Assessing a restoration project for lake sturgeon spawning habitat: Use of habitat suitability and numerical models

André-Marcel Baril

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Signed by the final Examining Committee

______________________________ Chair
Dr. P. Peres-Neto

______________________________ Examiner
Dr. R. Weladji

______________________________ External Examiner
Dr. D. Walsh

______________________________ Supervisor
Dr. J. Grant

______________________________ Supervisor
Dr. P. Biron

Approved by ______________________________

Dr. Grant Brown - Graduate Program Director

____________________ 2017 ______________________________

Dean of Faculty

General Abstract

Assessing a restoration project for lake sturgeon spawning habitat: use of habitat suitability and numerical models

The loss of spawning habitat has been identified as a limiting factor for population growth of lake sturgeon, *Acipenser fulvescens*, a species that is endangered or threatened throughout its range. Hence, the restoration of spawning habitat has become a common practice, with at least 17 projects completed in the last 20 years. One project on the Ouareau River in Quebec entailed the installation of three artificial spawning reefs and two sills to address a landslide, headward erosion and dam activity. Our study adopted an adaptive management framework that incorporated 3D hydrodynamic modeling and a habitat suitability index to assess the performance of the sills and the success of the restoration project. We first compiled data from 48 sites across the range of the species to produce univariate habitat suitability indices to describe the spawning niche. Peak suitability occurred at depth-averaged velocities of 0.6 $m \cdot s^{-1}$, depths of 0.55 – 0.85 m in small rivers (<100 $m^3 \cdot s^{-1}$ annual average discharge) and 0.75 – 5.25 m in large rivers (>100 $m^3 \cdot s^{-1}$), over cobble substrates (64 – 256 mm) and water temperatures of 13.8 – 14.3 °C. To assess the quantity of suitable habitat, univariate habitat suitability results were compiled into a multivariate index using a fuzzy weighted linear combination, and applied to the 3D hydrodynamic model of the Ouareau spawning area. Our model indicated an abundance of suitable habitat and that the artificial spawning sites were placed in poor locations (velocity at sites > spawning requirements). By simulating river conditions prior to sill construction using the 3D hydrodynamic model, we found that the sills only have a minimal effect on the site, including no significant effect on the water surface longitudinal profile or depth averaged current velocity. Using the adaptive management framework, we identified flaws in the restoration project, related to the pre-assessment process,

restoration design and evaluation, and hypothesis development. These results fill a knowledge gap by quantifying the reproductive niche of lake sturgeon, and identifying the need for multi-disciplinary insight in habitat restoration projects.

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Contribution of Authors

Chapter 1

Study conception and design: Baril, Biron and Grant

Acquisition of data: Baril, Buszkiewicz

Analysis and interpretation of data: Baril

Drafting of manuscript: Baril

Critical Revision: Baril, Biron, Buszkiewicz, Grant and Phelps

Chapter 2

Study Conception and design: Baril, Biron and Grant

Acquisition of data: Baril

Analysis and interpretation of data: Baril

Drafting of manuscript: Baril

Critical revision: Baril, Biron and Grant

Table of Contents

List of Figures

Chapter 1

Chapter 2

List of Tables

Chapter 1

Chapter 2

General Introduction

The sturgeon (family *Acipenseridae)*, a family so old it coexisted with the dinosaurs, is considered to be one of the most threatened of freshwater fishes, with 18 of 27 species classified as endangered (Thiem et al. 2013). Lake sturgeon (*Acipenser fulvescens*) is the most widely distributed species of the family (Fig. 1.1), and are threatened or endangered across most of its range (COSEWIC 2006; NatureServe 2012). The species holds special significance for a number of reasons: it is the largest obligate freshwater fish species in North America (Scott and Crossman 1998); it retains an ancestral cartilaginous skeleton dating back to the Devonian period (Harkness and Dymond 1961); it has economic significance as a gourmet food item (COSEWIC 2006); and, it is culturally significant to Aboriginal groups of the Eastern forests (Kelly 1998), by playing a role in Ojibwe and Algonquin mythology (Melancon 2006).

Despite the species' resilience through geological time (Secor et al. 2002), aspects of its life history make it vulnerable to human induced mortality, including not reaching sexual maturity until 25-28 years of age, periodic spawning every seven years for females, and a slow growth rate (Bruch and Binkowski 2002; Pratt 2008; Vélez-Espino and Koops 2009). In order to protect lake sturgeon, conservation efforts including annual allowable catch quotas for commercial harvests (Mailhot et al. 2011), strict harvest limits or complete bans for recreational anglers (Peterson et al. 2006; Mailhot et al. 2011) and criminal investigations into poaching activity (Vermot-Desroches 2014; Ferguson 2016) have been undertaken throughout the species' range. This project focuses on a particular component of the ecology of lake sturgeon that has been identified as a limiting factor for population growth, spawning habitat (Bennion and Manny 2014).

Spawning habitat for lake sturgeon has been compromised by altered flow regimes, dams cutting off access to historic spawning grounds, the excavation of coarse material from river beds, and other anthropogenic disturbances (Haxton 2006; Johnson et al. 2006; Manny et al. 2015). In spite of this concern, a range wide review of this critical habitat has never been conducted (Peterson et al. 2006). To address this issue, in the first chapter of the thesis, data were compiled from 48 sites located across all major watersheds in which lake sturgeon are found to describe the species' reproductive niche using a habitat suitability index (HSI). Using this knowledge, the second chapter focuses on reviewing a spawning habitat restoration project on the Ouareau River (Quebec) using an adaptive management protocol (AMP), a structured, iterative decision making process to reduce uncertainty in management decisions, originally developed for a successful spawning habitat restoration in the St. Clair-Detroit River System (Manny et al. 2015). By using this framework, we provide insight into the benefits of AMP and the importance of inter-disciplinary co-operation in setting restoration targets and designing restoration projects.

Chapter 1.

Lake sturgeon (*Acipenser fulvescens*) spawning habitat: A quantitative review

André-Marcel Baril[1], John T. Buszkiewicz[2], Pascale M. Biron[3], Quinton E. Phelps[4], James W.A Grant[1].

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1. Concordia University, Department of Biology, 7141 Rue Sherbrooke West, Montréal, Québec, H4B 1R6, Canada. andremarcelbaril@gmail.com, james.grant@concordia.ca
2. Southeast Missouri State University Department of Biology, Cape Girardeau, Missouri, 63701, USA. buszkiewicszj@gmail.com
3. Concordia University Department of Geography, Planning and Environment, 1455 Boulevard de Maisonneuve West, Montréal, Québec, H3G 1M8, Canada. pascale.biron@concordia.ca
4. Missouri Department of Conservation, Big Rivers and Wetlands Field Station, 3815 E Jackson Blvd, Jackson, Mo, USA, 63755. Quinton.Phelps@mdc.mo.gov

Abstract

The loss of spawning habitat has been identified as a limiting factor for population growth for lake sturgeon, *Acipenser fulvescens,* the most widely distributed species of the *Acipensiridae* family. While local information exists about lake sturgeon spawning habitat, a synthesis of all available data is needed across its range. Our study used meta-analytical techniques to describe the mean and range of critical spawning habitat characteristics based on data from 48 sites from all major watersheds in which lake sturgeon are found. Data were compiled into univariate habitat suitability indices to describe the spawning niche. Results indicate that peak suitability occurred at depth-averaged velocities of 0.6 $m \cdot s^{-1}$, depths of 0.55 – 0.85 m in small rivers (<100 $m^3 \cdot s^{-1}$ annual average discharge) and 0.75 – 5.25 m in large rivers (>100 $m^3 \cdot s^{-1}$), over cobble substrates (64 – 256 mm) and water temperatures of 13.8 – 14.3 °C. This study provides a comprehensive review of critical spawning criteria from which future habitat suitability models can be adapted.

Keywords: Spawning, Rivers, Habitat suitability, Environmental conditions, Lake sturgeon

Introduction

Throughout North America, habitat loss and degradation is the most significant threat to biodiversity (Wilcove et al. 1998; Venter et al. 2006). In freshwater environments, projected extinction rates are five times greater than those in terrestrial and marine settings, with habitat loss as the single greatest factor influencing these declines (Ricciardi and Rasmussen 1999). In order to mitigate the threat of habitat loss, identifying the key threats and conditions of ideal habitats is of critical importance (Venter et al. 2006).

Of the 27 species of sturgeon (family *Acipenseridae)*, 18 are classified as critically endangered (Thiem et al. 2013). Lake sturgeon (*Acipenser fulvescens*) is the most widely distributed species of the family (Fig. 1.1), and is threatened or endangered across most of its range (COSEWIC 2006; NatureServe 2012). Of the many potential threats to lake sturgeon, spawning habitat has been identified as a limiting factor for population growth (Lyttle 2008; Randall 2008; Bennion and Manny 2014). Unfortunately, the quality and quantity of existing habitat has been negatively affected by altered flow regimes, and reduced access to historic spawning grounds by dams (Haxton 2006; Bennion and Manny 2014). To counteract these effects, substantial effort has recently been dedicated to locating, restoring, and creating suitable lake sturgeon spawning habitat.

Over the past 20 years, spawning requirements have been described at specific rivers or sites, but a broad description of spawning habitat across its range is lacking (Auer 1996; Peterson et al. 2006; Daugherty et al. 2009). Lake sturgeon typically spawn in fast-flowing, main-channel river environments (Lyons and Kempinger 1992; Auer 1996), although anecdotal evidence of spawning in lakes exists (Harkness and Dymond 1961). Similar to other sturgeon species and to salmonids, four habitat characteristics are considered critical for spawning: flow velocity; water depth; water temperature; and substrate size (Threader 1998; Dumont et al. 2011). Ideal ranges for lake sturgeon have been estimated as: flow velocities from 0.5 to 1.5 $m \cdot s^{-1}$; coarse substrates from gravel to cobble with clean interstitial space; water temperatures from 11 to 15 °C; and depths of 1.1 to 3 m (Threader 1998; Peterson et al. 2006; Dumont et al. 2011).

To describe the habitat requirements for lake sturgeon, we synthesized available data across the species range using meta-analytical techniques. The data were then used to create a Habitat Suitability Index (HSI), a quantitative tool to determine suitable conditions for a particular life stage of a species (Bovee 1982). HSIs have been applied in a variety of contexts to determine usable habitat in rivers (Haxton 2006) or to assess habitat quality for re-introduction programs (Daugherty et al. 2009). Three main categories of HSI are defined as: (I) professional judgement via surveying experts; (II) habitat use data; and, (III) habitat preference data (Bovee 1986). Type I indices are most common, likely because they require no field sampling, but are considered to be of least value due to the subjective nature of expert opinion (Bovee 1986). Type II indices include presence-only data and are referred to as utilization functions, whereas type III indices include presence-absence data and are referred to as preference curves (Hastie and Fithian 2013). In general, type III indices are thought to provide the most insight, and are most transferable throughout the range of the species (Moir et al. 2005), but also require more resources to create. Consequently, many researchers opt for type II indices (Moyle and Baltz 1985; Parsons and Hubert 1988), which can provide reliable results without the extra expenditures to produce type III preference indices (Moir et al. 2005).

While habitat suitability indices have been used extensively for lake sturgeon juvenile habitat, less work has been devoted to adult spawning habitat (Jarić et al. 2014). Existing HSI for spawning requirements (Threader 1998) are limited by a lack of available data, are tailored to specific regions, and are unpublished. The objectives of this study were to: (1) provide a quantitative summary of the four key spawning habitat characteristics from documented spawning events across four major drainage basins, and (2) develop univariate type II indices for each characteristic.

Methods

Data Compilation

Literature was initially retrieved from the Web of Science database using the search terms "lake sturgeon" and "spawning". More information was then found by consulting the references within relevant articles. Due to a lack of peer-reviewed data, lake sturgeon researchers were contacted to contribute pertinent unpublished data. In total, 12 published and 22 unpublished reports representing 112 spawning events across 48 sites were analyzed (Fig. 1.1; Table 1.1; Appendix A).

Spawning sites were included in our analysis only if they had information regarding at least one relevant spawning habitat characteristic that was measured during or immediately following an observed spawning event. Spawning sites were classified by watershed (Mississippi, Great Lakes/St. Lawrence, Nelson, and James Bay/Hudson Bay), river magnitude (small = <100 $m^3 \cdot s^{-1}$, large = >100 $m^3 \cdot s^{-1}$) and whether or not data were from a peer-reviewed publication. The database was analyzed using ArcGIS, version 10.4. Distance to the nearest dam or other impediment to upstream migration (e.g. falls, rapids) was computed for each site using the distance tool in ArcGIS.

When only ranges were available for a particular variable, the mid-point was used in our analyses unless a mean or mode was specified. If no range was given, it was assumed that any reported value was the mean. For sites that had data for more than one spawning event, the mean was calculated for each habitat characteristic and used in the analyses. Additionally, if multiple spawning locations were found to be within close proximity of one another (<500 m), they were classified as a single site.

