Boulder Open Space and Mountain Parks

Tracking the Historical Prevalence of Algal Blooms in Boulder Waterbodies Using Satellite Imagery

Technical Report

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1. Abstract

Waterbodies in and near lands managed by Boulder Open Space and Mountain Parks (OSMP) are favored destinations for recreationists, wildlife watchers, and outdoor enthusiasts. In this context, the emergence of harmful algal blooms as a key water quality concern in Colorado's Front Range presents a variety of scientific and management challenges. Prime among these is how to effectively monitor algal blooms over large spatial extents and place current algal bloom data into a historic context. *In situ* water samples currently offer the only pathway through which algal species and toxicity can be identified, but such sampling cannot be applied retrospectively and it may miss the spatiotemporal variability inherent to algal blooms. Remote sensing, while it has drawbacks, offers a complementary approach whereby we can use satellite imagery to track the historical prevalence of algal blooms over a large number of waterbodies. In this work, we apply two different algorithms to 31 years (1990–2020) of reflectance data from five satellite platforms to identify waterbodies in Boulder County that may be experiencing algal blooms and cyanobacterial outbreaks. We also use these data to track whether algal bloom prevalence has changed over time. Overall, we found that algal blooms identified with remote sensing data express marked spatial variability in the waterbodies of Boulder County and that potential cyanobacterial outbreaks are relatively rare compared to other algae. The number of potential cyanobacterial blooms varies from year to year and blooms were not detected in all waterbodies. Satellite imagery also suggest algal bloom prevalence has increased in the previous 11 years (2010–2020) relative to previous levels and that potential cyanobacterial outbreaks reached a peak during 2019. These results indicate the importance of continued monitoring over the coming years in Boulder OSMP waterbodies.

2. Introduction

Although algae are a natural and important component of many aquatic ecosystems (Van Den Hoek et al., 1995), rapid growth may produce harmful algal blooms that pose various public health and water quality challenges. Overly dense algal blooms may reduce light levels within the water column, clog fish gills, or reduce water oxygen levels (Lake Erie Algae, n.d.). Similarly, blooms dominated by cyanobacteria, also known as blue-green algae, can pose serious human health risks, such as skin irritation, gastroenteritis, and neurological issues (Carmichael, 2001). Toxic strains of cyanobacteria can also be lethal to dogs (Edwards et al., 1992), livestock (Beasley et al., 1989), deer (Handeland & Østensvik, 2010), and fish (Malbrouck & Kestemont, 2006). In addition, algal blooms can reduce drinking water quality (Falconer, 1999) and impair recreational experiences (Carvalho et al., 2013; Pilotto et al., 1997). Harmful algal blooms have occurred in inland waterbodies throughout much of the United States, most notably in the Great Lakes region (Michalak et al., 2013). Recent news reports and testing results indicate Colorado waterbodies have not been immune to harmful algal blooms and other water quality issues (Brown, 2020; Colorado Department of Public Health and Environment, 2020; Colorado Department of Public Health and Environment, 2020).

The State of Colorado's *in situ* testing data show the presence of toxic strains of cyanobacteria (i.e., blue-green algae) along the Front Range in waterbodies such as Barr Lake, Sloan's Lake, and Bear Creek Reservoir, among others (Colorado Department of Public Health and Environment, 2020). In 2019, residents were warned that algal blooms in Boulder's Wonderland Lake and Thunderbird Lake may have contained cyanobacteria species (City of Boulder, 2019). This is in addition to previous water quality issues within Boulder County, such as temporary closings of Boulder Reservoir due to heightened bacteria levels and a 2018 fish die-off in Lagerman Reservoir (Boulder County, 2019). These phenomena, plus the previously detailed risks to human and natural systems, suggest that tracking water quality is and will continue to be an important management consideration for Boulder County land managers. From a management perspective, one approach is to monitor waterbodies for algal blooms, cyanobacteria, and other water quality parameters. Typically, such monitoring efforts have focused on discrete *in situ* samples that evaluate water quality at a given location and point in time. Such an approach overlooks the inherent spatiotemporal variability of algal blooms, the scope of sampling may be limited by staff time and financial resources, and sampling cannot be performed retrospectively.

A complementary approach to manual observations is the use of satellite remote sensing data to track the occurrences of algal blooms and cyanobacteria (Jia et al., 2019). Over the past two decades researchers have developed and refined algorithms to monitor algal blooms in inland and coastal waterbodies (Clark et al., 2017; Hu, 2009; Kudela et al., 2015; Oyama et al., 2015; Vincent et al., 2004). These algorithms rely on the differing reflectance properties of clear water versus algae and other vegetation, and they range from the simple to the complex. The recent emergence of open-source software solutions for the rapid mosaicking, processing, and analysis of freely available remote sensing data makes such analyses more time- and cost-effective than ever (Gorelick et al., 2017). Furthermore, the repeatability of such analyses, along with the considerable spatial and temporal coverage of the remotely sensed data, allows for the testing of various algorithms and the creation of long-term datasets of algal bloom frequency.

In this work, we will answer the following research questions using a processed time series of high-resolution remote sensing data:

- **Question 1: Where have algal blooms and cyanobacterial outbreaks historically occurred in Boulder County?** *Approach:* Analyze optical remote sensing scenes from the Landsat and Sentinel satellites to quantify the proportion of observations with potential blooms and outbreaks.

- **Question 2: Has the prevalence of algal blooms and cyanobacterial outbreaks changed over time in Boulder County?** *Approach:* Analyze long-term output from Landsat 5 and 7 to assess differences.

Along with answering the two above research questions, we will also present case studies of eight waterbodies in 2019 to discuss spatial patterning of algal blooms and cyanobacteria. The work presented herein stands to benefit Boulder OSMP, other Front Range municipalities, and the larger scientific community. Fishing, boating, dog-walking, birdwatching, and other recreational pursuits are important to residents of and visitors to Boulder County. However, the use of waterbodies can be limited by water quality issues such as those related to algal blooms. **Thus, a project that identifies where and when algal blooms have historically occurred (Q1) and evaluates changes over time (Q2) will allow for the development of targeted management (e.g., signage, mitigation and monitoring).** As an example, previous research in Vermont's Lake Champlain has informed management strategies on nutrient loading and recreational use of waterbodies (Smyth et al., 2009). From a scientific perspective, the algorithms developed to track algal blooms have been tested primarily in large waterbodies with frequent outbreaks, such as Lake Erie. Our work would therefore provide an opportunity to test these algorithms in small, inland waterbodies, which could both improve management on OSMP lands and enable improved scientific understanding of where and why algal blooms occur.

3. Methods

3.1. Remote sensing fundamentals

Remote sensing is the process by which features and phenomena are observed from a distance, often by airborne or spaceborne sensors. The work detailed in this report relies on the differences in spectral reflectance between clear water and algae as recorded by several satellite platforms. Spectral reflectance is the proportion of radiation reflected from the earth's surface at a given wavelength, or range of wavelengths, in the electromagnetic spectrum (Figure 1). Clear water absorbs most incident radiation, producing low reflectance at most wavelengths. Algae and aquatic vegetation also express low reflectance values in the visible portion of the electromagnetic spectrum but are highly reflective in the near infrared (i.e., wavelengths slightly longer than visible light). At these longer wavelengths, the reflectance of water in the near infrared approaches zero, meaning it absorbs nearly all incoming near infrared radiation. At low concentrations it is difficult to identify algae presence/absence as the spectral signal recorded by the satellite sensor resembles that of clear water; however, as algae prevalence increases, the signal comes to resemble that of algae only (Oyama et al., 2015).

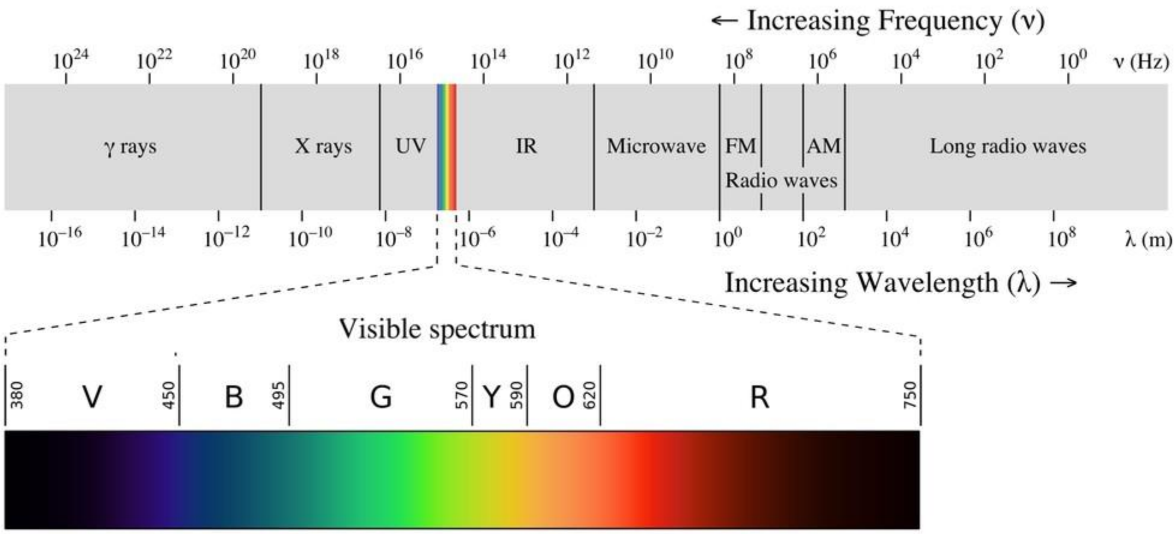

Figure 1. The electromagnetic spectrum with zoomed-in view of the visible portion of the spectrum (V = violet, B = blue, G = green, Y = yellow, O = orange, R = red). Image credit: Philip Ronan, Gringer, CC BY-SA 3.0, via Wikimedia Commons.

