2018 Project Abstract
For the Period Ending June 30, 2021

PROJECT TITLE: Providing Critical Water-Quality Information for Lake Management
PROJECT MANAGER: Jeffrey Peterson
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FUNDING SOURCE: Environment and Natural Resources Trust Fund
LEGAL CITATION: M.L. 2018, Chp. 214, Art. 4, Sec. 02, Subd. 03b

APPROPRIATION AMOUNT: $250,000
AMOUNT SPENT: $250,000
AMOUNT REMAINING: $0

Sound bite of Project Outcomes and Results
This project created an automated system, which is capable of delivering satellite derived near real-time data and maps of key water quality measures (chlorophyll, clarity, CDOM), and updated the Minnesota LakeBrowser with new data and capabilities to visualize the water quality of all Minnesota lakes to improve data-driven resource management.

Overall Project Outcome and Results
Using satellite imagery, we have been assessing lake water quality in Minnesota for over 20 years. For early assessments, we used analyst directed image processing techniques using remote sensing software and empirically calibrated each satellite overpass with in situ water clarity data. These assessments were at around five year intervals due to the effort required and availability of clear satellite imagery. Recent advances in satellite technology (improved spectral, spatial, radiometric and temporal resolution) and atmospheric correction, along with cloud and supercomputing capabilities have enabled the use of satellite data for automated regional scale measurements of water resource characteristics. These new capabilities provide opportunities to improve lake and fisheries management by measuring more variables (chlorophyll, colored dissolved organic matter (CDOM) and total suspended matter, the main determinants of water clarity) more often.

To utilize these capabilities this project developed field-validated methods and implemented them in an automated water quality monitoring system on University supercomputers. The system acquires satellite imagery, removes clouds, cloud shadows, haze, smoke, and land, and applies water quality models to deliver satellite-derived water quality products. Using this system we created statewide monthly open water (May through October) pixel level mosaics and lake level data for each clear image occurrence. The lake level (2017-2020) data included 603,678 lake measurements of chlorophyll, clarity and CDOM (1,811,034 total) that were compiled into a database that was used to calculate water quality variables for different timeframes (e.g. monthly, summer (June-Sept)) and linked to a lake polygon layer that was used for geospatial analysis and included in a web map interface. The Minnesota LakeBrowser was updated with monthly chlorophyll, clarity and CDOM data from 2017 to 2020 and new capabilities for citizens, resource managers and researcher to easily access the data for specific lakes and regions.

Project Results Use and Dissemination
Communication of project results used a range of outlets. The primary mode of dissemination is the update and expanded Minnesota LakeBrowser. This website provides content for diverse users including citizen scientists, lake users, homeowners, classrooms, natural resource managers, researchers at agencies and academic

institutions. The updates improved search and allow visualization of long term (1975-2020) and seasonal (May-October) trends for individual lakes in graphs, and for individual lakes or regions in pixel or lake level maps. Results were also disseminated through social media and in presentations made at conferences and state agencies and will be disseminated in peer reviewed literature.

Environment and Natural Resources Trust Fund (ENRTF)
M.L. 2018 ENRTF Work Plan Final Report (Main Document)

Today's Date: July 31, 2021

Final Report

Date of Work Plan Approval: 06/05/2018

Project Completion Date: June 30, 2021

PROJECT TITLE: Providing Critical Water-Quality Information for Lake Management

Project Manager: Jeffrey Peterson

Organization: University of Minnesota

College/Department/Division: Water Resources Center

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Location: Statewide

Total Project Budget: $250,000

Amount Spent: $250,000

Balance: $0

Legal Citation: M.L. 2018, Chp. 214, Art. 4, Sec. 02, Subd. 03b

Appropriation Language: $250,000 the second year is from the trust fund to the Board of Regents of the University of Minnesota to develop a semiautomated system to acquire, process, and deliver new satellite-derived water-quality data in near real time on water clarity, algae, and turbidity for Minnesota lakes. This appropriation is available until June 30, 2021, by which time the project must be completed and final products delivered.

I. PROJECT STATEMENT:

This project will create an automated system delivering near real-time data and maps of key water quality measures for all Minnesota Lakes. In a current LCCMR-supported project (Assessment of Surface Water Quality with Satellite Sensors, Finlay et al. 2016) we have developed methods to expand remote sensing capabilities beyond water clarity to include chlorophyll and color. This project will apply those methods in a fully automated system that acquires, processes, and delivers new satellite-derived water quality data as it becomes available (approximately biweekly). Citizens, government agencies, and researchers will have routine access to the data via an interactive web interface linked to a spatial database that will operate at minimal cost for years to come. This unique data source will dramatically improve data-driven resource management decisions and will help inform agencies and the public about water quality conditions statewide.

The project is a compelling opportunity that takes advantage of new data streams from recently operational satellites and the high performance computing resources at the University of Minnesota. The Water Resources Center (WRC) will coordinate the project and disseminate its products within a larger WRC "digital water" initiative to expand water quality information and strengthen understanding of our changing water resources. This proposal was developed in cooperation with staff from state water management agencies and is designed to support their information and management needs.

The project goals are to:

1. Develop automated methods to process satellite images to retrieve near real-time data on chlorophyll, water clarity and color based on conventional methods developed with previous R&D;
2. Create a database of satellite-based water quality during the open-water season in Minnesota's lakes using high performance computing;
3. Work with key government agencies to deliver data products useful for their monitoring and management needs;
4. Provide robust datasets to drive advances in understanding fish habitat dynamics, harmful algal blooms (HABs), and effects of land use changes on water quality;

The remotely sensed components of water quality (water clarity, chlorophyll, color) generated by this project will be useful for many applications. One example would be for MPCA and MDNR managers to account for differences among lakes across a range of spatial scales and follow changes through time. By being able to see regional anomalies and changes over time, managers will be able to target field monitoring where needed, leading to more effective decision making and improved water quality and habitat conservation outcomes. Another example is to enhance existing fish habitat models by accounting for key components that affect dissolved oxygen and temperature, the primary determinants of fish habitat quality. The MDNR is very interested in using these products to assess the impacts of changing land cover and atmospheric conditions on fish habitat and prioritize funding decisions for protection vs. restoration and other management activities.

II. OVERALL PROJECT STATUS UPDATES:

First Update January 31, 2019

Our major activities during this period focused on transferring our image processing methods that have been developed during other projects to computer code that can be implemented on MSI's supercomputers (Activity 1). We have been working on three major components to the image processing chain: **Data acquisition and Image Pre-processing**, **Satellite image processing, and Water Quality Algorithms.**

First, we developed an automated system to retrieve all Landsat 8 imagery over Minnesota in any specified date range and also automatically discover and retrieve new Landsat 8 imagery as it becomes available. Data is currently being downloaded from the USGS EROS Center to MSI's primary storage systems, archived locally, and made available for automated processing on MSI's High Performance Computing (HPC) systems. We have also set up a web-based server to house the data that is created through the processing chain. This server will be used to evaluate the products that are being produced. As the project develops, this server will be the basis for the water quality geospatial database (Activity 2) that will house the continually updated water quality maps at the pixel level that will be used in the upgraded Lake Browser to visualize seasonal and annual changes in water quality.

Second Update June 30, 2019
Continuing on to what we have already built in the first term, we tailored coding techniques to automatically discover and download all Sentinel-2 Level-1 satellite imagery data over Minnesota from the European Space Agency's Copernicus system. New Sentinel-2 imagery is now being downloaded to the same storage and archive as the Landsat-8 imagery, so that both may be used in the same automated processing pipeline to achieve a more complete time coverage over the state and to ensure that all available data is being used.

In the next period, the newly incoming L8 and S2 imagery will be processed using the implemented codes from previous research and rigorously evaluated in several different geographical regions of MN to gain the confidence in the water quality models.

Third Update January 31, 2020
We request to amend the completion dates for the following outcomes due to cloud masking issues discussed below that are taking longer than expected and delaying other activities: Activity 1 Outcome 2 to December 2020, Outcome 3 to June 2021, Activity 2 Outcomes 1 and 2 to December 2020, Outcomes 3 and 4 to June 2021. To accommodate these changes we request to change the end date in section VIII. REPORTING REQUIREMENTS: to June 30, 2021 and number of years to three. **"Amendment Approved by LCCMR 2/8/2020."** Since our previous update we have been working on developing new water quality models while improving our image processing methodology for suitability in an automated system. We have downloaded satellite imagery from Landsat 8 and Sentinel 2 spanning all of Minnesota and covering the 2018 and 2019 open water season May through October, and have implemented an automated processing chain to receive new incoming image tiles as they are available. This data is being collected on MSI's HPC storage systems, and made available for rapid and automated processing. We have generated one 2017 and one 2018 map of water clarity and chlorophyll-a derived from Sentinel-2 that combined cover the entire state, and have made them available in the UMN LakeBrowser (https://lakes.rs.umn.edu/). We have improved the current CDOM model and have prepared one manuscript that was submitted for publishing (Science of the Total Environment). In the context of making the data available online, we have started development of a new online interactive webmap using a subset of water quality data from the new processing chain. Unlike the current LakeBrowser in which data can be visualized at five-year binned intervals, the new online interactive webmap will have more frequent time-step intervals; bi-weekly to monthly averages. For this functionality, we have been ingesting a subset of our temporal raster-based product maps into an ESRI defined mosaic dataset which will allow users to control the time intervals of interest. Once we are satisfied filtering for only the valid pixels, we can populate the mosaic dataset will all of the water quality data that is available and make it available online.

