JOURNAL OF
EMERGING INVESTIGATORS

Article

Interaction of light with water under clear and algal bloom conditions

Padmalakshmi Ramesh[1], Ramesh Sivanpillai[2]
[1] Laramie High School, Laramie, Wyoming, USA
[2] Wyoming Geographic Information Science Center, University of Wyoming, Laramie, Wyoming, USA

SUMMARY

Algal blooms are a major problem in water bodies throughout the world. Algal blooms that produce harmful toxins are termed harmful algal blooms (HABs). It is important to monitor water bodies for algal blooms as they can be harmful to humans and animals. Monitoring can also allow management agencies to mitigate the blooms. There are challenges in monitoring water bodies such as time, cost, and remoteness. This study aimed to detect algal blooms with satellite images to enable earlier detection in the future. This can help with earlier warning and advisories that will mitigate negative health effects to humans and animals. Areas with algal blooms behaved like vegetation in certain regions of the electromagnetic spectrum (EMS), while in others it resembled water. As algal blooms became brighter, near-infrared values increased. We also observed a high ratio vegetation index and low mid-infrared values confirm the presence of algae and distinguish them from vegetation. Satellite images can be used to detect algal blooms in water bodies in Wyoming, based on how algae interact with light in the near and mid-infrared regions.

INTRODUCTION

Algal blooms are a type of floating vegetation that is produced by excess nutrients in water in the presence of sunlight and higher temperature (1). Algal blooms are a major problem in water bodies throughout the world (2). A global study conducted by the US Geological Survey (USGS) found that the number of lakes with the presence of algal blooms has increased rapidly from 1984 through 2013 (1). If algal blooms produce harmful toxins, they are termed harmful algal blooms (HABs) (2). Mild to serious health issues have been reported when humans and animals come into contact with HABs (3). Cyanobacteria, the most common type of algal blooms, produce toxins such as anatoxins and saxitoxins (i.e., cyanotoxins) (4). Cyanotoxins pose various health threats, including amnesic shellfish poisoning, vomiting, diarrhea, confusion, seizures, permanent short-term memory loss, or death (5). In addition to cyanobacteria, HABs contain many other types of microorganisms, some of which are also capable of producing toxins (5). Algal blooms form in warmer months when sunlight is abundant and excess nutrients are present in water and die off when the temperature drops (3). It is important to monitor water bodies for algal blooms due to their potential health risks. Monitoring water bodies for the presence of algal blooms can prevent injuries and possible deaths to humans and animals (6). It can also allow management agencies to issue alerts to the public about the blooms.

There are challenges in monitoring water bodies, such as time, cost, and remoteness (7). Agencies must determine if algal blooms are present in the water bodies and issue alerts. Traveling to various water bodies to collect and analyze water samples for the presence of HABs is resource-intensive. With satellite images, the time and cost of monitoring water bodies can be reduced. Different surfaces on the Earth reflect certain amounts of light in the electromagnetic (EM) spectrum **(Figure 1)** and these reflection patterns are used to monitor vegetation, urban areas, forests, water, fires, etc. (8).

Satellite sensors measure electromagnetic radiation from Earth's surface and store them as images (9). Each image includes measurements in different spectral regions such as blue, green, red, and infrared (9). Satellite data are characterized by four resolutions: spectral, spatial, temporal, and radiometric (10). The spectral resolution is the sensitivity of the sensor and its ability to distinguish between reflections in different regions of the EM spectrum (11). Spatial resolution is the size of the pixel size in an image (10). Temporal resolution is how frequently images are collected (9). Radiometric resolution is the range of values used for recording the reflected light in each pixel (11). By considering these parameters, satellite images can be used to monitor the Earth's surface features.

Spectral indices compare values in two or more bands, enabling analysis of light interactions from various surfaces (12). Specifically, indices can be used to detect changes in two or more images acquired at different time periods (12). In the context of assessing algal blooms, clear water reflects more light in the blue region compared to other regions. However, when materials such as sand, sediment and vegetation are present, the light interaction of water will change; turbid water reflects more light in the visible region (13).

