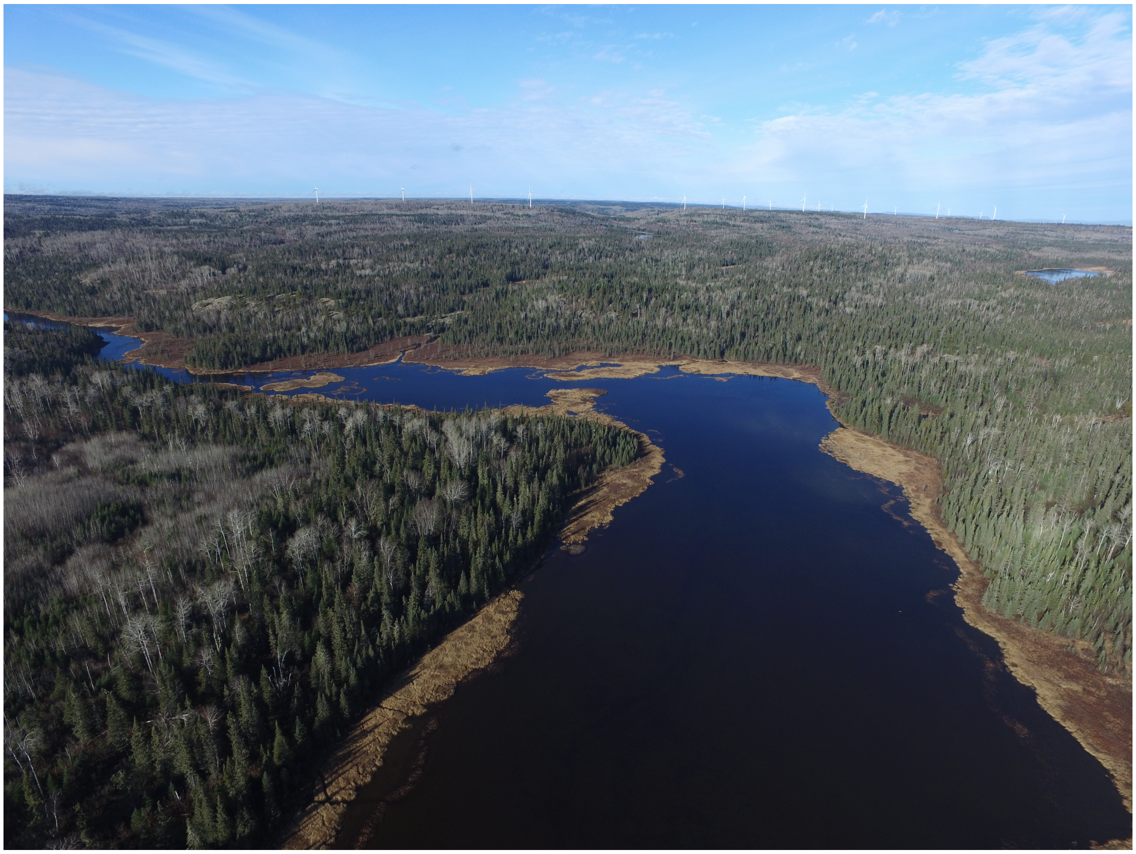
Hydromapping Tool Creation for Sprat Lake Using Unmanned Aerial Vehicles (UAV) Surface From Motion Analysis; A Proactive Approach to Reduce Potential Mercury Fluxes Following Forest Harvesting By Using Variable Retention Buffers and Preplanned Machine Travel Corridors

By: Colin Pendziwol



Hydromapping Tool Creation for Sprat Lake Using Unmanned Aerial Vehicles (UAV) Surface From Motion Analysis; A Proactive Approach to Reduce Potential Mercury Fluxes Following Forest Harvesting By Using Variable Retention Buffers and Preplanned Machine Travel Corridors

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____________________ Major Advisor

____________________ Second Reader

CAUTION TO THE READER

This HBEM thesis has been through a semi-formal process of review and comment by at least two faculty members. It is made available for loan by the Faculty of Natural Resources Management for the purpose of advancing the practice of professional and scientific forestry.

The reader should be aware that opinions and conclusions expressed in this document are those of the student and do not necessarily reflect the opinions of the thesis supervisor, the faculty, Lakehead University or Resolute Forest Products.

ABSTRACT

There has been an increase in the awareness and concern regarding mercury contamination in Northwestern Ontario fish. Wetland and low laying areas are considered hotspots for methylmercury production which, when disturbed by harvesting and site preparation equipment, can cause mercury to runoff into the aquatic system and bioaccumulate through the food chain. In this study, a hydromapping tool for Sprat Lake was created through surface from motion analysis of Unmanned Areal Vehicle (UAV) images. This tool determined areas of high water accumulation on the landscape that might otherwise go undetected. Variable retention buffers were also created with this tool as riparian zones may extend farther than fixed with buffers currently prescribed by Ontario forest management guidelines. Wetland environments were identified and classified to ensure that they could be avoided by heavy equipment during harvesting and tending treatments. Road corridors were also outlined to steer heavy equipment away from low laying areas. This proactive approach reduces surprises incurred when conducting harvesting and renewal operations and may reduce soil disturbance on sensitive areas, possibly helping to mitigate total mercury and methylmercury fluxes that may sometimes follow forest harvesting disturbance.

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INTRODUCTION

Mercury is a naturally occurring heavy metal found in different places in the environment. Traditionally used for measuring temperature in thermometers, mercury is a liquid at room temperature even though it is considered a metal. Mercury is a heavy metal and can persist in the environment and become toxic as it bioaccumulates up the food chain. Recently, there has been increasing awareness regarding the potential health effects that mercury contamination may have on people and the environment. Lately, the media has focused on this issue, increasing the concern from residents on lakes in Northwestern Ontario that fish will become too toxic to eat after natural resource extraction takes place.

Around 80% of all freshwater lakes in Northwestern Ontario have moderate to severe restrictions on fish consumption due to mercury contamination (Mackereth 2015). While this region tends to have higher levels of mercury in the environment based on its geology, soil, pH and climate, there has also been some evidence that forest harvesting and silvicultural activities can increase the amount of total mercury (THg) and methylmercury (MeHg), an organic state of mercury that may bioaccumulate readily after entering aquatic ecosystems (Danco 2013). Mercury entering the aquatic system from forestry may occur as an outcome of harvesting equipment disturbing the soil, releasing mercury and allowing it to be washed downstream into aquatic environments. The water table can also rise following tree removal, increasing the mobilization of mercury and methylation rates (Eklof et al. 2016). Harvesting does not create mercury. It just releases the stored atmospheric mercury in the soil through increased runoff. It should also be noted that while some studies have found a connection to forest operations and increased mercury levels in fish and other water organisms, other studies have found there is no significant connection between the two (Danco 2013).

Mercury and methylmercury contamination has been a hot topic in the local media lately and it has increased stakeholder concerns about this issue. Resolute Forest Products ltd. has teamed up with Lakehead University to design and create a proactive tool for forest operations. This tool could reduce possible harmful effects of forest operations on aquatic systems, alleviating stakeholder concerns. A hydromapping tool for Sprat Lake will be created that will enhance the protection of water quality from possible mercury contamination. The methods used to create this hydromapping tool for Sprat Lake can then be applied to other management areas. This tool can be used to locate areas where forest harvesting can be conducted with minimal impacts on water quality, to minimize damage from trucks and harvesting equipment driving on organic soils, and to optimize the design of riparian buffers (Laudon et al. 2016). This hydromapping tool can help determine hotspot locations for mercury release. Hotspots for mercury release are considered wetland and lowland sites as they can contain more mercury and are easier to disturb leading to the release of the mercury (Laudon et al. 2016).

The location of the study site is Sprat Lake and its catchment. Located in the most southeastern portion of the Black Spruce Forest Management Unit, Sprat lake is around 108km NE from Thunder Bay via car at the location 48°43'14.5"N, 88°47'51.5"W. Tartan and Question Mark Lakes are just beside the study area that surrounds Sprat lake. There has been no harvesting operation within the study region, but the location is eligible for harvesting within the next couple of years. The Ministry of Natural Resources and Forestry (MNRF) identified Sprat Lake as a sensitive area because it contains brook trout spawning and have tagged some of those fish. Hydromapping is a proactive approach that can be used to increase the amount of planning before a harvesting operation, and can help mitigate methylmercury fluxes following forest harvesting (Laudon et al 2016).

The study was conducted by taking high-resolution images from an Unmanned Aerial Vehicle (UAV), also known as a drone. These images were then used to create a surface elevation model that can then be applied to create a hydromapping tool. From there, it was determined where mercury hotspots occur and where the contaminants could flow once the soil is disturbed. While this tool has the possibility of reducing potential negative effects of forest harvesting operations on water quality, it is not possible to conduct this type of study for all forest management areas. This study took place on a small scale where there is a brook trout spawning area. There are, however, plans for the new Forest Resource Inventory (FRI) to contain a high quality surface elevation model. This model would be created by using ether radar or LiDAR scans from a helicopter or plane (Pers. Comm. Dr. Ulf Runneson. November 15th, 2016). A hydromapping tool would then be able to be produced quite easily for all forest operations. This small-scale study will therefore help to determine just how to use this tool on the landscape for future operations.

OBJECTIVE

The purpose of this study is to create a surface elevation model and hydromapping tool through the use of UAV imagery. This tool will help in determining where the lowland mercury hotspot sites in the Sprat Lake catchment are. An objective of this study is also to create road corridors for harvesting equipment to minimize site damage and mercury release. Creation of variable retention buffers is also a goal to make sure that riparian zones are protected, even if they extend past conventional buffer widths. Sampling for mercury will not take place, only the topography and vegetation of the harvest area will be looked at to determine what sites should be avoided. A comprehensive literature review will look at the effects that the environment and disturbances have on mercury concentration levels in aquatic systems and fish.

This study will provide the concerned stakeholders with a review of the possible effects of forest harvesting on methylmercury levels in local waterbodies and will help to demonstrate how Resolute Forest Products is taking a proactive approach to reduce potential mercury fluxes resulting from their operations.

LITERATURE REVIEW

Mercury is a non-essential element that is toxic to humans and animals (Park and Zheng, 2012). A naturally occurring heavy metal, it is present in the environment, however due to anthropogenic activities, the amount of mercury can be raised above 0.5 mg/kg level deemed safe by the World Health Organization (Pinheiro, 2000). Mercury is a neurotoxin, affecting cognition and brain development in children. It can also affect the central nervous system, kidneys and in extreme cases cause death (Park and Zheng, 2012). It is especially toxic to developing fetuses as it can lead to neurological damage and impaired development (Health Canada, 2007). First Nation communities in Ontario and other parts of the country tend to be more susceptible to mercury poisoning due to a large part of their diet being comprised of fish. Mercury is to blame for 86% of fish consumption restrictions for inland water bodies and fish are the primary source of human ingestion (Weiner et al 2003). The anthropogenic sources that cause elevated mercury levels include coal-fired power plants, incinerators, wastewater treatment, industrial manufacturing and base metal extraction (Driscoll et al. 2007). Globally, the highest contributor of mercury into the environment is from coal-fired power plants. In Canada, the greatest source of mercury comes from base metal recovery, accounting for 45.2% of emitted mercury (Pinheiro, 2000). Mercury is used in a wide variety of products such as batteries, switches, thermometers and fluorescent lights (UNEP, 2009). When these items are disposed of improperly, mercury can be released into the environment. The mercury is able to enter the air, becoming atmospheric mercury where it is able to travel far distances. This makes mercury contamination not just an issue for point source pollution but also a global issue. Ninety-six percent of mercury deposited from the atmosphere into the environment in Canada is from foreign emissions (Fitzgerald et al. 1998). This atmospheric mercury is able to make its way into the soil and water, plants and animals, and eventually into humans.

Mercury in the Environment

Mercury exists in three different states: Elemental mercury (Hg^0), inorganic mercury (Hg^{2+}) and organic mercury (Hg^{1+}) (Driscoll et al. 2007). Elemental mercury is liquid at room temperature and is used in thermometers. Inorganic mercury bonds with other elements such as sulfur to form compounds like mercury sulfide and mercuric chloride. Organic mercury forms when mercury bonds with carbon (CDC 2007). Inorganic mercury goes through methylation by microbial activity converting it into organic mercury, obtaining a methyl group it is then called methylmercury (MeHg) (Wiener et al. 2003).

Mercury is naturally released into the environment through the weathering of mercury-containing rocks and soils, volcanic eruptions and geothermal activities (UNEP, 2009). These natural sources can add up to half of the total mercury emitted into the atmosphere (Friske and Coker 1995). Because of this, surface geology, soil chemistry and glacial deposits play a large role in the amount of mercury entering lakes and rivers. Bedrock composition dictates lake-water chemistry, affecting the mercury concentration in a lake. Some of the highest mercury levels in lake sediment are in lakes southwest of Thunder Bay (Friske and Coker 1995). This is due to the amount of shale under the soil as shale contains a higher level of mercury and other trace metals than other types of bedrock.

Mercury Cycle

The mercury cycle includes four interconnected environments: atmospheric, terrestrial, aquatic and biotic. A graphic showing the biogeochemical mercury cycle can be seen in Figure 1. The mercury cycle is closely connected to the water cycle as the movement of the heavy metal is mostly through water or water vapor. The mercury can transfer between the solid, liquid, and gaseous phases within and between environments. In the atmosphere, mercury comes from anthropogenic sources like coal-fired power plants and incinerators, which release mercury as emissions. Natural sources of mercury include not only point sources like volcanoes but also volatilization and evaporation from earth's soil and water bodies (Environment and Climate Change Canada, 2013).