In this context, it appears straightforward to identify algal blooms via remote sensing. Complicating matters is the fact that optical satellite sensors do not measure the full electromagnetic spectrum but rather discrete wavelength ranges, referred to as bands. We therefore do not get the full picture from a satellite measurement. To circumvent this shortcoming, researchers have developed a set of algorithms designed to differentiate algal blooms from open water based on differences in spectral reflectance over different bands. Although many such algorithms exist (examples shown in Table 1), our preliminary analysis indicated two promising candidates: 1) the near infrared to red (NIR:Red) band ratio to estimate algal boom presence (Eq. 1) and 2) the floating algae index (FAI) combined with the normalized difference water index (NDWI) to estimate areas with potential cyanobacterial blooms (Eqs. 2 and 3).

$$NIR{:}Red = \frac{R_{NIR}}{R_{Red}} \quad \text{(Eq. 1)}$$

$$FAI = R_{NIR} - \left[R_{Red} + (R_{SWIR1} - R_{Red}) \times \frac{(865 - 655)}{(1610 - 655)}\right] \quad \text{(Eq. 2)}$$

$$NDWI = \frac{(R_{NIR} - R_{SWIR1})}{(R_{NIR} + R_{SWIR1})} \quad \text{(Eq. 3)}$$

In the above equations, R represents the top of atmosphere reflectance (0–1) for a given band (e.g., R_{NIR} is the reflectance value for the NIR band).

Table 1. Example remote sensing algorithms based on differences in spectral reflectance between algae and clear water. Results in this work rely on the NIR:Red band ratio and the FAI combined with NDWI.

Algorithm	Source(s)
Floating Algae Index	(Hu, 2009; Zong et al., 2019)
Normalized Difference Water Index	(Xu, 2006)

Normalized Difference Vegetation Index	(Kahru et al., 1993)
Floating Vegetation Index	(Gao & Li, 2018)
Phycocyanin Content	(Vincent et al., 2004)
Spectral band thresholds	(Oyama et al., 2015)
Band ratios	(Tebbs et al., 2013)

We chose the NIR:Red ratio as previous work has shown it expresses a statistically significant and linear relationship to chlorophyll-a, an indicator of algal bloom presence and magnitude. In general, the NIR:Red ratio increases as the concentration of chlorophyll-a increases in a given body of water. For our analyses, we chose a NIR:Red threshold of 1, where all values equal to or greater than 1 were indicative of an algal bloom. The algorithm based on FAI and NDWI is slightly more complex, employing two thresholds in a rule-based scheme to estimate the presence of a cyanobacterial bloom. First, the FAI differentiates between clear water and algae using a threshold of 0.05. FAI values greater than or equal to 0.05 are considered algae, while those below are considered to be clear water. Next, the NDWI is used to partition algae into cyanobacteria and non-cyanobacteria blooms using a threshold of 0.63. Values greater than or equal to this threshold are considered probable bacterial blooms while those below are not. Here, it is important to underline that both of our chosen methods are empirical and do not measure the concentration of algal blooms directly. Remote sensing is a tool that offers many advantages, but it cannot prove the harmful nature of an inferred algal bloom. Toxicity can only be confirmed via *in situ* sampling and lab testing.

For this project, we applied our selected algorithms to top of atmosphere reflectance data from 5 different satellite platforms, Landsats 5, 7, and 8, and Sentinels 2A and 2B (Table 2). The Landsat series of satellites is a joint venture between the United States Geological Survey (USGS) and the National Aeronautics and Space Administration (NASA). Each Landsat has a nominal spatial resolution of 30 m and a temporal resolution of 16 days. This means every pixel in Landsat imagery for our bands of interest covers a 30 m by 30 m area and each pixel is observed every 16 days. The Sentinel 2 satellites, which are part of the European Space Agency's (ESA) Copernicus Program, have both a higher spatial and temporal resolution than Landsat. This enables a more nuanced examination of algal bloom patterns; however, later launch dates mean they are currently unsuitable for long-term analyses. All satellites, except for Landsat 5, are still in operation. Additionally, we will refer to Sentinel 2A and 2B collectively as Sentinel 2 in the remainder of this report.

Table 2. Technical specifications for the satellite platforms used in this project.

Satellite	Spatial Resolution* (m)	Temporal Resolution‡ (d)	Spectral Range (nm)†	Launch Date	End Date
Landsat 5	30	16	450–12500 (8 bands)	1984-03-01	2013-06-05
Landsat 7	30	16	450–12500 (8 bands)	1999-04-15	NA
Landsat 8§	30	16	433–12500 (11 bands)	2013-02-11	NA
Sentinel 2A	10–20	10	443–2200 (13 bands)	2015-06-23	NA
Sentinel 2B	10–20	10	443–2190 (13 bands)	2017-03-07	NA

*Spatial resolution refers to the length of one side of a remotely sensed pixel. For Landsat, the pixel size for our bands of interest is 30 m X 30 m, or 900 m^2.

‡Temporal resolution is the number of days between satellite overpasses.

†Spectral range is the wavelengths of electromagnetic radiation that the sensor can detect. Landsat 5, 7, and 8 have a thermal infrared band at long wavelengths (> 10000 nm), but most of bands detect wavelengths between ~450 nm and ~2000 nm.

§Processed Landsat 8 time series and imagery data are included in our dataset, but are not detailed in the results section as they cover a shorter period of time than Landsat 7 and do not have the high resolution of Sentinel 2.

3.2. Data processing in Google Earth Engine

The majority of the remote sensing data processing for this project was performed using the open-source Google Earth Engine platform (Gorelick et al., 2017). Google Earth Engine simplifies much of the process of getting from raw satellite data to analysis-ready products through recent advances in cloud computing, allowing researchers to create time series of data from multiple satellites without having to download a single image. For us, it was important to understand how algal bloom prevalence has changed over time and to evaluate spatial patterns using high-resolution imagery over the past several years. To that end, we developed two types of scripts, one that processed the data into time series output at selected locations and another that produced maps showing the annual prevalence of algal blooms. The two scripts shared the following steps in common:

1. Select and load top of atmosphere reflectance data for each sensor into a Google Earth Engine ImageCollection object
2. Filter each imagery dataset to the bounds of Boulder County
3. Redefine bands for the individual sensors (Table 3 through Table 5) to a common naming convention
4. Remove cloudy pixels based on internal cloud mask algorithms
5. Define algorithms and apply them to each image in the collection

Following step 5, the processing protocol diverged for the time series and spatial analyses. For the former, we loaded a selection of sampling points from within 71 waterbodies in Boulder County and then extracted each reflectance and algorithm value for the entire cloud- free dataset. The reasoning for this was threefold: 1) create easily interpretable time series plots of algal bloom presence and magnitude; 2) account for the spatial variability of algal blooms within waterbodies; and 3) mitigate edge effects of pixels that include both water and terrestrial vegetation. Regarding the last item, we classified each sampling point as Edge, Near Edge, or Open Water. Edge, in this context, refers to the boundary between the waterbody and adjacent land or the internal boundary of dense, emergent aquatic vegetation and water. Pixels with the Edge classification share an approximately equal mix of land and water, while Near Edge pixels are primarily water but may include small bits of land or emergent vegetation. In contrast, Open Water points are at least 30 m away from the water-land boundary and should not include any edge effects. Boulder County does have several manmade waterbodies whose water surface area varies markedly throughout the year. In these cases, we identified most sampling points as Near Edge to account for these fluctuations (i.e., pixel may sometimes be Open Water and other times Edge).

For the spatial analyses, we focused our attention on 2019, the year that had the greatest number of cyanobacterial blooms according to the FAI and NDWI algorithm. After completing step 5 in the process detailed above, we created two separate functions that counted the number of times each Sentinel 2 pixel exceeded the NIR:Red threshold and the rule-based, dual thresholds of the FAI and NDWI algorithm. We limited the counting to occur between May and October of 2019, the main period of algal growth and senescence. Once the functions had been applied, we exported the images and used QGIS to mask the output to our waterbodies of interest. To note, the hot, dry summer of 2020 may have been conducive to algal blooms in Boulder County; however, the drought conditions also corresponded with frequent, dense wildfire smoke. As of now, there is little understanding of how wildfire smoke influences remote sensing retrievals of algal blooms, meaning smoke-obscured sensor retrievals from 2020 may not be telling the full story.

Table 3. Landsat 5 and 7 bands along with their associated spectral ranges and spatial resolutions.

Band	Name	Spectral Range (nm)	Spatial Resolution (m)
1	Blue	450–520	30
2	Green	520–600	30
3	Red	630–690	30
4	NIR	770–900	30
5	SWIR1	1550–7500	30
6	TIR	10400–12500	30
7	SWIR2	2090–2350	30
8	Panchromatic	520–900	15

Table 4. Landsat 8 bands along with their associated spectral ranges and spatial resolutions.

Band	Name	Spectral Range (nm)	Spatial Resolution (m)
1	Blue-Violet	433–453	30
2	Blue	450–515	30
3	Green	525–600	30
4	Red	630–680	30
5	NIR	845–885	30
6	SWIR1	1560–1660	30
7	SWIR2	2100–2300	30
8	Panchromatic	500–680	15
9	Cloud	1360–1390	30
10	TIR1	10600–11200	100
11	TIR2	11500–12500	100

Table 5. Sentinel 2 bands. Note: there are slight differences, typically less than 10 nm, between Sentinel 2A and 2B (https://sentinel.esa.int/web/sentinel/user-guides/sentinel-2-msi/resolutions/radiometric).

Band	Name	Spectral Range (nm)	Spatial Resolution (m)
1	Coastal Aerosol	432–453	60
2	Blue	458–523	10
3	Green	543–578	10
4	Red	650–680	10
5	Red Edge 1	698–713	20
6	Red Edge 2	733–748	20
7	Red Edge 3	773–793	20
8	NIR	785–899	10
8a	Narrow NIR	855–875	20
9	Water Vapor	935–955	60
10	SWIR1	1358–1389	60
11	SWIR2*	1565–1655	20
12	SWIR3	2100–2280	20

*SWIR2 for Sentinel 2 corresponds to Landsat SWIR1 when used in the NDWI algorithm (Eq. 3).

