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Ecohydraulic modeling of the St. Mary's Rapids

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Introduction

The St. Mary's River is the connection between two Great Lakes: Lake Superior and Lake Huron. It covers parts of the lower portion of the river from Echo Bay at the north end of Lake George to Maxton Bay near waters widening toward Lake Huron. The river varies in width, sometimes narrow, but often widening into large bays and lakes. It is 125 km long and drops 6.4 m through the sault (old french term meaning "rapids" or "falls" after which the Canadian and U.S. cities of Sault Ste. Marie were named), with a mean discharge of 2 140 m^3/s. For its entire length it is an international border, separating Michigan in the United States from Ontario in Canada (Figure 1).

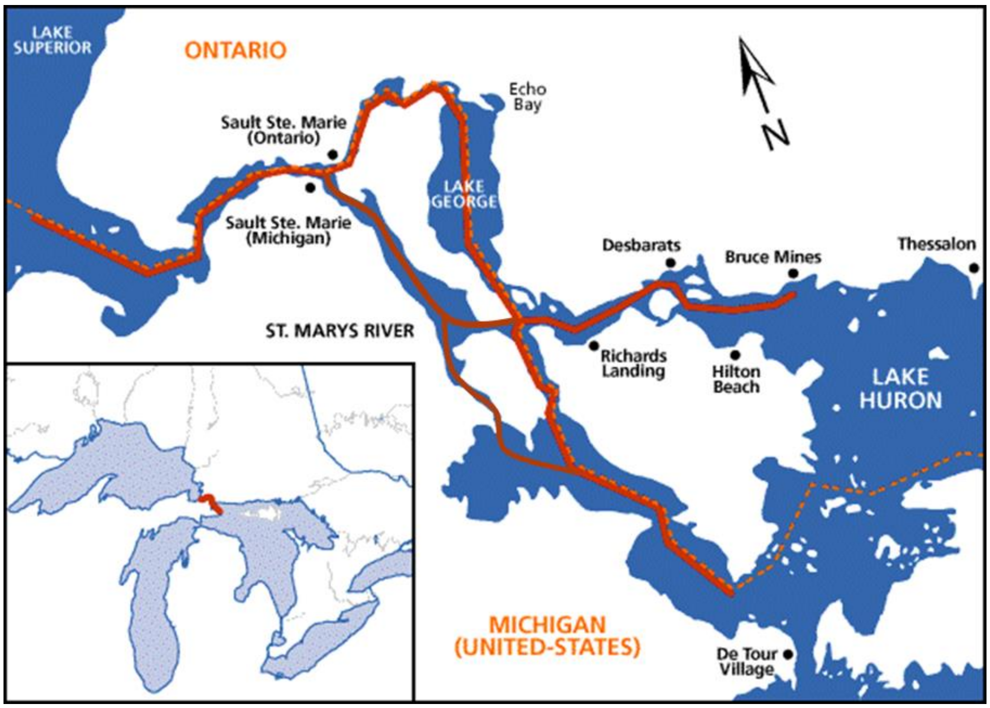


Figure 1: The St. Mary's River (Source:http://chrs.ca/the-rivers/St. Mary's/map/).

The river has three different hydrological reaches: the 22.5 km upper reach, from the narrow outflow of Lake Superior to Sault Ste. Marie (Soo), which is characterized by strong winds, clear cold water, and a generally shallow, sandy coastline with offshore sand and gravel shoals; the 2.5 km rapids reach at Sault Ste. Marie where 6.1 m of the river's drop occurs through a long, shallow fall over boulders and sandstone outcrops, past Whitefish Island, the Sault Canals and power dams; and the 100 km lower reach to Bruce Mines and Detour, along which broad shallow lakes and rock-fringed channels alternate. Along the shoreline are numerous and diverse marshes, wet meadows and swamps.

The St. Mary's River was designated as an Area of Concern (AOC) since a review of available data showed that water quality and ecosystem integrity were severely degraded. Pollution from local industries, inadequately treated municipal wastewater, and other pollutant sources have historically contributed to the environmental issues within the river. It has also been physically modified to accommodate ship navigation and hydroelectric power generation. Cumulatively, these issues have led to reduced water quality, contaminated sediments on the river bottom, and have impacted fish and wildlife habitat.

The water flow from Lake Superior to Lake Huron has been controlled for almost a century through a series of structures on St. Mary's River (Figure 2), which involves work crews turning manual cranks. Control structures on the St. Mary's River are under the supervision of the International Lake Superior Board of Control, and include a 16-gate structure called the Compensating Works. The St. Mary's Compensating Works are located at the headwaters of the Rapids and are used to regulate water levels on Lake Superior and, to a lesser extent, water levels on Lakes Michigan and Huron. There are eight gates on each side of the border. The Soo Locks connect the St. Mary's River with Lake Superior and enable commercial navigation to bypass the Rapids. Three hydropower plants use the Rapids to generate electricity.

Figure 2: Structures on the St. Mary's River

Problematic

The fish community in the St. Mary's Rapids (SMR) is unique and significantly dissimilar to fish communities in other habitats of the river. Historically, the rapids provided high quality spawning habitat for native species, including White Sucker, Slimy Sculpin, Lake Whitefish, Brook Trout, and Lake Trout. The rapids continue to provide spawning and feeding habitat for numerous game species, some introduced, including Steelhead, Brown Trout, and Chinook Salmon, and important forage fishes such as Longnose Dace, Alewife and Rainbow Smelt (e.g. Goodyear et al., 1982; Steimel, 2010). The rapids may also provide critical spawning habitat for Lake Sturgeon, a threatened species (Goodyear et al., 1982).

Reduction and deterioration of the rapids habitat has occurred due to the locks, the Compensating Works, and hydropower generation. Currently, less than 10% of Lake Superior outflows flow through the rapids; flows are now regulated by Compensating Works gates at the head of the rapids. Previous studies have indicated that the flows experienced at three open gates or less result in considerable drying of rapids habitat, which limits habitat available for biotic use and production (Koshinsky and Edwards 1983). Regulation of flow through the Compensating Works is an achievable strategy to enhance fish production in the rapids.

Objectives

The main goal of this project is to develop an Integrated Ecosystem Response Model (IERM) for SMR. This tool will be used to evaluate past, present and future water regulation plan on several ecosystem components. An IERM contains numerous physical and biological models. This report will present the physical models used in the IERM and the potential biological models to be developed.

Here, we evaluate the opportunity to use the Digital Elevation Model (DEM) and the hydrodynamic 2D model provided to us by the United States Army Corps of Engineers (USACE). This report describes the work undertaken to integrate these data into the IERM and explain the processes by which we can calculate and integrate the physical variables used to evaluate habitat through hydrodynamic modelling.

In the absence of substrate data, a procedure was developed by Environment and Climate Change Canada (ECCC) to assess and classify substrate roughness using unmanned aeriel vehicule (UAV-drone) pictures. This procedure will be exemplified summarized in this report.

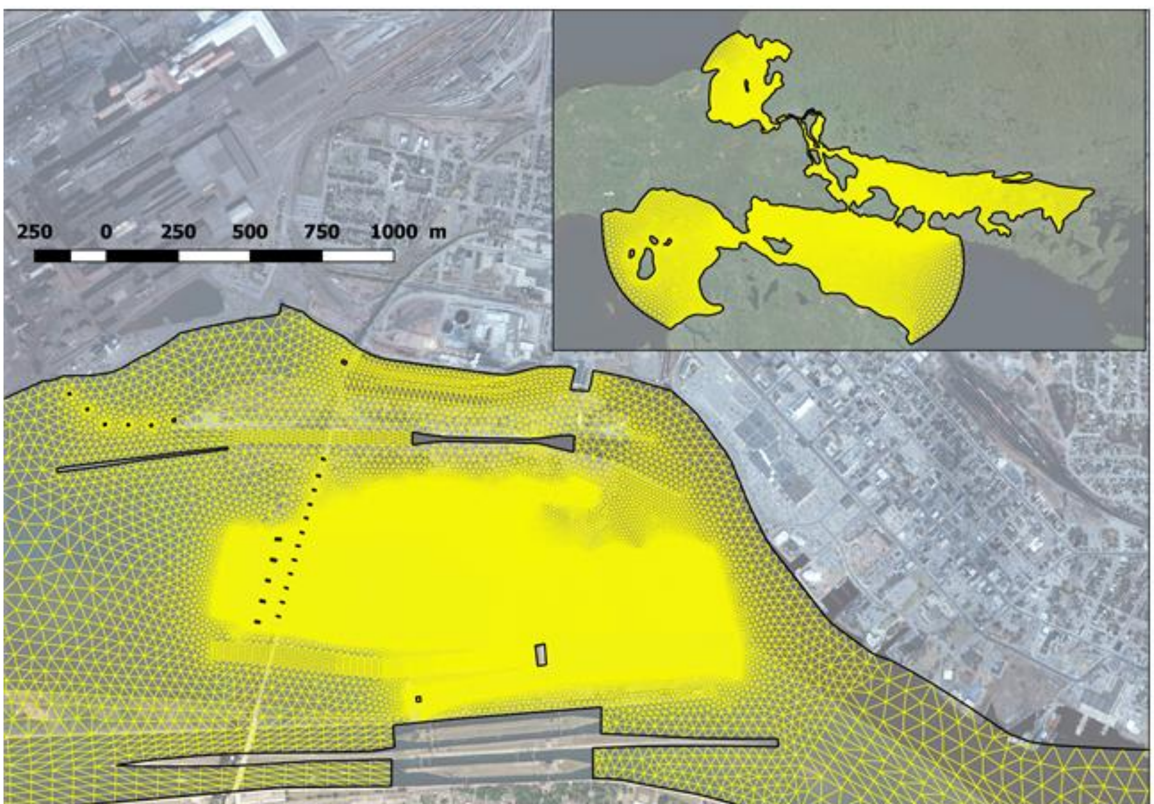
Also, this report details potential habitat models that could be developed and the research that was done to find reliable data on fish spawning in SMRSt. Mary’s from the literature or local agencies. Four species were targeted: the Lake Sturgeon (an endangered species and spring spawner), the Lake Whitefish (a fall spawner), the Walleye (a game fish and spring spawner), and the Sea Lamprey (an introduced species and spring spawner). Potential gaps in knowledge will be identified and recommendations will be provided to bridge them.

Modeling the ecosystem response: Physical aspects

Construction of the Digital Elevation Model (DEM)

The DEM is certainly the most essential data for building precise and relevant modeling in any spatially-explicit model. Vertical and horizontal precision, together with data density, are the most important characteristics that has to be verified in order to produce relevant datasets. In this project, density of bathymetric data is critical, especially in shallow water, because most of the habitat models to be developed or/and applied are effective in shallower portions of the system. Also, topographical data (floodplain and riparian areas) have to be acquired to model wetlands.

USACE (Detroit district) provided us with bathymetric data over the finite element mesh of the St. Mary's River. USACE also provided us with LIDAR data over the entire St. Mary's River. These data are not currently being used by USACE for their 2D hydraulics model. However, we may eventually add the LIDAR data into the 2D hydraulic model and on the IERM grid as the project evolves. Here, we only use USACE's DEM.



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community. Produit à l'aide d'ArcGis Online via QGIS.

Figure 3: USACE finite element mesh for the St. Mary's River.

Hydraulic model

2D Integrated Ecosystem Response Model (IERM2D)

The IERM2D approach enables the integration of a wide variety of information and models and their interactions. It is supported by a grid made of nodes and covering the entire study area. It is integrated into a spatial database containing all environmental data, either measured or simulated (Morin et al. 2006; Morin et al 2016). This database facilitates the interactions of all the information. Once terrain physical features are available, hydrological variables such as water levels and velocities can be calculated for each grid point using hydrodynamic modelling. This information is then used to estimate habitat models for the flora and fauna and, finally, evaluate the consequences of different physical modifications, like water gate opening patterns or water discharge time series, on different species or group thereof. Working in 2D with a large amount of environmental information brings tasks such as data research or treatment burdensome. Thus, the IERM2D is an efficient way to integrate, manage and produce data for large temporal and spatial scale models.

This section describes several methodological aspects regarding the IERM2D namely the production of spatially-explicit variables, the hydrodynamic variables spatial interpolation and the IERM2D database conceptual framework. Only a single gate setting has been simulated by USACE at the moment of writing this report. Examples are thus based on this simulation and one should keep in mind that many gate opening scenarios will eventually be simulated.