For flow velocity, if the location within the water column where measurements were taken was specified, it was transformed to estimate the depth-averaged velocity (hereafter velocity), the average velocity across the vertical transect where the measurement was taken, using the logarithmic velocity profile (Knighton 1998; Smart 1999). If the location in the water column was not mentioned, we assumed that the reported value represented the depth-averaged velocity.

The method used to classify substrate varied considerably between studies. Values based on a quantitative analysis were converted to the Wentworth (1922) scale (sand: 0.06 – 2 mm, gravel: 2.1 – 16 mm, pebble: 16.1 – 64 mm, cobble: 64.1 – 256 mm, boulder: 256.1 – 4096 mm, bedrock: N/A) and then used in the analyses. For studies that employed a qualitative approach and did not include a substrate classification scale, the value given for the named substrate type (e.g. cobble, gravel) were assumed to match the description in the Wentworth scale (see above; Wentworth 1922). When proportions of substrate size classes at a specific site were not specified, classes were assigned hierarchically as primary, secondary, tertiary, or quaternary, if possible. For instance, if a given report stated a spawning bed was "mostly composed of substrate x and y, with some z", substrate x and y would be considered primary and z would be secondary.

Analyses

We first determined whether there were significant differences in velocity, substrate size, and depth between watersheds, river magnitude and published and unpublished data, using un-paired t-tests to assess for geographic and hydrologic impacts and publication bias respectively (Møller 2001). Because most of the data were from the Great Lakes/St. Lawrence watershed, we compared this region to all others combined. For temperature, after observing a potential trend in a scatter plot, we analyzed the possible impact of latitude using a regression analysis.

Spawning habitat characteristics for velocity, depth, substrate size, and temperature were analyzed using simple arithmetic means and confidence intervals (95%). The mean or equivalent for each site was used as a datum in the analysis. We also calculated the mean minimum, and mean maximum value for each variable to quantify variability in spawning habitat used across the lake sturgeon range. Substrate size classes were then more thoroughly investigated by calculating the total proportion of each substrate type present across all sites, along with the confidence interval. For each substrate class, the proportion of times it occurred within each hierarchical classification (e.g. – primary, secondary, etc.) across all sites was calculated, as well as the respective confidence intervals.

Three approaches are typically used when analyzing suitability data: histogram analysis, nonparametric tolerance limits, or nonlinear regression techniques (Bovee 1986). Here, histogram analyses were used for the four key spawning parameters in order to fit type II indices (Bovee 1986). We fitted the suitability curve by manual interpolation, rather than using predetermined mathematical functions (e.g. quadratic, polynomial), which often do not describe the frequency distributions as precisely (Bovee 1986). Bin sizes to create frequency distributions were either in increments of 0.1 for velocity ($m \cdot s^{-1}$) and depth (m) in small rivers, 0.5 for water temperature (°C) and depth (m) in large rivers, or by existing substrate size classifications (Wentworth 1922). For each spawning site parameter, each bin documented at a site was assigned a value of 1. The total frequency of each bin was then standardized to an index from 0 to 1.

Results

Velocity

For velocity, the difference between the Great-Lakes/St. Lawrence and all other major watersheds (t_{22} = 1.5, p = 0.15), small and large rivers (t_{22} = 0.1, p = 0.92), and published and unpublished data (t_{17} = 1.52, p = 0.15) were all not significant. Across all 24 sites (Fig. 1.2; Table 1.2), the mean velocity for all sites was 0.85 $m \cdot s^{-1}$ (CI = ± 0.11). A type II curve, based on the frequency of use data (Fig. 1.3), indicated that suitability increased rapidly from a velocity of 0.1 $m \cdot s^{-1}$ until reaching a peak at 0.6 $m \cdot s^{-1}$. The curve slowly declined until reaching a value of 0 at 2.6 $m \cdot s^{-1}$.

Depth

The differences in depths between the Great-Lakes/St. Lawrence and all other major watersheds (t_{32} = 0.78, p = 0.44) and between published and unpublished data (t_{19} = 1.08, p = 0.30) were not significant. However, there was a significant difference (t_{32} = 4.18, p = 0.0002) between small and large rivers. The mean depth was 1.06 m (n = 15, CI = ± 0.33) for small rivers and 5.7 m for large rivers (n = 19, CI = ± 1.99) (Fig. 1.4; Table 1.2).

A type II curve based on the frequency of use data for small rivers (Fig. 1.5) indicated that suitable depth increased rapidly from 0.26 m, until a peak between 0.55 – 0.85 m. The curve slowly decreased until 2.05 m, after which it decreased rapidly until reaching 0 at 3.15 m. In large rivers (Fig. 1.5), suitability increased rapidly until reaching a peak maintained between 0.75 and 5.25 m, after which suitability decreased steadily until reaching 0 at 26.25 m.

Substrate Size

For substrate size, the differences between the Great-Lakes/St. Lawrence and all other major watersheds ($t_{32} = 1.75$, $p = 0.089$), small and large rivers ($t_{32} = 0.8$, $p = 0.43$) and published and unpublished data ($t_{17} = 0.89$, $p = 0.38$) were not significant. Across all 34 sites with substrate size data, the mean was 117 mm (CI = ± 16.52, Table 1.2), which corresponds to the size class cobble. Cobble was also the most common substrate size class observed across the 34 sites (Fig. 1.6), and was found at 85.3% of sites, followed by gravel at 67.7% of sites (CI = ± 15.7), pebble at 38.2% of sites (CI = ± 16.3), boulders at 26.5% of sites (CI = ± 14.8), sand at 5.9% of sites (CI = ± 7.9), and bedrock at 5.9% of sites (CI = ± 7.9).

A type II curve (Fig. 1.7) indicated that substrates finer than gravel or larger than boulders were not suitable for lake sturgeon spawning. In between these two extremes, suitability steadily increased from gravel to peak suitability at cobble.

Water temperature

Mean water temperature during spawning decreased significantly as latitude increased ($y = -0.47x + 35.529$, $p < 0.005$, $R^2 = 0.38$; Fig. 1.8), as did the changes in minimum ($y = -0.37x + 28.66$, $p = 0.01$, $R^2 = 0.22$) and maximum water temperature ($y = -0.54x + 40.78$, $p = 0.006$, $R^2 = 0.25$). Across 34 sites (Fig. 1.9), the mean temperature during spawning was 13.7 °C (CI = ± 0.78, Table 1.2).

A type II curve from the frequency of use data for temperature (Fig. 1.10) showed that suitability increased from 8 °C until reaching a peak between 13.8 °C and 14.3 °C, and then decreased until becoming unsuitable at 22.3 °C.

Discussion

Our study indicated that the four key spawning habitat variables did not differ between watersheds or between published and unpublished sources of data. Not surprisingly, spawning depth was greater in large than in small rivers, but river magnitude had no effect on velocity, substrate type, or water temperature. Interestingly, there was a negative correlation between the temperatures at which spawning occurs and a site's latitude, suggesting local adaptation of different populations to climatic conditions. Our overall findings that suitability peaked at velocities of 0.6 $m \cdot s^{-1}$, depths between 0.55 - 0.85 m in small rivers and 0.75 – 5 m in large rivers, substrate size class of cobble, and temperatures from 13.8 – 14.3 °C are similar to previous estimates, with the notable exception of velocity. In formulating a type I HSI for spawning habitat in Northern Ontario streams, Threader (1998) stated that several survey respondents indicated that sturgeon preferred to spawn in velocities over 1 $m \cdot s^{-1}$. High water velocities have been considered as critical habitat in much of the literature since (COSEWIC 2006; Pollock et al. 2015), with targets for spawning habitat restorations being as high as 0.8 – 1.5 $m \cdot s^{-1}$ in Quebec (Dumont et al. 2011). However, it has been shown that egg density at spawning sites decreases as current velocity increases from 0.6 – 1.1 $m \cdot s^{-1}$ (LaHaye et al. 1992) and increases from 0.4 – 0.6 $m \cdot s^{-1}$ (Johnson et al. 2006). Our study supports these conclusions, suggesting that spawning habitat suitability peaks at 0.6 $m \cdot s^{-1}$, but can occur across a wide range of velocities.

Typically, excellent habitat is considered to include all sites with an HSI value greater than 0.75 – 0.8 (Threader 1998; Daugherty et al. 2009). However, there is no standard criterion, with most studies setting arbitrary index values as thresholds. Based on the average minimum and maximum values obtained in this study, we have adapted the threshold values to represent the closest velocity, depth, or substrate index score (see horizontal lines in Figs. 3, 5, 7 and 10). Using this criterion, the most suitable habitat is defined by suitability index values greater than 0.7 for velocity, 0.9 for small river depth, 0.8 for large river depth, 0.8 for temperature and 0.8 for substrate size class.

In addition to the four criteria discussed, other factors can influence spawning site selection. Most importantly, lake sturgeon have high site fidelity to their native streams (Lyons and Kempinger 1992; Forsythe et al. 2012), although individuals have been known to visit multiple sites within the same spawning season (Fortin et al. 1992). Furthermore, lake sturgeon prefer to spawn as river discharge is decreasing (Auer 1996; Forsythe 2010), and will cease spawning activity if discharge rapidly changes (Dumont et al. 2011; Mackenzie 2015). Spawning cessation has also been observed during periods of drastic changes in water temperature (Bruch and Binkowski 2002). Additional cues may also predict timing of entry to spawning rivers. For example, spawning often commenced on the same calendar day over several years in the Black River (Forsythe et al. 2012), likely due to the effect day length has on the endogenous cycle of oocyte maturation (Doroshov et al. 1977; Forsythe 2010). Although grain size is known to influence spawning site selection, silt free interstitial space within the substrate may be even more important (Johnson et al. 2006; Dumont et al. 2011; Du et al. 2011). This space provides eggs with protection from predators and from being dislodged by water currents (Bruch and Binkowski 2002; Roseman et al. 2011), as well as acting as a refuge for newly hatched larvae (Auer 1999). Unfortunately, there is only one paper in our dataset (Manny and Kennedy 2002) describing this potentially crucial component of spawning habitat. Considerable attention has also been directed to the proximity of spawning areas to impediments to upstream migration such as dams, falls, or rapids (LaHaye et al. 1992; Auer 1999; Haxton 2006). We noted that 55% of sites were found within 1 km of a dam or impediment to upstream migration, with an additional 15% found within

10 km. These results may be biased however, because many studies focus on the effects of dams on local fish populations.

While it would have been ideal to synthesize data based on means, sample sizes, and standard deviations, such an approach would have excluded 79% of the available information. Instead we often used data based on mid-points calculated from a given range to increase our overall sample size and the geographic representation of our sample. In addition, we speculate that some qualitative substrate assessments may have used other classification schemes, such as the international scale (ISSS 1929), without our knowledge. This may account for why the size-class pebble was seemingly under-used, having instead been split into gravel or cobble by the individual assessing the site.

Because critical spawning habitat may differ between drainage basins due to characteristics such as hydrology, geomorphology, anthropogenic disturbance, and climate (Moir et al. 2005), some authors recommend using site-specific habitat criteria whenever possible (Armstrong et al. 2003; Haxton 2006). However, type II curves have shown good transferability between streams with distinct hydrology, biotic composition, and geomorphology (Mäki-Petäys et al. 2002). For lake sturgeon, the only attempt to validate an ex-situ model showed poor-predictive power for juvenile habitat (Haxton 2008). However, the quality of juvenile habitat may depend more crucially on local conditions, such as the quality and quantity of food available and the degree of interspecific competition (Moir et al. 2005). Ex-situ suitability indexes have proven to be valuable by reference points from which accurate river-specific models are developed (Daugherty et al. 2009; Krieger and Diana 2017).

Given the amount of resources that have recently been directed at restoring spawning habitat for lake sturgeon (Manny and Kennedy 2002; Dumont et al. 2011; Buszkiewicz et al. 2016), there is a clear need for a generalized index for reproductive habitat. While it is valuable to supplement or build an HSI with local data, such an approach can be resource intensive (Mäki-Petäys 2002). This study provides a comprehensive review of critical spawning habitat and identifies the ideal habitats from which a local-scale model can be adapted to mitigate or predict the effect of habitat loss.

Tables

Table 1.1. Summary of data used to describe characteristics of lake sturgeon spawning habitat. Y = Yes, N = No, L = Large, S = Small, GL/SL = Great Lakes and St. Lawrence, J/H Bay = James Bay and Hudson Bay.