3.3. Additional analyses in R and QGIS

Our final processing step in Google Earth Engine was to export CSV files for each sensor and observation point. We then used the open-source R programming language to aggregate the data from the five sensors into a single time series dataset. In R, we summarized data from all observations between May and October to compute annual prevalence of potential algal blooms and cyanobacteria outbreaks using the NIR:Red and FAI plus NDWI thresholds detailed above at each waterbody for each sampling point type. We next evaluated how annual prevalence has changed over time using data from Landsat 5 and 7, the two sensors with the longest data records. Then, to illustrate how potential changes manifest at a given point, we averaged daily data from a single location at Wonderland Lake for Landsat 5 and 7. The plotted data from this analysis show how the NIR:Red ratio increases in magnitude for the latter part of our study period. Finally, we used the open-source QGIS program to mask out land areas from our Google Earth Engine spatial analyses for 2019. We then mapped the number of NIR:Red and FAI plus NDWI threshold exceedances for eight Boulder County waterbodies.

4. Results

4.1. Algal bloom prevalence in Boulder County

Examining all study years and sensors at our sampling points, we found algae to be prevalent in many Boulder County waterbodies as based on a NIR:Red threshold of 1.0 (Figure 2). Edge points express the greatest percentage of observations exceeding the threshold, which is to be expected given the overlap between the water and land within each remote sensing pixel. Near Edge points, which may include some land parts and/or emergent vegetation, also exhibit high percentages, but to a lesser degree than Edge pixels. These sampling points may be detecting algal blooms as each sampled pixel includes a large portion of water. Open Water sampling points should be free of edge effects, making them the most reliable type for determining algal bloom prevalence. These results indicate the incidence of algal blooms varies markedly over Boulder County. Waterbodies expressing the greatest likely prevalence of algal blooms include B.L.I.P. II Pond, Cowdrey Reservoir No. 2, Suitts Pond, Caribou Pond No. 4, Mesa Reservoir near Boulder Valley Ranch, Sombrero Marsh, and Caribou Pond No. 2 (all with Open Water NIR:Red threshold exceedances greater than 80%). In contrast, 12 waterbodies have NIR:Red exceedances less than 10%, including McIntosh Lake, Left Hand Park Reservoir, Marshall Lake, Boulder Reservoir, Davis Reservoir 1, and Left Hand Valley Reservoir.

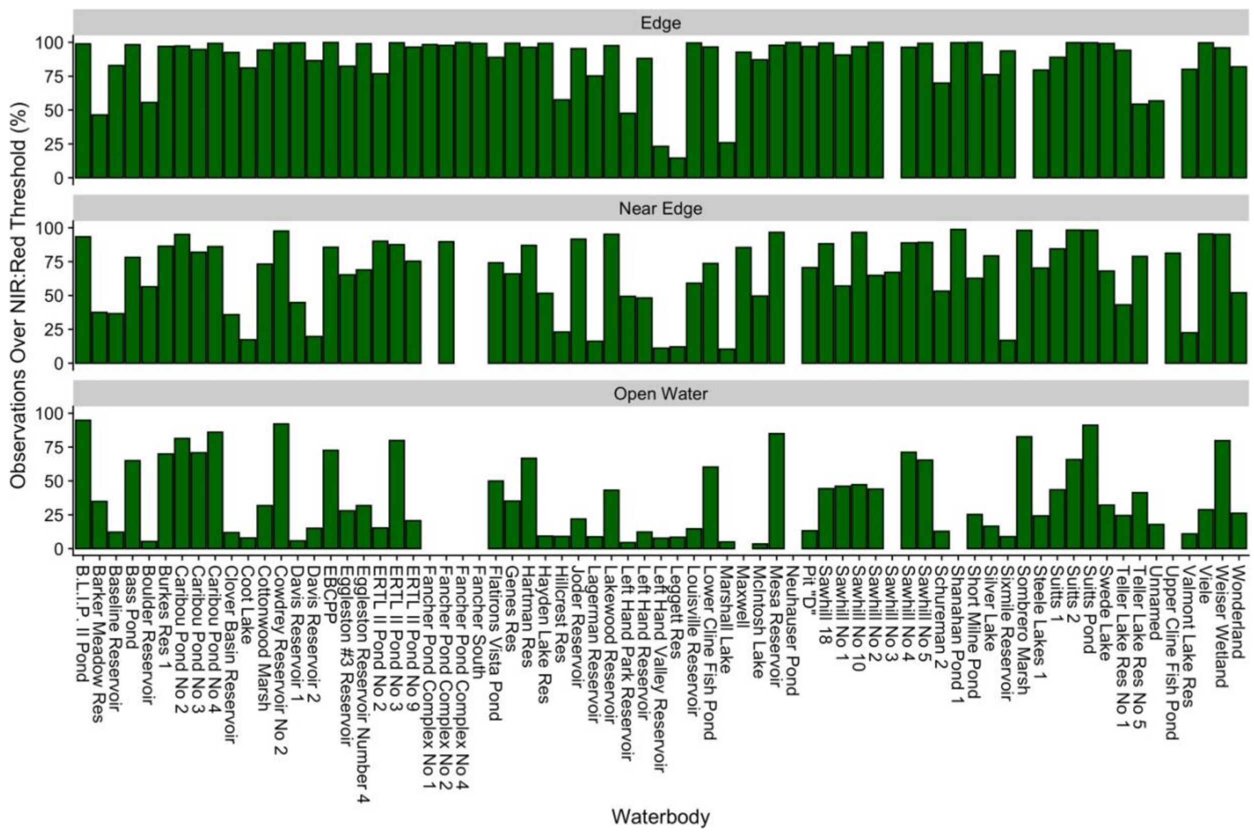

Figure 2. The percent of Edge (top), Near Edge (middle) and Open Water (top) observations exceeding the NIR:Red threshold of 1.0 between May and October across all study years and sensors. Note: Empty spaces in the bar plot mean that waterbody did not have a sampling point of that type (i.e., not all waterbodies have all sampling point types).

When examining sampling points that exceed both the FAI threshold of 0.05 and the NDWI threshold of 0.63, we see the prevalence of possible cyanobacterial blooms in Boulder County is quite low, typically less than 2% for most waterbodies (Figure 3). It is also notable that the differences between Edge, Near Edge, and Open Water sampling points are less pronounced in comparison to the NIR:Red results above. This may be related to the FAI and NDWI algorithm being more complex, whereby emergent or terrestrial vegetation may pass the FAI threshold but then fail the NDWI threshold. Overall, Sombrero Marsh expressed the greatest prevalence of Open Water observations with possible cyanobacterial blooms at 10.9%. This is more than three times greater than the next greatest value, which was 3.1% at Teller Lake No. 5. The only other waterbodies with Open Water possible cyanobacterial bloom prevalence values greater than 1.0% are Cowdrey Draw Reservoir No. 2, Mesa Reservoir near Boulder Valley Ranch, Sawhill No. 1, Caribou Pond No. 4, and Suitts 1. These data suggest cyanobacterial blooms are markedly less common in Boulder County when compared to other algal bloom types.

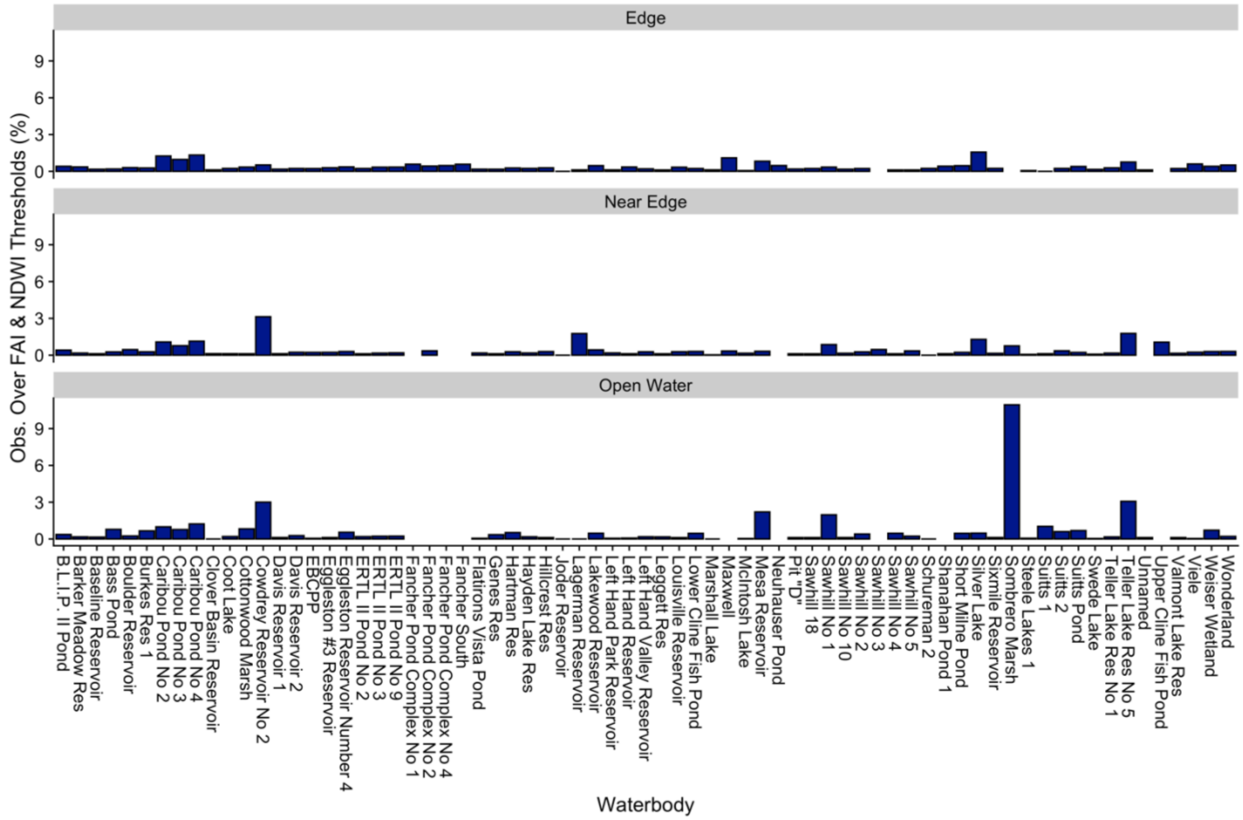

Figure 3. The percent of Edge (top), Near Edge (middle) and Open Water (top) observations exceeding the dual FAI and NDWI thresholds of 0.05 and 0.63 between May and October across all study years and sensors. Note: Empty spaces in the bar plot mean that waterbody did not have a sampling point of that type (i.e., not all waterbodies have all sampling point types).

