Multi-Instrument Stream Surveys with Continuous Data for Better Groundwater/SurfaceWater Understanding in Wisconsin

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Project Summary

Title: Multi-Instrument Stream Surveys with Continuous Data for Better Groundwater/Surface Water Understanding in Wisconsin

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Background/Need: Models and decisions require data. The advent of easily-acquired locations through GPS and easily-stored data through low cost memory and electronics allows for acquisition of large amounts of geolocated data. Small streams and lakes are sensitive to environmental changes and exhibit more variation in water chemistry making them a challenge to model and good locations to test the collection of dense sets of geolocated data. A geolocated record of stream in the form of water chemistry, temperature, stream bed type, stream stage, and video allows for an in-depth assessment of the stream condition.

Objectives: The ultimate objective of this project is to create a comprehensive methodology for rapid and accurate data collection on streams so that collection and handling the large data sets are efficient and readily provide inputs for models. In addition to use in groundwater flow models, the data collected by these methods will also apply to other objectives such as surveys of the stream ecology where temperature and channel morphology play major roles or where erosion by past or current farming practices may be responsible for changes in streambed sediments from clean sand to silt and organics.

Methods: We selected five streams from across Wisconsin representing the different physiographic regions. These streams are all lower order with variable water chemistries and bottom sediment. In addition to the five streams, we also collected data at three lakes in the Central Sand Plain. We collected water chemistry, temperature, ground conductivity, water depth, and video during each each stream survey or "float". The water chemistry was collected using an Arduino microcontroller based system that recorded GPS location, time, fluid temperature, conductivity, pH, and concentrations of dissolved oxygen, nitrate and chloride. The ground conductivity was collected using a Geonics EM-31 ground conductivity meter with an Arduino data logger that recorded the ground conductivity data, GPS location and time. The water depth was recorded with time and location using a Lowrance Hook 5 depth finder. Continous video was recorded on a GoPro Hero 4 camera. The data recorded by the Arduino controllers was stored as text files. The depth finder data was converted to text files using ReefMaster2.0 software. This geospatial data was managed and analyzed using ArcMap and Matlab scripts. We coupled the video to the geospatial data using RaceRender. These video editing software packages were originally designed for race car driving.

We had initially planned to use RTK GPS to record the stage of the streams. We did conduct several floats where that data was collected but we found tree cover often made collection

difficult. We and others (Leaf, 2019) have found that Lidar-derived digital elevation models provide a similar degree of accuracy, making collection of RTK GPS data unnecessary for accurate stream stage.

Results and Discussion: The overall goal of creating a methodology for collecting stream float data was met. We were able to collect data on a horizontal scale of around a sample every 1-5 meters over kilometers of stream reach and lake shoreline. The time needed for data collection was typically one to three hours. Although we were able to collect some data from all five of the streams and from three additional lakes, the quality of data varied from site to site. For this reason, not all sites are reported in-depth in this report.

At three of the sites, we were able to collect high quality data from the different instruments. Those sites were the Grant River, the Mukwonago River, and Plainfield Lake. We have data from all sites but these three best show the potential of the method and are discussed at length in this report. Around Plainfield Lake we observed variation in pH, dissolved oxygen, and fluid conductivity. We also mapped electrical conductivity of the near-shore bed sediments and correlated that electrical conductivity with sediments collected around the lake. In the Grant River, we found a clear difference in water quality between Borah Creek and Rogers Branch as indicated by temperature and fluid conductivity. The survey also identified a small unnamed inlet that had very low water quality. In the Mukwonago River, we were able to monitor evolving stream water chemistry over several miles of stream starting with groundwater discharge at a spring pool and going downstream to Lulu Lake. The observed pH, fluid conductivity, temperature, and dissolved oxygen all changed as the groundwater mixed with and came into equilibrium with the atmosphere and stream.

Conclusions/ Implications/Recommendations:

We were able to collect geolocated and time-stamped data sets, including stream water pH, temperature, conductivity, and dissolved oxygen. Also collected were video of the stream and bank, stream depth and stream bed electrical conductivity. These data allowed us to identify groundwater discharge, differentiate between high and low water quality tributaries, and geolocate variation in streambed lithology. However, we found some measurements rarely met basic levels of accuracy. The chloride and nitrate probes each had only one successful survey. We initially collected ground penetrating radar data of the streambed but found that data required a great deal of effort and provided little insight. We also attempted to collect turbidity data but found that we needed a filter to keep weeds and other floating debris out of the flow through cells. A coarser filter that allowed finer grained sediment to pass while blocking larger vegetation needed to be incorporated to allow for collection of turbidity data.

This method has great potential to provide reliable and extensive data for use in groundwater flow models and stream water and ecological quality. We plan to continue applying it with planned deployments in both lakes and streams in central and northern Wisconsin with the hope that its continued use will demonstrate its value to a wider audience.

Key Words: Water Quality, Groundwater/Surface Water Interaction, Data Acquisition, Video

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Chapter 1: Introduction

1.1 Purpose and Scope

Groundwater discharge to surface water carries unique thermal and geochemical signatures and provides important ecological services by providing baseflow and stable temperature habitats (*Hayashi and Rosenberry, 2002*). GW-SW interactions have proven to be highly variable at a local scale (*Shaw and Prepas, 1990*). Dense spatial variability is rarely documented with water-quality sensor technology due to cost, software, and power limitations. In a warming climate (*Cook et al., 2013*), environmental scientists will need additional tools to measure hydrologic data to understand and model complex environmental systems (*Lovett et al., 2007; Tauro et al., 2018*).

Currently, hydrologic properties in streams are most commonly measured at in-situ "point-scale" locations, sometimes continuously through time. Data from fixed stations provide information that are often used to characterize the cumulative upstream watershed (*Gilliom et. al, 1995*). Water-quality sensors that are used to collect continuous data at fixed stations are frequently purchased as a pre-compiled package with software, and are cost prohibitive. However, recent advances in low-cost, easy-to-use microcontrollers have made customizing sensor software as a scientific tool highly accessible (*Wickert et al., 2014*).

To overcome these issues of spatial heterogeneity and cost, we developed a method that collects spatially dense datasets of water-quality and streambed conductivity over lengths of streams and lakes via canoe utilizing low-cost microcontrollers. Parameters collected included stream temperature, dissolved oxygen content, pH, specific conductance, and nitrate and chloride concentrations in stream water, in combination with streambed electrical conductivity, water depth, and video data in order to create a synoptic view of a stream's quality and areas of groundwater-surface water exchange. The purpose of this study is to develop, validate and assess the utility of collecting high-density, geolocated data on small surface-water systems.

1.2 Review of traditional methods for collecting small-stream hydrologic data

Two reference-frames are used to conceptualize observing movement through rivers: 1) Eulerian, wherein a fixed location in space is observed as water moves through it; and 2) Lagrangian, wherein a parcel of water is tracked as it moves through time and space (*Tokaty, 1971*). The following discussion will review methods used to observe spatial and temporal stream characteristics within each of these frameworks.

Methods have been developed to characterize stream characteristics continuously along a stream at a fine scale, specifically related to temperature. The importance of characterizing

fine-scale temperature distributions in streams has been a research area of increased interest in recent years (*Briggs et al., 2012; Hare et al., 2012; Constantz, 2008*). Temperature variations can serve as an indicator of GW discharge, GW flow through fractures, and GW flow patterns (*Anderson, 2005*). Temperature regulated portions of streams provide important areas of habitat refugia for cold-water species (*Briggs et al., 2013*).

Fiber-optic distributed temperature sensing (FO-DTS) is a method that collects rapid, fine-scale profiles of temperature. This method operates by transmitting pulsed laser light down an optical fiber; it determines temperature across the fiber by measuring the ratio of temperature-independent Raman backscatter to temperature dependent backscatter (*Tyler et al., 2009*). Temperature measurements can be resolved to as precise as approximately 1-m resolution (*Briggs et al., 2012*). FO-DTS has been used to identify temperature anomalies along a stream reach in an effort to locate areas of groundwater discharge and hyporheic exchange (*Lowry et al., 2007; Briggs et al., 2011; Mwakanyamale et al., 2013*). In addition, DTS can aid in hydrostratigraphic characterization by monitoring advective heat movement in boreholes (*Leaf et al., 2012*). It can also be installed vertically in a streambed to assess temperature variation with depth and quantify groundwater flux. Although proven to be an effective tool, this method can be cost prohibitive and requires intensive labor to install and georeference (*Neilson et al., 2010*). FO-DTS cables are also easily damaged and can be difficult to calibrate and supply power.

Thermal infrared cameras can measure surficial stream "skin" temperature from air, satellite, and ground-based surveys (*Hare et al., 2015*). Ground-based thermal imaging is particularly well suited to identifying surficial groundwater seeps with relatively low field effort (*Deitchman and Loheide, 2009*). This method is limited by its ability to solely observe surface temperature of the stream, while GW-SW exchange processes may only affect water temperatures deeper within the stream column. In addition, processing and managing high-resolution images is a time-intensive process.

Electromagnetic methods have long been used by hydrogeologists to characterize subsurface flow and transport processes (*Singha et al., 2015; Sandberg et al., 2002*). Electrical conductivity is a geophysical parameter that indicates a substance's capacity to conduct electricity and the Geonics EM31 is one tool capable of measuring it (*McNeil 1980*). Electrical conductivity and resistivity, which have an inverse relationship, are sensitive to porosity, pore fluid conductivity, biologic material content, clay content and salinity (*Binley et al., 2015*). Characterizing differences in electrical conductivity within a streambed allows hydrogeologists to infer information about streambed lithologies and consequently hydraulic conductivities, which is an essential parameter for informing groundwater models (*Menichino et al., 2012*).

Finally, although much less common than the previously listed methods, some hydrologic studies have collected water-quality data in longitudinal profiles surveyed at ambient stream velocity, i.e. following a "Lagrangian" framework. Several United States Geological Survey (USGS) researchers have collected thermal and conductivity profiles along large river reaches throughout Washington with the goal of identifying cold-water zones of salmonid habitat (*Gandaszek, 2011; Vaccaro and Maloy, 2006*). This small group of studies serves as the most similar form of data collection to the stream float method we have developed.

More recently, scientists in the UW-Madison Limnology group developed a method called Fast Limnology Automated Measurement (FLAMe) to automatically sample water-quality parameters on large lakes and rivers at high-speeds (*FLAMe, 2019*). This method generates spatially resolved aquatic chemistry snapshots of parameters including temperature, pH, and CO_2 content (*Crawford et al., 2015*). This method of data collection has been used to increase understanding of ecological patterns, ecosystem processes, and biogeochemical fluxes in aquatic systems.

1.3 Applications of microcontrollers in hydrologic science

Microcontrollers are small computing devices that typically include a processor, memory, and input/output operators in a single chip. They are low-cost and simple, easily-powered, robust and customizable. Microcontrollers are of increasing value to scientists (*Genicot, 2015*); scientific publications including terms 'Raspberry Pi' or 'Arduino' (two types of microcomputing devices) increased from almost none prior to 2014 to nearly 400 in 2016 (*Cressey, 2017*). They have been applied hydrologically to operate automatic rain sampling (*Michelsen et al., 2019*), infiltrometers (*Fatehnia et al.,2015*), temperature sensing (*Hut et al., 2016*), water-level and snow depth monitoring (*Wickert, 2014*), among other applications. Arduino produces single-board microcontrollers designed with easy-to-use software with advanced capabilities (*Arduino, 2019*). Many scientific groups who utilize Arduino and other microcontroller data logging are contributing to a community of open-source electronics code sharing specifically for lab and field applications (*Wickert et al., 2018*).

Chapter 2: Methods

2.1 Field Methods

This chapter describes the stream-float instrumentation and best-use protocols established through a trial-and-error process over the duration of data collection and may serve as a reference for reproducing this stream-float data collection method. We conducted stream-floats between May and September 2018. Because the stream-float method was refined through a trial-and-error process, it is important to note that some data collected may have been subject to slightly different protocols prior to the final refinement of the method.

Instruments were mounted in a 16' polyethylene plastic canoe for the controlled stream-float (Figure 1). The plastic canoe was used, rather than an aluminum or fiberglass canoe with metal gunnels, to avoid blocking the electromagnetic signal from the EM31.

2.1.1 Selection of Study Areas

Five streams throughout Wisconsin were selected for field study for the purpose of developing and testing the stream-float method (Figure 2). The distribution of sites was chosen to represent major physiographic regions of Wisconsin and test the method in somewhat different environments. The streams hold similar characteristics in that they are all small, low-order streams within their respective watersheds, and each has been subject to substantial hydrologic study and data collection. Developing the method at a variety of field sites allowed us to appropriately judge field conditions that the method should be able to handle, and compare our results to existing hydrologic understanding. For the purposes of this thesis, only selected results from these sites are reported in order to illustrate the utility of the method. Data for other sites are available upon request.
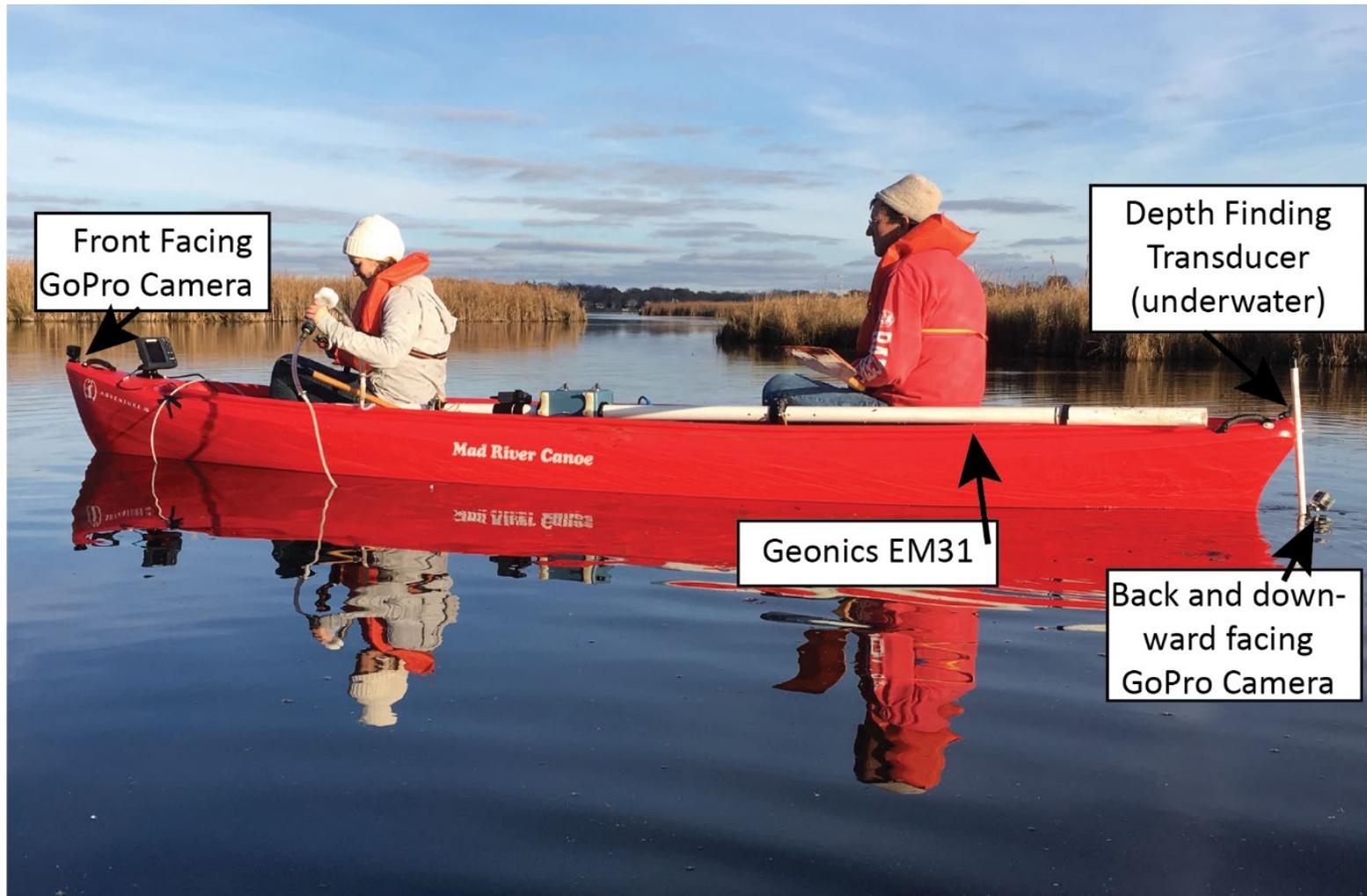
Figure 1. Basic stream float setup with Geonics EM31 extending the length of the canoe. Front and back-facing cameras are visible in addition to the depth finding transducer on the hull of the canoe. Inlet and outlet tubes for the flow through cell are visible.
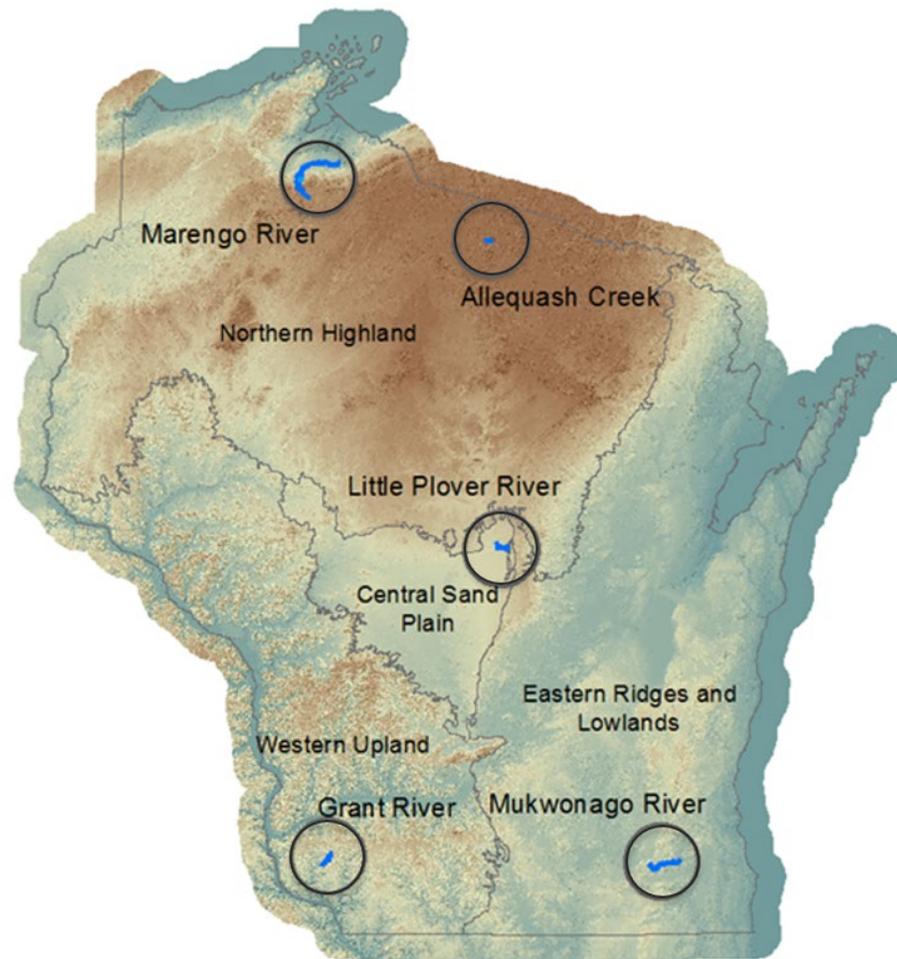
Figure 2. Streams selected to test the stream float method representing different physiographic regions of Wisconsin.

