 2019).

Table 5. Water quality indicators for cHABs derived from literature review

cHAB Water Quality Indicators & Drivers	Source
Ammonia Nitrogen	Su et. al
Total Nitrogen	Su et. al, Huang et. al, Wang et. al, Sangmok et. al, Gatz et. al
pH	Sangmok et. al, Gatz et. al
Total Phosphorus	Wang et. al, Sangmok et. al, Gatz et. al
Water Temperature	Su et. al, Huang et. al, Wang et. al, Sangmok et al,
Air Temperature	Huang et. al
Light Availability	Wang et. al, Sangmok et. al, Gatz et. al
Lake Stratification	Huang et. al, Sangmok et. al, Gatz et. al
Chlorophyll-a	Sangmok et. al, Kahn et. al
Wind Speed	Huang et. al

Sangmok and Donghyun conducted a literature review of existing literature related cHAB prediction modeling, they argue that prediction models lack clear indicating relationships between each factor when predicting toxic algal blooms (Sangmok & Donghyun, 2018). Sangmok and Donghyun investigated the causative factors of cHABs with deep learning algorithms and water quality models. They determined chlorophyll-a as a predictive indicator for cHAB likelihood and investigated causal factors of increased chlorophyll-a production because this parameter is used to measure eutrophication, which in turn creates algal bloom conditions. In their analysis they determined multiple physical and chemical parameters of interest related to algae. Physical parameters included time of year, water temperatures optimal for cyanobacteria (77 °F), and flow and circulation of water. Inadequate water circulation allows algae to remain at the upper layer of water following bloom occurrence, leading to longer than normal residence times, reoccurrence, and rapid spread (Sangmok & Donghyun, 2018). Chemical parameters included chlorophyll-a concentrations, pH, total nitrogen, and total phosphorous (Sangmok & Donghyun, 2018).

Another study concluded that chlorophyll-a is a viable indicator of cHABs (Khan et al., 2021). Chlorophyll-a is the predominant type of chlorophyll found in green plants and algae, allowing them to photosynthesize. Chlorophyll-a is often used as a measure of the amount of algae growing in a waterbody and can be used to classify eutrophic conditions. One of the most prominent symptoms of degraded water quality condition is the increase in algae biomass and is a useful indicator for cHAB risk (Khan et al., 2021).

In this correlation modeling study on chemical factors and physical factors used to predict cHABs, Wang argues that total phosphorus, total nitrogen, water temperature, and light intensity have been identified as primary factors influencing algal growth. They concluded that temperatures between 25°C to 30°C were positively correlated with algal bloom growth, and that nitrogen and phosphorus together with the optimum total nitrogen/phosphorus mass ratio, between 7.9 and 10.1, was the most significant stimulating parameter associated with algal bloom development (Wang et al., 2016).

Elevated nitrogen levels were also associated with higher concentrations of microcystin (cyanobacteria), deeming nitrogen a causal factor in increased algal toxin production. Huang determined that total nitrogen levels that exceed 650 μg/ L^{-1} were associated with a higher cyanobacteria exceedance in drinking water quality stands for microcystin (cyanobacteria). Water temperatures also indicated that cyanobacteria are able to outcompete other algal communities in a temperature range above 25°C. Increasing air temperatures paired with reduced wind speeds also increases lake stratification, which in turn reduces vertical mixing and provides cHAB optimal environments (Huang et al., 2020).

Su concluded that cHAB drivers differ depending on seasonality. They determined that the main drivers of cHAB during the dry season were water temperature and flow rate. During the wet season the main drivers were ammonia, nitrogen, and water temperature. Drivers throughout the entire year were mainly attributed to water temperatures and total nitrogen (Su et al., 2022).

<u>Objective 2- Use remote sensing applications to determine high priority FIR waterbodies that have potentially experienced cHABs</u>

<u>Canyon Ferry Reference Area</u>

Spectral similarities between the characteristics of cyanobacteria blooms and terrestrial vegetation were recognized in our reference site results. When analyzing remotely sensed data, I used FC (false color) channel bands (bands 5, 4, and 3) to visualize potential cHABs (Figure 5) that we are unable to see in RBG images. False color images help create visual spectral separation and allow the image reader to see red areas detected in water, where RGB images fail to present to image viewers. False color images are used to reveal and enhance features that are otherwise invisible or poorly visible to the human eye. False color images revealed potential blooms and were used as the first level of potential cHAB detection in this research.

The NDVI was successful in detecting multiple different stages of cHAB events located in Canyon Ferry Reservoir (Figure 6). Twelve classes were generated for each image to illustrate different vegetative intensities of potential photosynthetic activity within each swath ranging from -1.0 to +1.0. Results for the “no advisory” category (Figure 6 window 1) shows negative values throughout Canyon Ferry Reservoir, indicating no photosynthetic activity on the lake surface. Positive values of photosynthetic activity were detected at the southern end of Canyon Ferry for the “during” and “after” advisory categories documented by MT-DEQ (Montana Department of Environmental Quality, 2020) (Figure 6, windows 2,3,4, and 5). Advisories are triggered by cyanobacteria density measured in test strips or based off the likelihood of presence in reported photos (Montana Department of Environmental Quality, 2020). Lower NDVI values indicate lower photosynthetic activity (less green) and higher values indicate higher photosynthetic activity (more green). There were differences in size and intensity that were visualized from each category: no advisory, during advisory, and following the advisory period. However, values do not indicate the stage of advisory, only the presence of greenness in water.