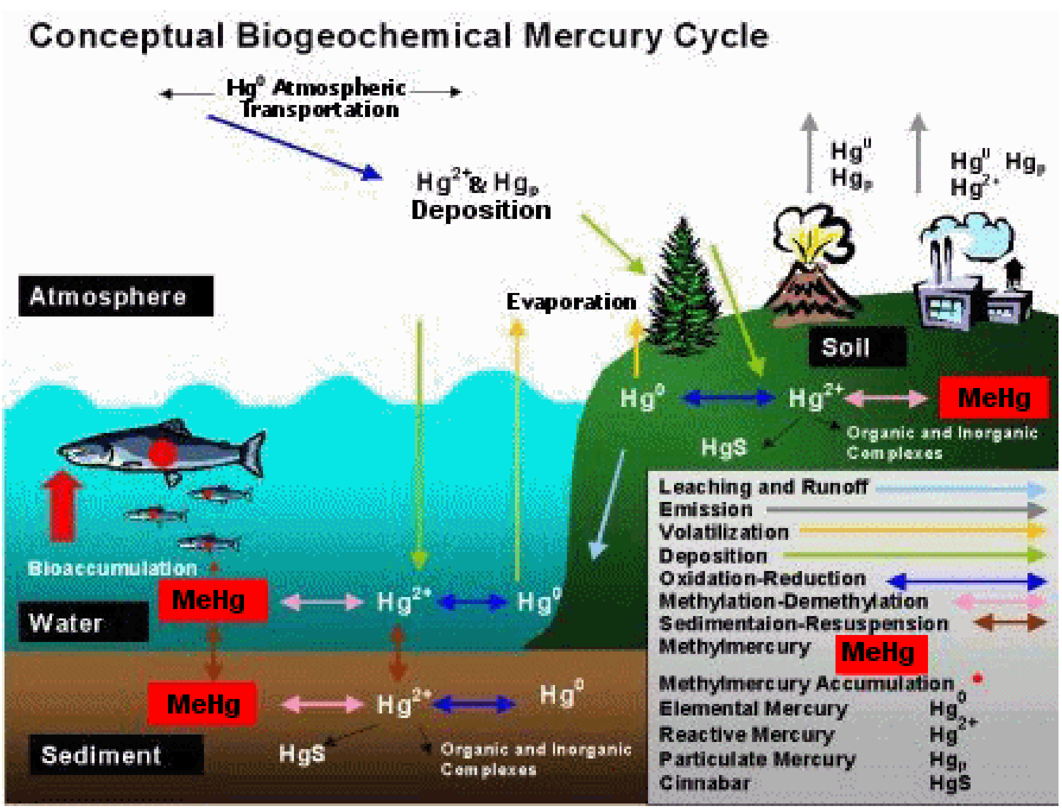


Figure 1: Shows the Biogeochemical Mercury Cycle. Source: Environment and Climate Change Canada

More than 95% of the total atmospheric mercury exists as gaseous mercury, making it different from most other heavy metals, which are mostly in the atmosphere in a particulate phase (Fu et al. 2010). Generally, more than 90% of the total atmospheric mercury is also in the form of gaseous elemental mercury (GEM) (Fu et al. 2010). GEM, compared to other forms of atmospheric mercury, is very stable. It has a residence time of between 6 months to 2 years (Zu et al. 2010). This makes mercury able to travel very far distances and makes mercury a global problem, effecting even the most remote locations around the world. The rest of the mercury that is in the atmosphere that is not GEM is either particulate mercury (PHg) or ionic mercury (Hg^{2+}), also known as reactive gaseous mercury (RGM) (Driscoll et al. 2007). The GEM can be oxidized, turning into RGM, which has a short residence time in the atmosphere of only 0.5 to 3 days (Driscoll et al. 2007; Wiener et al. 2003). PHg has a residence time in the atmosphere of between 1 to 2 weeks (Driscoll et al. 2007). Once the mercury is in its reactive state it is rapidly taken up into water or snow and deposited through precipitation in what is known as wet deposition. The Hg^{2+} state of mercury in the atmosphere is dissolved into water much more easily than the PHg or elemental mercury (Grigal 2002). The RGM and PHg can also be deposited through dry deposition. Dry deposition includes deposition from fog or clouds and stomatal uptake (Driscoll et al. 2007). The deposition can occur on either land or on water with 50-75% of total deposition occurring as dry deposition (Driscoll et al. 2007). Atmospheric deposition is the predominant input of mercury into a watershed as atmospheric mercury can travel vast distances. The highest periods of deposition are in the winter and spring

(Pinheiro 2000). The mercury that has been up taken by plants via their stomata can either be re-emitted to the atmosphere through volatilization or it can reach the ground surface through litter fall (Grigal 2002).

Once in the soil or water, mercury that was deposited through wet and dry deposition can either be reduced and emitted back into the atmosphere as elemental mercury through volatilization or evaporation, or it can be converted into organic mercury creating methylmercury (Wiener et al. 2003). On land, the inorganic mercury bonds easily with organic matter (Lucitte et al. 1995). This mercury bound to organic matter will then either remain in the soil as a sink or be transported into river and lake systems through erosion and overland flow. The podsolic soils of the Canadian Boreal Shield absorb a significant amount of mercury from wet and dry deposition and then act as long term sources of mercury to surface waters (Hultberg et al. 1995). Some of the factors affecting terrestrial inputs of mercury into lake water are: vegetation, climate, seasonality, rate of erosion, ratio of watershed area to lake surface, percentage of wetlands in the catchment, residence time of water in the soil and soil characteristics (Pinheiro 2000).

When mercury is transported to an aquatic environment by runoff and deposition, it has three major pathways it can take. It can be scavenged and transported towards the sediment in the lake, converted into dissolved gaseous mercury, the main form of elemental mercury in the water column and go through evasion from the water to the atmosphere, or it can undergo methylation and change from inorganic mercury to organic mercury (Pinhero 200). When the inorganic mercury undergoes methylation, the organic mercury obtains a methyl group creating MeHg (Driscoll et al. 2007). Methylation in water, sediment and soil is predominantly conducted by microbial activity in anoxic environments (Wiener et al. 2003). A lot of the inorganic mercury is bound to sulfur as mercury sulfide. This creates the perfect conditions for sulfide reducing bacteria to exist and create MeHg at the same time (Lucotte et al. 1994). There have also been some studies suggesting that methylation can also occur without microbial activity, and humic matter methylation is likely (Weber 1993). There are seasonal patterns of mercury input from rivers to several lakes in Ontario correlating with river colour which measures humic matter content (Mierle and Ingram 1991). This topic has only had limited study but does pose questions about the creation of MeHg. The main producers of MeHg are microbial populations and, even though sulfide reducing and methanogenic bacteria both possess the ability to demethylate mercury in freshwater sediments, it occurs at a much slower rate than methylation (Ullrich et al. 2001).

While methylation can occur in water, lake sediment and soils, MeHg only accounts for around 10% of the total mercury in the environment (Pinheiro 2000). It is, however, the most problematic state of mercury due to the fact that it bioaccumulates through the foodweb and is slow to be eliminated from animal tissues. This is because of its lipophilicity, its ability to dissolve in fats, oils and lipids (Pinhero 2000). The MeHg makes its way through the food chain from algae and microinvertebrates through fish up to higher trophic levels such as eagles and humans. The elimination of MeHg is slow and difficult as excretion of the mercury occurs through the feces after partial demethylation (Pinhero 2000). When moving up the food chain, fish are able to assimilate 65-80% of the MeHg present in their food (Wiener et al. 2003). That is around 5-10 times higher assimilation rates than ionic mercury (Trudel and Rasmussen 1997). This will cause the percentage of MeHg to ionic and elemental mercury to increase as the trophic levels increase. MeHg percentages of total mercury in the water column are at around 10%. It increases to 15% in phytoplankton, 30% in zooplankton, up to 95% in fish and 99% in piscivorous fish (Driscoll et al. 2007). Not only are assimilation rates higher for MeHg, but the excretion rates of ionic mercury are 3 times faster than rates for MeHg (Trudel and Rasmussen 1997). It was also found by Trudel and Rasmussen (1997) that excretion rates are negatively correlated to body size. This leads to larger, higher trophic level animals containing higher levels of MeHg.

The mercury cycle is complex, with many different factors affecting how the toxic heavy metal moves in the environment. Of ultimate concern is MeHg since it contains the capacity to move up the food chain and bioaccumulate, eventually leading to toxic levels. Mercury contamination has the highest percentage of restriction on inland lakes for fish consumption than any other toxin in Canada. This makes it important to understand how mercury reacts in the environment based on natural conditions but also on conditions that we may alter.

Dissolved Organic Carbon and pH

Dissolved Organic Carbon (DOC) is used as an indicator to detect watershed disturbance levels and other factors in lake environments. The amount of DOC in lake environments can have a substantial impact on the mercury cycle and the amount of harmful MeHg present. The DOC contains decomposable carbon, which can stimulate in-lake microbial methylation activity, increasing the amount of MeHg in the water (Pinheiro 2000; Garcia and Carignan 2000). The more DOC in the aquatic environment, the more MeHg. The increase of DOC may also decrease rates of photoreduction of MeHg to GEM that can under go evasion from the water system (Garcia and Carignan 2000). Logged lakes were found to have a lower efficiency of photoreduction than other sites due to the increased DOC that has mercury bound to its lignads (O'Driscoll 2004). This will then increase the persistence of MeHg in the aquatic system. A study by Miskimmin et al. (1992) found that there was a positive correlation between fish mercury and DOC in drainage lakes and a negative correlation in seepage lakes. That study also found that in brown-water lakes, in-lake methylation is inhibited by DOC concentrations, making terrestrial inputs of MeHg in the runoff more important than microbial methylation. Multiple studies have shown that DOC increases microbial activity, stimulating more MeHg in the system but that increased DOC also inhibits in lake methylation. DOC can inhibit methylation by bonding inorganic mercury to it, making it inaccessible to microbial populations. This makes the relationship between DOC and MeHg levels very complex and unpredictable.

One thing that is consistent however, is the correlation between pH and MeHg levels. Lower pH, meaning higher acidity, will increase methylation (Miskimmin et al. 1992). Higher acidity in a lake leads to a greater amount of mercury in fish in clear water lakes (Miskimmin et al. 1992). Garcia and Carignan

(2000) found that lake water pH was the most important predictor of Hg concentrations in Northern Pike. At low pH, exchange of H^+ with humic acid bound Hg^{2+} increases the availability of Hg^{2+}, increasing methylation rates (Garcia and Carignan 2000). pH may also interfere with uptake of mercury into aquatic organisms and it is a better indicator of MeHg in aquatic environments than DOC (Garcia and Carignan 2000).

Effects of Forest Disturbances on Hg Levels

Forest disturbances have the possibility of causing major alterations to the environment. Logging can alter the biogeochemical processes of Boreal forest watersheds with changes to the composition of the forest, soil moisture, temperature, microbial activity, and water fluxes (Kreutzweiser et al. 2008). Fire can have similar effects as harvesting; however, fire may release less mercury into aquatic environments due to the fact that fire is able to volatize the mercury and send it back into the atmosphere (Garcia and Carignan 1999). Increased fire intensity will volatize more mercury. This means that low intensity fires will have a similar effect as forest harvesting on mercury level in runoff (Garcia and Carignan 1999).

Clear cutting alters the forest hydrology, enhancing mobilization of mercury and enhancing methylation (Danco 2013). Runoff increases after forest disturbances, releasing the accumulated mercury and MeHg from the soil into the lake system. When silvicultural treatments occur, it increases runoff even more (Eklof et al. 2014). Fires and harvesting operations expose the upper organic layer of the soil allowing it to be eroded. This layer of soil contains the terrestrial mercury; therefore runoff post disturbance increases the amount of mercury reaching the water as well as the amount of DOC (Garcia and Carignan 1999). Increased levels of DOC however were only seen after 40% of the watershed had been clear-cut (Pinheiro 2000).

Any runoff from Boreal sites into the aquatic system tends to increase the amount of mercury in the water. When wetland and low laying areas are disturbed, it can release much more mercury and MeHg to the aquatic systems than upland sites. This is due to wetlands' ability to contain large stores of mercury (Rudd 1995). The amount of wetlands in a catchment can affect the total amount of mercury in the water, however a study done by Danco (2013) found no relation between the percent of wetland in a catchment and total mercury concentrations. That same study also found that in all species of fish, the total mercury concentrations did not differ between lakes that had been clear-cut, burned or used as reference lakes (Danco 2013). It was also noted, however, that the highest mercury concentrations in fish came from small darkly stained lakes that had been recently harvested and had higher percentages of wetlands and organic material within the catchment (Danco 2013). However, these results were not statistically significant.

Road density can be related to higher mercury concentrations in aquatic systems (Danco 2013). Roads can affect the movement of water by blocking and redirecting surface flow and increase the amount of sediment entering the aquatic system (Gillies 2011). Improper road building in wetlands can cause water to pool and increase the size of the wetlands, causing die-back and making further harvesting operations more difficult (Gillies 2011). Roads need to be designed in areas of wetlands and lowland environments in a way that does not affect hydrological flow. Wetland road construction should also initially take place in the winter when the ground is frozen and less damage to the soil will occur (Gillies 2011). Design in low relief areas can be difficult as it is not obvious where the water flows (Gillies 2011). With the use of a hydromapping tool, determining the location for road constructeion can be determined with greater effectiveness. Having a classified landscape to know exactly where the wetlands are can also help in determining areas that should be avoided for road construction.

Wetlands as MeHg Hotspots

Darkly stained lakes generally have catchments that have a high percentage of wetland and lowland sites in them. Many studies have shown that wetlands are an important source of MeHg (Bishop et al. 2009; Louis et al. 1994; Rudd 1995). Output of MeHg from wetland sites can be between 27-79 times higher than from upland sites (St. Louis et al. 1994). Total mercury levels in both upland and lowland sites tend to be similar as the major input is from atmospheric deposition. The difference lies in the MeHg ratios. Wetland sites have a higher production of MeHg than upland environments, making them a hot spot for mercury release (Braaten and Wit 2016). A study by Bishop (2009) in Sweden determined that the yield of MeHg per year from wetland environments was much greater than upland sites. Figure 2 depicts their finding with one location having higher MeHg levels than what could be fit into the graph. In the same study it was also noted that levels of

MeHg post clear cut were much higher than pre logging levels, although some sites have higher levels of mercury pre harvest than other sites post harvest (Bishop 2009). The range of variability between sites can be high, although clear-cut harvesting generally increases the output of mercury from those environments.

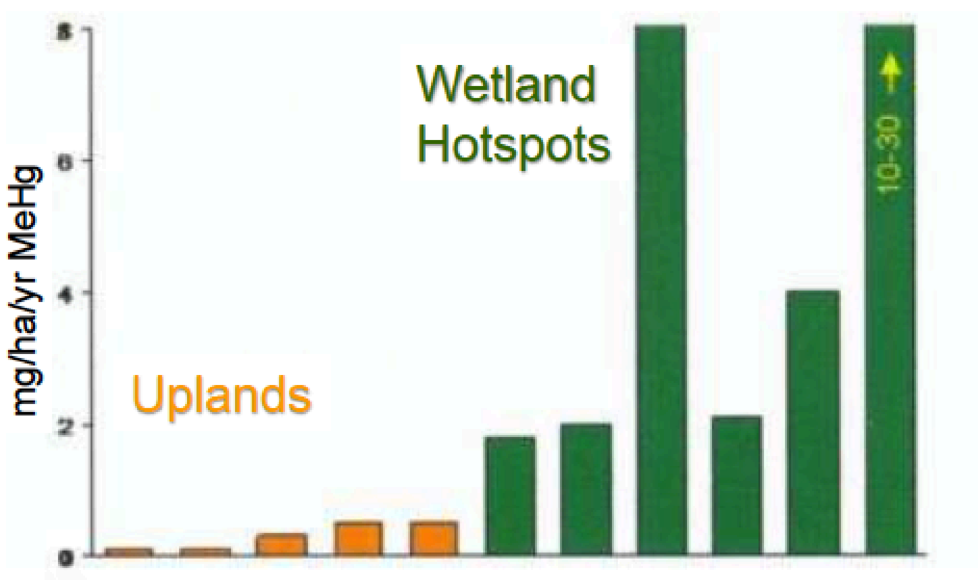


Figure 2: The output of MeHg per year from upland and wetland environments in Scandinavia. Source: Bishope et al. 2009.

Areas with very high accumulation of water, such as wetland environments, have lower growth potential compared to upland sites. While some wetlands are open and have no harvestable trees growing in them, other lowland and wetland sites do. The potential risk of water quality impacts from forestry operations on these sites is quite high (Laudon et al. 2009). These lowland and wetland sites tend to have a smaller load-bearing capacity on their soils, increasing the amount of rutting that occurs from harvesting equipment. Currently, guidelines are to harvest and build roads in wetland environments when it is frozen in the winter (Gillies 2011). When the ground is frozen, it has a higher bearing capacity so rutting is reduced. However, there is not enough research looking at the effects of winter harvesting on soil and water quality. While it is better to harvest treed wetlands in the frozen winter, the effects on water flow and mercury contamination once the ground thaws are not known.

