St. Marys River Biological Status and Hydrologic Performance Indicators

By

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Introduction

The St. Marys River is an atypical aquatic ecosystem because it is a large (mean discharge 2,140 m^3/s) and short (112 km) river connecting large lakes. This ecosystem has been well characterized in comprehensive reviews by Duffy et al. (1987), Kauss (1991), Bray (1993), HHC (1994) and others. The river includes three distinct sections: a 22.5-km Lake Superior outlet section at lake elevation; a 1.2-km rapids (6.1 m drop) section with facilities and channels for navigation, hydropower, water regulation, and high gradient fishery support; and a 88.3-km lower river section largely at Lake Huron elevation. The lower river has the morphology of a complex strait, with substantial water turnover and current like a river, and changing water surface elevations from natural and human factors. Narrow channels, broad and wide lakes, four large islands, and many small islands are present. St. Marys River water chemistry and pelagic biota often reflect the flow through nature of the river system. Water quality in the river is generally very high and similar to the nutrient poor, cold waters of Lake Superior. Phytoplankton and zooplankton are dominated by the same taxa that characterize pelagic waters of Lake Superior. Attached, rooted, and emergent plants in shallow and shoreline waters provide much of the organic material and habitat supporting the river biota. Fish and invertebrate faunas are diverse and explained by the diversity of habitats in the system and the connections to large lakes.

The connection among lakes provided by the St. Marys River makes the river a key element in the Great Lakes system. The Soo Locks set the maximum dimensions of ships moving cargo across the Great Lakes, the river provides an ideal site for hydropower production, and the rapids have always supported productive fishing and reproduction of migratory species. The human benefits have been improved by major alterations of the river. Navigation improvements started as early as 1797 and have continued with periodic upgrading of the locks and dredging of shipping channels. Hydropower plants were first constructed in 1902 and have been rebuilt and optimized for the site with water diversion channels and regulating structures. These actions have resulted in a loss of about half the rapids habitat, altered river hydraulics and flow paths, and continuous regulation of river volume. The development of Soo Harbor, urban centers on both sides of the river, and industrial facilities has altered the shoreline in some of the river. Today the river is greatly modified but remains a key aquatic resource in the Great lakes system for a variety of human uses and ecosystem benefits.

Conservation of the St. Marys River has been priority for many agencies and groups in the US and Canada for many years. This report is a part of the International Upper Great Lakes Study (IUGLS 2010) is being conducted by the International Joint Commission under the authority of the Boundary Waters Treaty to evaluate options for regulating levels and flows in the upper Great Lakes system. This study is aimed at assessing the need for changes to the water regulation plan in the upper Great Lakes to meet the contemporary and emerging needs, interests, and preferences for sustainable management of the system. A priority focus is on the options to improve the Lake Superior outflow through the St. Marys River. US and Canadian agencies and conservation groups are looking at the history of changes in the St. Marys River and considering how the environment can be improved while maintaining the important benefits to people in both countries.

No comprehensive assessment of the St Marys River ecosystem has been reported despite multiple detailed reviews of the river's environment and conservation efforts that propose numerous remedies and actions. We developed an ecosystem scale evaluation of the current river environment using many investigations and observations by river experts and conservationists. Also, in response to the current IUGLS study of water management options for the river, we defined a set of hydrologic performance indicators for the current US and Canadian assessment of Lake Superior outflows. Our objectives are to identify the current condition of the river environment emphasizing its biological status, and identify a series of water control changes that would address some of the deficiencies in the environmental quality of the river, anf specify water management performance indicators for use in the International Upper Great Lakes Study.

Biological Condition Assessment

A descriptive model of ecosystem change in response to stressors has been developed by Davies and Jackson (2006). Called a biological condition gradient, this model organizes changes in ecosystem structure and function to characterize the overall status. The model synthesizes observations into six status classes ranging from undisturbed or natural ecosystem condition to severely altered environments with major loss of ecosystem structure and function (Figure 1). This method builds on the characteristics of stressed ecosystems described by Odum et al. (1979), Odum (1985), Rapport et al. (1985), and Cairns and Pratt (1993). The status classification communicates ecosystem condition in a form that can be used in environmental management for planning restoration and protection measures.

We applied this model to the St. Marys River using comprehensive reviews of the river environment (Duffy et al. 1987; Kauss 1991; Bray 1993), a conservation assessment using more than 40 river experts (Harris et al. 2009), and our own workshop of St. Marys River biologists (authors and those listed in Acknowledgements). Observations of change in the river ecosystem were collected, and then organized in the six classes of condition using the specification for environmental attributes in Davies and Jackson (2006). Table 1 reports ecosystem changes by environmental attributes ordered in the six status classes. This allows an informed judgement of the overall ecosystem condition using the dominant class where changes were rated.

Using the pattern of observed and reported changes relative to the ecosystem status classes, we concluded that the St. Marys River currently has moderate changes in the structure of the biotic community and some change in ecosystem function (Class 4). Some changes were rated minimal or evident (Classes 2 and 3), and a fair number of observations indicate major change in the ecosystem. However, all environmental attributes showed change in the class 4 level and the changes noted cluster around this level. Class 4 is marked by moderate change in ecosystem structure and minor functional change. Changes in community structure involved replacement of some sensitive and specialized taxa by more tolerant taxa and nonnative species (Table 1). However, the presence of sensitive taxa has been generally maintained although in some cases at low levels. Small fishes, some birds, wetland plants, and salmonid fishes have shifted toward more tolerant taxa and nonnative species that are more generalized in environmental needs. The altered community compositions indicate some significant change in ecosystem structure and function such as altered food webs and benthic invertebrate composition.

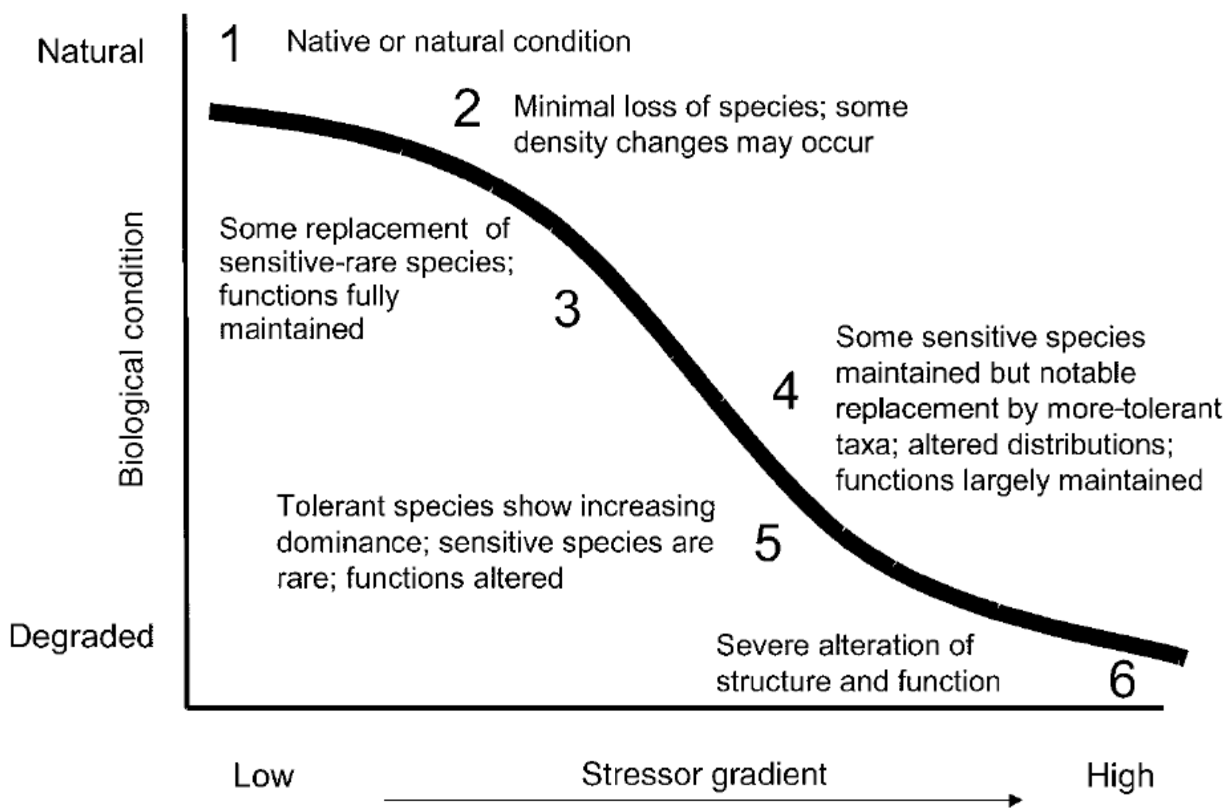

Figure 1. The biological condition gradient organized into 6 stressor classes (from Davies and Jackson 2006).

Table 1. Observed changes in the St. Marys River ecosystem tabulated using the biological condition assessment method of Davies and Jackson (2006).

Ecosystem attribute	**1** **Natural condition**	**2** **Minimal changes in biotic structure**	**3** **Evident changes in biotic structure and minimal changes in ecosystem function**	**4** **Moderate changes in biotic structure indicating some change in ecosystem function**	**5** **Major changes in biotic structure and moderate changes in ecosystem function**	**6** **Severe changes in biota and ecosystem**
Sensitive regional or rare taxa			Lake sturgeon sharply reduced, no evidence on spawning success.	Sandhill crane and lake trout now rare.	Brook trout was common and now absent.	
Sensitive ubiquitous taxa				Local walleye stocks sharply down and vulnerable to loss; northern pike and burrowing mayflies declined from high abundance.	Markedly diminished species include cisco, burbot, black tern, eagles, and osprey.	
Intermediate tolerant taxa				Increasing abundance: double-crested comorants, white pelicans, and freshwater drum.		
Tolerant taxa			White perch colonizing river.	Undesirable indicator bacteria, *Escherichia coli*, now abundant. Ring-billed gulls and herring gulls increasingly abundant.		
Nonnative, introduced taxa		Colonizing river: round goby, zebra mussels, spiny water flea, rusty crawfish, and phragmites.	Now common: three spine stickleback, rainbow smelt, alewife.	Rainbow trout and Pacific salmon species greatly increased in river. Rainbow trout now dominant in rapids habitat.	Very common: sea lamprey, purple loosestrife, reed canary grass.	

Table 1. Continued.

Ecosystem attribute	1 Natural condition	2 Minimal changes in biotic structure	3 Evident changes in biotic structure and minimal changes in ecosystem function	4 Moderate changes in biotic structure indicating some change in ecosystem function	5 Major changes in biotic structure and moderate changes in ecosystem function	6 Severe changes in biota and ecosystem
Organism condition			Morphological anomalies observed in white sucker.	Pacific salmon hybrids common, VHSv and BKD diseases in salmon.	Sea lamprey wounding and mortality common for large fish.	
Ecosystem functions			Sediment contamination effecting benthic organisms in some areas. Wetland and aquatic vegetation changes from dredging, ship traffic, and hydrologic alteration.	Altered food web through reduction of cisco and replacement by smelt and alewife. The change has been associated with thiamine deficiency in some large fishes.		
Spatial-temporal effects			Localized water pollution and contaminated sediments.	Wetland losses and littoral-shore modification (bulkhead and hardening) in much of upper section of lower river. Water temperatures have increased allowing species colonization of river.	Rapids habitat greatly reduced to one limited area, altered hydrodynamics by navigation structures and channel dredging in much of the lower river.	
Ecosystem connectance			Dominant water pathway changed from north to south channels by navigation works.	Compensating Works is a partial barrier. Water level controls isolate some embayments periodically.		

A key consideration of the fourth status class is that most sensitive taxa are maintained at a reduced level but still commonly detected in the system. Large changes in abundance may be seen in some taxonomic groups such as bacteria, some birds, and a variety of non-native species. At present, major changes in ecosystem function have not been reported although physical alteration of the river in terms of water flows, hydrologic regime, and water barriers have been profound.

Our conclusion is that the St. Marys River has experienced moderate biological structure change without major ecosystem functional breakdown. However, many species of different taxonomic groups are in the process of colonizing the river and increasing in abundance. We feel that the St. Marys River is approaching a point where major ecosystem functional change can occur given the strong alteration of water flows and paths combined with increasing water temperatures. These observations are consistent with the class 4 biological condition. Therefore, we want to emphasize the unique nature of the St. Marys River in the Great Lakes system, and draw attention to the need to constrain and possibly reverse ecosystem changes that could easily transform the river to a new ecosystem with much different characteristics.

Hydrologic Considerations

The International Upper Great Lakes Study (IUGLS 2010) is a currently active opportunity to address the management of St. Marys River levels and flows. We considered which changes in the river ecosystem that are shown in Table 1 can be improved by different management of river flows and levels. Not all changes that define the St. Marys River biological condition can be addressed by water management but many can be influenced by changes in river regulation and Lake Huron water level management. We review these grouped by related ecosystem attributes shown in Table 1. Our purpose is to identify water control changes that would address some of the deficiencies in river condition, and identify benefits that would come from changes in water regulation.

Sensitive Species

Lake sturgeon were once abundant in the Great Lakes and the St. Marys River, but the population is suspected to be 1% of its original size (Harkness and Dymond 1961). This fish species is a conservation priority in the Great Lakes Basin (Holey et al. 2000; Great Lakes Fishery Commission 2008; Harris et al. 2009). The lake sturgeon is now listed as threatened, endangered, or a species of concern in Michigan, Ontario, Illinois, Indiana, Ohio, Wisconsin, and Minnesota, and as a globally rare species by The Nature Conservancy (Goforth 2000). Thus the species is a conservation priority in the Great Lakes Basin (Holey et al. 2000; Great Lakes Fishery Commission 2008, Harris et al. 2009). The St. Marys River has an estimated population size of around 500 individuals that appear genetically distinct from other lake sturgeon populations in the Great Lakes (Gerig et al. *in press*). A major barrier to lake sturgeon recovery is the lack of suitable spawning sites (Daugherty et al. 2008). Lake sturgeon spawn in areas with moderate flow (Seyler 1997; Manny and Kennedy 2002; Friday 2006) and hard substrate (Auer

1996; Seyler 1997; Bruch and Binkowski 2002). The St. Marys River has several sites that meet these requirements (Goodyear et al. 1982), but maintenance of these spawning habitats is linked to flow regime to maintain adequate water velocities. In the St. Marys River, sufficient river flow must be maintained for lake sturgeon spawning to ensure adequate spawning success and recruitment.

Cisco have been important commercially and are still a popular sport fish, but their abundance has declined across the Great Lakes (Fielder et al. 2002; Mohr and Evener 2005). They are now listed as threatened in Michigan, a restoration priority in Lake Huron (Lake Huron Technical Committee 2007), and a conservation priority across the Great Lakes Basin (Great Lakes Fishery Commission 2008). The decline in cisco has altered the prey fish assemblage that is now dominated by species rich in thiaminase (Fitzsimons et al. 1998) causing thiamine deficiency complex in predator fishes (Ketola et al. 2000). In addition, cisco grow to larger sizes than many current prey fishes, which makes them a more energetically advantageous prey for lake trout (Lake Huron Technical Committee 2007). Therefore, maintaining or increasing the current cisco population may help restore a threatened species, but also may help restore lake trout. The St. Marys River is one of the few areas where cisco have persisted (Fielder 1998, 2002), making it a critical area for the collection of gametes for reintroduction elsewhere in the Great Lakes. Cisco are broadcast spawners that deposit eggs in shallow water in late fall with hatching in the spring. The eggs are sensitive to water elevation changes that occur during winter (Greeley and Bishop 1932). Furthermore, cisco eggs may hatch prematurely when exposed to light or physical disturbance, both of which may be associated with water elevation changes that disturb surface ice (Colby and Brooke 1970).

Many species of migratory birds nest in emergent vegetation of marshes along the Great Lakes shorelines. Black terns are one of most prominent of these migratory, emergent wetland nesting birds (Currier 2000) and we use black tern as a representative species for promoting control of water level changes. Black tern is a designated species of concern in Ontario, Wisconsin, Michigan, and Ohio because populations have been decreasing since the 1960s (Peterjohn and Sauer 1997). Specific hydrologic conditions are needed for black tern habitats; especially stable water levels during the breeding season (Mortsch et al. 2006). Black terns build nests from dried reeds, stalks, and grasses on mounds of vegetation often dominated by cattails (*Typha* sp.) or bulrushes (Scirpus sp.; Cuthbert 1954; Dunn 1979). Nesting sites are usually at the interface of emergent wetlands and open water where both vegetation and open habitats are about equally common (Hickey and Malecki 1997). Nesting sites are selected by black terns within a very limited range of water depths (Mazzocchi et al. 1997; Alsop 2001; Maxson et al. 2007). Nests are vulnerable to flooding and destruction by wave action, conditions that are often associated with increases in water level or its variability during the breeding and nesting seasons (Shuford 1999; Naugle 2004; Mortsch et al. 2006).

Nonnative and Tolerant Species

Sea lamprey is a nonnative species and a lethal parasite of the larger fishes in the Great Lakes (Bergstedt and Schneider 1988; Kitchell 1990). Sea lamprey have caused major changes in the fish communities, fisheries, and ecosystem characteristics in the Great Lakes. The St. Marys River produces more sea lamprey than all the Great Lakes tributaries combined (Great Lakes Fishery Commission 2000) and this results in the highest attack rate on large fishes in Lake

Huron compared to the other lakes (Johnson 1988). The size and volume of the St. Marys River makes the traditional lamprey control methods impractical; treatment with lampricides that kill lampreys in their larval stage (Brege et al. 2003). The Great Lakes Fishery Commission coordinates an integrated program to reduce lampreys in the St. Marys River using spot treatment with lampricide, trapping adults, and releasing of sterile male adults (Great Lakes Fishery Commission 2000). The St. Marys River rapids have an abundance of gravel and rubble substrate with flowing water that provides the prime spawning area for lamprey (Manion and Hansen 1980; Eshenroder et al. 1987; Schleen 1992) in the St. Marys River. Efforts to increase fish habitat in the rapids with control of rapids flow from gates on the Compensating Works would also increase the spawning habitat supporting lamprey production.

Ecosystem Functions

The structural complexity and reduced wave action provided by submerged aquatic vegetation (SAV) beds are important functions of nearshore ecosystems (Strayer and Findlay 2010). SAV beds reduce erosion and thus turbidity by stabilizing clay sediment (Liston et al. 1986). SAV beds are highly productive areas that support diverse assemblages of macroinvertebrates and fishes, and contribute to the majority of primary productivity in the St. Marys River (Liston et al. 1980; Williams and Lyon 1991). They are an important source of food for decomposers (Liston et al. 1980) and cover for a diverse and abundant macroinvertebrate community (Liston et al. 1980 [and references therein]; Duffy et al. 1987; Edsall and Charlton 1997). SAV also provide spawning and nursery habitat to a high proportion of Great Lakes fish species (Liston et al. 1980; Lane et al. 1996a,c) and resident habitat to warmwater fishes (e.g., centrarchids; Lane et al. 1996b). As such, SAV support the larger St. Marys River fish community by serving as an important link in lower food web material exchange (Liston et al. 1980). In the st. Marys River, SAV bed area is determined primarily by water depth (Williams and Lyon 1991), but also substrate, slope, water clarity, and water velocity (Liston et al. 1980; Liston et al. 1986; Duffy et al. 1987). Changes to water elevation will impact the availability of suitable habitat along and extending into the St. Marys River channel from the shoreline.