Negative NDVI values represent water or very poor vegetation health (no photosynthetic activity). The NDVI values in Figure 6 window 2 ranged from 0.0 - 0.1 at the edges of the bloom, and 0.2 - 0.4 near the center and 0.4 - 0.5 at its center. Window 3 results indicate a bloom mid advisory. Threshold values during this stage of the bloom ranged from 0.0 - 0.1 at the edges of the bloom, 0.1 - 0.2 in most of the bloom, 0.2 - 0.4 near the middle, and 0.5-0.6 at its center. Window 4 depicts another bloom near the start of the advisory period, threshold ranges for this period resulted in 0.0 - 0.1 at the edges, 0.2 - 0.4 towards the middle, 0.5 - 0.6 near the center, and 0.6 - 0.7 at its center. Window 5 visualized the same bloom, two days after the advisory was lifted. It’s smaller in size, but still reflecting similar threshold NDVI values of 0.0 - 0.1 at its edges, 0.2 - 0.4 near the middle, and 0.4 - 0.5 at its center.

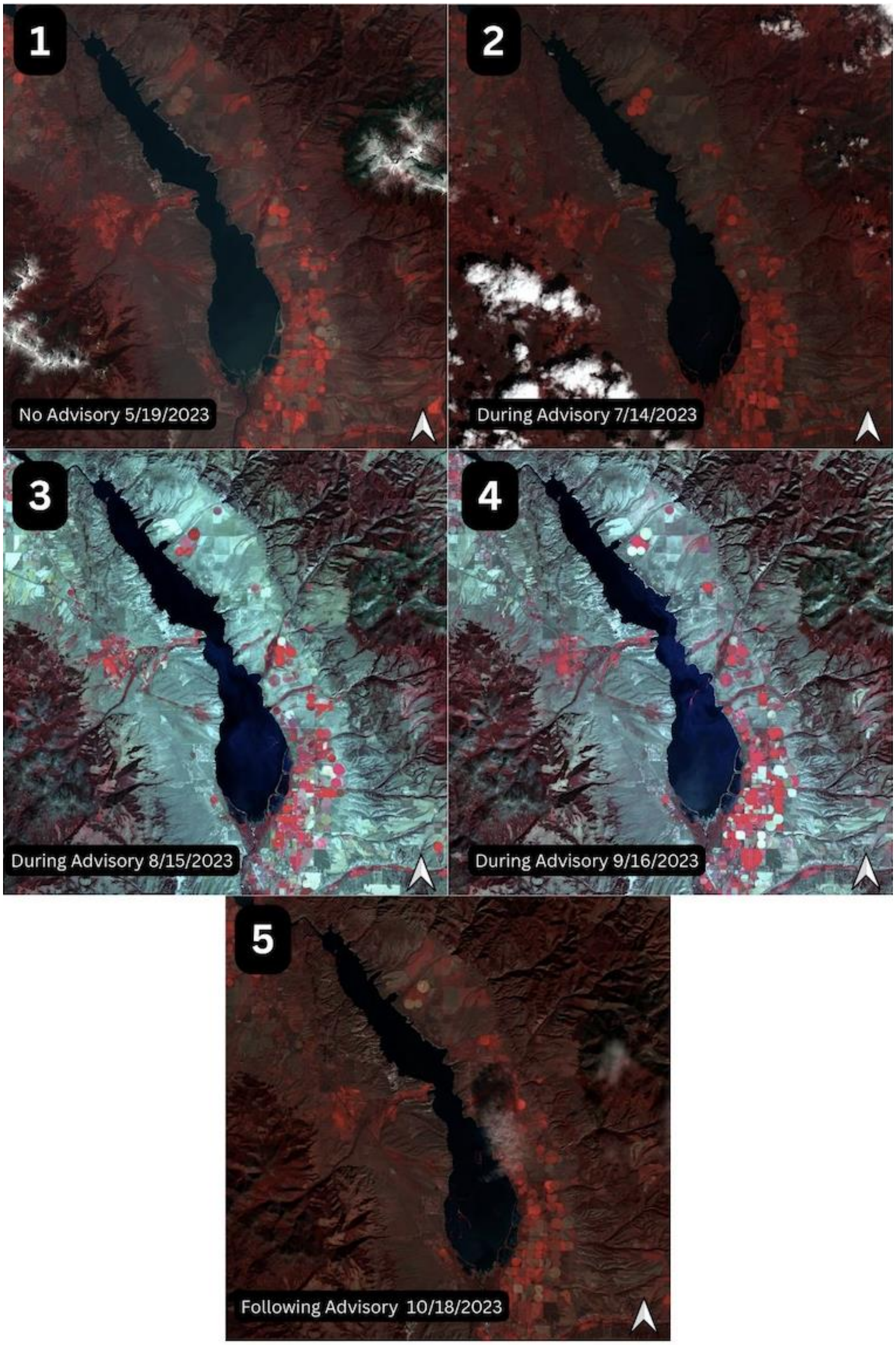

Figure 5. False color image visualization

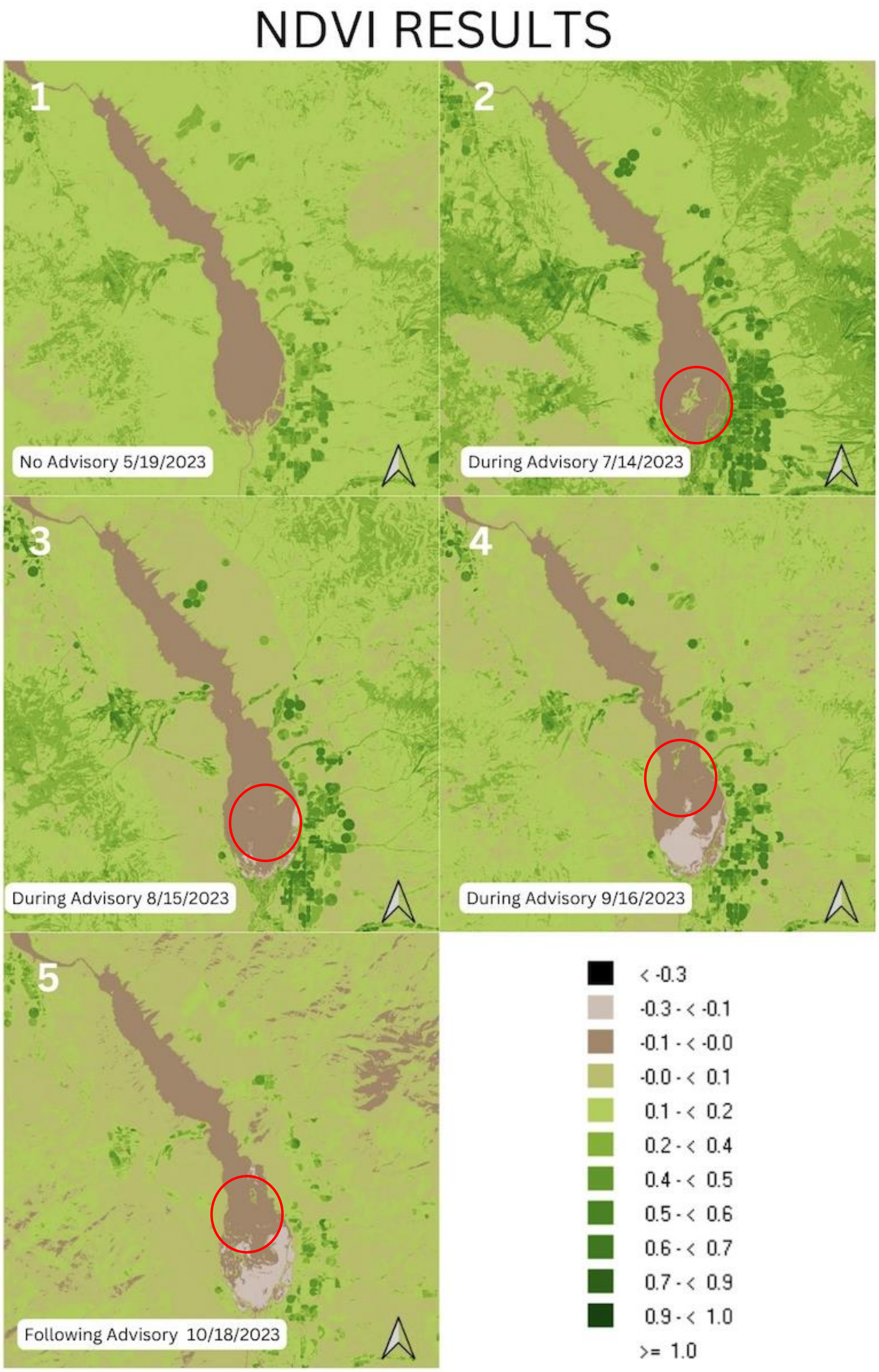

Figure 6. Canyon Ferry Harmful Algal Bloom NDVI Analysis. Red circles indicate cHAB detections

Flathead Indian Reservation

Lower Crow Reservoir cHAB events (Table 6) determined that both, false color composite and NDVI, failed to detect cHAB events that occurred in June-July 2021 (Figure 7 & 8), and October 2023 (Figure 9), even though FC and NDVI indices were successful in detecting cHABs at Canyon Ferry.

I found four potential cHAB events that occurred at two locations of the study area – Ninepipe and Pablo Reservoir – on the FIR (Figure 10). These Reservoirs are highly vegetated, therefore NDVI images that detected isolated measurements of photosynthetic activity were selected as potential algal blooms, instead of photosynthetic measurements located only at the water's edge, to avoid misclassification of terrestrial vegetation and the reservoirs' aquatic vegetation. NDVI threshold values ranged between 0.0 - 0.1 and 0.1 - 0.2. It is important to note that these results do not mean cHABs have occurred at these locations, just that there were instances of photosynthetic activity within these waterbodies at the time the images were acquired, which is a potential indicator of cHABs.

