2016 Project Abstract
For the Period Ending June 30, 2019

PROJECT TITLE: Assessment of Surface Water Quality with Satellite Sensors
PROJECT MANAGER: Jacques C Finlay
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FUNDING SOURCE: Environment and Natural Resources Trust Fund
LEGAL CITATION: M.L. 2016, Chp. 186, Sec. 2, Subd. 04i

APPROPRIATION AMOUNT: $345,000
AMOUNT SPENT: $345,000
AMOUNT REMAINING: $ 0

Sound bite of Project Outcomes and Results

This project developed methods to measure key water quality parameters across the state's waterbodies using satellite imagery. Current ground-based sampling has limited ability to measure status and trends in water quality across our lakes and rivers. Our innovative methods can routinely measure major water quality indicators in Minnesota's 10,000+ lakes.

Overall Project Outcome and Results

Water quality monitoring is essential for managing Minnesota's surface waters, maintaining the services they provide, and detecting changes caused by environmental stressors. Direct measurements of water quality are possible, however, in only a small fraction of the thousands of lakes and river miles in the state. Methods developed in this project allow use of increasingly frequent satellite observations to measure water clarity and the three key water quality indicators that control it: algae, colored dissolved organic matter (CDOM), and suspended solids. Because these parameters have distinct impacts on water quality, the ability to measure them directly across the state's waters enables comprehensive assessment of water quality status and trends and increases understanding of the causes and consequences of water quality degradation. We developed methods to relate direct measurements of water quality to satellite imagery, assessed atmospheric correction techniques and validated methods using independent datasets. We applied these methods to measure water quality parameters on lakes >10ha, and provide the information at https://lakes.rs.umn.edu. Examples are included in appendix 1. Our methods extract information at seasonal to annual scales for algae, CDOM and suspended solids in lakes at state, regional, county, and watershed scales. Water quality parameters were linked to disinfection byproduct formation potential in drinking water treatment and degradation of contaminants driven by sunlight. CDOM levels were closely related to formation rates of two classes of disinfection byproducts, trihalomethanes and haloacetic acids, and to the production photo-induced reactive intermediates that degrade pesticides. This information can be used with remote sensing to assess pesticide persistence and suitability of surface waters for drinking water sources. An ongoing LCCMR project uses methods developed here with automated imagery acquisition and analysis to gather information on lake conditions at potentially a weekly basis. Project outcomes are summarized at https://water.rs.umn.edu/ for use by researchers, managers, lake associations and the public.

Project Results Use and Dissemination

Information from this project has been disseminated through five ways during the three year project:

1) Data produced in the project is now freely available at https://lakes.rs.umn.edu/
2) Numerous presentations at meetings, agencies, and academic institutes have been given.
3) Five research articles documenting technical methodology and water quality relationships have been published. These publications have been included in our final report. Several other publications are being developed, and several others are planned.
4) We have engaged with state and agency partners in data gathering and interpretation, resulting in one publication, and plans for future collaborations with MPCA on refining water quality standards in the state based on project findings.
5) A widely used website for remote sensing of water quality (https://water.rs.umn.edu/) has been thoroughly revised with updated and expanded content.

Environment and Natural Resources Trust Fund (ENRTF) M.L. 2016 Work Plan Final Report

Date of Report: August 13, 2019

Final Report

Date of Work Plan Approval: June 7, 2016

Project Completion Date: June 30, 2019

PROJECT TITLE: Assessment of Surface Water Quality with Satellite Sensors

Project Manager: Jacques Finlay

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Location: Statewide

Total ENRTF Project Budget:	**ENRTF Appropriation:**	**$345,000**
	Amount Spent:	**$345,000**
	Balance:	**$0**

Legal Citation: M.L. 2016, Chp. 186, Sec. 2, Subd. 04i

Appropriation Language:

$345,000 the second year is from the trust fund to the Board of Regents of the University of Minnesota for a statewide assessment of water quality using new satellite sensors for high frequency measurement of major water quality indicators in lakes and rivers. This appropriation is available until June 30, 2019, by which time the project must be completed and final products delivered.

I. PROJECT TITLE: Assessment of Surface Water Quality with Satellite Sensors

II. PROJECT STATEMENT:

Minnesota's abundant surface waters face multiple threats related to land use change, eutrophication and invasive species. Water clarity is a key water quality indicator that can be monitored on many thousands of lakes in Minnesota with a simple Secchi disk or remotely using satellites. While water clarity data are highly valuable due to the ability to measure most water bodies on a frequent basis, current methods cannot distinguish between the three factors that affect water clarity in our lakes and rivers: algae, colored dissolved organic matter, and suspended solids (e.g., clay minerals). Because they have distinctly different impacts on water quality, the ability to measure them directly increases our understanding of the causes and consequences of water quality degradation. Technology now exists to make this advance. **This proposal takes an innovative next step in statewide assessment of water quality using new satellite sensors to remotely measure major water quality indicators in Minnesota's 10,000 lakes at high frequency and low cost.**

Background

The three major water quality drivers that are the focus of our project have distinct sources and impacts on surface waters. Algae are present in all surface waters and are a primary resource for lake and river food webs. *Algal biomass* is strongly affected by levels of phosphorus and nitrogen. When these nutrients are present at high levels, they result in eutrophication. Eutrophication reduces water quality by degrading habitat for native species, enhancing invasive species, reducing water quality for human use, and causing algal dominance by cyanobacteria, including species that produce harmful liver and neurotoxins. As a consequence, ability to monitor changes in algal biomass is a key part of understanding functioning of Minnesota's surfaces waters. *Colored dissolved organic matter* (CDOM) also occurs in all surface waters, and is the most abundant organic matter pool in many setting, especially in forested watersheds with wetlands. CDOM strongly affects water quality because it mobilizes metals and hydrophobic chemicals, serves as a source of reactive photochemical intermediates, controls many aquatic ecosystem processes, and has negative effects on production of safe drinking water. The paucity of data for CDOM distribution limits our understanding the quality and characteristics of surface waters in Minnesota and the US in general. *Suspended sediment* enters surface waters during large storm events that cause erosion. Sediments can also be reintroduced to surface water when sediments from lake and river bottoms are resuspended due to wind, or invasive species such as the common carp which destroy aquatic plants and stir up sediment deposits.

Conventional methods for water quality assessment rely heavily on manual collection and analyses of surface water samples to characterize these constituents and other water quality variables. While Minnesota has an excellent surface water quality monitoring program, water quality conditions are highly variable in space, and can change very rapidly due to climate, land management and invasive species. Effective lake management requires long-term water quality information on a large number of lakes and streams so that managers can take into account differences among lakes, as well as changes through time for individual lakes at the watershed or regional scale. Unfortunately, only a small percentage of inland waters are currently monitored regularly by conventional methods, and long term (i.e. at least 20 years) water quality data are lacking for most inland water bodies. Comprehensive assessment of water quality is not practical with conventional point sampling methods due to limited resources, and thus water quality data are sparse in many areas. Furthermore, traditional ground-based monitoring programs target larger recreational lakes and thus are not randomly selected. Extrapolation from these lakes to the larger population would likely bias conclusions. Remote sensing methods can provide a solution to many of these issues and generally complement ground based monitoring by providing frequent and extensive measurements in virtually all lakes larger than 10 acre surface area in the state. This project will develop methods to allow assessment of an unprecedented number of lakes, and lays the groundwork for future remote sensing based monitoring programs that can provide comprehensive data and near real-time monitoring of important water quality variables.

The quality of our lakes and rivers directly affects the availability of clean drinking water and habitat for fish and other wildlife. In much of Minnesota, lake and river water quality is influenced mainly by excessive algae (from nutrients), colored organic matter from decaying woody plants in forests and wetlands, and suspended solids from stormwater runoff and invasive carp. These factors thus have distinct causes, and each also requires different management responses in watersheds. Each also has distinct effects on water resources: too much algae decreases water quality and habitat; high levels of colored organic matter decrease fish growth and interfere with natural contaminant degradation processes and drinking water treatment processes; suspended solids destroy fish habitats and clog waterways. The ability to detect these problems in lakes on a regular basis would provide an early warning system for changes and allow management of watersheds and surface waters in ways that are specific to the particular stressors causing the degradation.

Major Project Objectives

Our goals are to: 1) develop remote sensing methods to permit routine measurement of colored organic matter, algae, and suspended solids levels in Minnesota's waters; 2) apply these methods to our 10,000 lakes and large rivers, creating a database and corresponding maps; and 3) explore how variations in these water quality indicators influence the fate of contaminants (e.g., pesticides, mercury) and the suitability of water bodies to serve as drinking water supplies. Dissemination of information gained in this project on lake conditions and methods for satellite based monitoring of conditions will reach diverse stakeholder in the state and the nation via publications, integration into Lake Brower and meeting presentations.

General Project Activities and Methods

The project develops methods to use recently enhanced satellite based remote sensing capabilities to measure key water quality parameters: algae, dissolved color, and suspended sediments. The project will acquire optical remote sensing imagery from Landsat and Sentinel satellites concurrently with sampling of surface waters for these three parameters. Using these datasets, analyses will be conducted to determine the most robust relationships between remotely sensed reflectance measurements and field conditions. These models will be validated with independent datasets. Data describing distributions of these parameters will be integrated into Lake Browser, and disseminated to state and federal agencies via presentations and peer reviewed publications.

Project Significance

By developing methods to measure algae, dissolved color, and suspended sediments by remote sensing, this project will provide the means to greatly increase understanding of our water resources in Minnesota. The capabilities developed in this project will enable measurement of indicators of key ecosystem parameters (e.g. algal biomass, light regimes, thermal properties) and functions (e.g. fish productivity, contaminant reactions). Future monitoring programs using methods developed here could gain high frequency records (up to one measurement per week with normal weather conditions) on all lakes and larger river reaches in the state. This information complements detailed ground based sampling programs at a smaller number of sites that provides information that can be used to interpret patterns detected by regional analyses conducted via satellite based monitoring.

III. OVERALL PROJECT STATUS UPDATES:

Project Status as of January 25 2017:

Our major activities focused on initiation of sampling of lakes in Minnesota to collect data for use in calibrating and validating remote sensing methods to measure surface water quality (Activity 1), as well as initiation of contaminant behavior sampling (Activity 2) and outreach activities (activity 3). A total of 152 lakes were sampled during 2016, including repeat sampling of 14 sites. Sites were selected to include the major lake rich ecoregions of Minnesota, and spanned wide range of lake size. Methods for accessing and sampling were adjusted and refined to improve efficiency of sample collection and to minimize sample holding time. Preliminary assessment of satellite imagery from Landsat (8) and Sentinel (2A) sensor indicates that water quality data to relate to satellite imagery is available for 2-3 dates for summer 2016, with additional clear-sky imagery available in autumn. The last half of the year was unusually wet and cloudy, which limited availability of clear imagery that corresponded with our field sampling. With greater satellite capacity available in 2017 (due to the expected availability of a new satellite, Sentinel 2B), more targeted sampling in response to clear imagery, and the likelihood of better conditions for image acquisition, we expect to continue construction of a robust dataset for development of remote sensing characterization of Minnesota's surface waters. Complementing our Activity 1 progress, we initiated research to relate surface water chemical composition to pollutant behavior and drinking water quality. Twenty-five large volume samples were collected for detailed chemical characterization to help inform subsequent sampling and laboratory experimentation. The post-doctoral fellow who will be central to Activity 2 was identified and hired. This scientist joined the project in January 2017. Activity 3 efforts included initiation of website enhancements and presentations.

Project Status as of July 2017:
During this period, our Activity 1 efforts focused on completion of laboratory analyses for samples collected in the previous year, methods development for satellite imagery, and initial analyses of remote sensing imagery from 2016 to measure concentrations of CDOM in MN lakes. For satellite imagery method development, we evaluated image normalization atmospheric correction methods and evaluated their performance for regional mapping of water quality. CDOM maps of Minnesota were created for 2015 Landsat 8 imagery and used to compare among alternative methods. Contaminant research (Activity 2) focused on completion of laboratory experiments in selected lake water samples to evaluate the reactivity of CDOM with chlorine to form disinfection byproducts (DBPs). The Uniform Formation Conditions (UFC) test was conducted in duplicate (or greater replication) to determine the DBP formation potential (DBPFP) for 24 lake samples. The formation potentials upon chlorination were obtained for two regulated DBP classes, trihalomethanes (THMs) and haloacetic acids (HAAs). A trial-and-error approach was used to evaluate the chlorine demand for each lake sample. Analytical methods for THMs and HAAs were developed to improve the accuracy of product quantification. Bromide levels of raw lake samples were measured to evaluate the formation of brominated DBP species. Correlations of chlorine demand, THM formation potential or HAA formation potential versus various indicators of DOM concentration and composition were built. The results indicate that THMs and HAAs follow different formation patterns upon chlorination, but both have positive correlation with CDOM, DOC, UV_{254} and $SUVA_{254}$. These results will contribute to generation of statewide DBPFP maps and assessments of water quality in Minnesota's lakes and rivers. Dissemination efforts (Activity 3) focused on redesign and update of the **water.rs.umn.edu** website for dissemination of research results and educational materials derived from the project. Project related presentations were shared at the ASLO Aquatic Sciences Meeting in Honolulu, Hawaii and the American Chemical Society (Environmental Chemistry Division) meeting in San Francisco, California.

Project Status as of January 2018:
Our Activity 1 research focused on methods development for satellite imagery and atmospheric correction methods, model development for CDOM and sampling of lakes across Minnesota to collect data for calibration and validation of remote sensing imagery needed to measure surface water quality (Activity 1). A total of 191 lakes and rivers were sampled in summer 2017. Including repeat sampling of 41 sites, a total of 273 samples collected. Many of the repeat sampling sites were re-sampled once, while 12 were sampled on a monthly basis. Sites were selected to include all major ecoregions of the state, and spanned wide range of lake size and land use. Methods were further refined to improve efficiency of sample collection and to minimize sample holding time. Preliminary assessment of satellite imagery from Landsat and Sentinel satellites indicates availability of high quality imagery corresponding to water quality sampling for the entire state during 2017. The data collected in 2017 will be used to develop and improve quantitative relationships between satellite observations and major water quality parameters (e.g., chlorophyll, total suspended solids, and turbidity) that are the focus of this project. Contaminant work (Activity 2) focused on the investigation of the role of CDOM in photodegradation of pesticides. The rate of formation ($R_{f,T}$) of triplet excited states of dissolved natural organic matter ($^3DOM^*$) was examined for 24 lake samples. One herbicide, 2,4,6-Trimethylphenol (TMP), was used as a probe compound to evaluate the formation of $^3DOM^*$. Photochemical experiments of TMP under simulated

sunlight were performed in triplicate to measure $R_{f,T}$. We initiated inhibition experiments to estimate an inhibition factor (IF) to correct the photodegradation rate of TMP at high CDOM levels. A positive correlation between CDOM and degradation rate will be built, which can be coupled with satellite CDOM assessments and contribute to the statewide assessments of pesticide photodegradation upon the impact of CDOM in Minnesota's lakes and rivers. Dissemination efforts (Activity 3) included continued updating and expansion of the **water.rs.umn.edu** website and several presentations, including two at the annual Water Resources Conference in October 2017.

Project Status as of July 2018:
Advances were made in all three project activities during the first half of 2018. Our Activity 1 research focused on methods development for satellite imagery and atmospheric correction, model development for water clarity, chlorophyll and CDOM. Final CDOM maps were created based on estimates of CDOM for the state's lakes, and statistics calculated at the ecoregion level for 2015 and 2016 using Landsat 8 imagery. We assessed the influence of CDOM on water clarity, and developed methods to identify water bodies highly affected by CDOM where water quality assessments based on Secchi depth (SD) measurements are biased. We presented and discussed our initial findings to MPCA. We continue working with data collected in 2017 by our group and others to develop and improve quantitative relationships between satellite observations and the water quality parameters (e.g., chlorophyll, total suspended solids, and turbidity) that are a major focus of the project. We investigated methods for Sentinel 2 imagery that work for optically complex lakes. Sentinel 2 imagery from two late summer 2017 dates was used to develop atmospheric correction methods, starting with water clarity data. We assembled available Secchi depth data from agency sources and tested atmospheric correction methods and SD models for use for both Sentinel 2 and Landsat 8 imagery. Dissemination efforts (Activity 3) included continued updates to and expansion of the **water.rs.umn.edu** website and the Lake Browser, and six presentations to agencies and academic institutions.