Grid

The ecosystem modeling grid (IERM2D grid) covers the study area and is based on the DEM and the hydrodynamic mesh described earlier and provided by USACE. It is a regular grid made of 4 m evenly-spaced nodes (Figure 4). In order to limit the number of nodes and thus the processing time, the IERM2D grid spatial distribution was limited by the extent of the SMR section. The IERM2D grid has a total of 74 559 nodes, each of them with a 16 m^2 surface area; the total surface covered by the grid is 1 192 944 m^2 or 11 929 ha.

Figure 4 : Extents of the St. Mary's Rapids IERM2D grid for all 74 559 nodes (red). The inset is a closer look to the grid near the southernmost gates and bridges.

In order to work with the most detailed topographical data possible, each elevation value was spatially interpolated from the hydrodynamic mesh. Elevation ranges from 166.88 to 198.08 m.

Other physical variables not influenced by hydrodynamic, such as bottom slope and curvature, were spatially interpolated from the hydrodynamic mesh and associated with each grid node. These variables are used directly or indirectly in habitat models. For example, components x and y of the slope, which stay locally constant irrespective of the flow, were indirectly involved in habitat models when combined with the flow-dependent components x and y of water velocity to create the bottom slope in flow direction (BSFD), which is itself a flow-dependent variable used directly in habitats models.

Spatially-explicit variables

Spatial interpolation

Since basic physical terrain characteristics and hydrodynamic variables are supported by the hydrodynamic mesh on one hand, and given that habitat models are computed on the IERM2D grid on the other hand, it was necessary to develop a method to transfer information across spatial supports. Considering that the mesh provides triangular elements linking all mesh points, it is straightforward to spatially interpolate all basic physical data or hydrodynamic variables calculated on the mesh points to any point on the surface of elements and, by extension, on the entire surface covered by the mesh.

Constant variables

Bottom slope

The bottom slope is the derivative of the elevation with respect to the distance and was calculated using the characteristics of the mesh. The x and y slope components were first calculated for each mesh element. Since a mesh point is, with a few exceptions, involved in many elements, slopes components are then weighted among the elements associated with the mesh point. The final values assigned to mesh points are the x and y slopes; they are then spatially interpolated on IERM2D points and the mean terrain variation (bottom slope) is their vector sum. Figure 5 (upper panel) shows the spatial distribution of the bottom slope (vector summation) at SMR as calculated on IERM2D grid points.

Bottom curvature

Bottom curvature is the first derivative of the bottom slope with respect to the distance. The calculation was also based on the hydrodynamic mesh and is essentially the same as that used for the bottom slope, but beginning with the x and y components of the slope. Curvature values spatially interpolated on IERM2D points is the vector sum of the x-x, x-y, y-x and y-y components of the slopes and represents the mean slope variation or bottom curvature. Figure 5 (lower panel) shows the spatial distribution of the bottom curvature slope at the SMR section as calculated on IERM2D points.

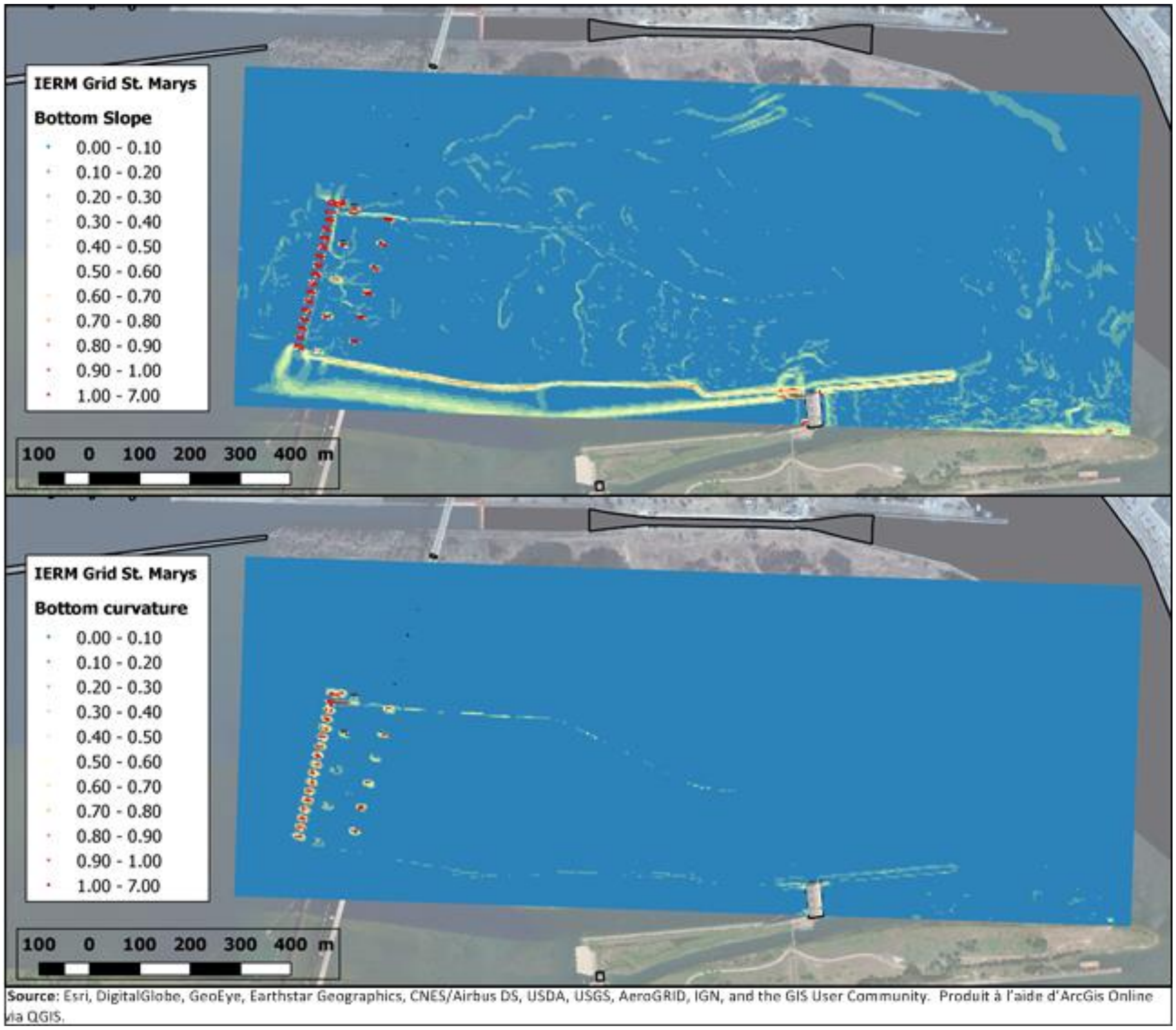


Figure 5: Bottom slope (upper panel) and bottom curvature (lower panel) spatial distribution in St. Mary's Rapids section.

Simulated hydrodynamic variables

Water depth and velocity

The water levels and water velocity (current speed) are calculated by the hydrodynamic model (ADH) for each simulation on each mesh point. ADH produces spatially-explicit fields for water levels (h) and vertically-averaged velocity components (x and y). Depth calculated on IERM2D grid points is the result of the subtraction of the elevation value assigned to IERM2D points from the water level spatially interpolated from mesh points for a given scenario. In the IERM2D, the vector summation of x and y velocities are used as velocity and these are spatially interpolated on IERM2D grid points for a given gate opening pattern scenario. Figure 6 shows the spatial distribution of simulated water velocities that would occur when scenario 15-2 is applied. The latter gate opening scenario is characterized by a 20 cm opening of gate 1, a 31 cm opening of gates 3 through 14; and gates 2, 15, and 16 remaining closed.

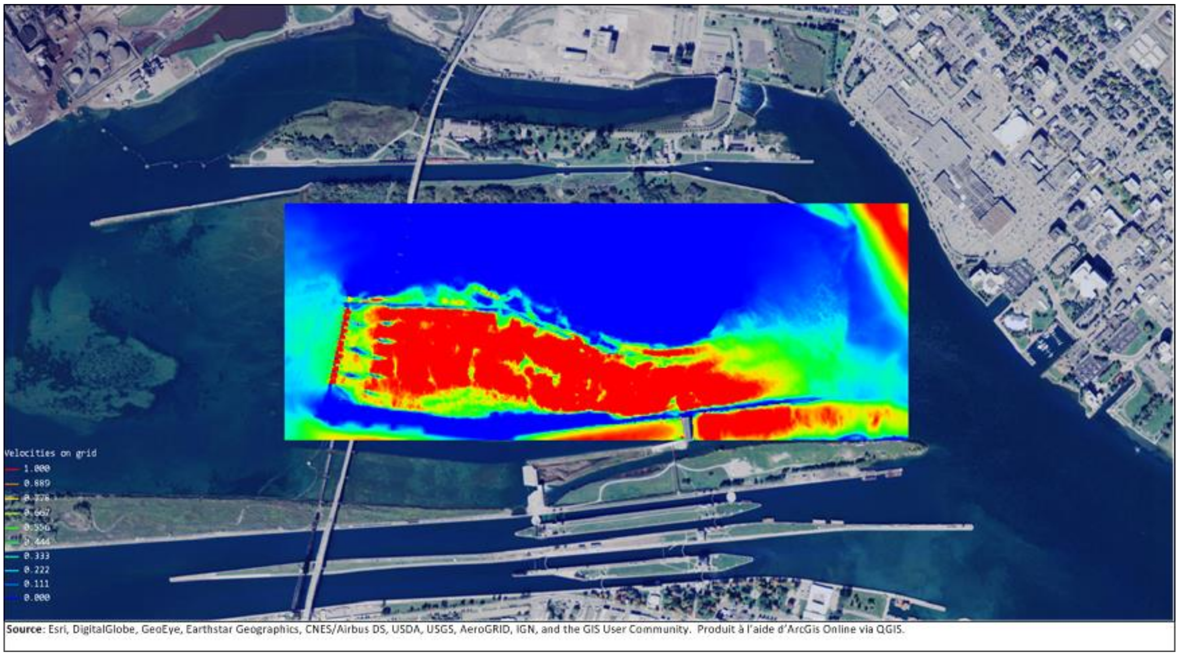


Figure 6: Simulated water velocity spatial distribution in St. Mary's Rapids section interpolated on the IERM2D Grid points for the scenario 15-2.

Bottom slope in flow direction (BSFD)

BSFD represents the pathway of water flowing downhill and reflects the heterogeneity of the sediment surface and macro habitat structures sometimes used as refuges or foraging by fish (Morin et al., 2003). A negative BSFD value represents an increasing depth in the direction of the flow, potentially a refuging or foraging area, while a positive BSFD value indicates a decreasing depth in the flow direction or potentially the absence of good refuge to flowing water. BSFD is the sum of products between x and y velocities and their respective bottom slope divided by the velocity as follows:

Equation 1: $$\boldsymbol{BSFD} = \frac{((\mathbf{vX}*\mathbf{slopeX})+(\mathbf{vY}*\mathbf{slopeY}))}{\sqrt{(\mathbf{vX}*\mathbf{vX})+(\mathbf{vY}*\mathbf{vY})}},$$

where vX and vY are x and y components of velocity and slopeX and slopeY are the bottom slope x and y components.

Assessing the accurate hydrodynamic values for a specific hydrologic event

As mentioned earlier, a number of gate opening scenarios will be considered to cover whole range of envisioned gate opening possibilities at SMR and each of them will be simulated and provide hydrodynamic results on the mesh points. Using this framework, any physical variables of any gate opening scenario can be interpolated on the IERM2D points and are available for future habitat models.

Conceptual database framework

The IERM2D conceptual database framework (Figure 7) is based on a main table (*IERM GRID* table, gray) that contains grid nodes on which all habitat models computations are done. It contains the basic spatial and physical constant attributes, ensuring the availability of this information to habitat models. All other tables linked to this table, either directly or indirectly.

