Remote Sensing Detection of Mixed Algal Blooms in a Shallow Eutrophic Lake Using Landsat-9 OLI

Sowmya Selvarajan
Utah Valley University, Faculty of Computer Science, sowmyas@uvu.edu

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ABSTRACT:

Monitoring algal blooms in shallow eutrophic lakes remains challenging due to subtle biomass signals and interference from bottom reflectance and high suspended sediment loads. Utah Lake, a large eutrophic and highly turbid freshwater lake in central Utah (average depth about 2.7 m), frequently experiences summer cyanobacterial blooms driven by elevated nutrient inputs and resuspension of sediments. This study evaluated two Landsat compatible spectral indicies for bloom detection: a Landsat adapted Normalized Difference Chlorophyll Index (NDCI_L) and the natural log transformed NIR/Red ratio (ln(B5/B4)). The study analyzed atmospherically corrected Landsat-9 OLI surface reflectance imagery, with water masking performed using the Modified Normalized Water Index (MNDWI). Both indices were compared to situ chlorophyll-A observations. Results indicate that ln(NIR/Red) exhibited stronger linear correlations with chlorophyll-A in relatively deeper portions of the lake; however, the logarithmic scaling amplified noise, making it more sensitive to reflectance uncertainty. Because chlorophyll-A in eutrophic lakes commonly follows a log-normal distribution, the log-transformed NIR/Red ratio can enhance regression models when high-quality surface reflectance data are used. In contrast, NDCI_L, being a normalized index, provided better discrimination under moderate conditions and is more suitable for threshold-based classification, cross sensor comparisons, and operational monitoring. This work highlights the importance of using atmospherically corrected surface reflectance rather than raw digital numbers, outlines preprocessing requirements, and evaluates the relative performance of two practical Landsat based indicies for algal bloom monitoring. These findings contribute to improving near real time bloom surveillance in shallow eutrophic systems such as Utah Lake.

1. INTRODUCTION

Algal blooms have become an increasingly common water quality issue in freshwater systems worldwide, particularly in shallow eutrophic water bodies subjected to high nutrient loading and frequent sediment resuspension. Elevated concentrations of cyanobacteria pose ecological, economic, and public health risks by degrading aquatic habitats, reducing water clarity, producing toxins, and limiting recreational use. Effective monitoring of algal blooms is therefore critical for lake management, early warning systems, and long-term eutrophication assessment.

Remote sensing has long been recognized as a valuable tool for monitoring algal blooms due to its synoptic coverage, repeat observations, and ability to capture spatial variability that is difficult to observe using in situ sampling alone. Satellite derived indictors such as chlorophyll-a (Chl-a) are commonly used as measures for algal biomass, with numerous algorithms developed for oceanic and deep inland waters. However, applying these techniques to shallow, turbid, and complex lakes remains challenging. In such environments, water leaving reflectance is influenced not only by cyanobacteria pigments, but also by suspended sediments. Dense surface scums, which exhibit strong reflectance in the near infrared (NIR), but dispersed blooms often produce weak and spatially heterogeneous signals that overlap spectrally with turbidity effects.

Shallow eutrophic lakes exemplify these challenges due to their limited water depth, high turbidity, and frequent occurrence of cyanobacterial blooms. In such systems, elevated nutrient inputs combined with internal nutrient recycling and sediment resuspension create conditions that promote persistent algal growth. These processes increase optical complexity, making it difficult to isolate algal signals from background turbidity and bottom reflectance in satellite observations. Despite routine water quality monitoring, in situ measurements alone often lack the spatial and temporal coverage needed to fully characterize the distribution and dynamics of dispersed algal blooms.

Several Landsat-compatible spectral indices have been proposed for estimating algal biomass in optically complex waters. Among these, the Normalized Difference Chlorophyll Index (NDCI) measures the contrast between red and near-infrared reflectance associated with chlorophyll absorption and scattering, while band-ratio approaches such as the NIR/Red ratio have demonstrated sensitivity to algal blooms abundance under certain conditions. Logarithmic transformations of reflectance ratios have also been shown to improve linearity with chlorophyll-a, particularly in eutrophic systems where biomass distributions are often log-normal. Nevertheless, the relative performance of these indices in shallow, highly turbid lakes remain site-specific and require empirical evaluation.

The objective of this study is to assess the performance of two practical, Landsat-compatible indices—the Landsat-adapted Normalized Difference Chlorophyll Index (NDCI_L) and the natural logarithm of the NIR/Red reflectance ratio (ln(B5/B4))—for detecting dispersed algal blooms in Utah Lake using Landsat-9 OLI surface reflectance imagery. By focusing on a shallow, eutrophic, and optically complex system, this study contributes to a better understanding of the strengths and limitations of Landsat-based approaches for near-real-time algal bloom surveillance in inland waters.