Emergent wetlands in the Great Lakes are important habitats supporting birds, mammals, fishes, invertebrates, and high biological productivity. They serve as key spawning, nursery, and feeding areas for 44 fish species of the river. Because the river has a very high water turnover rate, pelagic productivity by phytoplankton and zooplankton is minimal (Duffy 1987). The complex structured habitat formed by emergent wetlands provide more than 90% of the rivers overall dry weight biomass production (Kauss 1991). Benthic invertebrate productivity on a per unit area basis exceeds all other habitats types (Kauss 1991). Also, emergent wetlands are important to migratory waterfowl such as mallard, blue-winged teal, and the American black duck. Emergent wetlands are sensitive to water level change. The area of these wetlands has been photographed and mapped in Lake Nicolet for a half century; a large water body in the St. Marys River. A strong relationship exists between water level and the area of emergent wetlands for the St. Marys River (Kauss 1991), the Great Lakes (Kelsall and Leopold 2002; Ciborowski et al. 2008; Mortsch et al. 2006, 2008), and waterways in general (Harris and Marshall 1963; Dabbs 1971; Spence 1982).

Spatial-temporal Changes

The St. Marys River main rapids drops over 6 m in a 1.2-km reach, resulting in fast-flowing water dominated by cobble, boulder, and bedrock substrate. Large and diverse substrates and fast flows are lacking throughout the remainder of the 112-km river, which makes the rapids an important area for biotic production. The fish community in the rapids is unique and dissimilar to communities in other habitats of the river. Historically, the rapids provided high quality spawning habitat for several native species, and the rapids continue to provide spawning and feeding habitat for numerous game species and important forage fishes (Gleason et al. 1981; Goodyear et al. 1982; Steimel 2010). Macroinvertebrate composition and productivity in the rapids also differ substantially from other habitats in the river, and were dominated by net-spinning caddisfly larvae (Duffy et al. 1987; Kauss 1991). Reduction of the rapids habitat has occurred due to the construction of shipping locks and hydropower facilities and their canals. However, habitat is also reduced by flow regulation from the Compensating Works; a 16-gate structure regulating flows through the rapids. An average of about 5% of Lake Superior outflows pass through the rapids under rules of the Boundary Waters Treaty (Koshinsky and Edwards 1983).

Previous studies of rapids habitat and hydraulics (e.g., Hough et al. 1983, Koshinsky and Edwards 1983) have indicated that reduced flows result in considerable drying of rapids habitat. Increases in flow through the Compensating Works is a feasible strategy to enhance fish and benthic macroinvertebrate production in the rapids. Current flow regulation impacts biota by reducing habitat, stranding fish and invertebrates, drying and freezing of fish eggs, and alteration of spawning and nursery conditions. Changes in water regulation rules could enhance habitat available for fish and macroinvertebrate production and improve conditions for migratory fish spawning, rearing, and foraging.

The speed of water level change in the rapids caused by gate operations on the Compensating Works has been a concern of fisheries management (Godby 2006) and river conservations organizations (Harris et al. 2009). The speed of gate adjustments and changes in water releases is an issue that is limited to the rapids. Quick flow rate and water level changes on fishes can be severe and result in loss of a substantial portion of small, young fishes: a rate of 60 cm/hr change has been associated with 22% mortality of small salmonid fishes in similar rivers (Halleraker et al. 2003). The rate of fish losses due to abrupt declines in water level has been carefully studied to develop standards for mitigating this threat to river fishes. Salmonid fishes less than 100 mm length are most vulnerable to stranding. Protection criteria were developed for the speed of change that does not pose a threat to river fishes: less than a decline in water level of 10 cm/hour (Salveit et al. 2001; Halleraker et al. 2003, 2007). A change in Compensating Works operations to meet this water level rate of decline would reduce loss of young fishes considerably and could improve resident fish populations in the rapids.

The accumulation of sediment in habitats previously swept clear of fine sediment can make channels narrower and shallower, reduce formation of bars, and cover valuable spawning habitat (Reiser et al. 1989; Poff et al. 1997). These changes have obvious negative consequences for boating, vegetation, and fishes. Without flushing flows, eggs and larvae of many amphibians, fishes, and invertebrates may suffer high mortality rates (see references in Wiley et al. 1995). A lack of flushing flows can be especially important in areas where sediment input is high, as is the case in many of the low-gradient, clay and sand-dominated tributaries that flow into the St.

Marys River. A variable river flow regime influences sediment transport, which in turn affects channel morphology, habitat, and biota (Reiser et al. 1990; Poff et al. 1997; Kondolf and Williams 1999). Controlled water releases may be used to flush sediment in a manner approaching conditions prior to river regulation to maintain a more natural and productive environment. Proper implementation of flushing flows is necessary to maintain ecological integrity (see Table 2 in Poff et al. 1997) while allowing for control of flow for other purposes during the remainder of the year.

Ecosystem Connections

Backwater habitats include barrier protected and connecting channel wetlands and embayments. Along with other nearshore wetlands, backwater habitats are of high quality relative to Great Lakes wetlands overall (Harris et al. 2009). Backwater habitats are accessible to the river, enabling exchange of materials (e.g., nutrients) and organisms with the main river. Riverine and Great Lakes fishes depend on these areas as warmwater refuges in the spring (Brazner and Beals 1997; Edsall and Charlton 1997) and for important spawning and rearing habitat (Goodyear et al. 1982; Harris et al. 2009). These habitats are an important conservation priority because they provide essential habitat for waterfowl, migratory bird species, and native fishes that rely on wetlands for at least one life history stage (Harris et al. 2009). SAV beds in backwaters provide cover and complex habitat for macroinvertebrates and small fishes (Jude and Pappas 1992; Gore and Shields 1995; Randall et al. 1996; Brazner and Beals 1997). Finally, backwater habitats support submerged and emergent marsh communities composed of species that require slow water movement and reduced wave action (e.g., herbaceous species, species with long-floating propagules, and shallow submerged aquatic vegetation, SAV; Nilsson et al. 2002). River shoreline wetland habitat loss was a listed impairment in the designation of the St. Marys River area of concern (Selzer 2007). Maintaining connectivity between backwater habitats and the open river is vital for species that use these habitats during different life stages. Backwater habitat connectivity with open waters of the St. Marys River is determined by water elevation. Lower water elevations can result in hydrologic separation of backwaters through exposure of sand bars or other bathymetric features above the surface of the water column. Low water elevations also can cause loss of backwater habitat through dewatering of shallow areas.

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Performance Indicators

PI Name: Lake sturgeon spawning

Technical Workgroup: Environmental Technical Working Group
Subgroup: St. Marys River, Michigan and Ontario
Developed by: Geoffrey Steinhart

Performance Indicator Metric:

Lake sturgeon (*Acipenser fulvescens*) are an ancient fish species that were once abundant in the Great Lakes and the St. Marys River (SMR), but the population is suspected to be 1% of its original size (Harkness and Dymond 1961). The SMR has an estimated population size of around 500 individuals that appear genetically distinct from other lake sturgeon populations in the Great Lakes (Gerig et al. *in press*). Lake sturgeon spawn in areas with a moderate flow (Seyler 1997; Manny and Kennedy 2002; Friday 2006) and hard substrate (Auer 1996; Seyler 1997; Bruch and Binkowski 2002). The SMR has several sites that meet these requirements (Goodyear et al. 1982), but maintenance of these spawning habitats is linked to flow regime to maintain adequate water velocities.

Ecological Importance:

While once an abundant resource for the Ojibwe living near the SMR (Cleland 1982) and abundant throughout the Great Lakes (Harkness and Dymond 1961), lake sturgeon are now listed as threatened in Michigan and Ontario, including the area of the SMR. In addition, lake sturgeon are listed as endangered in Illinois, Indiana and Ohio, as a species of concern in Wisconsin and Minnesota, and as a globally rare species by The Nature Conservancy (Goforth 2000). The precipitous decline in lake sturgeon populations has made them a priority in the Great Lakes Basin (Holey et al. 2000; Great Lakes Fishery Commission 2008). In the SMR, lake sturgeon restoration is a conservation target for the SMR Conservation Action Plan (Harris et al. 2009). Two potential barriers to lake sturgeon recovery are the lack of suitable spawning sites (Daugherty et al. 2008) and intermittent spawning (Becker 1983). Male lake sturgeon may spawn as frequently as every other year, but females typically spawn every 4-8 years (Becker 1983; Threader et al. 1998). Therefore, to ensure adequate spawning success and recruitment, sufficient habitat and flows must be maintained for lake sturgeon spawning.

Temporal validity:

Lake sturgeon begin to stage, in preparation for spawning, around 9°C (Friday 2006). Spawning occurs at water temperatures ranging from 12-18 °C (Becker 1983; Threader et al. 1998). In the SMR, these temperatures typically occur in June (unpublished data from 1982-2007; Roger Greil, Lake Superior State University Aquatic Research Laboratory). We defined the period from 1 June through 30 June as the period of concern for lake sturgeon spawning in the SMR.

Spatial validity:

Our lake sturgeon performance indicator is tuned for the SMR with an emphasis placed on putative spawning areas. Lake sturgeon typically spawn in depths less than 5 m (Becker 1983; Threader et al. 1998). They prefer hard substrates and a moderate current for spawning (Auer 1996; Seyler 1997; Bruch and Binkowski 2002; Manny and Kennedy 2002; Friday 2006). The area between Sugar Island and East Neebish Island is a historic spawning area for lake sturgeon (Goodyear et al. 1982). Recent work by Gerig et al. (*in press*) has shown lake sturgeon moving from Lake George to this area. Although if lake sturgeon spawn in the Lake George Channel is unknown, telemetry studies have found that they commonly frequent these areas (Gerhig et al. *in press*) and that suitable substrate and depths exist, so spawning may occur if velocities were appropriate. The SMR Rapids are a historic breeding area for lake sturgeon (Goodyear et al. 1982), but the flow in the rapids was not considered since they are under separate hydrologic control (via the compensation works) than the rest of the potential spawning areas (e.g., flow through the three hydroelectric plants).

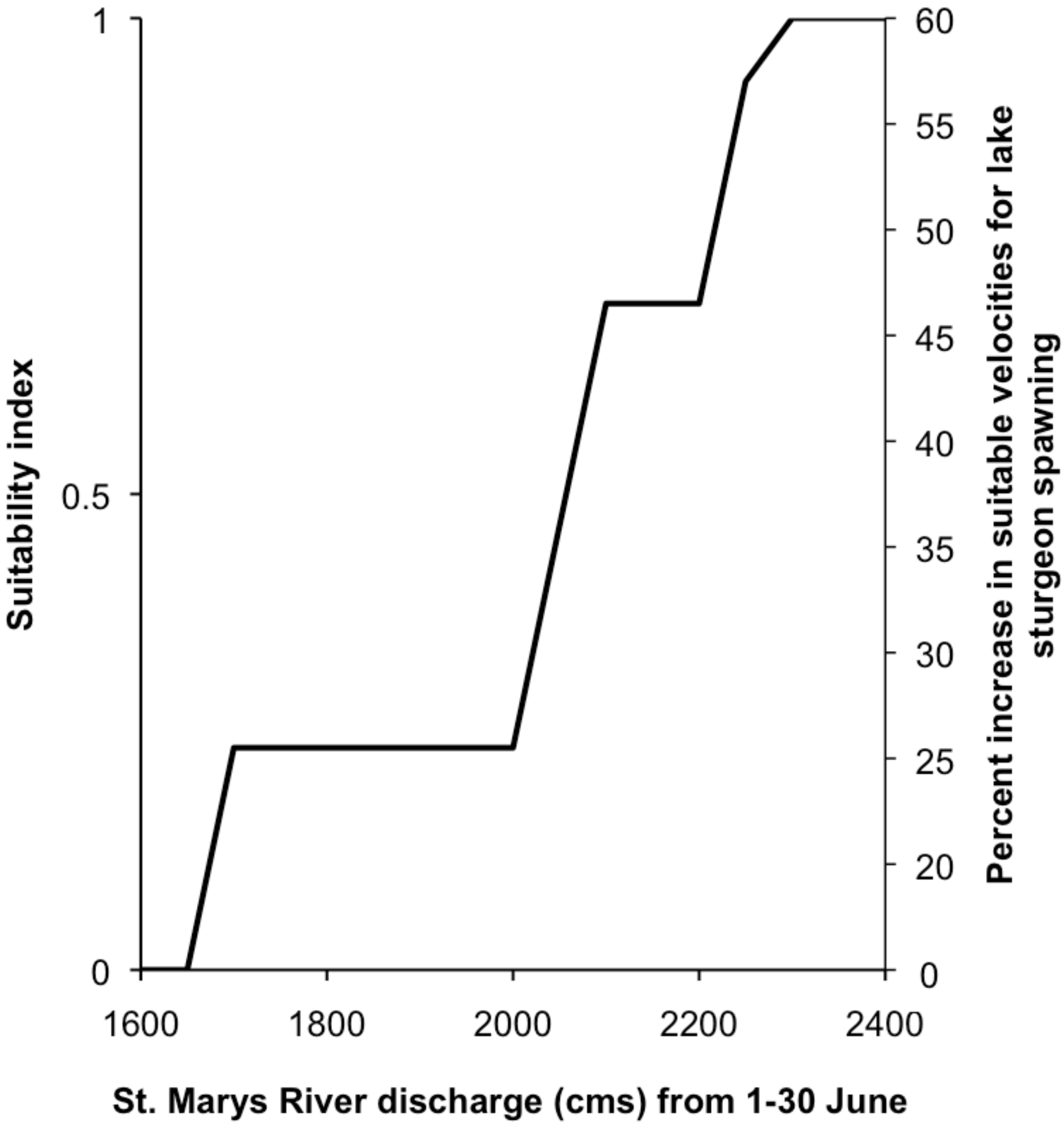
Hydrology Link:

Lake sturgeon spawn in areas with a distinct current (Threader et al. 1998). Typical velocities in lake sturgeon spawning areas range from 0.46-1.1 m/s (Seyler 1997; Manny and Kennedy 2002; Friday 2006), but can be as low as 0.2 m/s and as high as 1.4 m/s (LaHaye et al. 1992). Maintaining proper flows during the staging and spawning period has clear consequences for lake sturgeon reproductive and recruitment success (Brousseau 1987).

Algorithm:

We estimated current velocity using transects to estimate cross-sectional area along putative lake sturgeon spawning areas. Sites included in the analysis were the area between Sugar Island and East Neebish Island (5 transects, 0.2-km apart), the eastern end of the Lake George Channel, from the Garden River to Lake George (10 transects, 0.5-km apart), and mid-way along the Lake George Channel (7 transects, 0.25-km apart). The first three sites, all in or below the Lake George Channel, were assumed to receive 30% of the total SMR flow (ILSBC 2002). Average water velocity for each transect was estimated by dividing the total flow (m^3/s) by the cross-sectional area of the transect (m^2). All transects with a flow between 0.46-1.1 m/s were summed after weighting. Weighting was done by calculating the amount of suitable habitat in each site (i.e., the area with depths less than 5 m), and dividing by the sum of all suitable habitat in all sites. The performance indicator was created for total SMR flows ranging from 1600-2400 m^3/s.

A threshold for this performance indicator is at a flow of 1700 m^3/s which increases the number of transects with suitable spawning velocities by 25%, of the transects examined. This threshold was chosen because of the need to restore lake sturgeon populations and, thus, a need to increase reproductive and recruitment success. Peak suitability occurs at 2300 m^3/s. It should be noted that extreme velocities may interfere with lake sturgeon spawning, so discharge in excess of 2800 m^3/s may be detrimental for lake sturgeon spawning (data not shown).



Calibration Data:

Study results reporting lake sturgeon spawning locations, habitat requirements, and temperature were used to create the spatial and temporal validity of this performance indicator.

Validation Data:

Model validation data do not exist for this performance indicator as many lake sturgeon spawning sites are known only from historical records or estimated from seasonal movements. Current velocity has not been recorded in the SMR while lake sturgeon were actively spawning. Future work should confirm these putative spawning sites and determine the flow in which specific aggregations of lake sturgeon spawn.

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Risk and Uncertainty Assessment:

The following are the main assumptions of the performance indicator model:

1. Lake sturgeon may move to other spawning areas, or find different velocities within a site, if velocities are not appropriate.

2. Egg survival is related to juvenile and adult abundance.

3. The simplification of velocity estimates (i.e., average velocity across transects) adequately reflects the true velocities across heterogeneous transects, at least within the accepted range of velocities.

Although where lake sturgeon spawn in the SMR today or how many spawn in tributaries to the SMR are still unknown, this performance indicator does use one known spawning area and other putative spawning locations. Furthermore, because these sites contain suitable depth and substrate, they should be representative of other spawning locations. Therefore, this is the best approach for calculating this performance indicator.

PI Name: Cisco (lake herring) spawning

Technical Workgroup: Environmental Technical Working Group
Subgroup: St. Marys River, Michigan and Ontario
Developed by: Geoffrey Steinhart

Performance Indicator Metric:

Cisco *(Coregonus artedi*; formerly called lake herring) have been a traditional component of the native fish community in the Great Lakes. Cisco are broadcast spawners that deposit their eggs in relatively shallow water. Because cisco, and other coregonids, spawn in late fall and do not hatch until spring, they are sensitive to water elevation changes that occur during winter (Greeley and Bishop 1932). Furthermore, cisco eggs may hatch prematurely when exposed to light or physical disturbance, both of which may be associated with water elevation changes that disturb surface ice (Colby and Brooke 1970).

Ecological Importance:

Cisco have been important commercially, and are still a popular sport fish, but their abundance has declined across the Great Lakes (Fielder et al. 2002; Mohr and Evener 2005). They are listed as threatened in Michigan, and are a priority for restoration in Lake Huron (Lake Huron Technical Committee 2007) and across the Great Lakes Basin (Great Lakes Fishery Commission 2008). Cisco restoration is being pursued because the current prey fish community lacks diversity and is dominated by species that are rich in thiaminase (Fitzsimons et al. 1998), the cause of thiamine deficiency complex (TDC; Ketola et al. 2000). TDC may be impeding efforts to restore lake trout in the Great Lakes. In addition, cisco grow to larger sizes than many current prey fishes, which makes them a more energetically advantageous prey for lake trout (Lake Huron Technical Committee 2007). Therefore, maintaining or increasing the current cisco population not only may help this threatened species, but also may help restore lake trout. The St. Marys River (SMR) is one of the few areas where cisco have persisted (Fielder 1998, 2002), making it a critical area to preserve and for the collection of gametes for reintroduction elsewhere in the Great Lakes.

Furthermore, other fall spawning fishes (e.g., lake whitefish, *Coregonus clupeaformis*) may be similarly affected by declines in water elevation.