Now the fundamental building blocks have been established, the next period will focus on (1) implementing a standardized cloud mask specifically for Sentinel-2 imagery, (2) begin rigorous evaluation in several different geographical regions of MN to gain the confidence in the cloud masks and water quality products, and (3) form a prototype version of a new online web map interface for the map products generated from the processing chain.

Fourth Update June 30, 2020
Since our previous update we have been working on improving our image processing methodology for better suitability in an automated system. We have explored different cloud and shallow water (bottom or vegetation affected pixels) masking techniques that are necessary to avoid erroneous water quality results. We have developed suitable methodologies and have added the code to our automated water quality monitoring system. With this code we have processed all of the available open water season (May through October) for chlorophyll,

water clarity and CDOM products for 2019 and 2020 open water imagery is being processed as the imagery becomes available and will continue until the onset of lake ice.

Now that the building blocks have been refined for the automated processing system, the next period will focus on (1) continued rigorous evaluation from different seasons and different geographical regions of MN to document confidence in the cloud/shadow and shallow water masks and water quality products, (2) develop a new online web map interface (Next Generation LakeBrowser) to utilize the high temporal series of map products generated from the processing chain, and (3) work with stakeholders and web service providers to provide more flexible and automated ways of disseminating the large and growing volume of water quality data.

Fifth Update January 31, 2021
Since our previous update, we have been working on improving our image processing methodology for better suitability in an automated system. We have streamlined the code developed in previous periods and translated it to Python. We have evaluated the new code against the previous version and have found it to be superior with improved processing speed. With this code we have processed all of the available Sentinel 2 imagery (May through October) for chlorophyll, water clarity and CDOM products for 2019 and 2020 open water imagery.

During this period, we also discovered that smoke from wildfires has become an increasingly important issue over the last few years. Since standard cloud masks (like Fmask4) and our custom thin-clouds over water and affected pixel masks can miss smoke, we have developed a new smoke mask that will be more thoroughly evaluated over the next period.

Now that the building blocks have been refined for the automated processing system, the next period will focus on: (1) Downloading and processing the new Landsat 8 Collection 2 products. (2) Continue rigorous evaluation from different seasons and different geographical regions of MN to document confidence in the cloud/shadow, smoke, and shallow water masks and water quality products. (3) develop a new online web map interface (Next Generation LakeBrowser) to utilize the high temporal series of map products generated from the processing chain, and (4) work with stakeholders and web service providers to provide more flexible and automated ways of disseminating the large and growing volume of water quality data.

AMENDMENT REQUEST January 31, 2021
We request amending the completion dates of two outcomes in Activity 2 due to EROS Center release of Landsat Collection 2 imagery on December 1, 2020. Specifically, Outcomes 1 and 2 in Activity 2 will be completed in June 2021 instead of December 2020. Because of changes in the new data release, our code and water quality models need to be updated to accommodate these new products as discussed in update for Activity 1. With our new streamlined code this will be feasible within the timeframe.

We also request budget transfers of unused travel and lab fees to personnel expenses.

- Travel budget item would be reduced by $1,000 to a revised budget of $0
- Other budget item would be reduced by $550 to a revised budget of $1,450
- Personnel budget item would increase by $1,550 to a revised budget of $248,550

This change is because additional effort required to update the code to the new EROS release. Travel funds have not been expended due to the pandemic and actual lab fees were lower than expected.
Amendment Approved by LCCMR 2/26/2021

Final Update June 30, 2021
Since our previous update, we have (1) developed and tested wild fire smoke masks for Landsat 8 and Sentinel 2 imagery, (2) downloaded and processed the 2017 and 2018 Sentinel 2 imagery for clarity, chlorophyll and CDOM maps, (3) downloaded new Landsat 8 Collection 2 products for 2017 through 2020 and have modified our computer code to process the Landsat 8 products for clarity and CDOM, and (4) modified the LakeBrowser

(https://lakes.rs.umn.edu/), our online web map interface, to utilize the high temporal series of map products generated from this project to allow easy access to the data and visualization of seasonal and annual water quality data for 10,000+ lakes in Minnesota. The current version of the LakeBrowser has added monthly (May – October) clarity, chlorophyll and CDOM for 2017 through 2020.

Now that the building blocks are in place for the automated image processing system for water quality products, we have the capability for near real-time monitoring of water quality. Due to some delays, discussed in the previous update, we will be meeting with water quality and fisheries managers to discuss ongoing updates of water quality products and how managers could utilize ongoing near real-time water quality data to improve lake and fisheries management.

Overall Project Outcomes and Results
Using satellite imagery, we have been assessing lake water quality in Minnesota for over 20 years. For early assessments, we used analyst directed image processing techniques using remote sensing software and empirically calibrated each satellite overpass with in situ water clarity data. These assessments were at around five year intervals due to the effort required and availability of clear satellite imagery. Recent advances in satellite technology (improved spectral, spatial, radiometric and temporal resolution) and atmospheric correction, along with cloud and supercomputing capabilities have enabled the use of satellite data for automated regional scale measurements of water resource characteristics. These new capabilities provide opportunities to improve lake and fisheries management by measuring more variables (chlorophyll, colored dissolved organic matter (CDOM) and total suspended matter, the main determinants of water clarity) more often.

To utilize these capabilities this project developed field-validated methods and implemented them in an automated water quality monitoring system on University supercomputers. The system acquires satellite imagery, removes clouds, cloud shadows, haze, smoke, and land, and applies water quality models to deliver satellite-derived water quality products. Using this system we created statewide monthly open water (May through October) pixel level mosaics and lake level data for each clear image occurrence. The lake level (2017-2020) data included 603,678 lake measurements of chlorophyll, clarity and CDOM (1,811,034 total) that were compiled into a database that was used to calculate water quality variables for different timeframes (e.g. monthly, summer (June-Sept)) and linked to a lake polygon layer that was used for geospatial analysis and included in a web map interface. The Minnesota LakeBrowser was updated with monthly chlorophyll, clarity and CDOM data from 2017 to 2020 and new capabilities for citizens, resource managers and researcher to easily access the data for specific lakes and regions.

III. PROJECT ACTIVITIES AND OUTCOMES:

ACTIVITY 1: ***Build advanced near real-time methods for measuring water quality in surface waters of Minnesota using remote sensing.***
Description: We will develop computer code to automate methods for acquisition and processing of satellite imagery for water quality monitoring using high performance computing techniques. Water quality data resulting from the computerized system will be validated with field data to provide confidence in the results.

Satellite imagery *Landsat-8 and Sentinel-2 Imagery*
This project will use optical imagery from the Landsat-8 (http://landsat.usgs.gov) and Sentinel-2 (https://sentinel.esa.int/web/sentinel/missions/sentinel-2) satellites to map water quality variables. Landsat-8 Top-of-atmosphere (TOA) and surface reflectance (SR) products (referred to hereafter as level-1 and level-2, respectively) will be obtained from the USGS Earth Resources Observation Science (EROS) Center. Sentinel-2 Level-1 TOA products will be obtained from either the European Space Agency (ESA) *Sentinels Scientific Data Hub* (https://scihub.copernicus.eu/) or the USGS EROS Center depending on evolving international data transfer and archiving agreements. Both Landsat and Sentinel-2 data are available at no cost. We will derive level-2 SR

products using the Sentinel-2 Toolbox full source code distributed under the GNU General Public License (GPL), and available through GitHub or best available method as determined in our current LCCMR (Finlay et al. 2016) and NSF (Hozalski et al. 2015) projects.

Level-2 SR imagery from Landsat-8 and Sentinel-2 will be clipped using an open water mask (OWM). This product will be constructed using clear-sky warm season Landsat-8 or Sentinel-2 TOA imagery using methods used to map water clarity in Minnesota (Olmanson et al. 2008).