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Overall Project Outcomes and Results:
Water quality monitoring is essential for managing Minnesota's surface waters, maintaining the services they provide, and detecting changes caused by environmental stressors. Direct measurements of water quality are possible, however, in only a small fraction of the thousands of lakes and river miles in the state. Methods developed in this project allow use of increasingly frequent satellite observations to measure water clarity and the three key water quality indicators that control it: algae, colored dissolved organic matter (CDOM), and suspended solids. Because these parameters have distinct impacts on water quality, the ability to measure them directly across the state's waters enables comprehensive assessment of water quality status and trends and increases understanding of the causes and consequences of water quality degradation. We developed methods

to relate direct measurements of water quality to satellite imagery, assessed atmospheric correction techniques and validated methods using independent datasets. We applied these methods to measure water quality parameters on lakes >10ha, and provide the information at https://lakes.rs.umn.edu. Examples are included in appendix 1. Our methods extract information at seasonal to annual scales for algae, CDOM and suspended solids in lakes at state, regional, county, and watershed scales. Water quality parameters were linked to disinfection byproduct formation potential in drinking water treatment and degradation of contaminants driven by sunlight. CDOM levels were closely related to formation rates of two classes of disinfection byproducts, trihalomethanes and haloacetic acids, and to the production photo-induced reactive intermediates that degrade pesticides. This information can be used with remote sensing to assess pesticide persistence and suitability of surface waters for drinking water sources. An ongoing LCCMR project uses methods developed here with automated imagery acquisition and analysis to gather information on lake conditions at potentially a weekly basis. Project outcomes are summarized at https://water.rs.umn.edu/ for use by researchers, managers, lake associations and the public.

IV. PROJECT ACTIVITIES AND OUTCOMES:

ACTIVITY 1: *Build advanced methods for measuring water quality in surface waters of Minnesota*

Description: Physically-based predictive relationships will be developed to determine dissolved organic matter, chlorophyll (algae), and suspended solid levels from available satellite data. The predictive relationships will be developed or "calibrated" using approximately 150 lake and river sites, plus additional ~50 sites used for validation. We will evaluate the frequency with which state or region-wide assessments of these water quality indicators are possible within a given year by assessing availability of clear imagery and testing assumptions related to efficacy of automated image processing.

Field sampling methods. To obtain sufficient calibration data to map chlorophyll, suspended solids (SS), and CDOM at the statewide scale, we will sample ~200 lakes in summer 2017 to measure their optically-related water quality characteristics nearly contemporaneously with Landsat 8 and/or Sentinel-2 image acquisitions. We will select sites to obtain a wide range of CDOM, chlorophyll and SS values, including systems where one of these variables dominates the optical (reflectance) properties of the water body and systems where various combinations of the three variables also affect reflectance. Samples will be collected across the state in proportion to the density of lakes in a given region.

We will leverage sampling to be done in 2016 on a related study to refine sampling procedures for the 2017 field season and to collect preliminary calibration data. To the extent possible, we also will use Secchi depth (SD) data from the citizen monitoring program and water quality data from ongoing monitoring programs of the MPCA to expand the database for calibration/validation of images. The usability of these ancillary data will depend on close in time the sampling was done in relation to acquisition of the satellite images we will use for the statewide mapping.

Field data collected at each site will include clarity (as Secchi depth), temperature, dissolved O_2, pH and conductivity. Samples will be collected for measurement in the laboratory of the following water quality variables: dissolved organic carbon (DOC), total suspended solids (TSS), volatile suspended solids (VSS, a measure of suspended organic matter), turbidity, color (CDOM by absorbance measurements on filtered samples), and chlorophyll *a*. SD will be measured with a standard 20-cm disk from the sunny side of the boat using the average of the depths where the disk just disappears and re-appears when raised from below. Dissolved oxygen, temperature, pH and conductivity will be measured using calibrated field meters. Water samples for dissolved organic carbon (DOC) and CDOM will be filtered through ashed glass filters (Whatman GF/F) in the field and stored in the dark in washed polycarbonate or ashed glass bottles at 4 C until analysis. Field-filtered chlorophyll *a* samples will be stored frozen in foil until analysis following acetone extraction. Water samples for TSS, VSS and turbidity will be stored on ice at collection and processed on return to the lab.

UV/Vis absorbance scans (250-700 nm) will be obtained in 1- and/or 5-cm quartz cells on filtered (Whatman GF/F) samples using a Shimadzu UV-1601PC UV-Visible spectrophotometer. Results will be used to compute a_{440}, $SUVA_{254}$, and spectral slope, *S*, over the ranges: 275-295, 350-400, and 400-460 nm. Filtered water will be analyzed for DOC using a Sievers 900 Portable Analyzer or a Shimadzu Vcpn Analyzer calibrated with dilutions of potassium hydrogen phthalate. Blanks prepared with ultrahigh purity water will be used to confirm that contamination is not occurring in sample handling. Procedures from *Standard Methods* will be used to measure TSS, VSS, turbidity, and chlorophyll.

Two state-of-the-art characterization techniques, fluorescence spectroscopy and Fourier transform-ion cyclotron resonance mass spectrometry (FT-ICR-MS), will be used to obtain information on the chemical composition of fractionated dissolved organic matter (DOM) collected from selected lakes. We will relate the compositional information with data from satellite images and results from DOM reactivity testing. Fluorescence excitation-emission matrices (EEMs) will be generated on filtered samples (Millipore 0.2 µm nitrocellulose membrane filters) using a Horiba Aqualog fluorometer over an excitation range of 200-400 nm (5 nm intervals) and emission range of 290-550 nm (2 nm intervals). Scans will be corrected for variations in Raman scattering, lamp intensity, and cuvette imperfections. Contour plots representing the resulting matrix will be created and parallel factor analysis will be performed using reference components identified in similar work of others. FT-ICR-MS analyses will be done at the Old Dominion University Major Instrumentation Cluster, Norfolk, VA (http://www.sci.odu.edu/sci/cosmic/ index.shtml) by electrospray ionization using a Bruker Daltonics 12 Tesla Apex Qe FT-ICR-MS following standard procedures. We have worked previously with this group to characterize DOM from wetlands; they analyze samples on a fee for service basis.

Satellite imagery processing. Cloud-free satellite imagery for Minnesota will be downloaded from the Earth Resources Observation and Science (EROS) Center operated by USGS in Sioux Falls, South Dakota. We will rely primarily on Sentinel-2, which has some advantages of image size and frequency of repeat coverage, but will also use Landsat 8 imagery. Image processing will be based on methods we developed previously.

We will evaluate several methods for atmospheric correction: the Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes (FLAASH), based on the MODerate resolution atmospheric TRANsmission (MODTRAN) v5 algorithm, and QUick Atmospheric Correction (QUAC), Atmospheric Correction for OLI 'lite' (ACOLITE), along with Landsat Surface Reflectance Data Products provided by EROS. Areas obscured by clouds and haze will be masked out during preprocessing, and images will be processed in ERDAS IMAGINE. After preprocessing, spectral data for each lake will be extracted using the signature editor and used for modeling and data analysis.

Final image processing will use procedures that produce superior results, as determined by comparison with in situ data. To use satellite imagery to develop colored organic matter, algae, and suspended solids measurements, we will need in situ lake data that represent the wide range of optical conditions found in the imagery. Measurements of CDOM, chlorophyll and TSS will be used to develop robust algorithms and determine whether they work well under all optical conditions or if different algorithms are needed for optically complex waters and also to evaluate atmospheric correction methods. If we find that different algorithms are needed, we will develop screening techniques to group water bodies into appropriate optical classes prior to applying retrieval algorithms. The maps produced for Minnesota will include over 10,000 lakes and many large rivers.

Summary Budget Information for Activity 1:	**ENRTF Budget:**	**$ 205,000**
	Amount Spent:	**$ 205,000**
	Balance:	**$ 0**

Outcome	**Completion Date**

1. Measurements of algae, colored organic matter, and suspended solids in 125 selected lake and river sites to obtain a data set for developing predictive relationships	*December 2017*
2. Analysis of field and satellite data to develop predictive relationships to permit routine monitoring of algae, organic matter, and suspended solids in the state's waters	*February 2018*
3. A method for comprehensive water quality monitoring for Minnesota's 10,000 lakes	*June 2018*

Activity Status as of January 25 2017:
Our research in Activity 1 since project initiation focused on sampling lakes for major water quality constituents and acquisition of complementary satellite imagery. Samples for algae, colored organic matter, and suspended solids were collected from a set of 152 sites during the summer. Fourteen sites were sampled repeatedly (3-4 dates) to assess and characterize temporal variation. Sites ranged from very small (e.g., 14 acres) to some of the largest inland lakes in the state (e.g., Mille Lacs). Analyses of chemical parameters, algal biomass, and suspended sediment are ongoing. A total of 191 samples of colored organic matter have been analyzed, including repeat sampling of selected sites. Analyses of dissolved organic carbon and total dissolved nitrogen samples are 85% complete, and all available dissolved inorganic carbon samples have been analyzed. Algal biomass and suspended sediments were not collected at a few sites owing to logistical restraints. All available suspended sediment samples and algal biomass samples will be analyzed by February 2017.

Thus far, the lakes sampled in Minnesota show a wide range of optical and chemical measurements. For instance, colored organic matter absorption at 440 nm ranges from 0.3 m^{-1} (Six Lake in western MN) to 32.5 m^{-1} in Itasca County's Johnson Lake. Lakes within close proximity to each other can vary quite dramatically in colored organic matter, likely based upon differences in hydrology and land use. For instance, Burntside Lake absorption measured 0.8 m^{-1}, while less than 10 miles away Blueberry Lake measured 21.6 m^{-1}. Despite this heterogeneity, lakes in the Twin Cities metropolitan region tended to be low in color while most highly colored lakes were found in the Northern Lakes and Forests ecoregion, in the northeast portion of the state.

Similarly, we found a wide range in algal biomass and total suspended solids. Chlorophyll *a*, a proxy for algal biomass, ranged from 1.4 µg/L to 99 µg/L. TSS varied from 0.2 mg/L to 24.0 mg/L. Total suspended solids tended to be correlated with algal biomass, particularly at low concentrations (R^2 = 0.63). This, combined with available suspended sediment data, indicates that algal biomass is likely the primary control on the amount of total suspended solids and that mineral suspended sediments are a minor contributor in most lakes included in the study, to date. Exceptions to this likely are related to re-suspension of bottom sediments in lakes sampled during stormy or windy conditions. More comprehensive analysis will be performed upon completion of all laboratory analyses.

This dataset of lake chemical and optical properties provides a rich database upon which to develop remote sensing models for monitoring Minnesota's 10,000 lakes. The year 2016 was an unusual climatic year – indeed, it was the wettest year on record for the Twin Cities, and August was the wettest month of the year. The timing of rain events and overall cloudiness of the summer and early autumn overlapped with much of our sampling activities. Late summer and early fall were targeted for our most intensive sampling efforts because of the seasonal timing of algal blooms and because the historical satellite record indicates that this is an optimal period for acquisition of imagery. Despite the high cloud cover in 2016, there are several Landsat 8 and Sentinel 2A images that can be used for model development. We anticipate many more opportunities for imagery in 2017 with Sentinel 2A at full operation (images every 10 days vs. every 20 in 2016), launch of Sentinel 2B (March 2017), and the likelihood of more favorable climatic conditions.

Activity Status as of July 2017:
Our activity 1 research focused on methods development for satellite imagery, model development for CDOM and completing analysis of 2016 water quality analyses and preparation for the 2017 field season. During the late spring, we identified 100+ lakes to target for sampling during the field season that would include a large variety of watershed types and lake characteristics across the state. Undergraduate technicians were hired for

summer research activities. Initial sampling in May and June targeted 12 lakes that would be sampled on a monthly basis throughout the summer, as well as opportunistic sampling of other sites. Data collected in 2015 were used for initial development of relationships between field and satellite based measurement of CDOM. We evaluated one normalization (Radiometric Rectification (RR)) and three atmospheric correction methods (EROS Surface Reflectance v. 2.2 (SR), ACOLITE, FLAASH using five paths of Landsat 8 imagery (Figure 1). The RR and SR methods both showed promise as consistent normalization techniques for regional mapping of water quality. CDOM maps of lakes in Minnesota were created for 2015 using Landsat 8 imagery using the RR and SR corrected imagery and compared for consistency. Both produced reasonable results, with the SR method less labor intensive and amendable to automated image processing methods. Over the next period we will develop a more robust model using CDOM data from 2015 and 2016 and apply the same universal model to map CDOM across the state.

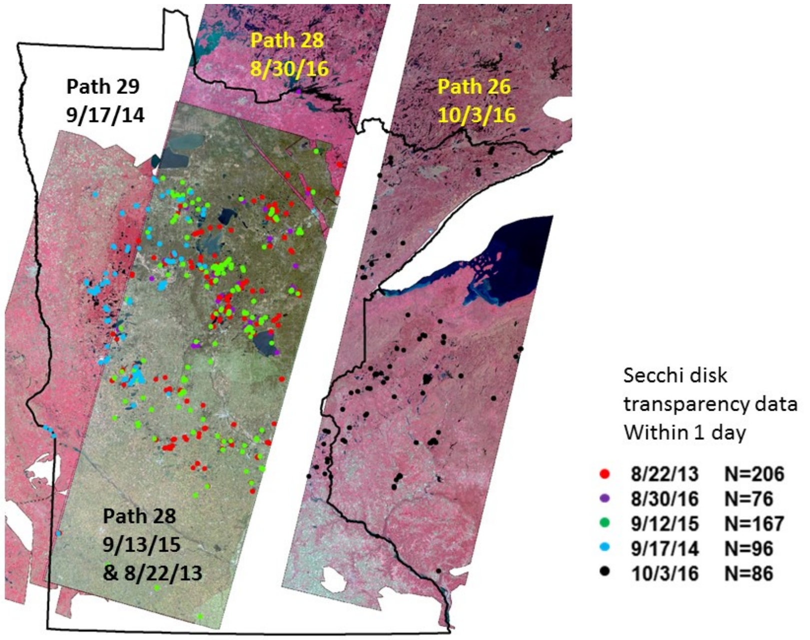


Figure 1. Landsat 8 imagery and available Secchi disk transparency data used to evaluate atmospheric correction and normalization techniques for regional water quality mapping.

Activity Status as of January 2018:

Our Activity 1 research focused on methods development for satellite imagery, model development for CDOM and extensive field sampling and laboratory analyses of samples collected, and access and integration of data collected by partners. During the summer and early fall we sampled 191 lakes for major water quality parameters needed to develop algorithms to relate satellite imagery to concentrations of algae, colored organic matter, and suspended sediments. Sampling was done with a UMN group of students and staff, and via collaboration and coordination with other groups. These included the Itasca Biological Station, the Red Lake Nation, DNR, the Minneapolis Parks Board, Minnesota Science Museum St. Croix Research Lab, and citizen volunteers from the Brainerd and Lake Vermillion areas to expand our ability to collection data from a large number of diverse lakes. We coordinated with MPCA in order to leverage data collections for our projects. The large majority of samples have been analyzed, and we are in the final stages of review for use. The best satellite imagery from 2017 has been acquired and stored for use. Once field data are finalized (in January 2018) we will begin to perform the necessary analyses needed to develop and improve methods to measure algae, colored organic matter, and suspended sediments across all the states' lakes.