2.1.2 Water-Quality Apparatus

We assembled an apparatus to record water-quality data throughout the float by compiling individually purchased, relatively low-cost sensors for each parameter, which we installed into a custom-designed flow-through cell (Figure 3a). The details of each water-quality sensor, in addition to the calibration protocols that were followed, are described in Table 1. Each of these sensors ranges in price from $20-$200. Perhaps the most significant advantage of utilizing an Arduino microcontroller system to power our water-quality apparatus is cost-efficiency. Individually purchased probes, Arduino hardware, and the water-proof Pelican case to hold the electronics cost approximately $1,200. The custom-designed flow through cell constructed at the University of Wisconsin – Madison mechanical engineering workshop, was the more expensive component, at a cost of approximately $900. At just over $2,000 this setup is significantly less expensive than a multi-parameter sonde with complimentary probes purchased by a company such as YSI, which would market at approximately $10,000 or more (*YSI, personal communication*). Of course, cost is only one comparative measure to consider between the systems. Another advantage of this system, is its ability to spatially locate each data point. Data from a multi-parameter sonde would need to be located using a separate GPS unit and linking location to data using times in the sonde and GPS.

A thermocouple was used to measure temperature within the flow-through cell. Due to initial implementation troubles with the thermocouple, a secondary DS182B20 Digital Temperature Sensor was also utilized. This sensor was attached to the depth transducer that extended on the back of the canoe, so was placed directly into the water rather than in the flow-through cell.
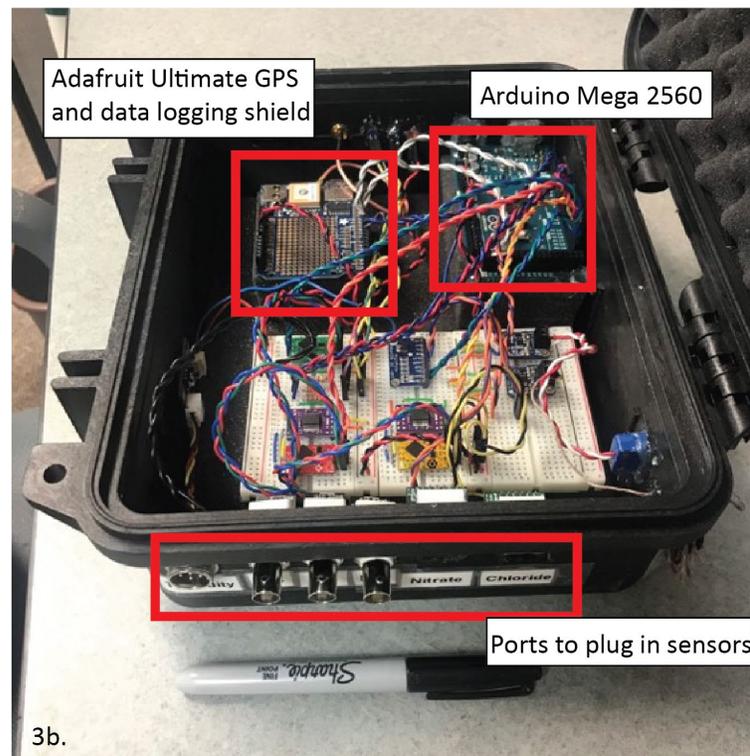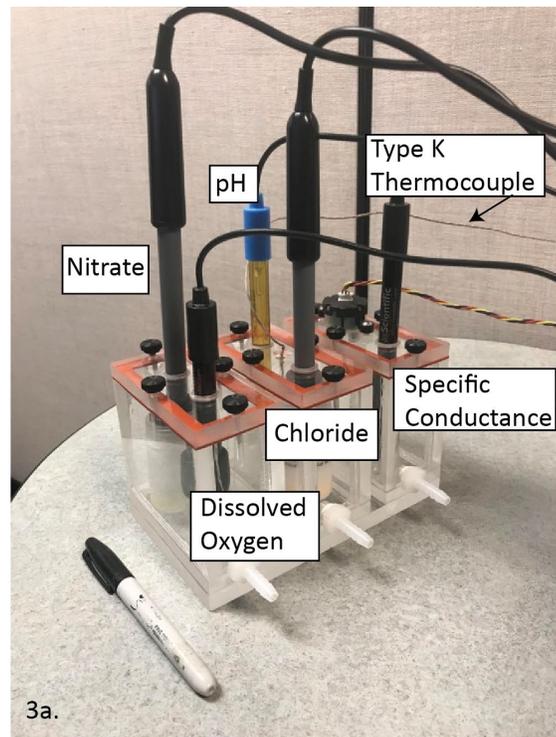
Figure 3.a) Custom built flow-through-cell with 6 individually purchased water-quality parameter sensors. b) Pelican case containing Arduino board connections.

Table 1. Water-Quality Sensor Details, Accuracy, and Calibration Information

Parameter	Probe Type	Flow through cell chamber	Response Time	Accuracy	Calibration Proceedure	Cost
Dissolved Oxygen	Atlas Scientific	3	~0.3mg/L/sec	+/- 0.05 mg/L	1 point calibration to 100% saturation weekly	$283
Temperature	K Type Thermocouple	2	99% in 1s	+/- 2.2 deg C	1 time calibration	$20
Specific Conductance	Atlas Scientific	2	90% in 1s	+/- 2%	2 point calibration to 14.13 and 1413 uS/cm weekly	$215
pH	Atlas Scientific	2	95% in 1s	+/- 0.002	3 point calibration to pH 4, 7, and 10 weekly	$164
Nitrate (NO3-)	Vernier Nitrate Ion-Selective Electrode	1	varies	+/- 0.1 ppm	2 point calibration to 1ppm and 50ppm daily	$199
Chloride	Vernier Chloride Ion-Selective Electrode	3	varies	+/- 10% of full scale	2 point calibration to 2ppm and 50ppm daily	$199
Additional Temperature	DS182B20 Digital Temperature Sensor	N/A	90% in 35s	+/-0.01deg C	--	$3.95

The flow-through cell contains three chambers, with dimensions of 90mm x 33m x 80mm and an internal volume of 240mL. The minimum volume required to hold the tubes was used in order to minimize flow-through time in the system. Each of the chambers is connected by silicon tubing, with a segment of 4" copper tubing between the first and second and second and third chambers. The inlet and outlet nozzles are on opposite sides of each chamber, with the inlet nozzle located on the bottom of the chamber and the outlet nozzle located on the top. This placement was intentional to ensure that inlet water properly flushed through the entirety of the chamber without missing the sensors. The purpose of using three separate chambers in the flow-through cell was to separate ion-specific electrode probes, which emit an electrical voltage into the fluid in order to measure a given water-quality parameter. The copper tubing in between each chamber acted as an electrical ground as the water moved between chambers. Each of the chambers is constructed with a removable top secured by 4 plastic screws. A rubber gasket sits between the removable top and the flow-through cell to prevent leakage.

We used a peristaltic pump to pump water at an approximate rate of 1.4 L/min from an inlet line (secured to the bottom of the canoe, drawing water from approximately 4-6 inches below the stream surface) that connected to a filter normally used to filter gasoline in a vehicle to prevent coarse river sediments and plant material from entering the flow-through cell. The outlet tubing was secured on the opposite side of the canoe from the inflow to prevent water from being recycled into the system. It took an average of 20 seconds for water to move from inlet to outlet of the system. The flow rate would intermittently slow down when the filter began to clog, at which point the float would pause and the filter cleared manually or by briefly reversing the flow direction of the pump.

Each of the water-quality sensors is connected to a water-proof Pelican™ case (Figure 3b), inside of which the data and GPS location were logged using open-source electronic prototyping platform Arduino. Scripts used to run and calibrate the water-quality sensors were written in the Arduino programming language primarily by Susan Richmond, a graduate student in the Geological Engineering department at UW-Madison working with Professor Dante Fratta (*Richmond, 2019*). We used an Arduino Mega 2560 Rev3 to log output readings every 2-3 seconds from water quality probes to a microSD card (*Arduino, 2019b*). An Adafruit Ultimate GPS Breakout™ receiver logged time, date, longitude and latitude coincidentally with each data point. The Adafruit GPS receiver requires 5 satellite signals in order to fix and record the signal. Water-quality data logged every 2-3 seconds, even if the GPS does not have a signal. The water-quality data collection apparatus is powered by an external battery pack containing four AA Lithium batteries. A computer can alternatively power the apparatus, where the collected data is displayed and commands are provided to the program. Three lights on the side of the Pelican case indicate 1) whether the system is powered, 2) if GPS data are logging, and 3) if water quality data are logging. The

lights allow us to ensure that data are logging without requiring the use a computer in the canoe.

2.1.3 Ground Electrical Conductivity

Electrical conductivity of the subsurface was measured using a Geonics EM-31 ground conductivity meter, which extends the length of the canoe, secured by zip ties. The EM31 contains coils on opposite ends, with one end as the transmitting coil where an electrical current of known frequency and magnitude creates a primary magnetic field in the space surrounding the coil. A secondary magnetic field is then generated by the conductive materials in the underlying surface, the current of which is read by the receiving coil of the EM31 (*McNeil, 1980*). The ratio of the magnitudes of the transmitting and receiving currents is proportional to the subsurface conductivity, reported in milli-Siemens/meter (mS/m). The device was operated in the horizontal dipole orientation fixed approximately 6" above the stream surface. We oriented the device horizontally in the canoe to optimize shallow (<1m) depth contributions to EM31 signal (*McNeil, 1980*). The effective sensing depth of the instrument in the horizontal orientation is approximately 3m.

EM31 conductivity readings were logged every 2-3 seconds approximately throughout the duration of the stream float using the Arduino Uno microcontroller (*Arduino, 2019c)* and GPS readings are recorded using an Adafruit GPS logger shield (Figure 4). Lights on the logging box indicate the same information provided by the lights on the water-quality set up; the red light indicates power, the blue light indicates GPS information is logging, and the green light indicates conductivity measurements are logging. The Adafruit GPS logger shield is powered by a 9V battery and holds a MicroSD chip to store data.

4a
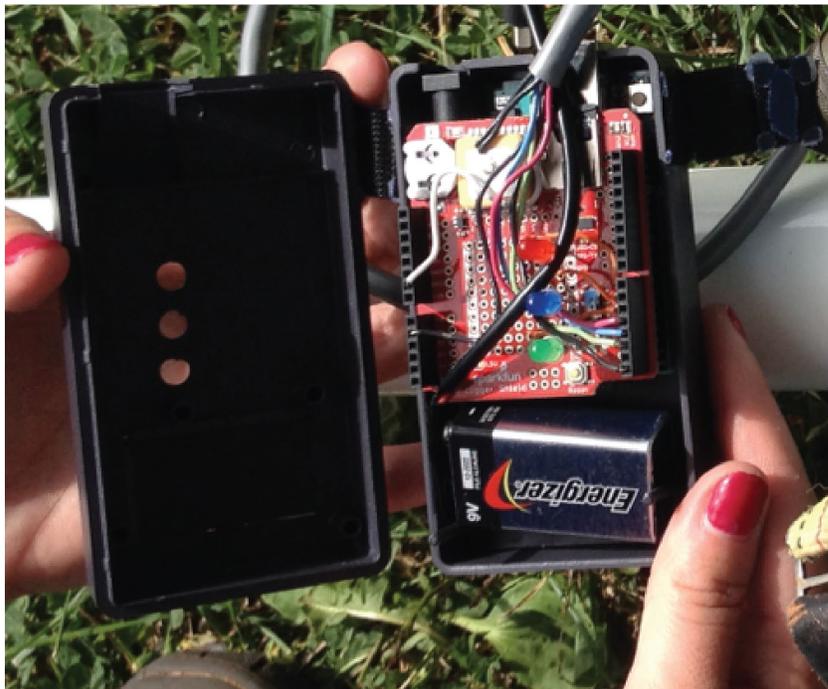
4b

Figure 4. a) Analog reader for Geonics EM31 with connection to box containing Arduino hardware. b) Arduino Adafruit GPS logger shield with lights and 9V battery for power.

2.1.4 Depth Sensing and Video Recording

A Lowrance HOOK-5™ fishfinder is mounted on the back of the canoe and measures depth of water to an accuracy of 0.1 ft. Sonar readings from the fishfinder are displayed via a monitor at the front of the canoe. An external 12V battery supplied power to the fishfinder. Depth data are geolocated using Lowrance software and logged every 1-4 seconds approximately. Data were downloaded and processed using ReefMaster 2.0™ software. The transducer sat approximately six inches beneath the surface of the water in a fully weighted canoe, and this correction was added to the depths during data processing in ReefMaster.

We used GoPro Hero5 cameras to record video throughout the duration of the stream float. One camera was placed on the bow of the canoe to record the surficial stream and streambank as the canoe moved in the stream. The other camera was placed in a waterproof case and was secured to a rod at the stern of the canoe, with the camera submerged in water and facing downward toward the stream bottom to record lithological changes throughout the duration of the stream float. The battery life on the GoPro cameras (approximately 2.5 hours for high quality videography) was a limiting factor in the length of full stream floats.

2.1.5 Lab Sample Water Quality Data Collection

We collected water samples for laboratory analysis on select field trips in order to validate the results of the continuously logged water-quality data collection. We collected five water quality samples along the course of the river for two field trips: the Mukwonago River float on June 27th, 2018 and the Grant River float on July 25th 2018. Samples were collected from the outlet of the flow-through cell (i.e. coarsely filtered) and sent for analysis at the University of Wisconsin - Stevens Point Water and Environmental Analysis Lab (WEAL), with GPS location noted. The bottles used to collect samples were provided by WEAL. An unpreserved sample was collected in addition to a sample preserved with sulfuric acid. Samples were analyzed for major ions and nutrients provided in the WEAL Lake Package A. These ions and nutrients include each of the parameters measured in our continuous water-quality collection, with the exception of dissolved oxygen content and temperature, which are not preserved in a sample.

2.1.6 Stream Discharge Measurements

Stream discharge measurements were collected on the streams for each of the stream floats in order to provide hydrologic context for a given stream float data collection event, i.e. whether a stream was experiencing high or low flow conditions. For some of the sites, USGS stream gages existed with 15-minute discharge data on the stream reaches that we were studying, so those datasets were used for hydrologic context (Little Plover River, Allequash Creek). For sites where USGS stream gages do not exist, stream discharge measurements

were calculated at upstream and downstream portions of the stream reaches by collecting stream velocity and depth measurements with a Marsh-McBirney Flo-Mate Flow Meter. Measurements were taken at 1ft intervals across a lateral stream-section; each cross-sectional area was multiplied by its respective flow velocity and added to determine volumetric streamflow. These data are reported in a spreadsheet in Attachment A – StreamFlow_MultiInstrumentCanoeStudy.xlsx. We also collected streambed groundwater flux data at the Little Plover River and Allequash Creek and streambed hydraulic gradient data at the Little Plover River. Those data are also reported in Attachment A - StreamFlow_MultiInstrumentCanoeStudy.xlsx.

We also tested an alternative method of determining streambed groundwater flux using thermal profiling. A thermal profile was combined with the streambed hydraulic gradient data to provide another estimate of flux in the Little Plover River at Eisenhower Rd. The method uses a time series of temperatures collected at the streambed surface and depths below the streambed to estimate groundwater flux. If groundwater is discharging to the streambed, the daily temperature variation is compressed to the shallow depth beneath the streambed but if the stream discharging to groundwater, the daily temperature variation is carried deeper beneath the stream bed. If there is no groundwater flow into or out of the streambed, the heat moves only by diffusion.

We used 1DTempPro (Koch and others, 2015) to analyze the data. Figure 5 shows the data and model results. A downward streambed flux of -0.018 m/day out of the stream was calculated. This is much larger than the average flux measured with the seepage meters of -0.0009 m/day. We can test which value is more likely by using them with the head gradient to calculate streambed hydraulic conductivity of using Darcy's law, $q = K \, dh/dz$. Substituting for $q = -0.0009$ determined by the seepage meters and $dh/dz = -0.154$ gives a value of $K = 0.006$ m/day. This value seems too low for the sandy bottom seen at Eisenhower Rd and from values measured by Browne and Guldan (2005) in the Little Plover River. The temperature profile flux gives a corresponding value for $K = 0.12$ m/day, a more reasonable value. This trial test shows the potential for this method. A longer time interval would provide more confidence in the results. This will be accomplished by using a larger capacity battery than the 9-volt battery used here. We plan to use this method in future groundwater/surface water flux measurements.
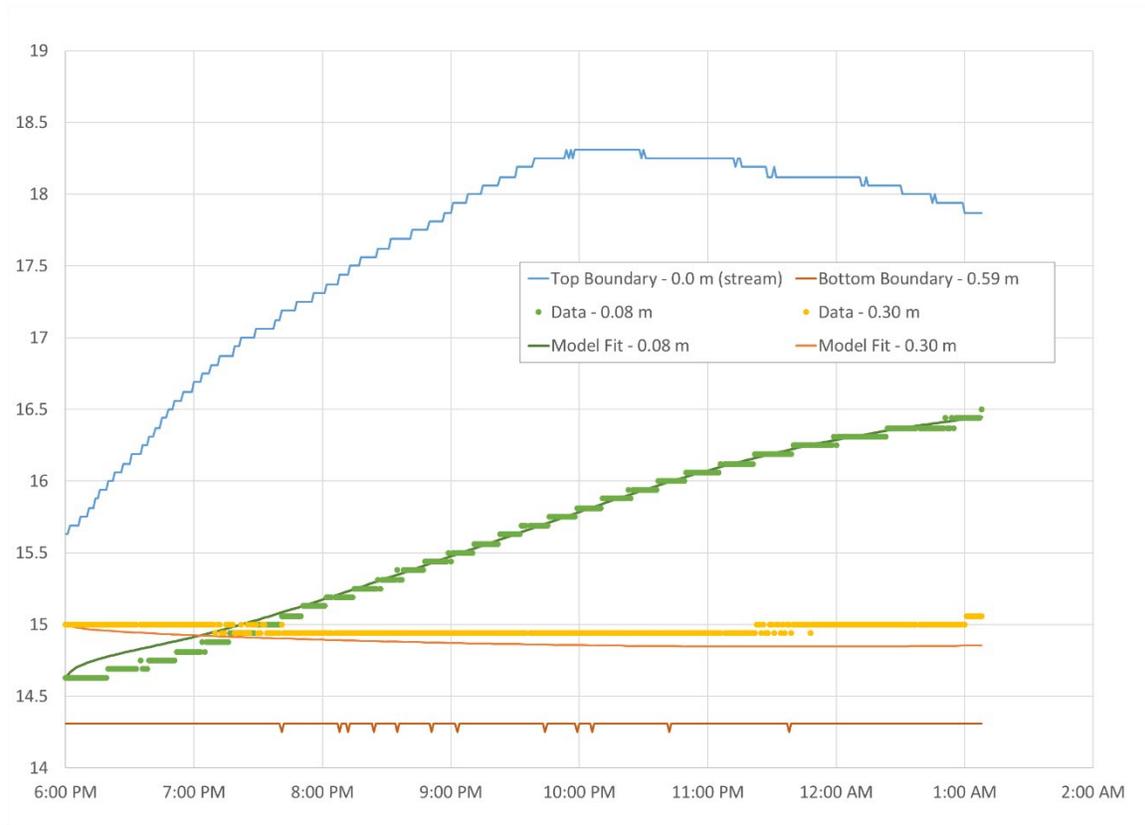
Figure 5. Thermal profile data and model. The stream temperature (blue) and the streambed termperature at 0.59 m below the stream bed are boundary conditions. The corresponding groundwater flux is 0.018 m/day downward.