Water Quality (in situ) *Calibration/Validation Measurements*
This project will rely on well-established water quality monitoring programs of agencies in Minnesota, along with existing/ongoing in situ spectroscopic measurements of lake optical properties and targeted sampling for water clarity, chlorophyll, , and color being collected by related ongoing projects (Finlay et al. 2016, Hozalski et al. 2015). These datasets will be used as calibration and validation (Cal/Val) measurements to establish confidence in the use of remote sensing data for water quality management, an important component of this project, which will require documentation of data quality and associated uncertainties. Operational use of remote sensing water quality products necessitates long-term quality-assured match-up data for continued validation of retrieval algorithms.

We will inventory existing water quality sampling activities for continued Cal/Val of remote sensing algorithms. To use these data appropriately, we will collect information on their efficacy by inventorying federal, state and tribal databases. Metadata will be compiled on sample locations, collection methods and equipment, and analytical methods for the parameters of interest, and the continuity of the programs will be confirmed. We also will establish staff contacts and secure data-use agreements for future data retrievals. An easily accessible database structure will be designed and populated with existing water quality data that will be updated annually following each field season.

Remote Sensing Methodology and Supercomputing
We will use digital image data from the Landsat-8/Sentinel-2 constellation to retrieve water clarity, chlorophyll, and color water quality variables during the warm season (May-October). Using in situ measurements, we will be able to constrain uncertainties between ground and satellite-derived water properties caused by varying atmospheric conditions and calibrate/validate water quality retrieval algorithms to yield verifiable water products for Minnesota lakes.

Our approach to develop water quality products (hereafter referred to as level-3 data) for Minnesota will consist of two steps. First, we will develop image pre-processing routines, prototype retrieval algorithms, and prototype level-3 data products for sub-regions in Minnesota. Prototype source code will be developed using Python and Matlab programming languages, and the project team will vet prototypes iteratively during project year 1 to ensure that level-3 data products match end-user decision-making needs. Second, we will translate the prototype source codes into the Minnesota Supercomputing Institute's (MSI) HPC infrastructure.

<u>Image Pre-Processing</u>. Level-3 water quality data products will be derived from Landsat-8 and Sentinel-2 level-1 TOA and level-2 SR imagery at each sensor's nominal acquisition scale. Using the Sen2cor source code (i.e., ESA's atmospheric correction module), we will derive level-2 SR products for Sentinel-2. Cloud masks for Landsat-8 and Sentinel-2 will be constructed using the level-1 TOA products. Imagery having cloud cover percentages > 50% will be excluded from further processing. Cloud masks and level-2 SR images will be clipped with the Minnesota OWM product. Water quality retrieval algorithms will be applied to level-2 SR images containing only open water areas of lakes.

<u>Cloud Masking Algorithm</u>. We will generate cloud masks for Landsat-8 and Sentinel-2 by methods similar to Crawford et al. (2013), whose algorithm combines the accumulated cloud cover assessment (ACCA) algorithm (Irish et al. 2006) and includes the solar geometry cloud shadow algorithm for Landsat (Huang et al. 2010). The cloud algorithm includes a dynamic dimension that accounts for seasonality in land surface and cloud brightness temperatures and a pass-3 screen for optically thin clouds using the water vapor cirrus spectral band. Because

Sentinel-2 does not acquire thermal infrared measurements, we will modify the Landsat-8 cloud algorithm by removing the pass-2 thermal screen, and use only pass-1 and pass-3 screens.

Optical Water Quality Algorithms. Water quality mapping using visible-near infrared imagery has primarily relied on Landsat satellites, which have spatial resolution suitable for lakes > 10 acres. Their few spectral bands, however, have limited measurements primarily to water clarity and CDOM. The increased frequency and additional spectral bands of Sentinel-2 satellites will enable estimation of chlorophyll (Olmanson et al. 2011, 2013 & 2015, Matthews 2011). We will build on these advances to develop procedures to assess > 10,000 Minnesota lakes multiple times per year using semi-automated processing methods and lay the groundwork for operational programs based on remote sensing to provide ongoing data on water quality and fish habitat variables.

Remote sensing assessments of lakes at regional scales typically have used regression models that relate spectral reflectance data to concurrent field data. The resulting models then predict water quality variables for lakes in the image where field data are lacking (Olmanson et al. 2015, Matthews 2011). A more useful approach would correct the radiance measured by a sensor to a standard surface reflectance, which then would allow development of "universal algorithms" for water quality variables, i.e., algorithms not requiring concurrent calibration data. Correction of radiance to reflectance – i.e., removal of effects caused by atmospheric moisture, haze, sun angle, and other factors not related to the optical properties of the water body has improved significantly recently with the new Landsat 8 and Sentinel 2 sensors. In current LCCMR (Finlay et al. 2016) and NSF (Hozalski et al. 2015) projects, we are evaluating, with in situ water quality data, several methods for atmospheric correction: MAIN, ACOLITE, SeaDAS/l2gen, FLAASH, along with Landsat surface reflectance products provided by EROS.

With these products, we are developing water quality models that can be used on similarly corrected imagery. To date we have obtained reliable results for CDOM in optically complex waters using a two-term model (Olmanson et al. 2016a) and have applied that model to radiometrically corrected imagery in Minnesota to create the first state-wide CDOM map (Olmanson et al. 2016b). The method that provides the most consistent reliable results, if different from the level-2 product mentioned above, will be used for the water quality variables. We also have found that by using in situ CDOM data we have been able to improve the model we have been using (Olmanson et al. 2008) for water clarity ($R^2 = 0.58$ without vs. 0.79 with CDOM) to account for reduced transparency from CDOM. We anticipate similar results with satellite derived CDOM (These results were obtained with in situ spectra to simulate Landsat 8 data and included many high CDOM waters). In a related project (Finlay et al. 2016), we are developing models for chlorophyll using Sentinel-2 imagery. We expect that these models will be similar those reported in the literature (e.g., Matthews et al. 2011, Olmanson et al. 2011, 2013 & 2015).

Supercomputing using MSI HPC Resources. Translation of prototyped source code for image pre-processing, retrieval algorithms, and level-3 data products will require efficient, timely, and automated scripting to disseminate diverse, complex, voluminous, geographically distributed, and growing Earth observation assets. The HPC component will support both standard scripting and customizable scripting workflows that can be dynamically modified as new level-1/2 Earth observation data pipelines and formats become available. We anticipate that both background (batch) and interactive processing will be needed as the project evolves. Background automated processing is needed periodically for ongoing ingestion of level-1/2 satellite imagery as they are collected and made available in the form of level-3 data products.

Water quality remote sensing investigators will provide prototype source code for image pre-processing, retrieval algorithms, and level-3 data products. MSI personnel will translate this prototype source code into efficient and automated processes within a flexible workflow framework that can be extended by the project team. To achieve this, we will: (1) identify and maintain a working list of level-1/2 Earth observation data archives; (2) establish methods for automatically downloading level-1/2 data as it becomes available from both the USGS EROS Center and ESA Sentinels Scientific Data Hub; (3) implement automated workflows for processing level-1/2 data into level 3 products (including pixel level, basin averages); (4) automatically post these level-3 water quality products, as they are generated, to MSI's tier-2 (CEPH) storage; and (5) make level 3 products on CEPH accessible to web based services.

ENRTF BUDGET: $132,231
Amount Spent: $132,231
Balance: $0

Outcome	Completion Date
1. System to automatically acquire and prepare satellite images for further processing	June 2019
2. Automated method to apply water quality algorithms from previous R&D to open water pixels for comprehensive and frequent water quality monitoring of Minnesota lakes	December 2020
3. Validation of satellite results with routine water quality data collected by citizens, local and state agencies	June 2021

First Update January 31, 2019
For Activity 1 our major activities focused on transferring our image processing methods that have been developed during other projects to computer code that can be implemented on MSI's supercomputers. There are three major components to the image processing chain that we have been working on for Landsat 8 imagery:

1. **Data acquisition and Image Pre-processing**:
   - **a.** Develop automated system to retrieve all Landsat 8 imagery over Minnesota in any specified date range and also retrieve new Landsat 8 imagery as it becomes available;
   - **b.** Develop automated system to download any new (i.e., not already downloaded) Landsat 8 imagery from USGS EROS Center to MSI's high performance storage systems.
   - **c.** Satellite imagery will be archived and made available for automated processing on MSI's High Performance Computing (HPC) systems;
2. **Satellite image processing**
   - **a. Atmospheric correction:** To maintain consistent image products on a temporal scale, a comprehensive atmospheric correction is applied to the incoming imagery to remove the scattering and absorbing effects in the atmosphere which are responsible for generating unrealistic values and potential false-positives. We adopted atmospheric correction theory from traditional ocean color techniques. We translated the modified atmospheric correction for inland waters (MAIN) method from Page *et al.* (2019) into a Matlab script to be run on all incoming imagery at MSI. This robust correction generates similar cross-sensor remote sensing reflectance (Rrs) image products from different sensors, and was chosen for our application so that other sensors can be included later in the project.