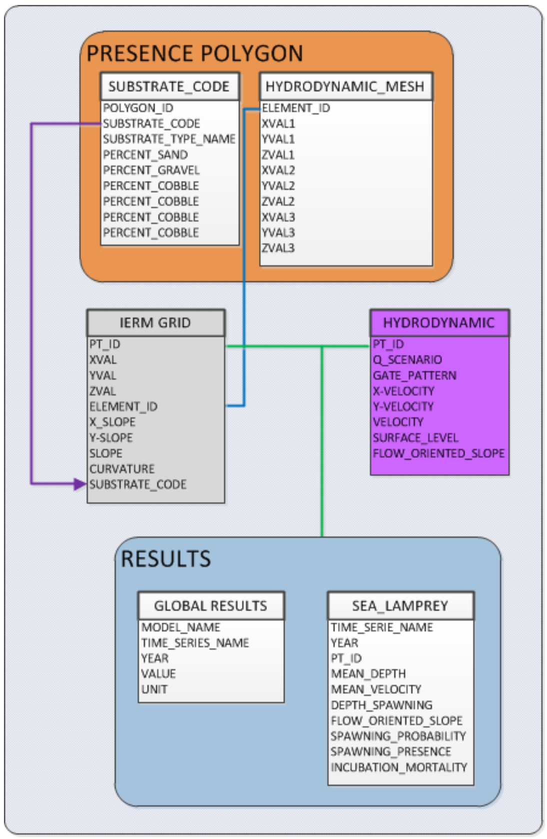


Figure 7: IERM2D conceptual database framework.

The *PRESENCE POLYGONS* tables (Figure 7, orange frame) enable the identification and the designation of a landscape attribute (for example substrate codes) to each grid node based on polygons attributes and can then be used to manage models behavior. For example, the substrate type used for egg deposition is involved to define spawning probability. They also allow spatial interpolation by assigning a mesh element number to each IERM2D point. This table group will have to be updated as new data become available.

The *HYDRODYNAMIC* table (Figure 7, purple table) stores hydrodynamic results calculated for each gate opening scenario and spatially interpolated on IERM2D grid nodes.

Results and variables relevant to each habitat model will be compiled in model specific tables (Figure 7, blue frame). Results from 2D models are stored for grid nodes and gate opening scenarios. Since species-specific performance indicator will be processed on grid nodes with 2D models, specific data table will be linked to the *IERM GRID* table, which stores spatial information. This storage scheme allows us to effectively manage data resulting from the spatial distribution of model results and intermediate variables for any given gate opening scenario. It can then be used to visualize results and validate the models. Here, the table storing Sea Lamprey model results is shown as an example. These results do not exist yet.

Finally, the *GLOBAL RESULTS* table stores summed results from each model and gate opening scenarios. Here, the global performance of a species, mostly expressed as surface area of suitable habitat, will be stored.

Meteorological conditions

Temperature

Sault Ste. Marie has a humid continental climate. Winters in Sault Ste. Marie tend to be long, cold, and snowy. Because of its northern latitude, it receives about 8 hours of sunlight per day during winter. Its close proximity to Lake Huron and Lake Superior does, however, moderate temperatures. Temperatures drop below −20 °C 24 days per year. Summers are warm with a July high of 24.0 °C and temperatures above 30 °C occur 4 days per year. Historical air temperature data in the study area were available at two stations between 1970 and 2012 (Table 1).

Table 1: Summary of collected data (AT: air temperature, WSD: wind and speed direction, BP: Barometric pressure, WT: water temperature)

Source	Station name	Station ID	Data	Dates	Time interval (s)
ECCC	Sault Ste.Marie Airport	6057592	AT	1971 to 2012	3600
ECCC	Sault Ste.Marie Airport	6057592	WSD	1971 to 2012	3600
NOAA	S.W. Pier, MI	9076070	AT	2002 to 2012	360
NOAA	S.W. Pier, MI	9076070	BP	2002 to 2012	360
NOAA	S.W. Pier, MI	9076070	WSD	2002 to 2012	360
NOAA	S.W. Pier, MI	9076070	WT	2002 to 2016	360

The water temperatures of the St. Mary’s River are typically cold and are close to 0 °C for 4 months of the year. Water temperatures are primarily dictated by the surface temperatures of Whitefish Bay, which range from 0 to 16 °C. These waters are warmer than the main body of Lake Superior; at the time of maximum water temperature in mid-September this difference can be as great as 4 °C. The typical annual cycle for Whitefish Bay begins with water temperatures near freezing for the months of January, February, and March, reaching a minimum sometime during March. By late April waters begin to warm, reaching a maximum of 16 °C by mid-September, after which the water cools roughly 12 to 16 °C between October and January. A similar cooling cycle has been reported for waters of the power canal at Sault Ste. Marie, Michigan. For these waters, the mean date at which the water cools to, and remains at, 0 °C is January 2, with the date ranging from

December 6th to January 20th. Historical water temperature data were available at one station between 2002 and 2012 (Table 1).

Water temperature will be used as a trigger to determine the beginning and ending of different spawning periods over multiple years (for example 1980 to 2016). Since water temperature data do not cover this time range, an equation between air and water temperature will be developed to back-calculate water temperature.

Substrate

USACE provided a wide variety of data including unmanned aerial vehicle (UAV-drone) high-definition (4 cm pixel) pictures of the rapids. We are currently looking to find methodology to extract the substrate information from these pictures. However, this method may only be usable for the SMR area. For the whole St. Mary's River, it seems that substrate data could be hard to find, if existing.

We investigated the potential usefulness of aerial imaging in characterizing riverbed composition. We were given a 1 197 m wide (West-East) by 659 m (North-South) raster with 4.455 cm resolution obtained by collating multiple high resolution images taken from an UAV (Unmanned Aerial Vehicle; Figure 8). That raster has four layers, one for each of the tri-spectral red, green, and blue (RGB) visible light channels commonly used in digital photography, and a transparency (i.e. Gamma) layer used to circumscribe the sampled area from the area not sampled. To ease subsequent analyses, we drew a set of polygons to be used as a water mask. The latter and the gamma layer were used to select areas with effectively sampled substrate. All subsequent analyses were performed on 5 m (i.e. 112 pixels) square windows positioned on a grid with points regularly spaced by 2 m intervals.

Texture observable in the sampling window was quantified by performing two-dimensional type-II Discrete Cosine Transforms (2D DCT-II) of the pixel intensities. For the sake of simplicity, we analyzed the RGB layers as a Mean intensity Layer (I) and a second layer being the standard deviation of the RGB values for each pixel (C). The I and C layers were treated separately in texture analysis. The 2D DCT-II coefficients were used to generate a (optical) texture spectra associating mean feature size (φ) with their amount of among-pixel variation in the sampling window (Figure 9). These spectra were integrated within three ranges of mean feature size: $\varphi > 1$ m, 1 m > φ 25 cm, and $\varphi < 25$ cm. Mean pixel values in addition to the three resulting texture descriptors for the I and C layers were obtained for 100 434 points of the 2 m interval grid. An in-depth report covering the computational details and rationales of texture analysis is currently underway at ECCC.

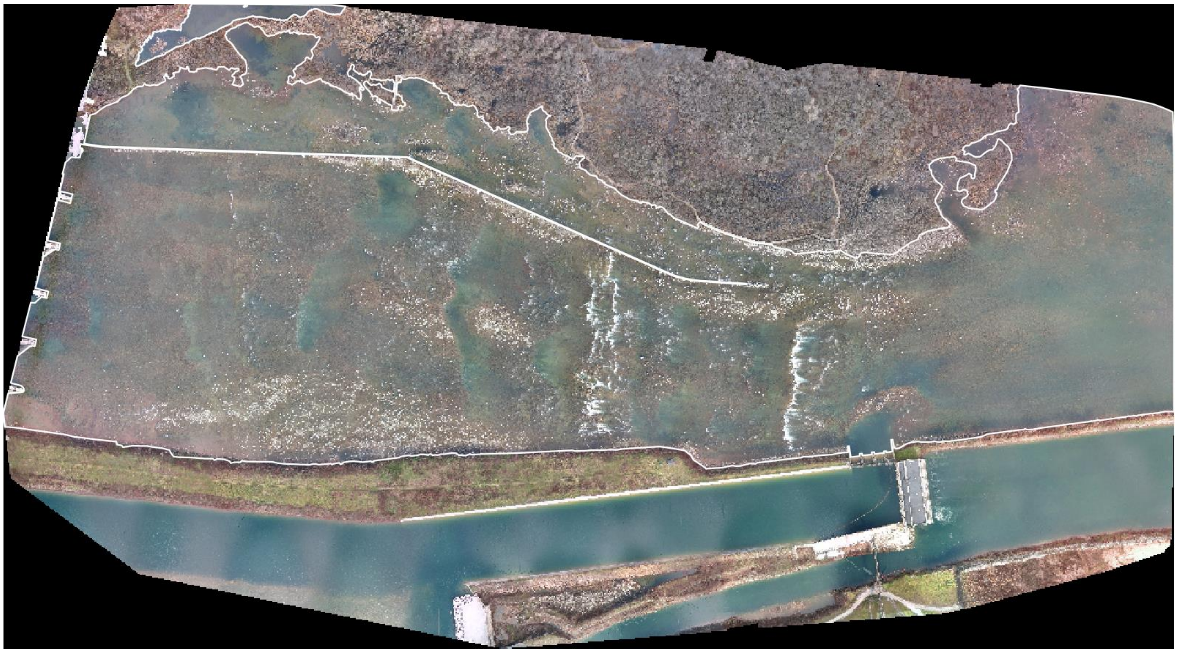


Figure 8: Compound image obtained from multiple aerial pictures shot from an Unmanned Aerial Vehicle flying over a trans-border stretch of the St- Mary's River located north of Edison Sault Hydroelectric Plant (Michigan, USA; +45.5062,-84.3493). Dimensions (x × y): 1197 m × 659 m, resolution: 4.455 cm . White lines represent the limit of the water mask used for the analysis.

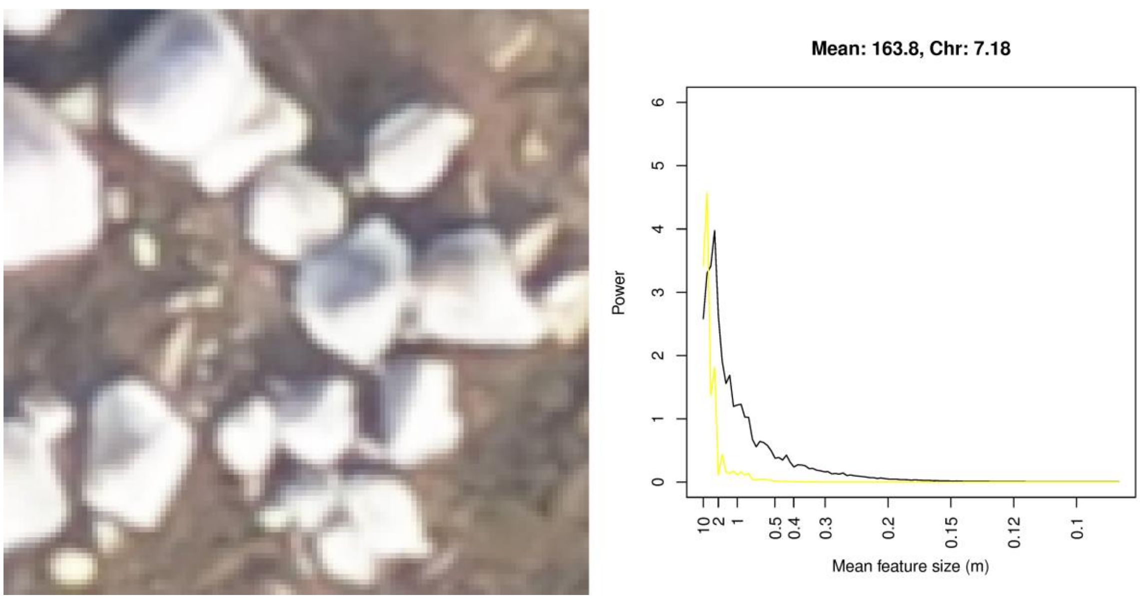


Figure 9: Image of rough substrate (metric boulders; left) and power spectrum of pixel intensity (I; black) and chromatic variability (C; yellow) calculated using a window with N=112 (resolution: 0.04455 m, window width: 4.990 m).