Riparian Buffers and Their Effect on Water Quality

Riparian areas are the zones between the terrestrial and aquatic environment. They often have saturated soils as they are right beside lakes and rivers and can be affected by floods (Luke et al. 2007). Riparian zones generally have high levels of biodiversity within them and are important for bank stabilization, runoff interception, and affecting stream temperatures (Parkyn 2004). Riparian buffers affect stream flow and water quality by intercepting runoff from the disturbed site that includes washed away sediment (Luke et al. 2007). The runoff intercepted by these buffers would also include some level of mercury, making them important for reducing the MeHg reaching aquatic environments. While these buffer zones are important in maintaining water quality, the guidelines on how wide they have to be is arbitrary. Based on the Stand and Site Guide (2010), buffer or area of concern (AOC) widths only depend on the adjacent slope angle. The width related to the slope steepness can be seen in figure 3. These buffer widths may be effective for interception of sediment as steeper slopes will have faster flowing run off, needing a thicker buffer to capture it all. In areas of lower relief, sediment movement is not substantial (Luke et al. 2007). These guidelines, however, do not take into consideration the hydrologic connections that may extend beyond the buffers, especially in low relief areas (Mackereth 2015). Figure 4 shows this feature that is not taken into consideration. With a hydromapping tool, it shows where groundwater discharge areas are present. These areas of higher groundwater discharge tend to be prone to higher levels of degradation when disturbed and will greatly alter the biogeochemical properties of the discharge area (Luandon et al. 2016). This is one of the reasons why a hydromapping tool is so useful in riparian management. It allows the user to optimize the use of riparian buffers (Laudon et al. 2016). Varied buffer widths have the potential to reduce harmful site damage by extending buffer widths into areas of ground water discharge while also increasing harvest in areas that don't need as large a buffer or AOC. Within the Stand and Site Guide (2010), harvesters are allowed to cut trees within the AOC if certain criteria are met. According to the Stand and Site Guide (2010), harvesting within shoreline AOC will not have adverse affects on water quality if thoughtfully planned and implemented. Knowing how the riparian zone and hydrological connectivity near these aquatic environments is therefore crucial in carefully planning buffer thicknesses and harvesting within them.

- For *large lakes, medium lakes, small lakes*, and *HPS* ponds, 30 to 90 m AOC based on slope as follows:

Slope (%)	Slope (degrees)	Width of AOC
0 –15	0 – 8.5	30 m
>15 – 30	8.6 –16.7	50 m
>30 – 45	16.8 – 24.2	70 m
>45	>24.2	90 m

- For *MPS ponds,* 30 m AOC

Figure 3: Width of buffer for different sized lakes and ponds depending on their shores slope. Source: MNR 2010.

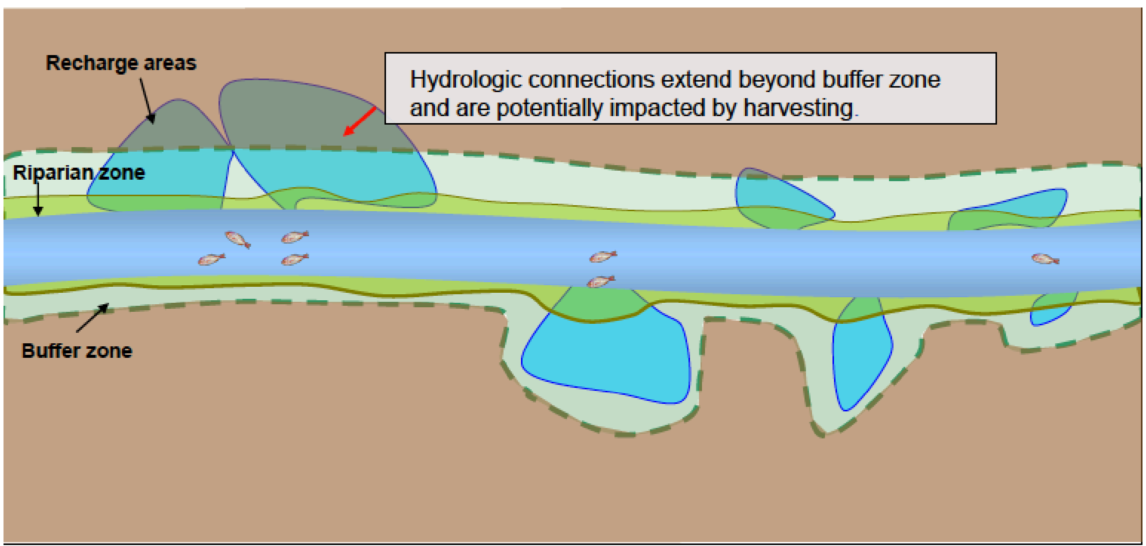


Figure 4: Displays the hydrologic connections that can be affected past the buffer zone that is created. Source: Mackereth 2015.

Aerial Photography and UAV's in Resource Management

Aerial photography in natural resource management has been around for quite some time. First by taking photos from an aircraft and then by taking images from a satellite such as SPOT or Landsat (Ozami and Bauer 2002). While satellite imagery is excellent for looking at large areas of land to determine land use changes, the pixel resolution is quite large. That makes it quite difficult to pick out small wetlands on the landscape. Planes can easily pick up wetlands on the landscape and cover a fairly large area at once, but operational costs are very high. Recently there has been a growing use of UAVs by land managers. These drones quickly obtain fine scale data cost-effectively (DeBell et al 2016). Land managers are able to conduct land classifications 45% faster than with traditional methods (Marcaccio et al. 2015). The downside of these UAVs is that their range is restricted and cannot cover areas as large and area as a planes or satellites (DeBell et al. 2016).

Land classification using multispectral and hyperspectral reflectance can be done using all three imaging platforms: satellites, planes and drones (DeBell 2015). This spectral imagery can be modified using different indexes such as the Normalized Difference Vegetation Index (NDVI). This index takes into account the infrared wavelength whose reflectance is much greater affected by the presence of water than the visible Red, Green, Blue (RGB) wavelengths (NASA 2016). Airplanes and UAVs can be outfitted with different sensors depending on what is being studied. Thermal cameras can be used to identify wildlife in the forest and surface moisture (DeBell 2015). Planes can also be outfitted with laser scanners, also known as LiDAR, but these scanners are currently too heavy for lightweight drone use. LiDAR scanners are an excellent tool for creating digital elevation models (DEM) and digital surface models (DSM) that can be used for creating hydrological flow maps (DeBell 2015). Radar scanners can also be used, as they are a cheaper alternative to LiDAR (Pers. Comm. Dr. Ulf Runneson, November 15th, 2016). These LiDAR sensors are very expensive and would not be available to the average land manager. Radar and LiDAR scanners are also currently too big and cannot be attached to a small quad copter. Other methods of creating flow maps have to be used. One of these ways is to use multiple overlapping multispectral images. These images can be imputed into a surface from motion (SfM) processing software such as AgiSoft to create a 3D model of the landscape (DeBell 2015). These 3D models can then be used to create a hydromapping tool through models such as flow accumulation, topographic wetness index and cartographic depth to water index. These models can also help to determine wetland areas. UAVs are a fast and cost effective may for resource managers to classify the landscape, although doing any large-scale operations is currently not practical. For small, fine scale research however, it is the perfect tool. With the new Forest Resource Inventory set to be conducted within the next few years, there is talk that the new imagery taken should also include LiDAR or radar scans (Pers. Comm. Dr. Ulf Runneson, November 15th, 2016). This will greatly enhance the hydromapping capabilities over a large scale, improving water quality and reduce MeHg contamination to Northwestern Ontario's fish.

MATERIAL AND METHODS

The area of interest for this study is the southeastern portion of Sprat Lake and it's surrounding catchment. The area of interest overlaid on a Google Earth image can be seen below in figure 5. In figure 6, the area of interest can been seen in a zoomed out Google Earth image to give perspective on the surrounding region of the study site. The total study area is around 2 km long by 1.3 km wide.

5.a) b)

Figure 5: Satellite image of Sprat Lake and the surrounding lakes (a), along with the proposed study area overlaid (b). Source: Google Earth 2016.

Figure 6: Study area in relation to the Thunder Bay Area. Source: Google Earth 2016.

On November 16th 2016, 1846 aerial photos were taken of the southern portion of Sprat Lake and its surrounding catchment. The photos were acquired with the use of a DJI Inspire, which was equipped with a ZENMUSE Z3 camera manufactured by DJI. The images were input into Agisoft PhotoScan Professional version 1.2.6 (2016). Agisoft is a surface from motion processing program that creates a DEM and ortho mosaic image. Within the program, photo alignment was created at a medium accuracy. The amount of overlap that occurred between the photos taken can be seen in figure 7. Building of the dense cloud within Agisoft was also set at a medium accuracy. The DEM was then built off of the dense cloud and an orthomosaic was created. The report generated from the Agisoft processing can be found in Appendix 1.

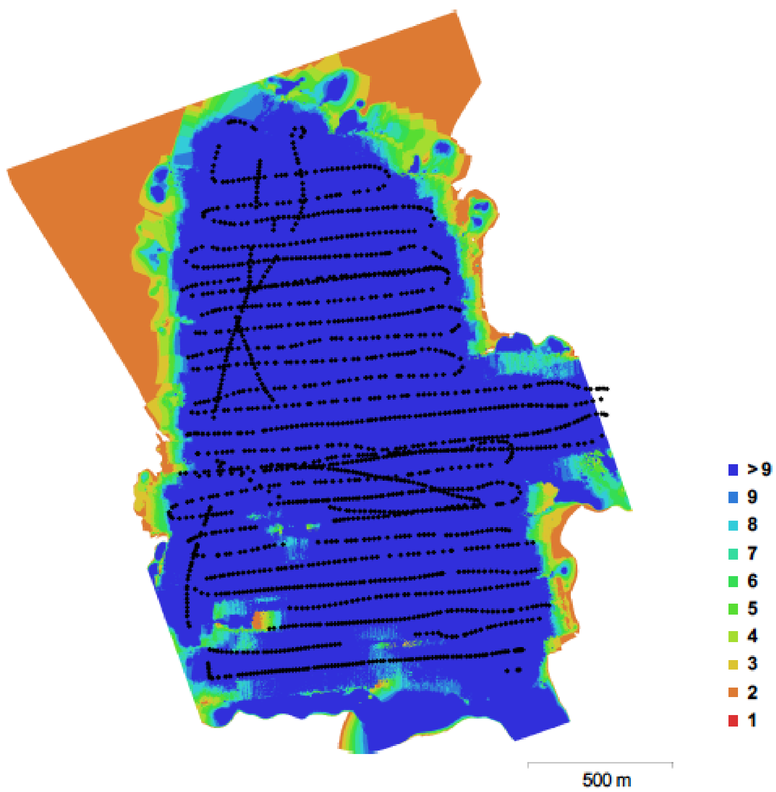


Figure 7: Locations of photos taken as well as amount of photo overlap.

ERDAS IMAGINE (2014) was used to create an Area of Interest (AOI) from the output of the surface from motion processing. The edge of the orthomosaic image and DEM is distorted and broken, as there is not enough overlap of images to accurately create elevation values and properly stich every part of the photos together. Figure 10 shows this distortion. The AOI removes these distorted areas that will cause problems in further processing.

The cleaned image and DEM was then brought into ESRI's ArcMap version 10.2.2 (2014). From this point, a flow accumulation model can be applied to create a hydromapping tool. The DEM layer's holes were filled and the resolution of the pixels was changed from 2.92e-006x1.93e-006 to 3e-005x3e-005 to reduce the effects of small irregularities. Because the DEM is created through surface from motion processing, it picks up tree heights and crowns that then act as the ground in the flow accumulation modeling. By increasing pixel size, it will smooth out some of the pointy treetops within the DEM. The open wetlands and water was masked out of the DEM to increase the sensitivity of small changes on the landscape when the flow accumulation model was run. A flow direction model was executed in ArcToolbox spatial analysis hydrology tools. From the output of this tool, a flow accumulation model can be run, again from the hydrology spatial analyst toolbox. The result of this model is the hydromapping tool. Areas with higher water accumulation will be brighter than areas with low accumulation. Points of high accumulation that should be protected from harvesting through the use of increased sized buffers were identified on the map. They are seen in figure 14 as green stars.

To create variable retention buffers, again the open wetlands and water were masked out. The landscape was also broken into two different zones. The area of Sprat Lake is in one zone and the two open wetland areas are in the second. These areas were exported into eCognition Developer 64 (2016). Using pixel distance to the edge of the DEM and a maximum elevation, it can be estimated where the edge of the riparian zone would be or water recharge zone. A value of 10 was used to determine the point on land were the DEM was higher than the now masked out open wetlands. The classified area of buffer was then input back into ArcMap and a polygon vector layer was traced around the classified area to have one continuous variable retention buffer layer. The process tree for classifying the buffer area can be seen in figure 8. The segmentation used for the buffers is the exact same as the segmentation used for classifying the wetlands and water. Segmentation had a shape of 0.5 and a compaction of 0.9.

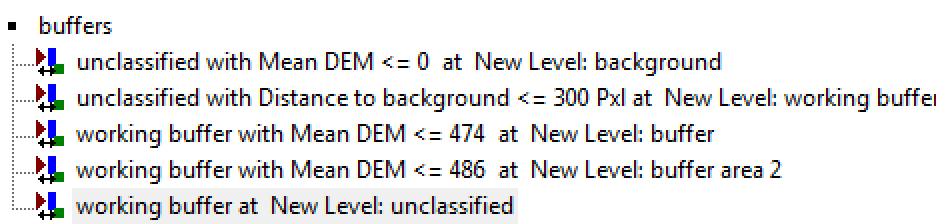


Figure 8: Process tree for classifying buffer area in eCognition.

The DEM and true colour image of Sprat Lake were input into eCognition to classify out the lake, open wetland and treed wetlands. The process tree can be seen in figure 9. It was impossible to classify the treed wetlands in eCognition as their reflectance values were too similar to the rest of the forested landscape. The identification of these MeHg hotspots was therefore mapped from photo interpretation. The river systems were also drawn as a vector file in ArcMap for a visual aid.

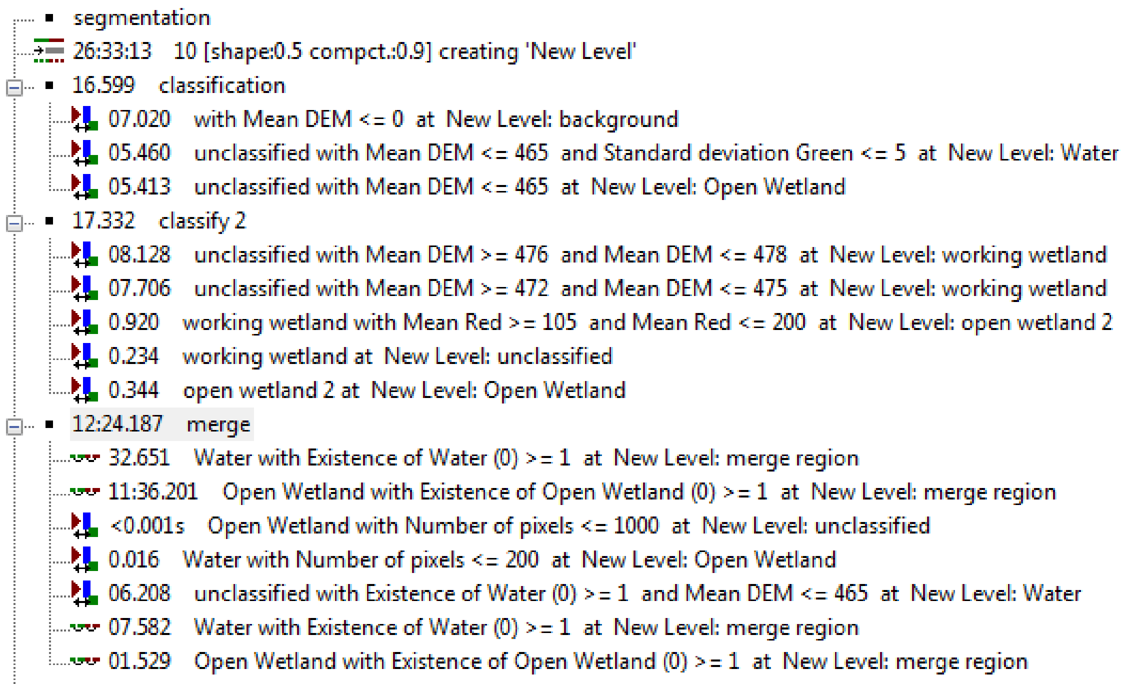


Figure 9: Process tree for the classification of Sprat Lake and the open wetlands.