     Page, B.P., Olmanson, L.G., Mishra, D.R., 2019. A harmonized image processing workflow using Sentinel-2/MSI and Landsat-8/OLI for mapping water clarity in optically variable lake systems. *Remote Sensing of Environment* (in review).

   - **b. Cloud Masking:** Due to the lack of acceptable cloud masks that are currently available, we are modifying an existing cloud mask algorithm created by collaborator Christopher Crawford (USGS EROS) for snow studies. Computer scripts were created for this cloud and cloud shadow removal method and implemented on MSI's HPC systems in automated batch queue. Three dates of imagery from path 27 with varying levels and types of clouds were tested. Validation procedures identified haze and thin clouds that were still present and were causing erroneous water quality results in these areas. To identify and remove thin haze we determined that a threshold method using the blue and thermal band ratio was able to remove the remaining haze and thin clouds. Computer scripts for this haze and thin cloud mask were created and implemented as an additional mask in the automated batch queue. The test images were reprocessed and evaluated. Further testing over a wider range of images and cloud conditions will be implemented and evaluated over the next period.

Crawford, C.J., S.M. Manson, M.E. Bauer, and D.K. Hall. (2013). Multitemporal snow cover mapping in mountainous terrain for Landsat climate data record development. *Remote Sensing of Environment* 135:224-235. DOI:10.1016/j.rse.2013.04.004.

3. **Water Quality Algorithms:** For testing purposes we have been using the water clarity algorithm that we have developed using the MAIN AC method. Our water clarity model for Landsat-8 in terms of Secchi Depth (SD) (meters) has a mean average percent error of around 30%, or, ± 0.3 m per meter. A manuscript was prepared that combined the atmospheric correction procedure in addition to the SD model created and is currently under review. The SD model(s) will be continuously tested as incoming imagery and future field measurements become available and will improve as the project moves forward.

We currently have all of these components working on MSI's supercomputer for Landsat 8 imagery. We completed some preliminary assessments of the results and are working on some modifications to the processing chain to ensure reliable results. Over the next period we will develop a similar processing chain for Sentinel 2 imagery and will continue to evaluate the products that are created and make modifications to the code as needed. We are currently on track to meet the completion date of June 2019 for activity 1.

Second Update June 30, 2019

Continuing on to what we have already built in the first term, we tailored coding techniques to automatically discover and download all Sentinel-2 Level-1 satellite imagery data over Minnesota from the European Space Agency's Copernicus system. New Sentinel-2 imagery is now being downloaded to the same storage and archive as the Landsat-8 imagery, so that both may be used in the same automated processing pipeline to achieve a more complete time coverage over the state and to ensure that all available data is being used.

1. **Data acquisition and Image Pre-processing**:
    a. Develop automated system to retrieve all Sentinel-2 imagery over Minnesota in any specified date range and also retrieve new Sentinel-2 imagery as it becomes available;
    b. Develop automated system to download any new (i.e., not already downloaded) Sentinel-2 imagery from ESA Copernicus to MSI's high performance storage systems;
    c. Satellite imagery is being archived and made available for automated processing on MSI's High Performance Computing (HPC) systems;
2. **Satellite image processing**
    a. **Atmospheric correction, Cloud Masking and Water Quality Algorithms:** we have implemented image processing techniques (atmospheric correction, water quality models) to apply to new incoming imagery so that preliminary evaluation of atmospheric correction and water quality retrievals can be conducted for both Sentinel-2 and Landsat-8 imagery. Now until the third update, we will be continuously evaluating the performance of newly calibrated water quality models, cloud mask and atmospheric correction algorithms in different geographic regions of Minnesota to reduce uncertainties and gain the confidence in the models.

Third Update January 31, 2020

Continuing on to what we have already built in the first two terms, we now have all warm season Sentinel-2 and Landsat-8 imagery for 2018 and 2019 available for easy access on MSI's high performance storage systems. Atmospheric correction is working well for both Sentinel-2 and Landsat-8 imagery. The cloud mask that was implemented for Landsat 8 seems to be working reasonably well but is not suitable for Sentinel-2 imagery. Therefore, we have embedded an available cloud mask (Fmask 4.0, Qiu and He 2019) in the automated system as a placeholder. However, due to the inconsistencies of the products generated by Fmask4, a modified approach for the Minnesota state will need to be implemented. To this extent, we will continue to improve and evaluate our cloud masking algorithm over the next period.

Qiu, S., Zhu, Z., He, B. (2019). Fmask 4.0: Improved cloud and cloud shadow detection in Landsats 4–8 and Sentinel-2 imagery. *Remote Sensing of Environment.* 231. DOI:10.1016/j.rse.2019.05.024.

1. **Data acquisition and Image Pre-processing**:
    a. Automated system to retrieve Landsat-8 and Sentinel-2 imagery over Minnesota during the warm season (May through October) as it becomes available is now operational;
    b. Satellite imagery for 2018 and 2019 that has been acquired and is archived in MSI tier 2 storage. All of the imagery is available for automated processing on MSI's High Performance Computing (HPC) systems;
    c. In May, 2020 the automated system to retrieve Landsat-8 and Sentinel-2 imagery will resume operations to acquire imagery from 2020 warm season;

2. **Satellite image processing**
    a. **Atmospheric correction:** the MAIN (Page et al., 2019) atmospheric is working well on both Sentinel-2 and Landsat-8 imagery and has been applied to a subset of images that we are using for evaluation.
    b. **Cloud Masking:** for Landsat 8 the cloud mask is operational and working fairly well for our evaluation images. A new approach is needed for Sentinel 2 imagery since it lacks a thermal band which is essential to the method we have developed for Landsat 8. We have implemented an available cloud mask (Fmask4) that will work for Sentinel-2 imagery in the automated processing on MSI's HPC system. Although this seem to work well for most clouds there are still some artifacts that we are developing methods to remedy. As an alternative method we are developing a neural network method that should provide superior results and can be implemented with both Sentinel-2 and Landsat 8 imagery. We will continue working on evaluating and improving these methods over the next period.
    c. **Water Quality Algorithms:** during our testing period we have implemented the water clarity algorithm that is documented in Page et al. 2019 and the chlorophyll algorithm developed in previous R&D. These appears to be working well with our evaluation subset and one 2017 and one 2018 Sentinel-2 imagery that when combine cover the entire state. These new water clarity and chlorophyll maps are available in our LakeBrowser (https://lakes.rs.umn.edu/). The CDOM model we developed in previous R&D was reevaluated with additional calibration and validation data and improved significantly. Statewide CDOM maps for 2015 and 2016 were created and the manuscript (Olmanson et al. In Review) was submitted for publication. This new CDOM model along with the chlorophyll and water clarity models discussed earlier are

ready to be implemented in the automated system once we have confidence in the cloud masking.

Olmanson, L.G., Page, B.P., Finlay, J.C., Brezonik, P.L., Bauer, M.E., Griffin, C.G., and Hozalski, R.M. 2020. Regional Measurements and Spatial/Temporal Analysis of CDOM in 10,000+ Optically Variable Minnesota Lakes using Landsat 8 Imagery. *Science of the Total Environment.* In review.

Fourth Update June 30, 2020

Continuing on to what we have already built in the first three terms, we have developed and evaluated cloud/shadow and shallow water masks and have identified methodologies that work well for Sentinel-2 imagery. We have processed all available 2019 and 2020 open water season imagery for water quality products.

For the cloud/shadow mask we developed some machine learning methods using cloud classifications developed using standard image processing techniques as training data. After evaluation of many cloud and shadow masking including Fmask 4.0 (discussed above) we determined the by added a buffering algorithm to the Fmask code we were able to get good cloud and cloud shadow removal for both Landsat 8 and Sentinel 2 imagery.

For shallow water masks (areas where bottom or submerged vegetation affect pixel response) we developed an algorithm using machine learning techniques trained with images classified for open water and bottom/vegetation effected pixels using standard image processing techniques.

These masks have been embedded into the image processing system on MSI supercomputers and is currently operating on new as imagery as it becomes available.

Fifth Update January 31, 2021

Continuing on to what we have already built in the first four terms, we have streamlined the code previously developed for atmospheric correction, cloud/shadow and shallow water masking by translating it to Python. The new code was evaluated against the previous code and checked for bugs. It was determined that the new code is superior to the old code and runs much faster. Using the updated code, we processed all available 2019 open water season Sentinel 2 imagery and linked it to all available water quality data.