As an appreciation of the value of the texture descriptor approach for practical purposes, we calculated a k-means clustering of the different types of textures present of the image raster on the basis of the Mahalanobis distance (Figure 11). Nine groups were used following the Calinski criterion (see Legendre and Legengre (2012) for more details). The texture descriptors can be used as surrogates to help mapping substrate composition using, for instance, supervised machine learning models. Besides substrate characterization, the texture descriptors can be employed at predicting biological responses such as fish spawning ground distribution. These possibilities will be investigated in the works to follow.

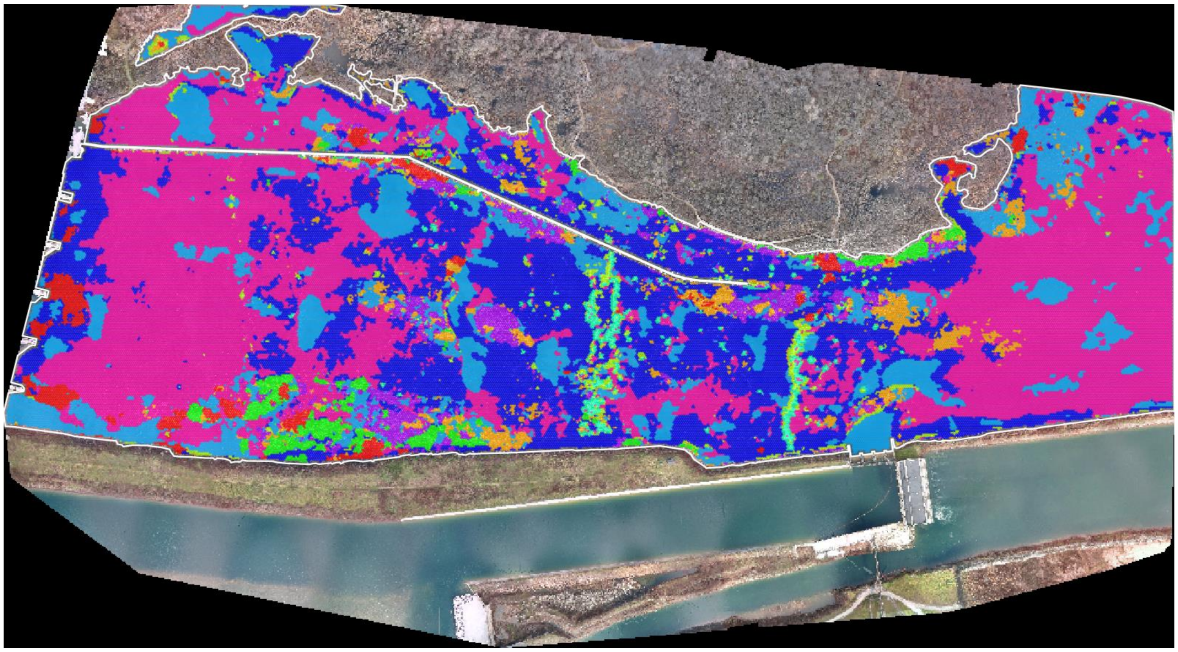


Figure 10: Map of the k-means clustering obtained from the texture descriptors developed in the present study. Least squares were calculated on the basis the Mahalanobis distance. The (nine) groups are shown with different rainbow colors. Zones with the same color are similar in terms of their pixel intensity (I) and chromatic variability (C) as well as in terms of their I and C textures.

Vegetation Mapping

We found some vegetation maps over the land or floodplain portion of SMR. For aquatic vegetation, we did not find anything. Given the fast flowing water on the rapids, aquatic plants may not play a major role in the hydraulics and only a few plants can be found in this area. On other parts of the river, aquatic vegetation mapping is a potential data gap.

Biological models

Many computational approaches may be used to assess the often complex, and sometimes intricate, relationships between environmental variables and species habitat. The choice of a suitable method will often be guided mostly by both the quantity and the quality of the biological and environmental data available. In this project, we will use two modeling techniques. In both techniques, we will first identify the periods (here, it is chiefly the spawning period) when each species is most sensitive to given water levels/flow, and variation thereof, to ensure that we use the appropriate environmental variables.

Two approaches will be used. The first approach, Habitat Suitability Index (HSI), will be used when no biological observations of spawning in SMR is available. Habitat models based on HSIs are developed using preference curves for key environmental variables, like water depth and water velocity. The curves represent the tolerance of a species to the value or /and variation of a physical variable. HSIs are standardized between 0 and 1. Hence, an HSI of 1 represents a highly suitable habitat, while 0 represents a poor habitat.

The second approach, which we will use when biological observations are available in the St. Mary's Rapids, are probabilistic models. We will use binomial logistic regression to compare conditions on sites where a species was present with conditions on sites where it was absent using data from field surveys. For each logistic model, we will use the AIC (Akaike Information Criteria) and the AICc (Corrected Akaike Information Criteria) to determine the best combination of variables for prediction. This criteria estimates the quality of each model based on a trade-off between information loss and model complexity, the latter being defined as the number of variables in the model (Burnham and Anderson, 2002). The predictions of the logistic regression will be combined with the environmental limits of the targeted species to obtain the final description of the suitable habitat.

The following sections present the biological description, SMR locations, and possible model development of four species identified as relevant in the study area.

Lake Sturgeon

Species description

The Lake Sturgeon (*Acipenser fulvescens*) is a large, bottom-feeding, freshwater fish that is member of the family Acipenseridae. The Lake Sturgeon is one of the largest freshwater fish in North America, weighing up to 180 kg and reaching over 2 m long (OMNR, 2011). Based on pectoral fin ray sections it has been determined that Lake Sturgeon can live to over 100 years (St-Pierre and Runstrom, 2004). It has a cartilaginous skeleton and a heterocercal (ie. shark-like) caudal fin. It also has an extended snout with four mustache-like sensory organs hanging near the mouth. Its body is covered with large bony plates, pronounced for juveniles, but less so for adults. It is dark to light brown or grey on its back and sides, with a lighter belly (e.g. Scott and Crossman, 1998). The fish uses its elongated, spade-like, snout to stir up the sediments on the river bed and lake bottom for feeding. Lake Sturgeon feed on a variety of benthic organisms depending on the season and substrate type. Food items may include small fishes, mollusks, insect larvae, and, on time, fish eggs. They may also feed on pelagic zooplankton, such as *Daphnia*, and occasionally on insects at the water surface (Nilo et al., 2006).

Habitat description

Lake Sturgeon spawns in the high-gradient, fast flowing reaches of large rivers over gravel or cobble substrates (e.g. Manny and Kennedy, 2002; Friday, 2014). Spawning generally occurs in late May through late June when water temperatures range from 8.5 to 18 ^{o}C (e.g. Priegel and Wirth, 1971; Kempinger, 1988; Houston, 1986; Fortin et al., 2002; Smith, 2014), although optimum temperatures range between 12 and 16 ^{o}C (Kerr et al., 2010). Water velocity and water depth are also considered to be important factors for spawning habitat selection. General spawning habitat is typically fast-flowing waters, usually below waterfalls, rapids, dams or headwaters with clean, hard, substrates (e.g. Auer, 1996; Adams et al., 2006; COSEWIC, 2006). Egg deposition is maximal in transparent water ranging from 0.1 to 18.0 m (Scott and Crossman, 1973; LaHaye et al., 1992; Caswell et al., 2004; Randall, 2008; Kerr et al., 2010), with average water velocity between 0.1 and 1.5 m/s (Kerr et al., 2010; Dumont et al., 2011). Lake Sturgeon eggs are adhesive and bind to stable substrate (Peterson et al., 2007). The number of eggs may range from 50 000 to over 1 000 000 depending on the size of the fish.

Timing of spawning and egg incubation period

Successful spawning of Lake Sturgeon depends on the timing, magnitude, and duration of spring rise and water temperature regime (Friday, 2014). Egg incubation takes 8-14 days, and larval drift begins 13-19 days after hatching depending on water temperature (Randall, 2008). They remain negatively buoyant until the swim bladder starts to form about 60 days post-hatch (COSEWIC, 2006). During incubation, eggs are vulnerable to changes in water level and velocity. Impacts on eggs can range from total dewatering to being washed from the substrate if flows are too high (Kerr et al., 1997).

As a way to estimate when Lake Sturgeon larvae were drifting in SMR, we used cumulative water temperature units (CTU; the sum of daily mean temperature above 5.8 ^{O}C). Friday (2014) found that larval drift of Lake Sturgeon begins at 149.5 CTU in Kaministiquia River and ends at 398.6 CTU (Figure 11).

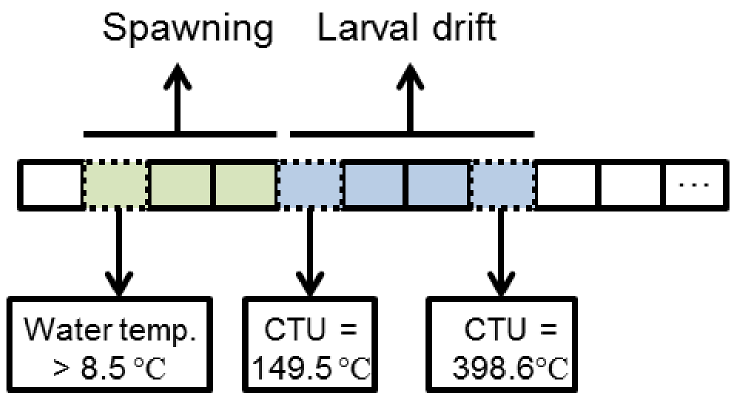


Figure 11 : Timing of the different periods used to model Lake Sturgeon spawning habitat. The spawning and egg incubation period begins when mean daily water temperature reaches 8.5°C for five consecutive days and finishes when larvae drifting is completed according to cumulative degree days (CTU). One square represents a quarter-month.

Lake Sturgeon in the St. Mary's River

Lake Sturgeon was once abundant in the Great Lakes and the St. Mary's River, but the population is suspected to be 1% of its original size (Harkness and Dymond, 1961). It is now a conservation priority in the Great Lakes Basin (e.g. Holey et al., 2000; Harris et al., 2009). The numbers of St. Mary's River Lake Sturgeon are around 500 individuals (Bauman et al. 2011) and may be a genetically distinct from other Lake Sturgeon in the Upper Great Lakes (Gerig et al. 2011).

A major barrier to Lake Sturgeon recovery in the area is the lack of suitable spawning sites (Daugherty et al. 2008). The St. Mary's River has several sites that meet requirements for Lake Sturgeon spawning (Goodyear et al. 1982), but maintenance of these spawning habitats is linked to flow regime to maintain adequate water velocities.

Available data in the St. Mary's Rapids (spawning observations)

The SMR area was historically a spawning ground for the Lake Sturgeon (Goodyear et al., 1982). We unfortunately did not find a database with spawning observations in the Rapids.

Model development

To evaluate the possible impact of water management in the SMR on Lake Sturgeon, we will developed a HIS of suitable habitat for spawning and egg incubation. To ensure that we will predict suitable Lake Sturgeon habitat where conditions are appropriate during the spawning and egg incubation period, we will limit the distribution of suitable habitat to specific ranges of water velocity and water depth during this sensible period. Based on the literature, the model will consider that Lake Sturgeon eggs would not be found at IERM2D nodes where water velocity exceeds 2 m/s (LaHaye and Fortin, 1990) or where water depth exceeds 12 m (Manny and Kennedy, 2002). Also, substrate particle size is an important factor in spawning site selection by Lake Sturgeon. Gravel, cobble, boulder, and bedrock are considered appropriate for Lake Sturgeon eggs, therefore nodes that will be found in sand or vegetation will be thus excluded (LaHaye et al., 1992, Deslandes et al., 1994). Node not meeting conditions presented above will be classified as unsuitable habitat for Lake Sturgeon spawning.