The road corridors were drawn on the map starting from the already existing road and extended around the landscape where they do not cross any points of high water accumulation or areas of lowland environments.

RESULTS

The following section will display the results of the image processing conducted on Sprat Lake. A step-by-step flow of results are presented to allow for each step of the processing to be examined and act as a guide for others conducting similar studies.

The Agisoft surface from motion analysis created both an ortho mosaic photo as well as a DEM. The stitched together orthomosaic photo can be seen in figure 10 in true RGB colouration. The edges of the image are distorted, as there were not enough photos overlapping to accurately stitch those parts of the photo together and create a continuous elevation model. Perspective photos from the 3D model in Agisoft can be seen in figure 11. It can be noticed that while overall the elevation change is smooth, there are individual trees being picked up, giving the DEM a slightly peppered appearance. The area of interest image of Sprat Lake, after all the edges and areas of distorted DEM can be seen in figure 12. The projection in Arcmap is WGS_1984 UTM zone 16.

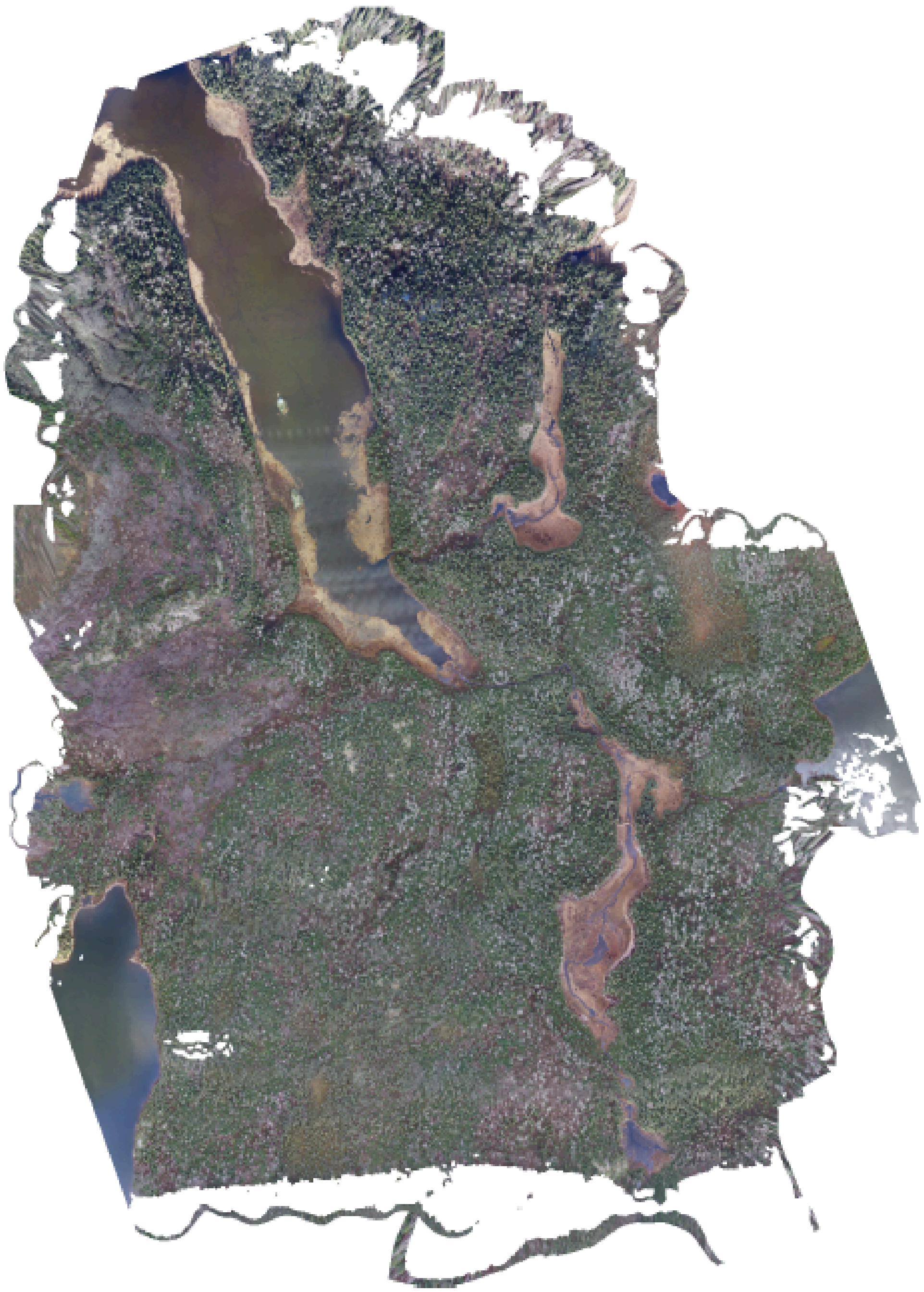
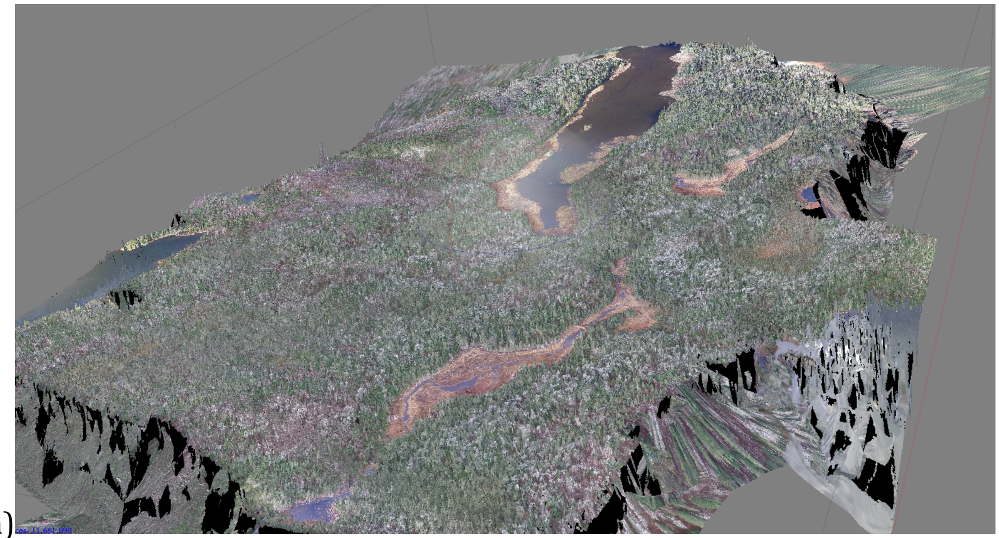
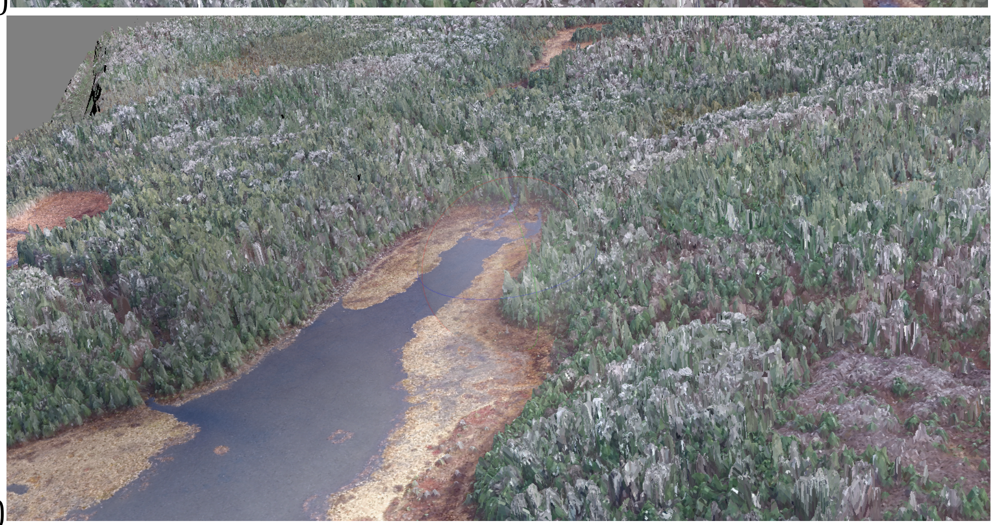


Figure 10: The ortho mosaic photo of the southern portion of Sprat Lake and it's surroundings.



a)

b)



c)

Figure: 11:Perspective images of the 3D model a) over the entire area b) looking at the Southern portion of Sprat lake from the South c) Looking at Sprat Lake from the North.

Figure 12: Area of Interest (aoi) of Sprat Lake.

While the RGB image can be used to help with land classification and photo interpretation, it does not work in creating a hydromapping tool. The DEM created from Agisofts surface from motion analysis was therefore used. The created DEM from that image processing can be seen in figure 13. The DEM seems like it has a bit of a spotty elevation change. This is because with the surface from motion analysis, the trees are what the elevation is based off of. This creates a bumpy surface from the treetops. It should also be noted that on the very Southern portion of the DEM, it starts to slope downward away from Sprat Lake. This is from the surface from motion analysis without enough photo overlap. This is not a landscape feature. From the DEM, flow direction can be determined. This can be seen in figure 14. It can be noted that the lake and open wetland areas of the image have been masked out as those areas of basically no elevation change skewed the data and made flow accumulation results inaccurate. The only flow accumulation that could be seen was in the middle of the lake.

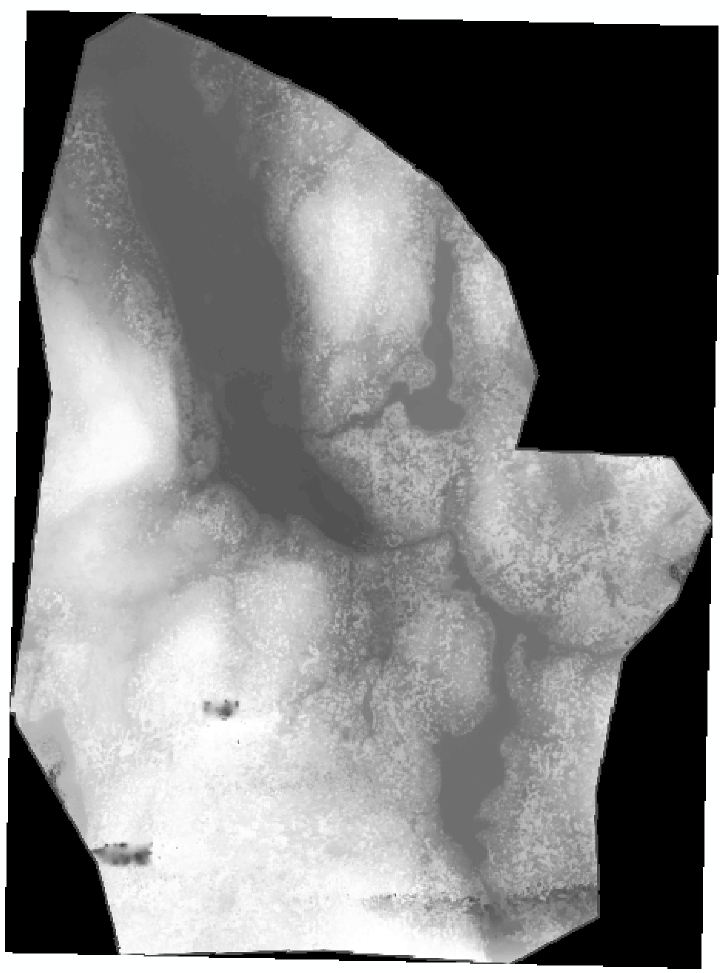


Figure 13: Digital Elevation Model of Sprat Lake

Figure 14: Flow direction of Sprat Lake with the lakes and open wetlands masked out.

In figure 15, the flow accumulation of the surface can be seen. This is the hydromapping tool. Accumulation runs from green into yellow, orange and finally red. Some of the more distinct accumulation patterns tend to end abruptly. This is due to the bumpiness of the DEM caused by the tree crowns.

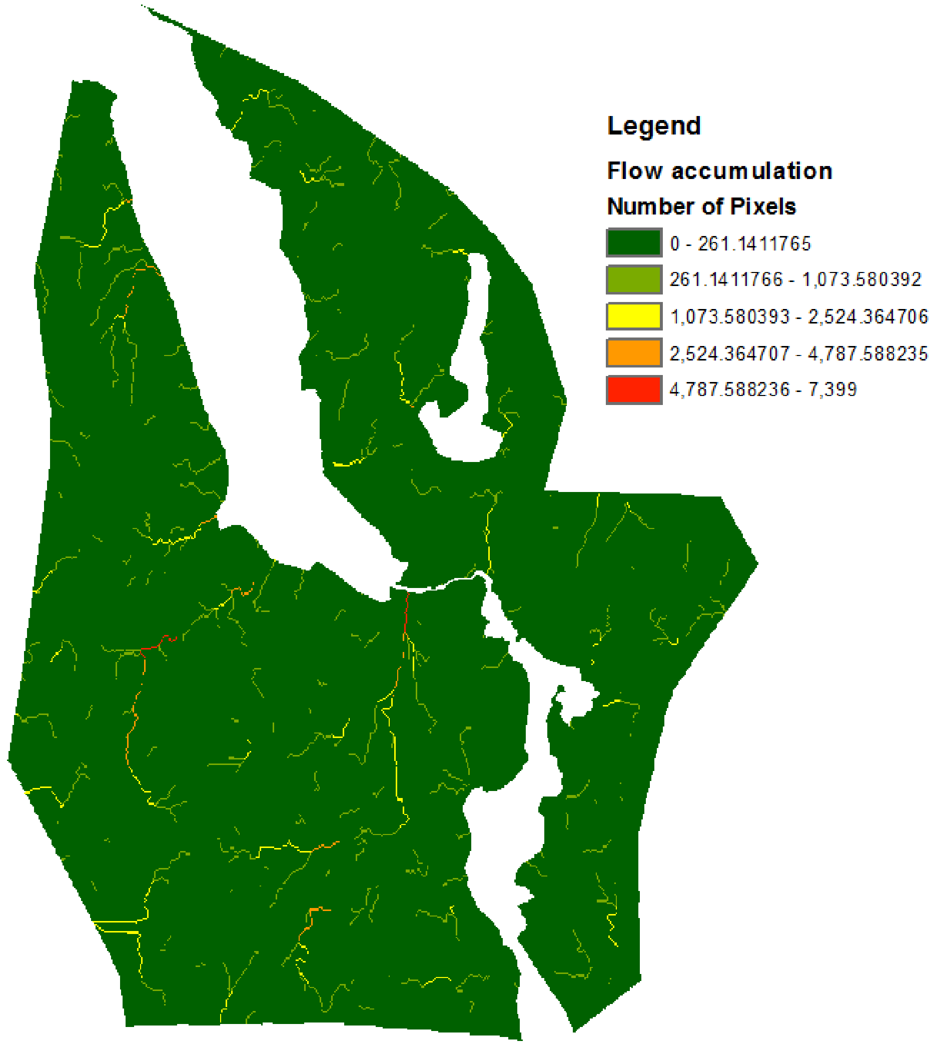


Figure 15: Flow accumulation results.