ID	Major drainage	River	Published	Dam within 10km	River magnitude	State/ Province	Citation
1	Mississippi	Upper Mississippi	Y	Y	L	Mo.	Buszkiewicz et al. (2016)
2	Mississippi	St. Croix	N	Y	S	Wis.	Engel (Pers. Comm., 2016)
3	Mississippi	Red Cedar	N	Y	S	Wis.	Engel (Pers. Comm., 2016)
4	Mississippi	Yellow	N	N	S	Wis.	Engel (Pers. Comm., 2016)
5	Mississippi	East Fork White	N	Y	L	Ind.	Fisher (Pers. Comm.,2016)
6	GL/SL	St. Louis	N	Y	S	Minn.	Varian (Pers. Comm., 2016)
7	GL/SL	Sturgeon	Y	Y	S	Mich.	Auer (1996)
8	GL/SL	Kaministiquia	N	Y	S	Ont.	Friday (2013)
9	GL/SL	Wolf	N	Y	S	Wisc.	Koenigs (Pers. Comm., 2016)
10	GL/SL	Embarrass	N	Y	S	Wisc.	Koenigs (Pers. Comm., 2016)
11	GL/SL	Little Wolf	N	Y	S	Wisc.	Koenigs (Pers. Comm., 2016)
12	GL/SL	Upper Fox	N	N	S	Wisc.	Koenigs (Pers. Comm., 2016)
13	GL/SL	Big Manistee	Y	Y	S	Mich.	Chiotti et al. (2008)
14	GL/SL	Big Manistee	Y	Y	S	Mich.	Chiotti et al. (2008)
15	GL/SL	Lower Muskegon	Y	N	S	Mich.	Peterson and Vecsei (2004)
16	GL/SL	Menominee	N	Y	S	Mich.	Baker (Pers. Comm., 2015)
17	GL/SL	Muskegon	N	N	S	Mich.	Baker (Pers. Comm., 2015)
18	GL/SL	Grand	N	Y	S	Mich.	Baker (Pers. Comm., 2015)
19	GL/SL	Kalamazoo	N	Y	S	Mich.	Baker (Pers. Comm., 2015)
20	GL/SL	Peshtigo	Y	Y	S	Wisc	Baker (Pers. Comm., 2011)
21	GL/SL	Upper Black	N	Y	L	Mich.	Baker (Pers. Comm., 2015)
22	GL/SL	Moon	N	Y	S	Ont.	Finucan (2008)
23	GL/SL	St. Clair	Y	N	L	Mich.	Manny and Kennedy (2002)
24	GL/SL	St. Clair	Y	N	L	Mich.	Manny and Kennedy (2002)
25	GL/SL	Detroit River	Y	N	L	Mich.	Manny and Kennedy (2002)
26	GL/SL	Detroit River	Y	N	L	Mich.	Roseman et al. (2011)
27	GL/SL	Richelieu	Y	Y	L	Que.	Thiem et al. (2013)
28	GL/SL	Des Prairies	Y	Y	L	Que.	Dumont et al. (2011)
29	GL/SL	St. Lawrence	N	Y	L	N.Y./Ont.	NYSDEC (2012,2013)
30	GL/SL	St. Lawrence	N	Y	L	N.Y./Ont.	NYSDEC (2012)
31	GL/SL	St. Lawrence	Y	Y	L	N.Y./Ont.	Johnson et al. (2006)
32	GL/SL	St. Lawrence	N	Y	L	Que.	Environnement Illimite (1987)
33	GL/SL	Mille Iles	N	Y	S	Que.	Provost et Fortin (1982)
34	GL/SL	St. Lawrence	N	N	L	Que.	LaHaye et al. (2003)
35	GL/SL	Assomption	Y	N	S	Que.	LaHaye et al. (1992)
36	GL/SL	Ouareau	N	Y	S	Que.	Gauthier (2014)
37	GL/SL	Saint François	N	Y	S	Que.	LaHaye et al. (2014)
38	GL/SL	Saint Maurice	N	Y	L	Que.	GDG Conseil (2001)
39	GL/SL	Missisquoi	N	Y	S	Vt.	Mackenzie (Pers. Comm., 2015)
40	GL/SL	Lamoille	N	Y	S	Vt.	Mackenzie (Pers. Comm., 2015)
41	GL/SL	Winooski	N	Y	S	Vt.	Mackenzie (Pers. Comm., 2015)
42	J/H Bay	Rupert	N	N	L	Que.	LaHaye et al. (2013)
43	J/H Bay	Rupert	N	N	L	Que.	LaHaye et al. (2013)
44	J/H Bay	Rupert	N	N	L	Que.	LaHaye et al. (2013)
45	J/H Bay	Rupert	N	N	L	Que.	Guay et al. (2011)
46	Nelson	Little Fork	N	Y	S	Minn.	Aadland (Pers. Comm., 2016)
47	Nelson	Winnipeg	N	Y	L	Man.	Manitoba Hydro (2016)
48	Nelson	Winnipeg	N	Y	L	Man.	Manitoba Hydro (2016)

Table 1.2. Quantitative summary of a synthesis of lake sturgeon spawning habitat. $\bar{x}$ = mean, $\bar{x}$ min = mean minimum, $\bar{x}$ max = mean maximum and ±CI = the 95% confidence interval.

Variable	$\bar{x}$	±CI	$\bar{x}$ min	±CI	$\bar{x}$ max	±CI	Range
Velocity ($m \cdot s^{-1}$, n = 24)	0.85	0.11	0.42	0.14	1.35	0.22	0.03 – 2.51
Depth – all (m, n = 34)	3.65	1.30	1.95	0.93	4.82	1.35	0.03 – 25
Depth – small river (m, n = 15)	1.06	0.33	0.66	0.36	1.54	0.41	0.03 – 2.8
Depth – large river (m, n = 19)	5.7	1.99	3.23	1.99	8.1	1.81	0.1 – 25
Substrate size (mm, n = 34)	117	16.5	31.8	16.5	202.2	23.8	0.01 – 256.1
Water temperature (°C, n = 34)	13.7	0.8	11.5	0.8	15.5	1.1	8 – 21.5

Figures

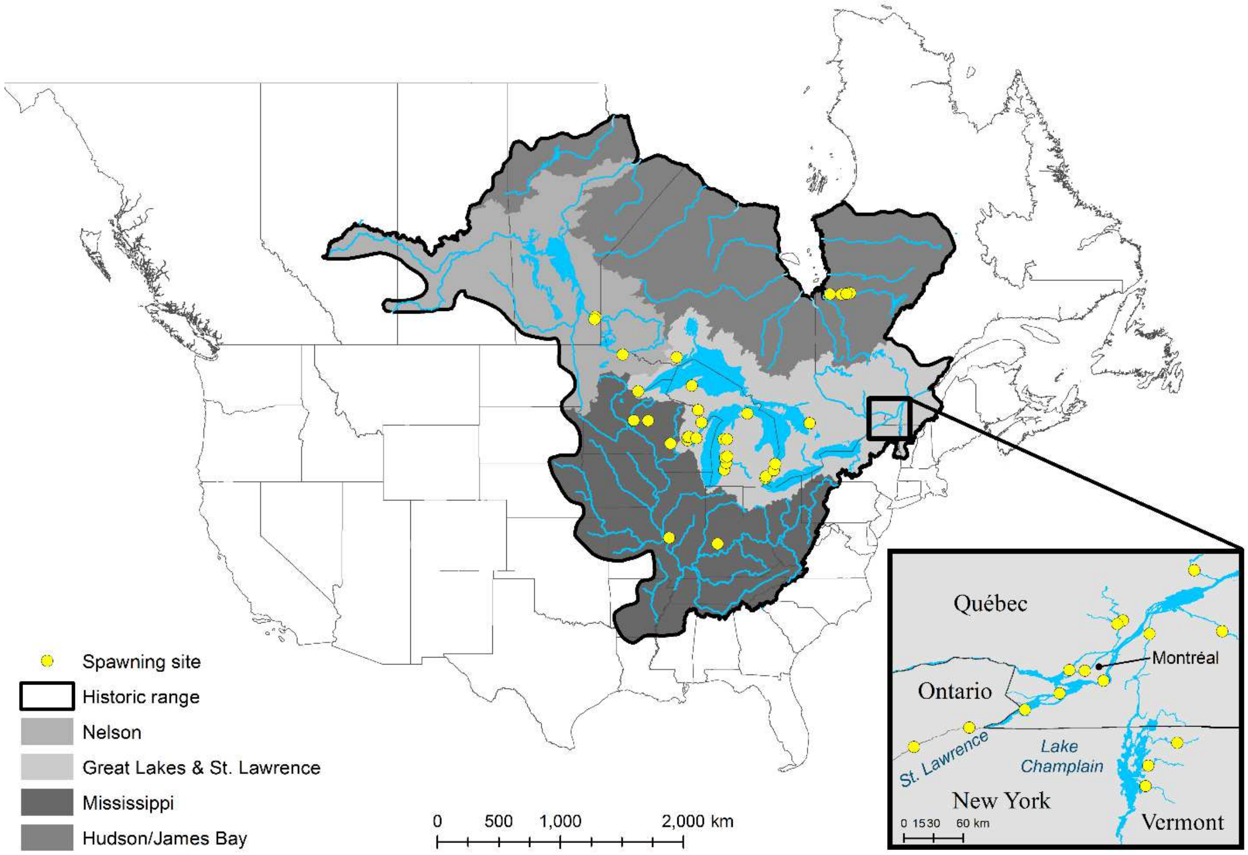

Figure 1.1. Lake sturgeon historic range adapted from COSEWIC, 2006 and NatureServe, 2012, with locations of spawning sites used in study and major watersheds within the range.

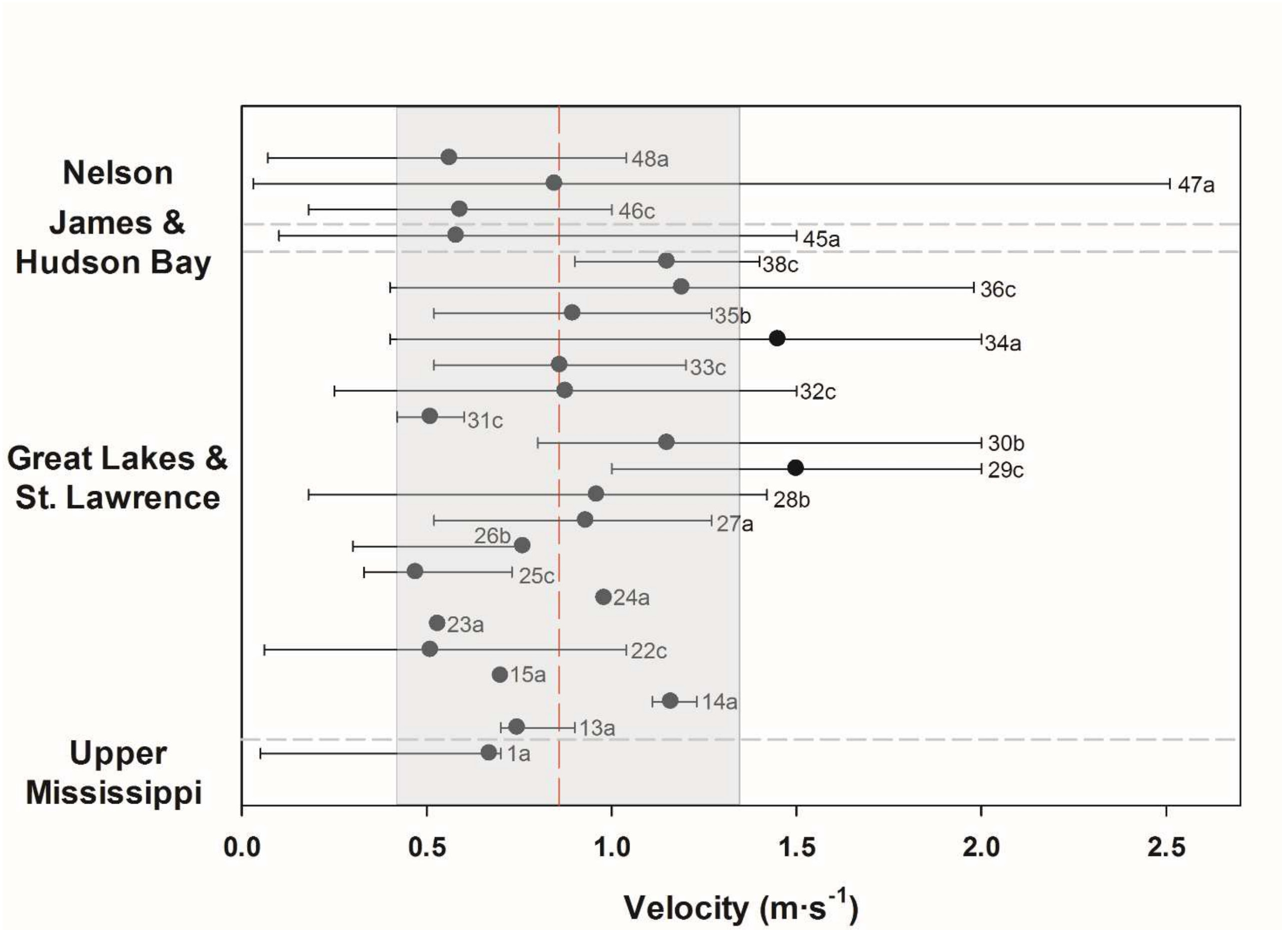

Figure 1.2. Mean (a), mode (b) or mid-point (c) of depth-averaged velocity at lake sturgeon spawning sites (ID number, n = 24) organized by major watershed. Horizontal bars = the range of velocities observed per site; red dashed line = mean; and grey bar = mean range (i.e. mean minimum to mean maximum).