Lake Whitefish

Species description

Lake Whitefish (*Coregonus clupeiformis*) is widely distributed throughout Canada and the northern United States (Scott and Crossman, 1973). It occurs in lakes and rivers all across Canada, from Newfoundland and Labrador to British Columbia, in the Great Lakes, and throughout the Northwest Territories, Nunavut and Yukon (Luna 2008). Lake Whitefish pertain to family Salmonidae. It is relatively elongated, with a small head and a body ending with a forked tail. It has a snout which overhangs a short lower jaw in such a manner that the mouth opens in a slightly inferior position (COSEWIC, 2005). The latter trait enables the fish to feed on the bottom of lakes, or grab food particulates out of the water or at the surface. Another notable feature of the Lake Whitefish is the presence of small flaps in each nostril. Being covered with large scales, Lake Whitefish are silver on their sides and greenish-brown to almost black dorsally, with a silvery-white underside. The ventral fins are white and the tail has a dark trailing edge (Scott and Crossman, 1973). The tail fin of the Lake Whitefish is severely forked, making it a fast swimmer. Lake Whitefish weighs 1.80 Kg on average. They can grow up to 0.79 m total length and commonly reach 0.51 m. Lake Whitefish begin to reach sexual maturity at approximately 4 to 5 years of age, full maturity being reached by 8 years and over for both sexes (Evans et al., 1988).

Habitat description

Clear, cold waters of large water bodies and deep inland lakes are characteristic habitats of the Lake Whitefish**Erreur ! Source du renvoi introuvable.**. Lake Whitefish have been known to regularly descend to deep brackish waters where they may spend considerable time, but return to fresh clear water at spawning time (Scott and Crossman 1973). In fall, when shoal waters become cool again, they move inshore and spawn over reefs and shoals composed of gravel and rubble. In Lake Simcoe (Ontario), Lake Whitefish first move to spawning shoals in October and remain until early December (Willox 1986; McMurtry 1989; Amtstaetter 1997). Spawning usually occurs at night in relatively shallow littoral areas (2.0 m to 5.0 m; Hart 1930; Machniak 1975) over substrates such as cobble, boulder, sand, gravel, or detritus (Scott and Crossman 1973; Bidgood 1972; Ash 1975; Begout-Anras 1999). Wismer and Christie (1987) reported spawning at water temperatures ranging from 0.5 to 12°C. Eggs are deposited haphazardly and settle within the interstitial spaces of the shoals. The duration of the spawning season ranges from a week to 10 days although some fishes may remain on the spawning grounds for a considerable period following the main run for the open water (Machniak 1975).

Egg survival increases with the severity of the winter and the degree of ice formation, partly because the ice cover protects eggs from wind and wave action (Taylor et al. 1987). On the contrary, egg survival decreases with increasing sedimentation rate and is low over soft bottoms susceptible to wave action (Ash 1975; Fudge and Bodaly 1984). Eggs hatch in April or May (Scott and Crossman 1973), after incubating for about 133 days in waters averaging 1.7°C. Hatching time increases with decreasing water temperature. In laboratory settings, optimum water temperature for incubation was found to be between 3.2 and 8.1°C. Young fishes leave shallow inshore waters by early summer and move to deeper water (Scott and Crossman 1973). Lake Whitefish eggs are eaten by other fishes, including the Yellow Perch, ciscoes, and other whitefishes (Hart 1930).

Most Lake Whitefish mortality occurs at the egg and larval stages. Only about 13% of eggs survive to become larvae and these are heavily preyed upon by larger fish (Becker 1983; Luna 2008). Juvenile Lake Whitefish are also eaten by predatory fish, including Lake Trout, Northern Pike, Burbot, and Walleye (Michigan Department of Natural Resources 2008). The first movements of the newly hatched fry are inshore close to the surface. Later they form schools and finally head toward deeper water (Hart 1930).

Timing of the spawning and incubation period

Ice-out dates and water temperatures computed via a water temperature model will be used to identify the spawning and egg incubation period (Figure 12) for each year. For modeling purposes, we will define the spawning period as beginning when modeled water temperature reaches 12°C in fall, the upper limit of the optimal spawning temperature (Wismer and Christie 1987). The spawning period is 2 quarter-months (QM, approximately 2 weeks) long. The egg incubation period occurs between the spawning period and the first QM containing the day where water temperature becomes over 8°C in spring.

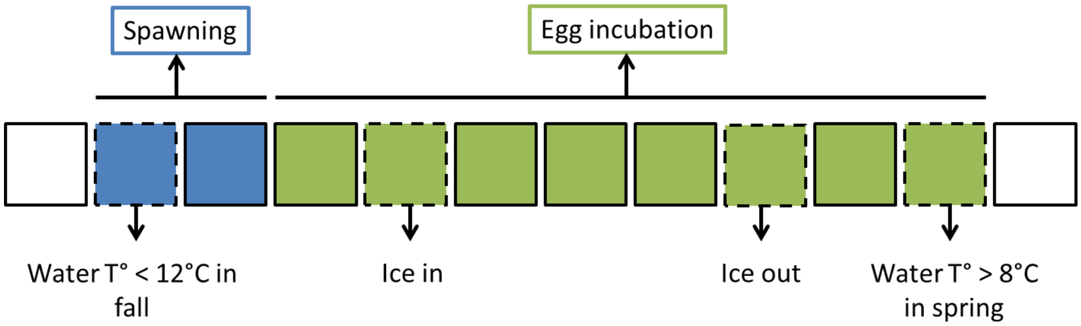


Figure 12 : Periods used to model the spawning habitat of Lake Whitefish. One square represents a quarter-month.

Lake Whitefish in the St. Mary's River

Fish harvest records maintained by Canadian and American authorities from the 1870's to the 1910's indicate that Lake Whitefish was the most important (in terms of quantities caught) commercial species in the St. Mary's River (Bray, 1992).

Available data in the St. Mary's Rapids (spawning observations)

In the 1760s, Lake Whitefish were taken with nets in September and October from the shoals around SMR, but it is not known whether those fish were spawning or not (Goodyear et al., 1982). In 1824, Lake Whitefish were abundant in the SMR in October (MacDonald, 1978). Consequently, this area is regarded as an historical spawning ground of this species. We were told by Peter J. Hrodey (U.S. Fish and Wildlife Service) that spring creel surveys were done between 2006 and 2008 in SMR (Smith and Greenwood, 2010). Lake Whitefish was one of the 11 species captured by anglers during this period. Unfortunately, no spawning data was obtained during this study.

Model development

We will use the HIS approach to evaluate the possible impact of water management on Lake Whitefish in SMR. In order to ensure that suitable habitat will be predicted where conditions are appropriate for egg survival, we had to constrain the distribution of suitable habitat has to specific ranges of water depth during the spawning and egg incubation period. To this end, we will consider that no viable eggs are found on sites where water depth exceeds 3.50 m (De Graff 1993; Gaboury and Patalas 1984, Begout-Anras et al. 1999; Mills et al. 2002). Also, only nodes with adequate substrate (cobble, boulder, sand, or gravel) will be considered as suitable habitat for Lake Whitefish spawning.

Sea Lamprey

Species description

Sea Lampreys (*Petromyzon marinus*) belong to a group of fish called Agnathans, which lack a jaw. Sea Lampreys resemble eels in shape, but lack paired fins and jaws, and have a cartilaginous, rather than bony, skeleton. Their mouth takes on an oval shape while attached to their host, but once opened it becomes larger than the head and pharynx together. It has sharp teeth arranged in many consecutive circular rows (Page and Burr, 1991; Jenkins and Burkhead, 1994). There are 7 branchial openings behind the eye. They are olive or brown-yellow on the dorsal and lateral part of the body, with some black marblings, with lighter coloration on the belly. The maximum length and weight of Sea Lampreys in marine environments is 120 cm and 2.5 kg, respectively, but land-locked individuals rarely exceed 64 cm and 0.6 kg.

The Sea Lamprey is an aggressive parasite, which uses its toothed, funnel-like sucking mouth and rasping tongue to bore into the flesh of other fishes to feed on their blood and body fluids. A single lamprey will typically destroy up to 18 kg of fish during its adult lifetime. The loss of body fluid and scaring left by Sea Lamprey are so severe that only one out of seven fish attacked will survive under unfavorable conditions.

The complete life cycle of Sea Lamprey can take an average of 5 to 8 years. Adult Sea Lampreys swim upstream rivers to spawn. They die just after spawning. Fertilized eggs hatch into small, wormlike ammocoetes larvae which burrow into stream substrate and feed on debris and small plants for 1.5 to 7 years before they transform into the parasitic adult. The adults migrate into the Great Lakes where they spend 12 to 20 months feeding on fish. The habitat model for Sea Lamprey will focus on the spawning and egg incubation period.

Habitat description

Sea Lamprey is anadromous: living in marine environments but spawning in freshwater rivers and streams. Migration is triggered by changes in water temperature. In general, they prefer shallow coastal areas, though they are found at depths between 0.91 and 4.57 m. There are several stages in the life cycle of Sea Lampreys. The first of these stages is the spawning phase, which occurs between April and June. Sea Lampreys use coarse substrates and rapidly flowing water as spawning habitat. Sexually mature adult Sea Lampreys migrate up tributaries to spawn. They locate spawning streams by following pheromones (naturally produced chemical attractants) released by ammocoetes living in those waters. A pair of male and female Sea Lampreys build a nest, called a redd, in a gravel stream bottom. The female lays a large number of eggs, and the male fertilizes them, then having completed this act the Sea Lamprey die. The eggs lie in the gravel interstitial spaces, and are provided with oxygen by the flowing water.

During the second phase, fertilized eggs settle into the sand or gravel and begin to grow. After 13 or 14 days, the eggs hatch. The larvae then drift downstream with the current. When they locate suitable habitat - usually silt/sand stream bottoms and banks in slower moving stretches of water - they burrow in and take up residence, filter-feeding on algae, detritus and microscopic organisms and materials.

In the third phase, known as transformation, larvae metamorphose into adult Sea Lampreys. During this phase Sea Lampreys develop a mouth, teeth and eyes. They also migrate to larger bodies of water, such as oceans or large freshwater systems like the Great Lakes. Sea Lampreys remain in this habitat for 12 to 18 months as a mature adult and begin to feed, attaching themselves to fish. This is known as the parasitic phase, during which reproductive organs develop.

Timing of the spawning and incubation period

Sea Lamprey spawns in the spring. Adults assemble in the estuaries of rivers during late winter, starting to migrate upstream when water temperature exceeds 4.4 °C. They migrate where the bottom is a mixture of sand, gravel, and rubble, water depth is between 0.30 to 0.60 m and water velocity is moderate. Early migrants can arrive on the ground six weeks before spawning begins. Nest building begins in late May or early June. Spawning activity starts when water temperature exceeds 11° C (Figure 13), around mid-June, and its peak when water temperature is around 15° C. Late migrants can spawn until the end of July when water temperature can reach 24° C. Eggs hatch after two weeks of incubation at a water temperature between 14 to 18° C. Ammocoetes burrow out and leave the nest in 18 to 21 days after completion of spawning or 4 to 8 days after hatching. They quickly drift downstream in areas of sandy silt and mud where they burrow. The buried ammoceote period cans take between 1.5 to 7 years (Scott and Crossman, 1998).

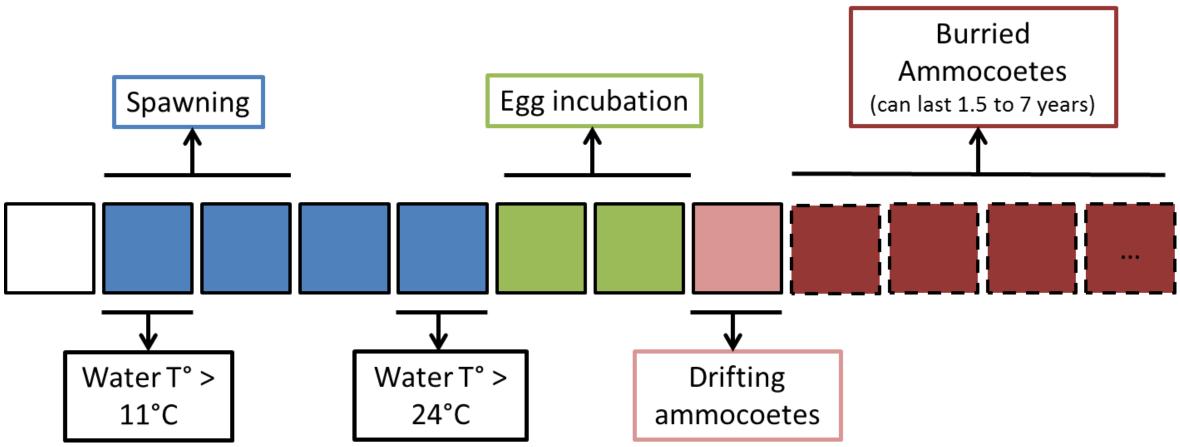


Figure 13 : Periods used to model the Sea Lamprey spawning habitat

Sea Lamprey in the St. Mary's River

Historically, Sea Lamprey has inhabited Lake Ontario and the St- Lawrence River, as they are connected to the Atlantic Ocean. In 1921, lampreys appeared in Lake Erie for the first time, crossing the Welland Canal, which was built for ships to avoid Niagara Falls going up to the St- Lawrence Seaway. Shortly thereafter, Sea Lamprey rapidly colonized the upper Great Lakes. Consequently, Sea Lamprey is found in St. Mary's River. The first Sea Lampreys were detected in the St. Mary's River in 1962. Surveys between 1962 and 1987 shown larval distributions that extended from 5 km upstream of the Compensating Works to 25 km downstream on the North Channel, and 35 km downstream through Lake Nicolet and East and West Neebish Channels to the entrance of Lake Munoscong. It was estimated that up to 88% of Sea Lamprey in Lake Huron originated from the St. Mary's River (GLFC, 2009).