Based on the hydromapping tool, points of high water accumulation can be identified. These points have been highlighted in Figure 16 with green stars. These are areas that should be treated of areas of special concern when creating variable retention buffers.

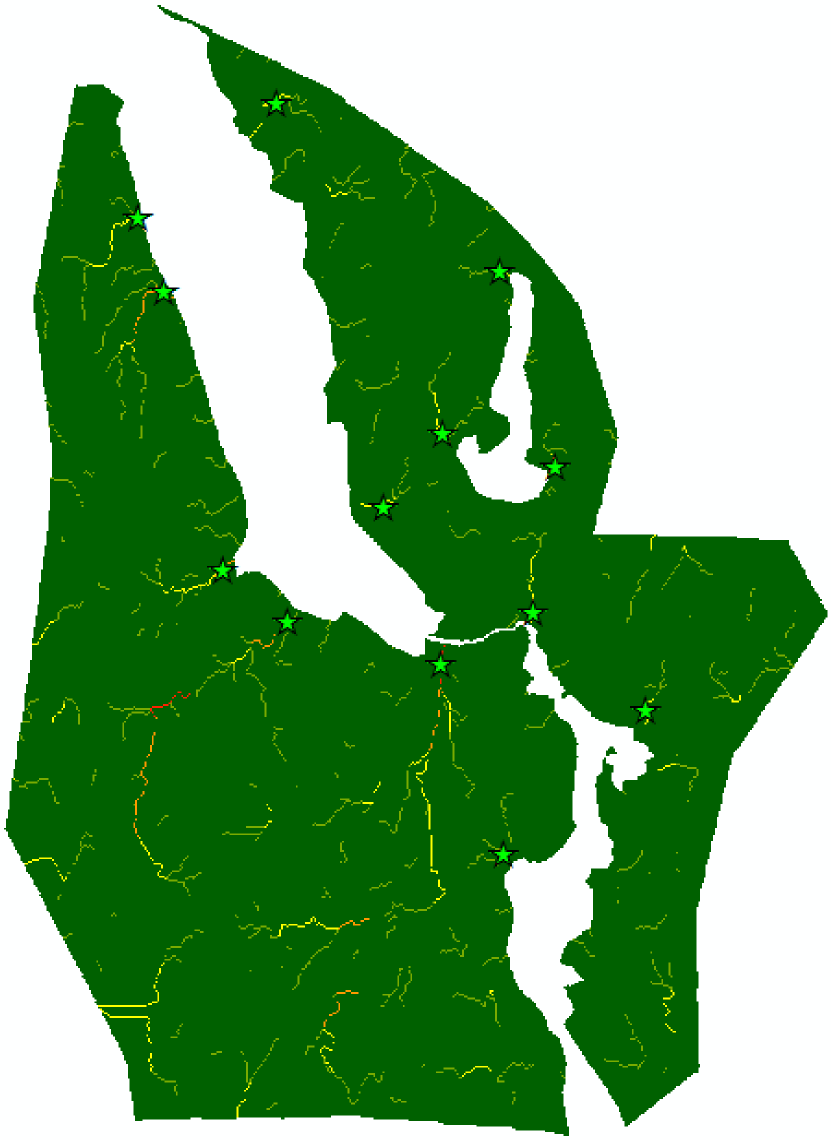


Figure 16: highlighted points of high flow accumulation around Sprat Lake.

The classification process tree for determining the variable retention buffers can be seen in figure 8. The results of that classification can be seen in figure 17 below. A single vector file was drawn over the classified area to smooth out lines and make it easier to interpret. The buffer widths range from just under 10 m to almost 80 m.

a) b)

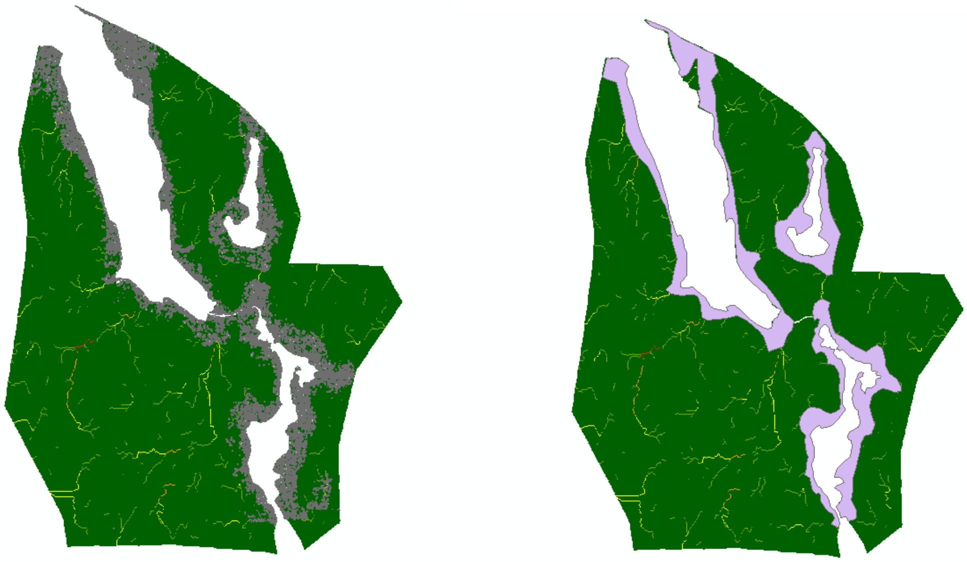


Figure 17: a) Classified buffers exported from eCognition b) smoothed variable retention buffers.

When overlaying the flow accumulation points of interest on the variable buffers, it can be seen that these points of interest correspond directly to the areas of widest buffers. This can be seen in figure 18.

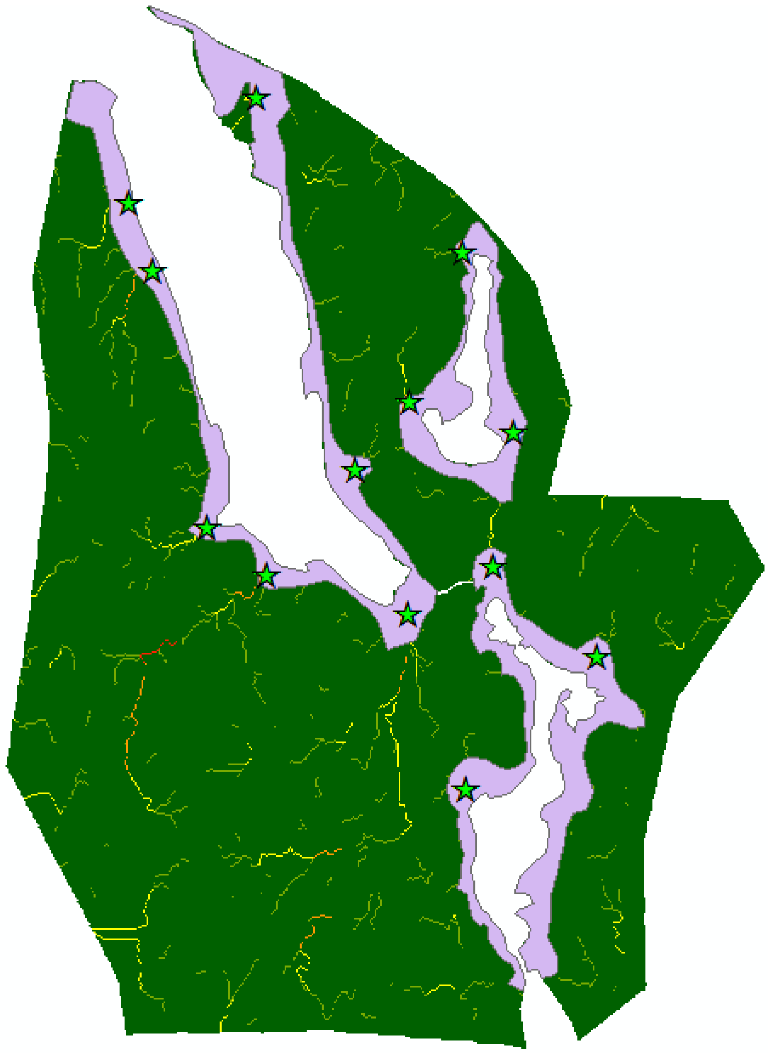


Figure 18: Flow accumulation points of interest overlaid on the variable retention buffers

In figure 9, the classification process tree can be seen for Sprat Lake and the open wetlands surrounding it. The results of this classification can be seen below in figure 19. The file was exported as a polygon and input into Arcmap and can be seen in figure 20. It should be noted that there are some small gaps between the open wetland and the buffer zone because when the water and wetlands were masked out, some of the land was masked out as well in order to make sure that none of the water area was included, as it would have distorted the results.

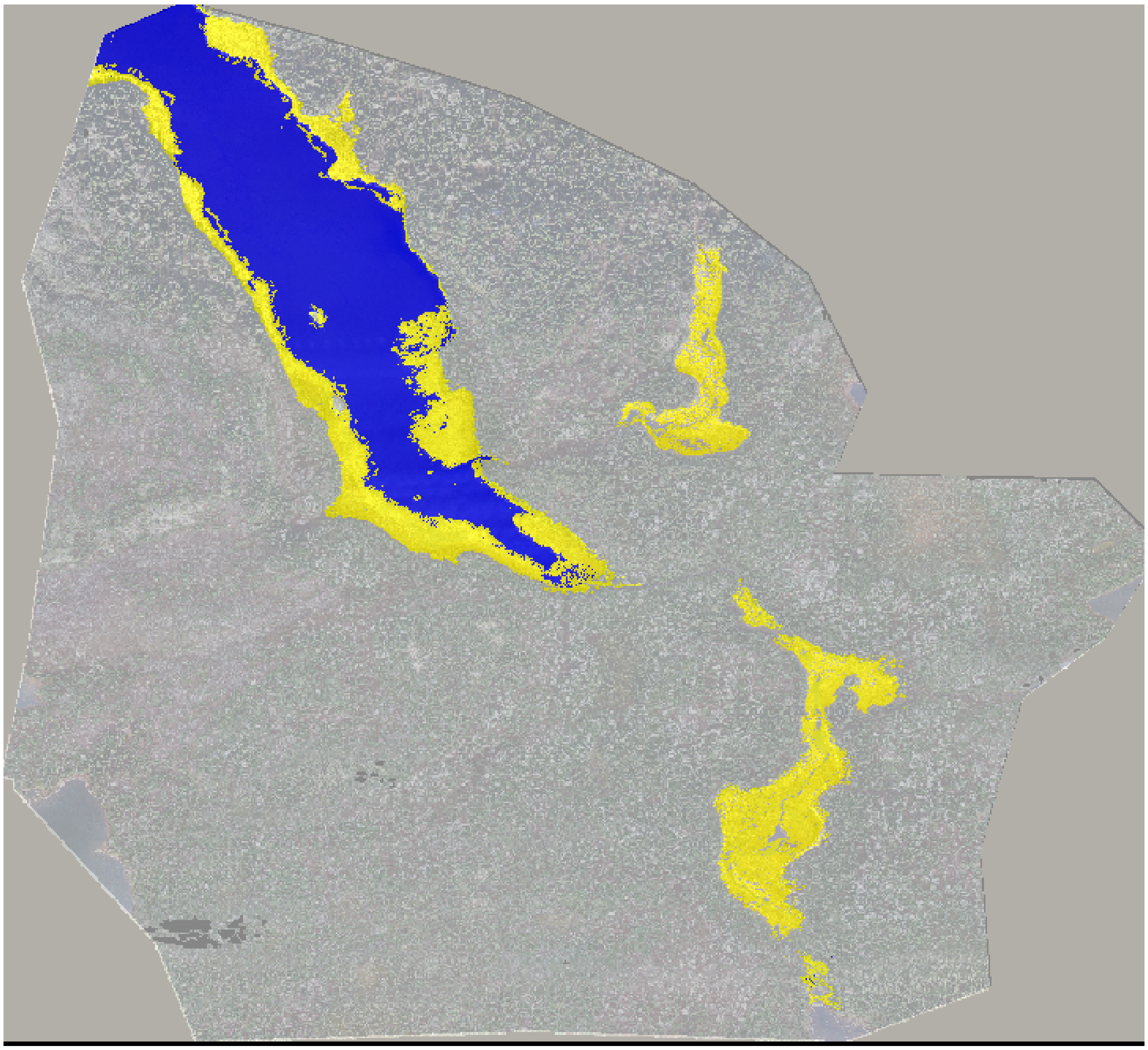


Figure 19: Classification results in eCognition of Sprat Lake.

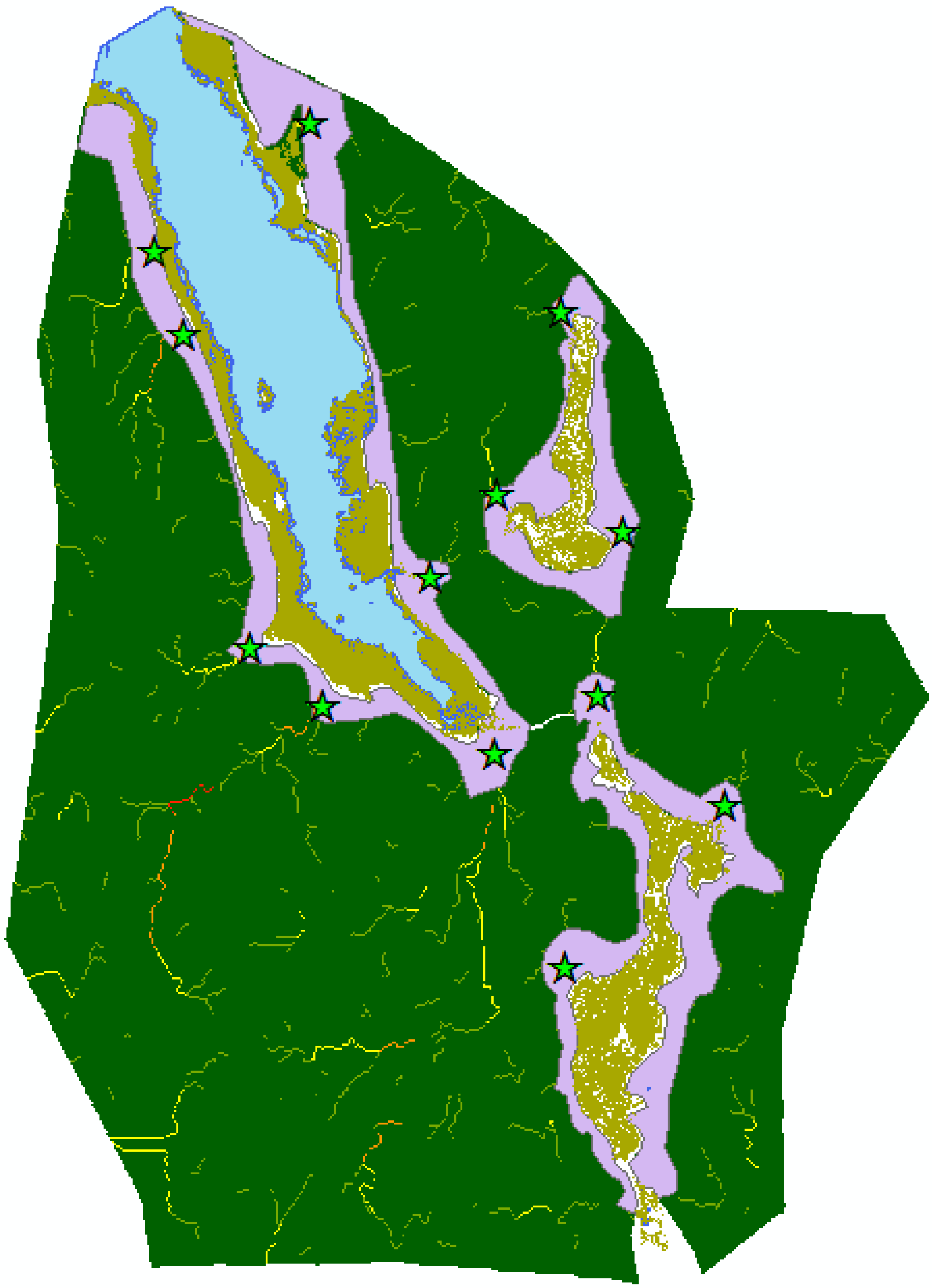


Figure 20: classified Sprat Lake and open wetlands input into the hydromapping tool.