Temporal validity:

Cisco typically spawn in November in the SMR and peak larval abundance usually occurs in May, coinciding with typical ice-out (Colby and Brooke 1970; Liston and McNabb 1986; Fielder 1998, 2000). We defined 1 November through 15 May as the period of concern for water elevation change in the SMR.

Spatial validity:

Our cisco performance indicator is tuned for the SMR with an emphasis placed on known spawning areas. Fielder (1998, 2000) documented the locations of gravid, ripe, partially spent, and spent cisco in the SMR. With this information, he hypothesized that cisco spawned in areas of the Lake George Channel, Lake George, Baie de Wasai, and downstream from the Rock Cut. However, using transport models, eggs deposited in the Rock Cut were suspected to be carried downstream by currents (Fielder 1998) and Lake George may be only a staging ground for cisco. Therefore, we limited our analyses to the Lake George Channel and Baie de Wasai, the latter being the focal site of recent efforts to collect spawning cisco (Chuck Madenjian, USGS, Ann Arbor, personal communication) and repeatedly cited as an important spawning area (Behmer et al. 1979, Gleason et al. 1979, Jude et al. 1988).

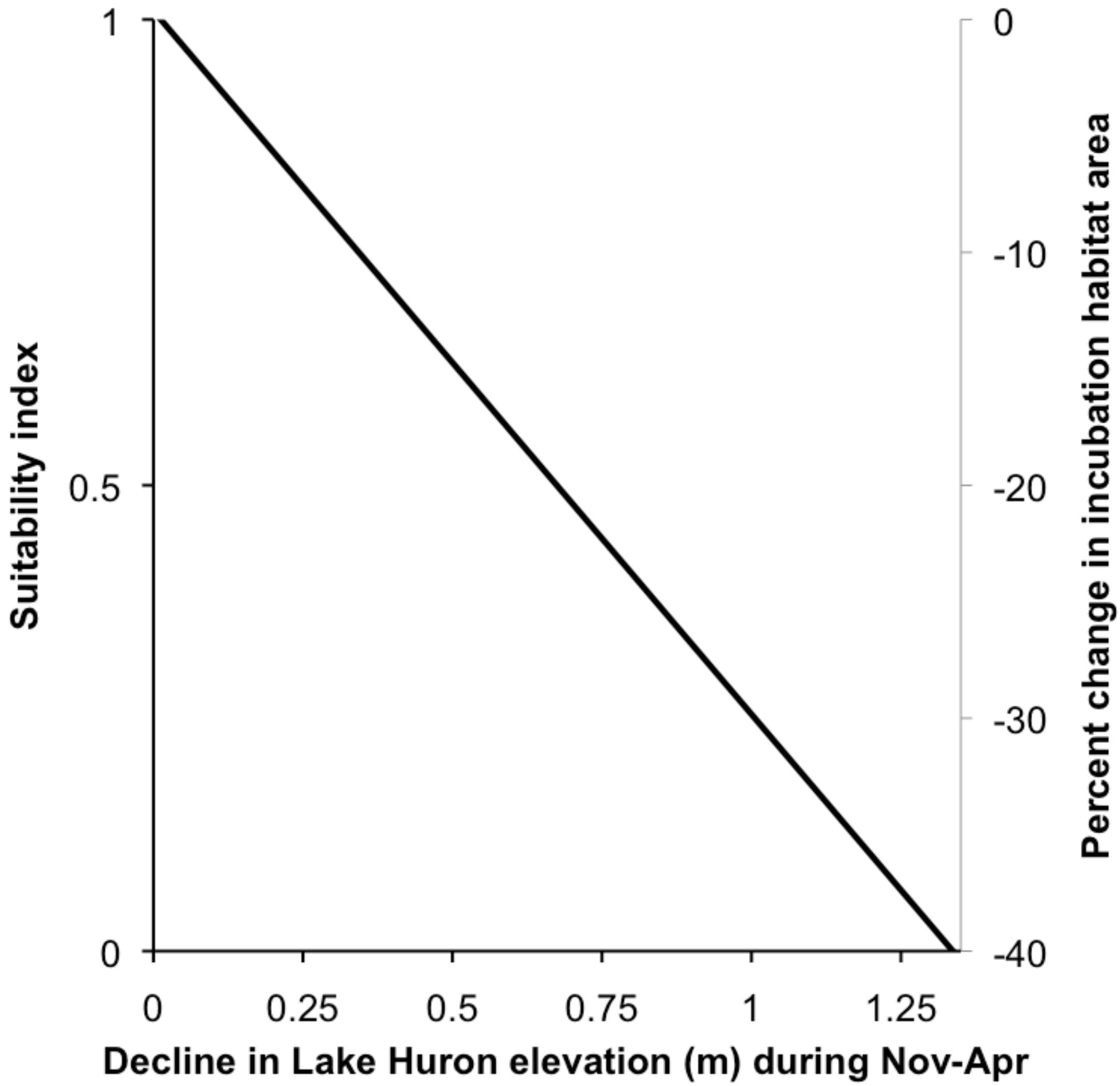
Hydrology Link:

Cisco eggs may be vulnerable to desiccation if water elevations drop. Furthermore, eggs may be vulnerable to dislodgement, destruction, or early hatching if ice-out is accelerated by dropping water elevations (Colby and Brooke 1970; Fielder 1998, 2000). Because these areas are driven more by Lake Huron water elevations than discharge through the compensation works and hydroelectric facilities (ILSBC 2002, Bain 2007), changes in Lake Huron water elevation could lead to undesirable effects on cisco egg survival.

Algorithm:

Cisco have been documented to spawn in water as shallow as 1 m (Cahn 1927), but more frequently between 3-6 m in depth (Smith 1956, Smith 1985, Savino et al. 1994). We assumed that eggs may be deposited in water depths ranging from 1-6 m. We constructed depth profiles using transects at 10-m intervals across the known spawning area in Baie de Wasai (6 transects approximately 0.5-km apart) and a putative spawning area in the Lake George Channel (7 transects approximately 0.25-km apart). Our base water elevation was 176.4 m in Lake Huron. We then used change in Lake Huron water elevation to predict new depth profiles across these transects. Any locations between 1-6 m that were later found to be less than 1-m deep (following a drop in water elevation) were assumed to be no longer suitable for incubation because there are no records of cisco spawning shallower than 1 m. We did not model an increase in water elevation because it was assumed that any temporary increase in depth would not affect incubation (cisco eggs have been found in 18-m deep water in Lake Superior; Dryer and Beil 1964). Under each water elevation change examined (-0.25, -0.5, -0.75, -1, and -1.25 m), the number of suitable 10-m sections were summed for each transect and, subsequently, scaled to create a suitability index.

A threshold for this performance indicator is zero on the suitability index: a drop of 1.25 m in Lake Huron would result in approximately 40% of the cisco spawning habitat decreasing in depth to less than 1 m. Because cisco are listed as threatened, and their annual recruitment is notoriously variable (S. Greenwood, Ontario Ministry of Natural Resources, personal communication), any loss of cisco incubation habitat could be seen as detrimental.



Calibration Data:

Study results reporting cisco spawning locations and timing were used to create the spatial and temporal validity of this performance indicator.

Validation Data:

Model validation data do not exist for this performance indicator. In fact, people are still investigating the reproductive behaviour and success of cisco in the SMR. Better validation data could be obtained with a more focused and intensive effort towards determining the exact depths at which cisco spawn in the SMR, the percent of eggs deposited at different depths, and the amount of egg movement after deposition.

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Risk and Uncertainty Assessment:

The following are the main assumptions of the performance indicator model:

1. Eggs, once deposited, are not carried away from the spawning site by currents.
2. Egg survival is related to juvenile and adult abundance.
3. Baie de Wasai and the Lake George Channel are suitable representatives for other putative spawning areas in the SMR.

Modelling results suggest eggs are not flushed from Baie de Wasai (Fielder 1998, 2000), but no such modelling has been completed for the Lake George Channel. Furthermore, the link between egg survial and adult abundance has rarely been demonstrated conclusively, possibly due to density-dependent effects. Much speculation exists about the extent of cisco spawning areas in the SMR. Baie de Wasai is a known spawning area, but other areas may receive some eggs. Finally, cisco are not the only fall spawning fishes, and we believe this algorithm is the best approach to predicting the potential loss of incubation habitat for fall spawning fishes in the SMR.

PI Name: Black Tern Nesting Success

Technical Workgroup: Environmental Technical Working Group
Subgroup: St. Marys River, Michigan and Ontario
Developed by: Mark Bain

Performance Indicator Metric:

Black terns (*Chlidonias niger*) are one of most prominent of the migratory birds that nest in marshes and emergent wetlands along the coast of the Great Lakes (Currier 2000). They build nests from dried reeds, stalks, and grasses on mounds of vegetation often dominated cattails (*Typha* sp.) or bulrushes (Scirpus sp.; Cuthbert 1954, Dunn 1979). Nesting sites are usually at the interface of emergent wetlands and open water where both vegetation and open habitats is about equally common (Hickey and Malecki 1997). Nesting sites are selected by black terns within a very limited range of water depths (Mazzocchi et al. 1997, Alsop 2001, Maxson et al. 2007). Nests are vulnerable to flooding and destruction by wave action, conditions that are often associated with increases in water level or its variability during the breeding and nesting seasons (Shuford 1999, Naugle 2004, Mortsch et al. 2006). When evaluating the implications of water levels on the black tern, the bird's nesting success and survival needs require direct consideration.

Ecological Importance:

Many species of migratory birds nest in emergent vegetation of marshes along the Great Lakes shorelines: Pied-billed Grebe (*Podilymbus podiceps*), American Bittern (*Botaurus lentiginosus*), Least Bittern (*Ixobrychus exilis*), Yellow Rail (*Coturnicops noveboracensis*), King Rail (*Rallus elegans*), Virginia Rail (*Rallus limicola*), Sora (*Porzana carolina*), Common Moorhen (*Gallinula chloropus*), American Coot (*Fulica americana*), Forster's Tern (*Sterna forsteri*), Black Tern (*Chlidonias niger*), Marsh Wren (*Cistothorus palustris*), Mallard (*Anas platrhynchos*), and Swamp Sparrow (*Melospiza georgiana*; Peck and James 1983, Timmermans 2001, Poole and Gill 2002). We will use the black tern as our representative species for evaluating water level changes on this important ecological guild of birds.

Black Tern is designated as a Vulnerable Species by Ontario Ministry of Natural Resources and an endangered or special concern species in many Great Lakes states including Wisconsin, Michigan, and Ohio. It has been a candidate for federal listing under the US Endangered Species Act. In the upper Great Lakes region, black tern occur mainly along the shorelines of Lakes Michigan, Huron, and eastern Lake Superior (Chu 1994, Brewer et al. 1991, Currier 2000). Black tern populations have been decreasing since the 1960s (Peterjohn and Sauer 1997). Specific hydrologic conditions are needed for black tern habitats and especially stable water levels during the breeding season (Mortsch et al. 2006).

Temporal validity:

Black terns nest in the upper Great Lakes region from mid-May through early to mid-August (Currier 2000, Chu 1994). However, in northern Michigan nesting has been observed to begin in late May and early June and extend to late July (Cuthbert 1954, Bergman et al. 1970). Eggs are incubated for 17 to 22 days, and young fledge 19 to 25 days after hatching. We define from 1 June through 15 August as the period of concern about water level change for the St. Marys River.

Spatial validity:

Our black tern performance indicator is timed for the St. Marys River area but can be applied more broadly to lakes Michigan and Huron with an expansion of the temporal validity period.

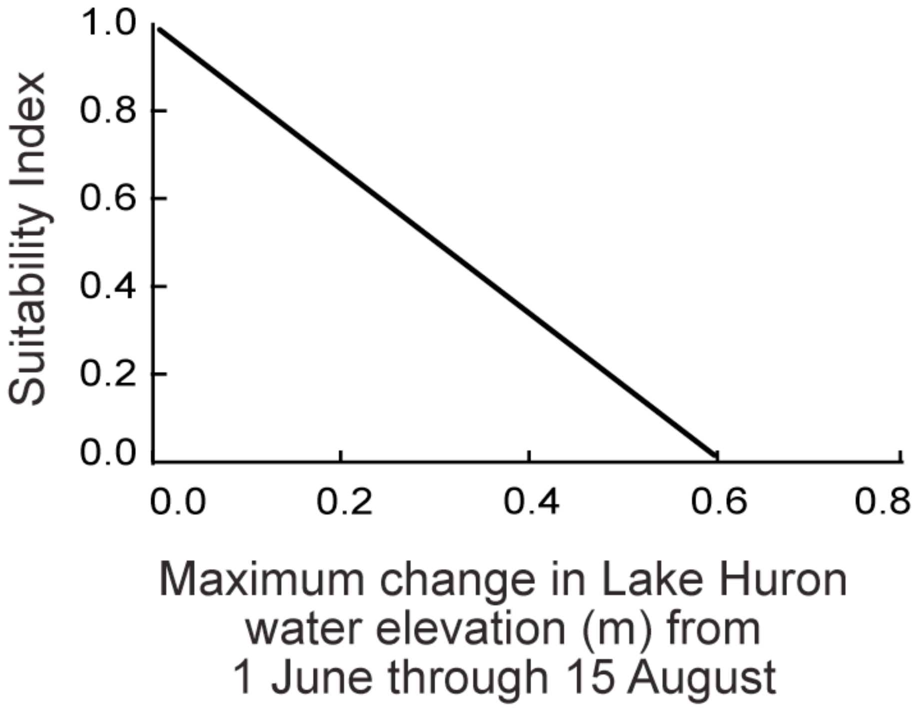
Hydrology Link:

Nests are vulnerable to flooding and destruction by wave action, conditions that could be exacerbated by increases in water level or its variability during the breeding and nesting seasons (Shuford 1999, Naugle 2004, Mortsch et al. 2006).

Algorithm:

Black terns have been documented to build nests in water ranging in depth from 0.2 to 1.2 m (Dunn 1979, Currier 2000, Alsop 2001, Maxson et al. 2007). Average water depth at nest sites is about 0.5 to 0.6 m deep (Mazzocchi et al. 1997, Zimmerman 2002). Stable water levels during nesting are critical for nesting success. Using an average nest water depth of 0.6 m and the maximum range of 1.2 m we estimate that a rise in water level of 0.6 m would impact nesting success because of flooding and water depths higher than normally used. Thus an increase in water level during the nesting period (1 June - 15 August) of 0.6 m would be unsuitable for nesting and no change in water level would be optimal. The performance indicator plot below shows this relations and links Lake Huron water level and black tern nesting success.

A threshold for this performance indicator is 0.5 on the suitability scale: maximum change in Lake Huron water level of 0.3 m. This threshold was selected to minimize any loss of nesting habitat. This species is a conservation priority in the multiple states and Ontario, and its represents other marsh nesting bird that are also conservation priorities.



Calibration Data:

Study results reporting microhabitat conditions of black tern nesting sites were used to parameterize the performance indicator. References cited provide the source of water depths used for nest site selection.

Validation Data:

The model provided is based on multiple published studies but a test of the relation developed has not been tested with measured nesting success.

Documentation and References:

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Zimmerman, A. L., J. A. Dechant, D. H. Johnson, C. M. Goldade, B. E. Jamison, and B. R. Euliss. 2002. Effects of management practices on wetland birds: Black Tern. U.S. Geological Survey, Northern Prairie Wildlife Research Center, Jamestown, ND

Risk and Uncertainty Assessment:

The following are the main assumptions of the performance indicator model:

1. Nesting success has a major influence on species abundances,

2. Nesting success declines with water level changes beyond the average conditions and maximum range used by the species,

3. Black terns select nesting sites based on the water depth ranges and emergent wetland conditions early in the nesting period.

We consider this performance indicator very sound and reliable because it was developed from multiple publishes studies with similar water level values. Also the threat of nest flooding and wave impacts brought on by water level changes has been repeated in multiple accounts of causes for the species decline.

PI Name: Lamprey Spawning Habitat in the Rapids

Technical Workgroup: Environmental Technical Working Group
Subgroup: St. Marys River, Michigan and Ontario
Developed by: Mark Bain

Performance Indicator Metric:

The St. Marys River rapids have an abundance of gravel and rubble substrate with flowing water that provides sea lamprey (*Petromyzon marinus*) spawning habitat. These conditions are limited in all other areas of the river making the rapids a prime spawning area for lamprey (Manion and Hansen 1980, Eshenroder et al. 1987, Schleen 1992). A survey of larval lamprey abundance across the St. Marys River indicated the zone including the rapids, power channels, and Soo Harbor is the 3rd most productive area for the species annually supporting an estimated 736,912 larvae (ammocoetes) in the 1980s (Eshenroder et al. 1987). Efforts to increase fish habitat in the rapids with control of rapids flow from gates on the Compensating Works would also increase the habitat supporting lamprey spawning. Therefore a performance indicator was formed that relates rapids aquatic habitat with suitability for reducing lamprey spawning success. This indicator is limited to the main rapids because the Fishery Remedial Works (flow diverting berm) on the Canadian shore of the rapids was designed and built to maintain aquatic habitat at a specific volume of flow and gate setting. There is little flexibility to change conditions north of the berm while flow changes and habitat area in the main rapids are still being considered (see main rapids wetted habitat performance indicator).

Ecological Importance:

Sea lamprey are a non-native species and a lethal parasite of the larger fishes in the Great Lakes (Bergstedt and Schneider 1988, Kitchell 1990). They have caused major changes in the fish communities, fisheries, and ecosystem characteristics in the Great Lakes (Smith and Tibbles 1980). In the 1980s, damage to Great Lakes fisheries was estimated at $2.6 million a year and about 70% of the fishery value of the most parasitized fishes (Eshenroder et al. 1987). The St. Marys River produces more lamprey than all the Great Lakes tributaries combined (Great Lakes Fishery Commission 2000) and this results in the highest attack rate on large fish in Lake Huron compared to the other lakes (Johnson 1988). The success of lamprey control for Lake Huron depends mainly on controlling lamprey in the St. Marys River (Eshenroder et al. 1995, Schleen et al. 2003).

The size and flow volume of the St. Marys River makes the traditional lamprey control methods impractical; treatment with lampricides that kill lampreys in their larval stage (Brege et al. 2003). The lack of a efficient control methods for lamprey in the St. Marys River has resulted in this river remaining as a major source of the parasite. The Great Lakes Fishery Commission coordinates an integrated program to reduce lampreys in the

St. Marys River using spot treatment with lampricide, trapping adults, and release of sterile male adults (Great Lakes Fishery Commission 2000). This combinations of control measures has reduced lamprey productivity by 90% in the river (Schleen et al. 2003).

Increasing the productive capacity of the St. Marys River to produce other fish and aquatic biota will likely work to counter efforts at lamprey reduction. Changes in rapids flow, habitat area, and the Fishery Remedial Works have not been evaluated for effects on lamprey spawning production (Young et al. 1996). Without specific data, we developed an approximate relation between rapids aquatic habitat area, water flow, gate openings, and lamprey production to consider this important water management effect for the St. Marys River.

Temporal validity:

The performance indicator applies to spawning habitat in the rapids for the spawning period: June and July. This is the general spawning period for sea lamprey in the Upper Great Lakes (Manion and Hanson 1980).