Available data in the St. Mary's rapids (spawning observations)

We obtained data on Sea Lamprey spawning from Peter J. Hrodey (U.S. Fish and Wildlife Service) and Gale Bravener (Fisheries and Oceans Canada). Figure 14 indicates the locations of the different observations from both databases. The first database contains trapping data at Gate 16 between 2010 and 2016. The database contains the collection date, the species, the stage of the captured fish and whether it was alive or not. The database from Fisheries and Oceans Canada contains data on sea lamprey spawning in the wadable areas (<25% of the total surface area) of SMR, from 1993 to 2016. It gathers information like number of lamprey observed (number of male, female), nests sampled (number, location), embryos collected from each nest (number, date, stage of development), and viability (% alive during the final sample of the nest when embryos should be at stage 12+ if they survived).

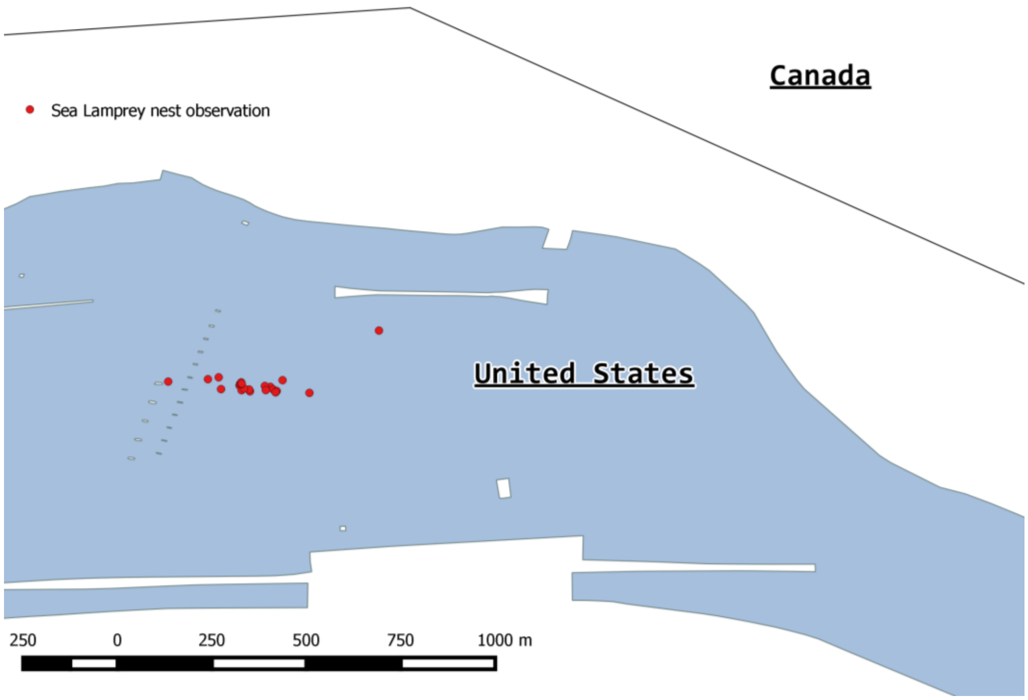


Figure 14: Observations sites of Sea Lampreys in the St. Mary's Rapids.

Model development

We will develop a probabilistic model for the reproductive habitat of the Sea Lamprey. This model will allow us to evaluate the impact of water management on the suitability of SMR for the spawning, egg incubation and drifting periods of Sea Lamprey. We will set aside a portion (~ 10%) of the biological data presented in the previous section for model validation purpose. The known environmental variables will be spatially interpolated on the sampling points and used to explore relationships between the occurrence of a species and abiotic factors.

Walleye

Species description

The Walleye (*Sander vitreus*) is a freshwater fish native to North America. It is an important sport fishing species throughout its range (Colby et al., 1979) and has been fished commercially for a number of years in several water bodies, including the large lakes of the Rainy-Namakan system (Kallemeyn et al., 2003; Palmer et al., 2005). The Walleye is one of the largest members of the Percidea family, growing to about 80 cm in length and weighing up to 9 kg. Walleye larvae and fry mostly consume zooplankton such as *Daphnia,* while juveniles and adults are mostly piscivorous, commonly feeding on Yellow Perch, Alewife, Rainbow Smelt, and suckers (Colby et al., 1979). During all life stages, Walleyes may also feed on invertebrate organisms, especially in early summer. A number of fish and bird species may feed on Walleye fry and larvae, but larger juveniles and adults have few aquatic predators, notwithstanding the Northern Pike and Muskellunge. Common Loons and cormorants are also known to consume small and medium size Walleyes (Colby et al., 1979).

Habitat description

Walleye spawning occurs soon after ice-out, generally beginning when the water temperature reaches 5 or 6°C and peaking when water temperature is around 8°C. The optimal fertilization temperature ranges from 6 to 11°C (Colby et al., 1979; Paragamian, 1989; Roseman et al., 1996; Manny et al., 2010). Water temperature and warming rate in spring are directly correlated with the number of eggs produced and incubation timing (Busch et al., 1975; Colby et al., 1979). Warmer temperature associated with a steady warming rate around 0.28°C/day will shorten the incubation period. Shorter incubation periods increase egg survival by reducing the time window where eggs are vulnerable to mortality from unsuitable environmental conditions or predation (Busch et al., 1975; Jones et al., 2003; Roseman et al., 2006). A short incubation period was also found to result in greater larvae and fry survival (Busch et al., 1975).

Walleye spawns in both lacustrine and riverine environments (Zhao et al., 2009), sometimes in water as shallow as a few centimeters (Colby et al., 1979). The nature of the substrate is also important to Walleye spawning. They prefer gravel or cobbles providing many small interstitial spaces that shelter eggs from displacement or predation (Zhao et al., 2009) and ensure a greater hatching success (Johnson, 1961; Corbett and Powles, 1986; Jones et al., 2003). These areas are also associated with limited sedimentation, that would otherwise cover the eggs and limit their oxygen supply (Colby et al., 1979). As such, water movement helps in maintaining clean spawning substrates that are free from sediments or detritus, thereby providing sufficient dissolved oxygen to eggs (Colby et al., 1979; Cooley and Franzin, 2008). It has been suggested that Walleye prefers to spawn in areas battered by waves at least occasionally during the year (Colby et al., 1979). However, too high a water velocity may displace eggs into deeper, colder water or onto unfavorable substrate, lowering egg survival (Humphrey et al., 2012). Water currents are limited in lakes, but strong winds may create significant waves and currents that could be detrimental to Walleye eggs (Roseman et al., 1996). Wind events may also significantly stir water from different depths and thus decrease water temperature and oxygen concentrations in the shallow areas where Walleye spawns (Busch et al., 1975). Ice-scour and temporary exposure to air could also contribute to maintain proper spawning substratum. In summary, Walleyes, which are broadcast spawners, will normally spawn in relatively shallow water to benefit from warm temperatures and wave or wind action that maintain a clean substrate (Johnson, 1961; Colby et al., 1979).

Walleye eggs usually hatch about three weeks after spawning, depending on water temperatures. Once hatched, larvae have limited swimming capability for the first two weeks. They survive on energy reserves contained in the yolk while passively drifting with the water currents (Colby et al., 1979; Jones et al., 2003). Favorable currents are thus required to bring larvae towards suitable nursery grounds (Corbett and Powles, 1986; Jones et al., 2003). As such, the number of larvae reaching nursing grounds has a strong influence on Walleye recruitment rate at the end of the first summer (Mion et al., 1998). Walleye nursery grounds are usually located in shallow lacustrine habitat rich in zooplankton (Colby et al., 1979; Jones et al., 2003; Roseman et al., 2005). The substrate found in nursery grounds is variable (from vegetated area to gravel shorelines; Kerr et al., 1997). Clean substrate, which appears to be preferred in the early larval stage, facilitates the detection of zooplankton, while more vegetated or structured habitat provides shelter from predation and light (Kerr et al., 1997). Nursery grounds are also associated with warm water, low water clarity, and high oxygen concentration as Walleye larvae benefit from these conditions (Colby et al., 1979; Roseman et al., 2005).

Timing of the spawning and incubation period

We will back-calculated water temperatures using an air to water temperature model to identify the spawning and egg incubation period for each year. Spawning begins when the water temperature remained above 2°C for 5 days (Figure 15). We will then assume that the last deposited eggs would hatch at a CTU of 138.3°C days (above a base temperature of 2.1°C). We will add an additional day following the end of hatching to ensure that newly hatched larvae had time to reach the water column as passive particles, at which time we assume they will no longer be vulnerable to water level variations (See Morin et al., 2016 for more details).

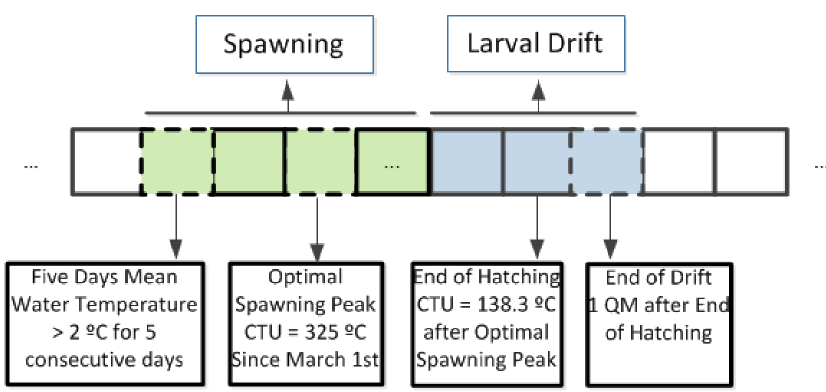


Figure 15: Timing of the different periods used to model Walleye spawning habitat. One square represents a quarter-month.

Walleye in the St. Mary's River

The St. Mary's River was considered to have one of the larger walleye populations in Lake Huron before large-scale perturbation in the mid 20th Century depleted them (Schneider and Leach, 1977). Walleye is among the most famous game fish species in the river and the fourth most frequently harvested by number (Fielder, 2002). Fisheries managers have been stocking native populations for over 25 years (Caroffino et al., 2011).

Available data in St. Mary's Rapids (spawning observations)

Spawning occurred historically in SMR area (Goodyear et al., 1982). David Fielder (Michigan DNR) and Stephen Chong (MNRF) provided us with a dataset that contains Catch per Unit Effort (CPUE) of Walleye (and others species) in the area in 1975, 1987, 1979, 1995, 2002, 2006, 2009 and 2013. Unfortunately this dataset does not include spawning observations.

Model development

We will use a HIS model to evaluate the impact of water management on the reproduction of Walleye in SMR. Once the eggs are deposited on the river bottom, they are sensitive to water movements that could move them beyond suitable depths. Simulated bottom water velocity greater than 1.4 m/s is sufficient to cause the mortality of all Walleye eggs, while velocity smaller than 0.12 m/s may not have a significant impact (Jones et al., 2003; Zhao et al., 2009). We will therefore assume that eggs would experience no mortality due to water velocity below 0.12 m/s, mortality at a rate linearly increasing from 0 to 1 for water velocities between 0.12 to 1.4 m/s, and no survival above 1.4 m/s. It will also be assumed that no Walleye egg survival occurs when exposed to air or to a water depth greater than or equal to 5 m at any time during the spawning and egg incubation. Also, substrate particle size is an important factor in spawning site selection by Walleye. In fact, Walleye prefer gravel and cobble where maximum egg densities were found (Corbett and Powles 1986). Every node that will not meet the conditions presented above will be classified as unsuitable habitat for Walleye spawning.