2.2 Data Processing Methods

2.2.1 Data Aggregation Process

An adjustment of 10 seconds was applied to the water quality data, i.e. for a given point of data collection, the location information from 10 seconds previous was applied to that point. A delay time of 10 seconds was chosen because it took approximately 20 seconds for a parcel of water to travel through the entire flow-through system, so 10 seconds is the approximate length of time that a parcel of water would take to travel to the center chamber of the flow through cell.

Raw conductivity data were converted to specific conductance after collecting data using the coincident temperature data using the following equation:

$$Specific\ Conductance = \frac{Raw\ Conductivity}{1 + 0.02 * (temperature\ °C - 25)}$$

A generalized coefficient of 0.02 was used. Our setup reported dissolved oxygen as percent saturation (relative to air) and was converted to ppm using simultaneously collected temperature data and known information about solubility of dissolved oxygen at given temperatures (*HACH, Inc*).

The output of tabular data from the overall stream float is held in three tables, each with an associated time and geolocation. The three sources of data were 1) the water quality apparatus output, containing time, location, and measured values for temperature, specific conductivity, pH, dissolved oxygen, nitrate, & chloride; 2) the EM31 output containing time, location, and conductivity reading of the subsurface; and 3) the depth finder output containing time, location, and depth of water. Each of these sources collects independent GPS information.

The following procedure was used in order to aggregate each of these data sources into one. While it may seem redundant to collect GPS information from multiple sources, it serves as useful backup data in case any portion of instrumentation fails throughout the stream float. When location information failed to log (due to insufficient signal) for one of the GPS sources, time values were interpolated between existing location points, and then the location information for the given time was assigned from a secondary GPS source. For example, at an earlier iteration of the water-quality-apparatus, a less robust GPS sensor was being utilized, and the water-quality data logged approximately every 2 seconds, but large gaps in location information existed within the datasets due to loss of GPS signal. The times between these gaps were interpolated linearly in MATLAB, and the location data from the EM31 dataset for that specific time was assigned to that point. This method of location assignment is subject to some error. An analysis in ArcGIS of both data sources where data do exist indicated that for a given time stamp, the location could vary on average up to 5m. Timestamps were ultimately used to link the three datasets together. Table 2 below shows a summary of the data quality from the completed surveys for all the lakes and streams in the study. Cells shown in blue have acceptable and usable data, cells in orange sometimes contain reasonable and potentially useful data, and cells shown in red contain no useful data. Attachment 2 is a compressed file of the MATLAB scripts used to analyze and process the data.

Table 2. Status of data at the study sites.

Stream/Lake	Date	EM31	Nitrate	Chloride	DO	EC	pH	Temp - original	Dave's Temp Sensor	Mike's Temp Conductivity	Video (above)	Video (below)	Fish Finder	Lab QW	Streamflow	Seepage Meters/Mini Pz	General Notes
Marengo	6/1	[red]	[red]	[yellow]	[blue]	[yellow]	[blue]	[red]	tidbit	[gray]	[blue]	murky.			[blue]	[gray]	missing script
Mukwonago	6/5	[red]	[yellow]	[yellow]	[blue]	[blue]	[yellow]	[red]		[gray]	[blue]					[gray]	
Grant	6/8	[blue]	[blue]	[blue]	partial	partial	partial		[blue]	[gray]	[blue]		[red]		[blue]		RAINY! Stopped power.
Little Plover	6/12	[blue]	[yellow]	[blue]	[blue]	[blue]	[yellow]	[gray]	[yellow]	[yellow]	[yellow]	murky	too shallow				QW system got very clogged, learned we need to go upstream, barely went anywhere
Allequash	6/13	[blue]	[yellow]	[blue]	[blue]	[blue]	[blue]	[gray]	[blue]	[gray]	[blue]	murky	too shallow			[blue]	went "wrong" direction
Plainfield Lake	6/19	barely varied 1.93-3ish?	[red]	[blue]	[blue]	[blue]	[blue]	[gray]	batt died	[gray]	[blue]	murky		?		[gray]	Temp battery died and we didn't notice
Long Lake	6/20	? Range may have been set incorrectly	[yellow]	[blue]	[blue]	[blue]	[blue]	[gray]	batt died	[gray]	[blue]	murky		?			
Pleasant Lake	6/21	? Range may have been set incorrectly	[yellow]	[blue]	[blue]	[blue]	[blue]	[gray]	batt died	[gray]	[blue]	murky		?			
Mukwonago	6/27	[blue]	[yellow]	?	[blue]	[blue]	[blue]	[gray]	[gray]	[gray]	[blue]	murky				[gray]	comparing lab chem to probe, EC variability may be understated using the probe. dropped phone
Marengo	7/17-7/18	All zeros? Something was wrong	all zeros??	hard to know if we can trust. Around 10, spikes..	[yellow]	[blue]	[blue]	[blue]	[blue]	[gray]	for 1st portion, not second	for 1st portion, not second		[blue]	[blue]	[gray]	Did two stretches- upstream and downstream. Upstream used canoe, downstream used miniboat.
Grant	7/25	[blue]	[red]	[red]	[blue]	[blue]	[blue]	[blue]	[blue]	[gray]	[blue]	[blue]			[blue]		
Little Plover	8/15	[blue]	[red]	[red]	something weird happened where it only read 100	1/3 of stretch	1/3 of stretch	[red]	1/2 of stretch	[yellow]	[blue]	[red]	[red]		also usgs		QW system got fried from water damage ; small boat
Allequash	8/16	blip from battery dying, but most of it is there	within acceptable range, generally don't trust	within acceptable range, generally don't trust	in the 20s?	[blue]	probe calibrated but read very weird. Death by natural causes	[gray]	[blue]	[gray]	[blue]	[red]		usgs		attempted to take seepage/mini Pz
Plainfield Lake	9/20	[blue]	[red]	[blue]	[blue]	[blue]	[blue]	[blue]	[blue]	[gray]	[blue]	[blue]		?		[gray]	
Long Lake	9/20	[blue]	[red]	[blue]	[blue]	[blue]	[blue]	[blue]	[blue]	[gray]	[blue]	[blue]		?		[gray]	
Pleasant Lake	9/21	[blue]	[red]	[blue]	[blue]	[blue]	[blue]	[blue]	[blue]	[gray]	[blue]	[blue]		?		[gray]	
Notes on Analyte			Inconsistent and unreliable. Despite best calibration efforts, this quality probe is really not intended for use in this manner.	Inconsistent and unreliable. Despite best calibration efforts, this quality probe is really not intended for use in this manner.		SC probe generally quite reliable	pH probe generally reliable, new one purchased at end of the summer					basically always pretty murky. Perhaps put thing at the front of the canoe would be better as it would be undisturbed					

Legend:
- [blue] good, full data
- [yellow] partial, varying quality
- [red] just bad or tried and failed
- [gray] N/A, didn't attempt to collect
- ? May be available from WDNR Central Sands Lake Study

2.2.2 Video coupled to data

One of the goals of this project was to combine video and data together. This should provide viewers with a more complete picture of the data and be more engaging. The hope is that outreach and understanding of the data could be enhanced. Videos of the Grant River and Plainfield Lake were created using RaceRender™ software. This software allows data to be synchronized with video so that the value of any data at any time and location is shown at the same time as the video corresponding to that same time and location. Figure 6 shows a screen shot of the Plainfield Lake video with associated data and underwater video. The video screen capture was taken where the dissolved oxygen and pH were near their lowest levels of the survey on the west end of Plainfield Lake. The underwater view at this location is mostly blocked by the floating algae. The complete video for Plainfield Lake and the Grant River are available from the WGNHS YouTube Channel, https://www.youtube.com/channel/UCwwucf9-W1qocovGx-uzs7w.
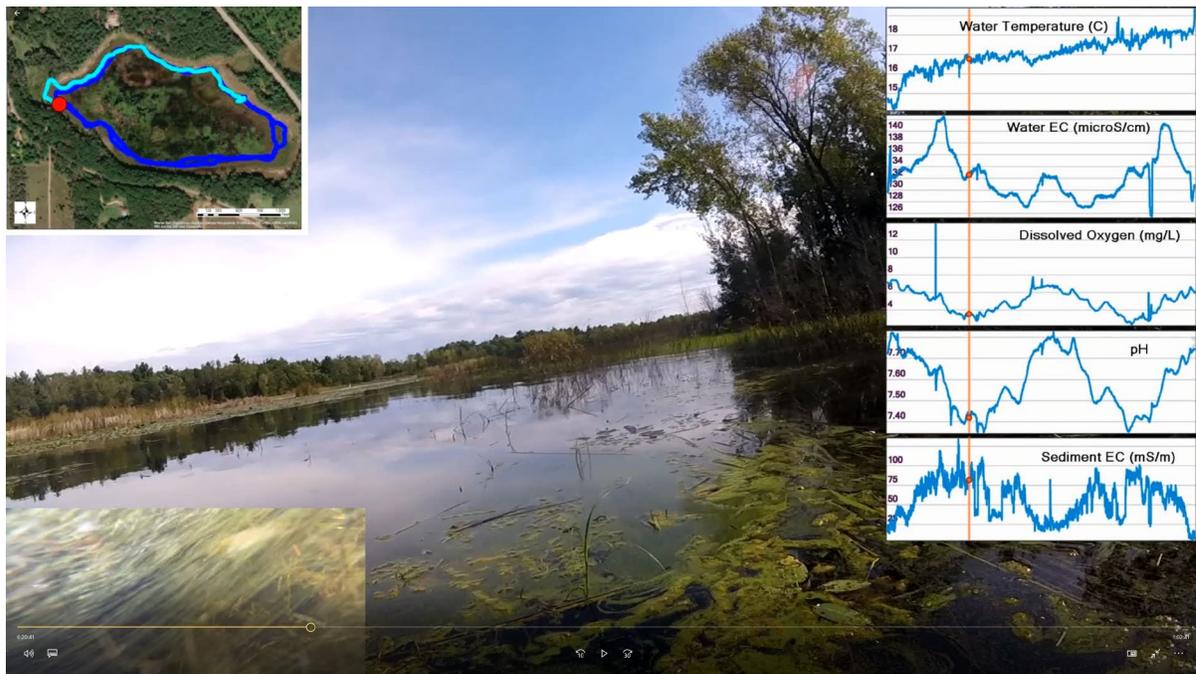

Figure 6. Screen capture of Plainfield Lake video in area of low dissolved oxygen and pH.

Chapter 3: Water Quality Data Collection Results

This chapter will first discuss the performance of each of the sensors used in the water quality apparatus as compared to alternative methods of water-quality data collection. We utilized a combination of laboratory samples, alternative water-quality sensors, and existing hydrologic knowledge related to our study areas in order to validate the water quality data collected by the stream float method.

Each stream or lake float included navigating the area of interest twice whenever possible in order to produce duplicate data for data cross-validation and trend analysis. For example, we collected data as we paddled upstream and then again downstream for streams, and circumnavigated each lake twice in opposite directions. We were limited in our ability to travel upstream on streams where the streamflow was too much to paddle against, so this was not possible in all scenarios. We were also limited at some locations from travelling downstream when the river was shallow and the bottom sediments became disturbed by the canoe activity, clogging our flow-through cell system. River systems are dynamic, and we do not expect that all parameters remain constant through time at a given location, but duplicating the length of study will help us understand temporal changes. For example, as thermal energy from the sun increases throughout the course of a morning we expect the temperature at a given point in a river to increase. Certain other spatial trends throughout a river are expected to remain constant, e.g., river temperature from a groundwater-fed portion of the river is consistently colder than that in losing portions of a river during the summer season. The remainder of this chapter will include examples for each parameter collected in which we were able to observe reproduced data and data trends. These examples contribute to validating the stream-float data collection method.

3.1.1 Temperature

We used a variety of external temperature measurements to validate those collected via the stream float method. Table 3 provides a comparison of temperature data collected via stream floats on June 13th and August 8th, 2018 on Allequash Creek, located in Northern Wisconsin, to temperature data logged continuously by the Allequash Creek (05357206) USGS stream gage (*USGS, 2019*). The location of the stream gage corresponds to the start and ending point of the stream float. The stream floats each took around two hours to complete so the comparison are two hours apart for each float. The temperature recorded at the stream gage at approximately the same time (the stream gage operates at a 15 minute sampling interval) as the temperature collected at that location during the stream float were compared. Corresponding results differed by 0.40-0.01° C. USGS data collection and publishing requires rigorous quality assurance plans, making USGS data a reliable metric against which to compare the stream-float data. It should be noted that the values collected in August were

physically closer to the USGS monitoring station than those collected in June by a couple of meters due to differing float trajectories. This difference in location may explain the smaller difference between the August stream float and USGS recorded values.

Table 3. Temperature comparison at beginning and end of Allequash Creek stream float with USGS monitoring station data.

Date/Time	Temperature (Degrees Celcius) Recorded at USGS stream gage 05357206	Time	Temperature (Degrees Celcius) recorded by Stream Float
6/13/2018 11:15 CDT	18.5	6/13/2018 11:12 CDT	18.0
6/13/2018 13:00 CDT	20.7	6/13/2018 13:03 CDT	20.37
8/16/2018 12:00 CDT	19.7	8/16/2018 11:56 CDT	19.79
8/16/2018 13:45 CDT	20.8	8/16/2018 13:38 CDT	20.8

3.1.2 Specific Electrical Conductivity

Specific electrical conductance is a measure of water's ability to conduct electricity. Higher levels of specific conductance correlate with higher concentrations of ions in the water. In addition to weekly sensor calibration (using 1440µS/cm and 100µS/cm standards), we validated our data collection using a calibrated handheld temperature and specific conductivity probe. We also compared selected results against laboratory sample results.

Figure 7 shows five specific conductance lab results from five hand samples collected throughout the duration of a stream float at the Mukwonago River on June 27th, 2019. The locations of data points were intentionally selected at points of specific hydrologic interest. We collected sample 1 directly upstream of the mouth of the Mukwonago River as it enters Lulu Lake, sample 2 was located in the central portion of the wetlands, sample 3 was located directly downstream of a somewhat heavily-trafficked road, sample 4 is directly downstream of a confluence with another contributing stream and sample 5 was collected from a spring discharge pool. The stream float values plotted include all those collected in the minute

following the water sample collection. The lab reported specific conductance falls within the range of values collected during the same duration by the stream float method.
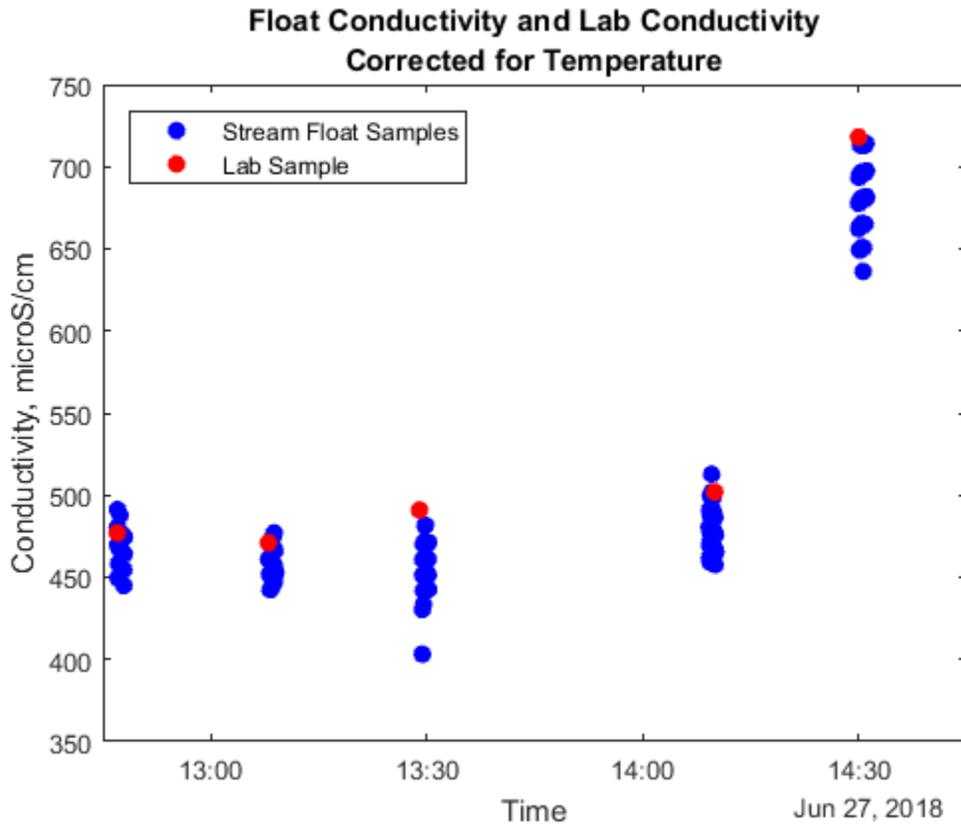
Figure 7. Lab reported specific conductivity compared with stream-float specific conductivity data collected during the 1-minute interval surrounding lab-sample collection.

We also compared recorded stream float conductivity values using a calibrated handheld specific conductance sensor during a stream float conducted at the Grant River on July 25th, 2018. The values recorded with the hand-held sensor, and the corresponding values collected during the stream float are recorded in Table 4.

Table 4. Comparison of specific conductance values collected on the Grant River via stream-float and with a comparable handheld sensor.

Location on the Grant River	Date Time	Hand-held Oakton sensor Conductivity	Stream float Conductivity
~70' upstream of Bluff Road	6/25/2018	588	528
~50' upstream of Klondyke Spring	6/25/2018	627	560-580
Klondyke Spring Discharge	6/25/2018	678	624
~10' downstream of Klondyke Spring	6/25/2018	645	580

Although the absolute values of specific conductance between these two sources differ, the overall trend between the different locations within the river is similar. Differences in the hand-held sensor reported values and those collected by the stream float could be due to a variety of factors. The measurements taken by the hand-held sensor did not sample the exact same parcel of water that ran through the flow through cell. For example, for the measurement taken at the point of discharge from Klondyke Spring, the sensor was placed directly in the water discharging from the spring, whereas the canoe measured water in the river directly adjacent to the spring discharge location.