Spatial validity:

The performance indicator was designed to represent flow changes, gate openings on the Compensating Works, and wetted habitat in the main rapids. The main rapids constitutes the best and large majority of suitable spawning habitat in the St. Marys River (Eshenroder et al. 1987, Krauss 1991, Schleen 1992, Young et al. 1996). Also, consideration of changing rapids aquatic habitat area by modifying gate opening rules for fish and aquatic biota will have an effect on lamprey spawning area in the rapids.

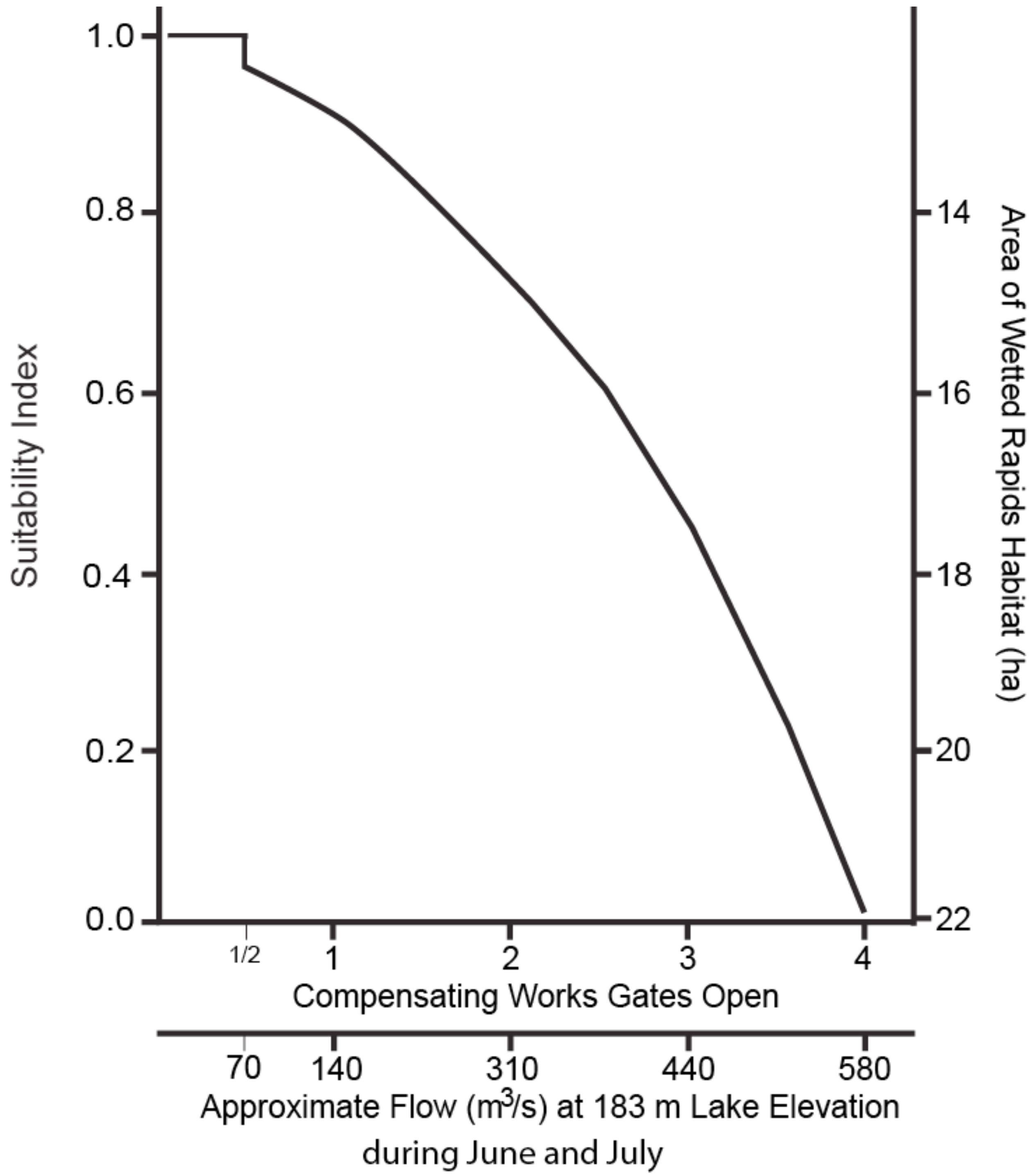
Hydrology Link:

The determinant of the area of aquatic habitat in the St. Marys River rapids is the volume of flow released by the Compensation Works. Studies of rapids flow and watered habitat have been reported in terms of the number of gates open. The specific volume of flow varies by open gates because of the elevation of Lake Superior. Therefore it is easier and more direct to measure volume in terms of gate openings. For this performance indicator, both the number of open gates and rapids flow volume are reported. Flow volume is based on gate discharges reported in Hough et al. (1981) for a lake elevation of 183.0 m.

Algorithm:

The performance indicator plot below was based on a similar wetted habitat and flow relation and plot in Koshinsky and Edwards (1983). This study and all data on flow and habitat area was developed prior to the Fishery Remedial Works in 1985 and 1986. This structure is a berm that starts at the Compensating Works and roughly follows the Canadian shore down the rapids. Its purpose is to maintain water released from Gate #1 (normally 1/2 open) along the Canadian shore and fill side channels in the area. The berm effectively isolates the Canadian shore from the main rapids that extend to the US shore; it elevates the water surface north of the berm. Prior to the construction of the Fishery Remedial Works, studies of flow and wetted habitat along the Canadian shore calculated that 4 to 6 gates needed to be open to have sufficient flow to inundate the Canadian shore and side channels (ILSBC 1974, Hough et al. 1981, Koshinsky and Edwards 1983, and others). The plot in Koshinsky and Edwards (1983) shows the increase in wetted habitat from 1/2 gate to 4 gates thus it does not largely include habitat in the area maintained by the Fishery Remedial Works. Thus this information shows the increase in wetted area primarily in the main rapids. The figure also shows there is aquatic habitat when no gates are open. This is expected because as much as 14 m^3/s leaks through the Compensating Works (ILSBC 1974) and standing water pools would exist at this minimum flow.

The suitability index for lamprey spawning in the rapids would be optimal at zero flow because this would be the minimum support for lamprey spawning - no habitat. However, we assigned the optimal conditions to be a half gate open so as to maintain the current habitat for other fishes. A suitability index score of zero would be the highest flow that would inundate the main rapids from the highest US shore to the Fishery Remedial Works berm along the Canadian shore. Four gates open would do this and that is the worst case for lamprey control. The relations between open gates, flow, and wetted habitat is gradual so there is no threshold level to be identified. Although four gates open would provide essentially all possible habitat in the main rapids for lamprey spawning. Thus four open gates could be considered a threshold and it is assigned a zero suitability index score.



1.0
0.8
0.6
0.4
0.2
0.0
Suitability Index
14
16
18
20
22
Area of Wetted Rapids Habitat (ha)
1/2
1
2
3
4
Compensating Works Gates Open
70
140
310
440
580
Approximate Flow (m3/s) at 183 m Lake Elevation
during June and July

Calibration Data:

Data used to form this relation that serves as the basis for the performance indicator was reported in Koshinsky and Edwards (1983). They used data, study results, and air imagery at different flows to compile their plot. This is the best data and information available at this time. Repeated assessments of habitat, flows, and gate openings were conducted prior to the final decision and design of the Fishery Remedial Works. After this structure was built, there has been no similar analyses of the rapids area.

Validation Data:

The model provided is based on multiple studies and reported assessment by fishery experts. However no test of the relation developed has not been conducted or a quantitative study of lamprey spawning habitat in the rapids. The rapids are difficult to survey and measure because of their variable topographic structure, high velocities in watered area, and the width of the channel.

Documentation and References:

Bergstedt, R. A., and C. P. Schneider. 1988. Assessment of sea lamprey (*Petromyzon marinus*) predation by recovery of dead lake trout (*Salvelinus namaycush*) from Lake Ontario, 1982-85. Canadian Journal of Fisheries and Aquatic Science 45:1406-1410.

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Eshenroder, R. L. and many others. 1987. Great Lakes Fishery Commission report of the St. Marys River sea lamprey task force. Great Lakes Fishery Commission, Ann Arbor, MI.

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ILSBC, International Lake Superior Board of Control. 1974. Feasibility study of Remedial Works in the St. Marys rapids at Sault Ste. Marie. Report to the INternational Joint Commission, Washington DC and Ottawa Canada.
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Young, R. J., G. C. Christie, R. B. McDonald, D. W. Cuddy, T. J. Morse, and N. R. Payne. 1996. Effects of habitat change in the St. Marys River and northern Lake Huron on sea lamprey (*Petromyzon marinus*) populations. Canadian Journal of Fisheries and Aquatic Science 53(Suppl. 1):99–104.

Risk and Uncertainty Assessment:

The following are the main assumptions of the performance indicator model:

1. The relation between flow and wetted rapids habitat represents the main rapids area at flows under four gates open.

2. The area of aquatic habitat in the rapids is an indicator of lamprey spawning habitat support.

3. Flowing water over gravel and rubble substrates provides lamprey nesting habitat.

These basic assumptions are used to project lamprey spawning area in the St. Marys River rapids and to target control measures. Thus confidence can be considered high for the general relation developed here.

PI Name: Submerged aquatic vegetation

Technical Workgroup: Environmental Technical Working Group
Subgroup: St. Marys River, Michigan and Ontario
Developed by: Kristin Arend and Pariwate Varnakovida

Performance Indicator Metric:

Submerged aquatic vegetation beds primarily occur on clay substrate throughout the St. Marys River (SMR) system at depths 2.0 – 7.0 m (Duffy et al. 1987). Clay substrate dominates within these depth ranges throughout the SMR (Liston et al. 1980; Liston et al. 1986), providing a substantial amount of suitable habitat for SAV communities (Liston et al. 1986). The spatial distribution, species composition, and biomass of SAV beds in the SMR have been relatively stable since 1935 (Liston et al. 1986; Williams and Lyons 1991). Total wetland area in the SMR has changed only 1.6% (Williams and Lyons 1991), with interannual fluctuations driven by variation in water elevation across a range of 1.04 m (Williams and Lyon 1991; Bray 1996). Intra- and interannual fluctuations in water elevation are thought to help maintain these nearshore, wetland habitats in an early successional state (Williams and Lyons 1991; Bray 1996).

Ecological Importance:

The structural complexity and reduced wave action provided by SAV beds are important functions of nearshore ecosystems (Strayer and Findlay 2010). SAV beds reduce erosion and thus turbidity by stabilizing clay sediment (Liston et al. 1986). SAV beds are highly productive areas that support diverse assemblages of macroinvertebrates and fishes. SAV contribute to the majority of primary productivity in the SMR (Liston et al. 1980; Williams and Lyons 1991). They are an important source of food for decomposers (Liston et al. 1980) and of food and cover for a diverse and abundant macroinvertebrate community (Liston et al. 1980 [and references therein]; Duffy et al. 1987; Edsall and Charlton 1997). Macroinvertebrates are more than 5 times as abundant outside of compared to within the navigation channel (Liston et al. 1980). SAV beds in the SMR also provide spawning and nursery habitat to a high proportion of Great Lakes fish species (Liston et al. 1980; Lane et al. 1996a,c) and resident habitat to warmwater fishes (e.g., Centrarchids; Lane et al. 1996b). As such, SAV support the larger SMR fish community by serving as an important link in lower food web material exchange (Liston et al. 1980).

Temporal validity:

SAV beds begin to develop in early spring (at 5°-6° C), with peak biomass in late August or early September (Liston et al. 1986). We define from 1 May through 31 September as the period of concern regarding water elevation change effects on SAV in the SMR.

Spatial validity:

Our SAV performance indicator is specific to the cooler thermal regime and higher water clarity of the SMR and Upper Great Lakes. The performance indicator includes the lower SMR starting below the main rapids at Sault Ste. Marie, ON, and extending through (1) the north channel ending at the head of Lake George and (2) the main channel through Lake Nicolet and its east and west branches ending at the head of Lake Munuscong. This area includes much of the area included in Liston et al (1986) and Williams and Lyon (1991) and some of the area included in Bray (1996). Lake George was not included in our performance indicator due to data limitations (see below) and because the primary sediment in Lake George is sand, which does not support SAV (S. Greenwood, Ontario Ministry of Natural Resources, personal communication; K. Arend, personal observation). This performance indicator directly applies to lower reaches of the SMR not included in our analysis. The indicator also can be applied more broadly to the upper SMR, Lakes Superior and Huron, and northern Lake Michigan by modifying the temporal period (to account for effect of different thermal regimes on length of growing season) and depth range (to account for SAV occurrence at greater or shallower depths under conditions of greater or lower light penetration).

Hydrology Link:

SAV bed area is determined primarily by water depth (Williams and Lyon 1991), but also substrate, slope, water clarity, and water velocity (Liston et al. 1980; Liston et al. 1986; Duffy et al. 1987). Changes to water elevation will impact the availability of suitable habitat along and extending into the SMR channel from the shoreline through direct or indirect effects on these additional factors.

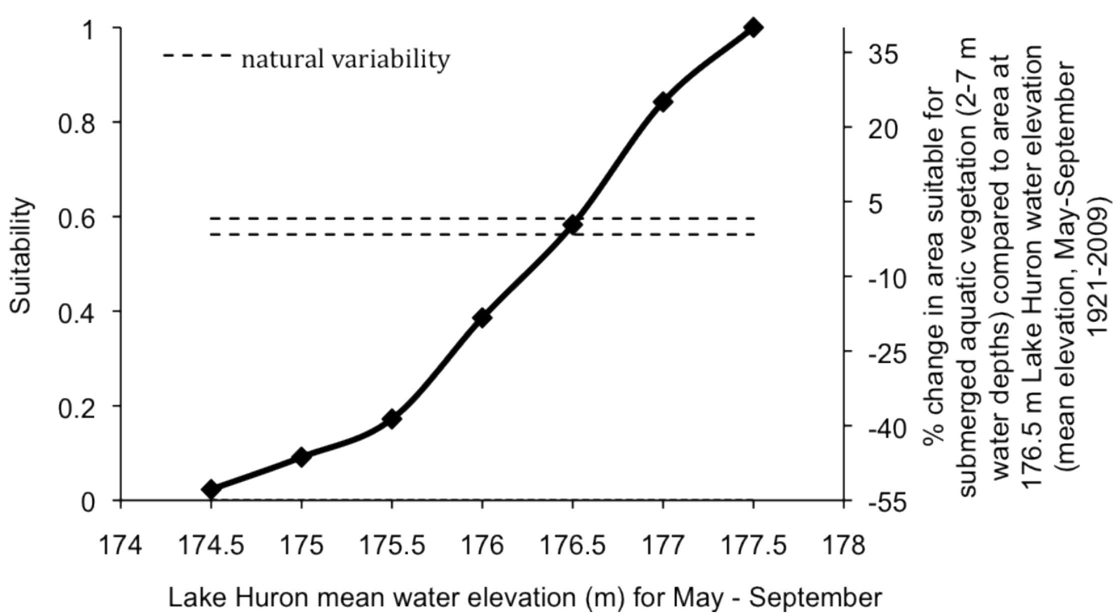
Algorithm:

Deep SAV beds have been documented to extend away from the river shoreline from a 2.0 m minimum depth to a 7.0 m maximum depth in the lower SMR (Liston et al. 1986). SAV primarily occupies clay substrate, which is the dominant substrate type in the SMR. Bray (1996) similarly determined areal of extent of lower SMR wetlands by defining SAV as occupying depth contours < 6 m. Contour and depth surfaces of the SMR in the areas described under "Spatial validity," above were created using GIS. Depth data and the SMR boundary were provided by Fisheries and Oceans Canada, Sea Lamprey Control Centre and included over 21,000 sampling points collected during 1993 to 2009 (Appendix 1). The SMR boundary was manipulated to fit our study area. The shipping channel was digitized from the National Oceanic and Atmospheric Administration's coast survey map. The Michigan boundary was downloaded from the Michigan Geographic Data Library. All data were projected to WGS84_1984_UTM_Zone_16N. Raster analysis and the interpolation scheme available with the spatial analysis extension in ArcGIS were used to interpolate the sampling points and create depth maps corresponding to 0.5 m Lake Huron water elevation intervals ranging from 174.5 – 177.5 m. This elevation range represents an approximate 2 m decrease and 1 m increase in water elevation compared to the mean water elevation during May through September (i.e., the SAV growing season), 1921-2009 (United States Army Corps of Engineers 2010). The Inverse Distance Weighted method with power of 2 and search radius of 12 points was employed with a pixel size equal to 10 m × 10 m. Raster files were then converted to image format for ERDAS IMAGINE inputs using a pixel depth of 32 bits. The Model Maker tool was used to query 2 to 7 m depth pixels (except for these depths present in the shipping channel) and overlaid with the study site (Appendix 2). The total area of the 2 to 7 m depth range at each 0.5 m water elevation interval was calculated from the number of 2 to 7 m depth pixels (Appendix 3).

Percent change in connected backwater habitat area for each 0.5 m Lake Huron water elevation interval was calculated as follows:

$$\frac{\text{(area at 0.5 m inteval – area at 176.5 m)}}{\text{(area at 176.5 m)}},$$

Suitability scores range from 1 to 0, respectively, for maximum percent gain in SAV-suitable area at 177.5 m and 55% percent loss in SAV-suitable area. We identified a threshold for maximum % loss of SAV as equal to 55%, which equals the % difference between the minimum and maximum wetland (SAV and emergent vegetation) area estimated from air photos for the Canadian shoreline from Gros Cap to Hay Bay and including St. Joseph Island in 1935, 1949, 1964, 1973, and 1981 (Bray 1996). Data for SAV wetland areas only were not available to our knowledge; however, we assume that SAV respond less strongly to water elevation change than emergent vegetation based on data presented in Williams and Lyon (1991). Natural variability in % change in SAV-suitable area was estimated as $\pm$1.6%, based on the average % change in wetland (SAV and emergent vegetation) area in Lake Nicolet between 1939 and 1985 (Williams and Lyon 1991).



Calibration Data:

Study results reporting depth ranges and locations for SAV beds in the SMR were used to parameterize the performance indicator. References provided report the depths at which SAV occur extending into the channel from the shoreline and the areal extent of SAV along the river from the late-1930s through the early-1980s.

Validation Data:

The model provided is based on published studies but a test of the relation developed has not been conducted with measured SAV area.

Documentation and References:

Bray, K.E. 1996. Habitat models as tools for evaluating historic change in the St. Marys River. Canadian Journal of Fisheries and Aquatic Sciences 53 (Suppl. 1): 88-98.

Duffy, W.G., T.R. Batterson. And C.D. McNabb. 1987. The St. Marys River, Michigan: an ecological profile. U.S. Fish and Wildlife Service Biological Report 85(7.10). 138 pp.

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Lane, J.A., C.B. Portt, and C.K. Minns. 1996c. Spawning habitat characteristics of Great Lakes fishes. Canadian Manuscript Report of Fisheries and Aquatic Sciences 2368: 48 pp.