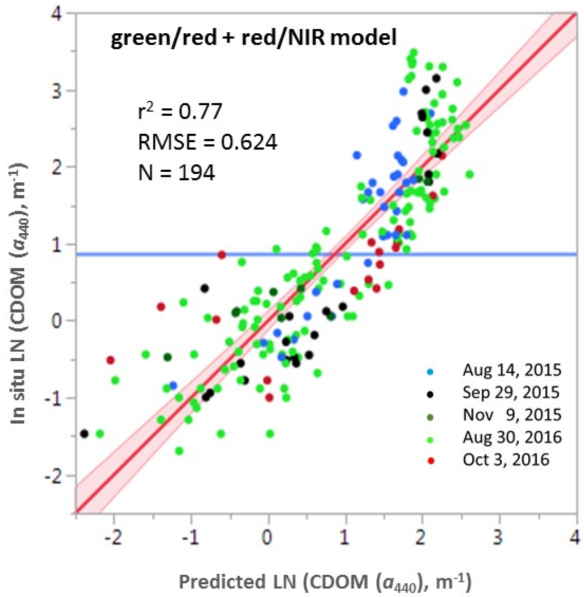


Figure 2. Landsat 8 EROS Surface Reflectance data from multiple dates used to create a universal model that was applied to 2015 and 2016 Landsat 8 imagery to create CDOM maps.

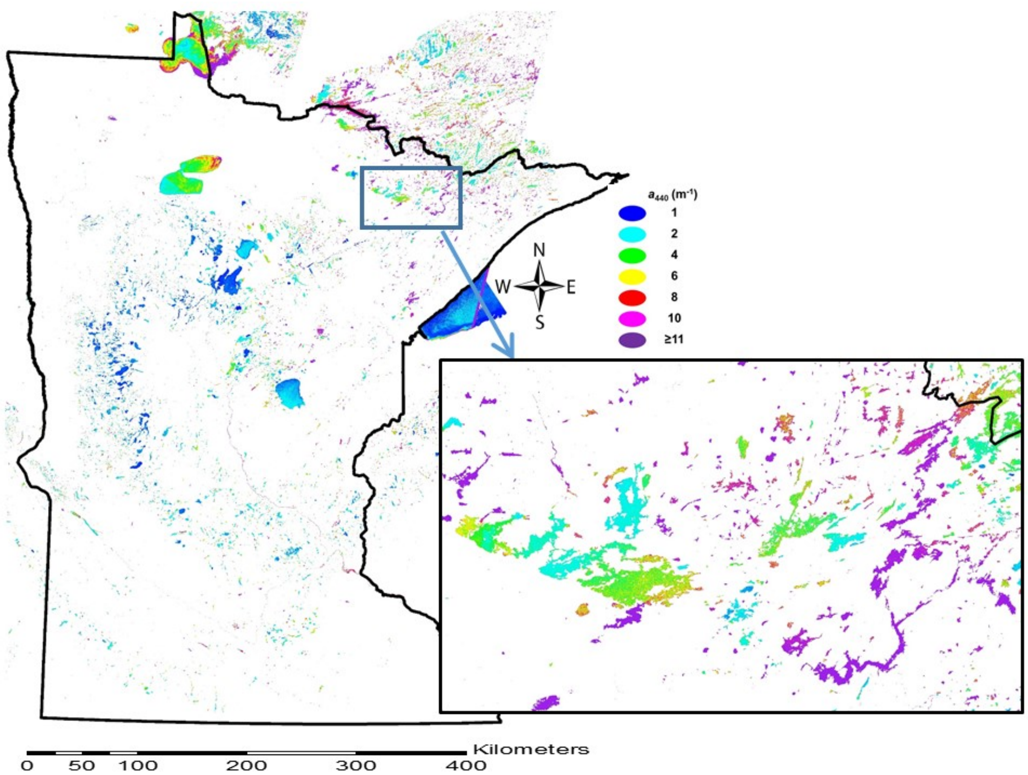


Figure 3. 2015 CDOM map for Minnesota created using the universal two-variable model (green/red + red/NIR), a440 = -5.478*OLI3/OLI4 -0.633*OLI4/OLI5) + 8.135 for SR imagery.

We evaluated four additional atmospheric correction methods (EROS Analysis Ready Data SR (ARD), SeaDAS l2gen, Modified atmospheric correction for inland waters (MAIN) and ESA Case-2 Regional/Coast Color (C2RCC) using five paths of Landsat 8 imagery (Figure 1). The SR method that showed promise in the previous period was used to create a more robust CDOM model from 2015 and 2016 in situ data to create a universal model (Figure 2). The universal model was applied 2015 and 2016 Landsat 8 SR imagery to create 2015 and 2016 CDOM maps (Figures 3 and 4 respectively).

Activity 2 requires minor revision of the target dates for completion of Outcomes 2 and 3, to June 2018 and August 2018, respectively. These changes are the result of three factors: acquisition of more samples and data than planned, shifts in personnel effort to accommodate other projects, and the renovation of Finlay's laboratory, which slowed some analyses this past fall. Despite these adjustments, Activity 2 and the project as a whole will remain on track.

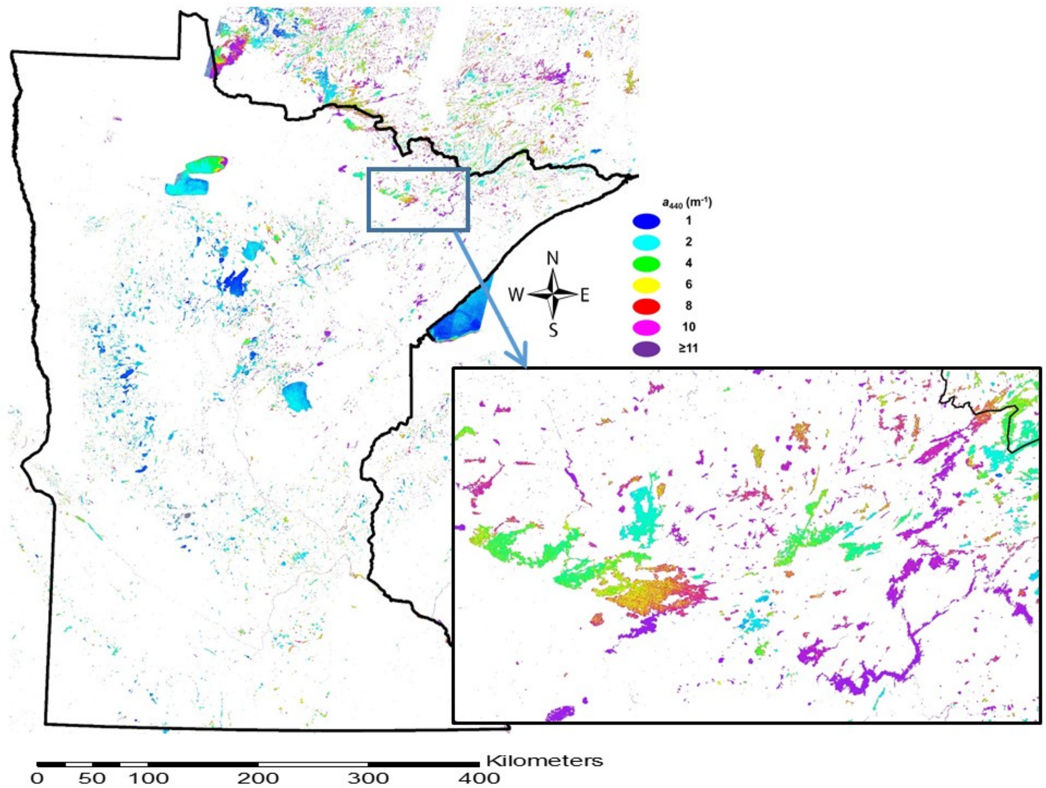


Figure 4. 2016 CDOM map for Minnesota created using the universal two-variable model (green/red + red/NIR), a440 = -5.478*OLI3/OLI4 -0.633*OLI4/OLI5) + 8.135 for SR imagery.

Activity Status as of July 2018:
The EROS SR method that showed earlier promise was used to create an improved CDOM model based on 2015 and 2016 in situ data that could be applied across atmospherically corrected images (hereafter referred to as a "universal model"). This model was applied to 2015 and 2016 Landsat 8 SR imagery to create final 2015 and 2016 maps that delineate CDOM levels in lakes across the state (Figures 5 and 6, respectively).

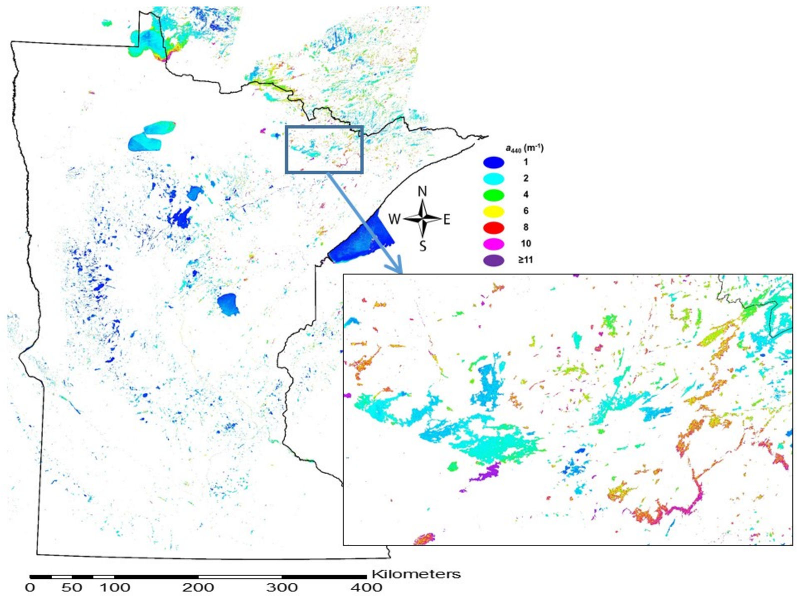


Figure 5. Final 2015 CDOM map for Minnesota created using the two-variable universal model (green/red + red/NIR), a440 = -5.478*OLI3/OLI4 -0.633*OLI4/OLI5) + 8.135 for Landsat 8 SR imagery.

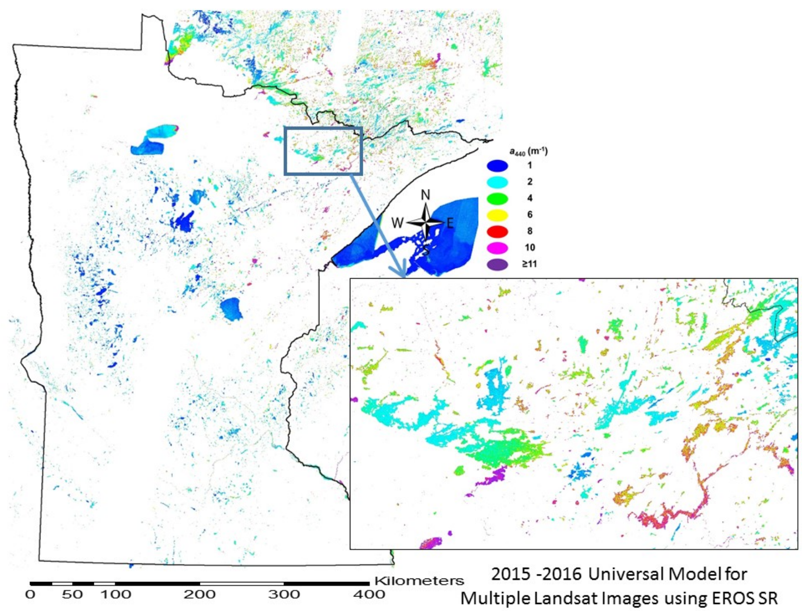


Figure 6. Final 2016 CDOM map for Minnesota created using the two-variable universal model (green/red + red/NIR), a440 = -5.478*OLI3/OLI4 -0.633*OLI4/OLI5) + 8.135 for Landsat 8 SR imagery.

We are using data for CDOM distributions across the state to understand implications for water quality and ecosystems. A recent manuscript, accepted pending minor revisions, establishes relationships between CDOM and dissolved organic carbon (DOC), an important controlling variable in freshwater aquatic ecosystems. These analyses show that in many northern Minnesota lakes, where dissolved organic matter comes primarily from terrestrial sources, CDOM is a reliable proxy for DOC, and satellite remote sensing can thus be used to estimate both parameters across broad spatial scales (Griffin et al., *accepted, July 2018*). DOC and CDOM are not strongly correlated in lakes where phytoplankton or macrophytes produce significant amounts of organic matter, however, as is often the case in central and southern Minnesota. Satellite remote sensing is useful for monitoring CDOM in these lakes, but resulting DOC estimates are not as reliable.

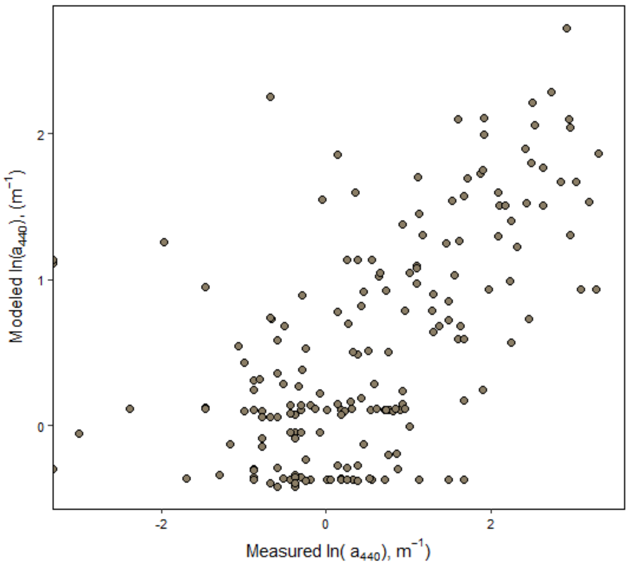


Figure 7: Variability in CDOM measured in lakes across the state was modeled, using watershed forested wetlands and lake area.

We are currently assessing landscape controls on CDOM using the data collected through Activity 1 and ancillary GIS data. Additional watershed data come from the MN DNR Hydrography and Watershed data suites, and land use data were extracted from the University of Minnesota Remote Sensing and Geospatial Analysis Laboratory's 2013 Minnesota Land Cover dataset. Initial analyses have focused on modeling CDOM from field-sampled lakes and headwater systems. The percentage of forested wetlands within the watershed is the largest driver of CDOM in these initial explorations, explaining 25-35% of variability in CDOM. For instance, Figure 7 shows field-measured ln(a_{440}) versus CDOM across all of MN modeled using forested wetland cover and lake surface area, which together explain 40% of CDOM variance. Other potential controls were tested but not significant in regression modeling, including lake area to basin ratios, percent watershed agriculture or impervious surface, and Strahler stream order. We are continuing to assess watershed controls on CDOM, using satellite-derived estimates from all lakes larger than 15 acres. Major regions in the state may differ markedly in terms of the landscape characteristics that most affect CDOM, and so these processes are being assessed on the scale of major watersheds (e.g., St. Louis River or Minnesota River watersheds), as well as on a statewide basis.

We developed atmospheric correction methods for use with both Sentinel-2 and Landsat 8 imagery. A promising method, the Modified Atmospheric correction for INland waters (MAIN), was evaluated for water clarity (Secchi depth, SD) during this period. We used SD data and Sentinel 2 imagery from August 23, 2017 (Figure 8a) that had some cloud cover but was clear for a large portion of Minnesota and an overlapping September 12, 2017 image (Figure 8b) that was clear throughout the state. In-situ SD data (hereafter referred to as SD_f, where subscript f stands for field) collected from the Citizen Lake Monitoring Program (CLMP) for calibration included 504 and 249 measurements within ±3 days of the clear portions coinciding with the Sept. 12 and Aug. 23 images, respectively (total of 753 measurements across the Western Cornbelt Plains (WCBP), North Central Hardwood Forests (NCHF), and Northern Lakes and Forests (NLF) ecoregions). The SD_f point locations were converted to a polygon shapefile with a 50 m circular buffer around the centroid. Corresponding mean remote sensing reflectance values (R_{rs}) of pixels within the polygons were extracted and tabulated.