Table 6. cHAB events on the Flathead Indian Reservation

HAB Location	Confirmed/Suspected cHAB Event Date	Landsat 8 Image Acquisition
Lower Crow Reservoir	June 28 2021- August 08,2021	7/6/2021, 7/22/2021
Lower Crow Reservoir	October 12, 2023	October 8, 2023

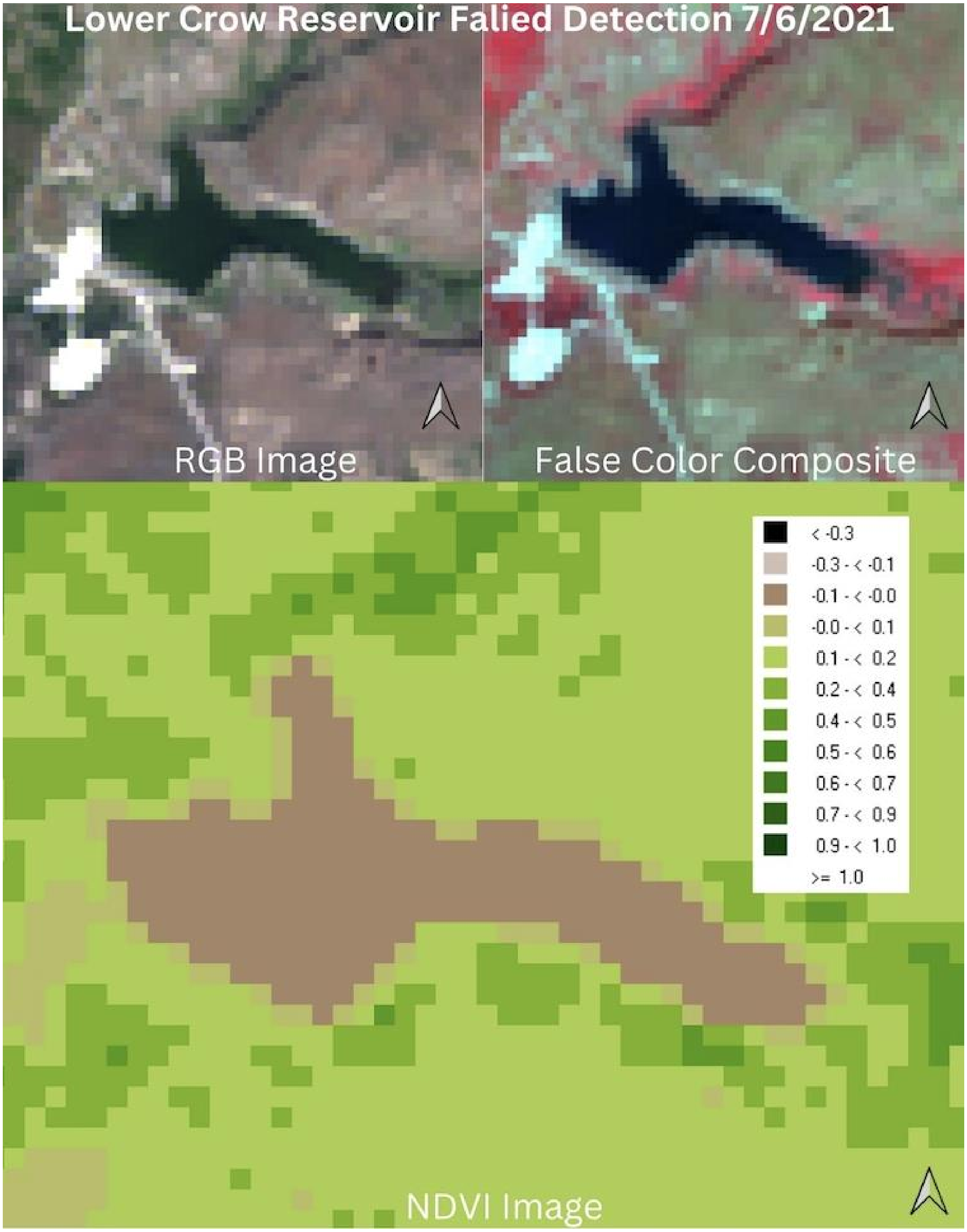

Figure 7. Detection failure at Lower Crow during confirmed cHAB event 7/6/2021

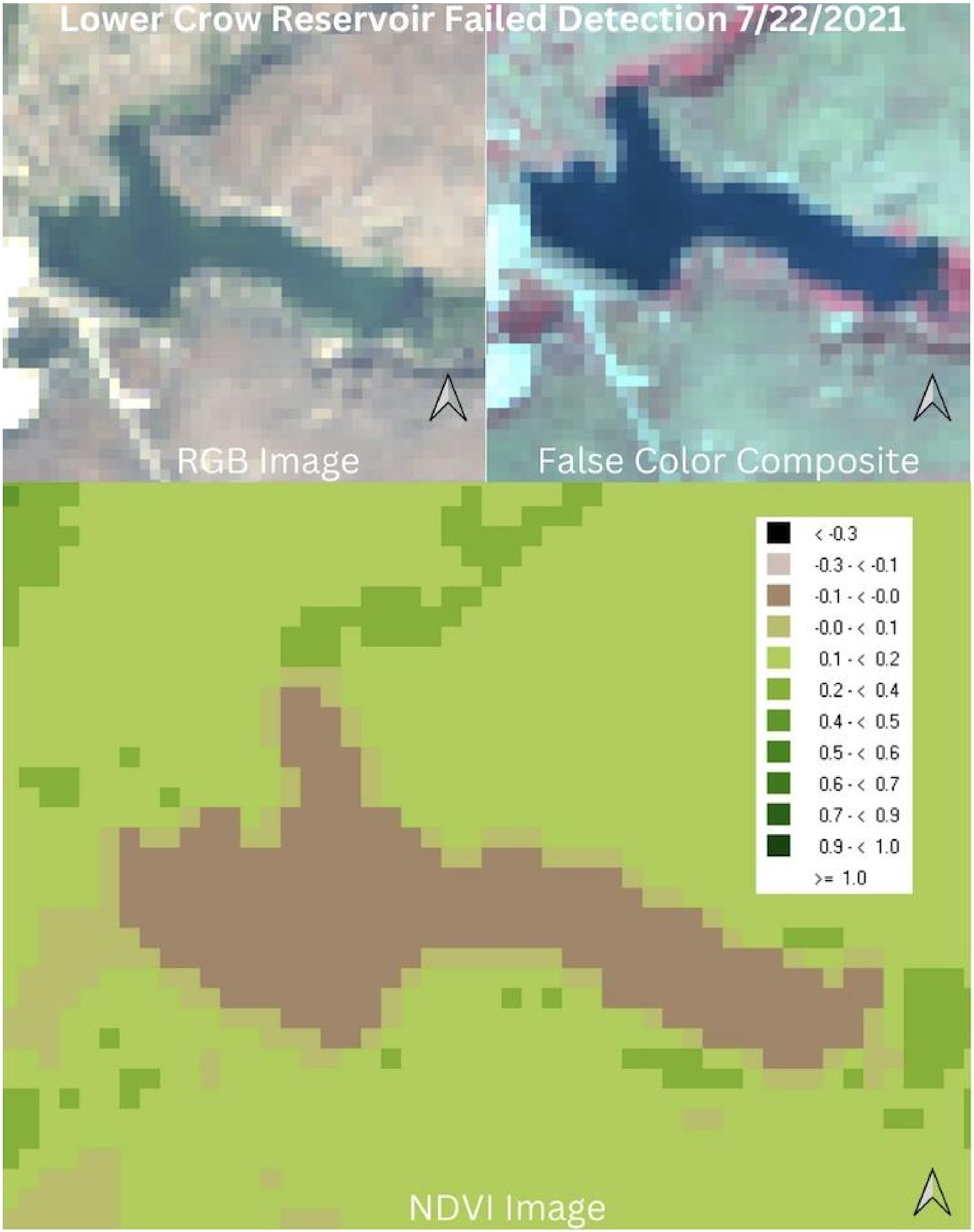

Figure 8. Detection failure at Lower Crow Reservoir during confirmed cHAB event 7/22/2021