Previous studies used a single satellite image to detect the presence of algal blooms in water bodies (14). However, this approach cannot determine if the change in light interaction was caused by algal blooms or other features such as water turbidity and seasonal changes. By comparing light interactions in the same locations when algal blooms were present (warmer months) and absent (cooler months), we can determine if the observed changes were caused by algal blooms.

The overarching objective of this study was to detect algal blooms based on the light interaction of clear and affected water in the Fontenelle and Wheatland 2 & 3 reservoirs in Wyoming. We used the following spectral bands from the Landsat 8 satellite: blue (B), green (G), red (R), near-infrared (NIR), mid-infrared (MIR), and far-infrared (FIR) in this study.

https://doi.org/10.59720/22-223

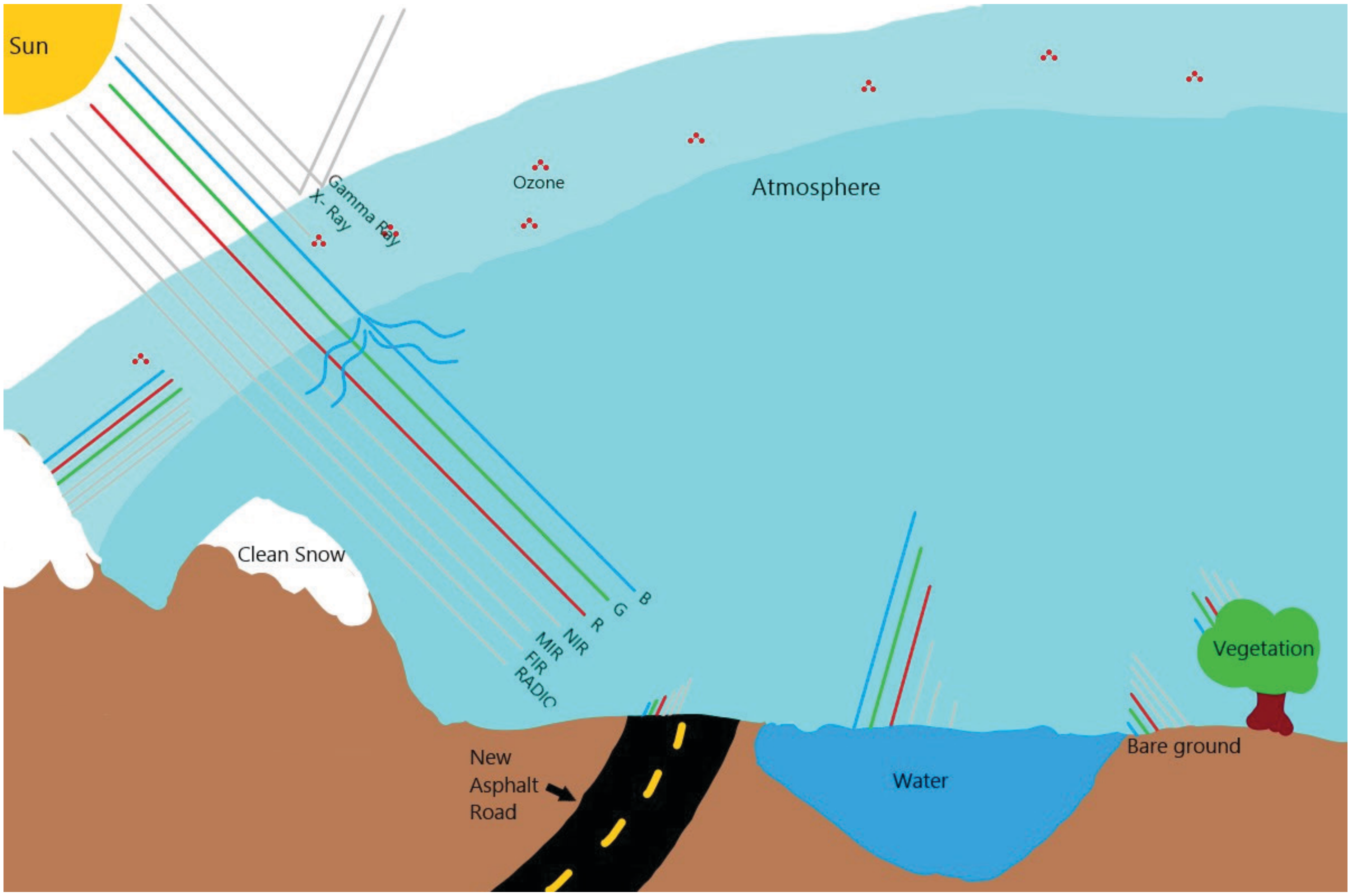


Figure 1: Cartoon depicting the interaction of electromagnetic radiation with earth's surface features. The height of the lines shown in each feature corresponds to the amount of reflection in each region of the spectrum.

Our first objective was to assess whether the presence of algae would change the light interaction in two Wyoming reservoirs. We hypothesized that since algae are photosynthesizing organisms, their light interaction would be closer to vegetation. Our second objective was to measure the impact of algae brightness on light interaction. We hypothesized that as the brightness increases, its similarity to vegetation will increase. Our third objective was to see whether Ratio Vegetation Index (RVI), an index used for monitoring vegetation (15), can be utilized to identify algal blooms in these water bodies. Since RVI is sensitive to the amount of vegetation, we hypothesized that it could be used for identifying algal blooms from clear water. RVI values for vegetation were higher than those of algal blooms. Algal blooms and vegetation can be distinguished using their MIR values. This can be used to detect algal blooms in the future and issue health advisories.