3.1.3 pH

The pH sensor was calibrated to standards of 4, 7, and 10 on a weekly basis during the period of data collection. The pH sensor maintained its calibration well throughout its field use, i.e., when the sensor was returned to calibration standards following field use, it consistently read expected values. Another method of data validation is showing repeatability of data collection. As previously mentioned, each lake or stream location was traversed twice when possible to produce duplicate sets of data on which to compare results. Figure 8 is one such example of pH results collected at Plainfield Lake, located in the central sands region of WI, in which pH trends show a repeated spatial trend throughout the lake, despite varying by only

a relatively small range of values (7.35-7.82).   Although the Atlas Scientific pH probe has a life expectancy of ~2.5+ years, we found that high frequency use of this probe in a field environment resulted in a shorter shelf life of approximately 6 months. The probe continued to respond to calibration practices, but drifted during use to values beyond the reasonable range for the environments in which we were utilizing it. The sensor was stored in the correct method for short and long term-storage conditions, but the reduced shelf life may have been related to intensive, continuous use during the 6 months of data collection.
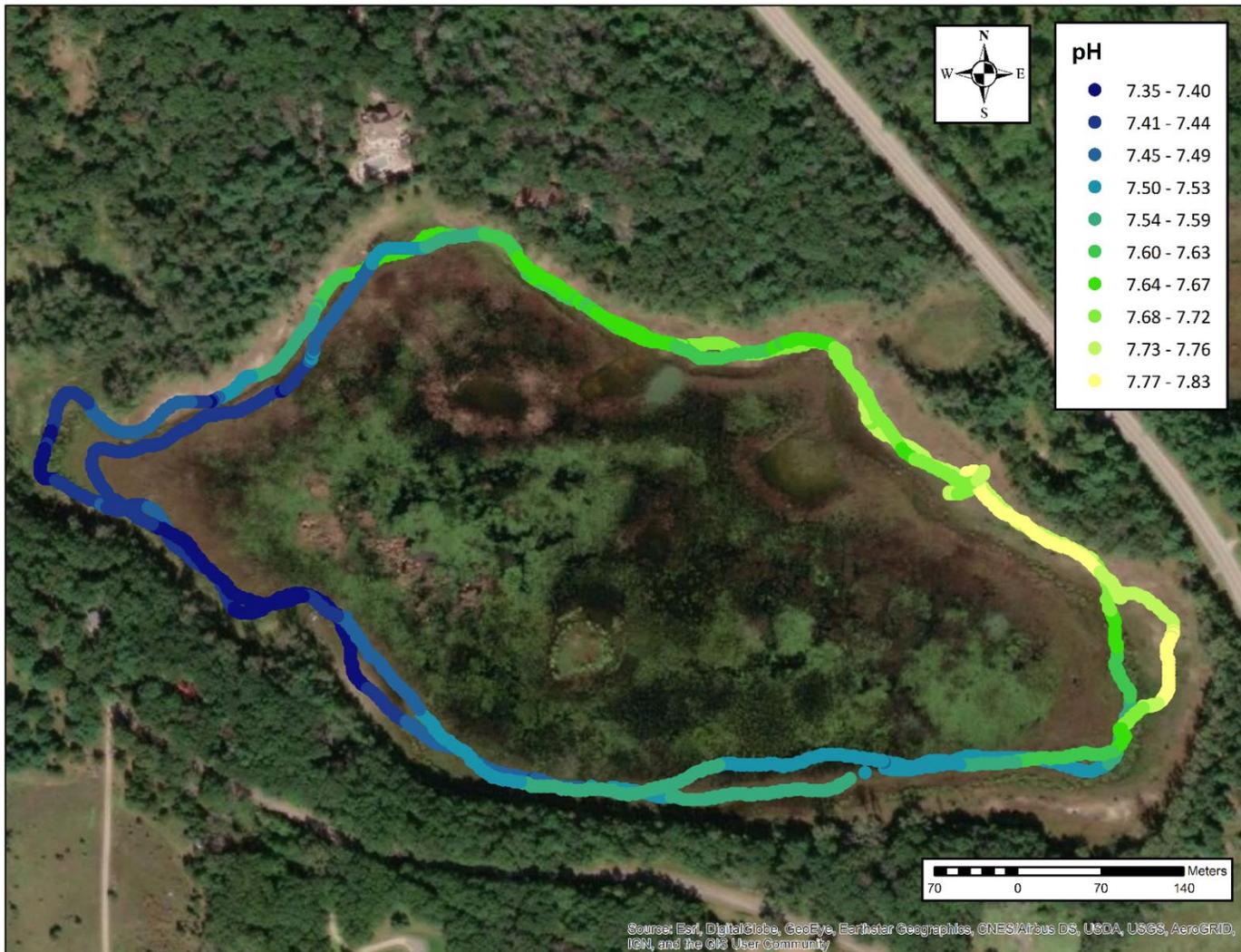
Figure 8. Results of pH data collected at Plainfield Lake on September 20th, 2018, showing a repeated spatial trend throughout the lake.

3.1.4 Dissolved Oxygen

Dissolved oxygen (DO) was recorded as a percent saturation, and converted to mg/L using simultaneously recorded temperature and known solubility of dissolved oxygen at a given temperature. Dissolved oxygen, unlike some other conservative water quality parameters, must be measured in-situ as a sample will equilibrate with its surroundings after data collection. Dissolved oxygen was not measured in-situ by an alternative method during any of the stream or lake floats conducted. In order to assure the quality of the DO data, we checked the probe dry in air to ensure it read at 100% saturation before and after data collection. We also assessed the quality of the dissolved oxygen sensor by observing repeated patterns within a given study area. Figure 9 represents dissolved oxygen (reported in mg/L) with a clearly repeated spatial pattern collected at Plainfield Lake, WI.
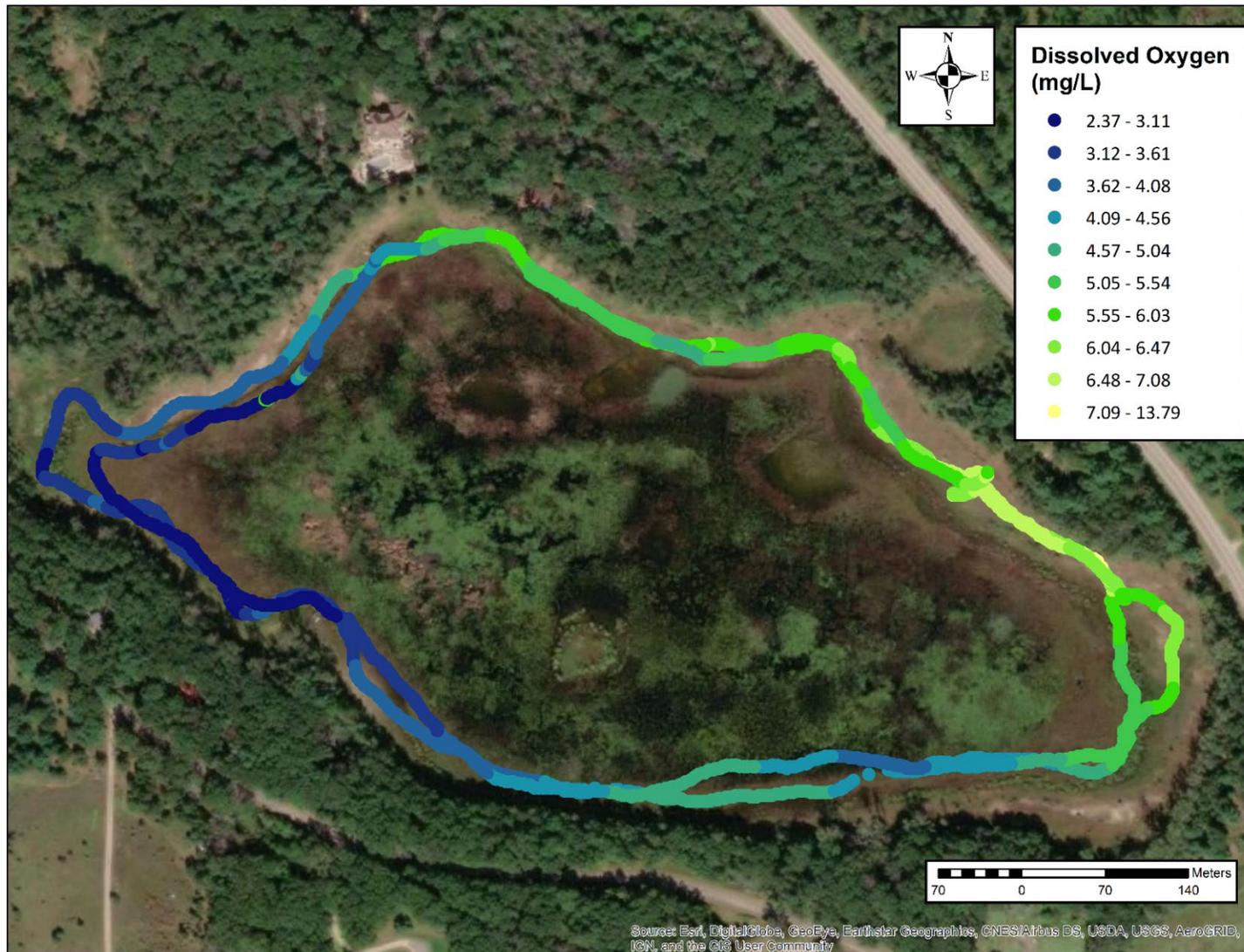
Figure 9. Dissolved oxygen results collected at Plainfield Lake on September 20th, 2018.

3.1.5 Chloride and Nitrate

The nitrate and chloride probes were consistently the most difficult probes to utilize during the stream floats. Despite daily calibration to high (50ppm) and low (1ppm) standards, the probes would frequently drift beyond a reasonable range of values (most frequently to values >100ppm, which for nitrate would be nearly unheard of in Wisconsin surface waters, and unlikely for chloride as well). We verified that the values were drifting because the sensors would continue to read erratically when returned to calibration solutions after the stream float. There are limited examples from our data collection in which the chloride and nitrate read reasonably. One such set of data was collected at the Mukwonago River on June 27th, 2018. Figures 10 & 11 show the time series of nitrate and chloride respectively collected during the stream float, with lab reported values of nitrate and chloride along the stream length. The stream float values shown in the figures include those recorded within a minute of the lab sample being collected. The WEAL lab reports total Nitrogen, which includes nitrate (NO_3^-) + nitrite (NO_2^-). We expect nitrite to be largely negligible in most hydrologic environments, so total Nitrogen can be used for basic comparison to nitrate in this setting. The stream-float values represent similar trends to those indicated by the lab samples or both nitrate and chloride. The absolute values for stream float collected chloride are slightly higher than the lab reported values for 3 of the 5 samples.
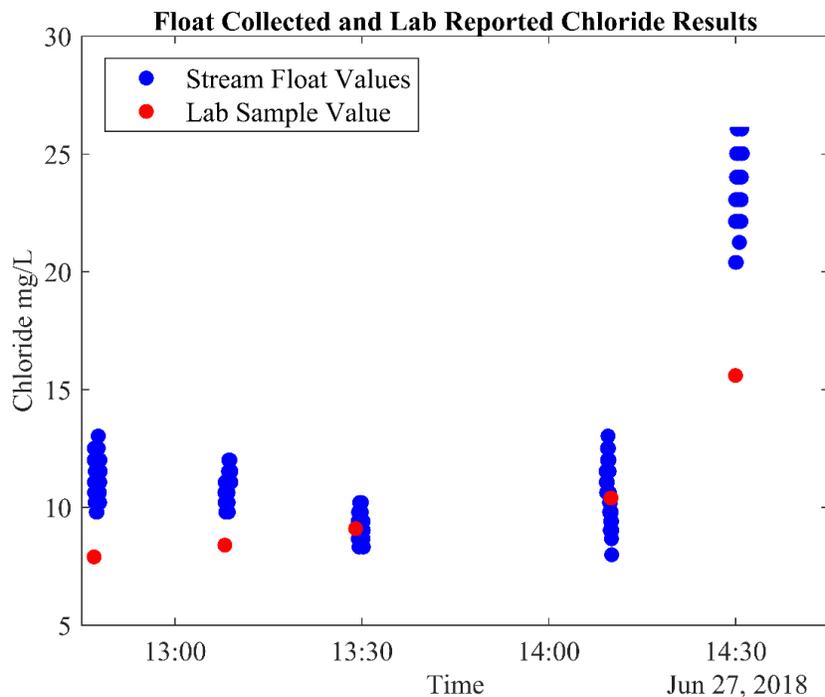

Figure 10. Lab-reported chloride compared with stream-float chloride data collected during the minute interval surrounding lab-sample collection at the Mukwonago River.
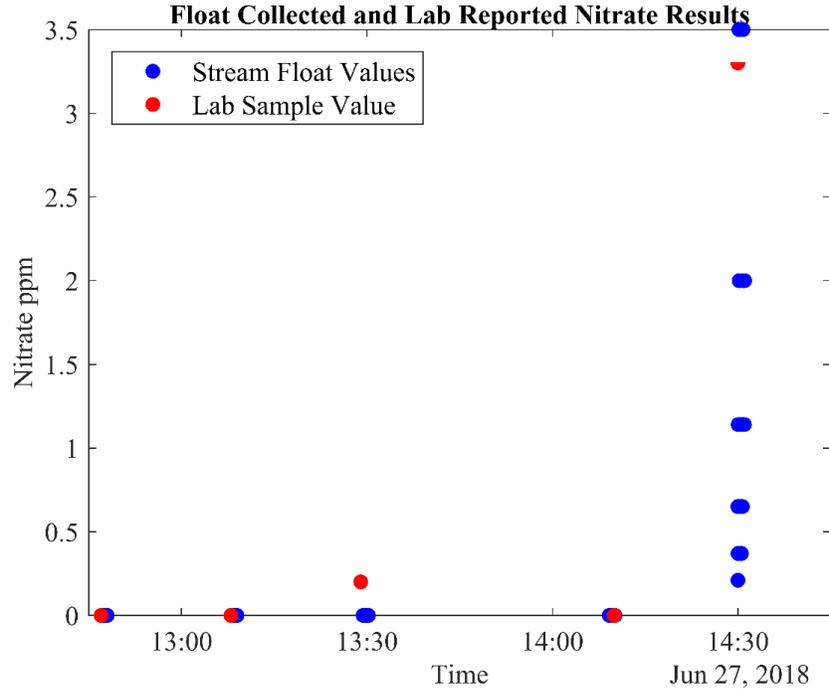
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Figure 11. Lab-reported nitrate compared with stream-float nitrate data collected during the minute interval surrounding lab-sample collection.

One hypothesis to explain the inconsistent performance of the nitrate and chloride probes relates to temperature variations of in-situ environments. Vernier, the sensor manufacturer, calibration protocols recommend calibration at a temperature similar to that of the sample you are measuring, however this is difficult to do when the "samples" (stream water) experience temperatures that vary by 20 degrees C. Due to the inconsistent reliability of the chloride and nitrate data results, many of the results we collected were not considered reliable. More robust sensors with temperature corrections applied, which will adapt better to the field environment, should be purchased in the future.

3.2 Utility of Method

The following portion of the chapter aims to answer the question: What further information can we gather about a stream or lake via floats (i.e., by collecting a few thousand data points across a multi-mile stream length over an hour or two) than we can from the more conventional method of collecting data at specified points of interest? In the following sub-sections, we discuss particular examples in which the increased spatial resolution collected by stream floats provides significant insight beyond that which could be obtained from point sampling. First, we provide a single parameter example from the Grant River in which this is observed. Finally, we provide a review of a full suite of water-quality data collected at the

Mukwonago River, in which I will discuss potential hypotheses as to how our collected data fit into the greater hydrologic setting in the area.

3.2.1 Finer data spatial and temporal resolution: Electrical Conductivity in Grant River

Collecting water quality data at a finer spatial resolution than conventionally collected provides more detailed spatial information about water quality health of a stream length. The following time series reflects water specific electrical conductivity collected via stream float on 7/25/2018 at the Grant River, located in the Driftless region of Wisconsin, compared with lab-reported values. The sample locations were intentionally chosen as points that represent environmental variation in the river system (Figure 12). Sample 1 was collected in Borah Creek, which is a cold, non-turbid headwaters stream. Sample 2 was collected below the confluence between Borah Creek and Roger's Branch, which together form the Grant River. Roger's Branch runs through an agriculturally-dominated area and is visually significantly more turbid than Borah Creek. Sample 3 was collected adjacent to an agricultural field growing corn. Sample 4 was collected directly downstream of a roadway, adjacent to a cow pasture. Finally, Sample 5 was collected downstream of a location of spring discharge.
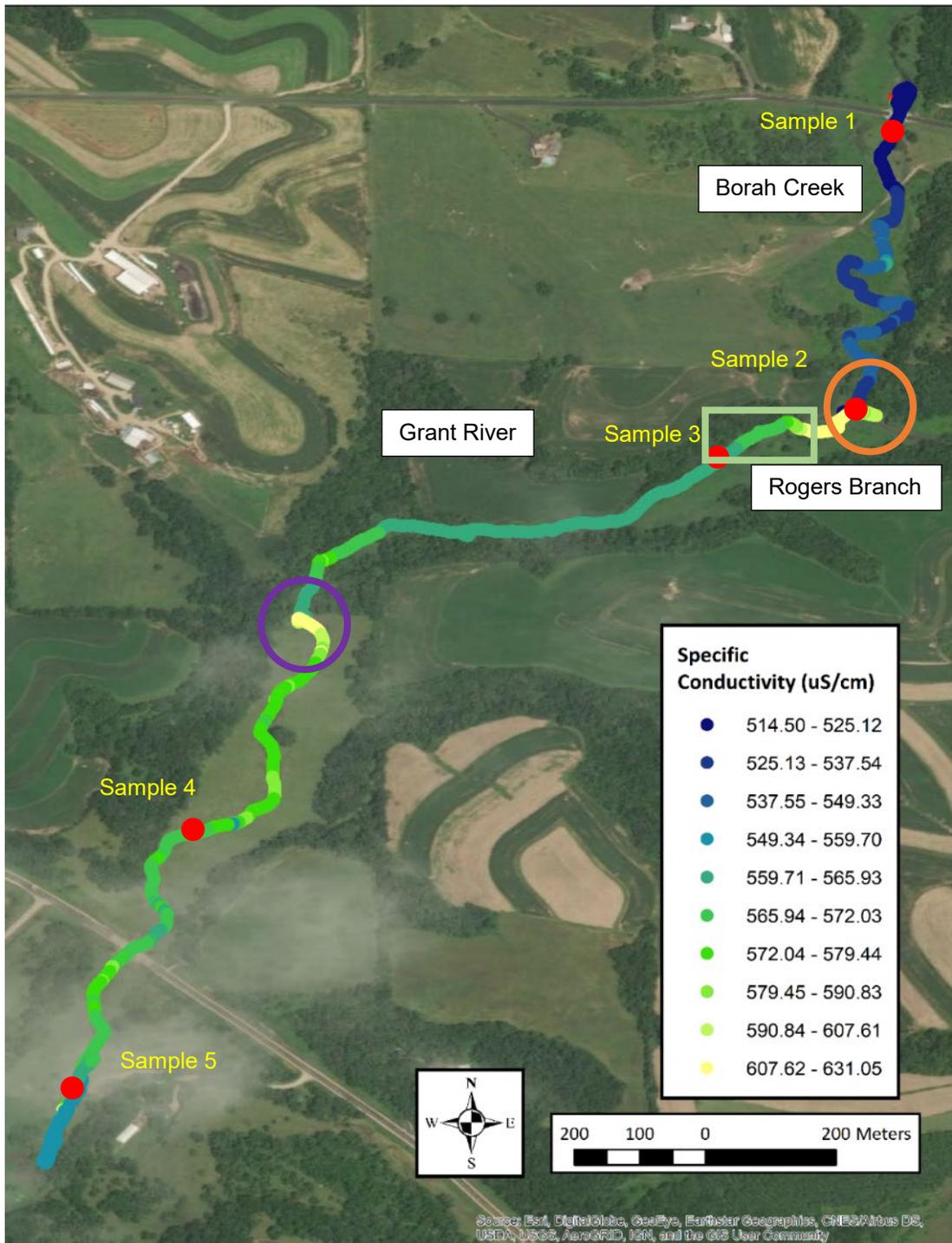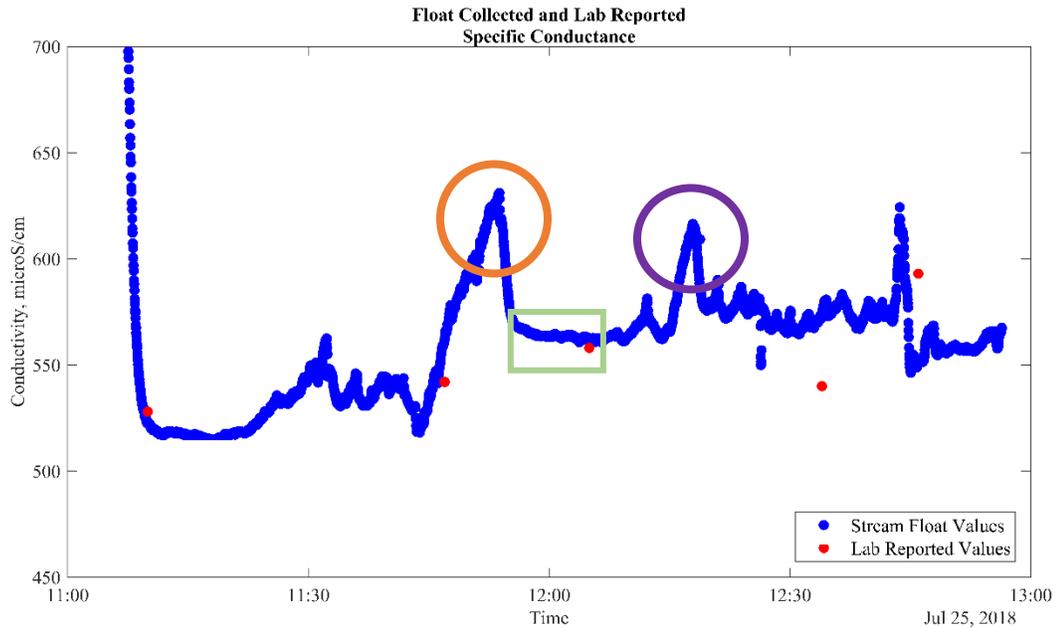
Figure 12. Specific conductance data collected via stream-float at the Grant River, WI, on June 27th, 2018.