As mentioned previously, the treed wetlands could not be classified out due to their similar reflectance values to the rest of the landscape. These MeHg hot spots still needed to be identified so photo interpretation was used. Other water bodies that were not classified out were also identified, as well and the rivers were drawn in to act as a visual aid. The result of this photo interpretation can be seen below in Figure 21.

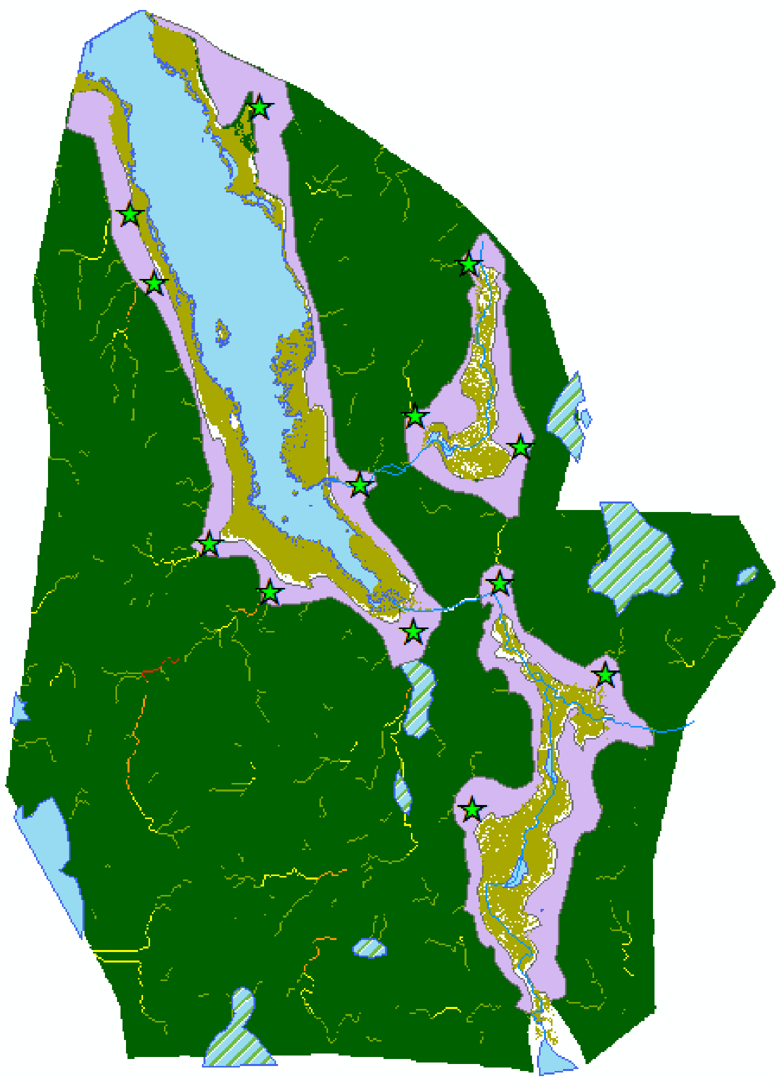


Figure 21: Sprat Lake hydromapping tool with photo interpreted treed wetlands and water bodies.

Finally, road corridors were placed on the map through areas of low flow accumulation. In figure 22 below, it can be seen on the left hand side of the catchment that there is an already existing road. The proposed new corridors extend from that point around the catchment and cross sensitive areas on the far side of wetlands that drain into Sprat Lake. A blue dot can also be seen in figure 22 and that is the location that was used to operate the UAV for this study.

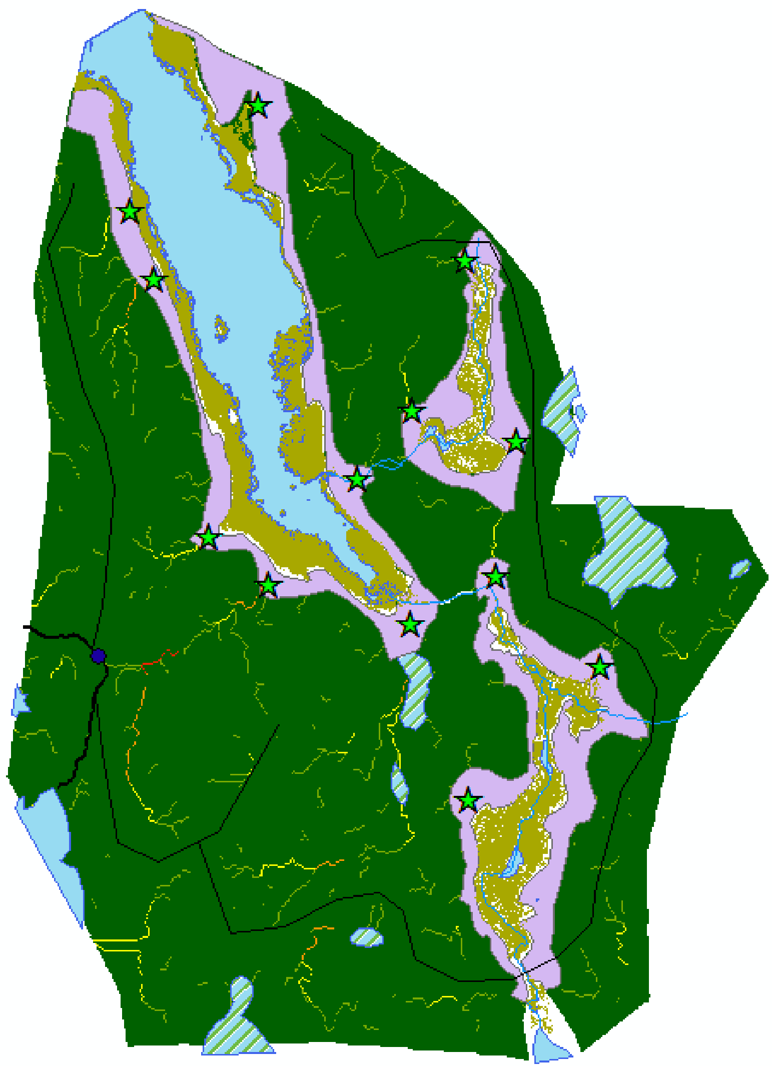


Figure 22: Sprat Lake hydromapping tool with road corridors and variable retention buffers.

While this study area is looking at a specific area of interest relating to brook trout spawning area, the entire catchment of Sprat Lake is much larger than what can be processed in a practical amount of time. Running time for the surface from motion processing took around 33 hours to complete, not including down time between steps. The segmentation for the eCognition classification also took around 30 hours to complete. Even though this is a small area, the amount of processing took a long time to complete.

DISCUSSION

Assumptions

The results from this study can be applied to the forest management plan of this area to minimize the disturbance on the landscape, reducing the amount of mercury entering the water system. The hydromapping tool created helps to divert management activities away from sensitive low laying areas onto upland sites. With this hydromapping tool, however, there are two assumptions that must be considered when using it. The first assumption is that hydrological flow is connected to surface topography. This is a good assumption as stated by Laudon et al. (2016) for boreal forests due to the till soil type. The second assumption is that the tree canopy represents the topography on the ground. The DEM created for Sprat Lake is based off of standard RGB photos that cannot penetrate to the ground level like a LiDAR sensor would be able to. With an even aged stand, tree heights should be similar and represent the ground elevation change. Slight deviation of hydrological flow path may occur but the general flow pattern should be accurate.

The pixel size is also very small at 21.5 cm/pixel. Even if there is a slight variation it is much more accurate than a landscape DEM that has a resolution of 20m/pixel. The purpose of this study is to determine wetlands and lowland areas where water accumulates. Open wetlands have no trees and as a result, their DEM values are much lower, making sure that the hydrological accumulation model flows into them. Treed wetlands tend to have smaller trees than upland environments due to the overabundance of water inhibiting growth (Feldpausch et al. 2006). This would again reduce the DEM values and steer the hydro accumulation model into those wetland areas.

This method of creating a hydromapping tool with SFM processing can only be conducted when there are no other site disturbances creating gaps in the canopy. This assumption that tree heights correlate with topography and therefore hydrological flow seems to hold true when inspecting the ortho mosaic photo and 3D model in AgiSoft. Areas determined to have high levels of groundwater accumulation reach the lake and open wetlands at points that to an observer, look like small ephemeral or intermittent streams. This would have to be confirmed in the field though. In a boreal forest like the area surrounding Sprat Lake, a hydromap created from surface from motion analysis is more accurate than anything that can be used in a practical, cost effective application.

Buffer Estimation

Based on the hydromapping tool, it can be determined where the areas of higher flow accumulation will occur. These areas could have ephemeral or intermittent streams, recharge zones or could just be areas where there are wet and saturated soils. The points on the map that have high water accumulation entering the open wetlands and lake are areas that will have higher saturation in their soils and the riparian zone and water recharge zone can extend further away from the shore compared to areas with less accumulation. These areas are highlighted on the map with green stars and should have extra consideration as ground water hot spots for MeHg release. Fixed width buffers may not take into consideration that the riparian zone and recharge zone extends farther than the conventional distance away from the hydrological feature. Riparian zones have high biodiversity and are instrumental in mitigating the effects of upland soil disturbances on aquatic systems (Kuglerova et al. 2014). Buffer widths should be variable, leading to wider buffers in areas with extended hydrological connectivity and they can be thinner where there is little connectivity to the aquatic system. Currently, buffers are only based on the adjacent land's slope. It does not consider that with a low slope, while runoff may be slower and easier to intercept, the hydrological connectivity beside the wetland or lake may extend quite far. Figure 22 shows this hydrological connectivity in the wet area. It might have ground cover, but the water table is just below ground and could even flood often. Because of this possible connectivity, land that had only a small change in elevation next to the wetland systems was classified out and a polygon was drawn around them to act as a variable buffer. It can be seen that the highlighted points of high flow accumulation are also the areas that have wider buffers. These variable buffers will help to protect the sensitive riparian features and allow for harvesting closer to aquatic environments that do not need as wide of protection. The variable buffers for the Sprat Lake's catchment are anywhere from just under 10m to almost 80m in width.

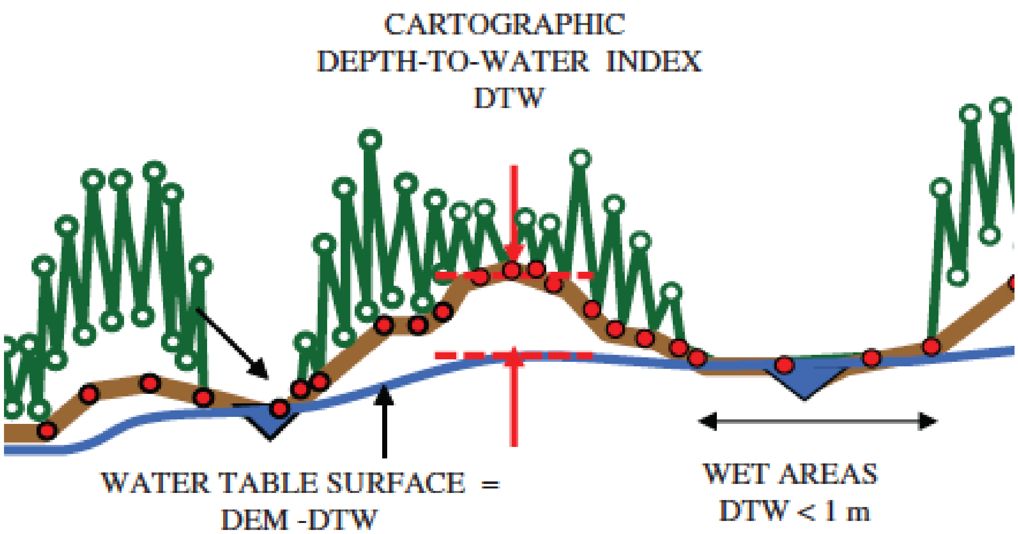


Figure 23: Water table in relation to surface topography. Source: White et al. 2012.

Road Corridors

In order to reduce soil disturbance, road corridors need to be laid out properly to avoid areas of high flow accumulation. Soils on upland environments tend to have a higher load bearing capacity due to the reduced amount of organic matter and water in their structure (Laudon et al. 2016). Heavy forestry equipment can damage the soil, but having them move along areas with the highest bearing capacity will reduce possible damages. Based on the hydromapping tool, a road corridor was laid out to avoid the areas of higher water accumulation, classified wetland areas and the variable buffers. This will ensure that the least amount of damage occurs on the site and any damage that does occur is not on MeHg hotspot environments. The roads do have to cross some lowland environments to make it over the entire catchment, however the roads cross on the opposite side of wetlands that drain into Sprat Lake. This allows the wetland to hopefully mitigate any negative effects of the road disturbance before that water reaches the brook trout spawning grounds of Sprat Lake.

Avoidance of Wetlands and Minimization of Disturbance

The hydromapping tool and wetland classification is a great resource for operational contractors to properly plan out their cuts. By avoiding the wetland environments and areas of flow accumulation, soil disturbance in MeHg hot spots will be reduced, minimizing the effects of harvesting on aquatic levels of MeHg. This tool will reduce the amount of operational surprises as ephemeral and intermittent streams that are not present on a provincial database are picked up and can be managed around. The Stand and Site Guide (2010) notes that harvesting on lowland sites should be conducted during the winter as the water freezes, increasing load bearing capacity. There are, however, very few studies that actually test this theory. Eklöf et al. (2014) determines that harvesting during the winter months when the ground is frozen, does reduce the amount of soil disturbance and may reduce the amount of mercury entering the aquatic system. The effects of careful winter logging, however, can be negated when site preparation occurs. Site preparation's main goal is to disturb the soil and this may release a higher amount of stored mercury (Eklöf et al. 2014).

While harvesting in the winter will reduce the amount of soil disturbance, during these operations there can be surprises. Eklöf et al (2014), Laudon et al. (2016) have noted that during winter harvesting, snow covers the ground and unmapped wetland and lowland areas may not be visible. These MeHg hotspots can then be easily disturbed. Having a hydromapping tool like the one in this study can outline areas of high water accumulation that may not be identified on a standard Forest Resource Inventory. It allows harvesters to know what areas to avoid even in the winter season.