4.2. Changes in algal bloom prevalence over time

Using a NIR:Red threshold of 1, we found that annual algal bloom prevalence increased over time in our study area when examining output from the two long-term sensors, Landsat 5 and 7 (Figure 4). The percentage of observations exceeding the NIR:Red threshold stayed relatively flat across the Landsat 5 period of record, while increasing during the later Landsat 7 period. Notably this pattern occurred for each of our sampling point types: Edge, Near Edge, and Open Water, suggesting increasing greenness regardless of the amount of water and land in a given pixel. From the first half of the Landsat 7 record (1999–2009) to the second half (2010–2020), NIR:Red exceedances increased from 88.2% to 90.9%, 67.3% to 73.9%, and 38.4% to 43.2% for Edge, Near Edge, and Open Water points, respectively. Open Water had the greatest relative increase of 12.5% with Near Edge slightly less at 9.8% and Edge markedly lower at 3.1%. All observation point types had their largest percentage of observations over the NIR:Red threshold during the 2018 drought year.

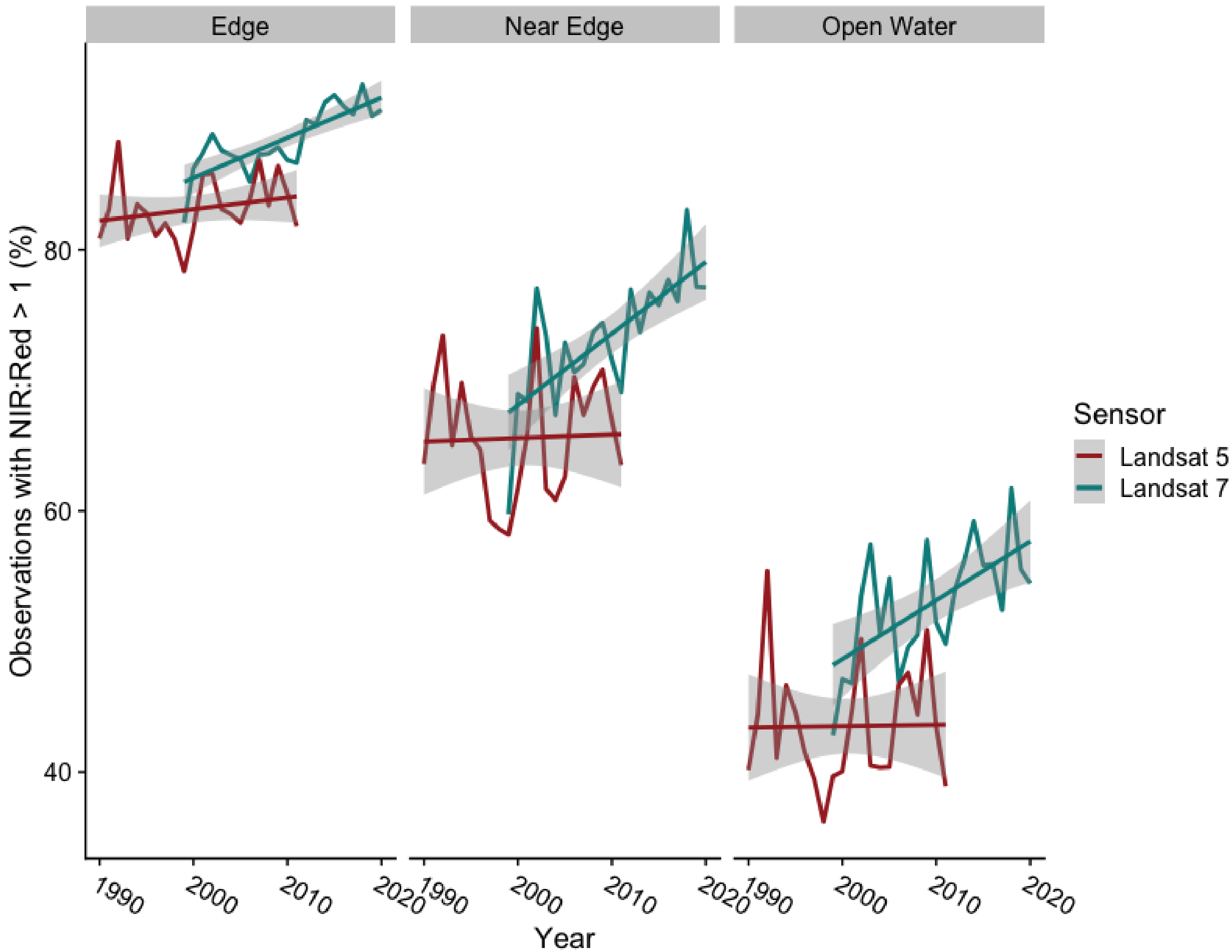

Figure 4. The proportion of edge, near-edge, and open-water observations with a NIR:Red equal to or greater than 1 in a given year between May and October for both the Landsat 5 and 7 sensors.

To illustrate what this phenomenon looks like at a single location, Figure 5 below shows the 10-day moving average of the NIR:Red ratio for all observations using Landsat 5 and 7 for the Near Edge pixel near the peninsula at Wonderland Lake. Here, the values from each sensor are averaged over their entire record and then we apply a 10-day moving average filter to smooth the data. This plot indicates the NIR:Red ratio increases earlier in the year, reaches a higher maximum, and stays higher for longer during the later period of record for Landsat 7 as compared to Landsat 5. This suggests algal blooms may be occurring earlier, lasting longer, and being more concentrated.

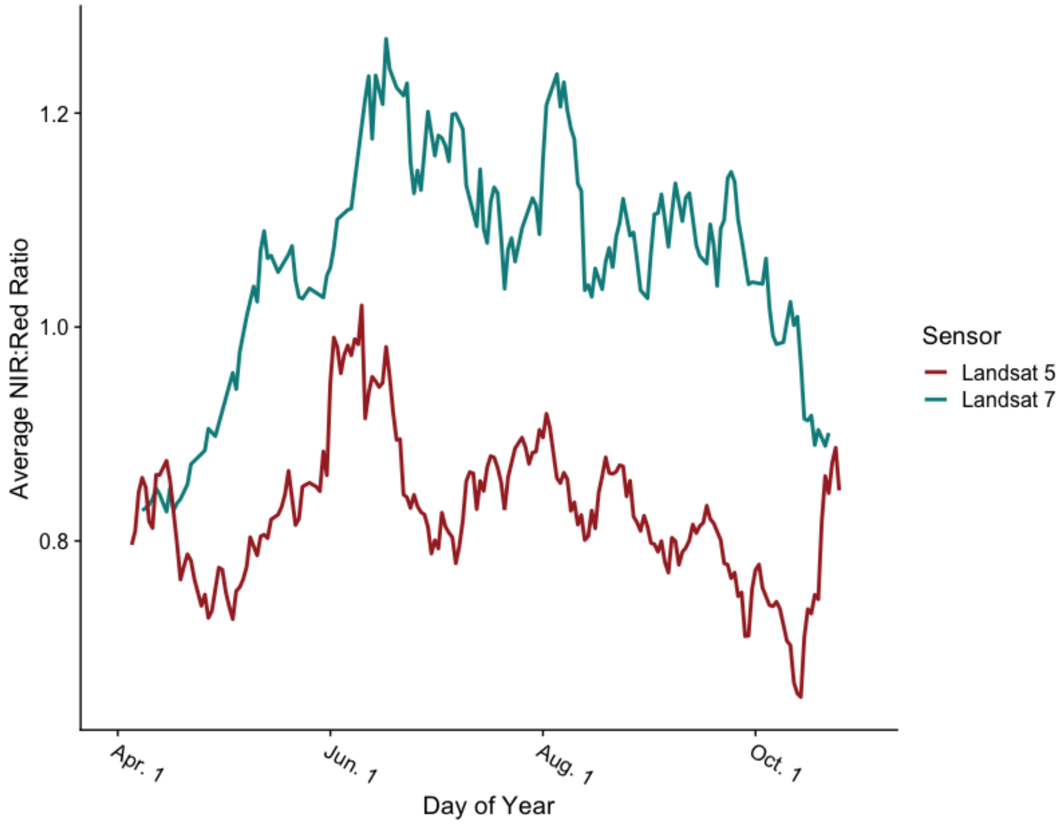

Figure 5. A 10-day moving average of the NIR:Red ratio at a Near Edge sampling point near the peninsula at Wonderland Lake for Landsat 5 and 7.

Possible cyanobacterial blooms, as indicated by exceedances over the FAI and NDWI thresholds, expressed a different temporal pattern than algal blooms in general. Figure 6 shows that total exceedances are typically low, between 0.1% and 0.5% in most years. There were no obvious temporal trends as seen in the NIR:Red exceedances, with the exception being the pronounced spike in 2019. In this year, the Edge and Near Edge sampling points recorded 2.1% and 2.0%, respectively, observations over the FAI and NDWI thresholds, providing a near-fourfold increase over their previous high values. The 2019 value for Open Water was 1.0%, which was less than its record of 1.4% in 1999. These data are consistent with Figure 3, showing low prevalence of probable cyanobacterial blooms in Boulder County.