Figure 13. Lab-reported specific conductivity compared with stream-float specific conductivity data collected continuously at the Grant River.

Despite the differing environmental factors of the lab sample locations, we observe little variation in electrical conductivity values across these locations, with values varying by <65 µS/cm. This may lead one to believe that there is overall little variation in electrical conductivity in the Grant River headwaters system. However, when these five sample points are placed within a more continuous time series, we observe a far more complex story (Figures 12 and 13). The overall range of values throughout the river reach is 125µS/cm. At least two additional peaks in conductivity can be identified.

When cross-referenced with their spatial locations, we see that the peak values in conductivity following collection of Sample 2 are observed when the canoe briefly paddled upstream into Roger's Branch (labeled in orange in Figures 12 and 13). Figure 12 also shows the full specific electrical conductivity results collected at Grant River. The peak circled in purple in Figure 13 is also circled in purple on the Figure 12 map. At this location, we identified a small creek (with an inflow of ~0.5 cfs) directly upstream from where the conductivity increased. When the source of this small creek is examined, there is a visible location of possible anthropogenic influence into this stream system. If the complete time series of data was not available, these points of interest for further investigation would likely not have been identified. Additionally, this time series and the spatial representation of the dense data set provide further insight to the effects of tributaries mixing, and the spatial scale at which mixing occurs. Following the peak in conductance at the confluence of Borah Creek

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and Roger's Branch, the Grant River stabilizes to a conductivity level around 560 μS/cm within about 75m downstream of the confluence. This location is boxed light green in Figure 12, corresponding to the light green box on the Figure 13 time series.

3.3 Mukwonago River Data Analysis

The following section of this thesis will synthesize stream float water quality data collected at the Mukwonago River on June 27th, 2019. First, I will briefly describe the hydrogeologic setting of the Mukwonago River in order to frame the context of these results. I will then describe the results of the stream float and discuss how they relate to the larger hydrogeologic understanding of the Mukwonago River's hydrologic and ecologic health, and provide more information about the stream than data collection by conventional methods would provide.

3.3.2 Mukwonago River Hydrogeologic & Climatic Background

The Mukwonago River watershed, located in southeastern Wisconsin in Walworth and Waukesha counties, is ecologically diverse and known for being one of the healthiest watersheds in southern Wisconsin (Figure 14). A subwatershed of the greater Fox River watershed, the Mukwonago River is 17 miles in total length and includes seven lakes in its basin. The portion of the river where we conducted our stream float is located in the Eagle Spring subwatershed between Lulu Lake and upstream spring "boils" indicated by the red rectangle in Figure 14. The Mukwonago River Basin is also an important natural resource to a number of stakeholders including state and local government and has been subject to intense regional urban planning in order to preserve the basin as a natural resource (SEWRPC, 2011). It serves as an important ecosystem for a variety of fish and plant species and is as an important resource for recreation such as canoeing and kayaking, fishing, hunting, and bird or wildlife viewing. Lulu Lake is considered an Outstanding Resource Water (ORW) by the state of Wisconsin, and 5.6 miles of the Mukwonago River are deemed an Exceptional Resource Water (ERW) (Mukwonago River Watershed Plan 2011).

Land-use in the watershed is predominantly rural (75%), which includes agriculture, wetland, woodland, open water and land, but increasing urbanization in the watershed is a major concern.
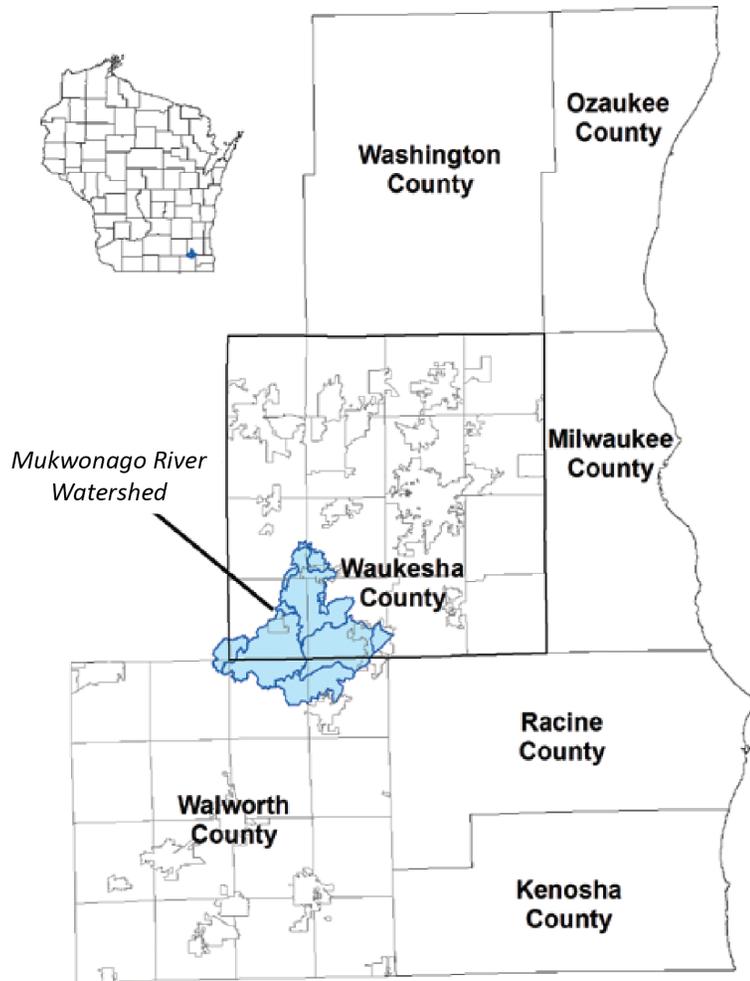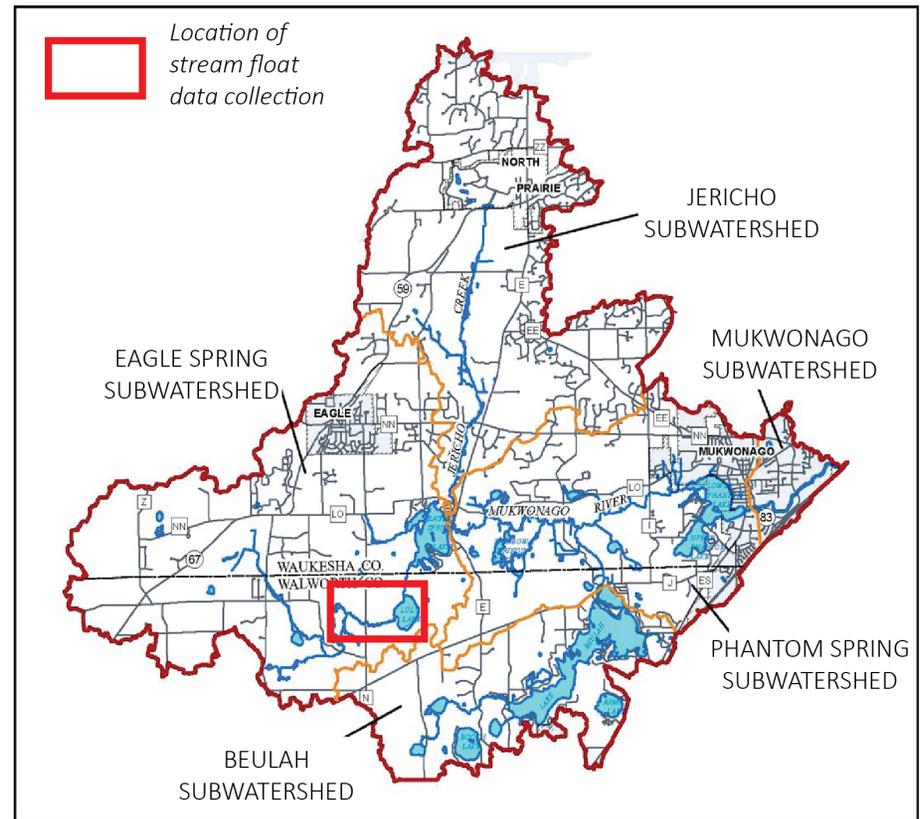
Figure 14. Mukwonago River Watershed with location of stream float data collection noted.

Specifically, urbanization in this region comes in the form of residential lands replacing agricultural or open land; it is anticipated that by 2035, 39% of land use in the watershed will be for urban land uses (*SEWRPC, 2011*). The hydrologic concern of this change is the creation of impervious surfaces in the watershed, which contribute to flooding and runoff. Other threats to the Mukwonago River include excessive nutrient input, surface runoff from urban and croplands, climatic threats to wetland water level stability, and invasive species such as Eurasian water milfoil and nonnative fish, the growth of which are spurred by shortened winters. Low dissolved oxygen content, in part spurred by temperature increases in the stream environment, threatens the survival of aquatic organisms.

The geologic framework of the Mukwonago River basin is characterized by surficial sand and gravel deposits underlain by dolomitic limestone. Groundwater flow in the Mukwonago River watershed is essential for sustaining lake and wetland levels, as well as providing base flow to the river and its tributaries (*Gittings, 2005*).

3.3.2 Mukwongo River Stream-Float Results (Geochemical parameters)

Results discussed in this section reflect the data collected while travelling upstream on the Mukwonago River on June 27th, 2018, between 11:50 and 14:40 CDT. The Mukwonago River is a complex river system with geological, climatic, and biological factors all contributing to variations in water chemistry throughout the system. In this section, I will identify some of these variations and potential hypotheses regarding factors contributing to geochemical patterns within the river stretch. This survey started in Lulu Lake to the east and ended in the northern spring pool to the west.

Temperature collected during the stream float ranged from coolest in the spring pool, between 11-12°C, to warmest in the lake, ranging between 21-22.5°C (Figure 15). Overall, the stream temperatures decreased in the direction of the spring pool. It should be noted that this trend was observed despite the effect that thermal warming would have had on the surficial stream temperature, as the air was continually warming as the day (and the stream float data collection) proceeded into the afternoon. One deviation from the overall observed warming trend between the spring pool and lake occurred where the smaller Crooked Creek meets the discharge from the spring pools, and the temperature decreases rather than increases. Crooked Creek could be groundwater fed, thus contributing colder temperatures to the river.

The pH pattern observed throughout the reach has a more complex pattern. The most basic pH level (around 8) is observed in Lulu Lake, which fits the understanding that it is a mesotrophic, hard water, alkaline lake (Figure 16) (*SEWRPC, 2011*). pH collected in the spring discharge pool is lower (around 6.95-7.00) than in the stream directly downstream of it. The most acidic results were found in the river nearly directly upstream from the lake.

This stretch of lower pH in the most downstream section of the river before the lake was repeated on the downstream portion of the stream float, so is not likely to be a sensor error.

pH levels in this area of the Mukwonago River are likely related to the presence of dissolved calcium carbonate from the underlying dolomitic bedrock delivered to the river via groundwater. Significant marl (calcium carbonate) deposits are visible along the bottom of the spring pool, directly adjacent to spring "boil" locations. At the spring location, where groundwater that is supersaturated with calcium and magnesium comes in contact with the atmosphere, calcite and magnesium precipitate due to rapid CO_2 degassing. As CO_2 degasses upon contact with the atmosphere, calcium carbonate precipitates to remain in equilibrium with CO_2, resulting in the pH of the groundwater itself increasing as the calcium carbonate decreases. The discharged groundwater is still acidic relative to the surface water and results in lower pH in the spring pool than in the downstream sections of the river. This pattern of behavior was previously described and studied in the form of a calcium carbonate budget at the nearby, downstream Eagle Spring Lake (*Hey and Associates, Inc., 2006)*. It would be important to collect nearby groundwater samples and analyze both ground and surface water samples for alkalinity in order to more clearly understand the changes in pH in the spring pool. Additional factors, such as biologic activity in the system, may be influencing pH variations. Relatively acidic pH levels (6.60-6.85) can be observed directly upstream of Lulu Lake.

Specific conductance across the river stretch ranged from 260 to mid-700s µS/cm (Figure 17). The highest specific conductance levels are observed in the spring pool. Increased specific conductance in the spring pool is likely driven by higher concentrations of calcium carbonate in groundwater inflows. Specific conductance in groundwater may be elevated as a result of increased ionic concentrations related to bedrock dissolution processes in the groundwater. Elevated specific conductance is observed below the confluence with Crooked Creek, downstream of the spring pool, further indicating that Crooked Creek has significant baseflow.

Dissolved oxygen is observed in its concentrations directly downstream of the groundwater-fed spring pools on the eastern portion of the study area, with the high values ranging from 12-16 mg/L, whereas the majority of the length traversed resulted in values ranging from 6.4-8.4 mg/L (Figure 18). The Wisconsin Administrative Code standard for dissolved oxygen in cold-water (trout) and warm-water streams is 6.0 and 5.0 mg/l respectively. 5.0 mg/l is roughly equivalent to 55% saturation (at 20°C). Some of the results collected in our stream float are near or beneath this standard. A smaller-scale variation is apparent in the westernmost portion of the stream survey, where the highest dissolved oxygen content is observed near the confluence the western spring pool, downstream of the north spring pool where the stream float terminated. Further downstream of this point, more fluctuations in

dissolved oxygen percent saturation are observed. This fine resolution of dissolved oxygen variation may be reflective of groundwater influx in a system where the cooler groundwater becomes highly oxygenated in comparison to the warmer surface water system (SEWRPC, 2011). Further hydrologic field investigation, such as the deployment of seepage meters and mini-piezometers throughout this smaller stretch would be required to confirm this hypothesis. However, these results demonstrate the utility of the stream float method for delineating locations of hydrologic interest. The dissolved oxygen concentration is higher in Lulu Lake than the majority of the river. We would expect a surficial lake environment to have higher dissolved oxygen as it is likely more affected by wind than the protected river system. Biological factors may also significantly influence the distribution of dissolved oxygen in the Mukwonago River system, and would be an important consideration for future investigation.

The only noted point of elevated nitrate concentration (~3.5ppm) is observed in the spring discharge pool (Figure 19). This nitrate is likely sourced from nearby agriculture that percolated into the groundwater system in the greater area, and then discharged to the spring pool feeding the Mukwonago River. Similar to nitrate, the most elevated chloride concentration is observed in the groundwater discharge pool (Figure 20). The stream-float sensors recorded values as high as 25 ppm in the spring pool, and the lab-reported value for this location was 16 ppm. Chloride can be attributed to urban run-off in the form of road salts that also could have travelled via groundwater to the spring pool. Elevated chloride concentrations can also be observed directly downstream from a couple of tributaries throughout the stretch, which provide guidance toward areas of potential groundwater inflow. Elevated nitrate levels are not as prevalent throughout the rest of the stream stretch; this can be attributed to the surrounding wetlands acting as a retainer of nutrients (*Johnston, 1991*) as groundwater flows through them toward the river. Chloride concentrations collected within Lulu Lake are within the range of previously collected samples (between 10-30ppm) reported by the Eagle Spring Lake Management District and SEWRPC (*SEWRPC, 2011*).

Overall, the spring pool, which is a well-known location of groundwater discharge, represents a change in most of the water quality parameters collected. The specific conductance, chloride, dissolved oxygen and nitrate all increased concentrations at the spring pool location, while the pH is more acidic than immediate downstream sections. As previously stated, these changes are likely caused by spring-fed groundwater coming into equilibrium with the atmosphere and waters from other tributaries.