RESULTS

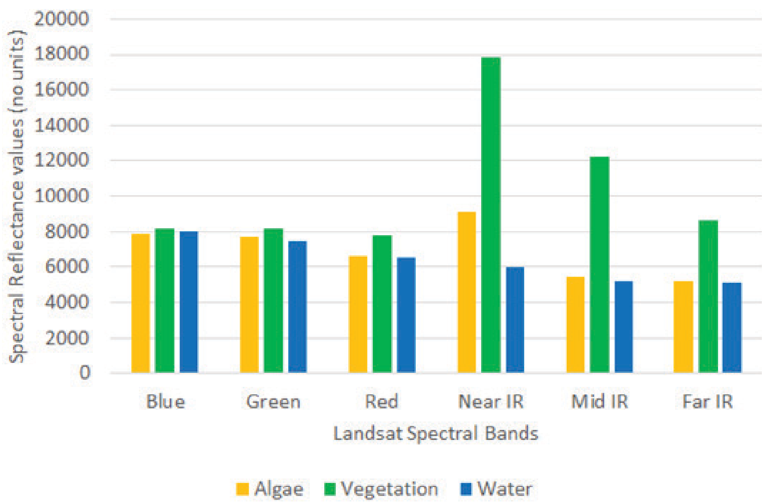
Compared to in-person monitoring, satellite images are a more efficient and cost-friendly method to detect algal blooms, based on their interaction in the near- and mid-infrared (IR) regions of the electromagnetic spectrum (14). Using images with and without algal blooms, we sought to determine if they caused a difference in light interaction.

We acquired Landsat images before and during the presence of algal blooms for two reservoirs. The spectral data collected by Landsat were extracted in three visible and three IR regions. This spectral data was extracted for water, bare ground, vegetation, and algae. Different vegetation indices were calculated using the red and infrared bands.

In locations where algal blooms were present in warmer months, the light interaction changed compared to when water was clear (cooler months). Areas in water bodies with algal blooms reflected similarly to vegetation outside the reservoir in the near-IR region and similar to water in other spectral bands in both Fontenelle **(Figure 2)** and Wheatland #3 **(Figure 3)**. When algal blooms were present, the near IR values changed regardless of the brightness ($p < 0.05$). The near IR values for brightness categories of dim, medium and bright algal blooms were significantly different from each other ($p < 0.01$). However, the mid-IR values for these three types of algae were not different from each other ($p > 0.05$). Bare ground reflected more light in all bands than the rest of the surfaces. Reflection patterns of bare ground, vegetation, and water were similar for both study sites.