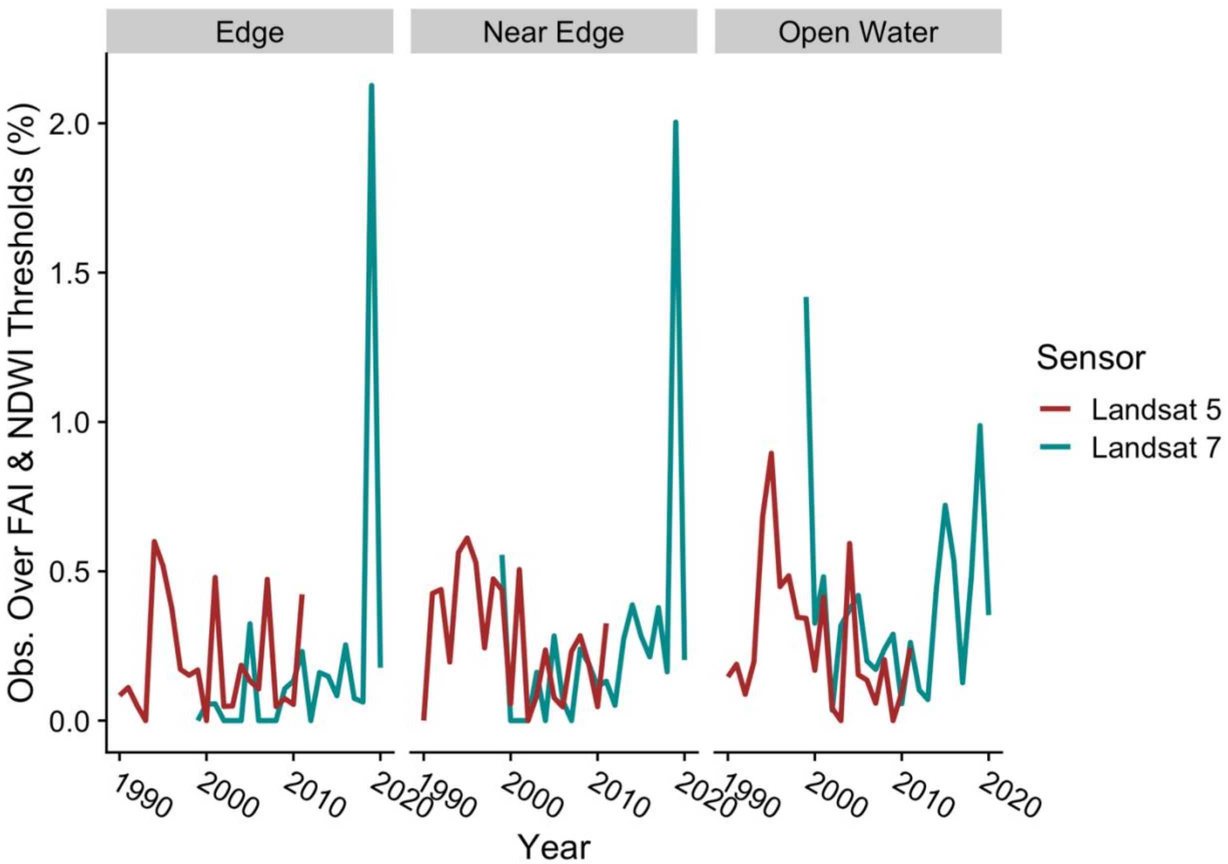

Figure 6. The proportion of Edge, Near Edge, and Open Water observations with an FAI > 0.05 and NDWI > 0.63 in a given year between May and October for both the Landsat 5 and 7 sensors.

4.3. Spatial pattern of algal and cyanobacterial blooms in 2019

In this section, we use high-resolution Sentinel 2 data from 2019 to examine the spatial patterning of probable algal and cyanobacterial blooms at a selection of waterbodies in Boulder County. This year was chosen as it had the highest incidence of observations over the FAI and NDWI thresholds at Edge and Near Edge pixels, and the second highest at Open Water pixels, according to Landsat 7 data (Figure 6). We chose waterbodies for spatial analysis in collaboration with Boulder OSMP, eight of which are shown below in alphabetical order: Boulder Reservoir, Lagerman Reservoir, Sawhill No. 1, Sombrero Marsh, Teller Lakes No. 1 and 5, Viele Lake, and Wonderland Lake.

Although Boulder Reservoir has experienced intermittent shutdowns as a result of elevated bacterial levels, there was limited evidence for algal and cyanobacterial blooms from 2019 in our spatial analysis (Figure 7). Most of the NIR:Red exceedances were located around the western fringe of the waterbody and may have resulted from emergent vegetation or edge effects. We recorded no probable cyanobacterial blooms.

Figure 7. The number of exceedances counted using the NIR:Red threshold (left) and the FAI and NDWI thresholds (right) from April 1st 2019 through October 31st 2019 at Boulder Reservoir. The greater the number of exceedances, the more persistent a probable algal or cyanobacterial bloom may be. Satellite imagery: © 2020 Google, CNES / Airbus, Maxar Technologies, Public Laboratory, U.S. Geological Survey, USDA Farm Service Agency.

In contrast, at Lagerman Reservoir in Longmont, satellite data indicated a potential cyanobacterial bloom and algal growth throughout much of the waterbody (Figure 8). Some of the NIR:Red exceedances can be attributed to edge effects and emergent vegetation, but exceedances in the open water suggest a potential algal bloom in 2019.

Figure 8. The number of exceedances counted using the NIR:Red threshold (left) and the FAI and NDWI thresholds (right) from April 1st 2019 through October 31st 2019 at Lagerman Reservoir. The greater the number of exceedances, the more persistent a probable algal or cyanobacterial bloom may be. Satellite imagery: © 2020 Google, CNES / Airbus, Maxar Technologies, Public Laboratory, U.S. Geological Survey, USDA Farm Service Agency.

Similarly, Sawhill No. 1 and Sombrero Marsh present evidence of widespread algal blooms and potential cyanobacterial outbreaks in 2019 (Figure 9 and Figure 10). Both waterbodies have emergent vegetation within their boundaries, but the areas of open water can be processed independently using the high-resolution Sentinel 2 data. This indicates algae were likely present at Sawhill No. 1 and Sombrero Marsh, making them candidates for future monitoring and testing.

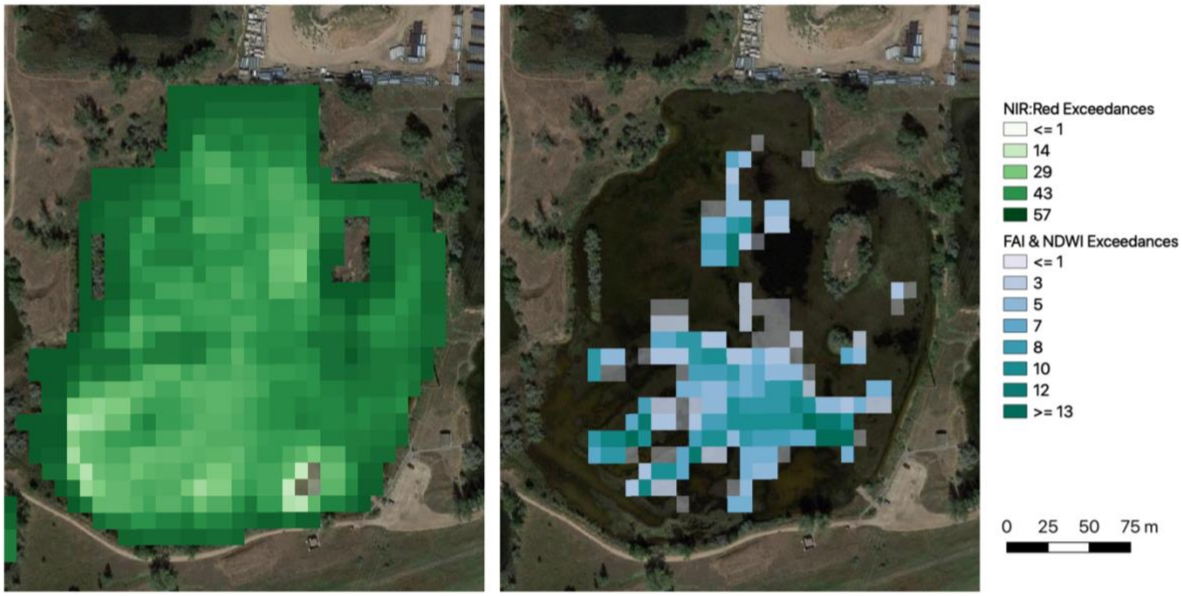

Figure 9. The number of exceedances counted using the NIR:Red threshold (left) and the FAI and NDWI thresholds (right) from April 1st 2019 through October 31st 2019 at Sawhill No. 1. The greater the number of exceedances, the more persistent a probable algal or cyanobacterial bloom may be. Satellite imagery: © 2020 Google, CNES / Airbus, Maxar Technologies, Public Laboratory, U.S. Geological Survey, USDA Farm Service Agency.

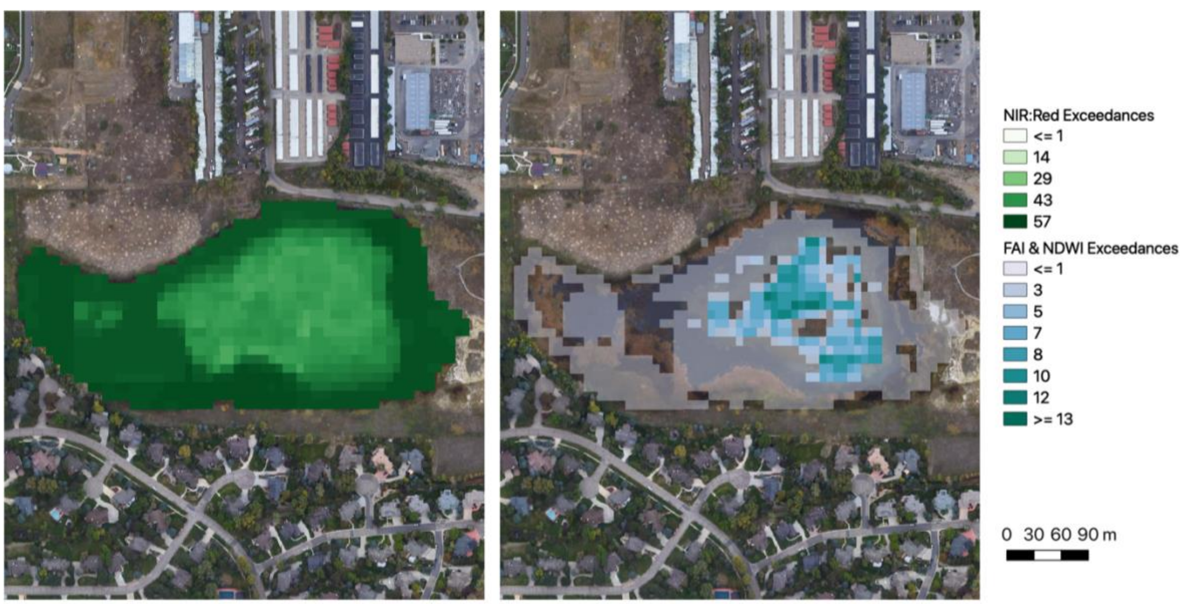

Figure 10. The number of exceedances counted using the NIR:Red threshold (left) and the FAI and NDWI thresholds (right) from April 1st 2019 through October 31st 2019 at Sombrero Marsh. The greater the number of exceedances, the more persistent a probable algal or cyanobacterial bloom may be. Satellite imagery: © 2020 Google, CNES / Airbus, Maxar Technologies, Public Laboratory, U.S. Geological Survey, USDA Farm Service Agency.