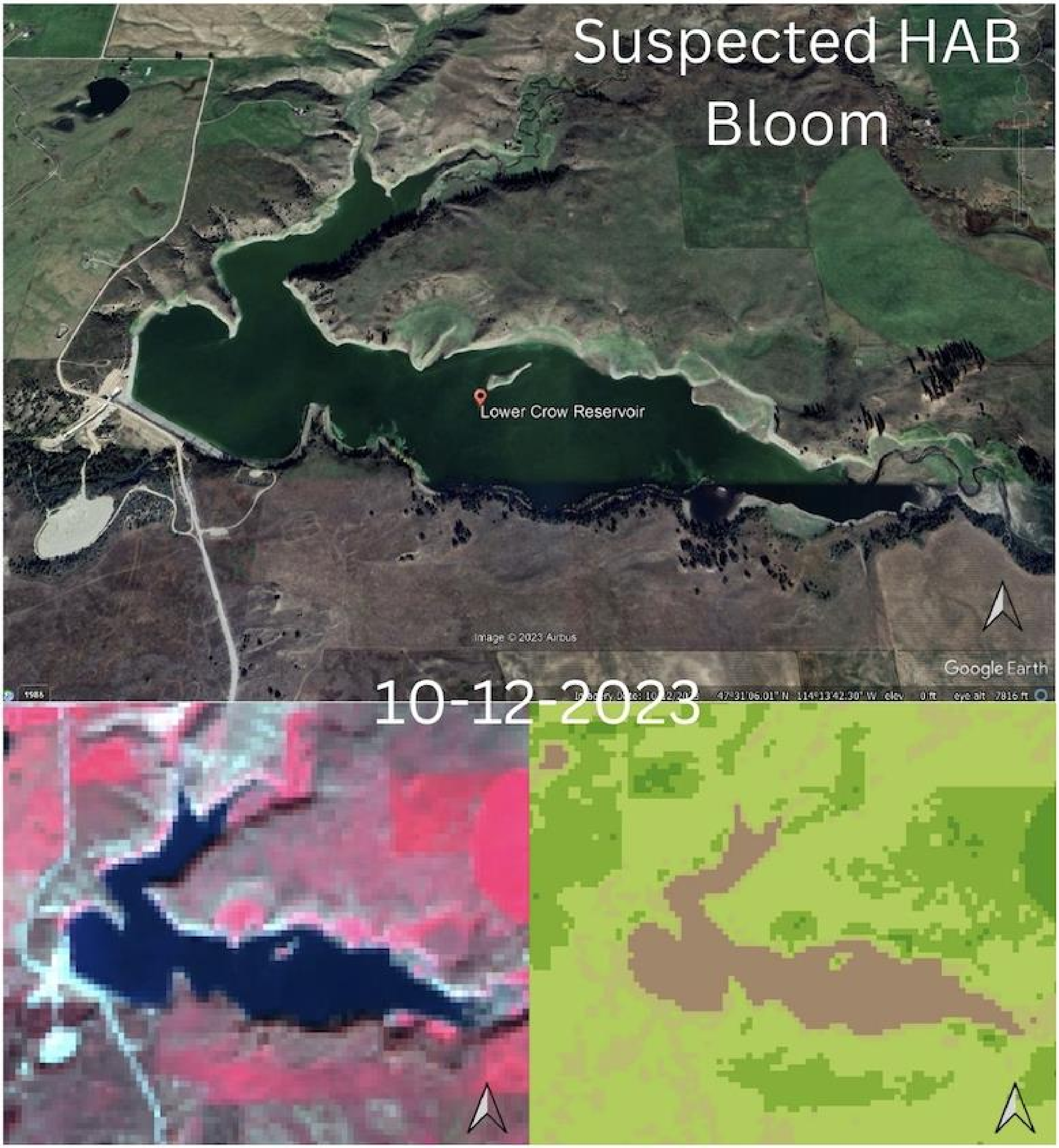

Figure 9. Detection failure at Lower Crow during suspected cHAB event on 10/12/2023

Figure 10. Potential Harmful Algal Bloom Detections in Ninepipe and Pablo Reservoir

Objective 3-Develop a reporting/advisory tool for CSKT water managers and tribal community members to report on cHABs located on the Flathead Indian Reservation

The CSKT Harmful Algal Bloom Report tool (Figure 11) and FIR cHAB Map (Figure 12) will be available to the public on the Confederated Salish & Kootenai Tribes Natural Resource Department website (www.csktnrd.org) following approval by appropriate CSKT personnel and Tribal Council. Questions for the reporting tool were modeled after what data would be useful for CSKT's water quality programs needs regarding future cHABs monitoring efforts on the FIR (Table 7).

Table 7. CSKT cHAB reporting tool questions and data they provide to CSKT managers

HAB Reporting Tool Questions	Data Acquired for Managers from Reporting Tool
Date of Observation (MM/DD/YYYY)	Information on cHAB seasonality that can be used for future modeling efforts
Harmful Algal Bloom Location (i.e., coordinate point collected)	Provides important cHAB location data within FIR for future modeling efforts
Description of Bloom (i.e., localized, widespread)	Provides insight into cHAB extent on the FIR
Waterbody Type (i.e., river, lake, reservoir)	Provides information regarding what type of waterbodies they occur in
Photos (2 photos minimum)	Provides managers with photo data and documentation of cHAB/Suspected cHAB Can be used as an indicator for immediate advisory actions
Accessibility (i.e., public, primitive, private)	Can be used as an indicator for immediate advisory actions
Fish Kills Associated with Bloom?	Provides immediate insight regarding toxicity of bloom Can be used as an indicator for immediate advisory actions
Human Related Illness Associated with Bloom? (i.e., gastrointestinal, rash…)	Provides immediate insight regarding toxicity of bloom to humans. Can be used as an indicator for immediate advisory actions
Animal Related Illness Associated with Bloom? (i.e., vomiting, lethargy, etc.)	Provides immediate insight regarding toxicity of bloom to domestic pets, livestock, and wildlife. Can be used as an indicator for immediate advisory actions