An important factor influencing the strength and reliability of ground–satellite relationships for water clarity is the size of the "time window" between ground and satellite observations (Kloiber, et al., 2002). To address this issue, regression statistics were calculated using the relationship between ln(SD_f) and the ratio of the Sentinel-2 R_{rs} values for the red and blue bands centered around 664 and 497 nm, designated bands B4 and B2, respectively. These bands have been used in all our previous studies for retrieval of SD data from satellite imagery. We successively increased the time window between satellite overpass and ground observations and found that data collected within one day of the image provided the best R^2 and RMSE while still maintaining a large calibration dataset. This resulted in a final dataset for further analysis of 365 SD_f values with satellite imagery data (Figure 8(c-d)).

We used multi-stepwise linear regression for water clarity model development with log-transformed SD, $\ln(SD_f)$, as the dependent variable and Sentinel-2 R_{rs} values for bands B1-B8A (443 nm to 865 nm). All Sentinel-2 band ratio permutations were considered as independent variables using JMPro 14. Models also were developed for simulated Landsat 8 bands based on the Sentinel-2 bands corresponding to those present on the Landsat 8-OLI sensor) by excluding the three red-edge (B5-B7) and one NIR band (B8) not available on the OLI sensor to establish a robust water clarity model when both sensors are used for time series analysis.

We examined many two-term regression models for the Sentinel-2 imagery, and the best model generated from the combined SD dataset has the form:

$$\mathrm{Ln}(SD_{S\text{-}2}) = a(R_{rs}(B2)/R_{rs}(B4)) + b(R_{rs}(B5)) + c$$

where coefficients a, b, and c were fit to the calibration data by regression analysis, $\ln(SD_{S2})$ is the natural logarithm of the Sentinel-2-derived SD, and B2, B4, and B5 are the Sentinel-2 blue, red and NIR bands. From the combined dataset, the $\ln(SD_{S2})$ prediction model generated a high R^2 of 0.81, an RMSE of 0.360 m and $p < 0.0001$. The band ratio term $(R_{rs}(B2)/R_{rs}(B4))$ was found to contribute the most to estimating $\ln(SD_f)$ from the 365 inland water bodies.

Three additional models that also had reasonable fits ($R^2 > 0.79$) included the same band ratio as in the above equation as the most significant predictor. Interestingly, one regression generated a two-term model containing the NIR band centered at 842 nm ($R^2 = 0.79$, RMSE = 0.377) within the band ratio $R_{rs}(B3)/R_{rs}(B6)$ ratio, further supporting the usefulness of NIR reflectance to assess water quality characteristics in optically complex waters.

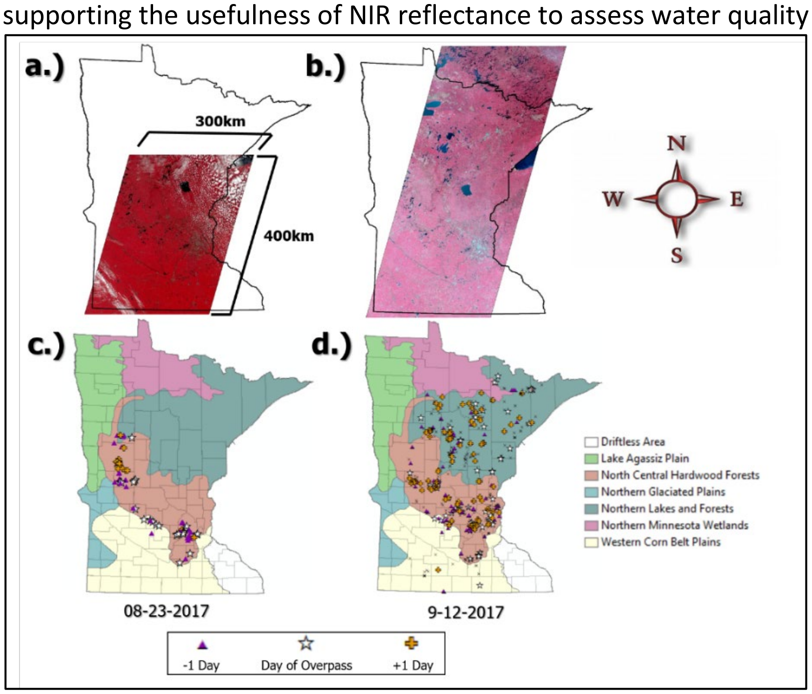


Figure 8. False-color Sentinel-2 image composites (R/G/B: B8A/B5/B4) of Minnesota on (a) August 23, 2017 and (b) September 12, 2017. (c-d) Corresponding time-window qualified SD_f sample locations ($\pm$ 1 day within satellite overpass, n = 365) collected by CLMP across the WCBP, NCHF, and NLF ecoregions.

An additional ln(SD) model was developed to enable subsequent cross-sensor comparisons between Landsat and Sentinel. This model was based on Sentinel-2 imagery using only Landsat-8 simulated bands as independent variables ($\ln(SD_{sL8})$). Using a similar two-term linear regression analysis, the following equation was generated:

$$\ln SD_{sL8} = a(R_{rs}(B2)/R_{rs}(B4)) + b(R_{rs}(B2)/R_{rs}(B3))$$

As expected, the B2/B4 (blue/red) band ratio also was the highest contributing factor in predicting $\ln SD_f$. The $\ln SD_{sL8}$ model generated an R^2 of 0.79, RMSE of 0.38 m, and $p < 0.0001$. A visual comparison of SD maps from the best performing two-term Sentinel-2 and simulated Landsat 8 models is shown in Figure 9.

We are currently exploring models to estimate algal biomass (i.e. chlorophyll) levels in Minnesota's lakes. Initial results show some promising models for chlorophyll that take advantage of the Sentinel-2 red edge (705 nm) band. These analyses will be completed in 2018; assembly of water quality data for suspended solids and turbidity analyses is ongoing.

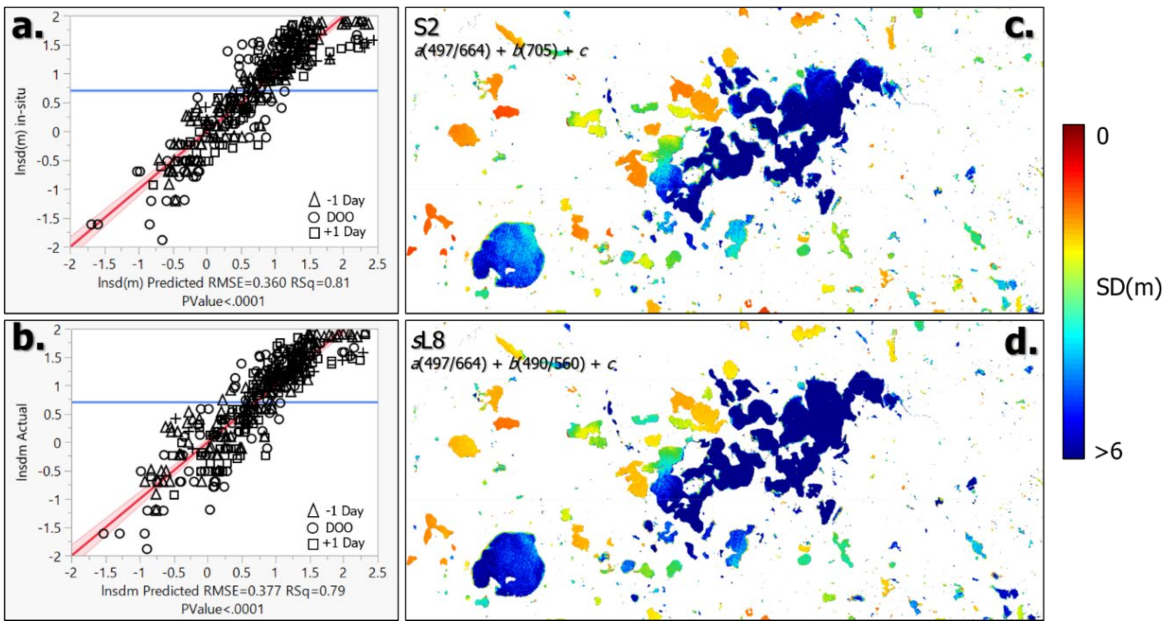


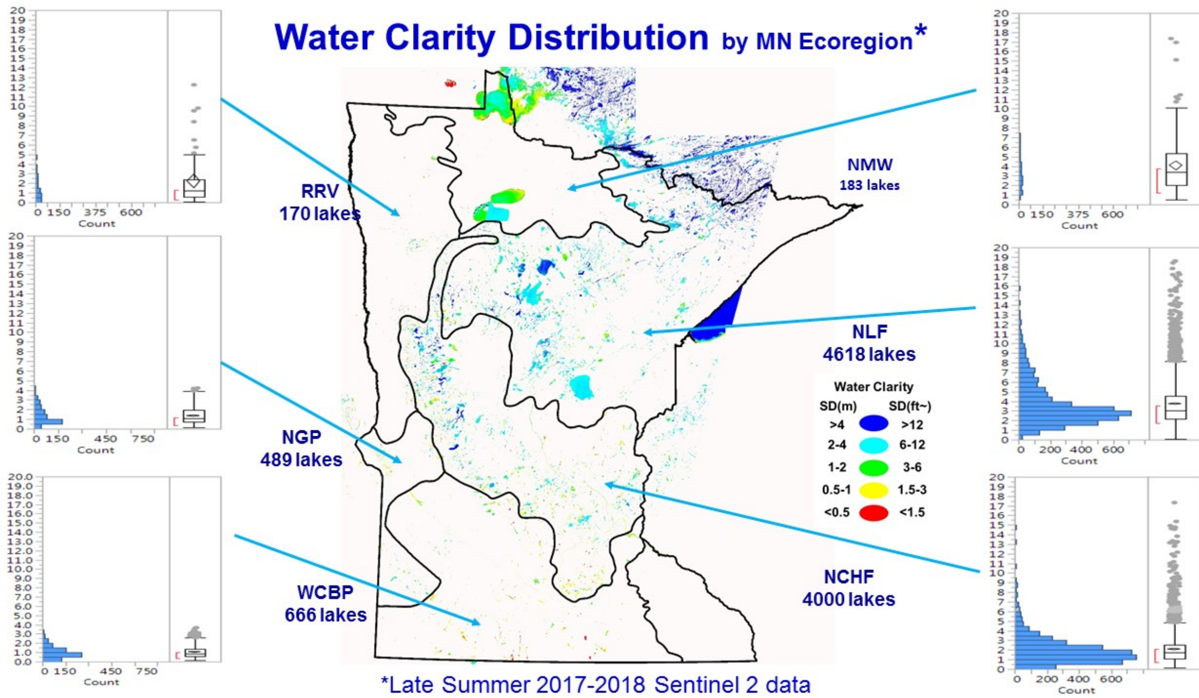
Figure 9. Average regression plots for (a) $\ln SD_{Sentinel\ 2\ (S2)}$ and (b) $\ln SD_{simulated\ Landsat\ 8\ (sL8)}$ from the calibration dataset collected on Aug. 23 and Sept. 12. DOO = Day of overpass (c-d) Corresponding pseudo-color SD_{S2} and SD_{sL8} maps of Lake Minnetonka, MN and surrounding water bodies.

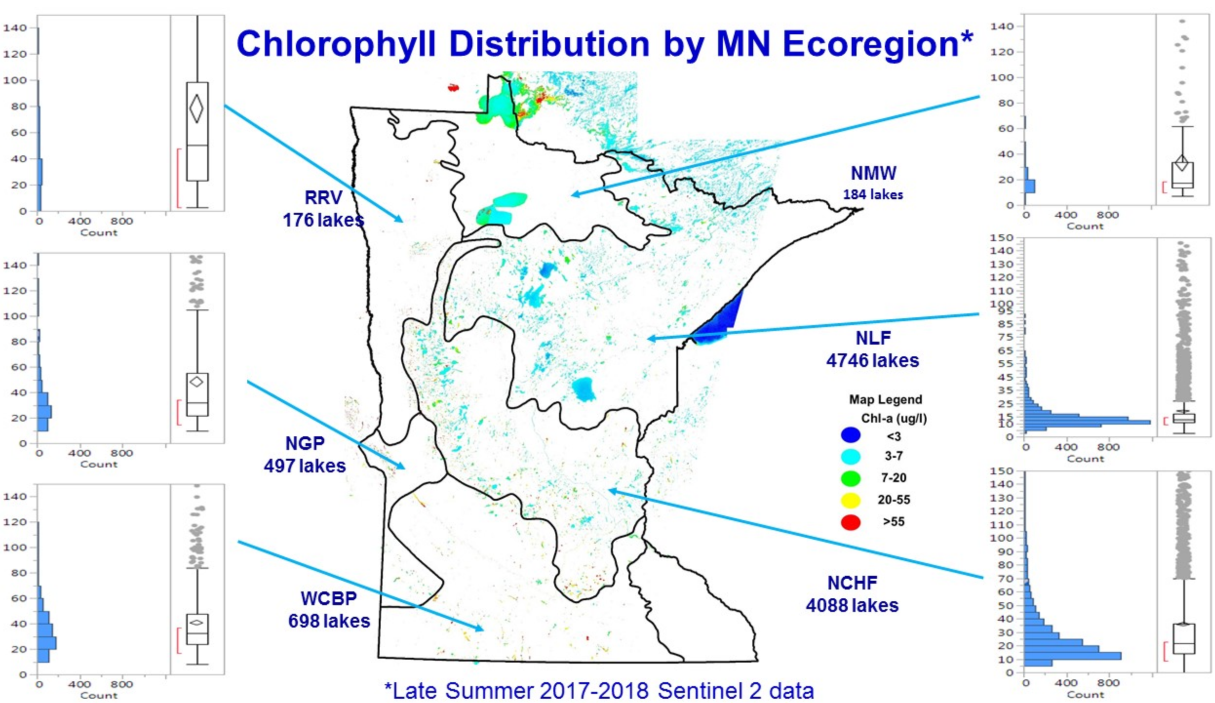
Activity Status as of January 2019:

During the summer of 2018, we sampled 30 lakes to expand our dataset for our remote sensing of TSS, chl-*a*, and CDOM from Sentinel 2 imagery. Sampling included lakes in the Twin Cities Metro Area and nearby agriculturally dominated regions. Sampling was coordinated to correspond with clear-sky imagery from August 30th and September 23rd. Lakes ranged from clear, with few algal blooms (chl-*a* of 2.46 µg/L in Square Lake) to hypereutrophic (172 µg/L in Elysian Lake).

Using remote sensing advances made in this and another LCCMR project, we estimated CDOM concentration and water volume for 12,000 lakes. Data for lake volume from an LCCMR project led by Professor John Nieber was combined with CDOM to estimate the amount of terrestrial DOC (tDOC) in Minnesota lakes. CDOM and tDOC pool sizes are important because they influence nutrient and contaminant cycling and greenhouse gas dynamics. Our estimates indicate that 1.1 Tg C of DOC is stored in the water column of Minnesota lakes. To put this in perspective, the Mississippi River annually discharges about 1.9 Tg C to the Gulf of Mexico. We plan to submit a related manuscript for publication in early 2019

We developed a preliminary chlorophyll map using 2017 and 2018 Sentinel 2 imagery to cover the entire state for the standard late summer index period (July 15 to Sept 15). Sentinel imagery from September 12, 2017 and associated field data were used to develop quantitative models for chlorophyll (R^2 of 0.69, RMSE of 0.646, and $p < 0.0001$. This model and the water clarity model previously developed (Figure 9) were applied to Sentinel-2 imagery for Sept 12, 2017 and August 21, 2018 to create chlorophyll and water clarity maps for the entire state. Using these and the CDOM maps created earlier, lake-average distributions of water clarity, chlorophyll and CDOM were calculated for each ecoregion (Figure 11, respectively). Validation of models and final statewide maps will be completed for all water quality variables during the final stages of the project.