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Risk and Uncertainty Assessment:

The following are the main assumptions of the performance indicator model:

1. We have modeled response of deep SAV, which occurs, on average, within a depth range of 2.0 – 7.0 m. Effects of water elevation change on shallow SAV habitat present in backwaters are reflected in the Backwater Connectivity PI.

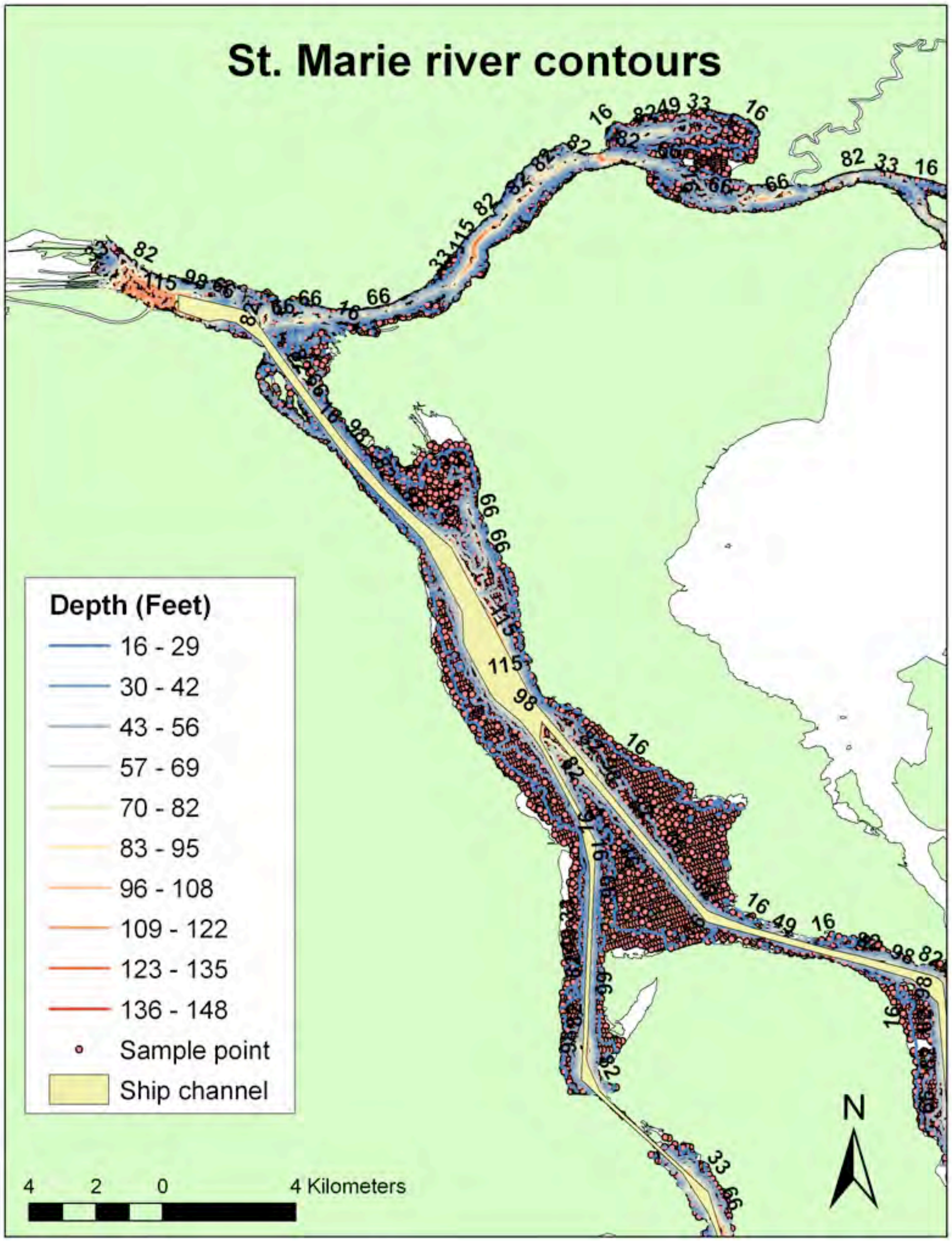
2. Water elevation (i.e., depth) is more of a limiting factor determining SAV distribution than water velocity.

3. Changes in SAV area over time primarily have been in response to changes in water elevation as opposed to human activities (Bray 1996).

4. SAV area declines under lower water elevations and increases under higher water elevations.

We consider this performance indicator to be sound and reliable because it was developed from multiple publishes studies with similar depth range values.

Appendices



Appendix 1. Spatial extent of the St. Marys River analyzed; dots represent depth sampling points; colored lines represent depth intervals (ft), and the shipping channel is indicated in yellow.

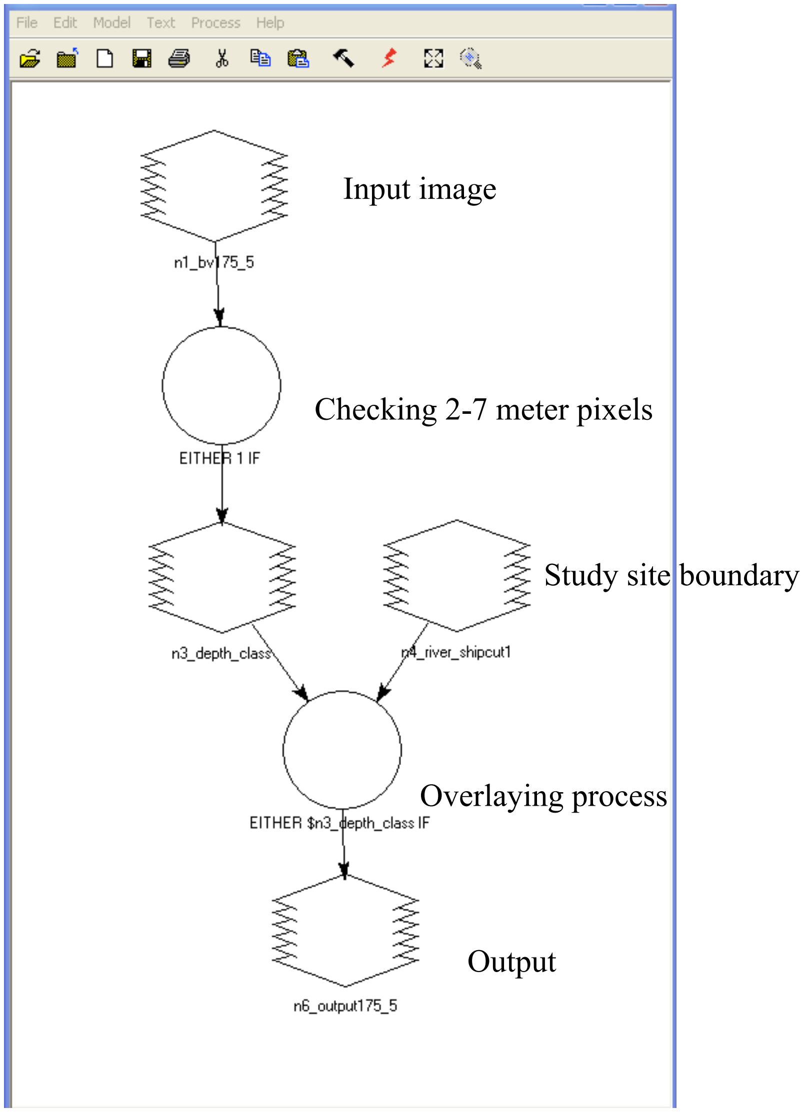


Figure 2: Process structure in the ERDAS Model Maker tool

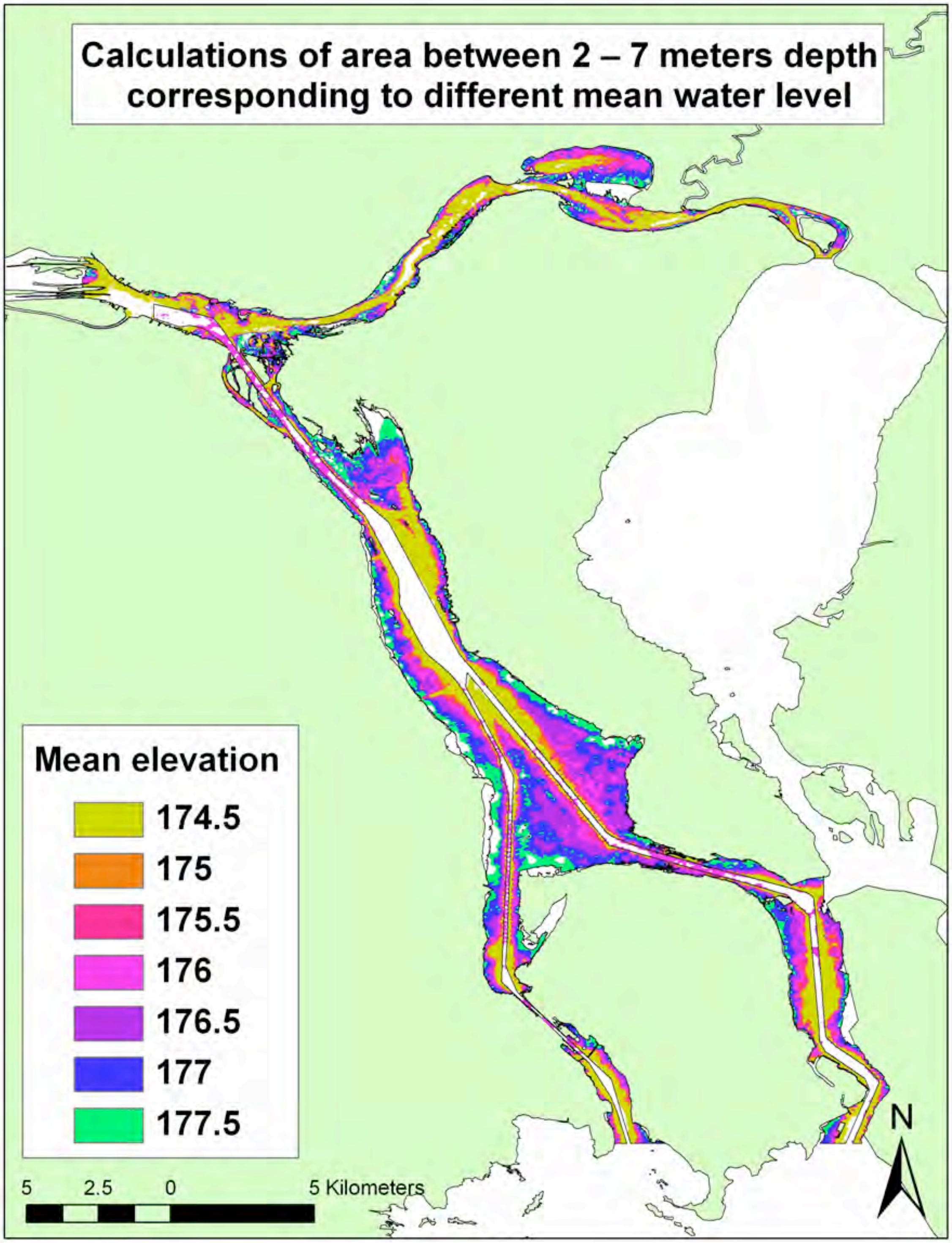


Figure 3: Area of the 2 to 7 meter depth range for each 0.5 m water elevation interval.

PI Name: Emergent Wetlands

Technical Workgroup: Environmental Technical Working Group
Subgroup: St. Marys River, Michigan and Ontario
Developed by: Mark Bain

Performance Indicator Metric:

Along the channels and lakes in the St. Marys River system there are extensive emergent wetlands. These are dominated by three species: hardstem bulrush (*Scirpus acutus*), bur reed (*Sparganium eurycarpum*), and spike rush (*Eleocharis smallii*). These plant taxa and emergent wetlands are sensitive to water level change. Over nearly a half century, the area of these wetlands have been photographed and mapped in Lake Nicolet; a large water body in the St. Marys River. Changes in the water elevation of Lake Huron has had a clear effect on the extent of emergent wetlands, and a formulae was developed to represent this relation by Williams and Lyon (1991). This relation was converted to a suitability index chart showing the effect that Lake Huron water surface elevation has on the area of emergent wetlands in Lake Nicolet. This performance indicator captures a hydrologic determinant of emergent wetland area in the St. Marys River below the point where river flow influences water level. Almost all of the extensive emergent wetlands are under the influence of Lake Huron water level, and these wetlands are especially important to river ecology and biological support.

Ecological Importance:

Emergent wetlands in the Great Lakes are important habitats support birds, mammals, fish, invertebrates, and overall biological productivity. For example, three migratory bird species often listed as conservation priorities nest in emergent wetlands: least bittern (*Ixobrychus exilis*), king rail (*Rallus elegans*), and black tern (*Chlidonias niger*; Evers 1997, Ciborowski et al. 2008). Also, emergent wetlands are important to migratory waterfowl such as mallard (*Anas platyrhynchos*), blue-winged teal (*Anas discors*), and the American black duck *(Anas rubripes*). The muskrat (*Ondatra zibethicus*) is a keystone mammal in Great Lakes wetlands because they feed on large plants in wetlands, clear channels, create open water areas and promote the patchiness of wetland habitats (Errington 1961). About a quarter of all Great Lakes fish species are strongly associated with emergent wetlands (Edsall and Charlton 1997) and many of these species use emergent wetlands for spawn and rearing habitats.

In the St. Marys River emergent wetlands serve multiple critical roles. They serve as key spawning, nursery, and feeding areas for 44 fish species of the river. Because the river has a very high water turnover rate, pelagic productivity by phytoplankton and zooplankton is minimal (Duffy 1987). The complex structured habitat formed by emergent wetlands provide more than 90% of the rivers overall dry weight biomass production (Kauss 1991). Also, benthic invertebrate productivity on a per unit area basis exceeds all other habitats including the rapids (Kauss 1991). Overall, emergent wetlands are key habitats in the Great Lakes and they are especially valuable in the St. Marys River because of the rapid flow of water through this system (Liston and McNabb 1986, Duffy et al. 1987).

Temporal validity:

The performance indicator emerged from a nearly half century of carefully assembled data. Therefore, the performance indicator can be considered sound for the range of water levels shown and be considered indicative of predicted effects of water level management.

Spatial validity:

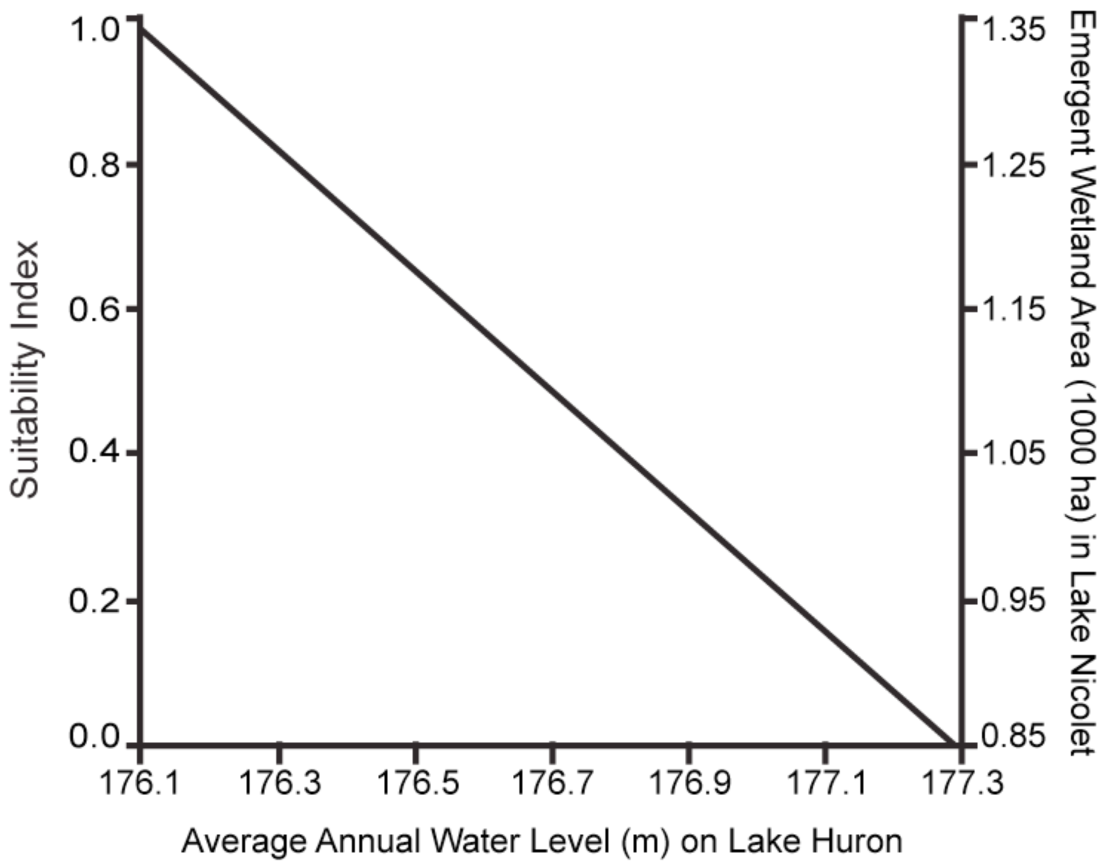
The performance indicator was developed on Lake Nicolet which is a major waterbody in the St. Marys River system. The spatial application of the performance indicator is appropriate for all areas of the river system under the influence of Lake Huron water level. Areas downstream of the Little Rapids and the Lake George Channel below Soo Harbor are not significantly influenced by variations in river volume (ILSBC 2002, Bain 2007). There are very limited wetlands in the Soo Harbor reach because it is largely composed or urban and bulkheaded shoreline (Bain 2007). Thus the performance indicator covers most of the river system and almost all areas where wetlands are abundant. Because of Lake Nicolet's size and central location in the river system, this waterbody can be considered representative of the St. Marys River wetlands.

Hydrology Link:

There is a strong relationship between water level and the area of emergent wetlands for the St. Marys River (Kauss 1991), the Great Lakes (Kelsall and Leopold 2002, Ciborowski et al. 2008, Mortsch et al. 2006, 2008), and waterways in general (Harris and Marshall 1963, Dabbs 1971, Spence 1982). Therefore, representing this relation in a performance indicator provides a close link between water management and the area of emergent wetlands.

Algorithm:

The US Army Corps of Engineers (Williams and Lyon 1991) assembled summer and fall aerial photographs for Lake Nicolet for seven years from 1939 to 1985. Across these years, water levels varied more than 1 m. Lake Nicolet water level is primarily determined by the elevation of Lake Huron because it is downstream of the control point where river volume influences water levels (Little Rapids; ILSBC 2002, Bain 2007). Emergent wetland boundaries were defined and entered into a geographic information system. There was a clear negative relationship between average annual water level and the area of emergent wetlands (linear regression, $P < 0.05$). For Lake Nicolet, there was a 32% change in the area of emergent wetlands through the 46 year study period. This relation is shown in the figure below with a suitability index axis for inclusion in the overall water management model.