Continued use of the stream-float data collection, coupled with alternative methods of physical and chemical hydrologic characterization, would provide increased understanding of the water chemistry fluctuations recorded by the stream float method. According to 2011 SEWRPC report, water quality projects in the watershed thus far have focused on either

stream or lake quality, rather than combining the two into one study. The stream-float method could provide a unique opportunity to combine stream and lake data throughout this watershed and others with a single, consistent method of data collection.
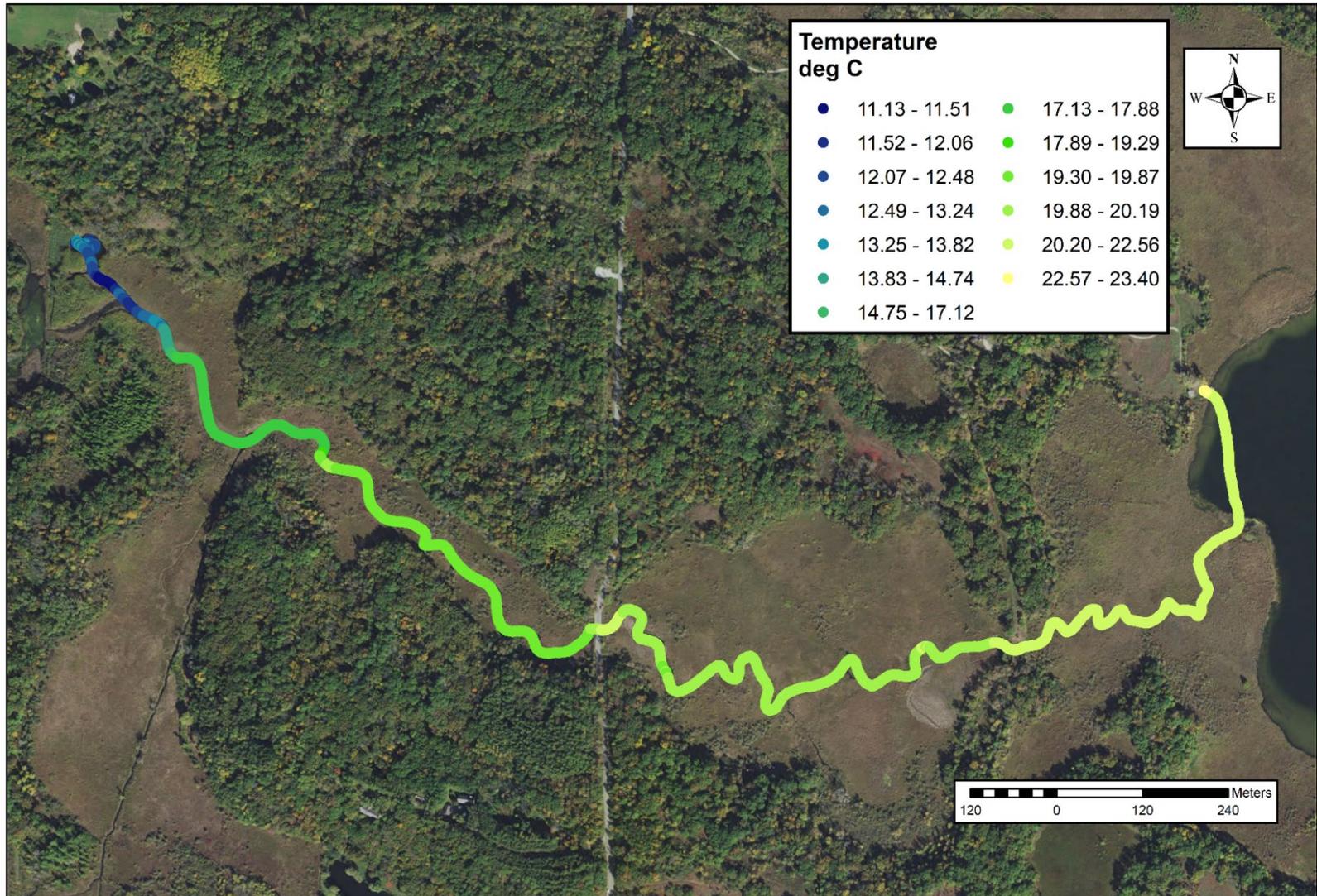
Figure 15. Temperature stream float results collected at the Mukwonago River, June 27th, 2018

Figure 16. pH stream float results collected at the Mukwonago River, June 27th, 2018

Figure 17. Specific Conductance stream float results collected at the Mukwonago River, June 27th, 2018.

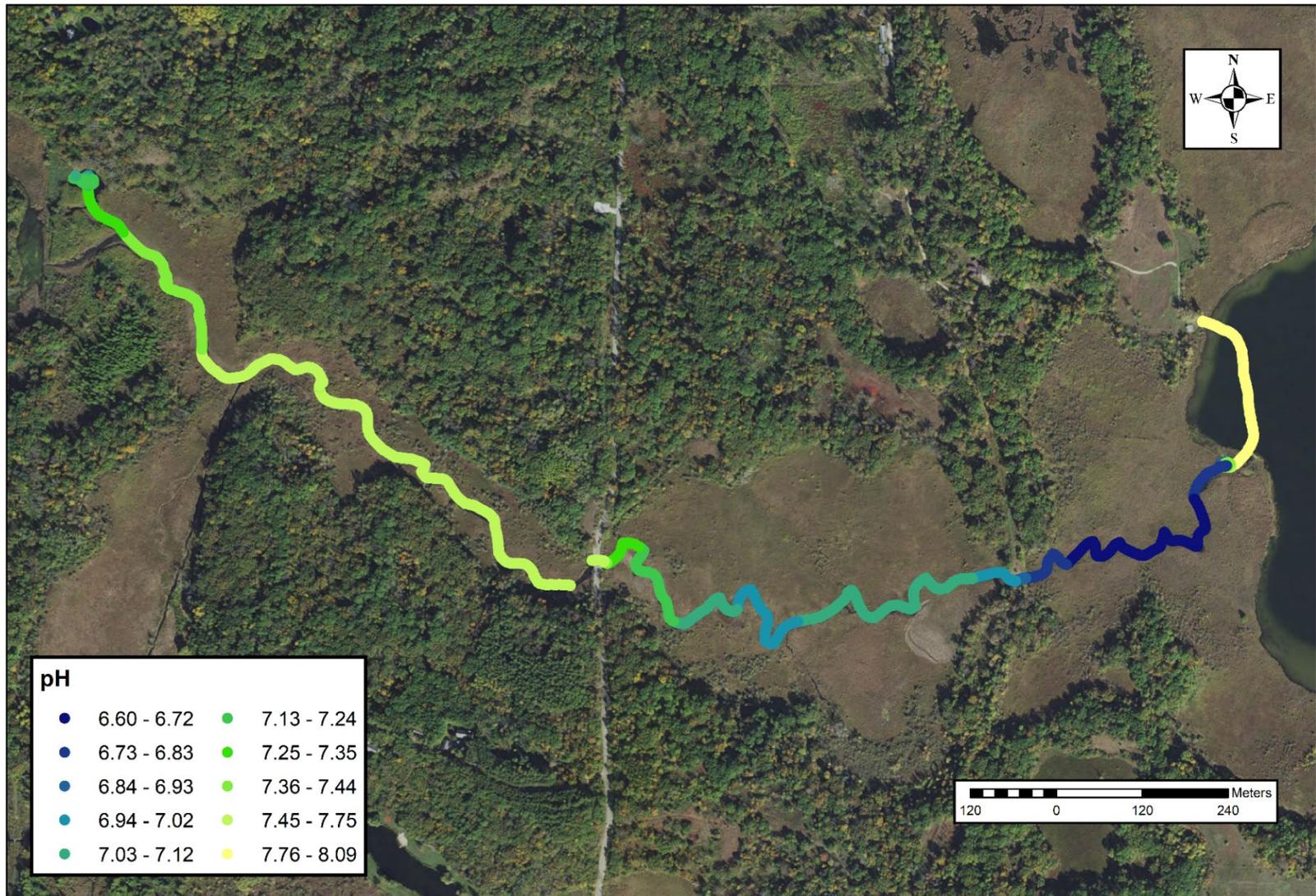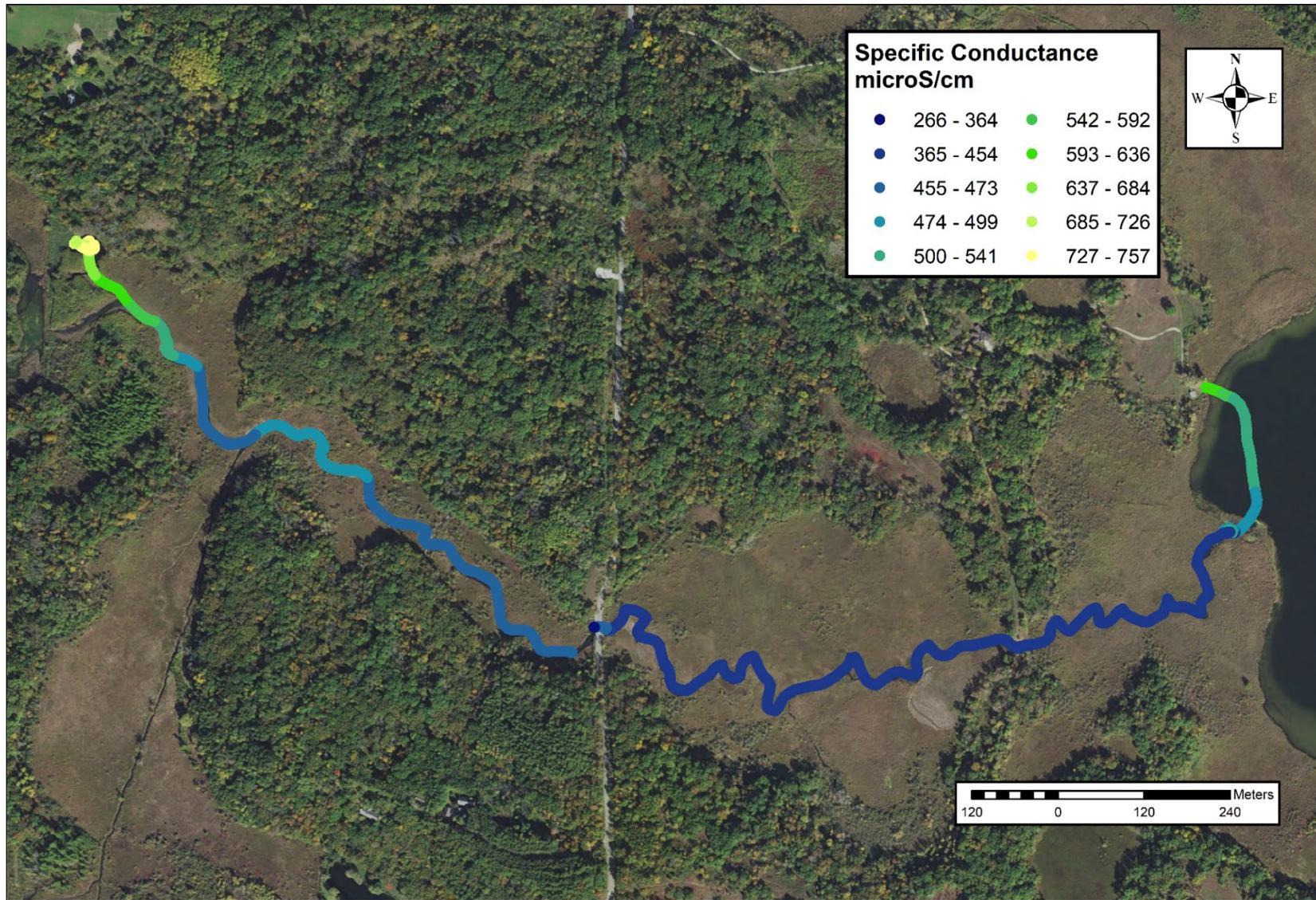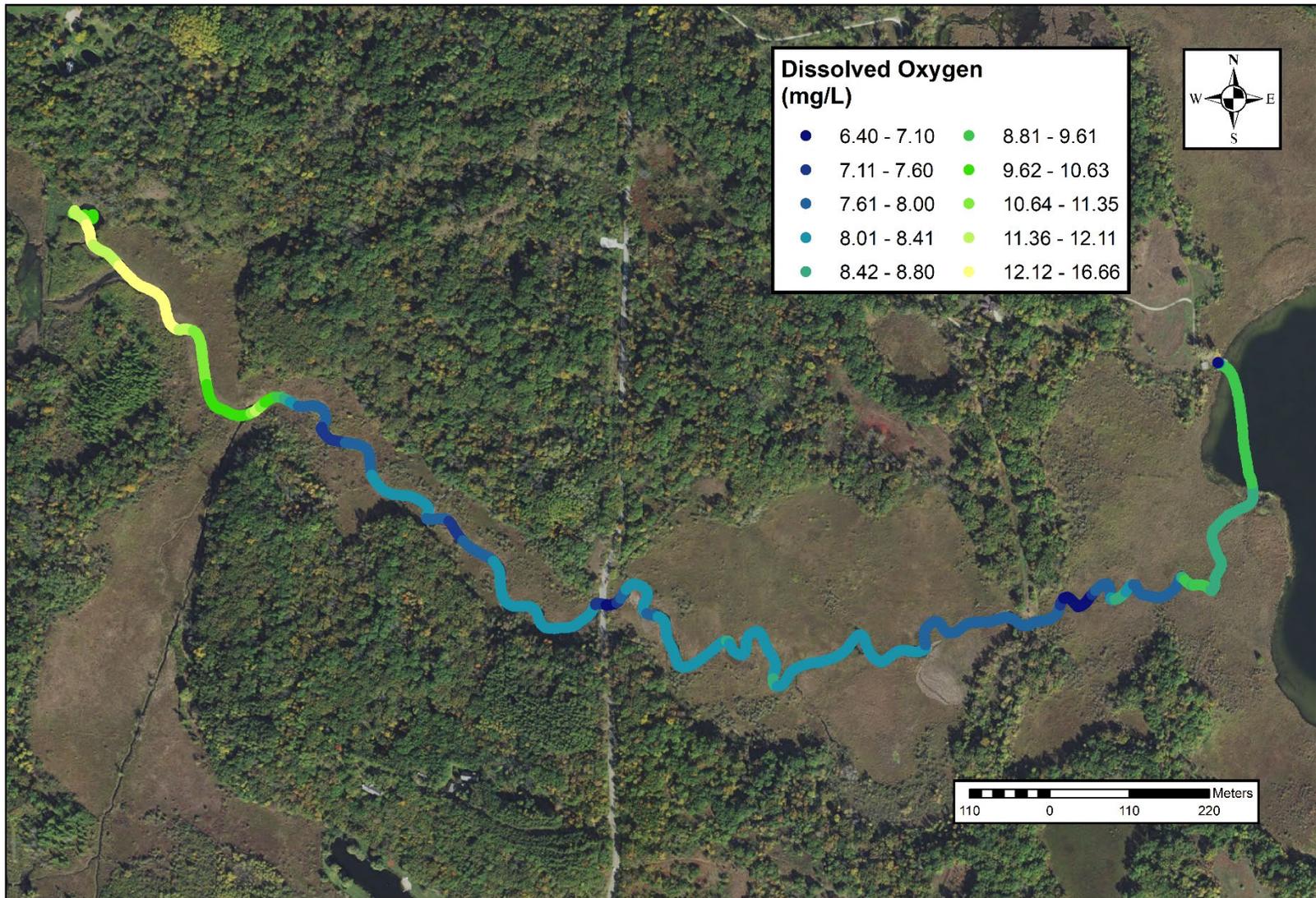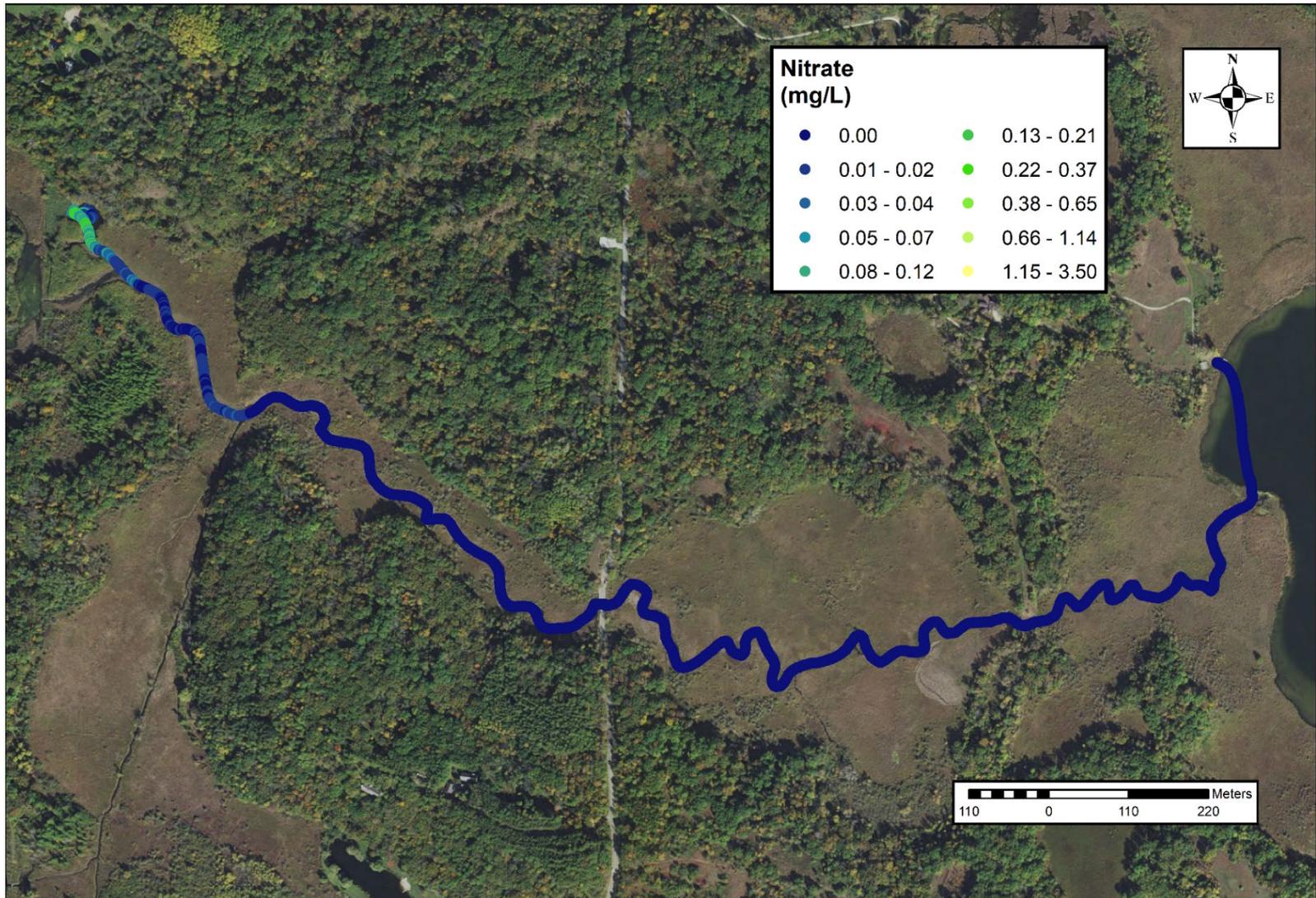*Figure 18. Dissolved oxygen stream float results collected at the Mukwonago River, June 27th, 2018*

Figure 19. Nitrate stream float results collected at the Mukwonago River, June 27th, 2018.
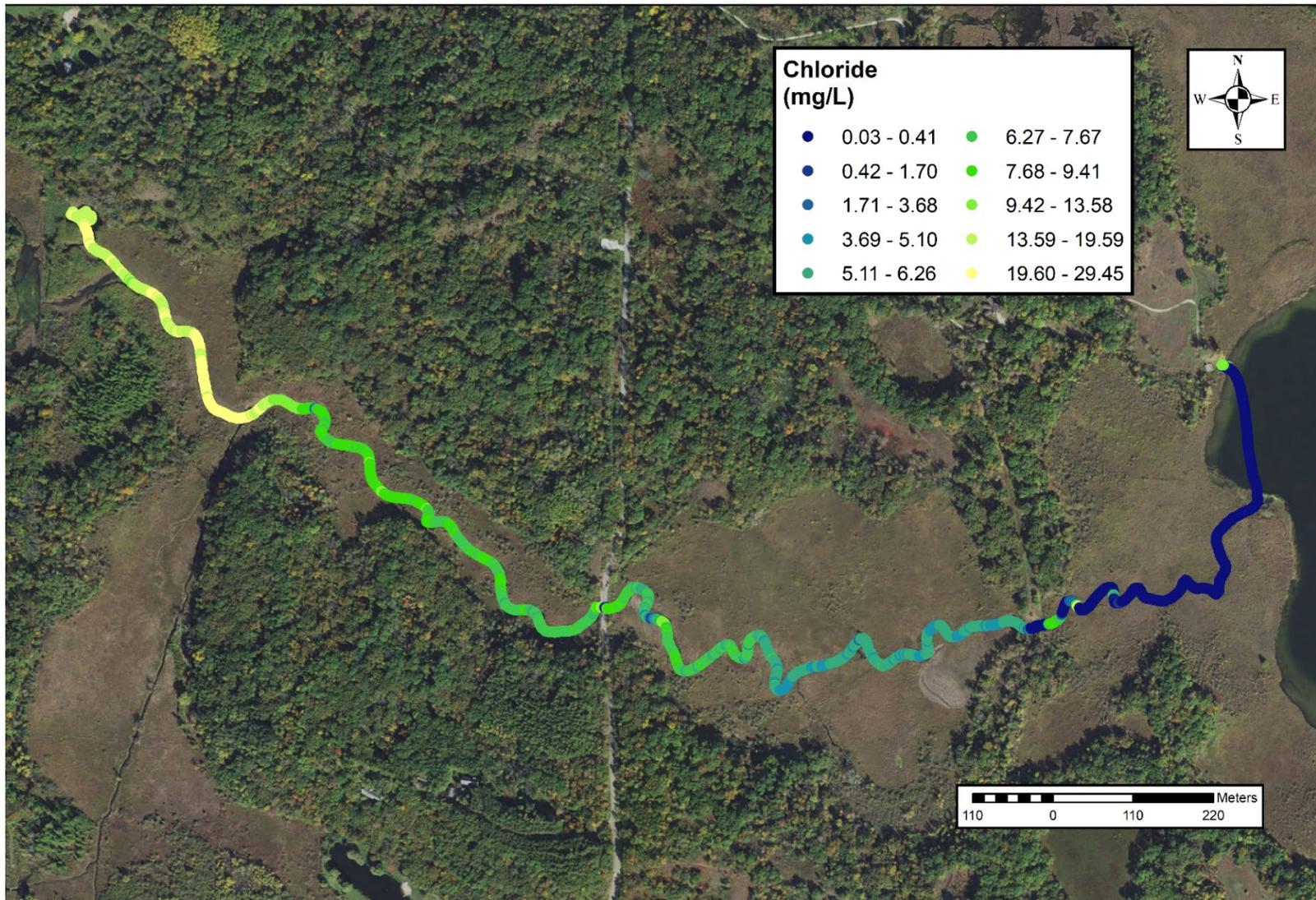
Figure 20. Chloride stream float results collected at the Mukwonago River, June 27th, 2018.