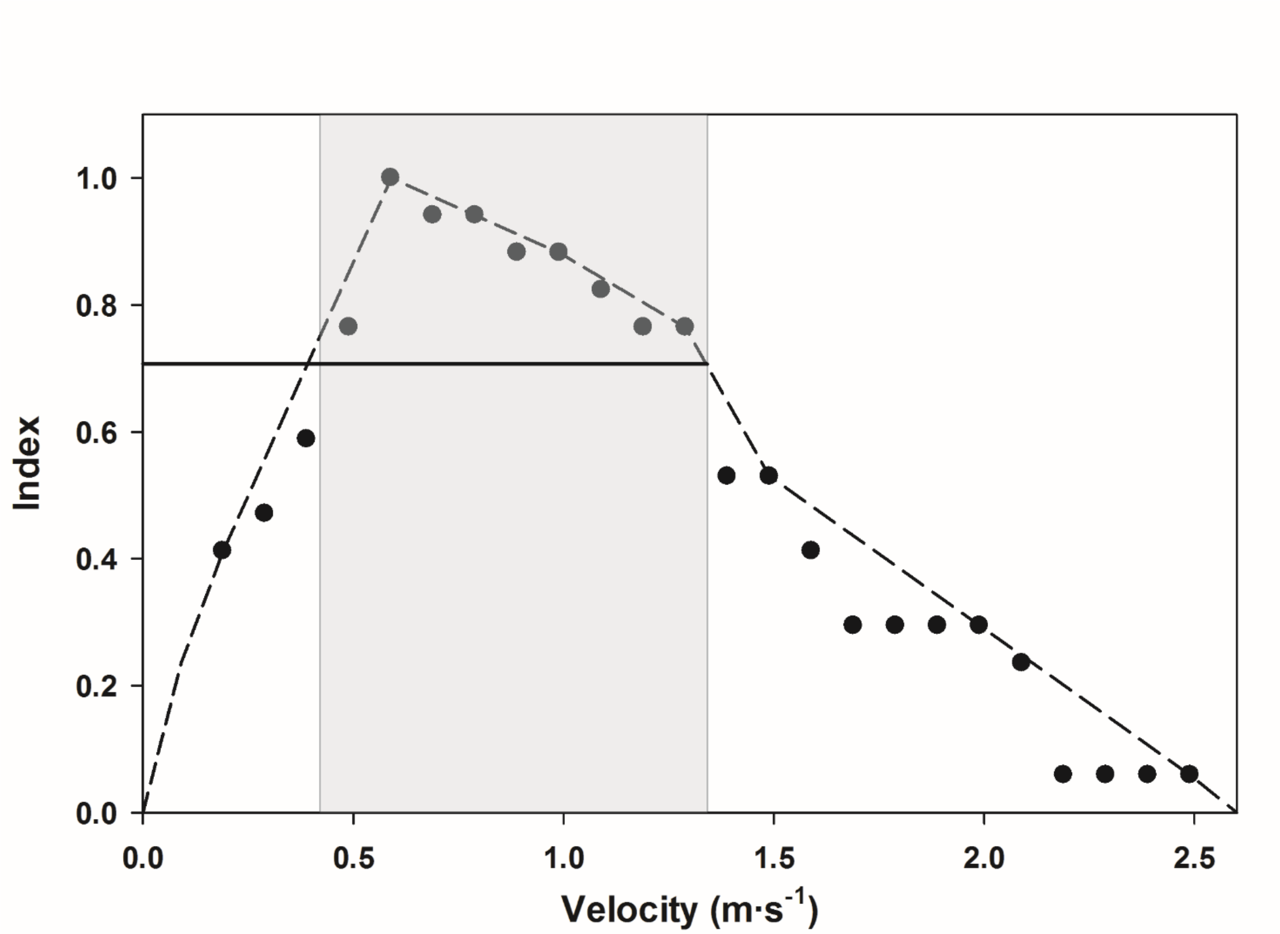

Figure 1.3. Type II utilization curve (black dashed line) for depth-averaged velocity at lake sturgeon spawning sites (n = 24), with bin sizes in increments of 0.1 and points showing the standardized frequency of velocity class occurrence. Grey bar = mean range of velocities; and black solid line = lower limit index score (0.7) of excellent habitat.

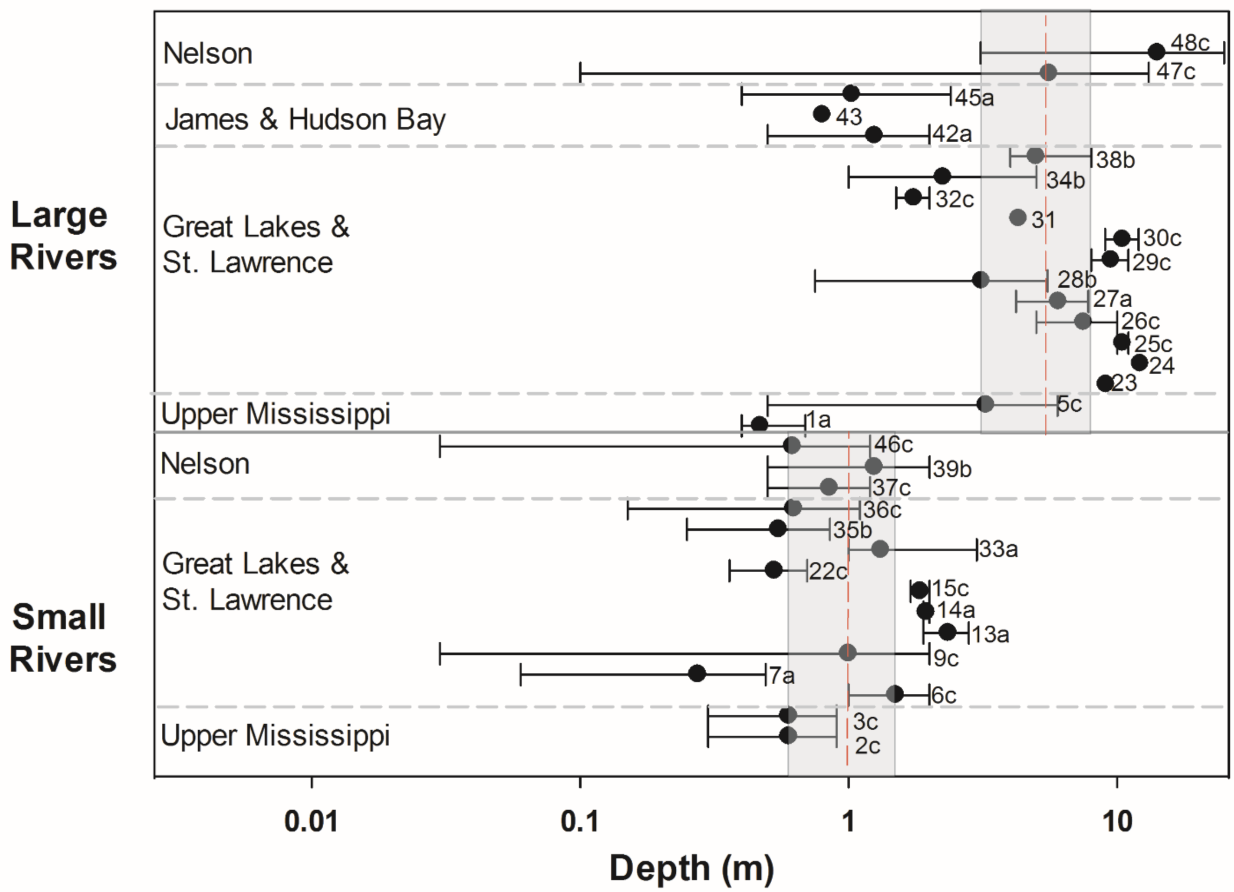

Figure 1.4. Mean (a), mode (b) or mid-point (c) of water depth at lake sturgeon spawning sites (ID number) organized by river magnitude (n small rivers = 15, n large rivers = 19) and major watershed. Horizontal bars = the range of depths observed per site; red dashed line = mean; and grey bar = mean range (i.e. mean minimum to mean maximum).

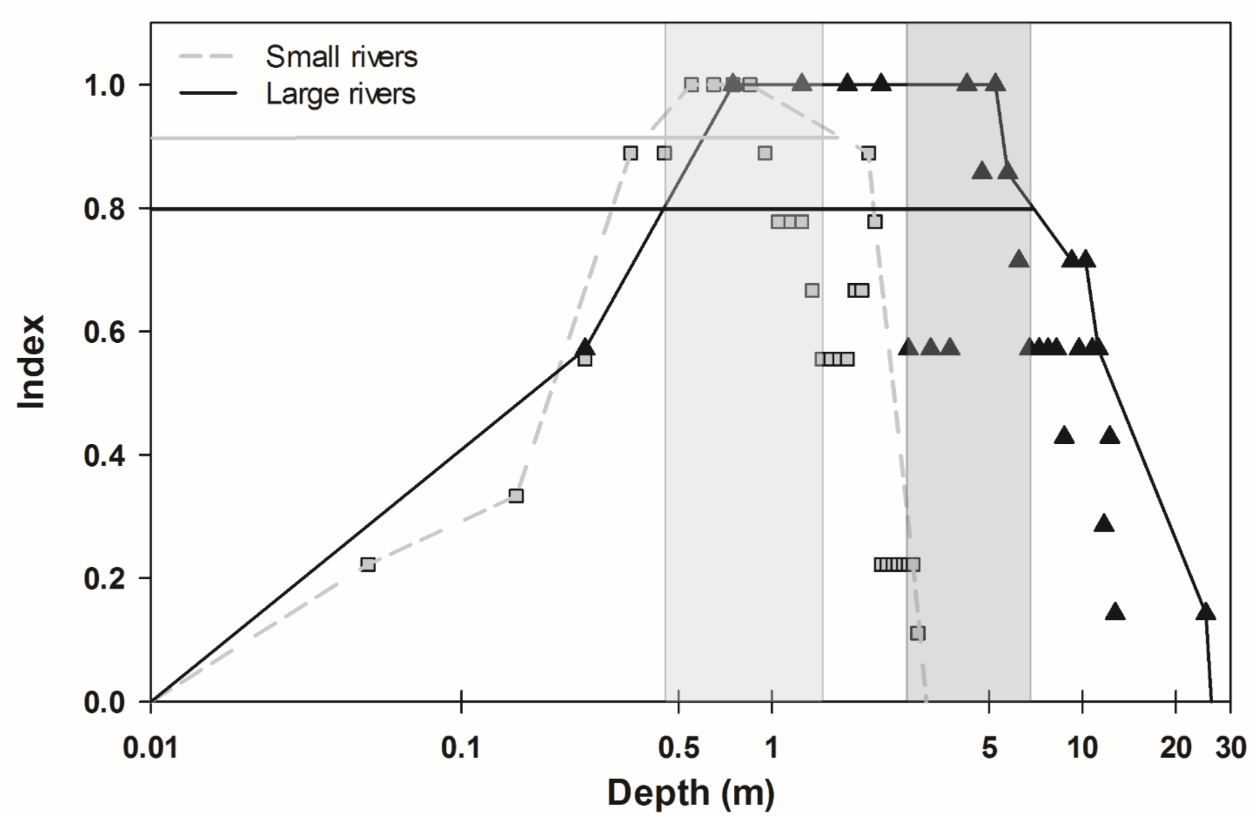

Figure 1.5. Type II utilization curve for lake sturgeon spawning site water depth in small rivers (n = 15) and large rivers (n = 19), with bin sizes in increments of 0.1 for small rivers, and 0.5 for large rivers with points showing the standardized frequency of depth class occurrence. Light grey bar = mean range of depth in small rivers; dark grey bar = mean range in large rivers; solid grey line = lower limit index score of excellent habitat (0.9) in small rivers; and solid black line = lower limit index score (0.8) of excellent habitat in large rivers.