Using the MAIN derived satellite Rrs data and field collected water quality variable matchup within 1 day for Secchi Depth (N=6,155), within 3 days for chlorophyll (N=3,584) and within 20 days for CDOM (N=126), we refined the water quality models and found strong models (R^2=0.71, RMSE=0.385; R2=0.72, RMSE=0.624; R^2=0.66, RMSE=0.505 respectively). The water quality models were added to the code and all available 2019 and 2020 open water season imagery were processed for water quality products. The 2017 and 2018 Sentinel 2 imagery will be downloaded and processed to water quality products using the new code early in the next period.

The USGS EROS Center, which maintains and processes Landsat imagery, had undertaken a major reprocessing effort on the Landsat archive to improve the absolute geolocation accuracy and radiometric calibration for Landsat 8 Operational Land Imager (OLI) data. The Collection 2 processed Landsat imagery was released on December 1, 2020. While these modifications will improve the water quality products that we are producing, the code will need to be modified and new water quality models will need to be developed to accommodate these new products since the older version will be retired. Over the next period, we will modify the streamlined Sentinel 2 code to work with Landsat Collection 2 imagery and process the 2017 through 2020 imagery for water clarity and CDOM products.

Obscuration of surface data by smoke from wildfires has become an increasingly important issue over the last few years. Standard cloud masks (like Fmask4) and our custom thin-clouds over water and affected pixel masks can miss smoke, even when it is optically thick in some of the bands used for determining water quality, and lead to erroneous water quality estimations. Recently, we have been developing a method for detecting and masking out pixels where smoke is thick enough to affect the results. In the next period, we plan to test and tune methods for detecting smoke based on how smoke progressively absorbs light at longer wavelengths, which we've observed to be detectable in top-of-atmosphere (TOA) reflectance. We will test and tune these methods against the 2019 and 2020 data we have already downloaded. The resulting method for detecting and masking out pixels affected by smoke will not only improve our final water quality maps and statistics, but also will be of use to other projects which rely on remote sensing for assessing surface conditions.

Final Update June 30, 2021
Continuing on what we have already built in the first five terms, we have developed and tested wild fire smoke masks discussed in the previous update for both sentinel 2 and Landsat 8 imagery along with cloud and vegetation masks for Landsat 8. We have also completed the downloading and processing of the 2017 and 2018 Sentinel 2 imagery to water quality products using the refined Sentinel 2 computer code. We have downloaded the Landsat 8 Collection 2 products for 2017 through 2020 and have modified the streamlined Sentinel 2 code to work with Landsat Collection 2 imagery and are currently working on processing the 2017 through 2020 imagery for water clarity and CDOM products. The automated near real-time water quality monitoring system developed during this project provides comprehensive water quality data that has never been available before. This advancement is of great value to the management of Minnesota's 10,000+ lakes has the potential for supporting a paradigm shift in improved lakes and fisheries management.

ACTIVITY 2: ***Build water quality geospatial database and provide it to the government agencies, the research community, and citizens.***
Description: We will develop a spatial database to store continually updated water quality maps at the pixel level to visualize seasonal and annual changes in water quality. The data will also be summarized by time (e.g., seasonal averages) in collaboration with agency staff who will advise us on data needs to improve management and better meet their missions. An upgraded version of the Lake Browser (http://lakes.rs.umn.edu/) will provide access to lake water quality data. Interactive processing will allow HPC experts and the water quality investigators to view results with the capability of filtering by location, time period, or product. This environment will allow the project team and users to discover what data products are most relevant to decision-making as the project evolves, thus enabling dynamic modification of existing scripting workflows to improve synergy in terms of ingested level-1/2 satellite data, level-3 water quality data products, and evolving end-user needs.

As described in activity 1, pixel level and basin averaged lake water quality data will be automatically stored on the Minnesota Supercomputing Institute's (MSI's) tier-2 (CEPH) storage as it is generated. An advantage of this CEPH storage is that it can share data as web addresses over the wide area network. To provide a flexible, standard, and user friendly access to this data, a geographic information system (GIS) database and web server will be available for this project. One virtual machine (VM) will host the geospatial database, and a second VM will host the web server that will present a user facing web page to the public. Both VMs, and software to run the database and web server, are freely available for this project through the Office of Information Technology (OIT) at the University of Minnesota (UM). The GIS database will be adapted from working examples from the UM's U-Spatial Institute. Scripts running the first VM will periodically pole MSI's CEPH storage for new data and post it to the database. The second MV will run an ArcGIS server which is configured to read data from the GIS database on the first VM. The user facing website, presented by the ArcGIS server, will be curated by staff at the UM's Water Resources Center (WRC) using the ArcGIS desktop.

ENRTF BUDGET: $117,769
Amount Spent: $117,769
Balance: $0

Outcome	Completion Date
1. Near real-time water quality data integrated into a continually updated, publically accessible web database and mapping tool.	June 2021
2. Seasonal summaries of water quality data needed for research needs.	June 2021
3. A web interface maintained by the University of Minnesota's Water Resources Center that provides access to lake water quality data.	June 2021
4. At least a two year database with ~bi-weekly water clarity, chlorophyll and color.	June 2021

First Update January 31, 2019
During this period, we set up a web-based server to house the data that is created through the processing chain. This server is being used to evaluate the products that are being produced. As the project develops this server will be the basis of the water quality geospatial database that will house the continually updated water quality maps at the pixel level that will be used in the Enhanced Lake Browser to visualize seasonal and annual changes in water quality.

Second Update June 30, 2019
Concurrently with Activity 1, we are assessing the best platform for end-users to visualize the data in order to maximize direct water quality trend information for decision and lake management purposes. To this end, we have conducted a workshop to receive user feedback to navigate the direction of what information needs to be presented. We are steering toward an ArcGIS Server to handle the incoming maps where users can interactively explore satellite estimated water quality data.

Third Update January 31, 2020
Concurrently with Activity 1, we have a subset of processed water quality products that are available for evaluation and development of an online interactive web map that will display and visualize the data. For this web map to have the functionality that we want we have added the individual image tiles (each image swath has many tiles for each overpass) into what is known as a mosaic dataset. There will be mosaic data sets for each water quality variable. So far we have added the subset of water clarity data for development and evaluation purposes. These dataset are aware of both space and time and allow for flexibility in accessing the data. We currently have this data in an ArcGIS Server that we are using to evaluate the cloud masking and water quality products. Over the next period we will create a graphical user interface for this mosaic dataset using a template within ArcGIS to handle and display the temporal map products. Once we have the image processing bugs worked out in Activity 1 we will be able to populate the mosaic dataset with all of our processed water quality data. As new imagery is acquired and new water quality data become available it can be added to the existing mosaics datasets and become available in the new web map.

Fourth Update June 30, 2020
Concurrently with Activity 1, we have processed water quality products for 2019 and 2020 that are available for evaluation and development of an online interactive web map. We are currently adding these data products to mosaic datasets (discussed above) that will be utilized in the Next Generation LakeBrowser to emphasize the seasonal and temporal components of the different water quality data products.

Over the next period we will continue to process imagery as it becomes available and once we are satisfied with the quality of the products we will process 2017 and 2018 open water imagery for water quality product to expand the data that will be available for Minnesota lakes. We will work with research teams and support staff at the Minnesota Supercomputing Institute (MSI), the Water Resources Center (WRC), and the University of Minnesota's geospatial services unit (U-Spatial_ to explore using Web Coverage Services allowing researchers more flexible and automated access to the continually updated water quality products. We will also explore the use of high performance computing data formats (such as datacube) for time series analysis focused on individual lake basins and small to moderate sized regions.

Fifth Update January 31, 2021

Concurrently with Activity 1, the water quality products for 2019 and 2020 created above have been made available for evaluation in a temporary online interactive web map (z.umn.edu/LakeBrowser). New data will be added as it becomes available. In working with the available data we have determined that monthly mosaics are the best options for statewide pixel level maps. Lake level data will be available for each occurrence and compiled at the monthly median (Figures 1 and 2).