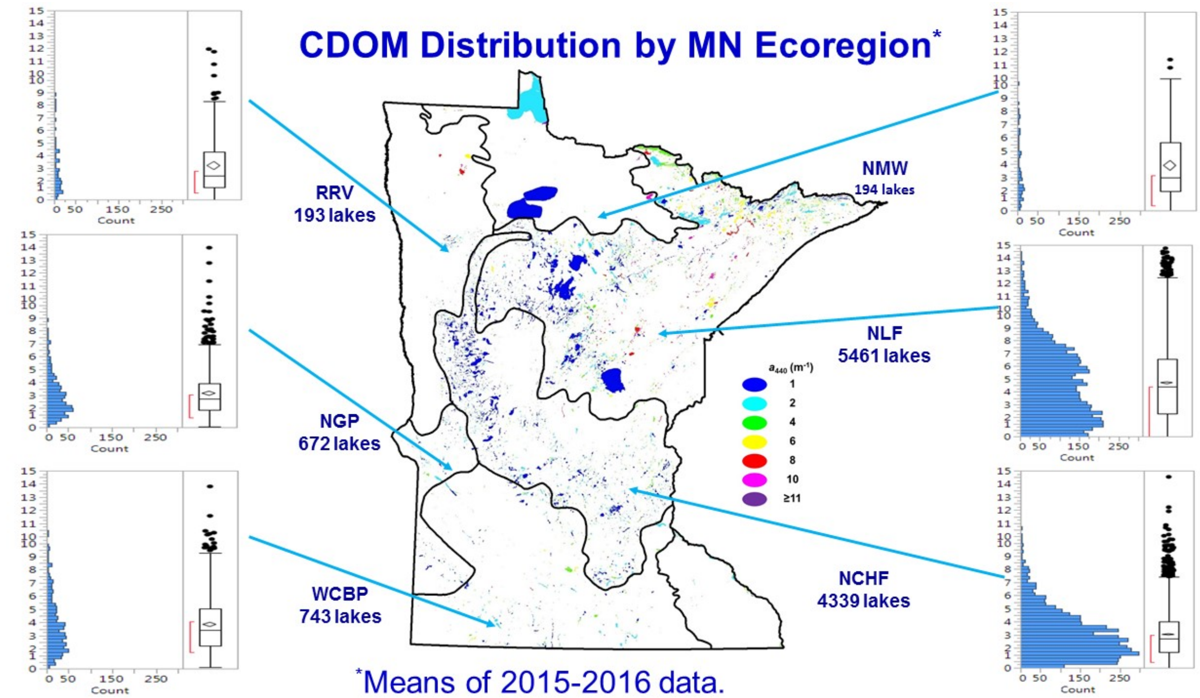


Figure 11 Statewide maps of water clarity, chlorophyll a, and CDOM for all lakes including summaries by ecoregion using remote sensing methods developed in this project. Landsat 8 was used for the CDOM map.

In collaboration with colleagues from the MPCA, we assembled a large database from our 2014-2017 ground-based sampling program and the MPCA's 2015-22017 lake monitoring program and used it to analyze interrelationships among the principal water quality variables that affect Secchi depth (SD) measurements. These variables are chlorophyll *a*, the main measure of algal abundance in lakes, total suspended matter (TSM), which reflects the abundance of both algae and mineral particles (clays, soil particles), and CDOM, the colored component of natural dissolved organic matter. The analysis showed clearly the conditions under which water clarity, as measured by SD, is controlled by one or several of the three driving variables. SD is one of the most common measurements on lakes and is widely used as a metric of lake trophic conditions. The MPCA uses SD to assess water quality impairment problems caused by eutrophication, and the agency established ecoregion-based SD criteria to aid in their decision-making on needs for watershed and lake interventions to manage such issues. For example, in the NLF ecoregion, the MPCA uses an SD criterion of 2 meters (m) for warm- and cool-water lakes; SD values below this criterion are assumed to indicate eutrophication-caused impairment relative to designated uses, such as body-contact recreation. Our analysis showed that many NLF lakes have SD values less than 2 m because of high CDOM levels, even though chlorophyll concentrations are low and the lakes do not suffer impairment due to eutrophication. We established guidelines for CDOM levels that render use of the 2-m SD criterion inapplicable for eutrophication assessments. In collaboration with MPCA scientists, we wrote a scientific paper documenting our findings. The paper was favorably reviewed for publication in the journal *Ecological Applications* and was recently accepted for publication in 2019.

Final Report Summary:
Development of methods for statewide assessments of water quality using new satellite capacity required three major components. First, we collected field data concurrently with high quality satellite imagery to relate optical image signals to water quality parameters**.** Second, we analyzed image processing methods needed to normalize imagery. Third, we developed and tested robust methods to use satellite imagery to measure water quality indicators. Field data collections (#1) were largely described previously and are briefly summarized here. Our data collection efforts were supplemented by collaboration and coordination with MPCA, citizen volunteers, and other groups. For CDOM, 250 measurements were coincident within 30 days of clear Landsat 8 and 134 for clear

Sentinel 2 imagery. Because of the relative stability of CDOM over short periods (Brezonik et al. 2015), these data were suitable for model calibration and validation. The other water quality variables (chlorophyll, TSS and turbidity) are commonly measured throughout the state but are more temporally variable. Because of this variability, only data collected within one day of the image date was used for calibration and validation. For chlorophyll, 213 measurements within one day of clear Sentinel-2 imagery were available from August 23, 2017 and September 12, 2017. For TSS and turbidity, 46 and 75 measurements, respectively, were available.

Our work on image processing (#2) resulted in major advancements in development of reliable methods for atmospheric correction (AC), which is needed to normalize imagery, which is applicable to both the Landsat L8/OLI and Sentinel S2/MSI sensor systems, and also is adaptable to future imagery from multiple sensor types. In our investigation of atmospheric correction methods, we discovered important differences among correction methods and between the specific versions of methods used. Many of these methods are under active development, and although modifications tend to improve performance for water quality sensing, they make models developed from previous version obsolete. This is a large problem relative to our goals for long term monitoring and automated image processing (discussed below). To address this issue, we evaluated the most widely used atmospheric correction methods, including the most recent versions of EROS SR, EROS Analysis Ready Data SR (ARD), SeaDAS l2gen, Modified atmospheric correction for inland waters (MAIN), ATmospheric REMoval (ATREM), ACOLITE (AC) and ESA Case-2 Regional/Coast Color (C2RCC) using three Minnesota paths of Landsat 8 imagery. Although all the evaluated methods could be used for water quality assessments, the EROS SR and MAIN discussed in the previous period performed best. MAIN has the added capacity for harmonization of remote sensing data from multiple sensors (Page et al. 2019). Following careful evaluation of these methods, we concluded that MAIN is best suited for present and future needs. The EROS SR AC method that showed promise in earlier periods was modified by EROS and is different from the version that we used to create a CDOM model and the 2015 and 2016 CDOM maps described previously. Because of the likelihood of further changes to EROS methods, we selected MAIN for all atmospheric correction tasks associated with image processing. For consistency, we reanalyzed earlier CDOM models with MAIN atmospheric correction.

The third major component of our work was development of models to quantitatively relate corrected satellite imagery to key surface water quality variables. We used a semi-empirical approach to develop robust algorithms for CDOM, chlorophyll, TSS and turbidity using field data described earlier. To explore the potential of Landsat 8 and Sentinel 2 to measure water quality variables we implemented a bootstrap forest technique (JMP®, Version 14. SAS Institute Inc., Cary, NC) that determined the most robust bands and band-ratio combinations to model the water quality variables. The calibration water quality dataset that corresponded with clear Landsat 8 or Sentinel 2 imagery was used as the dependent variable and MAIN-derived mean R_{rs} values from bands B1-B5 for Landsat 8 and B1-B8A for Sentinel 2 (Table 1) and all band-ratio permutations as independent variables (26 and 81 total terms, respectively).

Table 1. Sensor characteristics for L8/OLI and S2/MSI, including band center, bandwidth, spatial resolution and signal-to-noise ratio (SNR. SNR values have been scaled for radiances observed over clear coastal waters (adopted from Pahlevan et al., 2017).

				Landsat-8/OLI							
Band ID	**B1**	**B2**	**B3**	**B4**	**-**	**-**	**-**	**-**	**B5**	**B6**	**B7**
Band center (nm)	443	482	561	655	-	-	-	-	865	1609	2201
Bandwidth (nm)	20	65	60	40	-	-	-	-	30	85	190
Resolution (m)	30	30	30	30	-	-	-	-	30	30	30
Signal-to-Noise Ratio (SNR)	284	321	223	113	-	-	-	-	45	10.1	7.4
				Sentinel-2/MSI							
Band ID	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**	**B8**	**B8A**	**B11**	**B12**
Band center (nm)	444	497	560	664	705	740	783	842	865	1610	2190
Bandwidth (nm)	20	55	35	30	15	15	15	15	20	9	175

Resolution (m)	60	10	10	10	20	20	20	10	20	20	20
Signal-to-Noise Ratio (SNR)	439	102	79	45	45	34	26	20	16	2.8	2.2

The bootstrap forest technique uses decision trees to associate imagery data (R_{rs} data) with in situ (lake) data, chosen randomly to determine the terms that predict a lake variable based on the highest total sum of squares (SSTO) (Hastie et al., 2009). Prediction consistency of the bootstrap decision for each term was evaluated by splitting the samples into training (70%) and validation (30%) datasets and running 10,000 iterations. Only the two highest contributing terms that produced the highest coefficient of determination (R^2) with in situ data were used to develop models using the Landsat 8 and Sentinel 2 (using only the bands coincident with Landsat 8) (5 bands, 443–865 nm). A second model was developed for Sentinel 2 using all available bands (9 bands, 443–865 nm), including the red-edge bands (near 705 nm) that improved measurement of chlorophyll in other studies. Overall model accuracy was assessed based on how well the model forecast in situ water quality parameters.

After a review of the previous literature on satellite-based models for the water quality parameters and further exploration of various two-term regression models using Landsat 8 and/or Sentinel 2-R_{rs} imagery for CDOM, chlorophyll, TSS and turbidity, we identified the best models using the datasets described above. The two-term models took the form:

Ln(water quality variable) = a(term 1) + b(term 2) + c

where term 1 and term 2 represent R_{rs} data for various bands or band ratios; coefficients a, b, and c were fit to the calibration data by regression analysis; and Ln(water quality variable) is the natural logarithm of the satellite-derived water quality variable for a given pixel.

We also developed one term models for turbidity that had the form:

Ln(water quality variable) = a(term 1) + c

Model development. Model terms and statistics for the five focal water quality variables are summarized in Table 2. For water clarity (measured as Secchi depth, SD), CDOM (measured as a_{440}) and TSS, the Landsat 8 bands worked almost as well as the Sentinel 2 bands (even better in the case of a_{440}). Although the difference in R^2 between the Landsat 8 and Sentinel-2 models for CDOM (a_{440}) (0.85 and 0.73, respectively) could be partly due to differences in the datasets used for the two models, it likely is largely due to the lower signal-to-noise ratio of the Sentinel-2 MSI sensor for the bands used in the a_{440} model (Page et al. 2019 & Table 1). The differences in fit between the models for Sentinel-2 and models developed with only the Sentinel 2/Landsat 8 coincident bands (Table 1) for chl a and to a lesser degree turbidity and CDOM indicates that the additional spectral bands in the MSI sensor improve the relationships for chl a, turbidity and CDOM. When the difference in signal-to-noise ratio is taken into account, Landsat 8 is well suited for all of these water quality variables except possibly chl a. The red edge bands (at 705 and 740 nm) of Sentinel-2 are well suited for all these water quality variables due to the improved spectral bands although the lower signal to noise ratio of this sensor may decrease the relationship.

Table 2. Water quality model terms and statistics

Water quality variable	Sensor	Term 1[1]	Term 2[1]	R^2	R^2 range	RMSE	RMSE range	N
Water Clarity	Landsat 8	655/490	655	0.78	0.78-0.79	0.352	0.346-0.360	507
Water Clarity	Sentinel 2	655/490	705	0.79	0.79-0.80	0.337	0.330-0.342	348
Water Clarity	S2_LS	655/490	560	0.78	0.78-0.79	0.348	0.339-0.355	348
a440	Landsat 8	655/560	865/560	0.85	0.85-0.86	0.487	0.479-0.493	250
a440	Sentinel 2	655/560	740/560	0.76	0.74-0.79	0.628	0.589-0.654	134
a440	S2_LS	655/560	865/560	0.73	0.71-0.76	0.664	0.626-0.683	134
Chl a	Sentinel 2	490/705	665/560	0.78	0.76-0.80	0.569	0.551-0.593	213
Chl a	S2_LS	490/665	665/560	0.72	0.69-0.75	0.641	0.614-0.655	213
TSS	Sentinel 2	490/655	740/842	0.84		0.486		46
TSS	S2_LS	490/665	665/842	0.83		0.503		46
Turbidity	Sentinel 2	705/560		0.84		0.480		75
Turbidity	S2_LS	490/665		0.80		0.532		75

[1] *Band center wavelength in nm and listed as Landsat 8 band centers for coincident sentinel 2 bands*

Together, these analyses show strong relationships that can be used to measure and map water quality parameters for all lake conditions in the state. Initial results of this approach are displayed on the LakeBrowser (https://lakes.rs.umn.edu/) for water clarity (SD), CDOM (a_{440}) and chlorophyll a. In addition, more extensive data for the initial findings for TSS and turbidity are displayed on our web site (http://water.rs.umn.edu).

Outcomes for Activity 1, in particular the MAIN-based models for water clarity, CDOM, chlorophyll, TSS and turbidity, and other advances made by our project will be implemented for routine water quality monitoring across Minnesota by the ongoing LCCMR project *Providing Critical Water-Quality Information for Lake Management* (J. Peterson, PI). Our completed project developed the basis for an automated monitoring system that uses combined information from both Landsat and Sentinel satellite imagery. The increased availability of Sentinel and Landsat imagery, along with cloud-based and supercomputing capabilities, enables the development of automated routines using the improved spectral, spatial, radiometric and temporal resolution of these satellites for water quality monitoring and fisheries management. This new system is currently in testing phase; once complete, it will be implemented for the whole state. All water quality data produced has been made available in the Lake Browser as described in Activity 3.

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ACTIVITY 2: ***Relate surface water composition to pollutant fate and drinking water quality***

Description: Lakes and rivers in Minnesota are influenced by algae, colored dissolved organic matter, and suspended solids, but we do not fully understand how these constituents affect drinking water production or the fate of pollutants. We will conduct studies to understand how these features of surface waters, measured for all lakes in the state, influence formation of disinfection byproducts during drinking water treatment and degradation of pesticides and pharmaceuticals in surface waters. Experiments will be performed in laboratory systems that simulate drinking water treatment and natural processes (the latter leveraged through an active LCCMR project led by Arnold).

Laboratory experiments will be performed with water samples collected during field sampling (in Activity 1) to assess the reactivity of the natural organic matter in the sampled waters. Water samples will be collected from a variety of lakes that represent a range of water quality conditions including CDOM levels and algae levels. The water samples will be filtered and stored in the dark in the refrigerator until further use.

The first set of experiments will be designed to assess the reactivity of the organic matter with chlorine to form so-called disinfection byproducts (DBPs). DBP formation is a significant concern in the water treatment industry because chlorine is the most common chemical used for disinfection and because many DBPs are known or suspected human carcinogens. In our DBP experiments, we will focus on a specific class of DBP compounds referred to as trihalomethanes (THMs), one of which is the organochlorine compound chloroform. We will perform THM formation potential tests on each water sample. In the test, excess chlorine is added to a water sample, and the sample is incubated at 25°C for 7 days. At the end of the incubation period, the chlorine residual is measured and then quenched with sodium sulfite. Then, the THMs are analyzed via gas chromatography with an electron capture detector.