Calibration Data:

Data used to form this relation were assembled, analyzed, and reported by Willams and Lyon (1991). The quality is high and exacting methods were used to define the area of emergent wetlands over years of different average water levels. The years were widely spaced in time yielding independent measure of both water level and emergent vegetation area.

Validation Data:

The relation used here was statistically tested and significant. The years used were independent in time and formed a significant linear regression. Therefore, the data used constitute a very reliable basis for the performance indicator and this indicator was tested and found justified by the analyses.

Documentation and References:

Bain, M. B. 2007. Hydropower operations and environmental conservation: St. Marys River, Ontario and Michigan. Report to the International Lake Superior Board of Control/Conseil international du lac Supérieur, International Joint Commission, Washington, DC and Ottawa Cn.

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Spence, D.H.N. 1982. The zonation of plants in freshwater lakes. Advances in Ecological Research 12: 37-126.
Williams, D. C., and J. G. Lyon. 1991. Use of a geographic information system data base to measure and evaluate wetland changes in the St . Marys River, Michigan. Hydrobiologia 219:83-95.

Risk and Uncertainty Assessment:

The following are the main assumptions of the performance indicator model:

1. The years investigated represent future responses to water level change.

2. The study site is typical and reflective of the river system downstream of the water level control points: Little Rapids and the Lake George Channel.

3. Water level is a kay factor shaping the extent of emergent wetlands.

The performance indicator shows a negative relationship between water level and area of emergent wetlands. Other studies have also reported that annual low water levels in the Great Lakes results in increased emergent wetland area (e.g, Ciborowski et al. 2008, Mortsch et al. 2006, 2008). Thus the performance indicator relation is consistent with other sites in the Great Lakes and reports a relation reported from other sites.

PI Name: Main Rapids Wetted Area

Technical Workgroup: Environmental TWG
Subgroup: St. Marys River, Michigan and Ontario
Developed by: Ashley Moerke

Performance Indicator Metric:
The St. Marys River (SMR) Rapids drops over 6 m in a 1.2-km reach, resulting in fast-flowing water dominated by cobble, boulder, and bedrock substrate. Large and diverse substrates and fast flows are lacking throughout the remainder of the 112-km river, which makes the Rapids an important area for biotic production. Although this habitat was historically abundant in the Rapids area, construction of the compensating works and hydropower facilities diverted over 90% of the Lake Superior outflow and dewatered over 25 hectares of the Rapids (Duffy et al. 1987). In 1981, a berm (Fishery Remedial Works) was constructed to reduce dewatering of the main Rapids at lower flows, but available habitat still varies with compensating gate operations.

The remaining Rapids provides critical habitat for fish and benthic macroinvertebrates, but the habitat is limited to the area inundated by flows through the compensating works. Therefore, this performance indicator was developed to relate wetted area of the main Rapids to changes in water elevations associated with the compensating gates. Current water elevation regulations may lead to decimation of biota by reducing water flows over the Rapids habitat which may strand fish and invertebrates, freeze fish eggs deposited in the substrate, and eliminate spawning and nursery habitat. Future water elevation regulations via compensating gate operations could be altered to enhance habitat available for macroinvertebrate production and fish spawning, rearing, and foraging.

This indicator is limited to the main Rapids because the area north of the berm (Fishery Remedial Works) is isolated from the main Rapids and remains wetted with gate operation consistently open at 20 cm. Operational changes to the compensating gates would largely influence the main Rapids.

Ecological Importance:

The fish community in the Rapids is unique and dissimilar to communities in other habitats of the river. Historically, the Rapids provided high quality spawning habitat for native species, including white sucker (*Catostomus commersonii)*, slimy sculpin (*Cottus cognatus),* lake whitefish (*Coregonus clupeaformis)*, brook trout (*Salvelinus fontinalis)*, and lake trout (*Salvelinus namaycush)*. The Rapids continue to provide spawning and feeding habitat for numerous game species including, steelhead (*Oncorhynchus mykiss)*, brown trout (*Salmo trutta)*, and chinook salmon (*Oncorhynchus tshawytscha),* and important Great Lakes forage fishes such as longnose dace (R*hinichthys cataractae*), alewife *(Alosa psuedoharengus)* and rainbow smelt *(Osmerus mordax)* (Gleason et al. 1981, Goodyear et al. 1982, Steimel 2010). The Rapids may also provide critical spawning habitat for lake sturgeon (*Acipenser fulvescens*), a Michigan threatened species. Macroinvertebrate composition and productivity in the Rapids also differ substantially from other habitats in the river, and were dominated by net-spinning caddisfly larvae (Trichoptera: Hydropsychidae) (Duffy et al. 1987, Kauss 1991) due to the faster flowing waters and larger substrate. These hydropsychids likely serve as a valuable food source for benthic fishes such as sculpin, pelagic forage fishes such as longnose dace, and juvenile fishes.

Reduction of the Rapids habitat has occurred due to the locks, compensating works, and hydropower generation. Currently less than 10% of Lake Superior outflows flow through the Rapids, and flows are now regulated by compensating gates at the head of the Rapids. Previous studies (e.g., Hough et al. 1983, Koshinsky and Edwards 1983) have indicated that flows experienced at 3 gates or less result in considerable drying of Rapids habitat, which limits habitat available for biotic use and production. Regulation of flow through the compensating works is a feasible strategy to enhance fish and benthic macroinvertebrate production in the Rapids.

Temporal validity: Annual; the Rapids are used throughout the year for fish spawning, egg incubation, and larval rearing. For example, many salmonids spawn in the Rapids in the late spring (May-June) or fall (Aug-Nov) but their eggs incubate over the winter months. The Rapids also provides nursery habitat for species throughout the entire year.

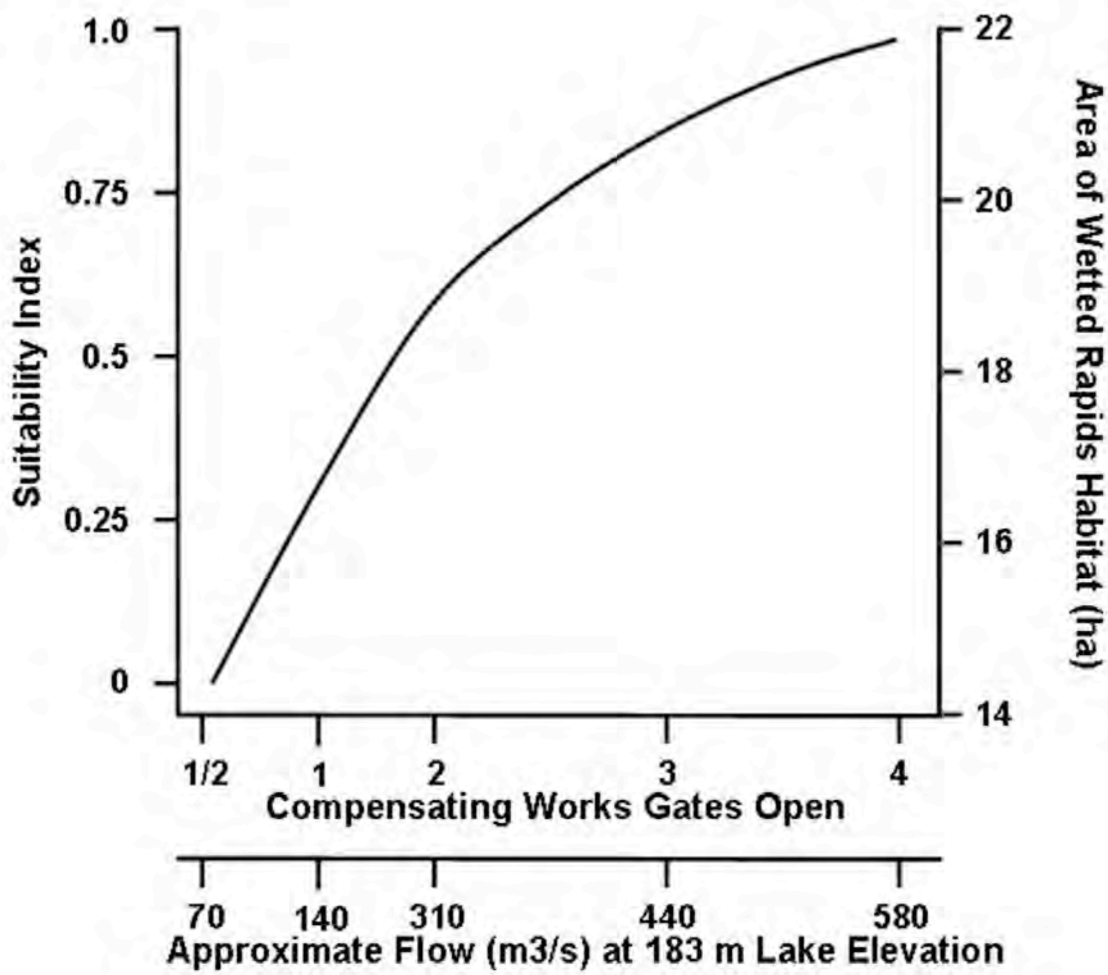
Spatial validity: This indicator applies to the main Rapids of SMR (south of the berm) where changes in compensating gate operations will alter wetted area and available habitat for biota. The area north of the berm (Canadian side) is isolated from the Main Rapids and remains wetted with gate operation consistently open at 20 cm.

Hydrology Link:
The wetted area of the Rapids was related to flow volume released through the compensating gates. Koshinsky and Edwards (1983) reported river discharge based on the number of gates open and then related this to wetted area in the Rapids.

Algorithm:
Data used in development of this performance indicator are summarized as a plot in Koshinsky and Edwards (1983). Flow volume is based on gate discharges for a lake elevation of 183.0 m. This and other existing studies relating flow and habitat area in the Rapids were conducted prior to the Fishery Remedial Works in 1985 and 1986. This structure is a berm that starts at the Compensating Works and roughly follows the Canadian shore down the rapids. Its purpose is to maintain water released from Gate #1 (normally open 20 cm) along the Canadian shore and fill side channels in the area. The berm effectively isolates the Canadian shore from the main rapids that extend to the US shore; it elevates the water surface north of the berm. Prior to the construction of the Fishery Remedial Works, studies of flow and wetted habitat along the Canadian shore calculated that 4 to 6 gates needed to be open to have sufficient flow to inundate the Canadian shore and side channels (ILSBC 1974, Hough et al. 1981, Koshinsky and Edwards 1983, and others). The plot in Koshinsky and Edwards (1983) shows the increase in wetted habitat from 1/2 gate to 4 gates and thus does not include habitat in

the area maintained by the Fishery Remedial Works. As such, this information shows the increase in wetted area primarily in the main Rapids. The figure also shows aquatic habitat exists when no gates are open. This is expected because as much as 15 m^3/s leaks through the Compensating Works (ILSBC 1974) and standing water pools would exist at this minimum flow.

The suitability index for wetted area in the Rapids would be optimal at 1.0 when four gates are open because this would provide maximum inundation of the Rapids and increase availability of habitat for macroinvertebrates and fishes. A suitability index score of zero would be when only ½ gate is open in the Rapids. A reduction in gates open from 4 to 1/2 would result in a loss of over 1/3rd of the existing Rapids wetted habitat.



Calibration Data:

Data used to develop this performance indicator are from Koshinsky and Edwards (1983). This is the best information currently available, but was developed prior to the final decision and design of the Fishery Remedial Works. After this structure was built, there has been no similar analysis of the Rapids area.

Validation Data:
The model provided is based on multiple studies, but no test of the relation developed has been conducted since the construction of the Fishery Remedial Works.

Documentation and References:

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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.

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

Risk and Uncertainty Assessment:

The following are the main assumptions of the performance indicator model:

1. The relation between flow and wetted Rapids habitat represents the main Rapids area at flows under four gates open.
2. The relation between flow and wetted Rapids habitat based on data prior to the construction of the Remedial Fishery Works is similar to the relation after construction of the berm.
2. The area of wetted habitat in the Rapids is an indicator of benthic macroinvertebrate and fish production.

These basic assumptions are used to project wetted areas in the SMR based on flow volume released from the compensating works. Confidence can be considered relatively high for the general relation developed here.

PI Name: Ramping Rates in the Rapids

Technical Workgroup: Environmental Technical Working Group
Subgroup: St. Marys River, Michigan and Ontario
Developed by: Mark Bain

Performance Indicator Metric:

The speed of water level change due to gate changes on the Compensating Works above the rapids of the St. Marys River has been a concern of fisheries management (Godby 2006) and river conservations organizations (Harris et al. 2009). The speed of gate adjustments and changes in water releases are often called 'ramping rates' and usually applies to hydroelectric plant discharges. For the St. Marys River, this issue is limited to the rapids and does not involve the hydropower plants. The rapids were maintained to support the river's famous salmonid fishery. Rapid ramping rates can impact fish resulting in loss of a substantial portion of small, young fish. This loss adds to natural mortality and can greatly diminish populations. The rate of rapid flow volume changes associated with changes in Compensating Works gate openings have been judged too erratic and damaging on fish in the rapids (Harris 2009). A performance indicator is presented that relates potential fish losses to the speed of change in gate openings and flow volume to accommodate this concern in reconsidering operations of the Compensating Works.

Ecological Importance:

Observations of fish stranding under rapidly declining river water levels have been reported below many hydroelectric facilities. The rate of fish losses due to abrupt declines in water level have been primarily studied in Norway which relies entirely on hydropower for its electric supply and has very important salmon and trout fisheries in its broad, boulder dominated, cold rivers. These studies are very appropriate for the St. Marys River: same kinds of fish, boulder strewn habitats, and cold climate. Studies have been done in the US and other countries but the Norwegian research has been the most thorough. A series of conclusions from experiments on fish losses from rapid and gradual water level changes are reported in Salveit et al. (2001) and Halleraker et al. (2003, 2007). Salmonid fish losses primarily occur because of stranding during rapidly falling water levels. Salmonid fishes less than 100 mm length are most vulnerable to stranding. Higher rates of standing occur in coarse substrates with high current speeds. Finally, criteria were developed for the speed of change that does not pose a threat to river fishes.

Temporal validity:

The ramping rate performance indicator applies to gate and flow changes in any season for the rapids. Salmonid fishes are present year round so rapid changes in water levels are a potential threat at any time.

Spatial validity:

The performance indicator applies only the St. Marys River rapids below the Compensating Works south of the Fishery Remedial Works - the main rapids. All of the St. Marys River hydroelectric plants discharge directly into deep channel waters where the ramping issue does not exist.

Hydrology Link:

The rate of water level change is central to this performance indicator. The Norwegian research on ramping rate impacts was summarized to develop protection criteria in Halleraker et al. (2003) which gives specific guidance for minimizing losses of salmonid fishes by stranding.

> *Dewatering slower than 10 cm an hour drastically decreased stranding of young trout, the most vulnerable group of fishes. For rivers dominated by coarse substrate, these slow ramping rates (<10 cm/hr) must be achieved. Gentle drops in discharge after long stable flow periods are recommended.*

I present a performance indicator (figure below) that was developed with the <10 cm/hr change rate defining optimum conditions (Suitability index = 1). In Halleraker et al. (2003) a rapid rate of change was measure for fish losses: 60 cm/hr with 22% mortality of small salmonid fishes. This rate of change was considered unacceptable and labelled as suitability of zero. The rate of fish loss was considered linear between these points, and an intermediate change rate of 13 cm/hr was computed and fell directly on the straight line in the plot.

Algorithm:

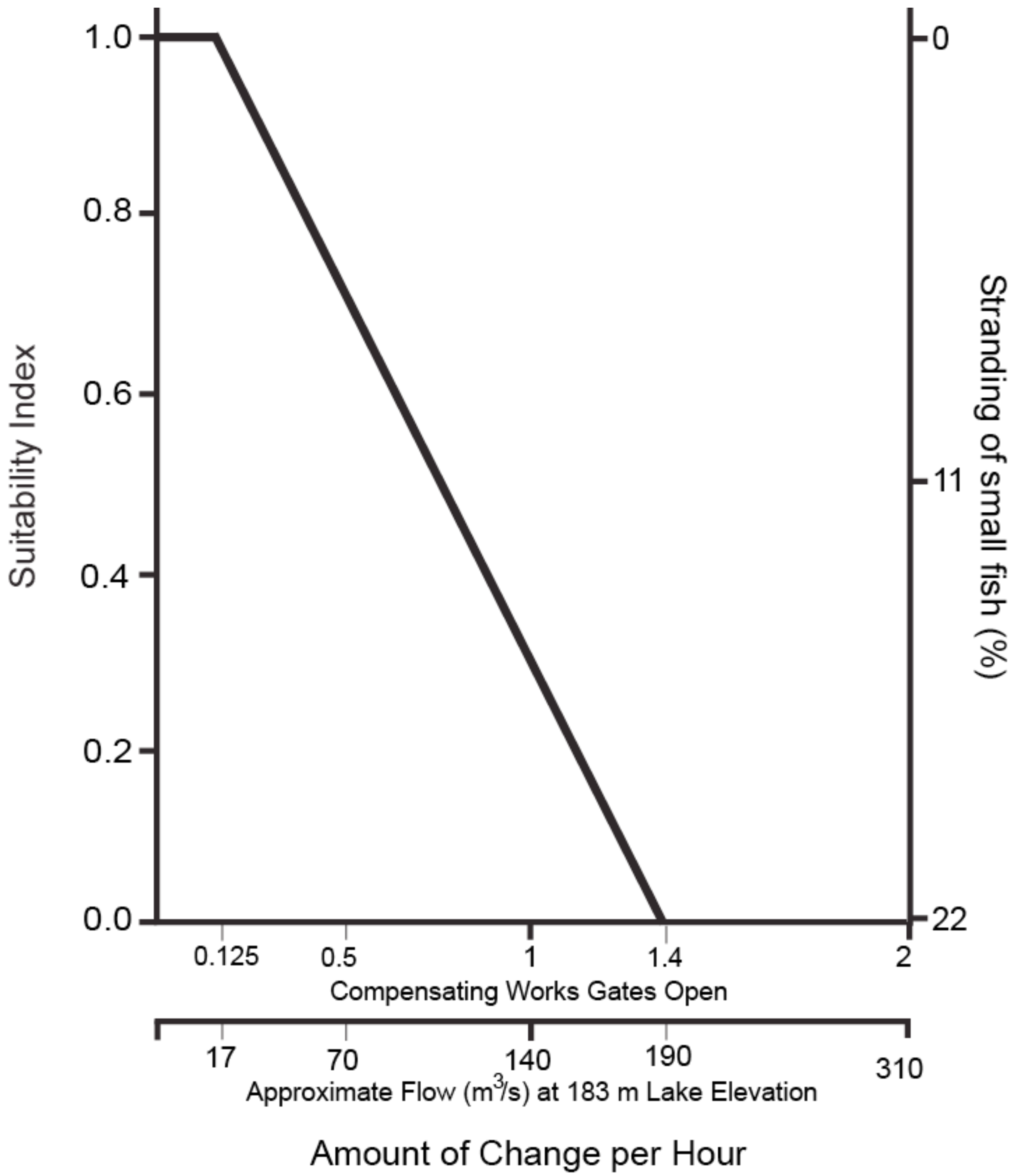
The key rates of change (10 and 60 cm/hr) were converted to main rapids flow and gate opening (at a common lake level 183 m, Houke et al. 1981) using a set of calculations based on standard hydraulic properties of river channels. Hydraulic rules in Leopold and Maddock (1953) and Dunne and Leopold (1978) provide the computations for this conversion. The conversion to a rate of change in Compensating Works operations started with the basic formulae:

$$\mathbf{d = cQ^{\mathit{f}}}$$

Where **d** is the average channel depth (ft), **Q** is the flow in ft^3/s, ***f*** is an exponent, and **c** is a numerical constant. Leopold and Maddock (1953) and Dunne and Leopold (1978) have parametrized this formulae in English units for many river channel around the World. The exponent ***f*** was set to 0.40 which is an average value for many rivers. The numerical constant **c** was calculated using data extracted from ILSBC (1974, p. 86) and St. Marys Rapids Working Group (1983, Table 2). The formulae above was rearranged to compute an estimate of **c** using rapids flow and average depths:

$$\mathbf{c = d/Q^{\mathit{f}}}$$

Six flows with average rapid water depths were used to compute **c** ranging from 2,500 to 46,000 ft^3/s. The estimates of c ranged from 0.06 to 0.16 and an average of these values was used (0.10). Then any flow can be inserted in the first formulae using ***f*** = 0.40 and **c** = 0.10 to calculate average water depth. Estimations were done to define the amount that rapids flow can be changed to match the 10 and 60 cm/hr rate of change. The results were then converted to metric units and plotted on the performance indicator below. The x-axis is in m^3/s and gate openings using common gate flow reported in Houke et al. (1981) for a Lake superior elevation of 183 m. The final performance indicator plot shows that suitability rating of gate and volume change per hour with an estimate of potential fish losses.