Next up are Teller Lakes No. 1 and 5. Although nearby one another, the two expressed markedly different spatial patterns in 2019 (Figure 11 and Figure 12). At Teller Lake No. 1, NIR:Red exceedances were most prevalent near the edges, with some potential algae recorded in open water. Cyanobacteria evidence was limited, with several pixels showing potential processing artifacts but no consistent outbreak patterns. On the other hand, Teller Lake No. 5 exhibited both a possible cyanobacterial bloom and a large number of NIR:Red exceedances in its open water areas. However, as a result of emergent vegetation and fluctuating lake levels, care should be taken in interpreting these results. Similar to Sombrero Marsh and Sawhill No. 1, these patterns warrant further investigation.

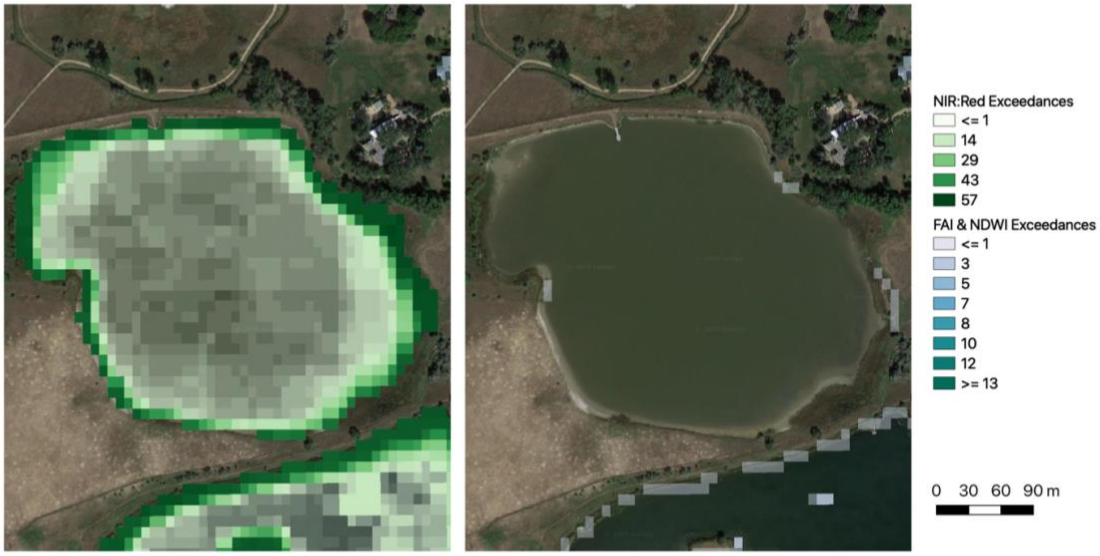

Figure 11. The number of exceedances counted using the NIR:Red threshold (left) and the FAI and NDWI thresholds (right) from April 1st 2019 through October 31st 2019 at Teller Lake No. 1. The greater the number of exceedances, the more persistent a probable algal or cyanobacterial bloom may be. Satellite imagery: © 2020 Google, CNES / Airbus, Maxar Technologies, Public Laboratory, U.S. Geological Survey, USDA Farm Service Agency.

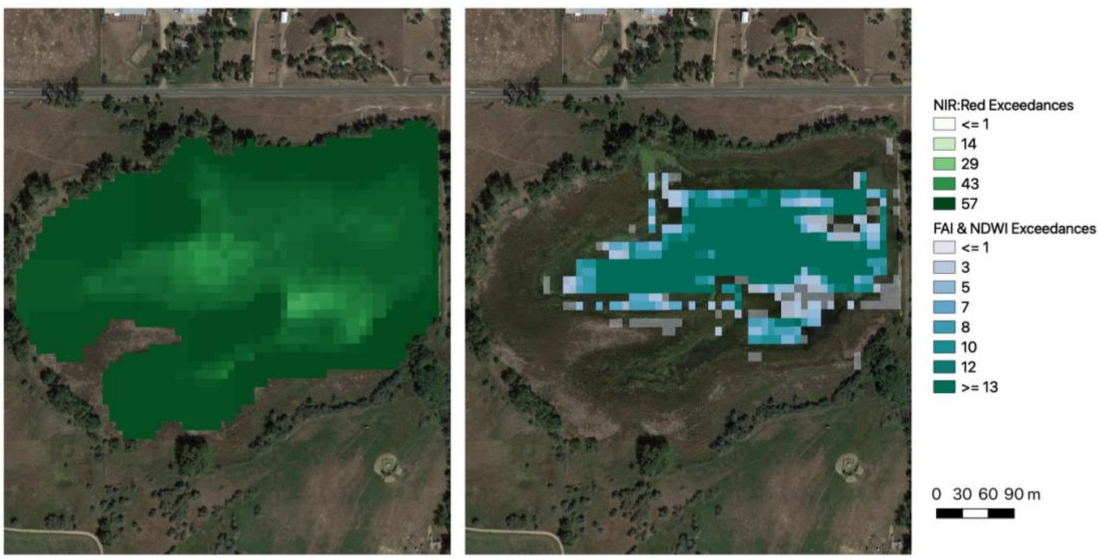

Figure 12. The number of exceedances counted using the NIR:Red threshold (left) and the FAI and NDWI thresholds (right) from April 1st 2019 through October 31st 2019 at Teller Lake No. 5. The greater the number of exceedances, the more persistent a probable algal or cyanobacterial bloom may be. Satellite imagery: © 2020 Google, CNES / Airbus, Maxar Technologies, Public Laboratory, U.S. Geological Survey, USDA Farm Service Agency.

Viele Lake, part of Harlow Platts Community Park, is located near Fairview High School in a residential area of Boulder. 2019 data suggest limited evidence for potential cyanobacterial presence, but large numbers of NIR:Red exceedances (Figure 13). Although large exceedances are primarily near the edge of the waterbody, many of the high-value pixels are far enough away to not be affected by terrestrial vegetation. As with other waterbodies we have examined, this indicates algal blooms may be most prevalent around near the lake-shoreline interface.

Figure 13. The number of exceedances counted using the NIR:Red threshold (left) and the FAI and NDWI thresholds (right) from April 1st 2019 through October 31st 2019 at Viele Lake in Boulder. The greater the number of exceedances, the more persistent a probable algal or cyanobacterial bloom may be. Satellite imagery: © 2020 Google, CNES / Airbus, Maxar Technologies, Public Laboratory, U.S. Geological Survey, USDA Farm Service Agency.

Our final waterbody, Wonderland Lake, is one of the crown jewels of the Boulder OSMP system. Similar to Viele Lake above, we found evidence of algal blooms primarily near the shoreline according to NIR:Red exceedances (Figure 14). Many of these pixels are far enough away to not be influenced by terrestrial vegetation, again indicating algal blooms were occurring at the edge of the waterbody. Although taken in 2020, a photo from the eastern shoreline in Wonderland Lake shows an ongoing algal bloom (Figure 15), which is consistent with the remote sensing data. We found no evidence of cyanobacterial blooms in 2019 when using the FAI and NDWI thresholds.

Figure 14. The number of exceedances counted using the NIR:Red threshold (left) and the FAI and NDWI thresholds (right) from April 1st 2019 through October 31st 2019 at Wonderland Lake in Boulder. The greater the number of exceedances, the more persistent a probable algal or cyanobacterial bloom may be. Satellite imagery: © 2020 Google, CNES / Airbus, Maxar Technologies, Public Laboratory, U.S. Geological Survey, USDA Farm Service Agency.

Figure 15. Algae visible on the east shore of Wonderland Lake, June 5th, 2020.

5. Discussion

5.1. Remote sensing results in context

Our remote sensing analysis indicates the prevalence of algal blooms varies over space and time in Boulder County waterbodies. While some Open Water pixels exceed the NIR:Red threshold over 80% of the time, others exceed it less than 10% of the time, meaning algal blooms can only be understood on a waterbody-by-waterbody basis. Older statewide data indicates chlorophyll-a concentrations vary by several orders of magnitude in large Colorado waterbodies, from the single to triple digits (Colorado Water Quality Forum, 2012). Boulder's own water quality data indicate chlorophyll-a levels in Barker, Boulder, and Silver Lake Reservoirs are typically less than 10 µg l^{-1}, making them relatively free of algae, at least at the sampling points. Because higher NIR:Red values are associated with greater chlorophyll-a concentrations (Tebbs et al., 2013), the waterbodies with larger ratios and a greater number of exceedances are possibly experiencing more concentrated, more persistent algal blooms.

In regard to cyanobacteria, the state has recently started publishing its testing data from various Colorado waterbodies (Colorado Department of Public Health and Environment, 2020). Their results show that the species of algae and toxicity levels vary from location to location and across time at a single waterbody. Similarly, we found from the remote sensing data that possible cyanobacterial blooms were not found in every waterbody and that the frequency varies from year to year. Additionally, the FAI and NDWI algorithm indicated cyanobacteria are relatively rare in Boulder, but this may warrant further investigation and *in situ* testing given the adverse public health and water quality impacts of blue-green algae.