2. STUDY AREA

Utah Lake is one of the largest freshwater lakes in the western United States and represents a significant hydrological and ecological feature in central Utah. The lake is located within Utah Valley and is a remnant of ancient Lake Bonneville, a large prehistoric lake that once covered much of western Utah. Today, Utah Lake functions as an important freshwater resource within a rapidly developing watershed.

The lake is primarily fed by three major tributaries—the Provo River, Spanish Fork River, and American Fork River—while its sole outflow is the Jordan River, which ultimately drains into the Great Salt Lake. Utah Lake is notably shallow, with an average depth of approximately 3 m. This shallow morphology makes the lake highly susceptible to wind-driven sediment resuspension, resulting in elevated turbidity and enhanced internal nutrient recycling.

Utah Lake is classified as highly eutrophic, receiving substantial nutrient inputs, particularly nitrogen and phosphorus, from a combination of agricultural runoff, urban stormwater, and wastewater discharges from surrounding communities. These elevated nutrient loads promote frequent algal and cyanobacterial blooms, especially during the warmer months. Such blooms can reduce water clarity, alter ecosystem function, deplete dissolved oxygen, and negatively impact aquatic life.

The lake supports unique biodiversity, including several fish species endemic to Utah Lake and its tributaries that have adapted to the lake's shallow and turbid conditions. However, the accumulation of organic matter in bottom sediments, coupled with recurring sediment disturbance, reinforces the eutrophic state of the system. This interaction between nutrient loading, algal proliferation, and sediment dynamics makes Utah Lake an optically complex and ecologically stressed environment, posing significant challenges for both in situ monitoring and satellite-based water quality assessment.

Figure 1: Utah Lake

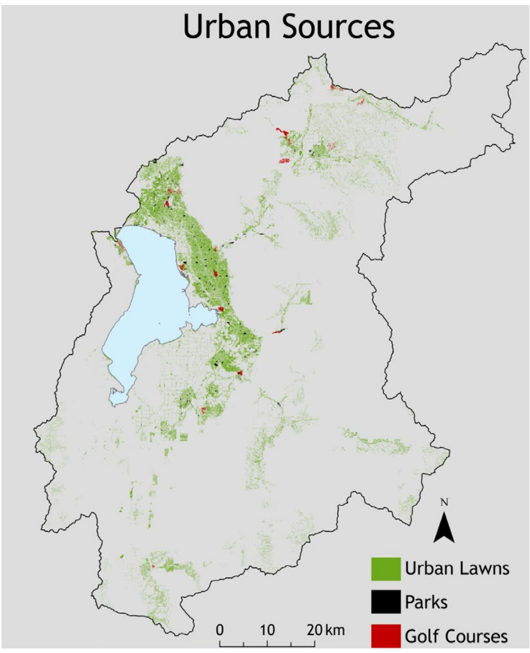

Figure 2: Utah lake watershed and urban composition

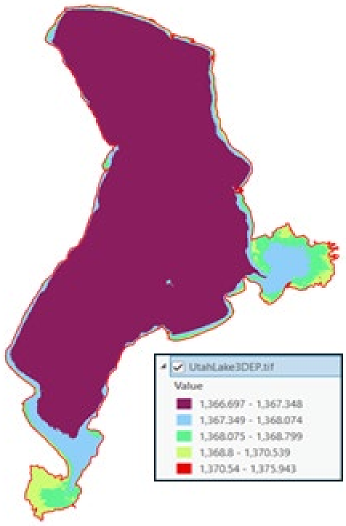

Figure 3: Elevation map of Utah lake – Prepared Using USGS 3DEP data (2022) – Units Meters

3. DATA AND PREPROCESSING

This study utilized imagery acquired by the Landsat 9 Operational Land Imager (OLI) on May 25, 2022. Landsat 9 OLI provides multispectral observations at a spatial resolution of 30 m, with each pixel representing a 30 × 30 m area on the Earth's surface. This spatial resolution is well suited for monitoring large inland water bodies such as Utah Lake while capturing spatial variability in water quality conditions.

The analysis focused on three spectral bands commonly used for water quality and vegetation-related applications: the green, red, and near-infrared (NIR) bands. Band 3 (Green; 0.53–0.59 µm) is sensitive to variations in water clarity and suspended materials, making it useful for assessing turbid waters. Band 4 (Red; 0.64–0.67 µm) corresponds to strong chlorophyll absorption and is widely used in vegetation and algal biomass studies. Band 5 (NIR; 0.85–0.88 µm) is particularly effective for differentiating water from land and for detecting vegetation density and algal scattering effects in eutrophic waters.