Chapter 4: Streambed Electrical Conductivity Calculation

This chapter will discuss an important application of the stream-float method in which we use a selection of collected parameters to calculate lake- or streambed electrical conductivity. First, we discuss in detail the method we used to make this calculation. We then provide examples from two study sites (Plainfield Lake and the Grant River) in which we compared calculated lake- and streambed sediment conductivity against physical samples from the sites. Lastly, We provide context about the importance that lake- and streambed electrical conductivity plays in understanding a study areas hydrologic setting.

4.1 Deriving Stream Bed Conductivity

Streambed conductivity is an important parameter to measure because it is indicator of lithology. Because the EM31 measures electrical conductivity of the entire underlying material, we used a layered-model approach to extract the lake- or streambed conductivity measurement. This approach is outlined in *McNeil, 1980*, and can be referenced for further detail. Our simplified model of the surfaces beneath the EM31 in the stream-float set up is illustrated in Figure 21. It consists of 3 layers: air, water, and sediment. The top layer of air is set consistently as six inches, as this was the average measured distance between the EM31 coils and the stream surface while the canoe was loaded with equipment. The electrical conductivity of air is set to zero, so no contribution to the signal should be derived from this layer. The layer of water has a depth determined by the Lowrance Hook5 depth finder. This device functions at depths greater than 1 ft, so for all values less than 1ft we assigned a water depth of 0.5 ft. This approximation is valid since the contribution to the overall conductivity signal from the water is less at shallow depths. The electrical conductivity of water was determined in the water quality apparatus. The bottom layer of streambed is modelled as one layer with an "infinite" thickness (to the effective penetrating depth of the EM31 oriented in the horizontal dipole position). The relationship between layers and their respective conductivity values as they contribute to the cumulative EM31 electrical conductivity reading (σ_{total}) is represented by the following equation (McNeill, 1980):

$$\sigma_{total} = \sigma_1[1 - R_H(z_1)] + \sigma_2[R_H(z_1) - R_H(z_2 - z_1)] + \sigma_3[R_H(z_2 + z_1)]$$

In this equation,

$$\sigma = electrical\ conductivity, with\ subscript\ indicating\ layer$$

$$z = normalized\ depth = (\frac{depth}{intercoil\ spacing})$$

$$R_H = relative\ influence\ of\ signal\ as\ a\ function\ of\ depth$$

$$R_H(z) = \sqrt{4z^2 + 1} - 2z$$

Because the electrical conductivity of the streambed, σ_3, is the only unknown, we can solve for it. The different variables are shown in Figure 19. The intercoil spacing of the Geonics EM31 is 3.7m. Calculations and results of electrical conductivity are reported in units of milliSiemens/meter (mS/m).

Layer 1: air	Depth = 6 inches (constant) Z_1	Conductivity = 0 (constant)
Layer 2: water	Depth = measured continuously by depth finder Z_2	Conductivity = measured continuously by QW apparatus
Layer 3: streambed	Depth = remaining depth of measurement by EM31	Conductivity = unknown variable
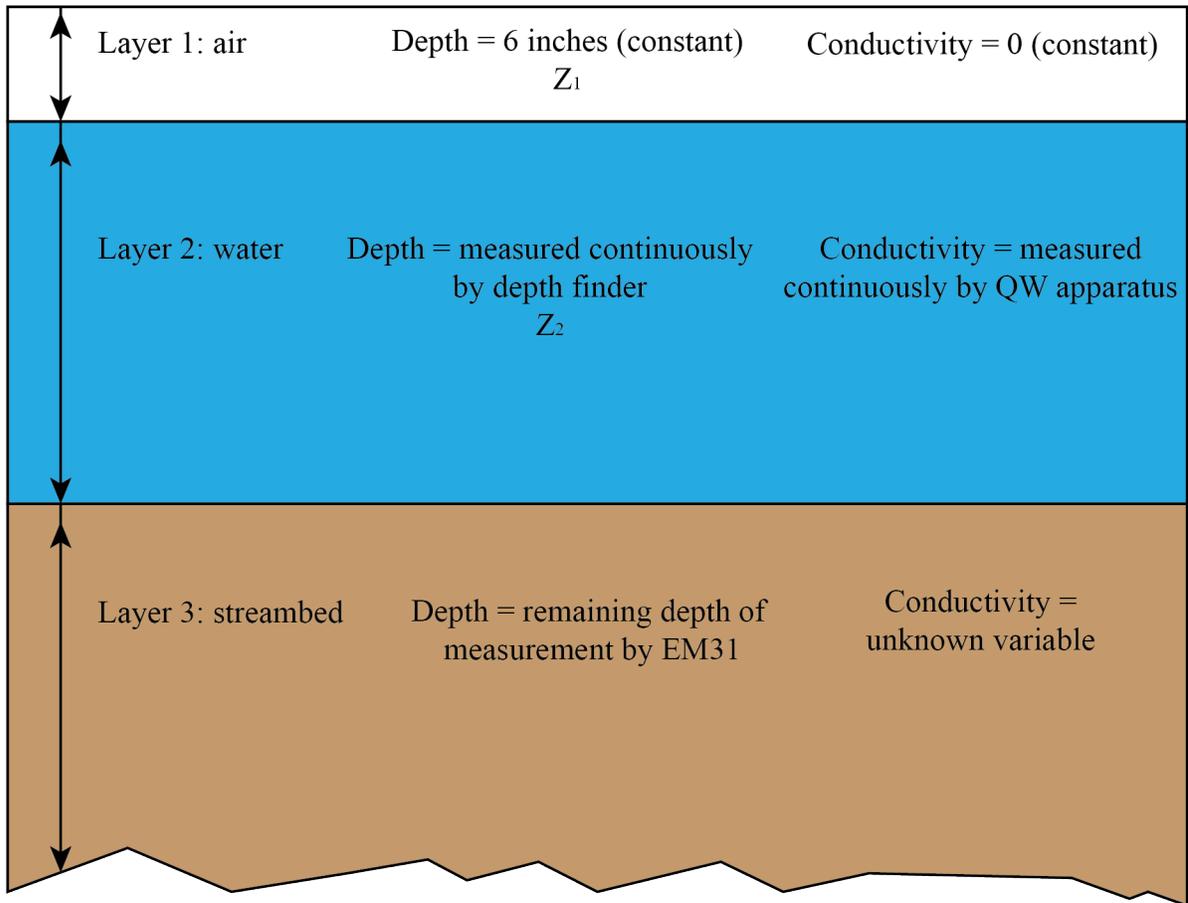
Figure 21. Conceptual of underlying layers contributing to EM31 signal.

4.1.1 Factors of Uncertainty

It is important to acknowledge the various sources of error that contribute to the overall uncertainty of our sediment electrical conductivity calculations. The first, and perhaps most significant, source of error is in the inaccuracy of the depth finder at low depths. The depth finder is not accurate at depths lower than ~0.3 m (1 ft) and reports these depths as zero. For depths reported as zero, a depth of 0.15 m (0.5 ft) was applied. This assumption leads to an overestimation of sediment electrical conductivity where the depth was underestimated, and vice versa. Another source of uncertainty comes from the fluid specific conductance

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measurement. We apply the value recorded by our water-quality sensor to the entire layer of water. In reality, variation in specific conductance likely exists within the water column, especially across greater depths. There is additional error in the calculation due to the various GPS devices utilized. The depth finder, water-quality apparatus, and EM31 each contain their own GPS unit, resulting in three sources that are linked on location in order to assign the calculated electrical conductivity to a location. The compounded errors of these sources were a primary motivation in the following case studies where physical sediment samples were collected and classified to validate the variations in sediment electrical conductivity.

4.3 Plainfield Lake Results

We conducted a stream float at Plainfield Lake, located in the Central Sands region of Wisconsin, on September 20th, 2018. Using the method listed above, we utilized the fluid electrical conductivity, depth of fluid, and EM31 ground conductivity results to calculate the electrical conductivity of the near surface lakebed sediments. The results from this calculation are spatially represented in Figure 22. Results indicate spatial variations in electrical conductivity across the lake; the highest values of electrical conductivity were calculated on the western edges of the lake and lower values were calculated on the eastern portion of the lake. In order to provide validation of the lakebed electrical conductivity calculation, we collected lakebed sediment samples from the near surface on May 28th, 2019. The points of sediment data collection are indicated by the colored triangles in Figure 22. The points of data collection were chosen to represent the different zones of electrical conductivity represented across the lake. Ideally, the sediment samples would have been collected exactly at the locations where the stream float was conducted, however, the depth of water in Plainfield Lake rose 3 ft between September 2018, when the stream float data were collected, and May 2019, when the sediment samples were collected making collection along the original transect difficult (*USGS NWIS Lake Gage, 05401067*). We collected sediment samples from approximately 6 inches to 1ft of depth below surface using a 2 in diameter soil auger. Sediment samples were visually classified using the Unified Soil Classification System. Results of this classification are listed in Table 5.
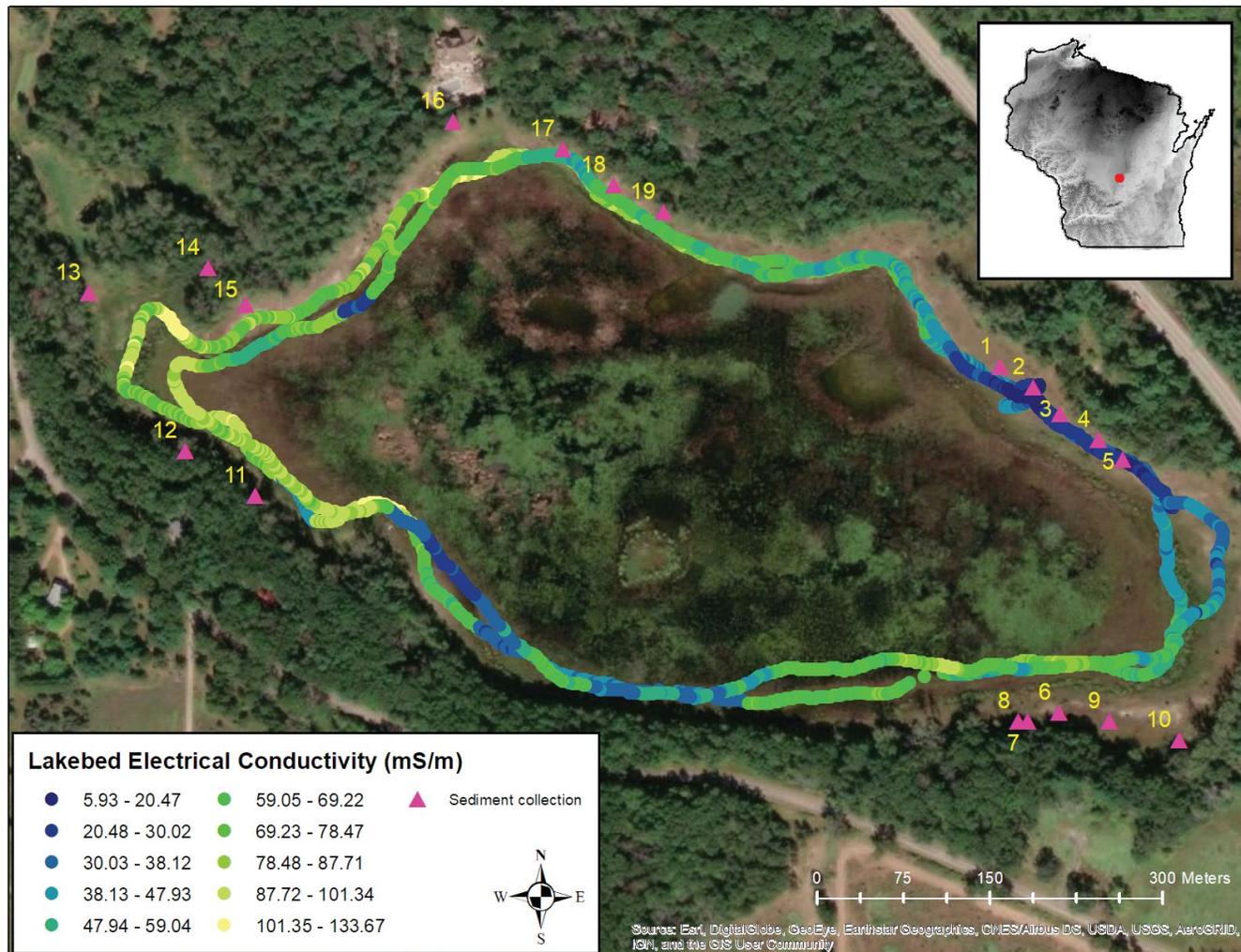
Figure 22. Calculated lakebed electrical conductivity results and locations of lakebed sediment collection.

Table 5. Soil Classifications and compositional break down of sediment samples collected at Plainfield Lake.

Sample	Average Nearby Sediment Electrical Conductivity	Soil Classification using the Unified Soil Classification System	% Gravel	% Sand	% Fines (Clay & Silt)	% Organic Material	Spatial Soil Grouping
1	48.52	Poorly sorted sand with gravel	15	75	5	5	1
2	26.02	Poorly sorted sand with gravel	15	75	5	5	1
3	26.19	Poorly sorted sand with gravel	25	65	5	5	1
4	26.65	Well sorted sand with gravel	5	75	10	10	1
5	32.60	Well sorted sand	10	75	5	10	1
6	79.09	Well sorted sand	5	75	5	15	2
7	71.71	Well sorted sand	5	75	5	15	2
8	63.35	Well sorted sand	0	90	0	10	2
9	64.00	Well sorted sand	0	85	0	15	2

10	51.38	Well sorted sand	0	80	10	10	2
11	63.32	Poorly sorted sand	10	75	5	10	3
12	85.34	Poorly sorted sand	10	75	5	10	3
13	87.25	Organic soil with sand	0	75	10	15	3
14	99.57	Organic soil with sand	0	50	30	20	3
15	68.84	Well sorted sand	5	80	5	10	3
16	81.48	Poorly sorted sand	20	65	10	5	4
17	68.21	Well sorted sand	10	75	10	5	4
18	72.78	Poorly sorted sand	20	65	10	5	4
19	60.82	well sorted sand	5	80	5	10	4

Overall, lakebed sediment samples are characterized as very sandy, containing 65-90% sand with varying smaller percentages of gravel, clay and silt, and organics. A ternary plot was used in order to interpret these data because simple correlation plots between electrical conductivity and a single variable were inconclusive. Figure 23 represents the samples plotted on a ternary diagram with the color of the dots represented as the calculated electrical conductivity of the sediment nearest to the sample point. The ESRI ArcGIS spatial join tool was used to calculate a spatial average of a discrete number of points along the float path closest to the sediment collection point in order to assign the point an electrical conductivity value. Percentages in Table 5 were slightly offset to generate Figure 23 so that samples of the same composition were not superimposed and so that all sample points would be visible on the plot. Although all of the samples collected at Plainfield Lake were predominantly sandy, and nearly all of the points are stationed in the sand and gravel dominated corner of the ternary diagram, we can still observe a relationship between soil composition and electrical conductivity. The samples with the highest gravel content are also the samples with the lowest electrical conductivity. The sample with the highest electrical conductivity (the red dot in Figure 23) contained no gravel and only 50% sand (15% less than any other sample), and the highest silt, clay and organics content.
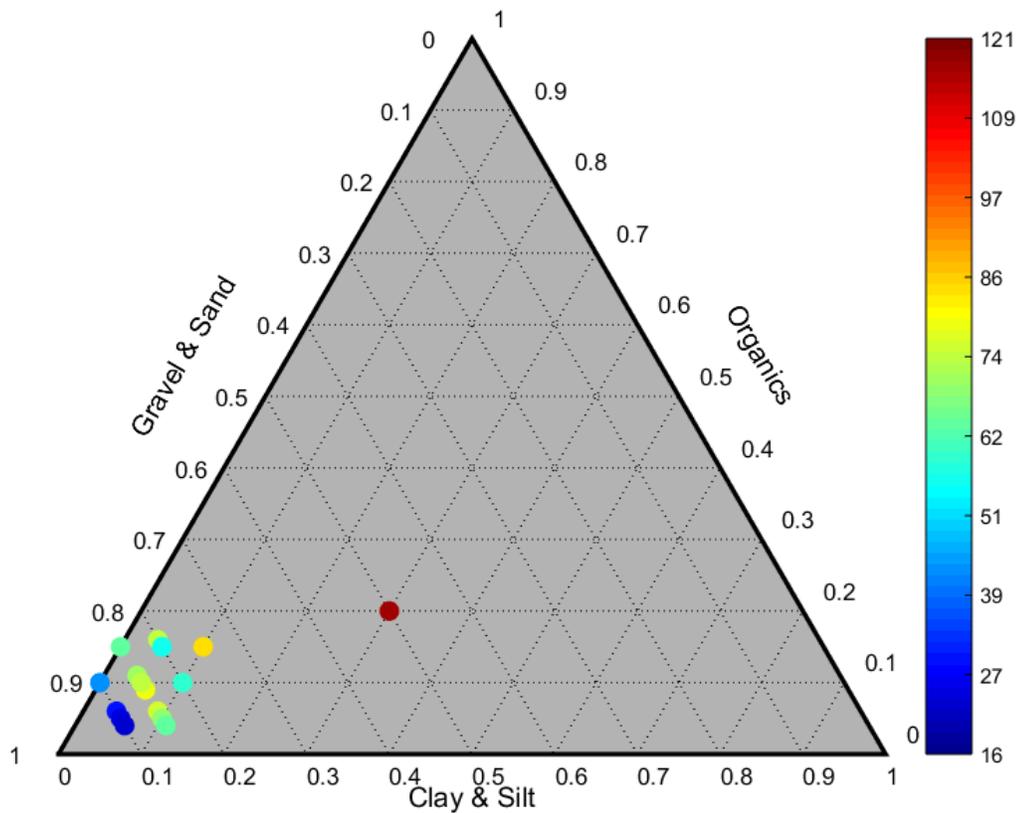
Figure 23. Ternary diagram of soil composition of all samples collected at Plainfield Lake with color indicating calculated electrical conductivity (mS/m) near the sample.