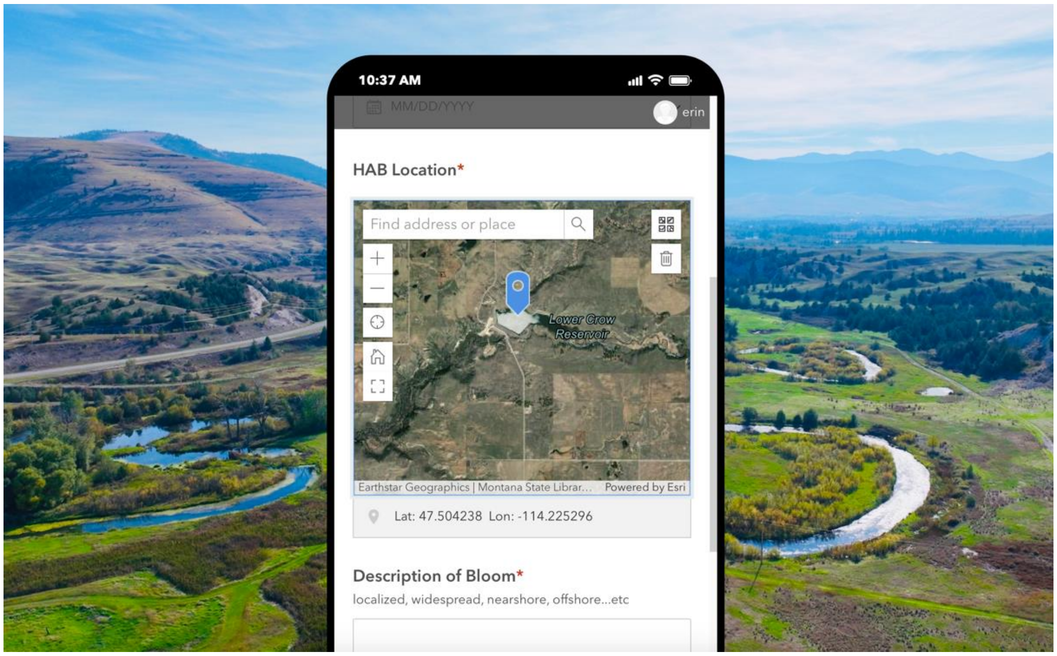

Figure 11. Preview of developed CSKT cHAB Report Tool

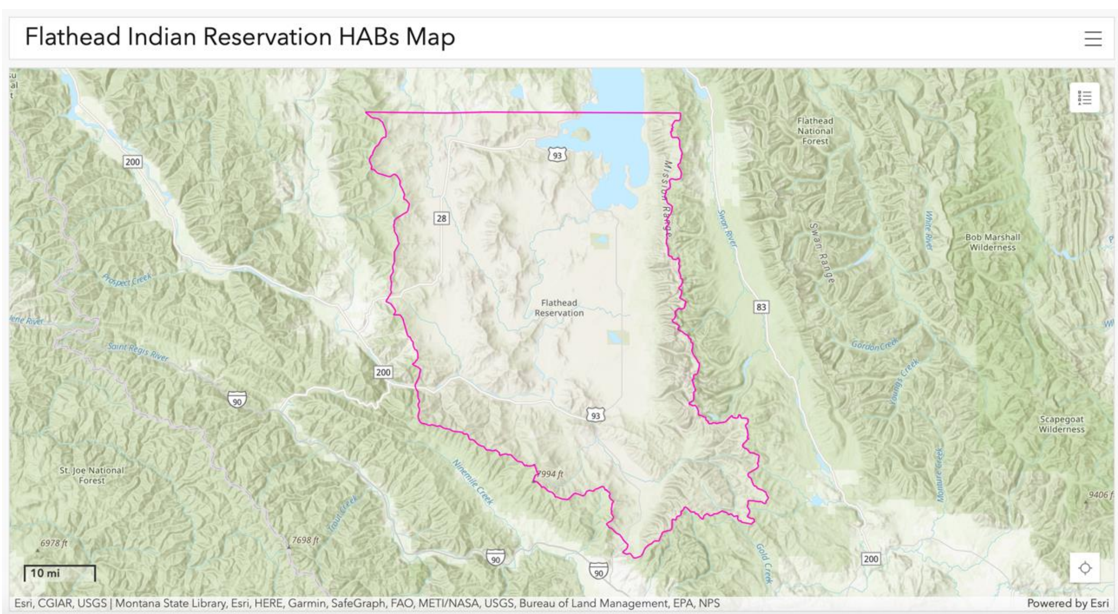

Figure 12. Preview of developed CSKT Flathead Reservation cHAB Map

DISCUSSION

HAB Indicator Limitations

The potential of widespread occurrence of cHABs and their associated health and ecological effects from toxin exposure requires frequent screening and monitoring of lakes and recreational areas. Vulnerabilities of these ecosystems and communities lack fundamental prediction modeling for cHAB events. The Flathead Indian Reservation's vast number of waterbodies challenges the water quality program's ability to monitor all waters. Lack of cHAB data at selected sites on the reservation also presents major challenges to forecasting and modeling potential cHAB events. Collection of field data during both bloom and non-bloom events are integral to modeling and forecast performance. Therefore, it is important that CSKT establish a more systematic and routine field data sampling strategy. This research identified multiple cHAB indicators that water managers should focus their future efforts on, allowing the program to optimize their staffing and financial capacity.

Remote Sensing's Limitations:

Satellite sensors and imagery can provide information regarding suspected cHAB locations and duration, these data can be used to develop monitoring programs and early warning systems that can advise natural resource managers and the public on potentially hazardous conditions. However, the study areas selected were typically small inland waterbodies, except for Flathead Lake, hence spatial resolution may have contributed to failed detection. This result presented challenges for detecting potential cHAB events. Due to the large size of the Flathead Indian Reservation, only a relatively small number of waterbodies were selected for analysis.