Practical Applications of UAVs in Hydromapping Tool Creation

UAVs have shown their many practical uses in natural resources management and other industries. Their ease of use and quick deployment times can make them an excellent tool for resource managers. Their greatest weakness, though, is their short flight range and the long processing time for the data they collect. Below in figure 23, the full extent of the catchment of Sprat Lake is shown. Sprat Lake is just to the left of the computer cursor. During processing, the amount of time to create the 3D model and ortho mosaic in Agisoft took around 33 hours of processing, not including time in between finishing one step and starting the next. The segmentation alone in the classification of open wetlands and water took 30 hours in eCognition. The use of Drones to create high resolution DEM is a practical solution when one is not available in an FRI, however, conducting this processing on a landscape scale would not be feasible. The best use of it would be to identify areas of concern like Sprat Lake, which contains sensitive brook trout spawning grounds, and then to create a hydrompapping tool for that immediate area. A 20m/pixel DEM will not properly map out small hydrological flow patterns but a fine scale hydromap will.

With this study, the images captured by the drone are standard red, green, blue (RGB) images. With these reflectance's captured by the sensor, it can be hard to pick out differences between the vegetation. The photos were taken for this study in November when the leaves had fallen off the trees and ground vegetation had died out. This made it easy for the open wetlands to be classified but the differences between treed wetlands and the upland conifer forests were unable to be classified differently on their reflectance values. Having a near infrared sensor (NIR) could provide the differences in reflectance needed to be able to identify these wetlands in a supervised or unsupervised classification. Having a LiDAR scanner to map out the ground topography would increase the accuracy of the DEM. These pieces of equipment are expensive and so far, unable to be equipped to a drone. They are just not practical at this time for general forest operational planning. The next step in this study would be to use a LiDAR scanner and compare the flow accumulation model created to the one in this study. This would test the second assumption that we consider in this study and can prove if LiDAR scanners are worth the money compared to surface from motion analysis. In future FRI surveys, a LidAR or radar scan with a high pixel resolution such a 1m/pixel would make this type of hydromapping possible over the entire landscape and reduce possible negative effects of forest operations on aquatic systems.

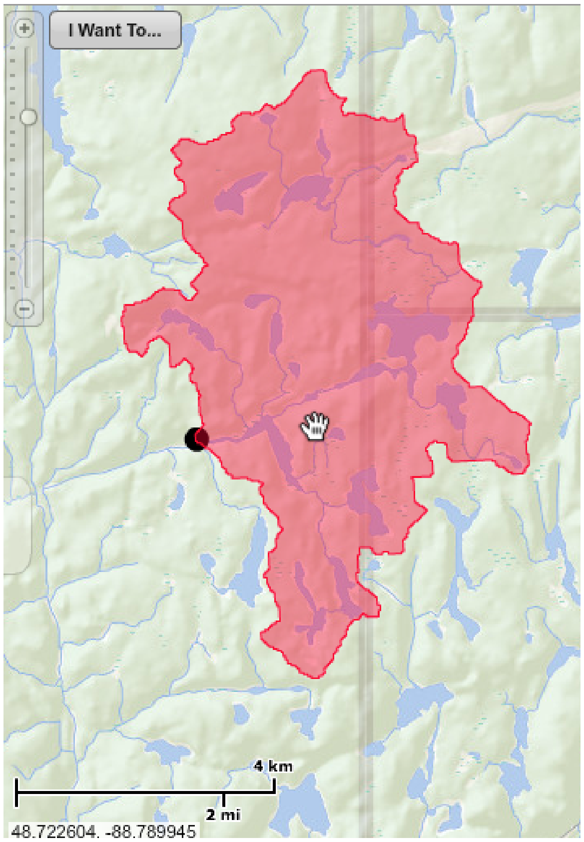


Figure 23: Outline of Sprat Lake's Catchment area. Source: Ministry of Natural Resources and Forestry; Ontario Flow Assessment Tool III.

CONCLUSION

The hydromapping tool and wetland classification is a great resource for harvesters and land managers to properly plan their forest operations. By avoiding wetland environments and areas of high flow accumulation, soil disturbance in MeHg hot spots will be reduced, minimizing possible effects of harvesting on aquatic levels of Hg. This will in turn help to prevent increases in MeHg in fish species. While this process of using UAV images to create a hydromapping tool may not be effective for the entire management area, it is a practical tool for areas of known sensitivity like Sprat Lake that contains a brook trout spawning ground.

Future FRI should include a higher resolution DEM from LiDAR or radar to be able to manage flow accumulation across a landscape scale. This hydromapping tool also provides the spatial information to properly lie out variable retention buffers to cover the full extent of riparian zones that would otherwise be wider then a standard buffer width. The most upland areas of the landscape as determined by the hydromapping tool should also be the road corridors for heavy forwarders to reduce soil damage. This proactive approach to harvesting will minimize operational surprises, ensuring that unmapped MeHg hotspots are not disturbed. By reducing site damage based on a hydromapping tool, the health of the aquatic system next to forest operations will be conserved helping to ensure the long-term sustainability of forest harvest operations.

LITERATURE CITED

Bishop, K., C. Allen, L. Bringmark, E. Garcia, S. Hellsten, L. Hogbom, K. Johansson, A. Lomander, M. Meili, J. Munthe, M. Nilsson, P. Porvari, U. Skyllberg, R. Sorensen, T. Zetterburg, S. Akerblom. 2009. The Effects of Forestry on Hg Bioaccumulation in Nemoral/Boreal Waters and Recommendations for Good Silvicultural Practice. *Ambio.* 38(7):373-380.

Braaten, H. and Wit, H. 2016. Effects of Disturbance and Vegetation Type on Total and Methylmercury in Boreal Peatland and Forest Soils. *Environmental Pollution*. 218: 140-149.

Center for Disease Control and Prevention (CDC). 2007. Mercury. Online https://www.cdc.gov/biomonitoring/pdf/Mercury_FactSheet.pdf . October 14th, 2016.

Danco, V. 2013. The Association Between Watershed Characteristics and Mercury Contamination in Fish in Northern Ontario Lakes. Masters thesis, Faculty of Biology, Lakehead University, ON. 171.

DeBell, L., K. Anderson, R. Brazier, N. King, L. Jones. 2015. Water Resource Management at Catchment Scales Using Lightweight UAVs: Current Capabilities and Future Perspectives. *Journal of Unmanned Vehicle* Systems*.* 4: 7-30.

Driscoll, C. Han, Y. Chen C. Evers D. Lambert K. Holsen, T. Kamman, N. Munson, R. 2007. Mercury Contamination in Forest and Freshwater Ecosystems in the Northeastern United States. *Bioscience.* 57(1): 17-28.

Eklöf, K., J. Schelker, R. Sørensen, M. Meili, H. Laudon, C. Brömssen, K. Bishop. 2014 Impact of Forestry on Total and Methyl-Mercury in Surface Waters: Distinguishing Effects of Logging and Site Preparation. *Environmental Science and Technology.* 48: 4690-4698.

Eklöf K., R. Lidskog, K. Bishop. 2016. Managing Swedish Forestry's Impact on Mercury in Fish: Defining the Impact and Mitigation Measures. *Ambio*. 45(2): 163-174.

Environment and Climate Change Canada. 2013. Biogeochemistry. Online https://www.ec.gc.ca/mercure-mercury/default.asp?lang=En&n=67E16201-1 . October 15, 2016.

Feldpausch T., A. McDonald, C. Passos, J. Lehmann, S. Riha. 2006. Biomass harvestable area, and forest structure estimated from commercial timber inventories and remotely sensed imagery in southern Amazonia. *Forest Ecology and Management,* 233:121-132

Fitzgerald, W., Engstrom, D., Mason, R. and Nater, E. 1998. The case for Atmospheric Mercury Contamination in Remote Areas. *Environmental Science & Technology*. 32(1): 1-7.

Friske, P. and Coker, W. 1995. The Importance of Geological Controls on the Natural Distribution of Mercury in Lake and Stream Sediments Across Canada. *Water, Air and Soil Pollution.* 80(1): 1047-1057.

Fu, X., Feng, X., Dong, Z., Yin, R., Wang, J., Yang, Z., Zhang, H. Atmospheric Gaseous Elemental Mercury (GEM) Concentrations and Mercury Depositions at a High-Altitude Mountain Peak in South China. *Atmospheric Chemistry and Physics*. 10:2425-2437.

Garcia E. and Carignan, R. 1999. Impact of Wildfire and Clear-Cutting in the Boreal Forest on Methyl Mercury in Zooplankton. *Canadian Journal of Fisheries and Aquatic Sciences.* 56:339-345.

Garcia, E. and Carignan, R. 2000. Mercury Concentrations in Northern Pike (*Esox Lucius*) from Boreal Lakes with Logged, Burned or Undisturbed Catchments. *Canadian Journal of Fisheries and Aquatic Science*s. 57(2):129-135.

Gillies, C. 2011. Water Management Techniques For Resource Roads in Wetlands: A State of Practical Review. FPInnovations. Online https://fpinnovations.ca/ResearchProgram/SiteAssets/Pages/research-program-forest-operations/FPInnovations_CR-652-CTG_State_of_Practice_Review.pdf November 30, 2016.

Grigal, D. 2002. Inputs and Outputs of Mercury from Terrestrial Watersheds: A Review. *Environmental Review* 10: 1-39.

Health Canada. 2007. *Human Health Risk Assessment of Mercury in Fish and Health Benefits of Fish Consumption*. Bureau of Chemical Safety Food Directorate Health Products and Food Branch. Ottawa, Ontario.

Hultberg, H. Muthe, J. and Iverdeldt, Å. 1995. Cycling of Methylmercury and Mercury- Responses in the Forest Roof Catchment to Three Years of Decreased Atmospheric Deposition. *Water, Air, and Soil Pollution.* 80(1): 415-424.

Kreutzweiser, D., P. Hazlett, J. Gunn. 2008. Logging Impacts on the Biogeochemistry of Boreal Forest Soils and Nutrient Export to Aquatic Systems: A Review. *Environmental Reviews.* 16:157-179.

Kuglerova L., A. Agren, R. Jansson, H. Laudon. 2014. Towards Optimizing Riparian

Buffer Zones: Ecological and Biogeochemical Implications for Forest Management. *Forest Ecology and Management.* 334: 74-84.

Laudon, H., L. Kuglerova, R. Sponseller, M. Futter, A. Nordin, K. Bishop, T. Lundmark, G. Egnell, A. Agren. 2016. The Role of Biogeochemical Hotspots, Landscape Heterogeneity, and Hydrological Connectivity for Minimizing Forestry Effects on Water Quality. *Ambio* 45(2):152-162.

Louis, V., J. Rudd, C. Kelly, K. Beaty, N. Bloom, R. Flett. 1994. Importance of Wetlands as Sources of Methyl Mercury to Boreal Forest Ecosystems. *Canadian Journal of Fish and Aquatic Science.* 51:1065-1076.

Lucotte, M. Mucci, A. Hillaire-Marcel, C. Pichet, P. Grondin, A. 1995. Anthropogenic Mercury enrichment in remote lakes of Northem Québec (Canada). *Water, Air Soil Pollution.* 80: 467-476.

Luke, S., N. Luckai, J. Burke, E. Prepas. 2007. Riparian Areas in the CanadianBoreal Forest and Linkages with Water Quality in Streams. *Environmental Review.* 15:79-97.

Mackereth, R. 2015. The Impact of Boreal Forest Disturbance on Watershed Mercury Dynamics. Ministry of Natural Resources, Thunder Bay.

Marcaccio, J., E. Mrkele, and P. Chow-Fraser. 2015. Unmanned Arial Vehicles Produce High-Resolution, Seasonally-Relevant Imagery for Classifying Wetland Vegetation. *Remote Sensing and Spatial Information Sciences*, 40: 249-256.

Mierle, G. and Ingram, R. 1991. The Role of Humic Substances in the Mobilization of Mercury from Watersheds. *Water, Air and Soil Pollution.* 56:349-367.

Miskimmin, B., W. Rudd, C. Kelly. 1992. Influence of DOC, pH and Microbial Respiration Rates on Mercury Methylation and Demethylation in Lake Water. *Canadian Journal of Fisheries and Aquatic Sciences.* 49:17-22

MNR. 2010. Forest Management Guide for Conserving Biodiversity at the Stand and Site Scale. Queen's Printer for Ontario, Toronto. pp. 212

NASA. 2016. Measuring Vegetation (NDVI and EVI). Online http://earthobservatory.nasa.gov/Features/MeasuringVegetation/measuring_vegetation_2.php November 30, 2016.

O'Driscoll, N., P. Lean, L. Loseto, R. Carignan, S. Siciliano. 2004. Effect of DOC on Photoreduction of DGM in Lakes: Potential Impacts of Forestry. *Environmental Science and Technology*. 38:2664-2672.

Ozesmi, S. and Bauer, M. 2002. Satellite Remote Sensing of Wetlands. *Wetland Ecology and Management.* 10: 381-402.

Park, J. and Zheng W. 2012. Human Exposure and Health Effects of Inorganic Elemental Mercury. *Journal of Preventative Medicine and Public Health.* 45: 344-352.

Parkyn, S. 2004. Review of Riparian Buffer Zone Effectiveness. Ministry of Agriculture and Forests. Online http://www.crc.govt.nz/publications/Consent%20Notifications/upper-waitaki-submitter-evidence-maf-technical-paper-review-riparian-buffer-zone-effectiveness.pdf November 30, 2016.

Pinheiro, F. 2000. Effects of Forest Fires and Clear Cutting on Mercury Leading to Boreal Lakes. Masters thesis, McGill University, Montreal, QC. 124.

Rudd, J. 1995. Sources of Methyl Mercury to Freshwater Ecosystems: A Review.*Water, Air and Soil Pollution.* 80(1):697-713.

Trudel, M. and Rasmussen, J. 1997. Modeling the Elimination of Mercury by Fish. *Environmental Science and Technology.* 31: 1716-1722.

Ullrich, S.M. Tanton, T.W., and Abdrashitova, S.A. 2001. Mercury in the aquatic environment: A review of the factors affecting methylation. *Critical Reviews in Environmental Science and Technology.* 31(3): 241-293.

United Nations Environment Programme (UNEP). 2009. *Global atmospheric mercury assessment: sources, emissions and transport.* UNEP-Chemicals. Geneva, Switzerland. December, 2009.

Weber, J. 1993. Review of Possible Path for Abiotic Methylation of Mercury (II) in the Aquatic Environment. *Chemosphere* 26(11):2063-2077.

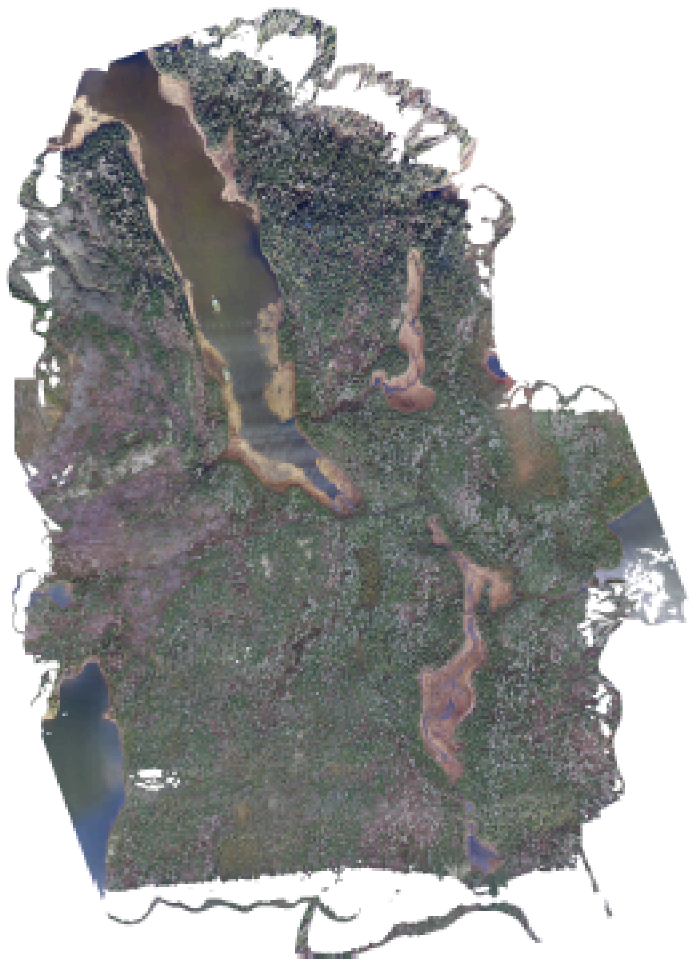
White, B., J. Ogilvie, D. Campbell, D. Hiltz, B. Gauthier, H.Chisholm, H. Wen, P. Murphy, P. Arp. 2012. Using the Cartographic Depth-to-Water Index to Locate Small Streams and Associated Wet Areas across Landscapes. *Canadian Water Resource Journal*. 37(4): 333-347.