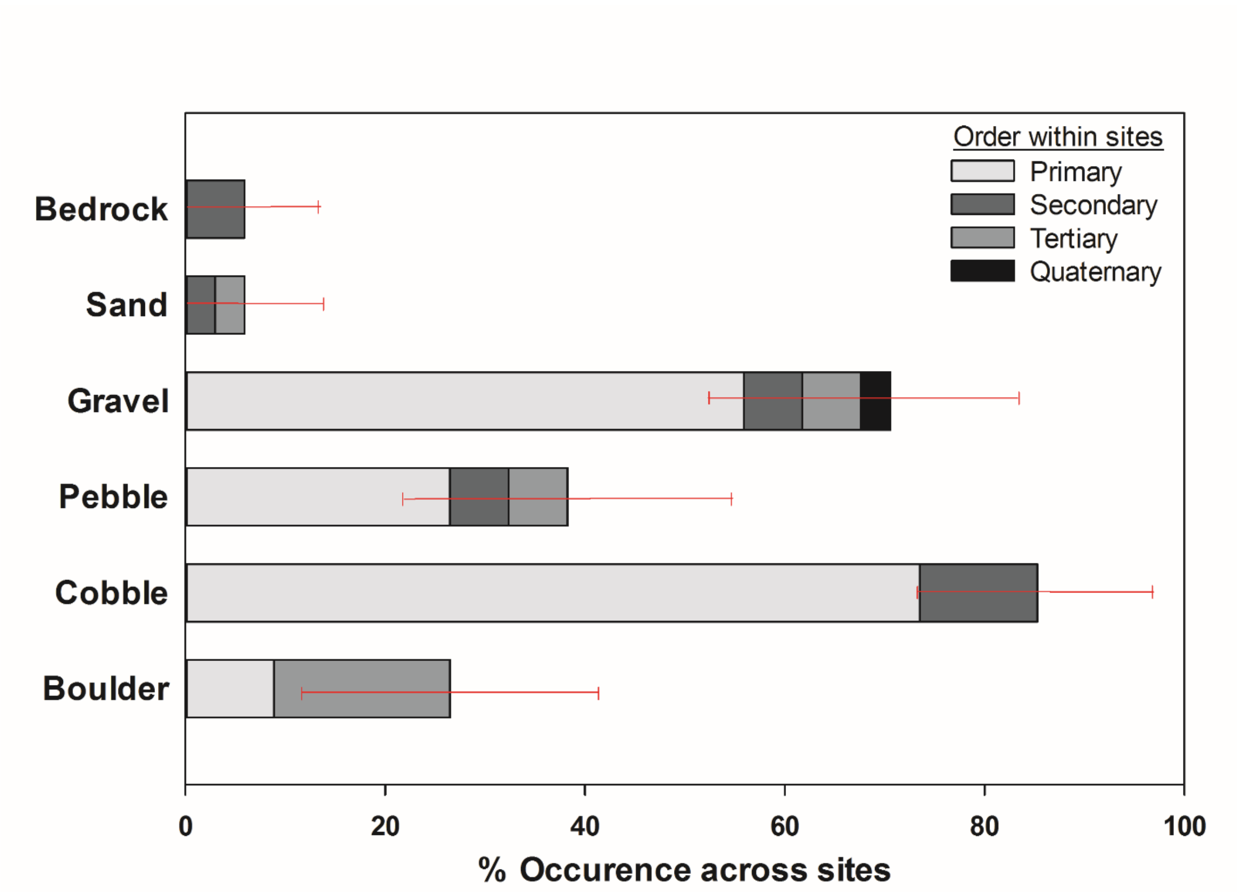

Figure 1.6. Percent occurrence of Wentworth substrate size class at lake sturgeon spawning sites (n = 34) with the 95% confidence interval (red bars).

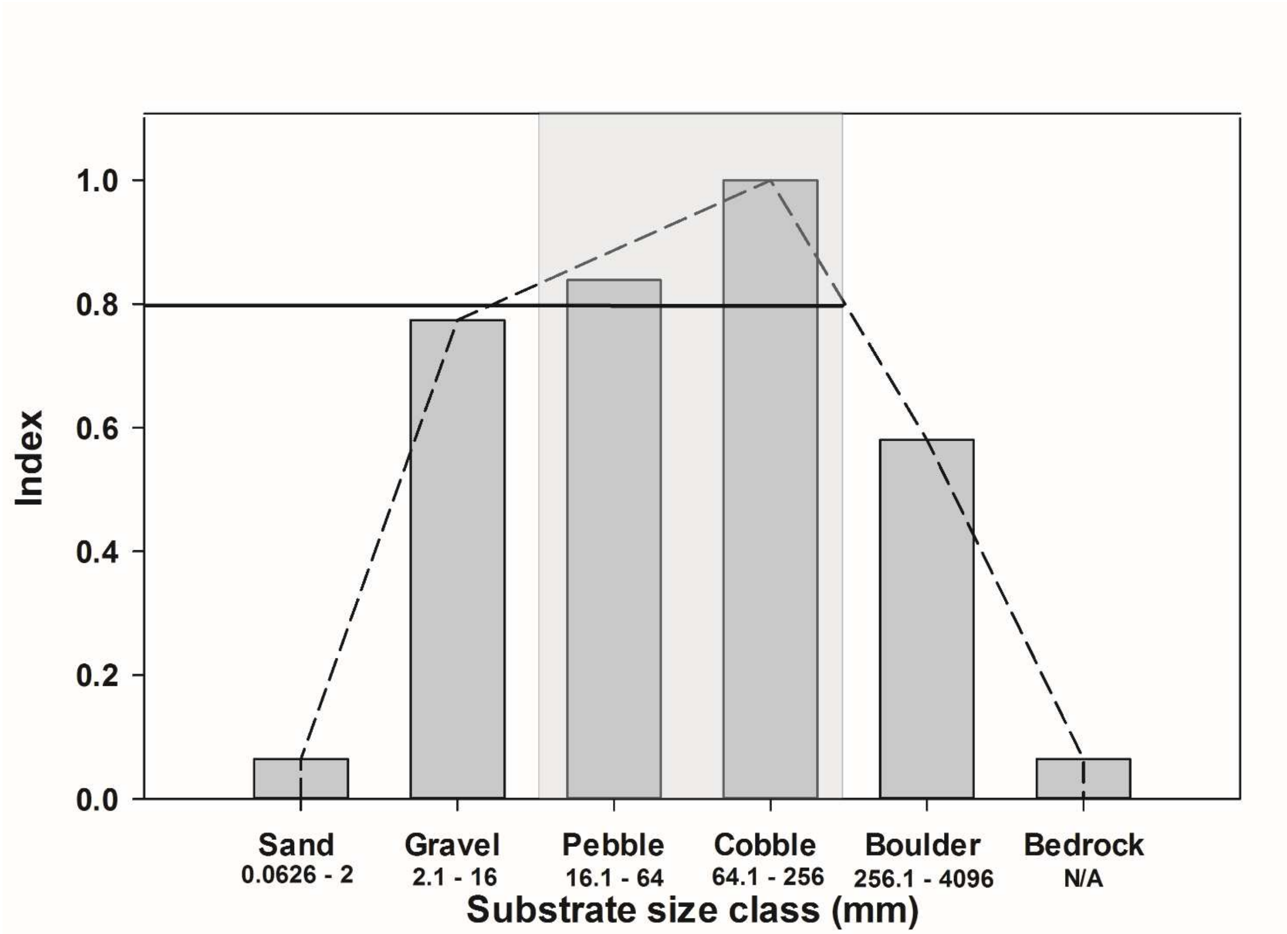

Figure 1.7. Type II utilization curve (black dashed line) for lake sturgeon spawning site substrate size (n = 34) with bin sizes organized by substrate size class (Wentworth scale) and vertical bars showing the standardized frequency of substrate size class occurrence. Transparent grey bar = mean range of substrate size, and black solid line = lower limit index score (0.8) of excellent habitat.

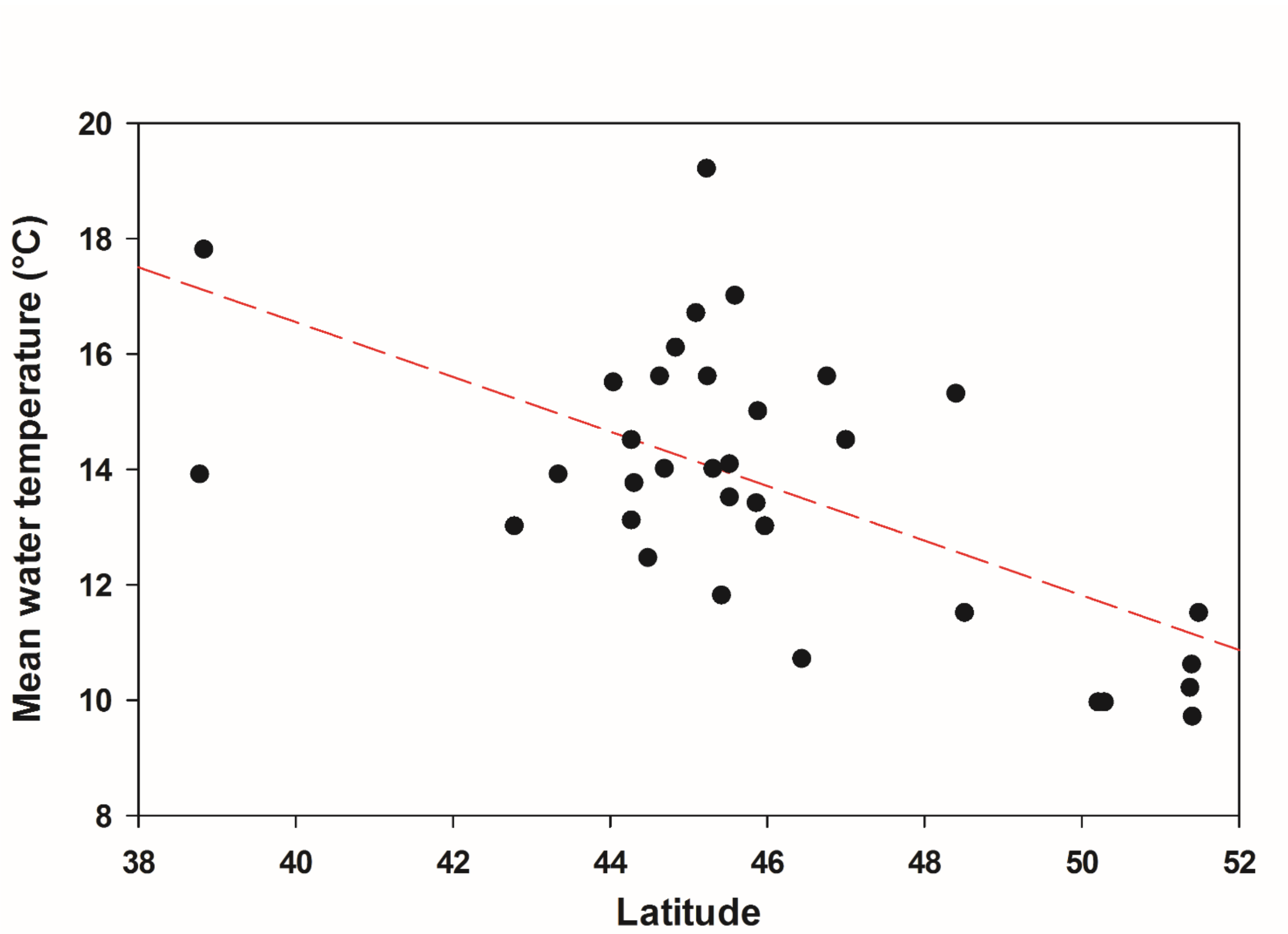

Figure 1.8. Linear regression ($y = -0.47x + 35.529$, $p < 0.005$, $R^2 = 0.38$) showing the relationship between mean water temperature and latitude at lake sturgeon spawning sites ($n = 34$).