Conclusion and next steps

Hydraulic and Integrated Ecosystem Response Model

We will integrate the entire USACE gate setting hydraulic results on the IERM grid. This will allow us to simulate the daily gates operation for the year 2015 and to perform habitat calculations for the entire year of 2015.

An IERM2D grid was built and covers the SMR section. Constants physical variables related to topography were calculated for each nodes and a methodology was established to assess hydrodynamic-dependent variables and assign them to each node. This methodology can also be applied to additional gate opening scenarios. Also, a conceptual database framework was created in order to manage all data used to model habitats or store and retrieve models results for evaluation or visualization. Therefore, since additional information may readily be integrated to it, the IERM2D is up to date in order to be used to develop future habitat models.

Substrate Model

Information on substrate roughness can be estimated from UAV aerial pictures. We will exploit that possibility to develop surrogate to help in habitat modelling or map point samples over larger areas. Coloration (i.e. variation among red, green, and blue layers) may also provide another worthwhile information channel. We will further investigate that possibility during the nest part of this study.

Biological models

Several contacts were made with specialists from local agencies to get access to their available biological data over the entire St. Mary's River, with a special focus on SMR. Throughout these contacts we got access to many dataset for several fish species all over the river. Unfortunately, very few observations on spawning were available for the rapids. We thus resorted on using the HIS method to develop biological models.

We envisioned two solutions to develop more complete biological models in the future:

- Survey the rapids for spawning sites

- Using a larger study area, for instance the St. Mary's River, where spawning observations are available and apply the model to the entire area, including the rapids.

Also, we selected four species that we think represent several situations observed in the rapids: ecological role, spring vs fall spawning, endangered species, species targeted by fishermen, introduced species, etc. Others species may be also good indicator of water management impact. There is still room to add some of them to our modeling effort.

Next steps

In next steps of the project, we will simulate the conditions (gate settings, flows, water levels) from April to December of either 2015 or 2016. Two reasons explain why we will target these two years:

1. During both these years, there was significant maintenance expected at the hydropower plants that would have required large increases in gate settings and SMR flows during the spring and fall, and lesser flows during the summer according to initial regulation plan. Hydraulic conditions would have

fluctuated throughout the non-winter months, increased in the spring, then decreased for July and August, increased again in the fall, and then decreased again in the winter. In reality, the Lake Superior Board of Control decided to deviate from the regulation plan and adjusted gate settings in such a way to reduce large fluctuations and their potential impacts on fish.

2. Generally, whenever there was a need to open more gates than the minimum ½ gate setting, the the Lake Superior Board of Control would always open the gates fully (so if the requirement was to open 3 gates, the 3 middle gates were opened all the way and l the water go blasting through the middle of the rapids). Over the past few years, the board experimented having multiple gates opened partially to try spreading water across the rapids.

Simulating the hydrological and gate setting conditions of 2015 or 2016 will allow us to compare the ecosystem response (here, the suitable habitat for the spawning of the four targeted species) to similar hydrological conditions with gate settings according to what is the normal regulation plan.

References

Adams W.E., L.W. Kallemeyn and D.W. Willis. 2006. Lake sturgeon population characteristics in Rainy Lake, Minnesota and Ontario. Journal of Applied Ichthyology 22: 97–102.

Amtstaetter, F. 1997. Fall trap netting on the spawning grounds of lake trout (*Salvelinus namaycush*), Lake Whitefish (*Coregonus clupeaformis*) and cisco (*Coregonus artedii*) in Lake Simcoe, 1989-1997. Ontario Ministry of Natural Resources, Lake Simcoe Fisheries Assessment Unit Report 1997–1. 36 pp.

Ash, G.W. 1975. The effects of thermal pollution on the egg survival of the lake whitefish (*Coregonus clupeaformis* (Mitchill)). Water Pollution Research in Canada 10: 9–16.

Auer, N.A. 1996. Response of spawning lake sturgeon to change in hydroelectric facility operation. Transaction of American Fisheries Society 125: 66–77.

Bauman, J.M., Moerke, A., Greil, R., Gerig, B., Baker, E. and J. Chiotti. 2011. Population status and demographics of lake sturgeon (*Acipenser fulvescens*) in the St. Mary’s River, from, 2000 to, 2007. Journal of Great Lakes Research 37(2): 47–53.

Becker, G.C. 1983. Fishes of Wisconsin. University of Wisconsin Press, Madison. Wisconsin.

Begout-Anras, M. L., P. Cooley, R.A. Bodaly, L. Anras, and R. A. Fudge. 1999. Movement and habitat use by Lake Whitefish during spawning in a Boreal lake: integrating acoustic telemetry and geographic information systems. Transactions of the American Fisheries Society 128: 939–952.

Bidgood, B.F. 1972. Divergent growth in lake whitefish populations from two eutrophics Alberta lakes. Ph.D. Thesis, University of Alberta, Edmonton. 120pp.

Bray, K. 1992. Changes to Fish Habitat of the St. Mary’s River: a Retrospective Analysis. M.Sc. Thesis, Trent University, Peterborough, Ontario.

Bruch, R.M. and F.P. Binkowski. 2002. Spawning behavior of lake sturgeon (*Acipenser fulvescens*). Journal of Applied Ichthyology 18: 570–579.

Busch, W.-D.N., Scholl, R.L. and W.L. Hartman. 1975. Environmental factors affecting the strength of walleye (*Stizostedion vitreum vitreum*) year-classes in western Lake Erie, 1960–70. Journal of the Fisheries Research Board of Canada 32(10): 1733–1743.

Burnham, K.P. and D.R. Anderson (2002) Model selection and multimodel inference - A pratical information-theoretic approach, 2nd ed., Springer, New York.

Carlander, K.D. and P.M. Payne. 1977. Year class abundance, population and production of walleye, *Stizostedion vitreum vitreum*, in Clear Lake, Iowa, 1948–1974, with varied stocking rates. Journal of the Fisheries Research Board of Canada34(10): 1792–1799.

Caroffino, D.C., Mwai, A.M. and B.I. Evans. 2011. Population genetics of walleye and yellow perch in the St. Mary's River. Journal of Great Lakes Research 37(2): 28–34.

Caswell, N.M., Peterson, D.L., Manny, B.A. and G.W. Kennedy. 2004. Spawning by lake sturgeon (*Acipenser fulvescens*) in the Detroit River. Journal of Applied Ichthyology 20: 1–6.

Colby, P.J., McNicol, R.E. and R.A. Ryder. 1979. Synopsis on the biological data on the walleye Food and Agricultural Organization of the United States, Rome.

Cooley, P. and W. Franzin. 2008. Predicting the spatial mud energy and mud deposition boundary depth in a small boreal reservoir before and after draw down. Lake Reservoir and Management 24(3): 261–272.

Corbett, B.W. and P.M. Powles. 1986. Spawning and larva drift of sympatric walleyes and white suckers in an Ontario stream. Transactions of the American Fisheries Society 115: 41–46.

COSEWIC, 2005. COSEWIC assessment and update status report on the lake whitefish (Lake Simcoe population) *Coregonus clupeaformis* in Canada. Committee on the Status of Endangered Wildlife in Canada. Ottawa, Ontario.

COSEWIC. 2006. COSEWIC assessment and update status report on the lake sturgeon *Acipenser fulvescens* in Canada. Committee on the Status of Endangered Wildlife in Canada. Ottawa, Ontario.

Daugherty, D.J., Sutton, T.M. and R.F. Elliot. 2008. Potential for reintroduction of lake sturgeon in five northern Lake Michigan tributaries: a habitat suitability perspective. Aquatic Conservation: Marine and Freshwater Ecosystems, 18: 692–702.

De Graaf, N. M. 1993. Fisheries assessment of Aishihik, Canyon and Sekulman lakes, 1991-1992. Yukon Renewable Resources, Fish and Wildlife Branch, Technical Report TR–93–1. Whitehorse.

Deslandes, J., S. Guénette and R. Fortin. 1994. Evolution of fish communities in environments affected by the development of the La Grande Complex, phase I (1977-1992). Hydro-Québec and the Université du Québec à Montréal. Montréal.

Dumont, P., D'Amours, J., Thibodeau, S., Dubuc, N., Verdon, R., Garceau, S., Bilodeau, P. Mailhot, Y. and R. Fortin. 2011. Effects of the development of a newly created spawning ground in the Des Prairies River (Québec, Canada) on the reproductive success of lake sturgeon (*Acipenser fulvescens*). Journal of Applied Ichthyology 27: 394–404.

Evans, D.O., Houston, J.J. and G.N. Meredith. 1988. Status of the Lake Simcoe whitefish, *Coregonus clupeaformis*, in Canada. Canadian Field Naturalist 102(2): 103–113.

Fielder, D. G. 2002. Sources of walleye recruitment in Saginaw Bay, Lake Huron and options for further recovery. Michigan Department of Natural Resources, Fisheries Research Report 2062, Ann Arbor.

Fortin, R., D'Amours, J.D. and S. Thibodeau. 2002. Effets de l'aménagement d'un nouveau secteur de frayère sur l'utilisation du milieu en période de fraie et sur le succès de reproduction de l'esturgeon jaune (*Acipenser fulvescens*) à la frayère de la rivière des Prairies. Rapport synthèse, 1995-1999. Pour l'Unité Hydraulique et Environnement, Hydro-Québec et la Société de la faune du Quebec, Direction de l'aménagement de la faune de Montréal, de Laval et de la Montérégie, Département des Sciences biologiques, Université du Québec à Montréal, Montréal, Québec.

Friday, M.J. 2014 Estimating the critical reproductive periods of lake sturgeon (*Acipenser fulvescens*) using daily water temperature units. Technical Note TN-48. Ministry of Natural Resources, Thunder Bay, Ontario.

Fudge, R.I.P. and R.A. Bodaly. 1984.Postimpoundment winter sedimentation and survival of lake whitefish (*Coregonus clupeaformis*) eggs in Southern Indian Lake, Manitoba. Canadian Journal of Fisheries and Aquatic Sciences 41: 701–785.

Gaboury, M. N., and J. W. Patalas. 1984. Influence of water level drawdown on the fish populations of Cross Lake, Manitoba. Canadian Journal of Fisheries and Aquatic Sciences 41:118–125.

Gerig, B., Moerke, A., Greil, R. and S. Koproski. 2011. Movement patterns and habitat characteristics of Lake Sturgeon (Acipenser fulvescens) in the St. Mary's River, Michigan, 2007-, 2008. Journal of Great Lake Research 37(2): 54–60.

GLFC, 2009. St. Marys River: Opportunities to Improve Integrated Sea Lamprey Management by Manipulating Flow, Great Lakes Fishery Commission, Sea Lamprey Control, PowerPoint presentation presented at IUGLS St. Marys River meeting in Sault St. Marie, June 2009.

Goodyear, C.D., Edsall, T.A., Ormsby Dempsey, D.M., Moss, G.D. and P.E. Polanski. 1982. Atlas of the spawning and nursery areas of Great Lakes fishes. Volume III: St. Mary's River. Fish and Wildlife Service . U.S. Department of the Interio. Washington, DC.

Harkness, W.J.K. and J.R. Dymond. 1961. The lake sturgeon. Ontario Department of Lands and Forests, Toronto, Ontario.

Harris, R., Kinder, B., Marino, A., Parker-Geisman, V. and T. Patterson. 2009. The St. Mary's River watershed: Planning for biodiversity conservation. The Nature Conservancy of Michigan and the School of Natural Resources and Environment, University of Michigan, Ann Arbor, Michigan.

Hart, J.L. 1930. Spawning and early life history of the whitefish (*Coregonus clupeaformis*) in the Bay of Quinte, Ontario. Contributions to Canadian Biology and Fisheries VI(7) : 50 .

Hatch, R.W., Nepszy, S.J., Muth, K.M. and C.T. Baker. 1987. Dynamics of the recovery of the Western Lake Erie walleye (*Stizostedion vitreum vitreum*) stock. Canadian Journal of Fisheries and Aquatic Science 44: 15–22.