The second set of experiments is designed to assess the role of CDOM in sunlight-mediated or 'photochemical' reactions. Photochemistry is important in the fate of pollutants in surface water bodies such as lakes because sunlight can react both directly with pollutants and indirectly via formation of reactive oxygen species (ROS) when sunlight reacts with other constituents in the water. CDOM can play two roles in photochemistry. One is to absorb sunlight and diminish the role of direct photolysis and photochemically-mediated contaminant degradation. Conversely, CDOM can act as a photosensitizer and convert sunlight into ROS (such as hydroxyl radical). These ROS can then react with the pollutants to transform or degrade them. In our experiments, the target pollutants will be pesticides. A few pesticides will be selected to represent the range of chemicals commonly used in Minnesota including atrazine and imidacloprid (i.e., Roundup). We will select water samples that have different spectral characteristics based on the satellite and laboratory measurements. These experiments will be performed by adding the pesticide to the water sample and incubating the sample in a solar simulator that mimics the light spectrum of natural sunlight. At the end of the incubation period, the target contaminant will be analyzed by appropriate techniques (e.g., liquid chromatography). Additional experiments will be performed with the same water samples but without added pollutants to quantify the formation of specific ROS during exposure to simulated sunlight using chemical probes. Leveraging current LCCMR funding for Arnold, we will evaluate whether the satellite and laboratory measured spectral characteristics provide predictive power in regards to ROS production.

After the experiments are completed, we will investigate relationships between indicators of DOM composition and content generated in Activity 1, including DOC, CDOM, chlorophyll *a*, spectral slope, UV absorption, EEMs indicators, and molecular structure information from FT-ICR-MS, and both DBP formation potential and the potential for photochemical intermediate formation. We will investigate single parameter correlations as well as multivariate relationships. These analyses will help develop the use of satellite data to perform large-scale assessments of water treatability and photochemical contaminant degradation rates.

Summary Budget Information for Activity 2: **ENRTF Budget: $ 95,000**
Amount Spent: $ 95,000
Balance: $ 0

Outcome	**Completion Date**

1. Evaluate the influence of algae and organic matter on formation of disinfection byproducts upon chlorination	*December 2018*
2. Identify waters least and most likely to degrade pesticides by photolysis	*December 2018*

Activity Status as of January 2017:
We collected large volume (20-liter) carboys of water from 25 surface waters (mostly large lakes) during the 2016 sampling season for subsequent laboratory studies on the effects of CDOM on formation of disinfection by-products during the chlorination process in drinking water treatment and on *in situ* photochemical intermediate production. All samples were filtered (0.45 µm) immediately after collection, transported in a large freezer, and stored in a cold room in the dark prior to the onset of laboratory studies. Water bodies from which the samples were collected were selected to provide a wide range of CDOM levels, and the emphasis was on large lakes that could serve as potential drinking water supplies in the future. The list includes Rainy Lake, Lake of the Woods, Lake Mille Lacs, Lake Bemidji, and several sites on the Mississippi River. These samples were collected under the Activity 1 budget, since sites were used for both activities.

We hired a postdoctoral scientist to lead the laboratory studies on photochemistry and treatment process effects. She received her Ph.D. in environmental engineering from Temple University in December and arrived on campus in early January. She currently is completing lab safety training requirements and will be starting the lab studies by the end of January 2017.

Activity Status as of July 2017:
Our Activity 2 research focused on evaluating the reactivity of CDOM in 24 lake water samples with chlorine to form disinfection byproducts (DBPs). A trial-and-error exercise was performed to evaluate the chlorine demand for each lake sample. The Uniform Formation Conditions (UFC) test was conducted in at least duplicate to determine the DBP formation potential (DBPFP) upon chlorination. Analytical methods for two regulated DBP classes, trihalomethanes (THMs) and haloacetic acids (HAAs), were developed to improve the accuracy of product quantification. Bromide levels of raw lake samples were measured to estimate the formation concentration of brominated DBP species.

Two THM species including chloroform and bromodichloromethane (TCM and BDCM), and five HAA species including monochloro-, monobromo-, dichloro-, bromodichloro-, and trichloroacetic acid (MCAA, MBAA, DCAA, BDCAA, and TCAA) have been observed as chlorination products. Specifically, TCM, DCAA and TCAA are predominant over other species. The chlorine demand of 24 lake samples varied from 3.7 to 61.5 mgCl_2/L. The THM formation potential (THMFP) we obtained ranges from 104.0 to 2019.1 µg/L, while HAAFP ranges from 592.1 to 2819.7 µg/L.

We built a series of correlations between chlorine demand, THMFP or HAAFP and various indicators of DOM concentration and composition. No correlation was observed between chlorine demand and other indicators such as total suspended solids (TSS), chlorophyll α and so on. $SUVA_{254}$ has a linear correlation with specific chlorine demand, while DOC, CDOM, and UV_{254} correlate well with chlorine demand.

Similar to chlorine demand, positive and strong correlations were observed between THMFP and CDOM, DOC and UV_{254}, indicating that the CDOM, DOC and UV_{254} level are key drivers of the THM yields, especially in lower ranges. Meanwhile, $SUVA_{254}$ and specific THMFP are well correlated. Meanwhile, a lower level of CDOM, DOC or UV_{254} has a linear correlation with HAAFP, respectively, which is similar with THMFP. However, as the level of CDOM, DOC or UV_{254} increases, HAAFP starts to level off, leading to a logarithmic correlation. On the other hand, $SUVA_{254}$ and specific HAAFP were poorly correlated, suggesting that the effectiveness of $SUVA_{254}$ in predicting HAA yields is water-specific. Specifically, different trends were observed among mono HAAFP, di HAAFP and tri HAAFP, indicating that they have different precursors. These results indicate that THMs and HAAs follow different formation patterns upon chlorination, but both have positive correlation at low levels of CDOM, DOC, UV254 and SUVA254, which can contribute to generate statewide DBPFP maps and perform assessments of water quality in Minnesota's lakes and rivers.

Activity Status as of January 2018:

Our Activity 2 research focused on investigating the role of CDOM in photodegradation of pesticides. The rate of formation ($R_{f,T}$) of triplet excited states of dissolved natural organic matter ($^3DOM^*$) was examined for 24 lake samples. One representative herbicide, 2,4,6-Trimethylphenol (TMP), was used as a probe compound to evaluate the formation of $^3DOM^*$. Photochemical experiments of TMP under simulated sunlight were performed in triplicate to measure $R_{f,T}$.

We found that TMP degradation follows pseudo-first order kinetics. A linear correlation was observed between the pseudo-first order rate constant, $k_{obs,TMP}$, and CDOM at low levels. However, a positive nonlinear trend that approached plateau was observed between $k_{obs,TMP}$ and CDOM increasing to higher concentration (logarithmic fit). We initiated inhibition experiments to estimate an inhibition factor (IF), which can be used to correct the $k_{obs,TMP}$ upon high CDOM levels. A linear correlation between $k_{obs,TMP}$ and CDOM level will be built, which can be coupled with satellite CDOM assessments and contribute to the statewide assessments of pesticide photodegradation upon the impact of CDOM in Minnesota's lakes and rivers.

Activity Status as of July 2018:

We established correlations between CDOM and the concentration of various DBP species in 24 lake samples, and proved that CDOM can be used as a predictor for chlorine demand and DBP formation. We generated pixel level maps to evaluate distribution of chlorine demand and DBP_{UFC} levels for > 10,000 lakes throughout Minnesota, based on models of CDOM-chlorine demand and CDOM-DBP_{UFC}, as well as Landsat 8 images obtained close in time to sampling. A much higher level of THM_{UFC} (> 150 μg/L) in northeast Minnesota, especially in the NLF ecoregion, and relatively lower THM_{UFC} were obtained in the NCHF), the Northern Minnesota Wetlands (NMW), and the WCBP ecoregions. Similarly, the NLF generally has higher levels of HAA_{UFC} (> 800 μg/L). The distribution of DBP_{UFC} levels in the four ecoregions clearly reflected their current situations of urban and agricultural land uses. Consistent with DBP_{UFC}, a higher chlorine demand (> 5 $mgCl_2$/L) was observed in the NLF.

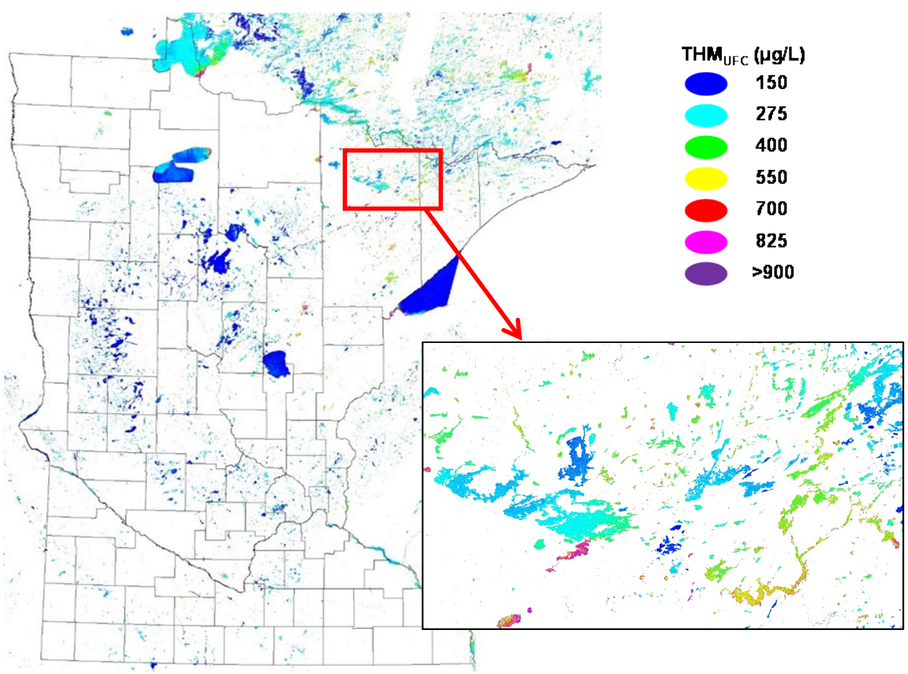

Figure 10. Distribution of lake THM_{UFC} levels in Minnesota using the two-variable universal model (green/red + red/NIR), a440 = -5.478*OLI3/OLI4 -0.633*OLI4/OLI5) + 8.135 for Landsat 8 SR imagery. Inset map shows detail in the Ely, MN area.

Our efforts to elucidate the role of CDOM in photochemical experiments focused on determining the steady-state concentrations of different photochemically produced reactive intermediates (PPRIs), including $^3DOM^*$, $^1O_2$, and •OH under simulated sunlight. Because the photodegradation of pesticides in aquatic environments may be facilitated via photosensitized processes in which PPRIs are involved. Knowing the concentrations of PPRIs plays an important role in predicting the fate of pesticides in natural waters. For $^3DOM^*$, we found that the degradation rate constant of its probe TMP ($k_{obs,TMP}$) followed a positive logarithmic trend across the entire CDOM/DOC range. We investigated the influence of DOC inhibition on TMP photodegradation using 4-carboxybenzophenone (CBP) as a $^3DOM^*$ model, and corrected the nonlinear correlation between $k_{obs,TMP}$ and CDOM. We also examined the formation of $^1O_2$ using furfuryl alcohol (FFA) as a probe. We found that FFA degradation follows pseudo-first order kinetics, and linearly correlated with CDOM level, suggesting that $^3DOM^*$ is the primary source for $^1O_2$ in sunlit natural waters. By monitoring the photodegradation of p-nitroanisole (PNA) as an actinometer, we measured the rate of light absorption by the samples, and calculated the rate of formation ($R_{f,T}$) of $^3DOM^*$and the efficiency of $^3DOM^*$ formation (the apparent quantum yield, AQY_T). In addition, we quantified the formation of •OH by the formation of 2-hydroxyterephthalic acid (hTPA) using terephthalic acid (TPA) as a probe. We will apply the established correlations between CDOM and the formation of PPRIs to generate state-wide maps, which can be used to further assess the treatment necessary to use Minnesota's lakes and rivers as drinking water sources.

Activity Status as of January 2019:

We made advances in elucidating the relationship between CDOM (a_{440}) and the generation of PPRIs upon photolysis. The DOM compositional parameters we investigated include the total rate of light absorption by the water samples (R_a), the formation rates (R_f), the steady-state concentrations and apparent quantum yields (Φ) of three PPRIs. We found that R_a was strongly and positively related to a_{440} levels, as found in other recent studies. For $^3DOM^*$ and $^1O_2$, the R_f and the steady state concentrations increased linearly with increasing a_{440}, while Φ were independent of a_{440}, but linearly correlated with E2/E3 (the ratio of UV absorbance at 250 to 365 nm), which is a direct proxy for the degree of photobleaching and an inverse proxy for DOM molecular weight. Consistent with previous studies, no correlation was observed between E2/E3 and $\Phi_{\bullet OH}$. Our ongoing work will apply the relationships between R_f and R_a values with a_{440} to provide estimates of the rate of contaminant loss via indirect photolysis within lakes. These relationships can then be scaled up in maps of reactive species production rates across all surface waters in Minnesota that will allow prediction of contaminant transformation rates. An example is shown in Figure 12.

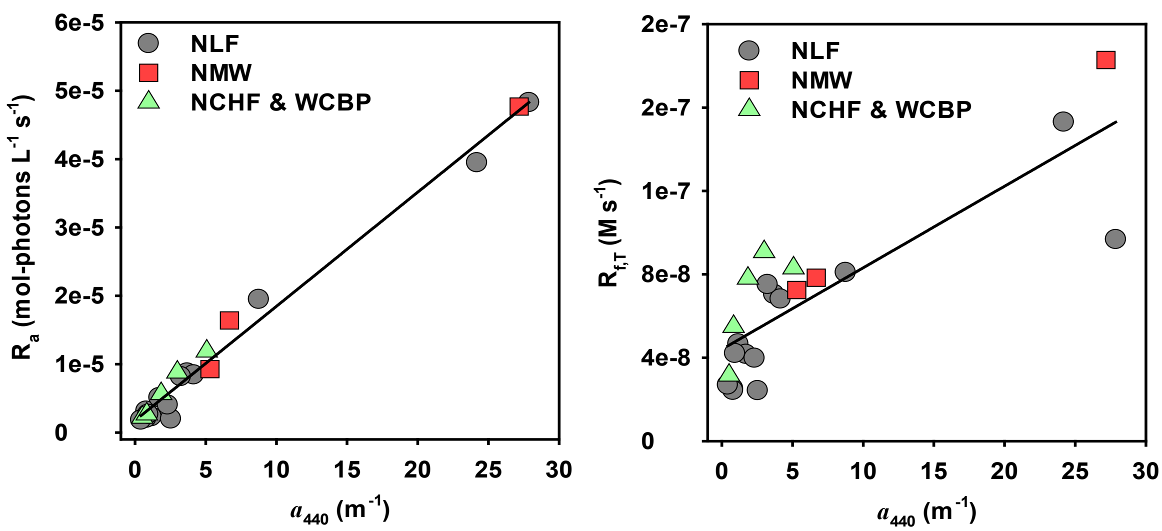

Figure 12. Correlations of CDOM (a_{440}) with R_a and R_f of $^3DOM^*$. The equations for the regressions shown are: (a) R_a (mol-photons L^{-1} s^{-1}) = 1.6695E-006 · a_{440} (m^{-1}) + 1.7708E-006; (b) $R_{f,T}$ (M s^{-1}) = 3.9125E-009 · a_{440} (m^{-1}) + 4.4028E-008.

Final Report Summary:

Laboratory experiments were completed to quantify the effects of CDOM on chlorine demand and the formation of two classes of halogenated disinfection byproducts (DBPs): trihalomethanes (THMs) and haloacetic acids (HAAs). Using 24 lake samples collected across Minnesota, we found that CDOM (a_{440}) is a useful predictor for both chlorine demand and trihalomethane formation potential (THMFP); strong linear correlations were observed between CDOM and these two parameters. For low- to moderately-colored waters ($a_{440} \leq 11\ m^{-1}$), a_{440} relationships with mono-, di- and tri-HAA formation potentials (HAAFPs) were best fit by a linear relationship, but over the entire CDOM range, di- and tri-HAA were best fit by a logarithmic relationship. Besides CDOM, other measured parameters related to DOM, including DOC, UV_{254}, and $SUVA_{254}$, also were observed to significantly affect DBPs yields, but a variety of other water quality indicators, including pH, TSS, chlorophyll a, and bromide, did not correlate with CDOM and did not affect the formation of DBPs.