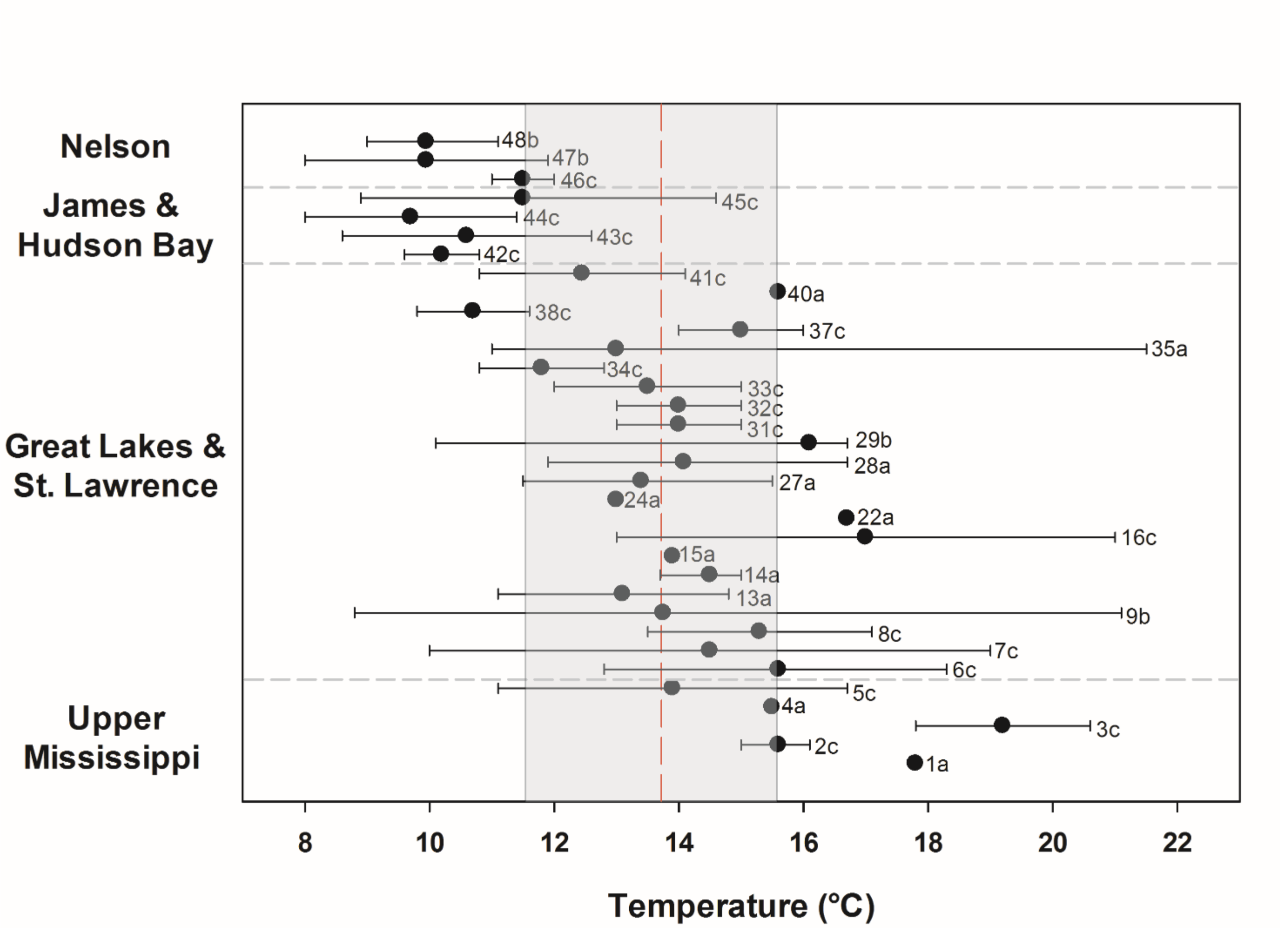

Figure 1.9. Mean (a), mode (b) or mid-point (c) of water temperature at lake sturgeon spawning sites (ID number, n = 34) and major watershed. Horizontal bars = the range of water temperatures observed per site; red dashed line = mean; and grey bar = mean range.

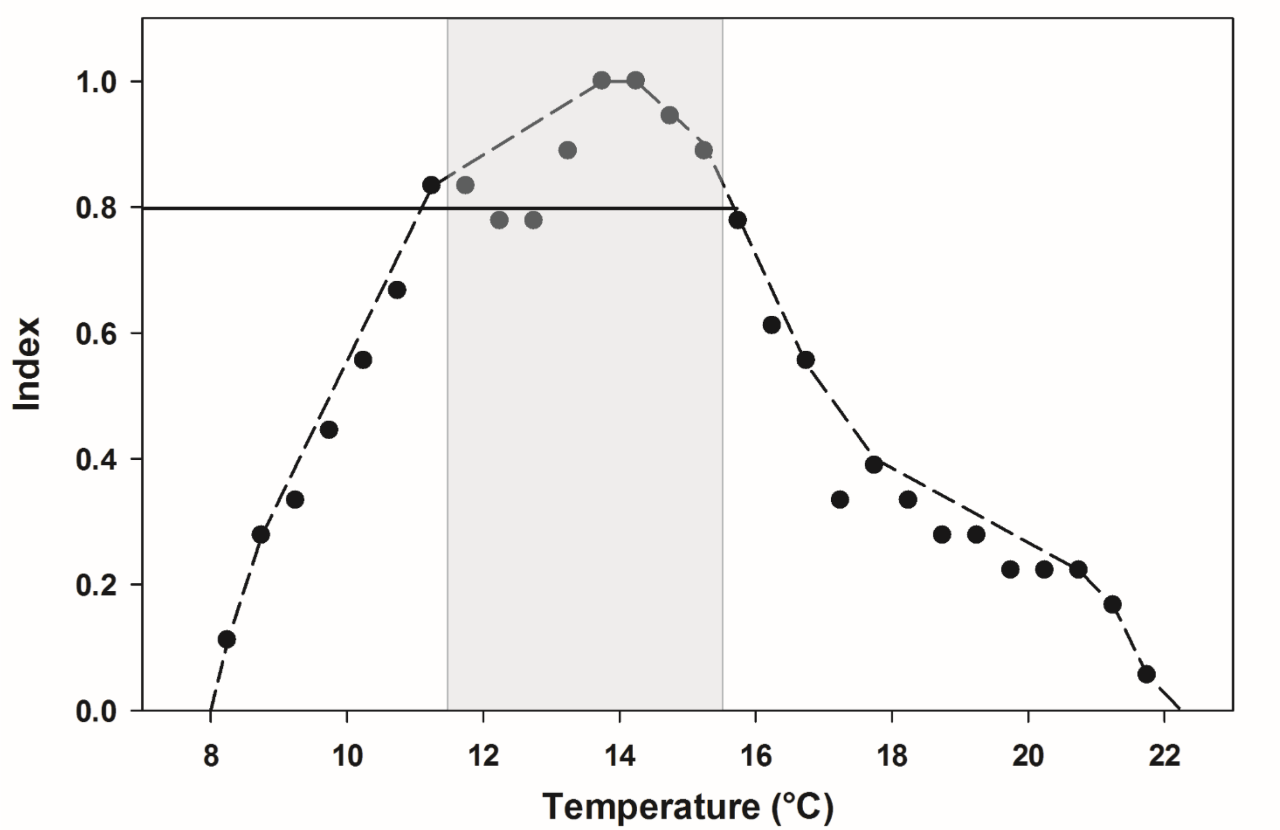

Figure 1.10. Type II utilization curve for water temperature at lake sturgeon spawning sites (n = 34) using bin sizes of 0.5 with points showing the standardized frequency of water temperature occurrence. Grey bar = mean range of water temperature, and black solid line = lower limit index score (0.80) of excellent habitat.

Chapter 2.

The need for science-based management protocols and multi-disciplinary insight in river restoration: A case study in the Ouareau River (Quebec, Canada)

Andre-Marcel Baril[1], Pascale M Biron[2], James W.A. Grant[1],
[1]Concordia University, Department of Biology
[2]Concordia University, Department of Geography, Planning and Environment

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To be submitted to: Restoration Ecology

1. Concordia University, Department of Biology, 7141 Rue Sherbrooke West, Montréal, Québec, H4B 1R6, Canada. andremarcelbaril@gmail.com, james.grant@concordia.ca
2. Concordia University Department of Geography, Planning and Environment, 1455 Boulevard de Maisonneuve West, Montréal, Québec, H3G 1M8, Canada. pascale.biron@concordia.ca

Abstract

The use of adaptive management protocols (AMP) in habitat restoration is widely acknowledged as being a crucial component to a successful project. We adopted the AMP of a successful lake sturgeon spawning habitat restoration in the St. Clair-Detroit River system (Michigan/Ontario) to evaluate a similar project on the Ouareau River (Quebec) which lacked an AMP. The Ouareau restoration differs from the St. Clair-Detroit River project in that it included the installation of two sills as part of the restoration design, and the artificial spawning sites have not been used by spawning lake sturgeon. Our study combined a comprehensive review of the criteria used to determine the necessity and design of the restoration using the AMP, with habitat suitability and 3D hydrodynamic modeling to evaluate the amount and quality of available habitat and to determine the effect of the sills at mitigating fluctuating water levels and resisting headward erosion. Our findings show that the lack of a thorough pre-assessment in the Ouareau project resulted in erroneous hypotheses and identified a communication breakdown between restoration designers and decision-makers regarding the purpose of the sills. Moreover, our models revealed that there was sufficient good quality habitat within the study area, the artificial sites were placed in inadequate locations, and that the instream structures did not meet either the expectation of raising water levels or resisting headward erosion. These results point to the need for AMPs which incorporate a rigorous science-based review, and the requirement for multi-disciplinary input, including hydrogeomorphology, in any restoration project undertaken in a river environment.

Keywords: Habitat restoration, Adaptive management, Lake sturgeon, habitat suitability, 3D hydrodynamic modelling, Instream structures

Introduction

To counteract biodiversity loss via habitat degradation, restoration projects in aquatic and terrestrial environments are increasingly seen as a valuable part of the solution (Palmer et al. 2005). In freshwater environments, an exponential growth of restoration projects was observed in the 1990s, and the most recent estimates showed costs exceed a billion dollars annually in the United States (Bernhardt et al. 2005; Lapointe et al. 2013). Unfortunately, too often these projects do not follow a systematic framework in the decision-making process to pursue restoration (Corsair et al. 2009) and lack comprehensive criteria to evaluate a project's success (Palmer et al. 2014). When post-project evaluations for habitat restorations are conducted, studies typically focus on biological endpoints such as species abundance or richness (Ford 1989; Palmer et al. 2014). However, these projects often involve the manipulation of river form and function through the introduction of instream structures, which increase the cost of restoration projects, but are rarely assessed for performance (Bernhardt et al. 2005; O'Donnell and Galat 2007; Whiteway et al. 2010).

Lake sturgeon (*Acipencer fulvescens*) is classified as either endangered, threatened or of special concern throughout their range, with spawning habitat considered as a limiting factor for population growth (COSEWIC 2006; Lyttle 2008; Bennion and Manny 2014). Subsequently, the restoration or creation of suitable spawning habitat has become a common practice, with at least 17 projects having been implemented throughout North America (Chapter 1). Spawning site restorations for lake sturgeon have generally been undertaken to address two issues: (1) to compensate for lost habitat from anthropogenic disturbances (Johnson et al. 2006; Manny et al. 2015); or (2) to expand existing habitat to address an insufficient quantity at the site (Dumont et al. 2011). One successful project was implemented in the St. Clair-Detroit River system of the Laurentian Great Lakes, and was driven by an adaptive management protocol (AMP), a structured, iterative decision making process which allows for changes in hypotheses and strategies to reduce uncertainty in management decisions. This AMP was used to guide decision making, hypothesis development, strategic implementation, and monitoring (Manny et al. 2015, Fig. 2.1). The project entailed the installation of 24 spawning reefs at three sites in locations deprived of suitable habitat for lake sturgeon, walleye (*Sander vitreus*), lake whitefish (*Coregonus clupeaformis*) and the northern madtom (*Notorus stigmosus*). For lake sturgeon, the project was successful with 21 out of 24 reefs being used for spawning (Manny et al 2015).

In contrast, the restoration project undertaken in 2004 and 2007 on the Ouareau River in Quebec represents a concerning trend in river rehabilitation of not using an AMP, in spite of a clear consensus of its merit (Bernhardt et al 2005; Brierley et al. 2010). The project entailed the installation of three spawning reefs in areas that were characterized as having lost suitable habitat for spawning lake sturgeon, as well as the installation of two arch sills to increase water levels and resist headward erosion (Beaulieu and Bélanger 2005). The initial causes for concern with this project were twofold: the artificial spawning beds were not being used by lake sturgeon; and, the downstream sill was rapidly degrading.

Sills are the simplest form of grade-control structures designed to reduce scour, create a minimal backwater effect and prevent headward erosion (Hey 2014). Headward erosion is the process by which a knick point, a steep abrupt change in the longitudinal profile of a river, migrates upstream through channel incision (Crosby and Whipple 2006; Sear et al. 2010). This process is driven by a decrease in the base level of a river through natural processes such as changes in sea level and stream capture or anthropogenically through the excavation of river sediments (Crosby and Whipple 2006; SEPA 2010). For rivers experiencing discharges greater than 300 $m^3 \cdot s^{-1}$ such as the Ouareau, or for lake sturgeon restorations in general, the use of sills is unprecedented (Chapter 1; Sear et al. 2010).

Given the similarity of the St. Clair-Detroit River and Ouareau projects, we used the AMP developed by Manny et al. (2015) for the St. Clair-Detroit River to assess the spawning site restoration on the Ouareau River. The objective of this study is to focus on the Evaluation stage of the AMP (Fig. 2.1, Step. 7) by reviewing three hypotheses for the Ouareau project: (1) there was a lack of suitable habitat within the spawning reach, (2) headward erosion was degrading the site, and (3) dam activity upstream caused water level changes during spawning season rendering conditions unsuitable. As well, the design, performance and decision making process relating to sill construction (Beaulieu and Bélanger 2005) is examined. The evaluation is based on a combination of 3D hydrodynamic modelling and a fuzzy multi-criteria analysis for suitability using a Geographical Information System (GIS).