The Landsat imagery was preprocessed using Top-of-Atmosphere (ToA) reflectance correction to convert raw digital numbers to physically meaningful reflectance values. Using ToA-corrected reflectance enhances the detection of water features, which typically exhibit low reflectance in the visible and NIR regions, and improves the signal-to-noise ratio necessary to capture subtle spectral variations associated with algal biomass and suspended sediments.

4. METHODOLOGY

Landsat scenes were exported using GPX VisualExporter, a customized interface developed to streamline data retrieval and organization. This tool integrates directly with Google Earth Engine (GEE), enabling efficient management of region-of-interest boundaries, metadata, and export parameters.

A GEE-based toolset was developed to automate the preprocessing workflow. Preprocessing included conversion of raw digital numbers to Top-of-Atmosphere (ToA) reflectance to ensure radiometric consistency and reduce atmospheric influence. Cloud and cloud-shadow corrections were applied. The Green (Band 3), Red (Band 4), and Near-Infrared (Band 5) bands were selected and stacked for spectral analysis, and all imagery was spatially subset to the Utah Lake boundary to focus the analysis on lake surface conditions and reduce extraneous data.

Open water pixels were delineated using the Modified Normalized Difference Water Index (MNDWI), which applies spectral contrast between green and shortwave infrared reflectance to effectively separate water surfaces from surrounding land and built-up areas called the Actual Water Line (AWL), representing the observed lake extent at the time of image acquisition was defined to further constrain the analysis domain. All spectral indices related to algal bloom detection were applied exclusively within the AWL to minimize mixed-pixel effects along shorelines and ensure consistency across the study area.

The Landsat-adapted Normalized Difference Chlorophyll Index (NDCI_L) was developed and evaluated in this study using the green and red bands. This index enhances spectral contrast associated with chlorophyll-a absorption in the red band relative to reflectance in the green band and is designed to detect dispersed algal biomass in optically complex waters. The normalized formulation reduces sensitivity to absolute reflectance magnitude, supporting threshold-based classification and cross-scene comparability.

In addition, the natural logarithm of the NIR-to-red reflectance ratio was computed to evaluate its sensitivity to variations in algal biomass. Logarithmic transformation improves linearity with chlorophyll-a concentrations, which commonly follows a log-normal distribution in eutrophic systems, and enhances subtle reflectance differences associated with algal scattering. However, this transformation can also amplify noise in highly turbid waters, making its performance dependent on reflectance quality and depth-related conditions. Both NDCI_L and ln(NIR/Red) were applied only within the Actual Water Line to ensure analysis was restricted to valid water pixels.

For supporting interpretation, the Normalized Difference Vegetation Index (NDVI) was calculated to characterize vegetation conditions in and around the lake and to identify potential interference from emergent or shoreline vegetation, especially along the Provo Bay and Goshen Bay areas.

5. RESULTS

The Modified Normalized Difference Water Index (MNDWI) was first applied to delineate open water and evaluate the difference between the mapped Utah Lake boundary and the observed water extent at the time of image

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acquisition (Figure 4). The results show a clear distinction between water and non-water surfaces, effectively separating the lake from surrounding built-up and terrestrial areas. The Actual Water Line (AWL) derived from MNDWI differs from the static Utah Lake outline, indicating spatial variability in water extent likely associated with seasonal water levels and shoreline conditions. Areas classified as non-water correspond to exposed shorelines and adjacent land surfaces, while pixels identified as actual water define the effective analysis domain used for subsequent index calculations. This result confirms the suitability of MNDWI for isolating valid water pixels and establishing a consistent boundary for inland water quality analysis.

The Normalized Difference Vegetation Index (NDVI) was used to further characterize surface conditions within and around Utah Lake and to differentiate water from vegetated areas (Figure 5). Very low NDVI values correspond to open water as the NIR band is absorbed by water and none is reflected back, while values between −0.1999 and 0 represent shallow, highly turbid water where suspended sediments influence reflectance. Sparse vegetation is indicated by low positive NDVI values between 0.001 and 0.2, primarily near the shoreline and in shallow regions, whereas higher NDVI values (0.201 to 0.867) correspond to terrestrial and emergent vegetation. The NDVI results highlight the optical complexity of the lake, particularly in nearshore zones where shallow depth, turbidity, and vegetation coexist. These patterns reinforce the importance of restricting algal bloom analysis to the AWL to minimize interference from vegetation and mixed pixels. Provo and Goshen Bay are highlighted in the figure for the mixed vegetation complexity.