Laboratory-measured CDOM levels from 194 lakes were used to develop a predictive relationship between measured CDOM and reflectance data obtained from Landsat 8 imagery. Correlations relating chlorine demand and THMFP and HAAFP values with CDOM, coupled with satellite CDOM assessments, were able to estimate chlorine demand and both THMFP and HAAFP values for low and moderate color surface waters larger than 12 acres in the state of Minnesota. The maps show relatively high levels of chlorine demand and disinfection byproduct formation potentials in northeastern Minnesota lakes, especially in the NLF ecoregion. The maps also suggest that only 22% of Minnesota lakes would meet both the THM and HAA maximum contaminant levels even if pre-disinfection treatment could remove 75% of DBP precursors. However, the models showed an increase in uncertainty for highly colored surface waters ($a_{440} > 11\ m^{-1}$), and CDOM and disinfection byproduct formation potential values were severely under-predicted due to various factors, including strong absorption of light resulting in a weak signal obtained by the satellite sensors. Overall, this study demonstrated that satellite imagery can be used to evaluate potential drinking water sources and water treatability metrics.

We measured the formation of photochemically-produced reactive intermediates (PPRIs) for 24 lake samples under simulated sunlight. These PPRIs include triplet excited states of dissolved organic matter ($^3DOM^*$), singlet oxygen ($^1O_2$), and hydroxyl radical (•OH). We measured their rates of formation (R_f), steady-state concentrations ($[PPRI]_{ss}$) and apparent quantum yields (Φ). The results showed that the total rate of light absorption by the water samples (R_a) and the rates of formation of $^3DOM^*$ and $^1O_2$ ($R_{f,\ ^3DOM^*}$, and $R_{f,\ ^1O_2}$, respectively), as well as steady state concentrations of triplet excited state organic matter ($^3DOM^*$) and singlet oxygen ($^1O_2$) linearly increased with increasing CDOM levels. The production rate of hydroxyl radical ($R_{f,\bullet OH}$) correlated linearly with CDOM, while the steady state concentration ($[\bullet OH]_{ss}$) versus CDOM revealed a logarithmic relationship. The efficiencies by which $^3DOM^*$ and $^1O_2$ were produced (which are known as quantum yields, and given the symbols $\Phi_{app,\ ^3DOM^*}$, and $\Phi_{\ ^1O_2}$) increased linearly with increasing ratios of the absorption coefficients at 250 nm and 365 nm (termed E2/E3), and were negatively correlated with $SUVA_{254}$, suggesting that photobleached CDOM, which tends to have a lower average molecular weight and lower aromaticity, leads to more efficient $^3DOM^*$ and $^1O_2$ production. On the other hand, the quantum yield for hydroxyl radical production, $\Phi_{app,\bullet OH}$, exhibited no significant correlation with either E2/E3 or $SUVA_{254}$. The correlations relating CDOM with rates of formation of PPRIs, steady state concentrations of PPRIs, or the rate of light absorbance were coupled with satellite CDOM assessments to develop maps of the production rates and concentrations PPRIs across all surface waters in Minnesota. These maps can be used with known rate constants for contaminants to predict the maximum rate of transformation of contaminants in sunlit surface waters. Further work is needed to adjust the findings for different light intensity, which varies seasonally. This work demonstrates that satellite remote sensing can be an effective tool to provide regional estimates for loss rates of contaminants via indirect photolysis in surface waters.

ACTIVITY 3: ***Dissemination and application for surface water monitoring and management***

Description: We have maintained a web site (http://water.umn.edu) for fifteen years to provide public access to results of our remote sensing studies on lake water clarity and quality. The Minnesota Lake Browser provides easy access of information for individual lakes or regions for seven time periods at five-year intervals from 1975 to 2008. Lake Browser is a Google Earth format mapping application that allows users to query for individual lakes or zoom into an area of interest to get not only the information for individual lakes but for all of the lakes in the area.

We will update the Lake Browser site to include the new data gained in Activity 1 during 2016 and 2017. This information will be used to construct a web-accessible statewide database of colored dissolved organic matter, algae, and suspended solid levels and descriptions of their relevance to citizens. Lake Browser will use information based on both pixel level maps, that allow identification of within lake differences, and lake level maps, that enable statistical analysis of geospatial and temporal trends. These additions will greatly enhance the site by providing up to date and more detailed information for >10,500 lakes. The site is currently extensively used with on average 8,000 unique visitors per month, and we expect that data and products provided by this project will increase use of Lake Brower substantially.

We expect at least 3-4 publications in high-impact, refereed journals will result from this research. Results will be presented at local and national conferences on environmental engineering, ecosystem ecology, humic substances, and remote sensing. The PIs have close relationships with scientists in regional water management agencies, and we will organize meeting for staff of those agencies (e.g., MPCA) and at state conferences to demonstrate capacity and effectiveness of remote sensing methods and to enhance their integration into water quality monitoring programs and assessments.

Summary Budget Information for Activity 3:	**ENRTF Budget:**	**$ 45,000**
	Amount Spent:	**$ 45,000**
	Balance:	**$ 0**

Outcome	**Completion Date**
1. Enhancements and expansion of Lake Browser	*June 2019*
2. Peer reviewed papers describing methods for submission to peer reviewed journals	*June 2019*
3. Presentations to MPCA describing remote sensing capabilities and methods	*June 2019*

Activity Status as of January 25 2017:
Our efforts toward dissemination of project products and applications for education, monitoring and management for Activity 3 included two presentations (described in more detail under our Section V update), sharing of information with MPCA on project activities, and an initial update of the water.umn.edu website to include CDOM. A statewide CDOM map was added to Lake Browser this fall (http://lakes.gis.umn.edu/cdom/. This map was created with previously collected data, and will be useful to target lakes with a wide range of water quality conditions for sampling in summer 2017. Field monitoring results from 2017 will be used to refine and improve mapping of CDOM and other water quality variables in this project using remote sensing. These results will continue to be integrated into the water.rs.umn.edu and Lake Browser websites for easy access by agencies, managers and citizens.

Activity Status as of July 2017:
Efforts begun in the previous period continued, largely focused on work on website improvements and expansions that describe this project and provide comprehensive explanation of the water quality parameters now available via remote sensing, and the methods being developed in this project. The water.umn.edu site has been readdressed as water.rs.umn.edu as part of a broader revision of the Water Resource Center's website and Digital Water initiative. Project related presentations were shared at the ASLO Aquatic Sciences Meeting in Honolulu, Hawaii and the American Chemical Society meeting in San Francisco, California.

Activity Status as of January 2018:
Revision of the water.rs.umn.edu website is nearing completion, with final editing underway. A key component of the site, Lake Browser, will be expanded and updated when substantial new data generated by this project

are available late in 2018 and 2019. Two project presentations were made at the 2017 Water Resources Conference. Discussions with MPCA about application of project results to trophic classifications of the states lakes are ongoing and will continue once analysis of 2017 water quality data has been completed. CDOM data for the Northern Lakes and Forest Ecoregion were tabulated from our CDOM maps and disseminated to the MPCA for use to identify lakes with high CDOM where water clarity data should not be used for nutrient impairment assessment.

Activity Status as of July 2018:
The revised and updated version of the water.rs.umn.edu website was implemented (launched) in February. It has a new homepage and organization. In addition to revising the material on monitoring lake clarity, we made major additions including new sections (pages) on chlorophyll *a*, phycocyanin, turbidity and suspended matter (TSM), and colored dissolved organic matter (CDOM). The sections for mapping river water quality and aquatic plants were also revised to be consistent with other topics and pages. Publications were updated and a new page on our research team (people) was added. New results from this and related projects will be added as they are available.

A key component of the water website has been the Lake Browser (lakes.rs.umn.edu) that has approximately 70,000 annual visits. It currently has lake clarity for seven dates from 1975 to 2008, and CDOM for 2015. We are working with staff of the U-Spatial (uspatial.umn.edu) to convert it to ArcGIS Server, a newer and easier to work with platform. The first phase, to be completed in August, is transferring the capability/functionality of the current MapServer version to ArcGIS Server. Lakes will be searchable by lake number and county name, as well as lake name, and selected lakes will have a dotted outline and symbol at their centroid. The next phase will add new data for chlorophyll, turbidity and CDOM. The third phase will add enhancements, including maps and statistical analyses on distributions by ecoregion, watershed and county, plus temporal trends for clarity. New data from current projects, including lake clarity for 2010 and 2015 from a new project sponsored by the MPCA, plus data from the current LCCMR project chlorophyll, suspended sediments and CDOM, will be added as they become available.

Other Activity 3 advancements included presentations at the St. Louis River Summit, the University of Minnesota HAB Workshop, Minnesota Supercomputing Institute Exhibition, and several other academic settings, as well as advancement on four publications related to our project.

Activity Status as of January 2019:
Lake Browser (lakes.rs.umn.edu) was successfully transferred to the ArcGIS Server. This transition represents a major improvement in the capacity and usefulness of the resources. Lakes now easily are searchable by lake number and county name, as well as lake name, and selected lakes have a dotted outline and symbol at their centroid. We will continue to add new data from this and other projects during 2019 and beyond. These data include lake clarity for 2010 and 2015 from Landsat imagery and for water clarity, chlorophyll, turbidity and CDOM using Sentinel 2 imagery from recent years. Further enhancements are in development, including maps and statistical analyses on parameter distributions by ecoregion, watershed and county, as well as greater detail on temporal trends in water clarity.

Other Activity 3 advancements included presentations at the Water Resources Conference, Minnesota Supercomputing Institute and several other academic settings, as well as advancement on four publications for peer reviewed journals arising from our work.

Final Report Summary:
The three outcomes for Activity 3 are now complete. First, we have extensively revised and updated our websites — *Remote Sensing of Water Quality* (**https://water.rs.umn.edu/**) and the LakeBrowser (**http://lakes.rs.umn.edu/**) — that have been providing information on remote sensing of water resources to agencies, researchers and citizens since 2002. The new version (released in August 2019) of the Remote Sensing

of Water Quality site describes how remote sensing provides key information about water quality, an overview of how remote sensing works, methods of extracting water quality properties from remote sensing data, and results of classifications of lake water quality, including clarity, chlorophyll, colored dissolved organic matter (CDOM), turbidity and suspended solids. Additional pages summarize past studies on aquatic plant mapping and mapping water quality of large rivers, along with research publications and presentations, current faculty, staff and students contributing to projects, and news on project activities and accomplishments.

An expanded and enhanced version of the LakeBrowser was also released in August 2019. **We highly encourage readers of this report to check out the new LakeBroswer at http://lakes.rs.umn.edu/.** LakeBrowser now includes nine statewide classifications of lake clarity from 1975 to 2015, along with recent classifications of chlorophyll *a* and CDOM. The site has been converted to an ArcGIS Server with improved capability for search and data download, additional base maps (including high resolution imagery and land cover), and display of temporal trends and geographic patterns. Users may now search for individual lakes by name or ID, or select a lake from a map. Reports for individual lakes includes lake clarity by year, and chlorophyll, and CDOM levels, along with a percentile ranking of clarity and the land cover in a 1000-foot (shoreland) buffer around the lake. Statistical summaries of lake clarity by year are available for lake clarity at state, county, ecoregion and watershed levels. Several examples of the various capabilities for display of water quality properties are shown in Appendix 1. The LakeBrowser is viewed by several thousand visitors each month and its data are used by state and county agencies, researchers, and citizens. We expect that its use will increase with the addition of new data and other capabilities added by this project.

Second, five manuscripts describing methods and project results have been published in peer reviewed journals. These papers describe (**1**) methods for correction of satellite imagery for atmospheric interference (Page et al. 2019), (**2&3**) relationships between CDOM, dissolved organic carbon and iron, providing information needed to interpret and use CDOM data (Brezonik et al. 2019a, Griffin et al. 2019), (**4**) relationships between remoted sensed lake water quality parameters and disinfection byproduct formation potential in drinking water treatment (Chen et al., In press), and (**5**) the influences of CDOM on water clarity based water quality standards in Minnesota (Brezonik et al. 2019b). The results of the last paper are described in more detail below because it directly addresses our third outcome for engaging with MCPA in interpretation of results. All five of these manuscripts have been included at attachments and the full citations are listed below. Several additional papers are under development.

Third, in collaboration with researchers at the Minnesota Pollution Control Agency (MPCA), we analyzed a large data set to evaluate the role of CDOM in affecting Secchi depth (SD) values in lakes. SD is a primary metric to assess trophic state because it is controlled in many lakes by algal population densities, measured in terms of chlorophyll-*a* (chl-*a*) concentration. Two other water quality variables also affect SD: non-algal suspended solids (SS_{NA}) and colored dissolved organic matter, CDOM, expressed as a_{440}. Using a database of 1460 samples from ~ 625 lakes comprised of our ground-based calibration data and MPCA lake monitoring data from 2015-2017, we analyzed relationships among these variables. Special focus was placed on CDOM levels that influence SD and implications for the Minnesota SD standards used to assess eutrophication impairment. Log-transformed chl-*a*, total suspended solids (TSS), and SD were strongly correlated with each other; log a_{440} had major effects on log SD but was more weakly correlated with log chl-*a* and log TSS. Regression models for log SD and 1/SD based on the variables chl-*a*, SS_{NA}, and CDOM explained ~ 80% of the variance in SD, but substantial differences in the form of the best-fit relationships were found among major ecoregions. High chl-*a* concentrations (> 50 µg/L) and TSS (> 20 mg/L) rarely occurred in lakes with high CDOM (a_{440} > ~ 4 m^{-1}). Moreover, all lakes with a_{440} > 8 m^{-1} had SD ≤ 2.0 m despite low chl-*a* (< 10 µg/L) in most lakes. Further statistical analyses revealed that CDOM starts to have significant effects on SD at a_{440} > ~ 4 m^{-1}. Thus, SD is not an accurate trophic state metric in moderately to highly colored lakes. We concluded that Minnesota's 2-m SD criterion should not be the sole metric to assess eutrophication impairment in warm/cool-water lakes of the Northern Lakes and Forest ecoregion. This work was published in the journal *Ecological Applications* in early 2019.

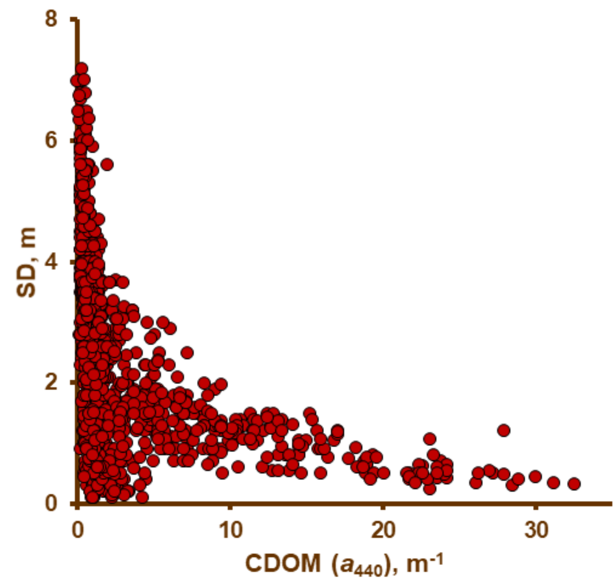

Figure 13 SD encompasses a wide range in low-color lakes, reflecting how much chlorophyll (algae) is present, but high colored lakes have low SD because of the light-absorbing properties of CDOM. Data points represent SD and CDOM values for lakes sampled in 2015-2018.