Wiener, J. Gilmour, C. and Krabbenhoft, D. 2003. Mercury Strategy for the Bay-Delta Ecosystem: A Unifying Framework for Science, Adaptive Management and Ecological Restoration. Online http://science.calwater.ca.gov/pdf/mercurystrategyfinalreport.pdf . October 15, 2016.

APPENDIX 1

sprat lake

Processing Report
29 November 2016



Survey Data

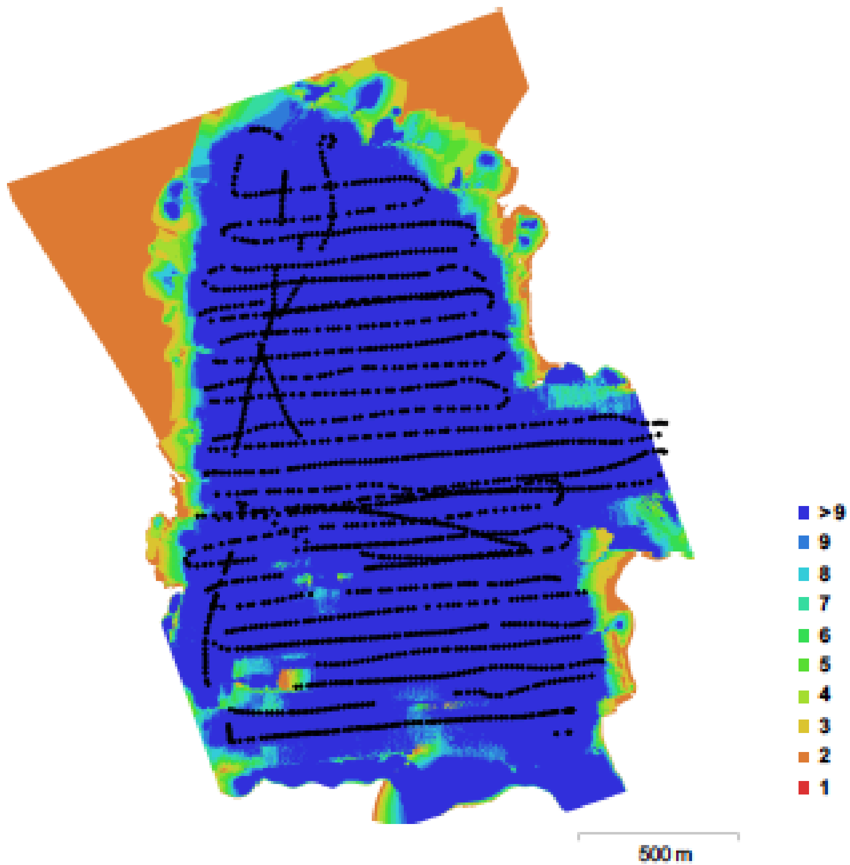


Fig. 1. Camera locations and image overlap.

Number of images:	1,846	Camera stations:	1,694
Flying altitude:	145 m	Tie points:	616,705
Ground resolution:	5.38 cm/pix	Projections:	1,730,453
Coverage area:	3.32 km²	Reprojection error:	2.46 pix

Camera Model	Resolution	Focal Length	Pixel Size	Precalibrated
FC350 (3.61 mm)	4000 x 3000	3.61 mm	1.56 x 1.56 μm	No

Table 1. Cameras.

Camera Calibration

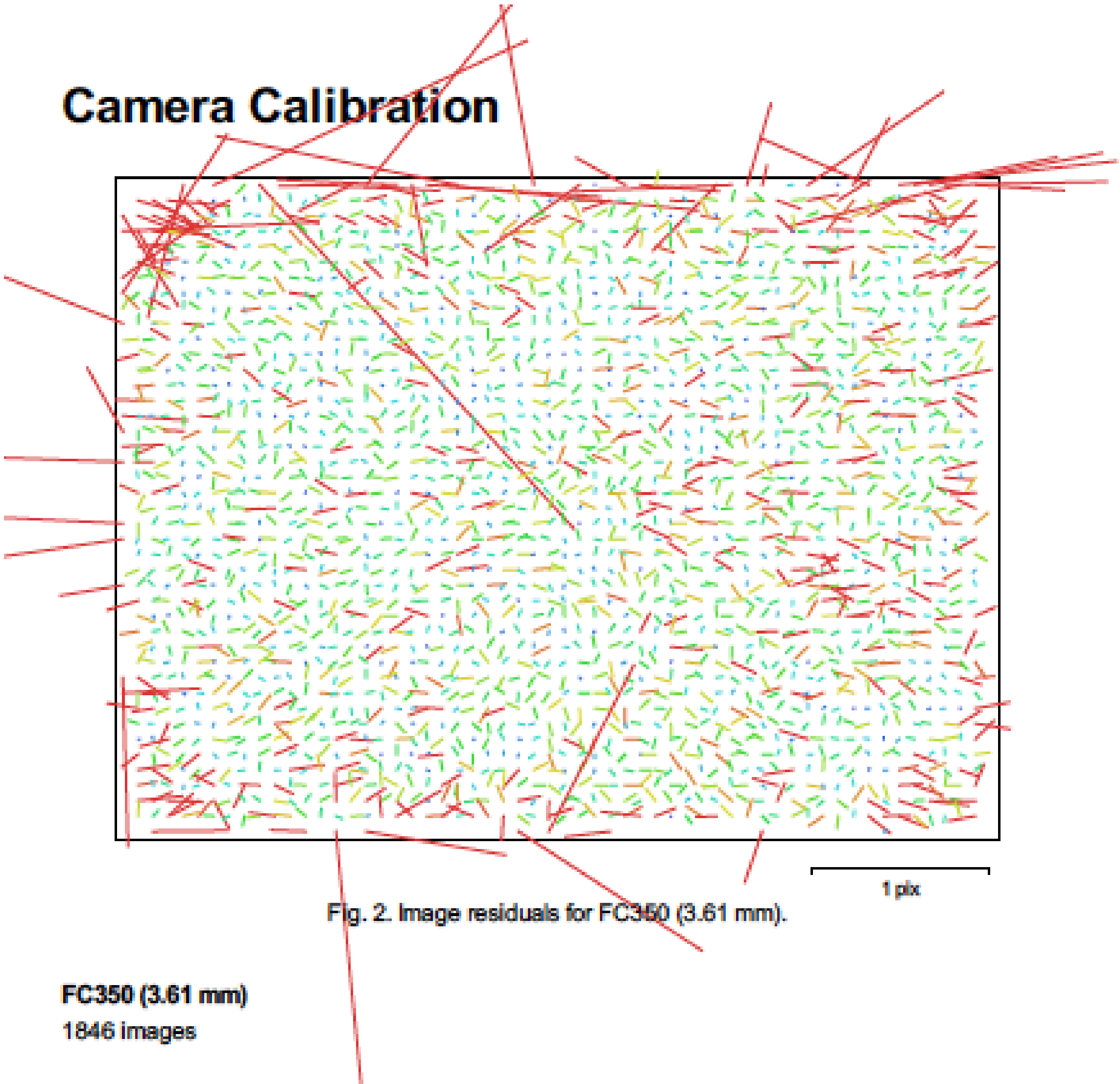


Fig. 2. Image residuals for FC350 (3.61 mm).

FC350 (3.61 mm)
1846 images

Resolution	Focal Length	Pixel Size	Precalibrated
4000 x 3000	**3.61 mm**	**1.56 x 1.56 μm**	**No**

Type:	Frame	F:	2311.25
Cx:	21.9611	B1:	-6.86118
Cy:	-5.69803	B2:	-0.462791
K1:	-0.126138	P1:	7.22807e-05
K2:	0.0986882	P2:	1.99686e-05
K3:	-0.0105938	P3:	0
K4:	0	P4:	0

Camera Locations

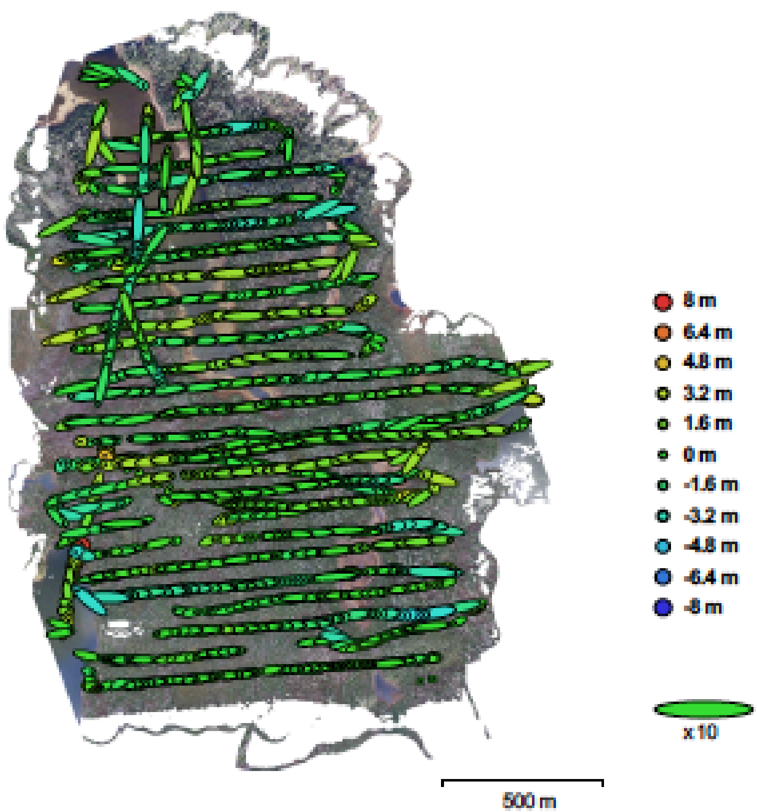


Fig. 3. Camera locations and error estimates.
Z error is represented by ellipse color. X,Y errors are represented by ellipse shape.
Estimated camera locations are marked with a black dot.

X error (m)	Y error (m)	Z error (m)	XY error (m)	Total error (m)
5.67818	1.98618	1.40508	6.01553	6.17745

Table 2. Average camera location error.

Digital Elevation Model

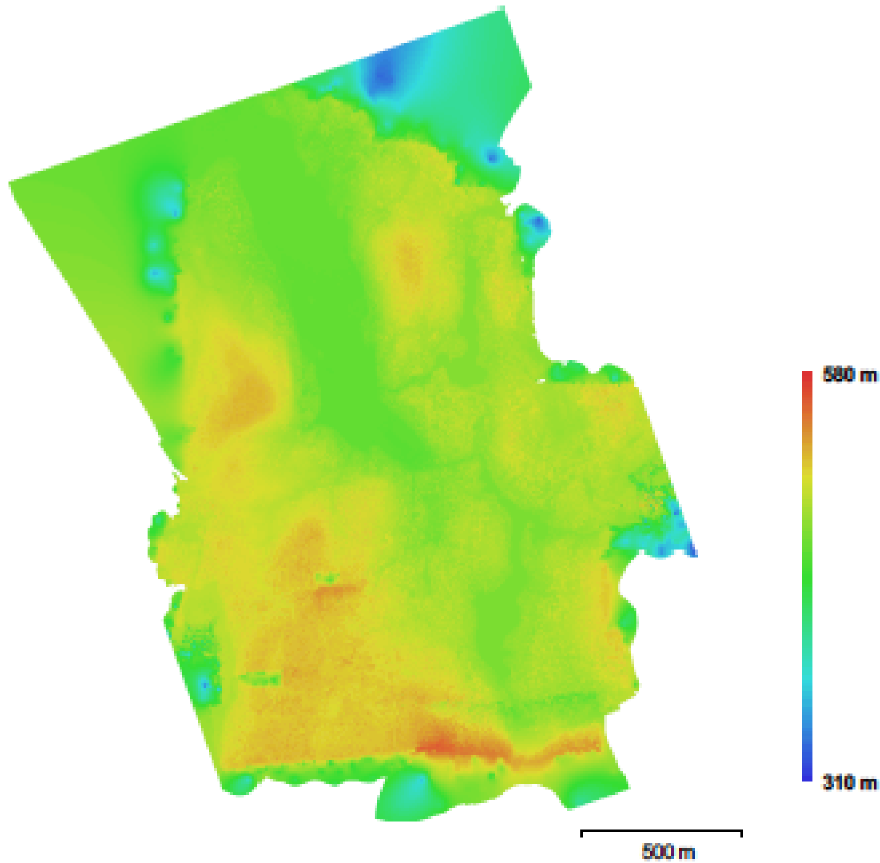


Fig. 4. Reconstructed digital elevation model.

Resolution:	21.5 cm/pix
Point density:	21.6 points/m²

Processing Parameters

General	
Cameras	1846
Aligned cameras	1694
Coordinate system	WGS 84 (EPSG::4326)
Point Cloud	
Points	616,705 of 690,884
RMS reprojection error	0.130922 (2.46254 pix)
Max reprojection error	0.397009 (45.8907 pix)
Mean key point size	16.4168 pix
Effective overlap	3.16899
Alignment parameters	
Accuracy	Low
Pair preselection	Reference
Key point limit	1,000,000
Tie point limit	10,000
Constrain features by mask	No
Adaptive camera model fitting	Yes
Matching time	25 minutes 31 seconds
Alignment time	18 minutes 27 seconds
Dense Point Cloud	
Points	116,905,669
Reconstruction parameters	
Quality	Medium
Depth filtering	Disabled
Depth maps generation time	2 hours 32 minutes
Dense cloud generation time	1 days 2 hours
Model	
Faces	23,315,399
Vertices	11,661,890
Texture	4,096 x 4,096, uint8
Reconstruction parameters	
Surface type	Height field
Source data	Dense
Interpolation	Enabled
Quality	Medium
Depth filtering	Disabled
Face count	23,381,109
Processing time	6 minutes 54 seconds
Texturing parameters	
Mapping mode	Adaptive orthophoto
Blending mode	Mosaic
Texture size	4,096 x 4,096
Enable color correction	Yes
Enable hole filling	Yes
UV mapping time	5 minutes 52 seconds
Blending time	3 hours 30 minutes
DEM	
Size	11,066 x 13,356
Coordinate system	WGS 84 (EPSG::4326)
Reconstruction parameters	
Source data	Dense cloud
Interpolation	Enabled
Processing time	2 minutes 37 seconds
Orthomosaic	
Size	40,436 x 47,952
Coordinate system	WGS 84 (EPSG::4326)

Channels	3, uint8
Blending mode	Mosaic
Reconstruction parameters	
Surface	DEM
Enable color correction	No
Processing time	49 minutes 17 seconds
Software	
Version	1.2.6 build 2834
Platform	Windows 64 bit