As algal blooms brightened, the near IR values increased, while the values in the other spectral regions did not change **(Figure 2)**. When the algal blooms were bright, the light reflection in near IR exceeded that of vegetation ($p < 0.05$). When the algal blooms were dim and of medium brightness, they were significantly lower than vegetation ($p < 0.05$). When the algal blooms were dimmer, the light reflection in all spectral bands was more similar to water **(Figure 3)**.

https://doi.org/10.59720/22-223



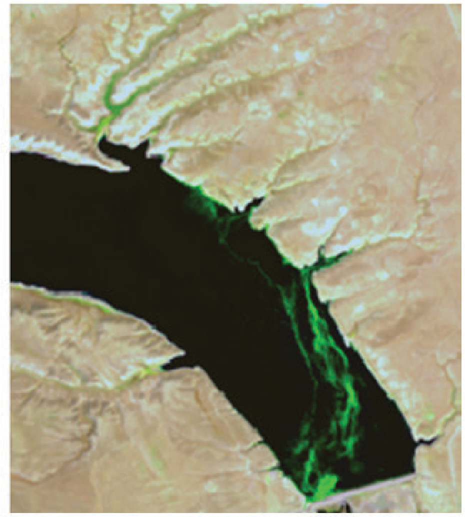
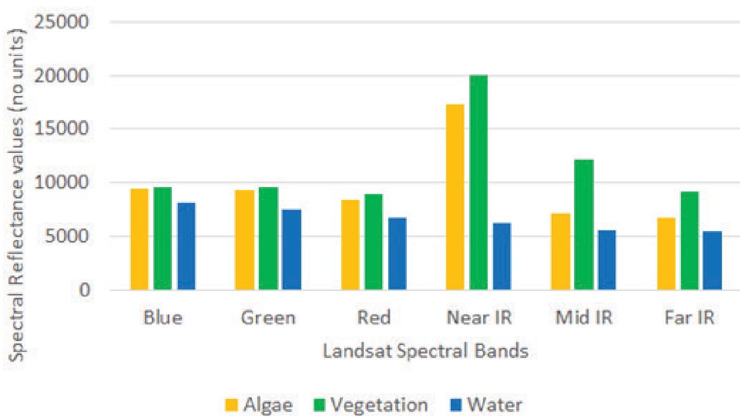


Figure 2: Spectral band values for the Fontenelle Reservoir. Raw spectral data recorded by Landsat 8 OLI sensor and extracted using Erdas ViewFinder. For the different features, algae, water, and vegetation, the raw spectral reflectance values were measured in the six different Landsat bands. Vegetation has much higher reflectance values in the near, mid, and far IR regions. Algae has a higher reflectance in the near IR region. Water has relatively the same reflectance in all six bands. Algal blooms were brighter in Fontenelle Reservoir.



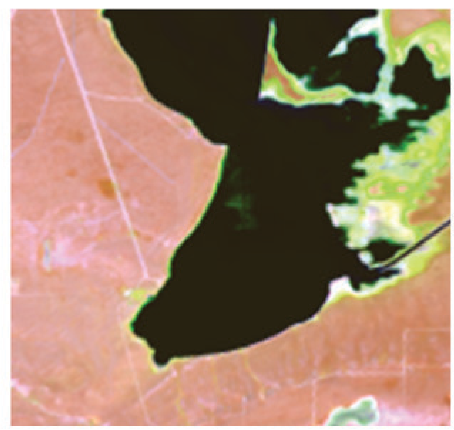


Figure 3: Spectral band values for the Wheatland #3 Reservoir. Raw spectral data recorded by Landsat 8 OLI sensor and extracted using Erdas ViewFinder. Vegetation has a higher reflectance in the near, mid, and far IR regions. The algal blooms had higher reflectance values in the near IR region. The reflectance values of water were relatively similar in all six spectral bands. Algal blooms were dimmer in Wheatland #3 Reservoir.

RVI values can be used to identify algal blooms in water bodies. For water, RVI values were lower than 1 **(Figure 4)**. When algal blooms were present, RVI values increased up to 3 at those locations. For dim algal blooms, the RVI values slightly increased (1.37), but for bright algal blooms (2.795), the RVI values exceeded vegetation values (2.31) **(Figure 4)**. From the RVI values, we can conclude that they increased as the brightness of the algal blooms increased.