A factor not included in this analysis that may be affecting the stream- or lakebed electrical conductivity is the fluid within the sediments. While we measured the electrical conductivity of the overlying fluid near the surface of the lake, the fluid within the sediment itself will not necessarily follow the same trend as the surficial water electrical conductivity. This was observed at the spring discharge at the Mukwonago discussed earlier and may be occurring here as well. Furthermore, the electrical conductivity of the fluid within the water column may vary to some degree. Assigning the fluid electrical conductivity for the entire water layer within this calculation is an assumption within the model. Plainfield Lake is generally considered a flow-through lake under typical hydrologic conditions (*Lippelt, 1981*), with groundwater flowing from the northeast. Because of its nature as a flow-through lake, it is likely that the fluid electrical conductivity within the sediments may differ spatially around the lake. Samples collected on the north and northeast sides of the lake are likely groundwater dominated, as that is the gaining portion of the lake, and other sections may be a mix of ground/surface water or dominated by surface water.

4.4 Grant River Results

We conducted a stream float in the uppermost portion of the Grant River, located in the driftless region of Wisconsin, on July 25th, 2018. Using the method described above, we utilized the fluid electrical conductivity, depth of fluid, and EM31 ground conductivity results to calculate the electrical conductivity of the near surface lakebed sediments. The results from this calculation are shown in Figure 24. We collected sediment samples from approximately 6" to 1' depth below surface using a 2" diameter soil auger. At certain locations, the gravel grain size was too coarse to collect with the 2" diameter soil auger, so we manually scooped samples from the first 6" of streambed depth, or characterized the sediments from visual observation in the field. Pink triangles on the map in Figure 24 represent locations of sediment collection. The sample locations represent a full range of calculated electrical conductivity values throughout the study area. We visually classified sediment samples using the Unified Soil Classification System (USCS). Results of this classification are listed in Table 6. The reported electrical conductivity values in Table 6 were determined as the closest electrical conductivity data point along the stream float transect. Clay, silt and organics were not differentiated for the purposes of this soil classification because distinguishing between the three was difficult to do visually given the consistency of the sediments, and would have resulted in unreliable results.

Table 6. USCS Soil classification, soil composition and electrical conductivity of streambed samples collected at the Grant River, WI.

Sample Number	USCS Soil Class	% Gravel	% Sand	% Clay, Silt, & Organics	Electrical Conductivity (mS/m)
1	Sandy silt	10	25	65	75.50
2	Poorly sorted gravel	91	9	0	19.42
3	Sandy silt	10	20	70	44.54
4	Silt with gravel	10	10	80	23.56
5	Poorly sorted gravel	95	5	0	44.11
6	Poorly sorted gravel with silt and sand	40	25	35	19.11

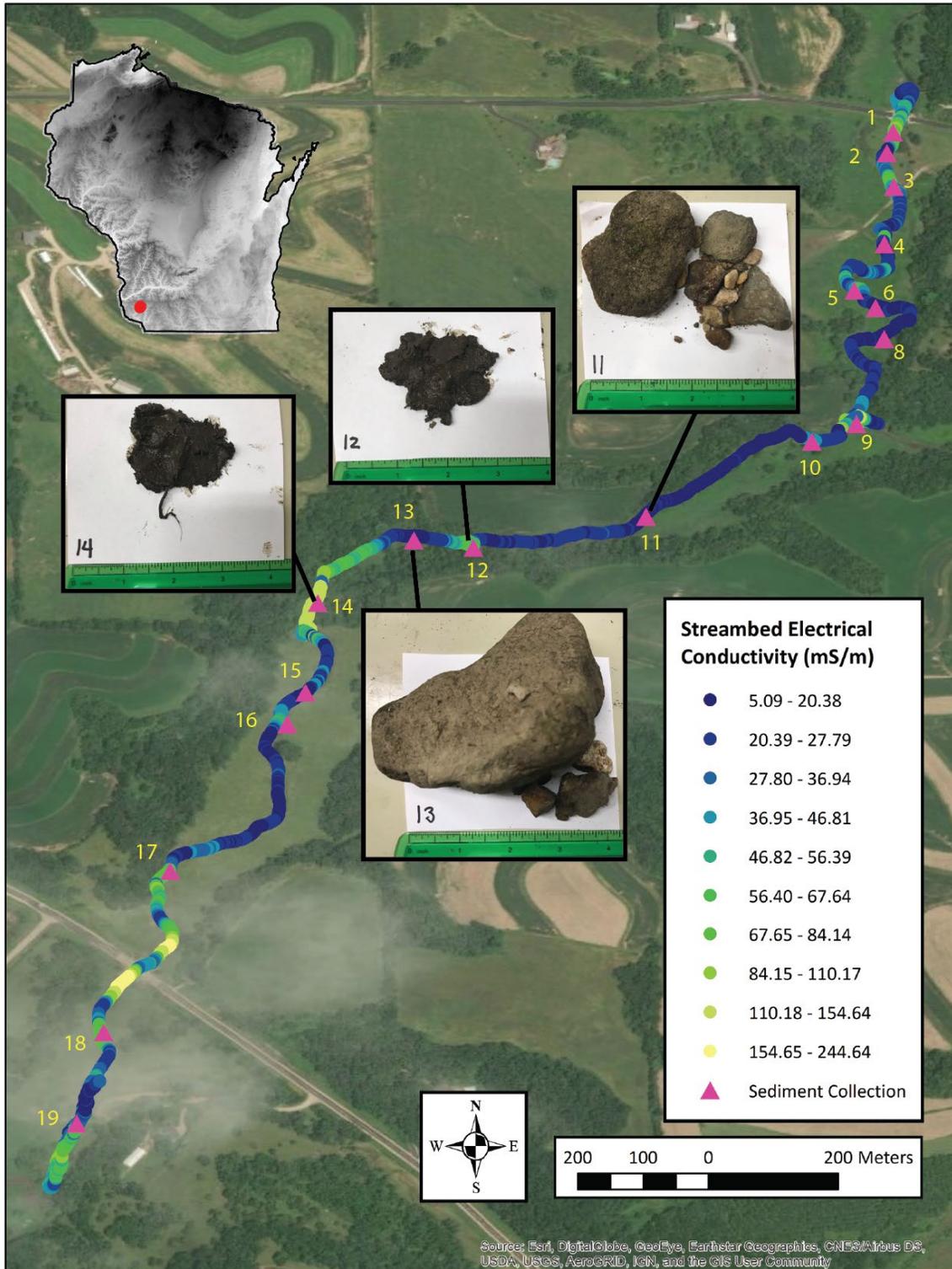					
8	Poorly sorted gravel	80	10	10	17.51
9	Sandy silt	10	25	65	52.17
10	Poorly sorted gravel	92	8	0	26.74
11	Poorly sorted gravel	90	10	0	17.20
12	Silt with sand	3	15	82	59.31
13	Poorly sorted gravel	88	11	1	18.78
14	Silt with sand	7	12	81	121.53
15	Poorly sorted gravel with sand	60	30	10	16.87
16	Well sorted sand	8	90	2	47.98
17	Well sorted sand	7	92	1	33.43
18	Sandy silt with gravel	20	15	65	75.11

Figure 24. Calculated electrical conductivity of the streambed in the uppermost portion of the Grant River. Pink triangles represent locations of streambed sediment collection.

Streambed sample composition varied widely, ranging from silt with sand to poorly sorted gravel. A wide range of calculated electrical conductivity values, ranging from 16-120 mS/m, corresponds with this variation. The streambed environment is characterized as intermittent transitions between organic, often sandy silty, and poorly sorted gravel deposits. The alternation between low (blue) and high (yellow) electrical conductivity along the river in Figure 24 reflects these depositional transitions. Figure 25 shows the samples plotted on a ternary diagram, where the color of the dots represents the nearest calculated electrical conductivity of the sample. Values with the highest conductivities lie in the corner of the diagram dominated by silt, clay, and organics, which is consistent with literature reports that those materials hold high values of electrical conductivity.

Sample 4, which is represented by the dark blue dot in the silt, clay & organics dominated corner in Figure 25, and is an anomaly among the samples collected, allows us to have an understanding of the fine-scale of accuracy at which the stream-float method can be applied to determine electrical conductivity of the streambed. Sample 4 was collected directly between a transitional zone, where the electrical conductivity calculations reflect the streambed transitioning from electrical conductivity values of 50-60 mS/m to electrical conductivity values of 15-23 mS/m . Sample 4 is likely be associated with the higher electrical conductivity zone that is mapped just upstream of where we collected the sample. The GPS plots sample 4 approximately 17 ft or 5 m from the higher conductivity zone. This suggests that our method is likely accurate down to approximately 5m scale.
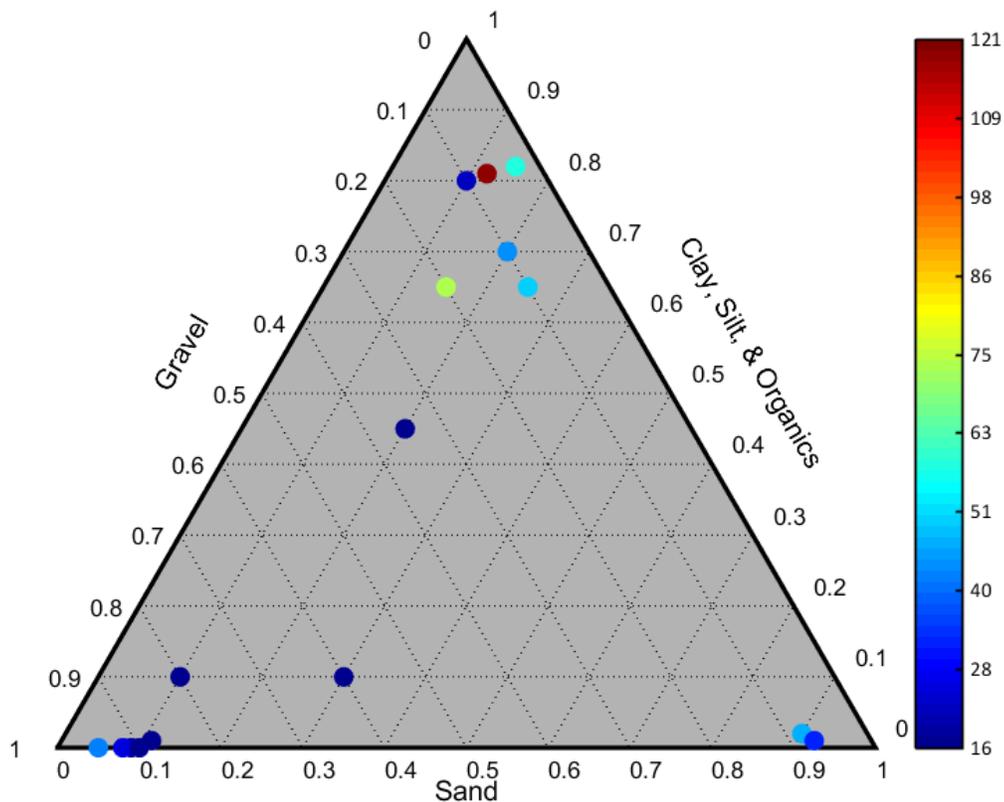
Figure 25. Ternary diagram representing streambed sediment composition of samples collected at the Grant River, WI with electrical conductivity (mS/m).

4.5 Conclusion and implications of stream/lakebed sediment electrical conductivity characterization

Characterization of physical sediment samples and comparison to calculated electrical conductivity values at sample locations at Plainfield Lake and Grant River suggest that the stream-float method is a useful tool for mapping variations in streambed electrical conductivity at a resolution of ~5m. Overall, the samples collected at Plainfield Lake are significantly more homogeneous than those collected at the Grant River. Sediments at Plainfield Lake are characterized as well- and poorly-graded sands with varying percentages of silt, gravel, and organic material, whereas sediment collected at the Grant River ranged from highly organic soil to gravel. Both site studies showed that lithological variations can be correlated to electrical conductivity variations, indicating that the stream-float method can be used to map lithologic variations at both homogeneous and heterogeneous stream/lakebed environments. However, we do not see a significant difference in the overall range of calculated electrical conductivities within the two study areas that would reflect the range of heterogeneity between them. Therefore, we cannot conclude that absolute values of electrical conductivity can directly lead to lithological assignment; variations in electrical conductivity at a particular site must be analyzed

within the context of a particular study site. This is due to the multitude of factors influencing electrical conductivity of a stream or lakebed including lithology, organic materials (and organic material composition), clay content, and electrical conductivity of the fluid within the materials.

Characterizing stream or lakebed electrical conductivities on a fine-scale has further implications for improving hydrogeologic understanding. Sediments with lower electrical conductivity, which indicates sand and gravel, will in general have a higher hydraulic conductivity than sediments with higher electrical conductivity, which contain higher silt, clay, and organic content. By mapping variations in lithology on a fine-scale, hydrogeologists will be able to infer differences in hydraulic conductivity based on known information about lithologic units. For example, if hydraulic conductivity were determined at a certain location within a lake via conventional field methods, the relative hydraulic conductivity around the lake based on the electrical conductivity values could be estimated better than it otherwise could be. Alternatively, the stream survey can be used to determine locations for the point measurements. Each of the two surveys discussed in this chapter took less than 2 hours to acquire the data. Installation of seepage meters, mini-piezometers, and thermal profile probes take 1 to 2 days and only provide point data.

Chapter 5: Conclusion

We designed, tested, and implemented a method for collecting spatially and temporally dense sets of water-quality and geophysical data that is particularly well suited for application in low-order, small river or lake systems. We utilized low-cost sensors and Arduino hardware and software to geolocate and log collected data. Low-cost sensors deployed in the field environment responded with varying reliability. Comparison of water-quality sensor data to alternative data-including lab reported data, data collected by alternative sensors, and previously collected data in our study areas- indicated that the low-cost temperature, specific conductance, pH, and dissolved oxygen sensors performed well in collecting spatially and temporally dense datasets on streams. Nitrate and chloride probes proved difficult to use under this field application, often calibrating well prior to field deployment, but then drifting significantly once deployed in the field setting. The low-cost specific-ion sensors utilized in this project are primarily intended for laboratory use, and did not hold up well to field environmental factors, such as significant temperature variation. In the future, it would be advisable to include dissolved oxygen and specific conductance sensors that had their own temperature sensors that applied corrections within themselves in order to decrease error.

Data results collected at the Mukwonago River reflect the utility of the stream float method in its ability to record fine scale stream water-quality variation, providing a breadth of data that would not otherwise be available. One notable result is the water-quality behavior observed in the groundwater-fed spring pool at the furthest upstream extent of our data collection. We observed unique temperature, dissolved oxygen, pH, nitrate and chloride groundwater signatures in the spring pool. Additionally, we observed the scale at which these signatures equilibrated within the river throughout the stream stretch. The stream float data collected at the Mukwonago River are further useful in that they indicate specific locations of hydrologic interest, where further data collection and analyses can be completed in the most strategic locations within the stream. Variations in the parameters collected indicate locations of potential groundwater discharge, biological change, or surface-water input into the stream system.

Another application of the stream float method is the ability to calculate electrical conductivity of a stream- or lake-bed utilizing EM31 response and the specific conductance and depth of water. Stream- or lake-bed electrical conductivity is a useful parameter in that it provides information regarding the lithological variations within an aquatic system, which could ultimately be useful in determining variations in hydraulic conductivity. Hydraulic conductivity is a difficult parameter to characterize on a small scale in stream systems, but is essential to calibrating surface water/groundwater interactions within groundwater flow models. We collected approximately 20 lake- and stream-bed samples at both Plainfield Lake and the Grant River at locations that represent the full range of electrical conductivity calculated in each study area. The samples were classified using the unified soil classification system and visually analyzed for percent gravel, sand, clay and silt, and organic content. The lithological results were

compared to the calculated electrical conductivity at the given sample locations. Samples with lower electrical conductivity generally had higher sand and gravel content (and thus expected to exhibit high hydraulic conductivity), while samples with higher electrical conductivity contained higher contents of clay, silt, and organic matter, which are expected to have lower hydraulic conductivity. Based on data validation through sediment sample collection, this method appears to be accurate to a scale of approximately 5m. Samples from Plainfield Lake were far more homogenous in nature than those collected in the Grant River, however variations in electrical conductivity correlated with lithological variations for both sets of data. This indicates that calculating stream- or lake-bed electrical conductivity using the stream-float method can be applied to a range of lithological environments within the penetrative range of the EM31, which is approximately 3m. However, samples should be collected to provide correlation between the electrical conductivity and the lithology.

Even after significant use and refinement, the water-quality apparatus could be further updated to provide additional utility in understanding stream environments. In future applications of our water-quality sensor apparatus, it would be advisable to purchase higher-quality nitrate and chloride sensors that are intended for field deployment. Additional parameter sensors can easily be added to the system if there is a particular interest. A phosphorus sensor, for example, would be able to sense this nutrient of specific interest in many areas of Wisconsin. Turbidity would be another parameter of interest. A different filter on the inlet of the current system would allow the apparatus to be more versatile in its field application as the system was limited when travelling upstream in areas where the water became disturbed as it was traversed, resulting in the filter or flow-through cell becoming clogged. A more coarse filter or screen might provide better results. It would allow smaller particles to pass through the flow through cell allowing for turbidity measurements and block larger particles and plants.

By combining the increased knowledge about spatial variations in water-quality and geophysical parameters variations within a stream, as provided by the stream float method, hydrologists are able to identify specific locations that should be further investigated as markers of influence on an overall water body. For example, locations that exhibit changes in pH could be paired with a larger suite of geochemical analysis; locations of temperature variation could be targeted as locations of potential groundwater recharge where seepage meters or mini-piezometers can be deployed. In a changing climate that is experiencing extreme seasons and precipitation events, the stream-float method will be a useful tool for characterizing small watershed environments under differing hydrologic conditions. This will ultimately aid hydrogeologists in understanding the short- and long-term effects of climate, and provide useful data that can serve as input to hydrologic and ecological models.

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