Spatial patterns of algal biomass were evaluated using the Landsat-adapted Normalized Difference Chlorophyll Index (NDCI_L) (Figure 6). NDCI_L values below zero are associated with clear or turbid non-algal water, while increasing positive values indicate progressively higher algal bloom intensity. Low-intensity algal blooms (0 to 0.05) and incipient blooms (0.05 to 0.1) are widely distributed across the lake, suggesting dispersed algal presence rather than localized surface scums. Moderate algal bloom conditions (0.1 to 0.2) appear more concentrated in specific regions, while the highest NDCI_L values (0.2 to 0.43), indicative of dense surface algal blooms, are spatially limited. The normalized structure of NDCI_L provides stable discrimination across a range of conditions, particularly in areas affected by turbidity and shallow depth.

The logarithmically transformed NIR-to-red ratio, ln(NIR/Red), reveals complementary but distinct spatial patterns of algal bloom intensity (Figure 7). Lower ln(NIR/Red) values (−2.91 to −1.5) correspond to dense algal blooms, while values between −1.49 and −1.2 indicate moderate bloom conditions. Incipient algal blooms are associated with values from −1.19 to 0, and positive values (0.01 to 0.84) indicate areas with no detectable algal bloom. Compared to NDCI_L, the ln(NIR/Red) index exhibits stronger contrast between bloom intensity classes, particularly in deeper portions of the lake. However, the broader dynamic range also introduces greater sensitivity to reflectance variability, resulting in sharper spatial transitions and increased noise in highly turbid regions.

Together, the results demonstrate that both NDCI_L and ln(NIR/Red) are capable of detecting dispersed algal blooms in a shallow eutrophic lake, though they differ in sensitivity and stability. NDCI_L provides consistent bloom delineation under mixed optical conditions, making it well suited for threshold-based classification and operational monitoring. In contrast, ln(NIR/Red) enhances contrast across bloom intensity levels and may improve regression-based analysis when reflectance quality is high. The combined use of water masking, vegetation discrimination, and multiple algal bloom indices allows for robust spatial characterization of algal conditions in Utah Lake.

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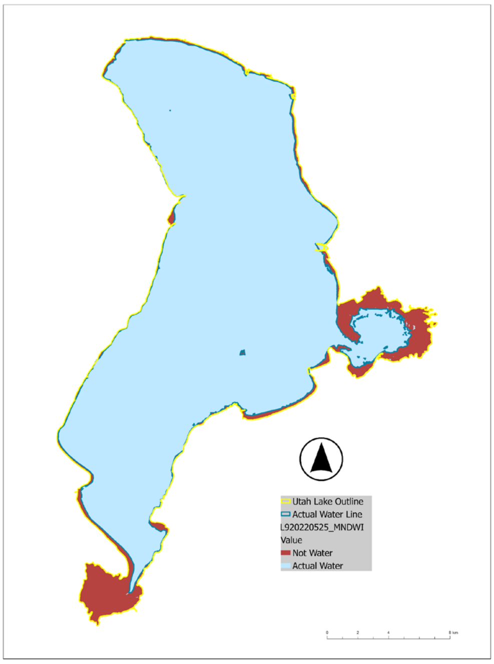