Since vegetation also had higher RVI values, mid-infrared (MIR) values can be used to differentiate between algae and vegetation; algae had lower MIR values in comparison to vegetation **(Figure 4)**. High RVI and low MIR values can confirm the presence of algae. When both RVI and MIR values are high, it is most likely vegetation growing outside the water body. Because our results show that RVI was high and MIR low, we can conclude that the changes in light interactions were caused by the presence of algal blooms **(Figure 5)**.

To summarize, as the brightness of algal blooms increased, the near-infrared and RVI values increased. When RVI values are higher, the algal blooms are brighter in that area. When the algal blooms are brighter, they are more similar to vegetation growing outside the reservoir.

DISCUSSION

This study aimed to use spectral information in satellite images to detect algal blooms. Satellite images can be used to detect algal blooms in water bodies in Wyoming, based on how algae interact with light in the near and mid-infrared regions. When algal blooms were present, the near IR values started to increase. Therefore, when algal blooms were present in the water, the light interaction was significantly different in the near IR region. These findings concur with

JOURNAL OF
EMERGING INVESTIGATORS
https://doi.org/10.59720/22-223

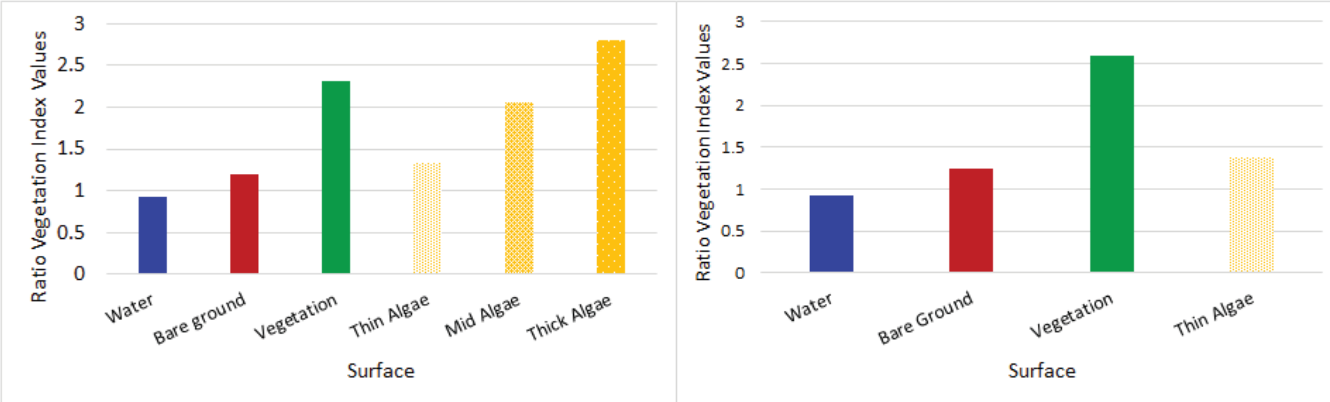


Figure 4: Ratio Vegetation Index Values for the Fontenelle and Wheatland #3 Reservoirs. RVI values were calculated for different features in and near Fontenelle Reservoir (left) and Wheatland #3 Reservoir 3 (right) using the NIR and Red bands. The dim, mid-bright, and bright algae RVI values were 1.3, 2.1, 2.8 respectively in Fontenelle Reservoir and 1.4 for Wheatland #3 Reservoir. As the brightness of the algae increased, the RVI value increased, approaching those of vegetation.

previous studies that used satellite images for monitoring algal blooms in ocean and coastal zones and the Great Lakes (17, 18).

When the algal blooms were brighter, the NIR and RVI values were higher. This could be due to increased photosynthetic activity at those locations. RVI values for algae were similar to those of vegetation. Both high RVI values and low MIR values can confirm the presence of algae in an area. Using RVI values along with mid-infrared can distinguish algae from vegetation growing outside the water bodies.

Algal blooms were observed only in September in the two reservoirs studied. However, there could have been features in the reservoirs throughout the year that affected the light interaction. In order to confirm that suspected algal bloom areas did not have pre-existing features, images from late spring and early summer acquired from the previous year(s) are required to confirm that those locations reflected like water.