1.0
0.8
0.6
0.4
0.2
0.0
Suitability Index
0
11
22
Stranding of small fish (%)
0.125
0.5
1
1.4
2
Compensating Works Gates Open
17
70
140
190
310
Approximate Flow (m3/s) at 183 m Lake Elevation
Amount of Change per Hour

One half gate is the common opening equivalent on the Compensating Works for the current flow rate for the rapids. There are 16 gates on the Compensating Works and a change of one half gate should be done in no less than four hours to meet the suitability index of 1. A rate of change in rapids flow should be ≤ 17 m^3/s per hour to maintain a rate of water surface change of no more than 10 cm/hr. Because one half gate open releases approximately 70 m^3/s water, this amount of gate change needs to be spread over 4 hours to approximate a flow rate of change of 17 m^3/s.

Calibration Data:

Calibration data were scarce because of the need for both rapids volume and an estimate of average depth. This was found for six widely varied rapids flows in ILSBC (1974, p. 86) and St. Marys Rapids Working Group (1983, Table 2). The resulting computations provided a narrow range of values used in the formulae to relate volume and depth in the rapids. The exponent of this formulae was a central value reported in standard river hydraulics references (Leopold and Maddock 1953, Dunne and Leopold 1978).

Validation Data:

There is no validation studies available for fish losses under varying water levels in the St. Marys River rapids. However, very thorough research in Norway was done to identify rates of change associated with near zero fish losses and high losses. These were combined with standard hydraulic formulas to predict rates of change in the St. Marys River.

Documentation and References:

Dunne, T. & L. B. Leopold, 1978. Water in Environmental Planning. W. H. Freeman and Company, New York.

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Risk and Uncertainty Assessment:

The following are the main assumptions of the performance indicator model:

1. The standards for fish loss under varying water levels applies to the St. Marys River.

2. Hydraulic properties for river channels with parameterization to the St. Marys River rapids is realistic.

3. The resulting standards will improve conditions for fish with modified Compensating Works operations.

Although many theoretical and approximate calculations were done to estimate operating standards, there are no alternatives at this time to address the issue of rapid flow changes and fish losses in the rapids.

PI Name: Flushing flows

Technical Workgroup: Environmental Technical Working Group
Subgroup: St. Marys River, Michigan and Ontario
Developed by: Geoffrey Steinhart

Performance Indicator Metric:

Stream flow regime influences sediment transport, which in turn affects channel morphology, habitat, and biota (Reiser et al. 1990; Poff et al. 1997; Kondolf and Williams 1999). When structures or diversions reduce flow, the amount of sediment transport may be reduced, leading to sediment aggradation (Reiser et al. 1989). To simulate more a natural environment, controlled releases may be used to flush sediment in a manner approaching conditions prior to implementation of control structures or diversions (Poff et al. 1997). These controlled releases are often called flushing flows. Proper implementation of flushing flows is necessary to maintain ecological integrity (see Table 2 in Poff et al. 1997) while allowing for control of flow for other purposes during the remainder of the year.

Ecological Importance:

The accumulation of sediment in areas previously swept clear of fine sediment can make channels narrower and/or shallower, reduce formation of bars, and cover valuable spawning habitat (Reiser et al. 1989; Poff et al. 1997). These changes have obvious negative consequences for boating, vegetation, and fishes (respectively). Without flushing flows, eggs and larvae of many amphibians, fish, and invertebrates may suffer high mortality rates (see references in Wiley et al. 1995). A lack of flushing flows can be especially important in areas where sediment input is high, as is the case in many of the low-gradient, clay and sand-dominated tributaries that flow from the Eastern Upper Peninsula into the St. Marys River (SMR).

Temporal validity:

Natural flushing flows typically coincide with spring run-off. Furthermore, unnaturally changing flows during periods of ice-cover may lead to early ice-out, which may influence the hatch timing of fishes (e.g., cisco *Coregonus artedi*; Colby and Brooke 1970; Næsje et al. 1995). Therefore, flushing flows are recommended to occur around the time of spring run-off, the typical date of ice-out, and before most spring-spawning fishes reproduce. Because high flows may attract lake sturgeon (*Acipenser fulvescens*) to suitable spawning areas (Seyler 1997; see lake sturgeon performance indicator), high flow before lake sturgeon spawn may serve two beneficial roles. We defined the time for flushing flows as between 15 May and 15 June, which corresponds to the staging and start of the lake sturgeon spawning season (based on spawning temperature preferences and unpublished temperature data from 1982-2007; Roger Greil, Lake Superior State University Aquatic Research Laboratory).

Three continuous days of flushing flow velocities per year are recommended, based on recommendations for other ecosystems, like the Colorado River (U.S. Department of the Interior 2002)

Spatial validity:

With the modifications to the SMR to facilitate shipping, some flow has been diverted away from the Lake George Channel to the shipping canal and through Lake Nicolet (ILSBC 2002). For this reason, we defined the spatial extent of this performance indicator to include the Lake George Channel because it is an area that historically experienced natural flushing flows, but due to channel and flow modifications, flow has been reduced. In addition, the Lake George Channel is likely spawning habitat for key fishes.

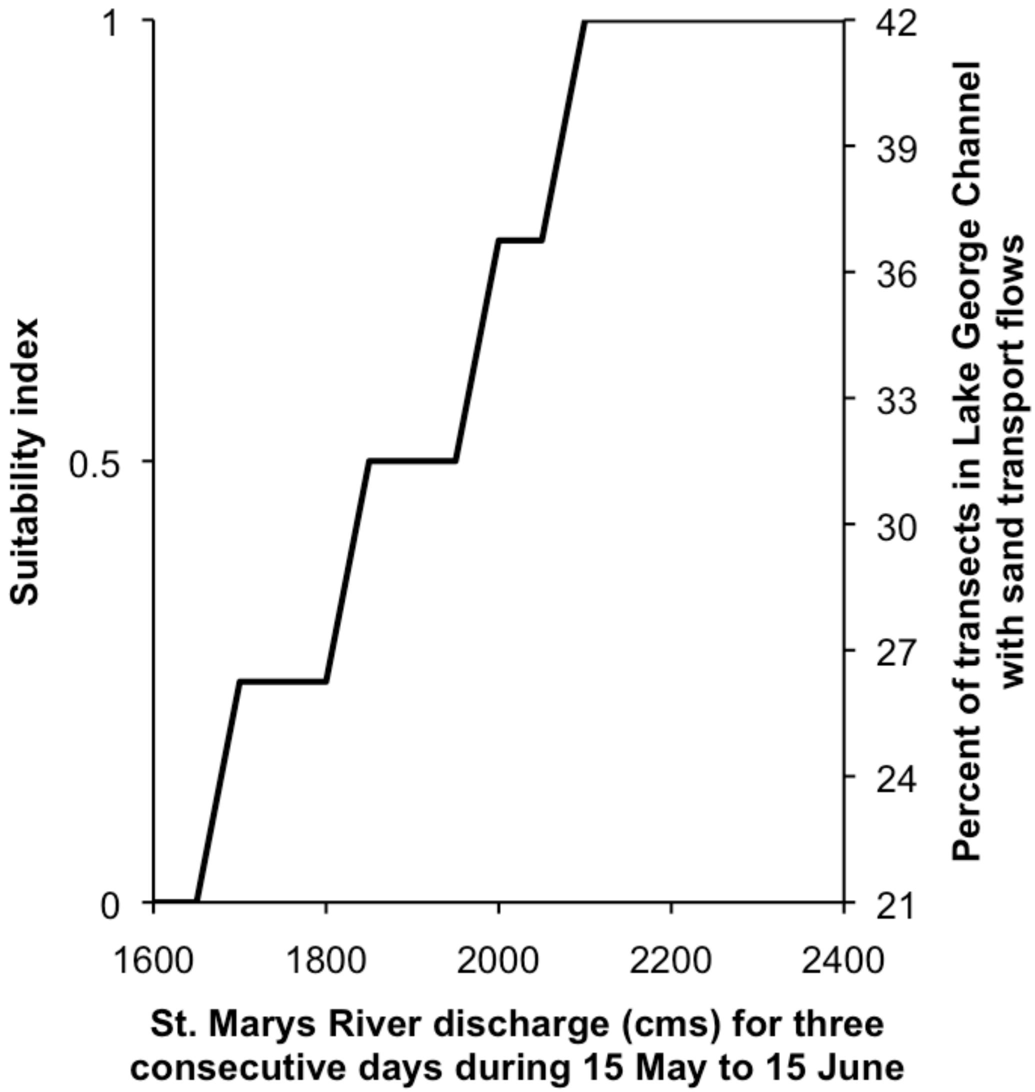
Hydrology Link:

Sediment resuspension and transport is a function of current velocity (Hjulström 1935; Leopold 1994). With the creation of the shipping channel and various upstream engineering projects, discharge through the Lake George Channel is now reduced and more seasonally stable than in the past (ILSBC 2002).

Algorithm:

For the Lake George Channel, our goal was the mobilization and transport of 1-mm diameter sand particles. We constructed depth profiles using 17 transects across the Lake George Channel (approximately 1-km apart). We assumed the Lake George Channel received 30% of the total SMR flow (ILSBC 2002). Average water velocity for each transect was estimated by dividing the total flow (m^3/s) by the cross-sectional area of the transect (m^2). The velocities needed to erode or transport particles were determined from Hjulström's curve (Hjulström 1935). Each transect was then given a score based on the mean velocity: 1 if the velocity met or exceeded the minimum velocity needed to mobilize the target particle size (0.35 m/s) and 2 if the velocity was able to mobilize a particle 85% larger than the target size (0.5 m/s). The latter computation was performed because the velocity needed for erosion of sediment may be impeded at depth or over rough substrate (Reiser et al. 1990).

A threshold for this performance indicator occurs at a flow of 2000 m^3/s which results in over 40% of the transects in the Lake George Channel having suitable mean velocities to mobilize and transport sand. It should be noted that these flow elevations also should produce adequate flows to transport smaller, clay particles within Lake George (data not shown).



Calibration Data:

Well documented physical hydrology studies were used to determine the critical velocities needed for this performance indicator. However, the depth and composition of the substrate were assumed to be homogenous and to represent the typical values used to generate Hjulström's curve.

Validation Data:

The flushing flow performance indicator should be field verified as the magnitude, timing, and frequency of flushing flows are unique for every system. In addition, data on substrate composition and depth would add additional detail.

Documentation and References:

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Risk and Uncertainty Assessment:

The following are the main assumptions of the performance indicator model:

1. Local current velocities are influenced by depth, rugosity, and channel morphology data, which were not available for developing this performance indicator.

2. The model focuses on the magnitude of flow required. Duration and frequency of flushing is based on ecosystem objectives for the Colorado River and may be different for the SMR.

3. Increased flows could mobilize potentially contaminated sediments from some locations in Lake George and the Lake George Channel.

PI Name: Backwater connectivity

Technical Workgroup: Environmental Technical Working Group
Subgroup: St. Marys River, Michigan and Ontario
Developed by: Kristin Arend and Pariwate Varnakovida

Performance Indicator Metric:

Backwater habitats, such as embayments and lagoons, provide slow-moving warm water habitat that is protected from the higher velocity, colder waters of the main St. Marys River (SMR).

Ecological Importance:

Backwater habitats include barrier protected and connecting channel wetlands and embayments. Along with other nearshore wetlands, backwater habitats are of high quality relative to Great Lakes wetlands overall (Harris et al. 2009). Backwater habitats are accessible from/to the river, enabling exchange of materials (e.g., nutrients) and organisms with the main river. Riverine and Great Lakes fishes depend on these areas as warmwater refuges in the spring (Brazner and Beals 1997; Edsall and Charlton 1997) and for important spawning and rearing habitat (Goodyear et al. 1982; Harris et al. 2009). Maintaining connectivity between backwater habitats and the open river is vital for fishes that occupy each habitat type during different life stages (Harris et al. 2009). Backwater habitats also support unique plant and animal communities, thus increasing species diversity of riverine floral and faunal communities. For example, backwater habitats support submerged and emergent marsh communities composed of species that require slow water movement and reduced wave action (e.g., herbaceous species, species with long-floating propagules, and shallow submerged aquatic vegetation (SAV); Nilsson et al. 2002). SMR coastal wetland habitat loss is included as a beneficial use impairment in the SMR Area of Concern (Selzer 2007). These marshes are an important conservation priority because they provide essential habitat for waterfowl, migratory bird species, and native fishes that rely on wetlands for at least one life history stage (Harris et al. 2009). Furthermore, SAV beds provide cover and complex habitat for macroinvertebrates and smaller-bodied fishes (Jude and Pappas 1992; Gore and Shields 1995; Randall et al. 1996; Brazner and Beals 1997). Great Lakes macroinvertebrate and fish species diversity are enhanced by the availability of habitat for species with less streamlined morphology (Gore and Shields 1995) and for warmwater fish species (e.g., smallmouth bass, *Micropterus dolomieu*; northern pike, *Esox lucius*; and yellow perch, *Perca flavescens*; Edsall and Charlton 1997).

Temporal validity:

Backwater habitats in the lower SMR are available year-round, thus our performance indicator assesses areal response to mean annual Lake Huron water elevations. Percent change in backwater habitat area was based on mean backwater habitat area at 176.43 m

Lake Huron water elevation, which is the mean annual water elevation from 1921-2009 (United States Army Corps of Engineers 2010).

Spatial validity:

Our backwater connectivity performance indicator is limited to the lower river, where the vast majority of this habitat occurs. Backwater habitat included major embayments or lagoons (e.g., Little Lake George, Echo Bay, Baie de Wasai, and Maskinonge Bay) with direct connections to the SMR and narrow, shallow areas within the SMR located between islands and the Canadian or U.S. shoreline (e.g., east of East Neebish Island, east of the island chain that includes Maskinonge Island, and east of Squirrel Island; Appendices 1 and 3). These relations can be applied more broadly to the upper Great Lakes where similar habitat occurs and is connected to the open lake through narrow and/or shallow openings.

Hydrology Link:

Backwater habitat connectivity to SMR nearshore and channel habitat is determined by water elevation. Lower water elevations can result in hydrologic separation of backwaters from the SMR through exposure of sand bars or other bathymetric features above the surface of the water column. Low water elevations also can cause loss of backwater habitat through dewatering of shallow areas. We account for both types of habitat loss in this performance indicator.

Algorithm:

Backwater connectivity was defined as the area (m^2) of backwater habitat having a direct surface water connection to the main SMR channel. GIS was used to create contour and depth surfaces from depth data available for the SMR and to calculate backwater area for 0.5 m Lake Huron water elevation increments ranging from 174.5 m to 177.5 m. This elevation range represents an approximate 2 m decrease and 1 m increase in water elevation compared to the mean annual water elevation from 1921-2009 (United States Army Corps of Engineers 2010). Depth data and the SMR boundary were provided by Fisheries and Oceans Canada, Sea Lamprey Control Centre (SLCC) and included over 21,000 sampling points collected during 1993 to 2009 (Appendix 1). The SMR boundary was manipulated to fit our study area. The shipping channel, 10 backwaters, and depth in areas not sampled by SLCC were digitized from the National Oceanic and Atmospheric Administration's (NOAA) coast survey map that was georeferenced to a base map (Appendix 1). The Michigan boundary was downloaded from the Michigan Geographic Data Library. All data were projected to WGS84_1984_UTM_Zone_16N. Raster analysis and the interpolation scheme available with the spatial analysis extension in ArcGIS were used to interpolate the sampling points and create depth maps corresponding to 0.5 m water elevation intervals. The Inverse Distance Weighted method with power of 2 and search radius of 12 points was employed with pixel size set to 10 m × 10 m. Raster files were then converted to image format for ERDAS IMAGINE inputs using a pixel depth of 32 bits.

The Model Maker tool in ERDAS was used to create two models (Appendix 2a-b). The first model calculated backwater area for each 0.5 m elevation interval between 174.5 and 176.5 m as follows: (1) identified pixel values greater than 0 and overlaid them with the digitized backwater boundary; and (2) checked if the backwater entrance no longer has a surface water connection to the river. If the backwater entrance was disconnected, then the entire backwater area was deducted from the total backwater habitat area value (i.e., summed area of all backwater habitats considered). Therefore, the final value for backwater habitat area represents area of only those backwaters with a surface water connection to the SMR.

The second model was created to calculate backwater area for the 177.0 and 177.5 m elevation intervals. Digital Elevation Model (DEM) was downloaded from the United State Geological Survey (USGS) National Map Seamless Server (USGS 2010). The model yielded the total conversion of land to backwater habitat at each interval representing water elevation increase beyond the elevation when depth data were collected by SLCC and NOAA. Areal calculations were performed by repeating the following steps for each pixel: (1) clipped backwater boundary and buffered 500 m; (2) used focal operation with 10 × 10 matrices to detect backwater boundary; (3) sequentially simulated water elevation at 177.0 and 177.5 m by adding 0.5 and 1.0 to backwater pixels; (4) identified if the pixel next to the boundary was less than the new boundary added value and, if so, changed that pixel to backwater. Total backwater habitat area was calculated from the total number of pixels identified as backwater (Appendix 3).