5.2. Assumptions and limitations

Our findings rely on remote sensing data and the application of two empirical algorithms to estimate the presence of algae and cyanobacteria. Although our approach has numerous advantages, including retrospective analyses and the ability to evaluate large spatial extents, it has several key assumptions and limitations. The NIR:Red algorithm, for example, assumes the difference in reflectance between clear water and algae can be leveraged to estimate the presence of an algal bloom. While this is true, the algorithm may infer a potential bloom when a remote sensing pixel also includes terrestrial vegetation and/or emergent aquatic vegetation. Making this even more problematic is that other remote sensing work has shown algae often accumulates at the land-water interface, meaning the most difficult areas to observe remotely are also the most likely to have algal blooms. Likewise, care should be taken when interpreting the cyanobacteria results. Toxicity and algal species can only be proved using water samples and laboratory sampling, so we recommend that our findings be used to guide future targeted monitoring strategies.

When examining the long-term satellite data, we detected a moderate increase in algal bloom incidence from the early to later part of the Landsat 7 record. Although this is indicative of an increasing trend in algal blooms, care should be taken in interpreting the results. One, Landsat 7 has a fairly short record for computing trends, meaning interannual variations may have an outsized effect on trend detection. In other words, a year with low algal bloom prevalence early in the record coupled with a high year later in the record could give the appearance of a trend, when a longer term analysis would not detect one. And, two, Landsat 7 appears to indicate greater algal bloom prevalence than Landsat 5. The satellites use similar sensors that detect reflectance over similar bands, but they are not identical. Therefore, small differences in algorithm output would be expected from the two instruments.

In addition to limitations from the algorithms, we also note that optical data from the Landsat and Sentinel 2 instruments are used less frequently than other sensors in algal bloom work. Previous and ongoing research has relied on output from the Moderate Resolution Imaging Spectroradiometer (MODIS), Sentinel 3, and the Medium Resolution Imaging Spectrometer (MERIS). These are multispectral satellite platforms that measure reflectance in 15 (MERIS) to 21 (Sentinel 3) bands. MODIS measures up to 36 bands when including wavelengths longer than the near-infrared. This large number of bands and generally higher spectral resolution when compared to Landsat and Sentinel 2 allows for the deployment of more advanced algorithms that may better detect algal blooms. However, a major shortcoming of these sensors is their large spatial resolution, which ranges from 300 m for Sentinel 3 and MERIS to 500 m for MODIS. This large footprint precludes their use in small waterbodies. To illustrate this problem, Wonderland Lake is approximately only 150 m wide as measured from north to south at its midpoint. Thus, a single remote sensing pixel from one of these platforms would include both water and land, making them unsuitable for analysis in our study area. To note, Lagerman Reservoir is currently tracked by the Environmental Protection Agency's CyAN project despite likely producing mixed pixels as a result of its size and shape.

Lastly, our findings only address the potential presence and trend in presence of algae and cyanobacteria in Boulder County waterbodies. Observing the presence and tracking any trends is a critical first step. However, additional detailed information, that was beyond the scope of this work, is needed to evaluate whether any of the observed changes we note is of ecological significance.

5.3. Management implications

The evidence presented above indicates algal blooms may be an increasingly important phenomenon in Boulder County waterbodies. Seeing the blooms as an emerging problem gives Boulder OSMP the opportunity to learn how algal blooms are being managed by other municipalities. For some, this starts with enhanced water quality monitoring and sharing those results with the community. In Austin, TX, the city has created a webpage with information about algal blooms, why they develop, and the risks they pose to humans and animals (City of Austin, 2020). From this page, users can access a desktop or mobile version of an online dashboard that displays algal presence, cyanotoxin, and water temperature data (Figure 16). Visitors to the site can thus identify which areas to avoid when planning water-based outings.

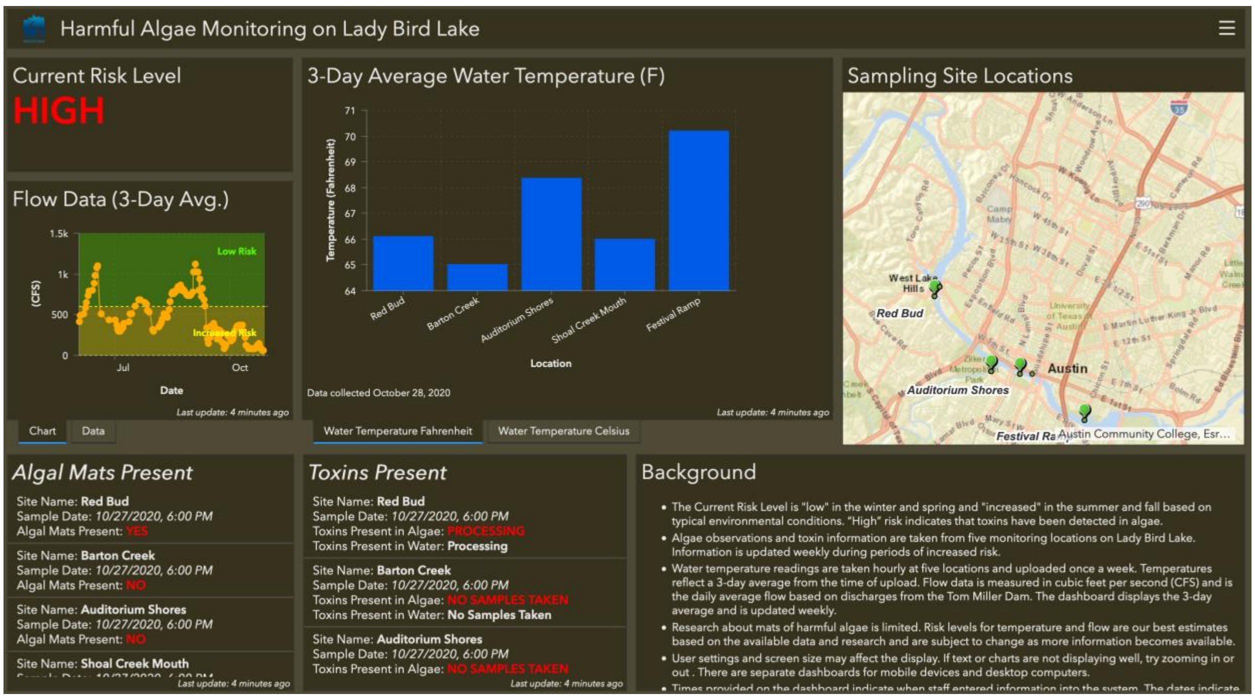

Figure 16. Algae dashboard for Austin, TX displaying risk level, water temperature, sampling locations, algae presence, cyanotoxin testing data, and other background information* (City of Austin, 2020). *Dashboard link: https://arcg.is/0KmGbO

At the state level, Vermont has a similar page where people can access information about harmful algal blooms, including testing data, risk levels, and potential dangers. The page also includes data and reports from previous years along with a link to an interactive dashboard that show current testing results and risk across the state (State of Vermont, 2020). In Colorado, the Department of Public Health and Environment publishes its own cyanobacteria dashboard to keep citizens informed of ongoing blooms and toxicity issues.

The cost of *in-situ* testing for the presence of cyanobacteria and associated toxins can be prohibitive, especially for a department like OSMP that has over 200 waterbodies on lands under its management. Additionally, cyanobacteria are known to exhibit spatial and temporal variability in the waterbodies they inhabit. This means simple random testing of waterbodies may yield results that are misleading, offering the public assurances that can change on a day-to-day basis (i.e., in between monitoring events). These considerations, along with cost, must be balanced when considering any new in situ monitoring program.

Some jurisdictions have turned to citizen scientists to help defray cost of monitoring. Vermont includes citizen observers in its program through its collaboration with the Lake Champlain Committee that trains volunteers to monitor algal blooms via photographs and water quality samples. Citizen Science Tahoe also uses crowdsourced photographs to track algal bloom presence in the Lake Tahoe area. Previous research in the citizen science domain has shown the use of volunteer observers can increase science literacy, engage the community, and stretch limited resources to accomplish scientific objectives. While volunteer programs are not cost-free for sponsor agencies, these ongoing projects suggest it may be useful to engage citizen scientists in monitoring efforts moving forward.

Other management strategies that may help defray the cost that are worth considering include drone-based monitoring, which would allow a higher spatial resolution analysis of algal bloom patterns than satellite data. Boulder OSMP may also wish to collaborate with the state as the state may have funding to support monitoring and management of this emerging concern.

In addition to identifying where and when algal blooms have occurred, it is important to evaluate why they have occurred in order to further guide *in situ* monitoring and management strategies. Previous research suggests algal blooms occur more frequently in stagnant waterbodies, during periods of warm air temperatures, and when phosphorous and nitrogen levels are elevated (Paerl et al., 2016). Many of the urban landscapes surrounding waterbodies within the city limits provide ample sources (e.g. fertilized lawns and parks) for these nutrients. While these patterns may be useful to management and planning, there are significant opportunities to improve our knowledge of the relationships between algal bloom frequency and easily observed climatic, hydrologic, physiographic, and land use/land cover quantities. In particular, machine learning strategies (Breiman, 2001) show promise in being able to quantify relationships between observed phenomena and predictor variables (Addor et al., 2018; Bachmair et al., 2017). As Boulder OSMP moves to tackle the management challenges posed by algal blooms, it may consider some of these strategies in the years to come.

6. Conclusions

We used two remote sensing algorithms to track the prevalence of algal blooms and cyanobacterial outbreaks in Boulder County waterbodies. Results from the NIR:Red algorithm, which is the reflectance ratio between the near infrared and red bands, showed possible algal bloom presence varies from less than 10% to over 80% in Boulder County waterbodies. Time series analysis indicated the prevalence of algal blooms has increased from the 1999–2009 period to the 2010–2020 period. Results from a dual-threshold (FAI and NDWI), rule-based algorithm showed possible cyanobacterial blooms are infrequent in Boulder County, with the greatest number occurring in 2019. High-resolution satellite data from 2019 covering eight different waterbodies revealed different spatial patterns in algal blooms and cyanobacterial outbreaks, depending on the location being examined. Although the remote sensing algorithms have key limitations, they offer an unparalleled look into the historical prevalence of algal blooms in Boulder County.