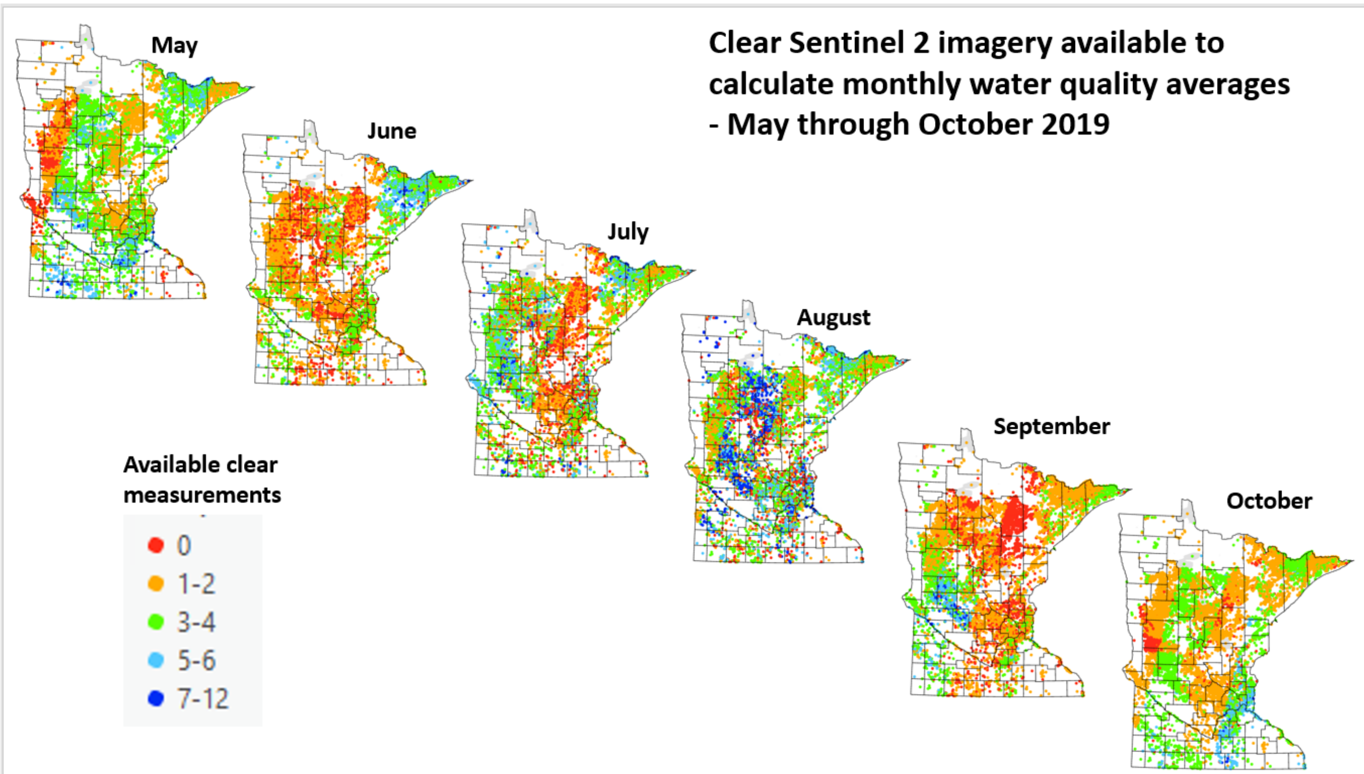


Figure 1. Number of clear image measurements for months May through October 2019.

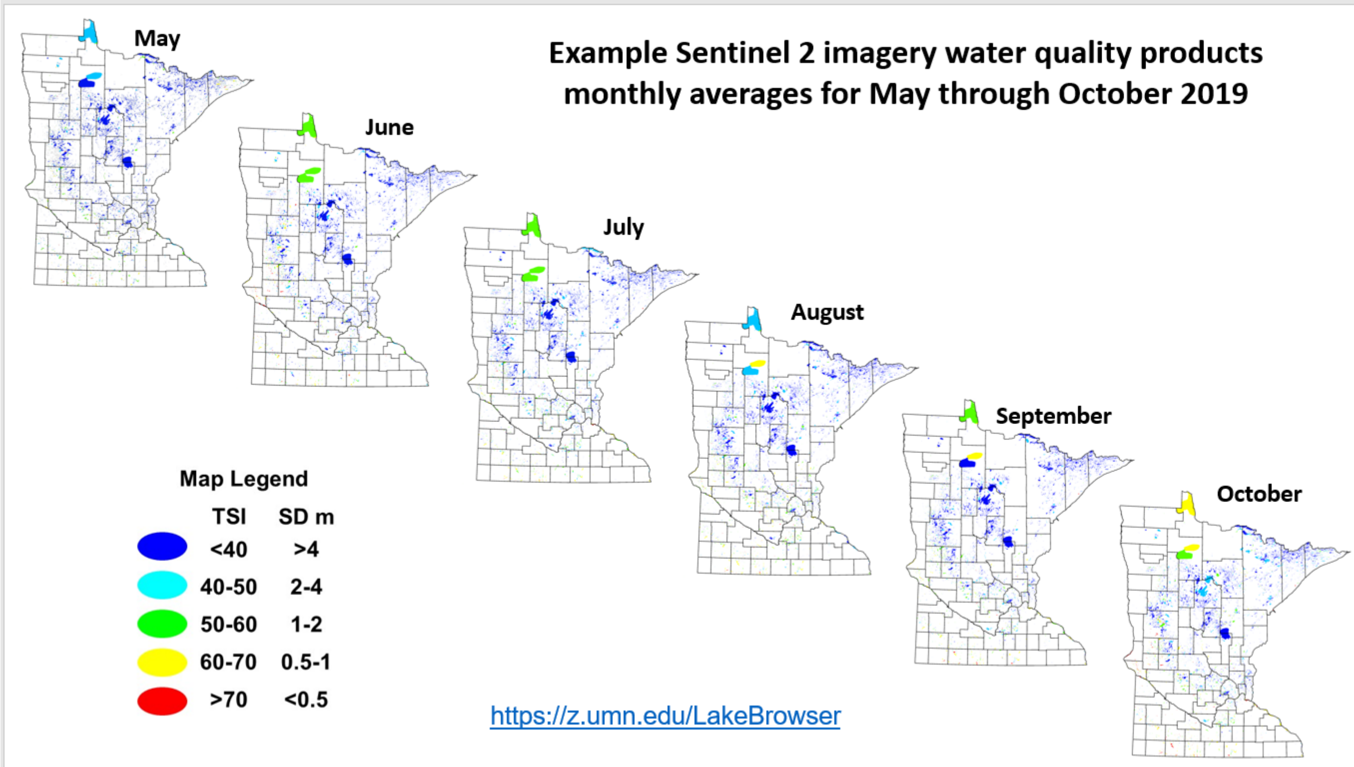


Figure 2. Monthly median water clarity for months May through October 2019.

Over the next period we will continue to process imagery as it becomes available and once we are satisfied with the quality of the products we will process Sentinel 2 2017 and 2018 and Landsat 8 Collection 2 2017 through 2020 open water imagery for water quality product to expand the data that will be available for Minnesota lakes. We will work with research teams and support staff at the Minnesota Supercomputing Institute (MSI), the Water Resources Center (WRC), and the University of Minnesota's geospatial services unit (U-Spatial_ to explore using Web Coverage Services allowing researchers more flexible and automated access to the continually updated water quality products. We will also explore the use of high performance computing data formats (such as datacube) for time series analysis focused on individual lake basins and small to moderate sized regions.

Final Update June 30, 2021

We have tested our image processing code for Sentinel 2 imagery and are satisfied with the quality of the water quality products that are being produced from it. We have processed all available open water season (May - October) Sentinel 2 2017 through 2020 and have created pixel and lake level water quality products. As discussed in the previous update the pixel level Minnesota statewide data were mosaicked at the monthly level and lake level data are available in tabular form for each occurrence and have been compiled at the monthly and seasonal (e.g. June – September, July 20 – Sept 20) average and/or median values for all Minnesota lakes. We have worked with research teams and support staff at the Minnesota Supercomputing Institute (MSI), the Water Resources Center (WRC), and the University of Minnesota's geospatial services unit (U-Spatial) to explore using Web Coverage Services allowing researchers more flexible and automated access to the continually updated water quality products. Now that the building blocks for an automated image processing system is built, we have the capability for near real-time water quality monitoring. To realize this capability we will need to work with fisheries and lake management agencies to explore how this data could be used to improve lake and fisheries management. In the meantime, we have added four years (2017 through 2020) of water quality (clarity, chlorophyll and CDOM) data to the LakeBrowser (https://lakes.rs.umn.edu/) and added new capabilities to visualize the water quality data of lakes throughout Minnesota, which will be discussed further in the next section. To facilitate automated update, management, and use of water quality data, we plan to make it available on the G.E.M.S platform (https://agroinformatics.org), where access will be made through a REST API. This will allow for web-based applications to automatically discover and access Minnesota lake quality data as it becomes available. Lake water quality data will be projected onto an Equal-Area Scalable Earth (EASE) grid for ready use with other data on the G.E.M.S. platform.

IV. DISSEMINATION:

Description: Project results will be communicated using a range of outlets. The primary mode of dissemination is the update and expansion of the Lake Browser. This website provides content for diverse users including citizen scientists, homeowners, classrooms, 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.