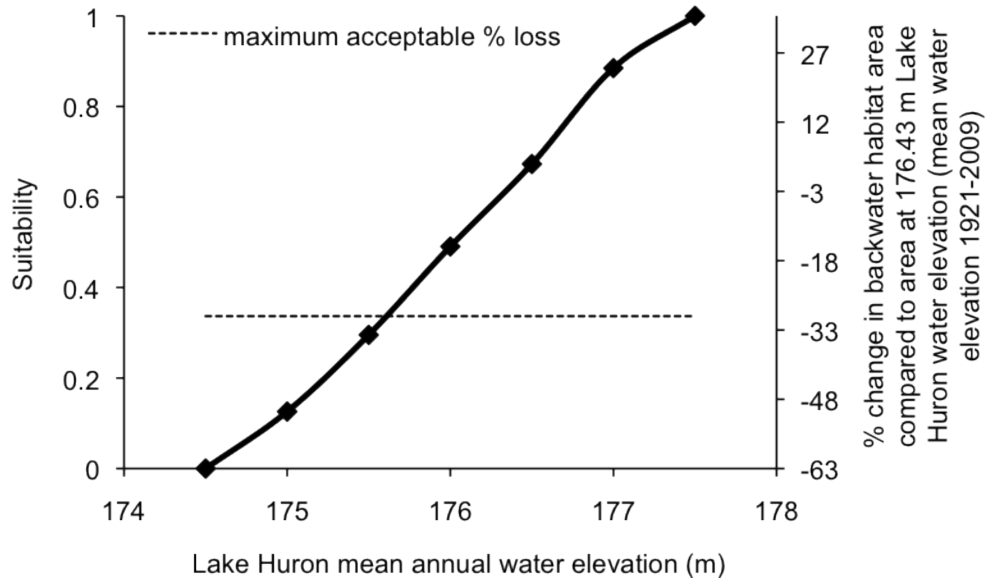
Percent change in connected backwater habitat area for each 0.5 m Lake Huron water elevation interval (e.g., area at 174.5 m) was calculated as follows:

$$\frac{(\text{area at 0.5 m inteval} - \text{area at 176.43 m})}{(\text{area at 176.43 m})},$$

where backwater habitat area at 176.43 m was estimated by regressing the GIS generated area estimates for each 0.5 m water elevation interval against water elevation:

$$\text{area} = 7.68 * 10^6 * \text{water elevation} - 1.33 * 10^9;\ R^2 = 0.995$$

Suitability scores range from 1 to 0, respectively, for maximum percent gain in backwater area at 177.5 m and maximum percent loss in backwater area at 174.5 m Lake Huron water elevation. Great Lakes backwater habitats are functionally important for supporting a variety of taxonomic groups, yet are frequently exposed to more concentrated human activities (Mackey and Goforth 2005) and have suffered from and continue to be threatened by loss and degradation due to shoreline development (Harris et al. 2009). Therefore, we set the threshold of habitat loss at 30% beyond the approximately 65% of wetland habitat degradation and loss that already has occurred due to human activities (Harris et al. 2009).



Calibration Data:

Studies reporting data that relate backwater habitat area to water elevations in the SMR are not available to our knowledge. Therefore, we used the best available bathymetric data to calculate connectivity and backwater habitat area under different Lake Huron water elevations.

Validation Data:

The model provided is based on bathymetric data available for the SMR but a test of the relation developed has not been conducted with measured backwater habitat area.

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Risk and Uncertainty Assessment:

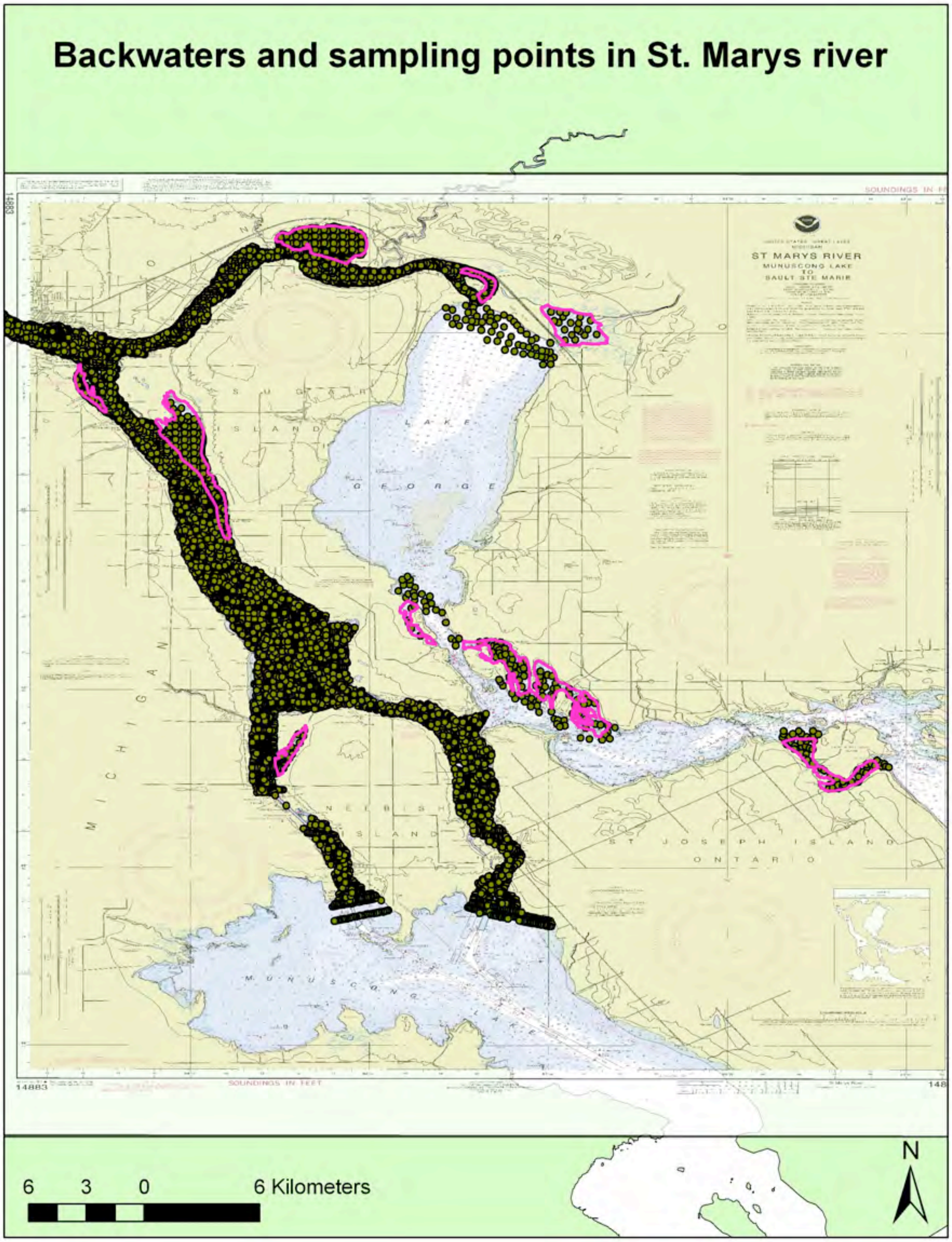
The following are the main assumptions of the performance indicator model:

1. The functional benefit of backwater habitat to the SMR ecosystem is lost when backwaters become disconnected from the river flow, regardless of if standing water persists within the backwater habitat.

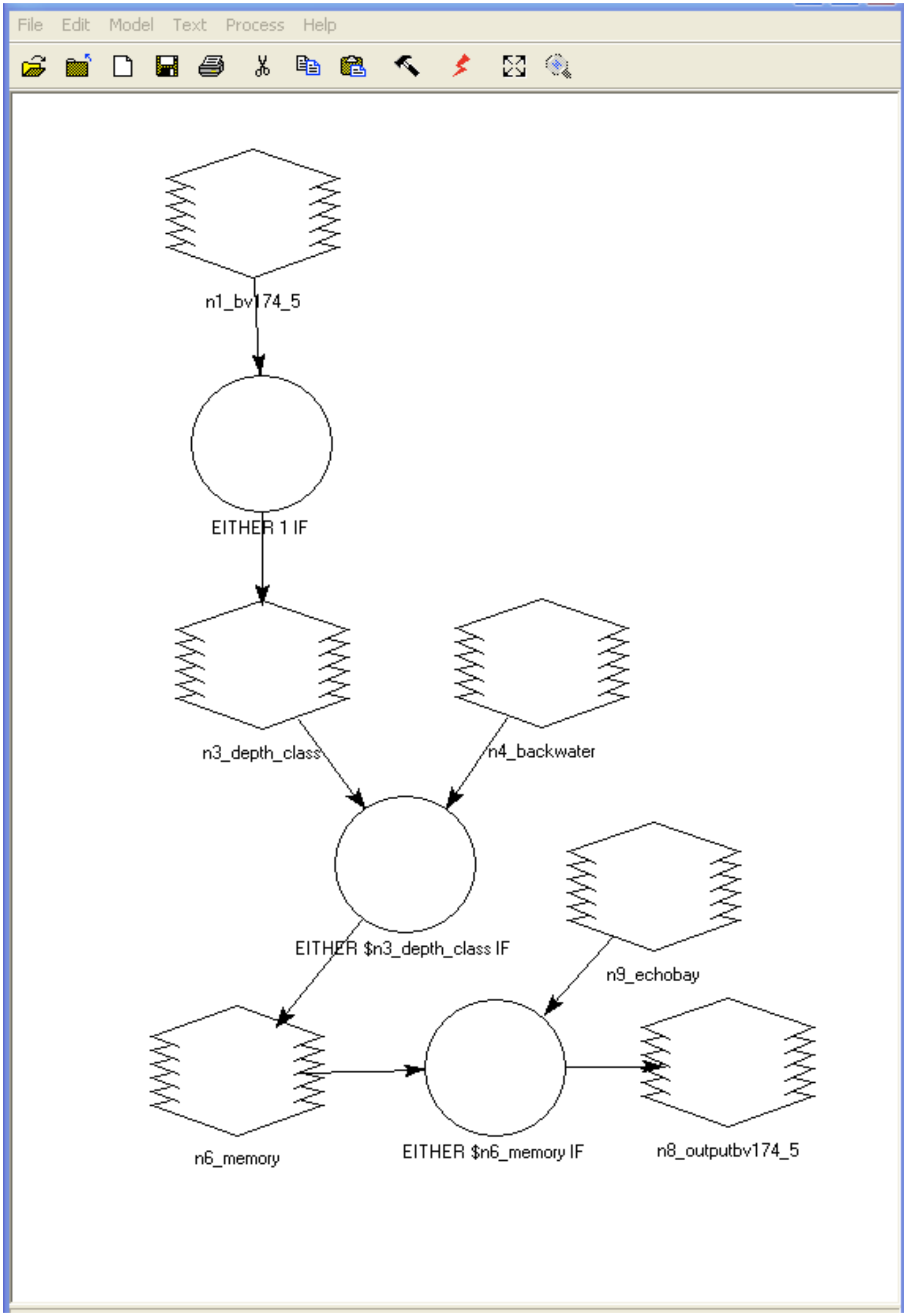
2. SMR backwater habitats support coastal emergent and submerged wetlands.

3. Additional loss of backwater habitat area could occur as the result of future human development, independent of water elevation change.

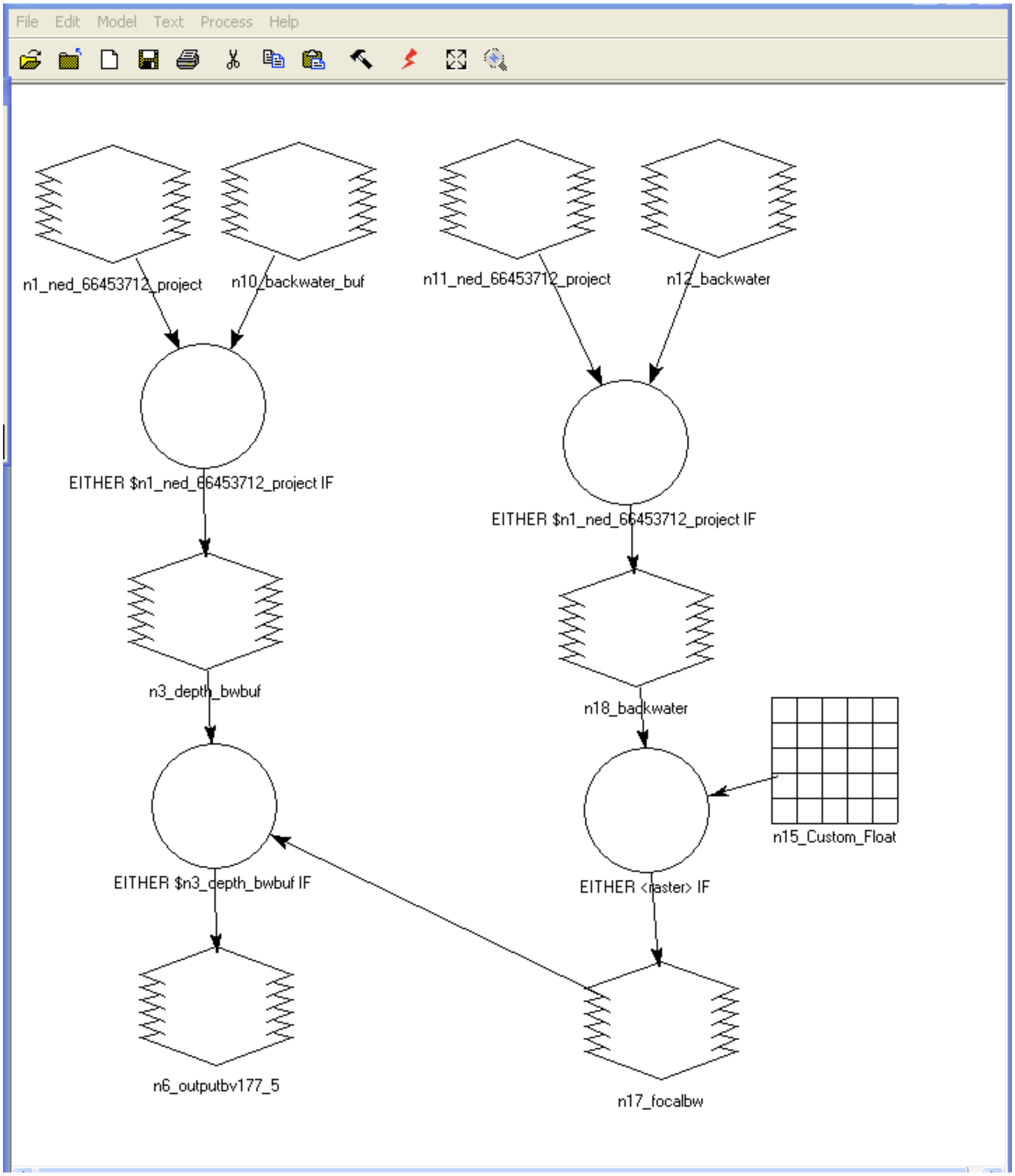
Appendices



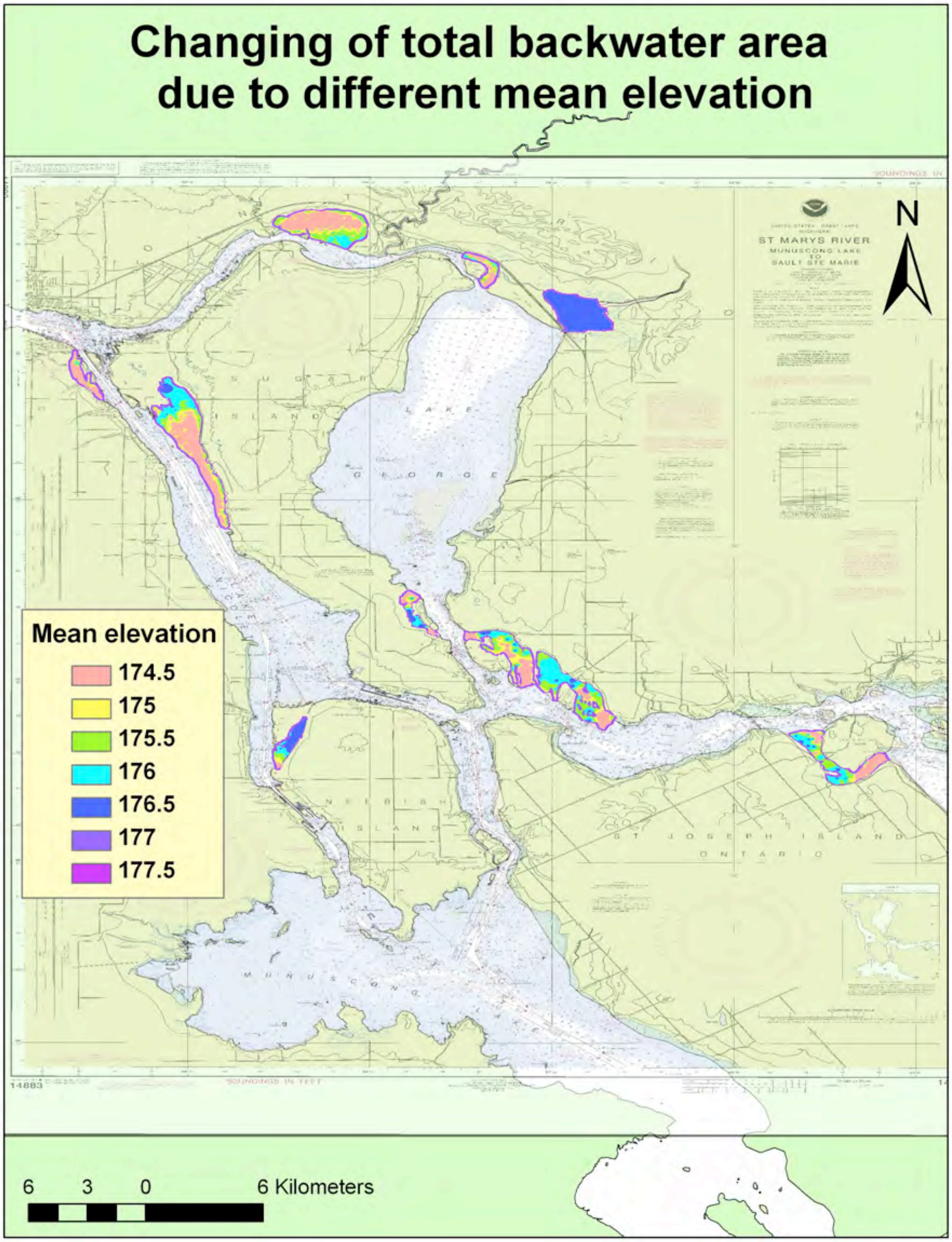
Appendix 1. Spatial extent of the St. Marys River analyzed; dots represent depth sampling points; pink lines outline the backwater habitats considered.



Appendix 2a. Model structure used to calculate backwater habitat area at each 0.5 m water elevation interval from 174.5 – 176.5 m.



Appendix 2b. Model structure used to calculate backwater habitat area for the 177.0 m and 177.5 m water elevation intervals.



Appendix 3. Total backwater habitat area at each 0.5 m water elevation interval ranging from 174.5 m to 177.5 m.