Water turbidity can affect the readings taken from each image as this can change light interactions for both water and algae. For more shallow water bodies, another problem

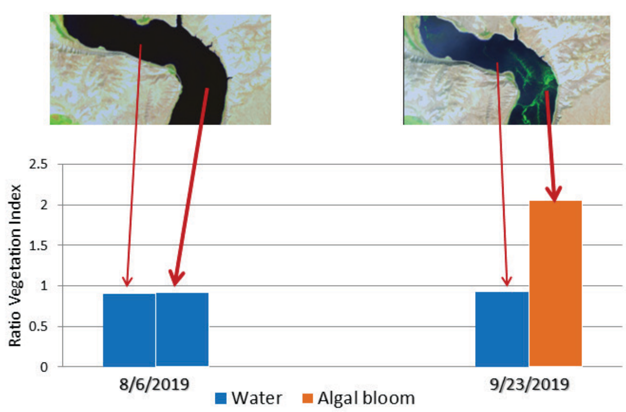


Figure 5: Comparison of RVI values for clear water and algal blooms in the Fontenelle Reservoir. Locations that had algal blooms in September (orange bar) had high Ratio Vegetation Index values. Algae was not present at those locations in August, hence the RVI values (blue bar) were comparable to water.

could be vegetation growing in the water (i.e., submerged vegetation, can be misinterpreted as algae).

When algal blooms are found along the shore, differentiating between them from vegetation growing nearby can be difficult. Along the shoreline, in one pixel there could be both algal blooms and vegetation. Future research should focus on separating the vegetation and algal blooms along the shoreline. Higher spatial resolution images could help separate vegetation growing along the shoreline from the floating algal blooms.

Finding images of the reservoirs was challenging as many were covered in clouds. In this study, we used only Landsat 8 images. In 2021, Landsat 9 was launched allowing us to monitor an area every 8 days instead of once every 16 days. This increases the chances of getting cloud-free images, thus being able to monitor more frequently. Relying on data only from two Landsat satellites might not be sufficient for finding suitable images and including images from other satellites can help to overcome this problem. Future studies can use images collected by other Earth observation satellites which will further increase the chances of monitoring the water bodies more frequently. However, using images from another satellite must have the same qualities as Landsat. For example, the spectral bands in all satellites must match. At least the red, near, and mid-infrared bands must be used as they are necessary to distinguish algae from vegetation growing outside the reservoir.

Using the red and NIR bands, we can calculate RVI values. When photosynthetic activity increases, RVI values will be higher. Vegetation and other organisms reflect higher amounts of NIR resulting in high RVI values. Hence, RVI is an effective index to distinguish algae from clear water. If water remained clear throughout the year, the RVI values varied minimally. However, if algal blooms appear in some areas of the water body, the RVI values at those locations increased. If the algal blooms become bright, their RVI values will be more similar to the values of vegetation growing outside the water body.

Because the main difference between algal blooms and vegetation is the reflection in the mid-infrared regions, this difference can be used to detect algal blooms remotely and without having to spend as many resources. Additionally, the