First Update January 31, 2019

The current Lake Browser (lakes.rs.umn.edu) was recently transferred to ArcGIS Server. This new Lake Browser will act as a prototype for the more complex Enhanced Lake Browser that will be created for this project. Having near real-time water quality data will add considerable complexity and many new opportunities for using the data. Over the next period we will be exploring enhancements, including additional maps and statistical analyses on distributions by ecoregion, watershed and county, plus temporal trends that can be used in the Enhance Lake Browser.

Communication of project progress included presentations to scientists and managers at the Water Resources Conference in St. Paul, Minnesota, Minnesota Supercomputing Institute and other academic settings (supported by matching funds), as well as one journal article directly related to this project, which is under review. Over the next period we will be collaborating on a Lake Management workshop to inform participants about the project and receive feedback of what and how information should be disseminated in the current and upcoming Enhanced Lake Browser.

> Page, B.P., Olmanson, L.G., Mishra, D.R., 2019. A harmonized image processing workflow using Sentinel-2/MSI and Landsat-8/OLI for mapping water clarity in optically variable lake systems. *Remote Sensing of Environment* (in review).

Second Update June 30, 2019

One notable achievement this term was the successful publication of a case study we conducted when evaluating our methodologies:

> Page, B.P., Olmanson, L.G., Mishra, D.R., 2019. A harmonized image processing workflow using Sentinel-2/MSI and Landsat-8/OLI for mapping water clarity in optically variable lake systems. *Remote Sensing of Environment* (accepted and published).

Second we presented the paper (Advanced Remote Sensing Methods for Automated Lake Water Quality and Ice Phenology Mapping) illustrating this work at the Rainy-Lake of the Woods Watershed Forum in International Falls, MN. And two papers (Evaluation of Atmospheric Correction Methods for Inland Water Quality Mapping Using a Large Database of In situ Water Quality Data from Minnesota U.S.A.'s Lakes and Advancing water quality monitoring capabilities across optically variable lake systems using S2/MSI and L8/OLI imagery in an automated high performance computing environment) illustrating this work at the European Space Agency's Living Planet Symposium in Milan Italy, which sparked international collaboration conversation while highlighting the program.

As part of the University of Minnesota Extension Applied Lake Management and Stormwater Series, we participated in a Lake Management Tools workshop on February 21, 2019 in Minneapolis to educate researchers, state workers, and other interested citizens about the project and receive feedback of what and how information should be disseminated in order to maximize decision making. User feedback has informed improvements to the LakeBrowser, and will continue to develop into what is preferred by users to enhance water quality monitoring capabilities.

Over the next period, we are participating in two events that will inform the public on the fundamental of satellite remote sensing of water quality that will include interactive learning with expert guidance. We will be hosting this interactive demo at the Aqua Chautauqua event on August 15, 2019 as well as the Minnesota State Fair on August 24 and 25, 2019. The attention and feedback received from these two events will be recorded and implemented into the proposed enhanced LakeBrowser.

Third Update January 31, 2020

Communication of project progress included presentations to scientists and managers at the Minnesota GIS/LIS Consortium in St. Cloud, Minnesota and at Pecora 21 Conference in Baltimore (supported by matching funds), as well as one journal article directly related to this project, which is under review. We also hosted an interactive demo of this project and the functionality of the current LakeBrowser at the Aqua Chautauqua in Detroit Lakes on August 15, 2019, at the Minnesota State Fair on August 24 and 25, 2019 and at a HABs workshop at the Water Resources Conference in St. Paul on October 16, 2019. The attention and feedback received from citizens, scientists and lake managers during these events was very insightful and will inform the development of the new LakeBrowser.

Olmanson, L.G., Page, B.P., Finlay, J.C., Brezonik, P.L., Bauer, M.E., Griffin, C.G., and Hozalski, R.M. 2020. Regional Measurements and Spatial/Temporal Analysis of CDOM in 10,000+ Optically Variable Minnesota Lakes using Landsat 8 Imagery. *Science of the Total Environment.* In review.

Fourth Update June 30, 2020

Communication of project progress was curtailed by the postponement of the Freshwater State of the Waters conference where we were going to have a booth to demonstrate the available data in the current LakeBrowser https://lakes.rs.umn.edu/ and demonstrations of the new data that will be available from this project and the Next Generation Lake Browser. And further curtailed by the cancelation of the ASLO-SFS conference in Madison Wisconsin where we were going to present "Satellite Remote Sensing for Water Quality Spatial/Temporal Trend Analysis in 10,000+ Minnesota Lakes Using an Automated High Performance Computing Environment". The paper submitted discussed above Olmanson et al. 2020 was accepted and has been published https://www.researchgate.net/publication/340108430_Regional_measurements_and_spatialtemporal_analysis_of_CDOM_in_10000_optically_variable_Minnesota_Lakes_using_Landsat_8_imagery.

Olmanson, L.G., Page, B.P., Finlay, J.C., Brezonik, P.L., Bauer, M.E., Griffin, C.G., and Hozalski, R.M. 2020. Regional Measurements and Spatial/Temporal Analysis of CDOM in 10,000+ Optically Variable Minnesota Lakes using Landsat 8 Imagery. *Science of the Total Environment.* Volume 724, Article 138141, doi.org/10.1016/j.scitotenv.2020.138141

Over the next period we will be developing the Next Generation LakeBrowser in ArcGIS Pro and publishing it the the web with ArcGIS Online. This web interface will allow for efficient evaluation of the data products that have been developed. To announce and facilitate the use of the Next Generation LakeBrowser, Web coverage Services, and Datacubes (mentioned previously), we will work with teams in the College of Food, Agricultural and Natural Resources Sciences (CFANS) and MSI at the University of Minnesota to make water quality data visible and available on the G.E.M.S. platform (https://agroinformatics.org). This will expand the user base of our water quality products in the agricultural and environmental communities. It will also combine Minnesota water quality data with information from a wide and growing number of sources. G.E.M.S. provides a federated web based environment for sharing cross-comparing geospatial data.

Fifth Update January 31, 2021

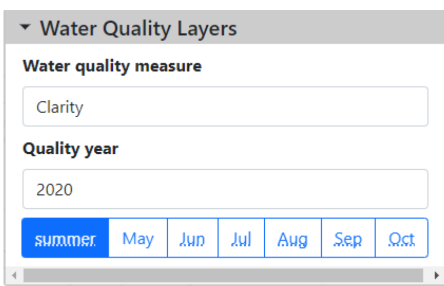
Communication of project progress included remote presentations to scientists and managers at the Water Resources Conference, Universities Council on Water Resources (UCOWR), North American Lake Management Society (NALMS) Minnesota Supercomputing Institute and other academic settings (supported by matching funds).

Over the next period, we will be merging the new datasets into the existing LakeBrowser https://lakes.rs.umn.edu/. This web interface will allow for efficient evaluation and use of the data products that are developed. To announce and facilitate the use of the Next Generation LakeBrowser, Web coverage Services, and Datacubes (mentioned previously), we will work with teams in the College of Food, Agricultural and Natural Resources Sciences (CFANS) and MSI at the University of Minnesota to make water quality data visible and available on the G.E.M.S. platform (https://agroinformatics.org). This will expand the user base of our water quality products in the agricultural and environmental communities. It will also combine Minnesota water quality data with information from a wide and growing number of sources. G.E.M.S. provides a federated web based environment for sharing cross-comparing geospatial data.

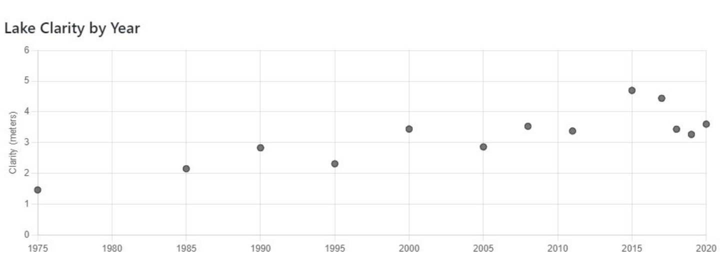
Final Update June 30, 2021

Communication of project progress included remote presentations to scientists and managers at Geo AquaWatch, Whitefish Area Property Owners Association (WAPOA), Water Data Forum, Association for Sciences of Limnology and Oceanography (ASLO), Minnesota Supercomputing Institute and other academic settings (supported by matching funds).