Holey, M.E., Baker, E.A., Thuemler, T.F. and R.F. Elliot. 2000. Research and assessment needs to restore lake sturgeon in the Great Lakes. Great Lakes Fishery Trust Workshop. Muskegon, Michigan.

Houston, J.J.P. 1986. COSEWIC Status Report on the Lake Sturgeon *Acipenser fulvescens* in Canada. Committee on the Status of Endangered Wildlife in Canada. Ottawa, Ontario.

Humphrey, S., Zhao, Y. and D. Higgs. 2012. The effects of water currents on walleye (*Sander vitreus*) eggs and larvae and implications for the early survival of walleye in Lake Erie. Canadian Journal of Fisheries and Aquatic Science 69: 1959–1967.

Jenkins, R.E. and N.M. Burkhead. 1994. Freshwater Fishes of Virginia. American Fisheries Society, Bethesda, Maryland.

Johnson, F.H. 1961. Walleye egg survival during incubation on several types of bottom in Lake Winnibigoshish, Minnesota, and connecting waters. Transactions of the American Fisheries Society. 90: 312–322.

Jones, M.L., Netto, J.K., Stockwell, J.D. and J.B. Mion. 2003. Does the value of newly accessible spawning habitat for walleye (Stizostedion vitreum) depend on its location relative to nursery habitats? Canadian Journal of Fisheries and Aquatic Science 60: 1527–1538.

Kallemeyn, L.W. 1987. Correlations of regulated lake levels and climatic factors with abundance of young-of-the-year walleye and yellow perch in four lakes in Voyageurs National Park. North American Journal of Fisheries Management 7(4): 513–521.

Kallemeyn, L.W., Holmberg, K.L., Perry, J.A. and B.Y. Odde. 2003. Aquatic Synthesis for Voyageurs National Park. U.S. Geological Survey, Information and Technology Report 2003-0001.

Kempinger, J.J. 1988. Spawning and early life history of lake sturgeon in the Lake Winnebago system. Wisconsin. pp. 110-122 in R.D. Hoyt, editor. 11th annual larval fish conference. American Fisheries Society, Symposium 5. Bethesda. Maryland.

Kerr, S.J., Corbett, B.W., Kinsman, H.N.J., Leach, J., Puddister, D., Stanfield, L. and N. Ward. 1997. Walleye habitat: A synthesis of current knowledge with guidelines for conservation. Percid community synthesis, Walleye habitat working group, Ontario Ministry of Natural Resources, Peterborough, Ontario.

Kerr, S.J., Davison M. J. and E. Funnell., 2010. A review of lake sturgeon habitat requirements and strategies to protect and enhance sturgeon habitat. Fisheries Policy Section, Biodiversity Branch. Ontario Ministry of Natural Resources. Peterborough, Ontario.

Koshinsky, G.D., and C.J. Edwards. 1983. Fish and fisheries of the St. Marys Rapids: An analysis of status with reference to water discharge, and with particular reference to Condition 1.(b). International Joint Commission Report, Ottawa, Canada.

Lahaye, M., and Fortin, R. 1990. Caractérisation de l'habitat de fraie et de l'habitat des juveniles de l'estureon jaune (*Acipenser fulvescens*) dans la région de Montréal. Département des sciences biologiques, Universite du Québec a Montréal, Montréal, Québec. ix + 81 p. + apps.

LaHaye, M., Branchaud, A., Gendron, M., Verdon, R. and R. Fortin. 1992 Reproduction, early life history, and characteristics of the spawning grounds of the lake sturgeon (*Acipenser fulvescens*) in Des Prairies and L'Assomption rivers, near Montréal, Québec. Canadian Journal of Zoology 70: 1681–1689.

LaHaye, M., Desloges, S., Côté, C., Rice, A., Philips, S. Jr., Deer, J., Giroux, B., de Clerk, K. and P. Dumont. 2004. Search for and characterization of lake sturgeon (*Acipenser fulvescens*) spawning grounds in the upstream portion of the Lachine Rapids, St- Lawrence River, in, 2003. Technical report 16-20E. Ministère des Ressources naturelles, de la Faune et des Parcs, Direction de l'aménagement de la faune de Montréal, de Laval et de la Montérégie, Longueuil, Québec.

Legendre P., and L. Legendre. 2012. Numerical Ecology, Third Edition. Elsevier, Amsterdam, 990 pp.

Luna, S. 2008. "*Coregonus clupeaformis*" fishbase.org. Accessed February 8th, 2016 at http://www.fishbase.org/Summary/SpeciesSummary.php?id=234.

MacDonald, G.A. 1978. The Ojibway fishery at Sault Ste. Marie, 1640-1920. M.Sc. Thesis. University of Waterloo. Waterloo, Ontario.

Machniak K. 1975. The effects of hydroelectric development on the biology of northern fishes (reproduction and population dynamics). 1. Lake whitefish *Coregonus clupeaformis* (Mitchill). Freshwater Institute, Research and Development Directorate, Technical report no 527, Ontario.

McMurtry, M.J. 1989. Fall trapnetting on the spawning grounds of lake trout and Lake Whitefish in lake Simcoe, 1985-1988. Ontario Ministry of Natural Resources, Lake Simcoe Fisheries Assessment Unit Report 1989-3. 58pp.

Manny, B.A. and G. W. Kennedy. 2002. Known lake sturgeon (*Acipenser fulvescens*) spawning habitat in the channel between lakes Huron and Erie in the Laurentian Great Lakes. Journal of Applied Ecology 18: 486–490.

Manny, B.A., Kennedy, G.W., Boase, J.C., Allen, J.D. and E.F. Roseman. 2010. Spawning by walleye (*Sander vitreus*) and white sucker (*Catostomus commersonii*) in the Detroit River: implications for spawning habitat enhancement. Journal of Great Lakes Research 36: 490–496.

Michigan Department of Natural Resources, 2008. "Lake Whitefish, Coregonus clupeaformis" (On-line). Michigan Department of Natural Resources, Fish Identification. Accessed July 12, 2016 at ttp://www.michigan.gov/dnr/0,1607,7-153-10364_18958-45680--,00.html.

Mills, K.H., S.M. Chalanchuk, D.J. Allan, and R.A. Bodaly. 2002. Abundance, survival, condition, and recruitment of Lake Whitefish (*Coregonus clupeaformis*) in a lake subjected to winter drawdown. Archiv Fur Hydrobiologie Advances in Limnology 57. Pages 209-219 *in* T. Todd and G. Fleischer, editors. Biology and Management of Coregonid Fishes – 1999. Stuttgart.

Mion, J.B., Stein, R.A. and E.A. Marschall. 1998. River discharge drives survival of larval walleye. Ecological Applications 8: 88–103.

Morin, J., O. Champoux, M. Mingelbier, J.A. Bechara, Y. Secretan, M. Jean and J.-J. Frenette. 2003. Emergence of new explanatory variables for 2D habitat modelling in large rivers: the St. Lawrence experience. Canadian Water Resources Journal 28(2): 249–272.

Morin, J., K. Turgeon, S. Martin and O. Champoux. 2006. Modelling changes in aquatic plant communities and wetlands of the Saint-Lawrence River. in Water availability issues for the St.Lawrence River : An environmental synthesis. T. A. (ed) (ed.). Montréal, Environment Canada. : 204 p.

Morin, J., M. Bachand, J. Hénault-Richard and S. Martin (2016) Modeling the Rainy Lake and Namakan Reservoir ecosystem response to water level regulation. Scientific Report SR-110 MSC Québec – Hydrology and Ecohydraulic Section, Environment Canada, Québec, prepared for the International Joint Commission study on Rainy Lake and Namakan Reservoir. Hydrology and Ecohydraulic Section, Environment Canada, Québec.

Nilo, P., S. Tremblay, A. Bolon, J. Dodson, P. Dumont and R. Fortin. 2006. Feeding ecology of juvenile Lake Sturgeon in the St. Lawrence river system. Transaction of the American Fisheries Society 135(4): 1044–1055.

Ontario Ministry of Natural Resources (OMNR). 2011. Lake Sturgeon (*Acipenser fulvescens*). Queen's Printer for Ontario.

Page, L.M. and B.M. Burr. 1991. A Field Guide to Freshwater Fishes of North America North of Mexico. The Peterson Field Guide Series, volume 42. Houghton Mifflin Company, Boston, Massachusetts.

Palmer, G.C., Murphy, B.R. and E.M. Hallerman. 2005. Movements of walleyes in Claytor Lake and the Upper New River, Virginia, indicate distinct lake and river populations. North American Journal of Fisheries Management 25: 1448–1455.

Paragamian, V.L. 1989. Seasonal habitat use by walleye in a warmwater river system, as determined by radiotelemetry. North American Journal of Fisheries Management 9: 392–401.

Peterson, D.L., Vecsei, P. and C.A. Jennings. 2007. Ecology and biology of the lake sturgeon: a synthesis of current knowledge of a threatened North American Acipenseridae. Review Fish Biology and Fisheries 17: 59–76.

Priegel, G.R. and T.L. Wirth. 1971. The lake sturgeon. Its life history, ecology and management. Wisconsin Department of Natural Resources, Madison, Wisconsin.

Randall, R.G. 2008. Narrative description and quantification of the habitat requirements of lake sturgeon (*Acipenser fulvescens*) in the Great Lakes and upper St- Lawrence River. Research Document. Fisheries and Oceans Canada. Ottawa, Ontario.

Roseman, E.F., W.W. Taylor, D.B. Hayes, R.C. Haas, R.L. Knight and K.O. Paxton. 1996. Walleye egg deposition and survival on reefs in Western Lake Erie (USA). Annales Zoologici Fennici 33(3–4): 341–351.

Roseman, E.F., Taylor, W.W., Hayes, D.B., Jones, A.L. and J.T. Francis. 2006. Predation on walleye eggs by fish on reefs in western Lake Erie. Journal of Great Lakes Research 32(3): 415–423.

Schneider, J.C. and J.H. Leach. 1977. Walleye (Stizostedion vitreum vitreum) fluctuations in the Great Lakes and possible causes. 1800-1975. Journal of the Fisheries Research Board of Canada 34(10): 1878–1899.

Scott, W.B. and E.J. Crossman. 1998. Freshwater Fishes of Canada. Galt House Publications Ltd. Oakville, Ontario.

Shuter, B.J. and J.F. Koonce. 1977. A dynamic model of the Western Lake Erie walleye (*Stizostedion vitreum vitreum*)bpopulation. Journal of the Fisheries Research Board of Canada 34: 1972–1982.

Smith A. 2014. Studies of the upper Rainy River food web and variations in spawning critical habitats in relation to flow. Master's thesis, University of Waterloo, Waterloo.

Smith, E. and S. Greenwood 2010. St. Mary's River Rapids Spring Creel Surveys 2006-2008. Upper Great Lakes Management Unit, Ontario Ministry of Natural Resources 14pp.

Steimel, N. 2010. Effects of temperature, rainfall events, and time of year on fish use of the St. Mary's River Rapids. Senior Thesis, Department of Biological Sciences, Lake Superior State University.

St- Pierre, R. and A. Runstrom. 2004. *Acipenser fulvescens*. The IUCN Red List of Threatened Species, 2004: e.T223A13036599.

Taylor, W.W., Smale, M.A. and M.H. Freeberg. 1987. Biotic and abiotic determinants of lake whitefish (*Coregonus clupeaformis*) recruitment in Northeastern Lake Michigan. Canadian journal of Fisheries and Aquatic Science 4(2): 313–323.

Willox, C.C., 1986. A summary of fall netting on lake trout and lake whitefish spawning shoals in Lake Simcoe from, 1980-1984. Ontario Ministry of Natural Resources, Lake Simcoe Fisheries Assessment Unit Report.

Wismer, D.A. and A.E. Christie. 1987. Temperature relationships of Great Lakes fishes: A data compilation. Great Lakes Fishery Commission, Ann Arbor, MI. Spec. Publ. 87–3.

Zhao, Y., Jones, M.L., Shuter, B.J. and E.F. Roseman. 2009. A biophysical model of Lake Erie walleye (*Sander vitreus*) explains interannual variations in recruitment. Canadian Journal of Aquatic Sciences 66: 114–125.

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