Therefore, results do not indicate that cHAB events are not occurring at other areas of the FIR. Satellite data gaps during suspected and confirmed bloom events at Lower Crow could have contributed to the inability to detect blooms using NDVI.

NDVI is typically used to quantify terrestrial vegetation by measuring the difference between near-infrared and red light. Because green algae have a similar spectral characteristic to terrestrial vegetation, NDVI can be used to detect the presence of photosynthetic activity in water. The NDVI analysis can detect offshore photosynthetic activity, but there are limitations to this method.

Failure to detect confirmed cHABs at Lower Crow Reservoir highlighted challenges to this method of detection. This failure could be attributed to the near or onshore distribution of cHAB events. Limitations that challenged the ability of this method to locate cHABs on the reservation were very limited on the ground observation of cHABs, data gaps in satellite images, cloud cover, and spatial resolution of the imagery.

Remote Sensing’s Future Role

Although understanding of cHAB characterization and assessment have improved, remote sensing has become an increasingly important tool for cHAB detection and monitoring (Liu et al., 2022). The U.S. Environmental Protection Agency (EPA), National Aeronautics Space Administration (NASA), National Oceanic Atmospheric Administration (NOAA), U.S. Geological Survey (USGS), and the U.S. Army Corps of Engineers (USACE) partnered on remote sensing cHAB detection methods and recently launched a provisional web application that provides access to satellite-derived cyanobacteria measurements. This allows water managers to pinpoint potential problem areas and where they should be focusing their monitoring efforts, without requiring computer programming expertise. With increased remote sensing technology (Nichols & Hogan, 2022) becoming freely available to water managers (Table 8), remote sensing will be used to maximize monitoring efforts amid low staffing and funding capacity. Remote sensing applications have the potential to play an important role in delivering advisory information to vulnerable communities on the FIR.

Table 8. Satellite sensors used for cHAB detection

Current Satellite Sensors	HAB Indicators in Satellite Sensors
MODIS- Moderate Resolution Imaging Spectro-Radiometer	Sea Surface Temperature (SST), turbidity, ocean color to estimate chlorophyll pigments
MERIS- Medium Resolution Image Spectrometer	SST, turbidity and ocean color to estimate algal biomass from chlorophyll pigments (higher special resolution than MODIS)
VIIRS- NOAA Visible Infrared Imaging Radiometer Suite	SST, turbidity and ocean color to estimate algal biomass from chlorophyll pigments
OLCI- Ocean and Land Color Imager	Chlorophyll a and SST
SeaWifi- Sea-viewing Wide Field-of-View Sensor	Ocean color to estimate algal biomass from chlorophyll pigments
MSI- Multispectral imager	SST, turbidity and ocean color to estimate algal biomass from chlorophyll pigments

cHAB Reporting Tool's Role

Data sovereignty is paramount in tribal governments for protection of important data, as well as keeping primitive areas and cultural sites sacred in nature. Western ideology often does not link ecological data to cultural significance, whereas the tribes view their environmental data as culturally important. The CSKT cHABs Report Tool and FIR Advisory map will better fit the needs of the indigenous community and be a more successful tool, due to the appeal of an internal tool, resulting in more tribal community participation while reinforcing the tribes' rights to data sovereignty. This tool's data will also help guide managers in creating a monitoring framework by understanding the extent and occurrence of cHAB events on the FIR. The cHABs map also provides important waterbody advisory information for the Reservation community and can be used as an early indicator warning system, which allows them to look at potential waterbody advisories or report sightings of cHABs. This tool provides data where there is limited insight into where water managers should start to investigate and monitor for cHABs in reservation waters, and more importantly, which water quality parameters should be used as indicators for vital cHAB environments for future modeling and forecasting efforts.

CONCLUSION

Development of a reporting and monitoring tool would give CSKT water quality managers access to on-the-ground observations of cHAB occurrence on the Flathead Indian Reservation. The cHAB indicators uncovered in this research will help water managers at CSKT to optimize their capacity for their monitoring efforts on Flathead Indian Reservation. It allows effective assessment of the need for cHAB monitoring in hotspot locations and provides tribal community members with an advisory map for waterbody conditions.

Water quality indicators and remote sensing applications did not detect all potential cHAB events on the Flathead Indian Reservation due to the difficultly of detection in small waterbodies. Despite the challenges near-shore cHAB events present, remote sensing plays a significant role in detecting cHABs over large geographical areas. To understand the extent and frequency of cHABs on the Flathead Indian Reservation, future efforts should be devoted to gathering more on-the-ground observations of confirmed cHABs occurrence paired with water quality sampling during bloom and no-bloom occurrences. Once this is achieved, managers can develop a more synthesized framework for cHAB detection where remote sensing applications for routine monitoring, forecasting, and mitigation efforts can be explored. Looking towards the future, this baseline research and recommended next steps aids the CSKT water quality program's efforts in applying for federal grant funding.

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