https://doi.org/10.59720/22-223

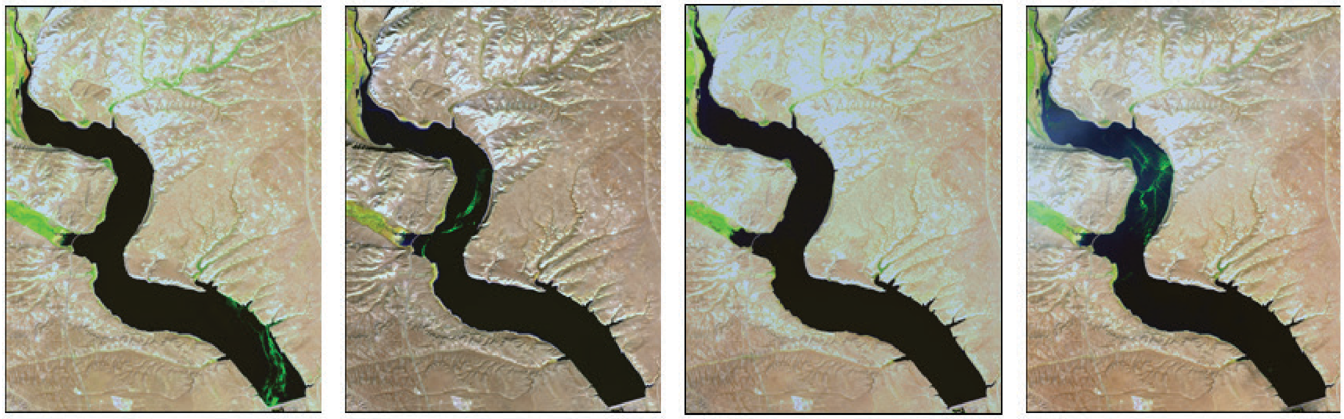


Figure 6: Four images acquired by the Landsat 8 satellite of the Fontenelle Reservoir. Images were acquired on 29 Aug 2016, 19 Oct 2017, 6 Sep 2019, and 23 Sep 2019 shown from left to right.

benefit of the remote monitoring is apparent for water bodies that are too remote to be easily accessed by other means. Our study therefore adds useful data to a growing body of literature on remote monitoring of algal blooms, which is important for reducing the negative impacts on human and wildlife health. Finally, we see many applications of our work, one of them being a potential monitoring system that issues early warnings and advisories to people in close proximity to affected water bodies.

MATERIALS AND METHODS

Pre-processed Landsat 8 Operational Land Imager scenes for two Wyoming reservoirs, Fontenelle **(Figure 6)** and Wheatland #3, were obtained from the US Geological Survey website (19). The spatial resolution of Landsat 8 images in the visible and infrared regions are 30 meters by 30 meters (i.e., each pixel covers 900 square meters of ground area). The Fontenelle Reservoir images were acquired on 29 Aug 2016, 19 Oct 2017, 6 Aug 2019, and 23 Sep 2019 (Figure 6). The Wheatland #3 images were acquired on 24 Aug 2016, 29 July 2017, 17 Aug 2019, and 18 Sep 2019. These images were free of clouds, shadows, snow, haze, and other obstructions.

First, the 2016 Landsat image for Fontenelle Reservoir was displayed in ERDAS ViewFinder software. Spectral values were extracted for the following six features: 1) water, 2) dim algae, 3) medium algae, 4) bright algae, 5) vegetation growing outside the reservoir, and 6) bare ground. The brightness of the algae was determined by their appearance in the image. For each feature, reflection values in each spectral band (blue, green, red, near-infrared, mid-infrared, and far-infrared) were collected at 11 different locations. In addition to the spectral values, the geographic coordinates of each sampling location were also recorded. These steps were repeated for the 2017 and 2019 images. This resulted in 198 (6 features x 11 locations x 3 years) samples containing 6 spectral values.

Next, the steps above were repeated for Wheatland Reservoir #3 using Landsat images acquired in 2016, 2017, and 2019. However, this reservoir had only one type of algae. This resulted in another 198 (4 features x 11 locations x 3 years) samples containing 6 spectral values.

The average spectral values for each of the six Landsat bands were computed. A plot showing differences in the average reflected values of water, different types of algae (for Fontenelle Reservoir), vegetation growing outside the reservoir, and the bare ground was generated.

Using the average spectral values, the Ratio Vegetation Index (RVI) was calculated for all features, where RVI = NIR / RED. We computed Tukey's test and p values for testing the relationships between different features based on their RVI values in MS Excel.

ACKNOWLEDGMENTS

We thank the US Geological Survey for no-cost public Landsat data. We also thank regional and state science fair judges, and three anonymous reviewers for their encouragement, valuable comments, and suggestions.

