## Satellite Remote Sensing

Protecting the quality of lakes and rivers is an important societal goal, but because of high costs, only a small fraction of these resources can be monitored by ground-based methods. The technology of satellite imagery has improved greatly in the past two decades, and key water quality features now can be measured at low cost by satellite sensors on virtually all lakes. These properties – chlorophyll, turbidity, colored dissolved organic matter (CDOM) and water clarity (Secchi depth) – control many important biological, chemical and physical characteristics of lakes.

Use of satellite technology has greatly expanded information available from ground-based monitoring, improved our understanding of the factors driving changes in surface waters, and helped improve data-driven resource management. This brochure describes current capabilities to measure key water quality characteristics of Minnesota's lakes using satellite imagery, as well as on-going studies by our research group to improve the effectiveness and use of these techniques.

## Future prospects

With the expanded availability of optical and radar data, remote sensing of water quality and other characteristics (e.g. lake snow/ice phenology) will become widely used over the next decade and will greatly expand our knowledge on the status of water quality and thermal characteristics in Minnesota lakes. Our research group is developing a state-of-the-art system that will automatically download Sentinel and Landsat imagery for Minnesota and use high-performance computing technology to provide water quality information more quickly and more completely than is possible with conventional image processing.

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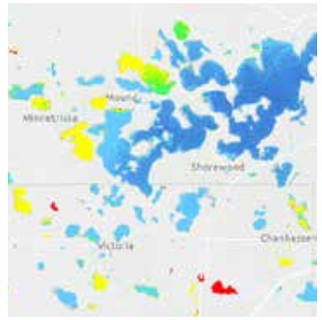

# Remote Sensing for Water Quality

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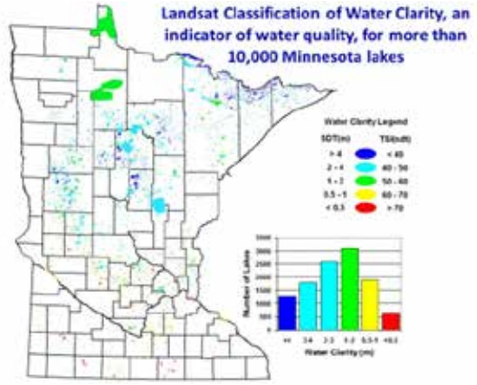
## Advantages and limitations of satellite-based water quality measurements

*Advantages:* Satellite imagery can measure key water quality characteristics (water clarity, algal abundance, color) important for fish habitat, human perceptions of water quality and human uses of lakes. It provides comprehensive spatial coverage, and as the number of satellite systems continues to grow, increasing temporal frequency of coverage. Availability of long term data allows us to follow changes over time.

*Limitations:* Cloud cover decreases frequency of observations; imagery captures only surface water conditions and not conditions at depth in the water column; imagery is limited to variables that affect optical properties and cannot measure nutrients and trace metal or organic contaminants.

## Water clarity

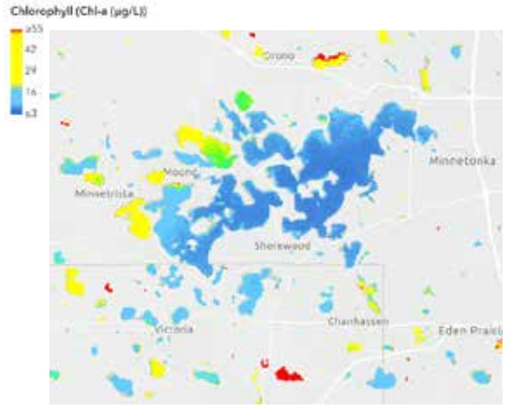
Since 1998, we have used Landsat imagery to measure lake water clarity, with the results reported in terms of the common ground-based technique, Secchi depth (SD). Many studies have documented strong relationships between responses of Landsat sensors and measurements of SD, and our technique has proven to be an accurate, economical method to monitor lakes over large geographic areas and time. Satellite-derived SD data on more than 10,000 Minnesota lakes are available at five-year intervals for 1975-2015 and can be explored in the LakeBrowser (https://lakes.rs.umn.edu), a web-based tool that enables searches and display of results for individual lakes.




Statewide map of 2015 water clarity and inset showing the number of Minnesota lakes in various ranges of water clarity.

## Chlorophyll

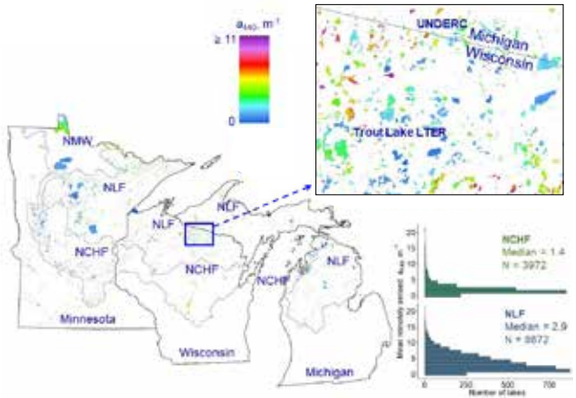
Statewide distribution of summertime chlorophyll concentrations, the most common measure of algal abundance, is now feasible for Minnesota lakes using the European Sentinel-2 satellites. The sensors of Sentinel-2 have more spectral bands, more frequent temporal coverage, and higher spatial resolution than Landsat sensors. These enhanced capabilities allow the accurate retrieval of chlorophyll data on water bodies larger than ~ 10 acres and potentially at biweekly frequency, although the exact frequency depends on cloud-cover.




Chlorophyll concentrations in lakes are highly variable, reflecting differences in nutrient loadings from surrounding watersheds and differences in the ways lakes respond to nutrient loadings. Results are from a Sentinel-2 image for an area around Lake Minnetonka (west metro Twin Cities) in summer 2017.

## CDOM

CDOM is the portion of organic matter that absorbs light primarily in the blue and ultraviolet UV parts of the electromagnetic spectrum, staining water a "tea-like" color. CDOM plays a major role in controlling freshwater ecosystem processes. Landsat 8 and Sentinel-2 imagery can be used to measure CDOM based on the ratios of light reflected from water surfaces to the green, red and NIR bands of the sensors. We have measured CDOM in lakes since 2015 with support from the National Science Foundation and the Legislative and Citizen Commission on Minnesota Resources.




CDOM distribution in lakes of the Northern Lakes and Forests and North Central Hardwood Forests ecoregions across the Great Lakes states of Minnesota, Wisconsin and Michigan.