Manuscripts published arising from this project:

Brezonik, P. L., J. C. Finlay, C. G. Griffin, W. A. Arnold, E. H. Boardman, N. Germolus, R. M. Hozalski, and L. G. Olmanson. 2019a. Iron influence on dissolved color in lakes of the Upper Great Lakes States. Plos One **14**:e0211979.

Brezonik, P. L., R. W. Bouchard Jr, J. C. Finlay, C. G. Griffin, L. G. Olmanson, J. P. Anderson, W. A. Arnold, and R. Hozalski. 2019b. Color, chlorophyll a, and suspended solids effects on Secchi depth in lakes: implications for trophic state assessment. Ecological Applications **29**:e01871.

Chen, Y. et al. 2019. Assessment of the Chlorine Demand and Disinfection Byproduct Formation Potential of 1 Surface Waters via Satellite Remote Sensing. Water Research. **165**, 115001

Griffin, C. G., J. C. Finlay, P. L. Brezonik, L. Olmanson, and R. M. Hozalski. 2018. Limitations on using CDOM as a proxy for DOC in temperate lakes. Water Research **144**:719-727.

Page, B.P. and L. Olmanson, and D.R. Mishra. 2019. A harmonized image processing workflow using Landsat-8 and Sentinel-2 for mapping water clarity in optically complex lake systems. Remote Sens. Environ. **231** 111284.

V. DISSEMINATION:

Description: Project results will be communicated using a range of outlets. A primary mode of dissemination is the expansion of Lake Browser. This website provides content for diverse users including citizen scientists, homeowners, classes, natural resource managers, researchers at agencies and academic institutions. Results will also be disseminated in the peer reviewed literature, and in presentations made at conferences and at state agencies.

Activity Status as of January 25 2017:
Communication of project progress included a presentation to scientists and managers at NASA Goddard Space Flight Center in Greenbelt, Maryland (Washington D.C. area) titled "Using new enhanced satellite remote sensing systems for regional water quality measurements in optically complex inland waters". (Travel funding supplied by a related project). In addition, a presentation was given at the 2016 Minnesota GIS/LIS Consortium Conference in Duluth titled "Regional lake water quality measurements beyond water clarity using new enhanced satellite remote sensing systems". The NASA visit resulted in an article titled "Minnesota: Land of the Many-Colored Lakes" in NASA's *Earth Observatory Images of the Day* highlighting the preliminary CDOM map we developed from 2015 Landsat 8 imagery (http://earthobservatory.nasa.gov/IOTD/view.php?id=88971).

Activity Status as of July 2017:
Communication of project progress included a presentation at the ASLO Aquatic Sciences Meeting in Honolulu, Hawaii titled “Using Landsat 8 and Sentinel 2 data for regional water quality measurements in optically complex inland waters”. (Travel funding was supplied by a related project). Another project-related presentation was made in a symposium at the American Chemical Society (Environmental Chemistry Division) National meeting in San Francisco, California titled “Cross-scale Advances in CDOM Biogeochemistry: From Molecular to Eco-Regional Perspectives.” The presenter (a project co-PI) covered travel and conference expenses from personal funds.

Activity Status as of January 2018:
Communication of project progress included a presentation to scientists and managers at the Pecora Conference in Sioux Falls, South Dakota titled “Water Quality Measurements of Optically Complex Inland Waters Using New Enhanced Landsat 8 and Sentinel 2 Imagery” (travel funding was supplied by America View). In addition, two presentations were given at the Water Resources Conference in St. Paul, Minnesota.

Activity Status as of July 2018:
We have made substantial enhancements to a widely used website, and presented project results in seminars at six academic and research institutions. Dissemination of project findings to MPCA has been initiated with further collaborations planned for fall.

Activity Status as of January 2019:
We have completed upgrade and enhancements to a widely used website for lake water quality data and presented project results in seminars at six academic and research institutions. Dissemination of project findings to MPCA and DNR is ongoing, and has resulted in development of a collaborations on a journal article submitted for publication in fall 2018.

Final Report Summary:
Project findings have been disseminated through diverse means. We have extensively revised and updated our websites — *Remote Sensing of Water Quality* (**https://water.rs.umn.edu/**) and the LakeBrowser (**http://lakes.rs.umn.edu/**) — that have been used for dissemination of information on remote sensing and water resources since 2002. The new version (released in August 2019) of the Remote Sensing of Water Quality site describes how remote sensing provides key information about water quality, an overview of how remote sensing works, methods of extracting water quality properties from remote sensing data, and results of classifications of lake water quality, including clarity, chlorophyll, colored dissolved organic matter (CDOM), turbidity and suspended solids. Additional pages summarize past studies on aquatic plant mapping and mapping water quality of large rivers, along with research publications and presentations, current faculty, staff and students contributing to projects, and news on project activities and accomplishments.

An expanded and enhanced version of the LakeBrowser was also released in August 2019 and we highly encourage readers of this report to explore its capabilities (**http://lakes.rs.umn.edu/**.) LakeBrowser now includes nine statewide classifications of lake clarity from 1975 to 2015, along with recent classifications of chlorophyll *a* and CDOM. The site has been converted to an ArcGIS Server with improved capability for search and data download, additional base maps (including high resolution imagery and land cover), and display of temporal trends and geographic patterns. Users may now search for individual lakes by name or ID, or select a lake from a map. Reports for individual lakes includes lake clarity by year, and chlorophyll, and CDOM levels, along with a percentile ranking of clarity and the land cover in a 1000-foot (shoreland) buffer around the lake. Statistical summaries of lake clarity by year are available for lake clarity at state, county, ecoregion and watershed levels. Several examples of the various capabilities for display of water quality properties are shown in Appendix 1. The LakeBrowser is viewed by several thousand visitors each month and its data are freely available for use by state and county agencies, researchers, and citizens. We expect that use will increase substantially with the addition of new data and other capabilities added by this project.

Collaborations with MPCA and DNR developed in this project resulted in a joint authored journal publication in 2019. These results will be used to help development of more accurate water quality standards for water clarity by distinguishing between effects of algae (which are increased by excessive nutrient loading) from those of CDOM (which come from natural sources), so they will have a broad impact on water monitoring and assessment. Results from this project have been presented at more than 10 meetings, including six at the Minnesota Water Resources Conference. Finally, five manuscripts presenting the results of this work have been published in academic journals (citations given above denoted with *), and several manuscripts are in preparation.

VI. PROJECT BUDGET SUMMARY:

A. ENRTF Budget Overview:

***This section represents an overview of the preliminary budget at the start of the project. It will be reconciled with actual expenditures at the time of the final report.**

Budget Category	$ Amount	Overview Explanation
Personnel:	$ 303,000	Salary support for project partners, postdoctoral researchers, a junior scientist, and undergraduate researchers
Professional/Technical/Service Contracts:	$ n/a	
Equipment/Tools/Supplies:	$ 11,000	Laboratory supplies and analytical time/costs
Capital Expenditures over $5,000:	$ 20,000	Multi parameter water quality datalogger
Fee Title Acquisition:	$ n/a	
Easement Acquisition:	$ n/a	
Professional Services for Acquisition:	$ n/a	
Printing:	$ 1,000	
Travel Expenses in MN:	$ 6,000	In state travel for sample collection and presentation of results
Other:	$ 4,000	Laboratory services
TOTAL ENRTF BUDGET:	**$345,000**	

Explanation of Use of Classified Staff: N/A

Explanation of Capital Expenditures Greater Than $5,000: YSI Sensor package - A Yellow Springs Instruments (YSI) sonde capable of measuring and data logging multiple parameters including algal pigments and DOM fluorescence is requested. This instrument will be used to verify the correspondence between remotely sensed parameters and field observed values. The equipment will be used throughout the project for collection of data to needed to ensure that sampling sites are representative, to examine assumptions related to effects of shoreline and water depth effects on satellite data, and to monitor pH, oxygen and organic matter levels in laboratory experiments. We will continue to use the equipment for purposes related to the proposed research throughout the life of the instrument as new satellite sensors added to the ones currently available.

Number of Full-time Equivalents (FTE) Directly Funded with this ENRTF Appropriation: 4.73 total

Number of Full-time Equivalents (FTE) Estimated to Be Funded through Contracts with this ENRTF Appropriation: N/A

B. Other Funds:

Source of Funds	$ Amount Proposed	$ Amount Spent	Use of Other Funds
Non-state			
n/a			
State			
n/a	$	$	
TOTAL OTHER FUNDS:	**$**	**$**	

VII. PROJECT STRATEGY:
A. Project Partners:
Project Partners Receiving Funds:

- Dr. Jacques Finlay (Project Manager, University of Minnesota)
- Patrick Brezonik (Co PI, University of Minnesota)
- Leif Olmanson (Co PI, University of Minnesota)
- William Arnold (Co PI, University of Minnesota)
- Raymond Hozalski (Co PI, University of Minnesota)

B. Project Impact and Long-term Strategy: This project directly addresses LCCMR funding priorities in *Water Resources* and *Foundational Natural Resource Data and Information.* Our project brings together expertise in remote sensing, aquatic ecology, contaminant cycling, water quality analysis, and drinking water treatment to advance our abilities to detect and understand spatial and temporal patterns in water quality. Our past development of remote sensing methods for water clarity, funded in part by LCCMR, has allowed routine monitoring of >10,000 Minnesota lakes. Expansion of these capabilities through the use of new satellite capabilities to include organic matter, algal abundance, and suspended sediments will be a major step in the development of more cost-effective and spatially comprehensive methods to monitor, understand and manage Minnesota's freshwater resources. Because water quality affects fisheries, drinking water, ecosystem integrity, and human enjoyment of water bodies, results from our project will be of immediate use to the Minnesota Pollution Control Agency and the Department of Natural Resources in decision making and prioritization of resources. At the end of this project, we will be able to provide these and other relevant agencies with the basic tools needed to initiate their own use of remote sensing techniques as operational tools for frequent, statewide assessments of surface water quality throughout the state. Subsequent integration by natural resources agencies of satellite-based monitoring based on the methods we will develop would be enabled by increasing the GIS expertise of the agencies, thus allowing them greater ability to process high-quality satellite imagery, which is becoming increasingly available at no cost. It is feasible that such an advanced monitoring program could be in place following the end of this project in summer 2019 if resources were devoted to this task. We also expect that techniques for detection of blue-green algae (the primary cause of harmful algal blooms) will become feasible within the next few years, and we further envision subsequent development of ways to further automate image processing to the point that near real-time assessments of important water quality conditions will be possible.

C. Funding History:

Funding Source and Use of Funds	Funding Timeframe	$ Amount
"Solar Driven Destruction of Pesticides, Pharmaceuticals, Contaminants in Water" Arnold is currently investigating pesticide/pharmaceutical fate in wetlands and the role of DOM plays in photolysis. The techniques developed will be used on the lake and river samples in this project.	July 1, 2014-June 30,2017	$291,000

VIII. FEE TITLE ACQUISITION/CONSERVATION EASEMENT/RESTORATION REQUIREMENTS:

A. Parcel List: N/A

B. Acquisition/Restoration Information: N/A

IX. VISUAL COMPONENT or MAP(S): See attached figure.

X. RESEARCH ADDENDUM: Research addendum is an unfunded but well reviewed proposal to USGS from 2016

XI. REPORTING REQUIREMENTS:
Periodic work plan status update reports will be submitted no later than January 2017, July 2017, January 2018, July 2018, and January 2019. A final report and associated products will be submitted between June 30 and August 15, 2019.

M.L. 2016 Project Budget
Project Title: Assessment of Surface Water Quality with Satellite Sensors
Legal Citation: M.L. 2016, Chp. 186, Sec. 2, Subd. 04i
Project Manager: Jacques Finlay
Organization: University of Minnesota
M.L. 2016 ENRTF Appropriation: $345,000
Project Length and Completion Date: 3 Years, June 30, 2019
Date of Report: August 13. 2019

ENVIRONMENT AND NATURAL RESOURCES TRUST FUND BUDGET	Activity 1 Budget	Amount Spent	Activity 1 Balance	Activity 2 Budget	Amount Spent	Activity 2 Balance	Activity 3 Budget	Amount Spent	Activity 3 Balance	TOTAL BUDGET	TOTAL BALANCE
BUDGET ITEM											
Personnel (Wages and Benefits)	$170,000	$170,000	$0	$90,500	$90,500	$0	$42,000	$42,000	$0	$302,500	$0
Jacques Finlay, Project Manager: $14,000 (75% salary, 25% benefits): 4% FTE each year for 2 years.											
Patrick Brezonik, Project Collaborator: $12,000 (93% salary, 7% benefits): 4% FTE each year for 2 years.											
Raymond Hozalski, Project Collaborator: $17,000 (75% salary, 25% benefits): Year 1 = 4% FTE, Year 2 = 3% FTE.											
William Arnold, Project Collaborator: $19,000 (75% salary, 25% benefits): Year 1 = 4% FTE, Year 2 = 3% FTE											
Leif Olmanson, Project Collaborator: $66,000 (75% salary, 25% fringe); Year 1 = 33% FTE, Year 2 = 25% FTE, Year 3 = 25% FTE											
Post doctoral associate: $83,000 (82% salary, 18% fringe); Year 1 = 100% FTE, Year 2 = 50% FTE, Year 3 = 0% FTE											
Post doctoral associate: $55,000 (82% salary, 18% fringe); Year 1 = 50% FTE, Year 2 = 50% FTE, Year 3 = 0% FTE											
Undergraduate Research Assistant: $15,000 (100% salary, 0% fringe) - One student at 22% FTE for year 1 and 2 students at 22% for year 2.											
1 Junior Scientist: $22,000 (79% salary, 21% fringe) - 22% FTE for year 1 and for year 2.											
Equipment/Tools/Supplies	$27,000	$27,000	$0	$4,500	$4,500	$0	$0	$0	$0	$31,500	$0
Lab and analysis consumables. Examples of laboratory supplies required for this research include glassware, sample bottles, filters, pipette tips, chemicals, and reagents needed for analyses of chemical constituents in water samples. Costs of analyses of a suite of basic parameters in our labs for each site sampled in the field sampling, and for lab experiments are included. The lab analyses cost includes instrument time, gases, reference standards and reagents for colored organic matter concentration and spectral properties/EEMS, total phosphorus and nitrogen, suspended sediments, particulate organic carbon and chlorophyll a.											

Field supplies including bottles, gloves, and filters required for collection, transport, and storage of samples, and for preparation for lab manipulations											
YSI Sensor package - A YSI sonde capable of measuring and data logging multiple parameters including algal pigments and DOM fluorescence is requested. This instrument will be used to verify the correspondence between remotely sensed parameters and field observed values. The equipment will be used throughout the project for collection of data to needed to ensure that sampling sites are representative, to examine assumptions related to effects of shoreline and water depth effects on satellite data, and to monitor pH, oxygen and organic matter levels in laboratory experiments. We will continue to use the equipment for purposes related to the proposed research throughout the life of the instrument as new satellite sensors added to the ones currently available. All other equipment needed for the project is currently available for the use of the research team in on-campus laboratories or in shared (core) facilities.	$20,000	$20,392									
Printing							$1,000	$1,000	$0	$1,000	$0
Travel expenses in Minnesota	$4,000	$4,000	$0		$0		$2,000	$2,000	$0	$6,000	$0
Travel funds are requested for travel to field sites in year 1 and 2. This includes vehicle rental, mileage, hotel, and meals, estimated according to UMN guidelines, for PIs, post docs, and undergraduates during year 1 and for the field sampling campaign in the second year. In addition, funds are requested for travel to meetings with collaborators and state agencies, and for registration at the Minnesota Resources Conference in years 2 and 3.											
Other	$4,000	$4,000	$0		$0		$0	$0		$4,000	$0
Lab Services - Lab services includes costs of sample analyses at external labs for metals and major ions via ICP and IC in the Dept. of Earth Sciences at the University of Minnesota ($31.50 per sample), and charges for FT-ICR-MS analyses ($100 per sample) to characterize DOC/DOM properties.											
COLUMN TOTAL	**$205,000**	$205,000	$0	**$95,000**	$95,000	$0	**$45,000**	$45,000	$0	**$345,000**	$0