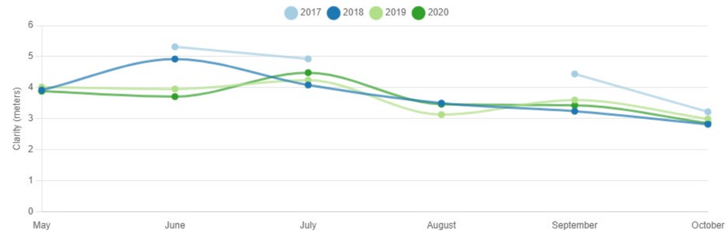
Over this period, we merged the new datasets into the existing LakeBrowser (https://lakes.rs.umn.edu/). This web interface allows for efficient evaluation and use of the data products that were developed. We organized the layout to display the water quality maps by water quality variable, year and month using dropdown menus.



When you click on a lake you get a full report of the long term and seasonal water quality data in easy-to-visualize graphs and in tabular form. Each lake is ranked by clarity percentile at the state, county, ecoregion and watershed levels. Land cover within a 1000-foot buffer is also included in the report.



Lake Clarity by Month



Lake Clarity Tabular View

The seasonal means for the years 2017–2020 are calculated using values from July 20 through September 20.

Year	Seasonal mean	May	June	July	August	September	October
1975	1.5						
1985	2.2						
1990	2.8						
1995	2.3						
2000	3.4						
2005	2.9						
2008	3.5						
2011	3.4						
2015	4.7						
2017	4.4	4.9	5.3	4.9	0.0	4.4	3.2
2018	3.4	3.9	4.9	4.1	3.5	3.2	2.8
2019	3.3	4.0	4.0	4.2	3.1	3.6	3.0
2020	3.6	3.9	3.7	4.5	3.5	3.4	2.9

Mean clarity (meters)

Unit Level	Unit Name/ID	Percentile
Statewide		74
County	Hennepin	87
Ecoregion	North Central Hardwood Forests	85
HUC4 Watershed	Mississippi Headwaters (0701)	65
HUC8 Watershed	Mississippi River - Twin Cities (07010206)	89

To announce and facilitate the use of the Next Generation LakeBrowser, Web coverage Services, we will work with teams in the College of Food, Agricultural and Natural Resources Sciences (CFANS) and MSI at the University of Minnesota to make water quality data visible and available on the G.E.M.S. platform (https://agroinformatics.org). This will expand the user base of our water quality products in the agricultural and environmental communities. It will also combine Minnesota water quality data with information from a wide and growing number of sources. G.E.M.S. provides a federated web based environment for sharing cross-comparing geospatial data.

V. PROJECT BUDGET SUMMARY:

A. Preliminary ENRTF Budget Overview: See attached budget spreadsheet

Explanation of Capital Expenditures Greater Than $5,000: N/A

Explanation of Use of Classified Staff: N/A

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

Enter Total Estimated Personnel Hours: 3,446	Divide by 2,080 = TOTAL FTE: 1.66

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

Enter Total Estimated Personnel Hours: N/A	Divide by 2,080 = TOTAL FTE: N/A

B. Other Funds:

SOURCE OF AND USE OF OTHER FUNDS	Amount Proposed	Amount Spent	Status and Timeframe
Other Non-State $ To Be Applied To Project During Project Period:	$ N/A	$ N/A	
Other State $ To Be Applied To Project During Project Period:	$ N/A	$ N/A	
In-kind Services To Be Applied To Project During Project Period: *unrecovered Indirect costs (54% MTDC)*	$135,000	$ N/A	Secured
In-kind Services To Be Applied To Project During Project Period: *Value of Landsat* ***satellite imagery*** *from EROS Data Center The estimated net value of Landsat imagery over the project period is* ***$326,400*** *(~544 images X $600/per image).* ***Minnesota Supercomputing Institute*** *is providing 300,000 core hours of compute time MSI's Linux cluster, 5 TB of primary (POSIX compliant) data storage and 10 TB of tier 2 (object oriented CEPH) data storage at a value of* ***$24,900****.The* ***Minnesota Department of Natural Resources*** *will provide 100 hours per year for 2 years in-kind support to this project, for a value of* ***$21,450****. The* ***Minnesota Pollution Control Agency*** *and The* ***Metropolitan Council Environmental Services*** *will provide their lake and river water quality data in support of calibration and validation of remote sensing results. Estimate value $150 per sample x 400 samples* ***$60,000****.*			
See description above.	$432,750	$N/A	Secured
Past and Current ENRTF Appropriation: *ENRTF: 2016 PI Jacques Finlay - Assessment of Surface Water Quality with Satellite Sensors - Activity 1 unspent funds available.*	$	$ 205,000	Secured
Other Funding History: *The National Science Foundation Award # 1510332 PI Raymond Hozalski "Spatial and Temporal Variability in CDOM at Large Regional Scales by Optical Remote Sensing: Effects on Water Quality, Water Treatment, and Aquatic Ecosystem Properties". Funds will all be expended before July 1, 2018.*	$	$ 230,000	Secured

VI. PROJECT PARTNERS:

A. Partners receiving ENRTF funding

Name	Title	Affiliation	Role
Jeffrey Peterson	Director WRC	UMN WRC	PI
Leif Olmanson	Research Associate	UMN FR & WRC	Co-PI Technical PI

David Porter	Scientific Computing Cons	UMN MSI	Co-PI

B. Partners NOT receiving ENRTF funding

Name	Title	Affiliation	Role
Marvin Bauer	Professor emeritus	UMN FR	Co-I
Patrick Brezonik	Professor emeritus	UMN CEGE	Collaborator

VII. LONG-TERM- IMPLEMENTATION AND FUNDING: 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, high performance computing, aquatic ecology and water quality analysis to advance the capability to monitor and understand spatial and temporal patterns in water quality. Our past development of remote sensing methods for monitoring 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 and automated image processing using supercomputing to include chlorophyll and organic color 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, Department of Natural Resources, and local agencies in decision making and prioritization of resources. At the end of this project, we will be able to provide data through the new water quality portal (updated Lake Browser) to these and other relevant agencies with the basic tools needed to initiate their own use of remote sensing water quality data as operational tools for frequent, statewide assessments of surface water quality throughout the state.

This automated image processing system using supercomputing and basic geospatial database of remotely sensed water quality data maintained by the WRC will make a strong foundation for ongoing research and addition of more advanced capabilities as resources become available:

1. Advanced exploration of the water quality data (e.g. visualization and customized infomatics).
2. More water quality variables (e.g. non-algal turbidity, harmful algal blooms).
3. Integration of other data sources (e.g. land use, BMPs).
4. Targeted field monitoring of optically complex waters underrepresented in routine monitoring efforts.

VIII. REPORTING REQUIREMENTS:

- **The project is for three years, will begin on July/1/2018, and end on June/30/2021.**
- **Periodic project status update reports will be submitted January/30 and July/31 of each year.**
- **A final report and associated products will be submitted between June 30 and August 15, 2021.**

IX. SEE ADDITIONAL WORK PLAN COMPONENTS:

A. Budget Spreadsheet
B. Visual Component or Map
C. Parcel List Spreadsheet
D. Acquisition, Easements, and Restoration Requirements
E. Research Addendum

Final Attachment A:
Environment and Natural Resources Trust Fund
M.L. 2018 Budget Spreadsheet

Project Title: Providing Critical Water-Quality Information for Lake Management
Legal Citation: M.L. 2018, Chp. 214, Art. 4, Sec. 02, Subd. 03b
Project Manager: Jeff Peterson
Organization: University of Minnesota
College/Department/Division: CFANS / Water Resources Center
M.L. 2018 ENRTF Appropriation: $250,000
Project Length and Completion Date: 3 years, June 30, 2021
Date of Report: 07/31/2021

ENVIRONMENT AND NATURAL RESOURCES TRUST FUND BUDGET	TOTAL BUDGET	AMOUNT SPENT	TOTAL BALANCE
BUDGET ITEM			
Personnel (Wages and Benefits)	$248,550	$248,550	$0
Jeff Peterson, PI, (75% Salary, 25% benefits) 1% per year, will coordinate project ($4,400)			
Leif Olmanson, Co-PI, (75% Salary, 25% benefits) 41% per year, will oversee technical aspects of project/RS coding/database/Lake Browser ($68,400)			
David Porter, Co-PI, (75% Salary, 25% benefits) 20% year1, 10% year 2, will oversee and conduct supercomputing and database aspects of the project ($44,500)			
Database Specialist, TBN,(75% Salary, 25% benefits) 17% per year, Build Spatial database ($21,700)			
Research Fellow, TBN , (75% Salary, 25% benefits) 80% per year, RS coding/database/Lake Browser ($108,000)			
Travel expenses in Minnesota			
Travel to meetings with collaborators and state agencies. Expenses will be charged in accordance with University of Minnesota travel reimbursement rates and guidelines	$0	$0	$0
Other			
Remote sensing and geospatial analysis laboratory fees	$1,450	$1,450	$0
COLUMN TOTAL	**$250,000**	**$250,000**	$0