Received: September 5, 2022
Accepted: July 25, 2023
Published: February 1, 2024

REFERENCES

1. "Global Study Finds Algal Blooms Intensifying in Freshwater Lakes Worldwide." *United States Geological Survey.* www.usgs.gov/news/global-study-finds-algal-blooms-intensifying-freshwater-lakes-worldwide. Accessed 4 Jul. 2022.
2. Sellner, Kevin, *et al.* "Harmful algal blooms: causes, impacts, and detection." *Journal of Industrial Microbiology and Biotechnology,* vol. 30, no. 7, 1 July 2003, https://doi.org/10.1007/s10295-003-0074-9.
3. "Harmful Algal Blooms." *Environmental Protection Agency.* www.epa.gov/nutrientpollution/harmful-algal-blooms. Accessed 4 Jul. 2022.
4. "New Study on Cyanotoxins in Lakes and Reservoirs Provides Insights into Assessing Health Risks." *United States Geological Survey.* www.usgs.gov/mission-areas/environmental-health/science/new-study-cyanotoxins-lakes-and-reservoirs-provides. Accessed 4 Jul. 2022.
5. "Cyanobacterial Harmful Algal Blooms (CyanoHABs) in Water Bodies." *Environmental Protection Agency.* www.epa.gov/cyanohabs. Accessed 4 Jul. 2022.
6. "Tracking the Bad Guys." *United States Geological Survey.* www.usgs.gov/news/tracking-bad-guys-toxic-algal-blooms. Accessed 4 Jul. 2022.
7. Sivanpillai, Ramesh, *et al.* "Improvements in mapping water bodies using ASTER data." Ecological Informatics.

https://doi.org/10.59720/22-223

vol 5, 2010, https://doi.org/10.1016/j.ecoinf.2009.09.013.
8. Fraser, R.H., *et al.* "Detecting long-term changes to vegetation in northern Canada using the Landsat satellite image archive." *Environmental Research Letters.* vol. 6, no. 4, 21 Oct. 2011, https://doi.org/10.1088/1748-9326/6/4/045502.
9. Roy, D.P., *et al.* "Landsat-8: Science and product vision for terrestrial global change research." Remote Sensing of Environment, vol. 145, 2014, https://doi.org/10.1016/j.rse.2014.02.001.
10. Congalton, Russell. "Remote Sensing: An Overview." GIScience & Remote Sensing, vol. 47, no. 4, 2010, https://doi.org/10.2747/1548-1603.47.4.443.
11. "Landsat Science." *National Aeronautics and Space Administration.* landsat.gsfc.nasa.gov/satellites/landsat-8/
12. Lyon, John, *et al.* "A change detection experiment using vegetation indices". *Photogrammetric Engineering and Remote Sensing,* vol. 64, no. 2, American Society for Photogrammetry and Remote Sensing, Feb 1998.
13. Moore, Gerald. "Satellite remote sensing of water turbidity/ Sonde de télémesure par satellite de la turbidité de l'eau". *Hydrological Sciences Bulletin,* vol. 25, no. 4, Feb. 1980, https://doi.org/10.1080/02626668009491950.
14. Klemas, Victor. 2012. Remote Sensing of Algal Blooms: An Overview with Case Studies. *Journal of Coastal Research* 28 (1A): 38-43. https://doi.org/10.2112/JCOASTRES-D-11-00051.1.
15. Jackson, Ray, *et al.,* "Interpreting Vegetation Indices". *Preventive Veterinary Medicine,* vol, 11, Dec. 1991, https://doi.org/10.1016/S0167-5877(05)80004-2.
16. "Introduction to Electromagnetic Spectrum." *NASA*. www.nasa.gov/directorates/heo/scan/spectrum/overview/index.html. Accessed 4 Jul. 2022.
17. Stumpf, Richard. "Applications of Satellite Ocean Color Sensors for Monitoring and Predicting Harmful Algal Blooms". *Human and Ecological Risk Assessment: An International Journal,* vol. 7, no. 5, 2001, https://doi.org/10.1080/20018091095050.
18. Lekki, John, *et al.,* "Airborne hyperspectral and satellite imaging of harmful algal blooms in the Great Lakes Region: Successes in sensing algal blooms." *Journal of Great Lakes Research,* vol. 45, no. 3, June 2019, https://doi.org/10.1016/j.jglr.2019.03.016.
19. "Landsat Missions." *United States Geological Survey.* www.usgs.gov/landsat-missions