Materials and Methods

Study area

The Ouareau River is a tributary of the L'Assomption River, which drains into the St. Lawrence River east of Montreal (Fig. 2.2), where the Ouareau population spend the majority of their life cycle (Fortin et al. 1992). The only known spawning site on the Ouareau River is located 2.6 km downstream of the Kruger Paper dam, constructed in 1918, in Crabtree (Fig. 2.2). The study site comprises an area of 62 478 m^2, within which three natural and three artificial spawning beds are found (Fig. 2.3). Bankfull discharge is 151 $m^3 \cdot s^{-1}$, with an annual average discharge of 32.5 $m^3 \cdot s^{-1}$. The mean width of the river is approximately 80 m at low flow until splitting into 2 channels flowing around an island composed of deposited alluvial material. The site has widely variable substrates, ranging from fine clay to boulders, which are generally located in distinct zones (Fig. 2.4).

The Ouareau restoration project

We analyzed 18 reports completed between 1990 and 2014 regarding the Ouareau spawning area provided by the Ministère des Forêts, de la Faune et des Parcs (MFFP) (Appendix A). Of these reports, seven concerned pre-construction biological assessments, one outlined the planning and execution of the restoration with reference to geomorphic, biological and hydrologic assessments, one independently reviewed the geomorphic state of the spawning area, one reviewed the sill performance and ten pertained to post-restoration biological assessments. The restoration project is summarized below using the first 6 steps of the adaptive management framework described in Figure 2.1.

1. Problem identification

The Ouareau River was deemed to have experienced a loss of habitat quantity and function due to a landslide event which occurred in March of 1990, which covered the traditional spawning site (Fig. 2.3) with clay and silt deposits.

2. Scientific pre-assessment

An initial investigation of the site was conducted in 1990 to assess habitat changes due to the landslide, and how it affected spawning lake sturgeon (LaHaye et al. 1990). In 1990, 1994 and on an annual basis from 1998 until restoration project implementation in 2007, the site was assessed for the presence of adult spawners, by visual inspection. Egg densities were also estimated using traps made up of adhesive artificial substrate or kick-net sampling within the island and traditional spawning sites, and larval production was assessed, using drift net sampling downstream of the spawning area. To describe the habitat, temperature and water levels within the reach were recorded during the spawning period, and current velocity and depth were measured at locations where egg sampling occurred. The only evidence of attempts to search for other lake sturgeon spawning sites within the Ouareau River outside of the documented reach occurred during the initial investigation of the site post-landslide (LaHaye et al. 1990); a 1 km sector of the river immediately downstream of the dam in Crabtree was surveyed, two weeks after lake sturgeon had been observed spawning at the known Ouareau site, and when water temperatures were 3 °C higher than the expected maximum for spawning (Chapter 1). No adults, eggs or larvae were observed.

A hydraulic and geomorphic assessment was conducted in 2005 which concluded that headward erosion was occurring at the Ouareau spawning reach (Beaulieu and Bélanger, 2005). This conclusion was reached by comparing aerial photographs from 1964 and 2004 and noting changes in the longitudinal profile of the river. Additional support for the need for restoration was the severe decline in population size (Mailhot et al. 2011).

3. Hypothesis development

The Ouareau river lake sturgeon spawning site was considered to have experienced a loss of habitat quantity and function based on the following criteria (Beaulieu and Bélanger 2005): (1) a lack of suitable habitat was believed to result in egg densities that were too high, likely causing high embryonic mortality rates; (2) headward erosion that was believed to cause degradation of the spawning reach, and deposit coarse material downstream of the spawning area; and, (3) water level fluctuations caused by dam activity upstream that were believed to result in unsuitable conditions for lake sturgeon spawning.

4. Consensus Building

A committee consisting of seven biologists from two provincial governmental ministries, a crown corporation and the local watershed agency, one engineer from the private sector and one from the MFFP, two coordinators from local watershed agencies and one technician were the experts responsible for the conceptualization, planning and execution of the restoration project. No hydrogeomorphologist was involved.

5. Prioritization and strategy development – Prioritizing restoration actions

To address the problems identified at the Ouareau site, a four-step process was identified: (1) remove the clay and silt material from the traditional spawning site; (2) install artificial spawning reefs comprised of suitable substrate to disperse spawners and ensure egg density did not exceed 500 eggs·m^2; (3) negotiate an agreement with the upstream dam managers to ensure ecological flows are maintained during the spawning period; and, (4) install sills to mitigate the effect of dam activity upstream and prevent headward erosion.

Construction design was undertaken in 2005. To select sites for artificial reef installation, a 1-D hydrodynamic model (HEC 2) was used to determine depth averaged velocity and water levels at several river cross sections. The model used discharge data from the Centre d'expertise hydrique du Québec (CEHQ) gauging station (ID 052212) located 40km upstream in Rawdon (Fig. 2.2), and water level measurements taken during field assessments as boundary conditions.

The location of artificial spawning sites was determined to be upstream of the constructed sills. The substrate comprising the spawning reefs was determined through investigation of the grain size used by lake sturgeon during spawning, with consideration given to avoid transport of substrate downstream using Bogardi's criteria (1965).

To design the sills, the maximum (332.5 $m^3 \cdot s^{-1}$) and minimum (12 $m^3 \cdot s^{-1}$) discharges were determined from calculating flood recurrence intervals using historic data from the gauging station upstream. The maximum was used to compute average velocities with the model HEC 2 at the cross-sections where sills were planned. These average velocities were not listed in the report, but were used to calculate the size of material selected for sill construction (700 mm in diameter). The sills were overlaid with geotextile fabric to facilitate fish passage and ensure water does not flow through them. Additionally, the sills were determined to not exceed 0.3 m in height to ensure that lake sturgeon were capable of breaching them.

6. Project implementation

The restoration was completed in the winter of 2007, at a cost of over CDN$500,000. The original project plan described the installation of four sills, and six spawning beds, but only two sills and three reefs were installed. A post-construction report stated that a sill and a spawning bed in the side channel north of the island were not constructed due to concerns over damaging the area with heavy machinery (Chagnon and Dumas 2008). The decision-making process used in determining that the other two artificial spawning sites and sill would not be constructed were not addressed.

Field Methods

A bathymetric survey of the river was conducted within an area beginning 100 m upstream of the first sill and ending at the traditional and restored traditional spawning sites. These two sites were not included in the analysis because they were outside of the area in which the sills had an effect.

A Spectra Precision SP80 Differential Global Positioning System (DGPS) was used to collect bathymetric data of the study area to a precision of ± 1.5 cm. A total of 2534 measurements were taken along 118 transects, at intervals of approximately 7 m over the study area, or whenever an abrupt change in bed topography was observed. Whenever adequate satellite reception was not available (usually near the banks), a Ziplevel Pro was used, with a precision of ± 2 cm. Wolman pebble counts (Wolman, 1954) were conducted at 17 locations with distinct substrate sizes (Fig. 2.4) to characterize substrate. They were classified according to the modified Wentworth scale (Wentworth, 1922). A pressure transducer (Solinst Levelogger) was installed in the river for 9 weeks to determine water levels at the site corresponding to varying discharges. Because of the presence of a major tributary (Rouge River, Fig. 2.2) between the study area and the gauging station, the discharge from CEHQ ID 052212 was increased by a factor of 1.26 based on the catchment area of the Rouge River.

Analyses

Datasets regarding egg deposition before and after restoration were made available by the MFFP, and summarized in Gauthier (2014). The results were compared with the literature to determine if there was a problem of high egg densities causing mortality during embryonic development.

To determine the range of discharges in which lake sturgeon spawning takes place on the Ouareau river, discharge was calculated for days in which spawning behavior was observed or which occurred 11 - 15 days prior to successful larval surveys, which generally occurred between mid-April and early May. This timeline was selected given that it takes 8 - 10 days after fertilization for eggs to hatch, and the larvae spend an additional 3 - 5 days within the substrate before migrating downstream (Auer and Baker 2002). Using these criteria, four discharges were chosen to represent the range of spawning conditions at the Ouareau site: 38, 55, 69, and 87 $m^3 \cdot s^{-1}$.

Bathymetric data were used to create a 3D grid in the Delft 3D hydrodynamic modelling software using triangular interpolation (Deltares 2014). The grid comprised 27435 cells (5487 horizontal), with an average horizontal size of 3.4 m, representing a total area of 62 478 m^2. Five vertical layers were used to represent the vertical variability in velocity between the bed and water surface, which is important in determining the effect of instream structures (Biron et al. 2012). The grid was compartmentalized into the 17 substrate zones, with each zone being assigned a Manning's n roughness coefficient corresponding to the results from the Wolman pebble count (Kondolf and Piégay 2016). Upstream and downstream boundary conditions were discharge and water level, respectively. The model predicts depth and velocity at each cell. The model was validated by comparing predicted and measured water surface elevation measurements at high flow (176 $m^3 \cdot s^{-1}$), a common method for evaluating hydrodynamic models. The model showed excellent agreement (Root Mean Square Error (RMSE) = 0.021 m) relative to other validation examples using water surface elevation (Hodge et al. 2011; Matte et al. 2017).

The numerical grid of the Ouareau bed was virtually modified to also represent the pre-restoration situation with no sills; we interpolated between the upstream and downstream bed elevation and replaced the sills with those interpolated values for zones located 5 m upstream and downstream of the structures. The same four discharge conditions were used to run these 3D simulations. In addition, a longitudinal water surface profile for the lowest spawning discharge (38 $m^3 \cdot s^{-1}$) were created to determine the effect of the sills on water levels at the site. The low flow condition was selected because the sills should have a more significant effect on water levels at lower discharges (Bariteau et al. 2008). Results from the hydrodynamic model were exported to ArcGIS where average velocities and depths within the spawning sites were compared to results of a habitat suitability index for lake sturgeon spawning (Chapter 1) for each spawning zone, both with and without sills.

To assess habitat suitability within the study reach, a fuzzy multi-criteria evaluation (MCE) using weighted linear combination (WLC) was conducted using GIS with three factors: velocity, depth and substrate. Because fuzzy models incorporate the uncertainty of boundaries set for habitat parameters, it is considered an appropriate technique in species distribution models (Mouton et al. 2011). A fuzzy analysis accomplishes this by differentiating from the Boolean overlay approach, which uses crisp boundaries and a binary true or false output in determining suitability for each variable (velocity, depth or substrate). It does this by using continuous variables and allowing a criterion with low suitability to be compensated by the high suitability of another factor (Pechanek and Machar 2013). It provides the degree of suitability on a continuous scale ranging from 0 (least suitable) to 1 (most suitable) for each cell or pixel. Our model used the habitat suitability index for lake sturgeon spawning habitat (HSI) from Chapter 1 regarding depth, substrate size and current velocity to standardize these variables on a continuous 0 to 1 scale. Each factor was assigned a weight to determine its relative importance to habitat suitability. The literature indicated that the primary drivers of lake sturgeon spawning site selection are velocity and substrate size, with depth having a less important role (Chapter 1). A sensitivity analysis was conducted comparing the mean suitability of all spawning beds for the four spawning discharges using four different series of weights (Table 2.1). This analysis revealed that the rank of each spawning site suitability did not change, indicating that results were not very sensitive to small changes in weight. Based on knowledge of known spawning sites, the third series of weights was chosen, i.e. 0.4, 0.5 and 0.1 for velocity, substrate and depth, respectively.

Results for the Fuzzy WLC habitat suitability model were analyzed for each spawning discharge by first determining the mean HSI score within each of the four spawning beds. Secondly, through a process called "defuzzification" (Malczewski 1999), a weighted mean was used to establish a threshold minimum suitability. These were determined for each factor from the criteria of Chapter 1, where the suitable threshold values were 0.7, 0.8 and 0.9, respectively, for velocity, substrate and depth. For the third series of weights, the minimum threshold value for suitable spawning areas is therefore 0.77, i.e. (0.4 * 0.7) + (0.5 * 0.8) + (0.1 * 0.9).

Results

Hypothesis 1 – Lack of suitable habitat, and high egg densities causing embryonic mortality

In a successful lake sturgeon restoration project on the Des-Prairies River near Montreal, Dumont et al. (2011) cited a threshold for egg density of 3000 – 3500 eggs·m^2 to avoid high embryonic mortality rates, based on a study of Khoroshko and Vlasenko (1970) for Sevruga sturgeon (*Acipenser stellatus*). Dumont et al. (2011) showed an increase in egg to larvae survival when egg densities decreased from a maximum of 5626 eggs·m^2 (1996) to under 2000 eggs·m^2 (1997 – 1999). The project goal for the Ouareau River stated that egg densities should not exceed 500 eggs·m^2. At the site, the maximum recorded egg density prior to restoration was 963 eggs·m^2 (1999), and 645.7 eggs·m^2 (2007) post restoration. Other than these two instances (out of 732 samples, so 0.27% of the time), there is no evidence of egg deposition exceeding the maximum threshold. The maximum mean density of eggs per spawning bed was 32.1 eggs·m^2 pre-restoration (2004) and 66.8 eggs·m^2 post restoration (2009). Given the low egg densities relative to the threshold at which a higher embryonic mortality rate is likely to occur from the literature (Khoroshko and Vlasenko 1970; Dumont et al. 2011), it is unclear why egg density was stated as a concern at the Ouareau site.