7. Data and code availability

All raw remote sensing data used in this project can be found on Google Earth Engine:

- Landsat 5
- Landsat 7
- Landsat 8
- Sentinel 2

The lead author can be contacted for all Google Earth Engine code and pre-processed remote sensing data (kjennings@lynker.com). R code used to analyze the data can be found on the lead author's GitHub page: https://github.com/SnowHydrology/algal_blooms.

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9. Citations

Addor, N., Nearing, G., Prieto, C., Newman, A. J., Le Vine, N., & Clark, M. P. (2018). A Ranking of Hydrological Signatures Based on Their Predictability in Space. *Water Resources Research*, *54*(11), 8792–8812. https://doi.org/10.1029/2018WR022606

Bachmair, S., Svensson, C., Prosdocimi, I., Hannaford, J., & Stahl, K. (2017). Developing drought impact functions for drought risk management. *Natural Hazards and Earth System Sciences*, *17*(11), 1947–1960. https://doi.org/10.5194/nhess-17-1947-2017

Beasley, V. R., Cook, W. O., Dahlem, A. M., Hooser, S. B., Lovell, R. A., & Valentine, W. M. (1989). Algae intoxication in livestock and waterfowl. *The Veterinary Clinics of North America. Food Animal Practice*, *5*(2), 345–361. https://doi.org/10.1016/S0749-0720(15)30980-4

Boulder County. (2019). Lagerman Agricultural Preserve - Boulder County. Retrieved January 7, 2020, from https://www.bouldercounty.org/open-space/parks-and-trails/lagerman/

Breiman, L. (2001). *Random Forests* (Vol. 45).

Brown, J. (2020, August 20). Toxic algae are filling Colorado lakes with slimy pea-green soup. Are hotter summers making it worse? . Retrieved November 25, 2020, from https://coloradosun.com/2020/08/20/toxic-algae-in-colorado-lakes/

Carmichael, W. W. (2001). Health effects of toxin-producing cyanobacteria: "The CyanoHABs." *Human and Ecological Risk Assessment (HERA)*, *7*(5), 1393–1407. https://doi.org/10.1080/20018091095087

Carvalho, L., Mcdonald, C., de Hoyos, C., Mischke, U., Phillips, G., Borics, G., et al. (2013). Sustaining recreational quality of European lakes: Minimizing the health risks from algal blooms through phosphorus control. *Journal of Applied Ecology*, *50*(2), 315–323. https://doi.org/10.1111/1365-2664.12059

City of Austin. (2020). Algae | AustinTexas.gov. Retrieved November 5, 2020, from http://austintexas.gov/page/algae

City of Boulder. (2019). City of Boulder Encourages Residents to Be Cautious of Algae Blooms at Lakes and Ponds. Retrieved January 7, 2020, from https://bouldercolorado.gov/newsroom/city-of-boulder-encourages-residents-to-be-cautious-of-algae-blooms-at-lakes-and-ponds

Clark, J. M., Schaeffer, B. A., Darling, J. A., Urquhart, E. A., Johnston, J. M., Ignatius, A. R., et al. (2017). Satellite monitoring of cyanobacterial harmful algal bloom frequency in recreational waters and drinking water sources. *Ecological Indicators*, *80*, 84–95. https://doi.org/10.1016/j.ecolind.2017.04.046

Colorado Department of Public Health and Environment. (2020). Toxic Algae (Harmful Algae Blooms) | Department of Public Health and Environment. Retrieved November 5, 2020, from https://www.colorado.gov/pacific/cdphe/harmful-algae-blooms

Colorado Department of Public Health and Environmnent. (2020). *Integrated Water Quality Monitoring & Assessment Report*. Retrieved from https://drive.google.com/open?id=1tkjTqyKeti4lgs42d2hLh-Q6IFLJF4bh

Colorado Water Quality Forum. (2012). Nutrient Criteria - Data Summary on the Average Chlorophyll in Colorado Lakes. Retrieved September 28, 2020, from http://colowqforum.org/pdfs/nutrient-criteria/04-2011/Data Summer Avg Chlorophyll CO Lakes.xlsx

Edwards, C., Beattie, K. A., Scrimgeour, C. M., & Codd, G. A. (1992). Identification of anatoxin-A in benthic cyanobacteria (blue-green algae) and in associated dog poisonings at Loch Insh, Scotland. *Toxicon*, *30*(10), 1165–1175. https://doi.org/10.1016/0041-0101(92)90432-5

Falconer, I. R. (1999). An overview of problems caused by toxic blue-green algae (cyanobacteria) in drinking and recreational water. *Environmental Toxicology*. https://doi.org/10.1002/(SICI)1522-7278(199902)14:1<5::AID-TOX3>3.0.CO;2-0

Gao, B.-C., & Li, R.-R. (2018). FVI—A Floating Vegetation Index Formed with Three Near-IR Channels in the 1.0–1.24 μm Spectral Range for the Detection of Vegetation Floating over Water Surfaces. *Remote Sensing*, *10*(9), 1421. https://doi.org/10.3390/rs10091421

Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., & Moore, R. (2017). Google Earth Engine: Planetary-scale geospatial analysis for everyone. *Remote Sensing of Environment*, *202*, 18–27. https://doi.org/10.1016/j.rse.2017.06.031

Handeland, K., & Østensvik, Ø. (2010). Microcystin poisoning in roe deer (Capreolus capreolus). *Toxicon*, *56*(6), 1076–1078. https://doi.org/10.1016/j.toxicon.2010.06.023

Van Den Hoek, C., Mann, D. G., & Jahns, H. M. (1995). *Algae: an introduction to phycology*. *Search*. https://doi.org/10.2307/1468159

Hu, C. (2009). A novel ocean color index to detect floating algae in the global oceans. *Remote Sensing of Environment*, *113*, 2118–2129. https://doi.org/10.1016/j.rse.2009.05.012

Jia, T., Zhang, X., & Dong, R. (2019). Long-term spatial and temporal monitoring of cyanobacteria blooms using MODIS on google earth engine: A case study in taihu lake. *Remote Sensing*, *11*(19), 2269. https://doi.org/10.3390/rs11192269

Kahru, M., Leppanen, J. M., & Rud, O. (1993). Cyanobacterial blooms cause heating of the sea surface. *Marine Ecology Progress Series*, *101*(1–2), 1–8. https://doi.org/10.3354/meps101001

Kudela, R. M., Palacios, S. L., Austerberry, D. C., Accorsi, E. K., Guild, L. S., & Torres-Perez, J. (2015). Application of hyperspectral remote sensing to cyanobacterial blooms in inland waters. *Remote Sensing of Environment*, *167*, 196–205. https://doi.org/10.1016/j.rse.2015.01.025

Lake Erie Algae. (n.d.). Algae vs. "harmful algae" – what's the difference? Retrieved January 8, 2020, from http://lakeeriealgae.com/algae-vs-harmful-algae/

Malbrouck, C., & Kestemont, P. (2006). Effects of microcystins on fish. *Environmental Toxicology and Chemistry*, *25*(1), 72–86. https://doi.org/10.1897/05-029R.1

Michalak, A. A. M., Anderson, E. J., Beletsky, D., Boland, S., Bosch, N. S., Bridgeman, T. B., et al. (2013). Record-setting algal bloom in Lake Erie caused by agricultural and meteorological trends consistent with expected future conditions, *110*(16), 6448–6452. https://doi.org/10.1073/pnas.1216006110

Oyama, Y., Matsushita, B., & Fukushima, T. (2015). Distinguishing surface cyanobacterial blooms and aquatic macrophytes using Landsat/TM and ETM+ shortwave infrared bands. *Remote Sensing of Environment*, *157*, 35–47. https://doi.org/10.1016/j.rse.2014.04.031

Paerl, H. W., Gardner, W. S., Havens, K. E., Joyner, A. R., Mccarthy, M. J., Newell, S. E., et al. (2016). Mitigating cyanobacterial harmful algal blooms in aquatic ecosystems impacted by climate change and anthropogenic nutrients. *Harmful Algae*, *54*, 213–222. https://doi.org/10.1016/j.hal.2015.09.009

Pilotto, L. S., Douglas, R. M., Burch, M. D., Cameron, S., Beers, M., Rouch, G. J., et al. (1997). Health effects of exposure to cyanobacteria (blue-green algae) during recreational water-related activities. *Australian and New Zealand Journal of Public Health*, *21*(6), 562–566. https://doi.org/10.1111/j.1467-842X.1997.tb01755.x

Smyth, R. L., Watzin, M. C., & Manning, R. E. (2009). Investigating public preferences for managing Lake Champlain using a choice experiment. *Journal of Environmental Management*, *90*(1), 615–623. https://doi.org/10.1016/j.jenvman.2007.12.016

State of Vermont. (2020). Cyanobacteria (Blue-Green Algae) Tracker | Vermont Department of Health. Retrieved November 5, 2020, from https://www.healthvermont.gov/tracking/cyanobacteria-tracker

Tebbs, E. J., Remedios, J. J., & Harper, D. M. (2013). Remote sensing of chlorophyll-a as a measure of cyanobacterial biomass in Lake Bogoria, a hypertrophic, saline-alkaline, flamingo lake, using Landsat ETM+. *Remote Sensing of Environment*, *135*, 92–106. https://doi.org/10.1016/j.rse.2013.03.024

Vincent, R. K., Qin, X., McKay, R. M. L., Miner, J., Czajkowski, K., Savino, J., & Bridgeman, T. (2004). Phycocyanin detection from LANDSAT TM data for mapping cyanobacterial blooms in Lake Erie. *Remote Sensing of Environment*, *89*(3), 381–392. https://doi.org/10.1016/j.rse.2003.10.014

Xu, H. (2006). Modification of normalised difference water index (NDWI) to enhance open water features in remotely sensed imagery. *International Journal of Remote Sensing*, *27*(14), 3025–3033. https://doi.org/10.1080/01431160600589179

Zong, J.-M., Wang, X.-X., Zhong, Q.-Y., Xiao, X.-M., Ma, J., & Zhao, B. (2019). Increasing Outbreak of Cyanobacterial Blooms in Large Lakes and Reservoirs under Pressures from Climate Change and Anthropogenic Interferences in the Middle–Lower Yangtze River Basin. *Remote Sensing*, *11*(15), 1754. https://doi.org/10.3390/rs11151754