Figure 4: Water Index – MNDWI

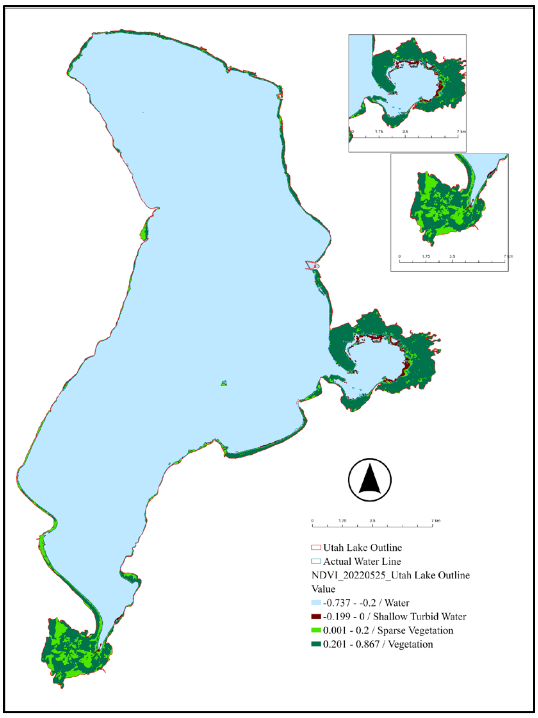

Figure 5: Vegetation Index – NDVI

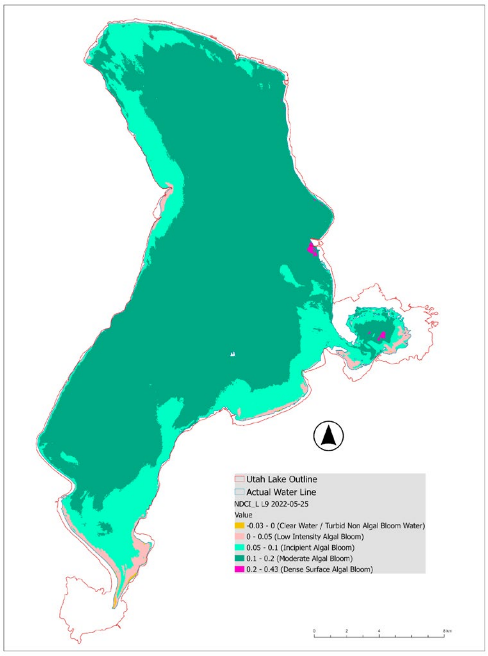

Figure 6: Algal Bloom Index - NDCI_L

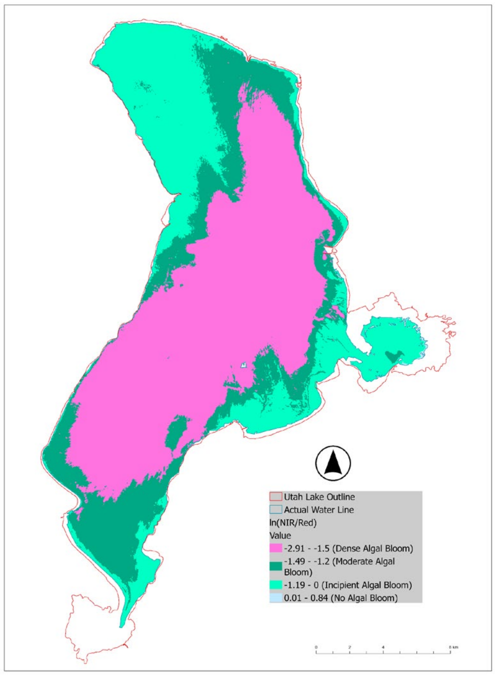

Figure 7: Algal Bloom Index - Ln(NIR/Red)

6. CONCLUSIONS

This study evaluated two Landsat-compatible spectral indices—NDCI_L and ln(NIR/Red)—for detecting dispersed algal blooms in a shallow eutrophic lake using Landsat-9 OLI top-of-atmosphere corrected reflectance. The results demonstrate that moderate-resolution satellite sensors can effectively support algal bloom monitoring in optically complex inland waters when appropriate preprocessing and index selection are applied.

Both indices successfully identified spatial patterns of dispersed algal blooms across Utah Lake. The logarithmically transformed NIR/Red ratio exhibited a stronger linear relationship with chlorophyll-a in relatively deeper portions of the lake, indicating enhanced sensitivity to variations in algal biomass. However, logarithmic scaling also increased sensitivity to reflectance noise, particularly under highly turbid conditions. In contrast, the Landsat-adapted NDCI_L provided more stable and consistent performance across moderate to high turbidity levels, making it better suited for threshold-based classification and operational monitoring applications.

Accurate top-of-atmosphere reflectance correction and robust water masking using the Modified Normalized Difference Water Index (MNDWI) were found to be essential preprocessing steps for minimizing interference from bottom reflectance and suspended sediments in shallow systems. The use of NDVI further improved classification reliability by effectively distinguishing shoreline and emergent vegetation from open water, reducing the likelihood of false algal bloom detection.

Overall, this work demonstrates that Landsat-based spectral indices, when combined with appropriate preprocessing and sensor-specific adaptations, can support near real-time monitoring of dispersed algal blooms in shallow eutrophic lakes. The comparative evaluation of NDCI_L and ln(NIR/Red) highlights important trade-offs between sensitivity and stability, providing practical guidance for selecting indices in operational inland water quality monitoring.

For future work, integrating multi-temporal Landsat observations could improve temporal resolution and enable tracking of rapid bloom evolution. Combining Landsat with Sentinel-2 MSI data would leverage finer spatial resolution (10–20 m) and higher spectral resolution, improving delineation of bloom boundaries. Additionally, developing automated Google Earth Engine workflows for near real-time processing, masking, and index computation could facilitate continuous monitoring of eutrophic lakes and support timely management responses.

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