The total suitable areas for spawning lake sturgeon are presented in Figures 2.5 and 2.6. Suitable habitat was predominantly located outside of the documented natural and artificial spawning sites for all discharges, with around 60% of the suitable area (Fig. 2.6). The artificial sites contributed a mean of 8.8% ($CI^{95\%}$ = 4.8%) of suitable habitat across all discharges (min = 2.6% at 87 $m^3 \cdot s^{-1}$, max = 13.7% at 38 $m^3 \cdot s^{-1}$). The natural island site had the most suitable area at discharges of 38 $m^3 \cdot s^{-1}$ and 55 $m^3 \cdot s^{-1}$, followed by the natural upstream, artificial upstream and artificial downstream spawning zones. At discharges of 69 $m^3 \cdot s^{-1}$ and 87 $m^3 \cdot s^{-1}$ the natural upstream site had the most suitable area, followed by the natural island site and artificial downstream site. There was no suitable habitat within the artificial upstream site for the two higher discharges.

In terms of habitat quality, the natural upstream site had the highest mean HSI value for all discharges, followed by the natural island site (Fig. 2.7). Notably, the mean conditions at the artificial sites were only considered suitable at the 55 $m^3 \cdot s^{-1}$ discharge, while the natural sites were suitable for all discharges with the exception of the natural island site at 87 $m^3 \cdot s^{-1}$.

Hypothesis 2 – Headward erosion degraded the spawning area

The reports provided by the engineering consulting firm did not provide any evidence that processes causing headward erosion have occurred within the Ouareau system, or that a knick point was present. The only material consulted to establish bed changes was the aerial photograph from 1964 (Beaulieu and Bélanger 2005), which does not provide information about the longitudinal profile of the bed of the river. It is therefore unclear why headward erosion was used to justify the installation of the sills.

Hypothesis 3 – Fluctuating water levels from dam activity

The concern over dam activity causing flows to be insufficient for spawning lake sturgeon has been observed for many other fish species, and an agreement to maintain ecological flows is an effective manner of addressing the problem (Richter and Thomas 2007). However, the sills at the Ouareau site are not the appropriate design to maintain water levels over the spawning area. This was recognized in pre-construction reports (Beaulieu and Bélanger 2005), where it was stated that the sills have a minimal effect on water levels, no more than 30 cm, and that their purpose is to resist headward erosion. However, in subsequent documents there is no mention of headward erosion, and the role the sills play at creating a backwater effect is emphasized and stated as their purpose (Chagnon et al. Dumas 2007; Beaulieu 2010).

Sill design

An investigation into the criteria used to design the sills revealed that the discharge used by the engineering consultant firm at the Ouareau site, which served both as a boundary condition in the HEC 2 model and in flood recurrence calculations, was incorrectly considered equivalent to that of the upstream CEHQ gauging station. Using these data, the 100-year flood was estimated at 332.5 $m^3 \cdot s^{-1}$, which was set as the maximum discharge the sills were designed to withstand. However, because the Rouge River, which drains an area of 328 km^2 (26% of the drainage area at the Ouareau site, Fig. 2.2) was not taken into account, the discharge at the spawning sites was underestimated. Therefore, the 332.5 $m^3 \cdot s^{-1}$ flood has in reality a recurrence interval of 6 years instead of 100 years at the site. Since the installation of the sills in 2007, this flood threshold has already been exceeded four times.

An additional issue, presented in an independent geomorphological assessment of the site after construction and in the literature, is that fine material accumulates upstream of sills (Bariteau et al. 2008; Salant et al. 2012). This is of concern since the artificial reefs were installed immediately upstream of the sills, and since the accumulation of fine sediment in the interstitial space of substrate is known to be detrimental to spawning lake sturgeon (Johnson et al. 2006; Manny et al. 2015). Moreover, the accumulation of fine sediment from the landslide at the traditional site was the original point of concern at the Ouareau site. The biological reviews of the project since the sill construction confirm that the degree of sedimentation at the artificial sites is higher than at natural sites (Gauthier 2014), confirming that sediment is accumulating upstream of the structures.

Sill Performance

The longitudinal water surface profile from the hydrodynamic model did not differ significantly between conditions with and without the sills at 38 $m^3 \cdot s^{-1}$ (paired t-test: $t_{43} = 1$, $p = 0.323$). Our results differ from those in Beaulieu (2010), which described water surface elevations at four discharges (equivalent to 18.9, 37.8, 50.4 and 126 $m^3 \cdot s^{-1}$ after compensating for the Rouge River) and for conditions prior to (unknown date) and after sill construction (2010, Fig. 2.8). To determine these elevations, the following formula was used (Lencastre 1969):

$h = (\frac{Q}{\mu\sqrt{2gl}})^{2/3}$ where: h = head on the weir (m), Q = discharge, μ = discharge coefficient (~0.385), g = gravitational constant (9.81 $m \cdot s^2$) and l = sill length

This formula is meant to be used for a free flow situation, with critical flow depth above the sill, whereas in reality the sills are submerged. Critical flow depth occurs when the Froude number (($Fr = V / (g\,D)^{0.5}$, where V is mean velocity and D is flow depth)) is equal to one (Akan 2011). In this instance, flow was subcritical ($Fr = 0.62$). Using this formula, it was reported that water levels were raised by 0.8 m upstream of sill 1 for all discharges. In contrast, the maximum difference in water surface elevation between the sill and no-sill situations predicted by the 3D model along the longitudinal profile was less than 0.06 m (Fig. 2.8). Upstream of sill 2, water levels were also reported as higher with sills installed, but the increase varied depending on the discharge (ranging from 0.35 m at 18.9 $m^3 \cdot s^{-1}$ to 0.55 m at 50.4 $m^3 \cdot s^{-1}$ and 126 $m^3 \cdot s^{-1}$). This variation in the effect of the two weirs with a change in discharge, and the subsequent inconsistent water surface slopes, are not acknowledged in the report. These results are also contrary to the expectation that the slope of the water surface over the same reach would remain approximately equal as discharge increases. Moreover, the reported water surface elevation data at 18.9 $m^3 \cdot s^{-1}$ is actually lower than the river bed elevation. This is clearly incorrect since field observations, even at very low discharge (<10 $m^3 \cdot s^{-1}$) revealed that water was present at all times in this area.

For all discharges, the differences in velocity (Fig. 2.9) and depth (Fig. 2.10) between the sill and no-sill situation were minimal. The natural upstream site shows the largest change in velocity and depth with sills installed, largely as a result of the removal of rip-rap at the edge of sill 1 during grid creation for simulations without sills. A paired t-test showed that the differences were statistically significant for depth and velocity at all sites and for all discharges. However, the cumulative mean difference in velocity at spawning sites across all discharges was only 0.05 $m \cdot s^{-1}$ ($CI^{95\%} = 0.01$), and the cumulative mean difference in depth was only 0.02 m ($CI^{95\%} = 0.02$). The impact on spawning lake sturgeon would therefore be barely perceptible.

Discussion

The use of heavy machinery and hard engineering solutions to reconstruct channel form are often the first step to address concerns with fish habitat, in spite of many failures and growing consensus to shift away from these methods as an initial response to perturbations (Palmer et al. 2014). Roni et al. (2002) suggests that the prioritization of stream habitat restorations should be first, to protect habitat, second, to connect habitat, third, to restore habitat forming processes and fourth, to create or enhance habitat. When human intervention is necessary to create or enhance habitat, it is critical that thorough management protocols are adhered to, and allow for multi-disciplinary and multi-stakeholder input and review (Kondolf and Micheli 1995; Manny et al. 2015). Through the comparison of a project which lacked an adaptive management protocol and one which adopted it, valuable insight can be gained into its merit.

The St. Clair-Detroit River restoration was instigated by the need to address anthropogenic disturbance from dredging and the excavation of coarse substrates (Manny et al. 2015). The project benefitted from a thorough assessment of the affected species in the system, the establishment of a clear hypothesis, the insights of a multi-disciplinary committee, and the use of an iterative process with feedback and adjustment opportunities. As a result, the project identified areas which lacked adequate spawning habitat resulting from anthropogenic disturbances, and created habitat which is being used by the target species (Manny et al. 2015). In contrast, the Ouareau site experienced a natural disturbance ubiquitous to watersheds flowing through Champlain Sea quick clays such as the Ouareau (Levy et al. 2012), and within the site itself as shown by landslide scars in the valley (Bariteau et al. 2008). The Ouareau restoration did not conduct a thorough assessment of lake sturgeon spawning habitat in the system, and established a maximum egg density threshold five times lower than what was used at other sites (Dumont et al. 2011), without offering any science based justification for the decision. Even with this low threshold, the limit was only surpassed in 0.27% of sampling efforts. Yet, the belief that an augmentation of suitable habitat was necessary persisted.

With regard to hypothesis development, the goal to increase the spawning habitat available to lake sturgeon within the known spawning reach didn't waiver. However, confusion over the function of the sills points to a problem in scientific pre-assessment, consensus building and communication, with the structures initially stated as a means to resist headward erosion (Beaulieu and Bélanger 2005) and later as a means to maintain water levels (Chagnon and Dumas 2007; Beaulieu 2010). Our evaluation of the decision making process guiding this choice has shown that the necessity of sills was conceived with no clear evidence of headward erosion, and that these structures are not designed to create a relevant backwater effect (Beaulieu and Bélanger 2005; Sear et al. 2010). Indeed, our study confirmed that they have a negligible effect in this regard, and brings into question the manner in which they were assessed by their designers.

Because the restoration project on the Ouareau did assess conditions at the site before and after restoration, we have the opportunity for a thorough evaluation of the project, and to offer new knowledge as part of step. 7 in Manny et al.'s (2015) adaptive management protocol. It seems clear that more resources should not be invested into maintaining the sills, which required most of the $500,000 of public funds allocated to the project. These structures have never been successfully installed on rivers larger than 40 m wide, experiencing discharges larger than 300 $m^3 \cdot s^{-1}$ or velocities over 3 $m \cdot s^{-1}$ (Sear et al. 2010), all of which are exceeded at the Ouareau site. They were designed using inaccurate baseline data regarding discharge, which caused the maximum tolerable floods for the sills to occur every six years rather than every 100 years. Both sills are accumulating sediment upstream, a process detrimental to the artificial reefs at the site and to the effectiveness of maintaining water levels by the sills, and the downstream sill is rapidly degrading. Most importantly, these sills do not provide any benefits to the spawning area, and are therefore best left to degrade. For the artificial spawning reefs at the site, there is no clear need to restore them or create more. They were installed in locations which will accumulate sediment, a critical factor for lake sturgeon spawning habitat, and experience average velocities above the suitable range for lake sturgeon, therefore any maintenance on the structures would be futile as a long-term solution. It was also not clear that the creation of artificial spawning sites was needed since there are extensive areas with suitable habitat (Figs. 2.5 and 2.6). Before making decisions about creating artificial sites in other locations, it is necessary to conduct a more thorough search for spawning habitat in the system. There are many methods to conduct such a study, including adapting the HSI from Chapter 1 to build a river scale model, or to use telemetry, an increasingly popular and effective method for identifying spawning habitat (Lapointe et al. 2013; Thiem et al. 2013).

Conclusion

As experts are expressing concern over "privately produced science" dominating the field of stream restoration (Lave et al. 2010; Palmer et al. 2014), it is important that the organizations which hire contractors for a restoration project have the ability to independently review the science behind a project proposal. The St. Clair-Detroit River project had multi-disciplinary insight from within the committee, however in the case of the Ouareau project, the committee from within the organization which contracted out the restoration had an expertise in biology, but no geomorphologists or hydrologists with the training to analyze the instream structure design. The problem regarding the purpose of the sill structures can likely be attributed to this communication breakdown. Such problems will persist until a management protocol is adopted for all restoration projects, including a requirement for multi-disciplinary insights into aquatic habitat issues with a team consisting of engineers, biologists, and hydrogeomorphologists. Additionally, this study has shown how using a 2D or 3D numerical modelling approach prior to the implementation stages could greatly help reducing the cost of a restoration project. Modelling results would also have served to adjust hypotheses, for example concerning the impact of the sills on water levels, which were overestimated by restoration designers. It might even have revealed at the onset that this restoration project was unnecessary given the sufficient quantity of suitable habitat at the Ouareau spawning site.

Tables

Table 2.1. Weights used in the sensitivity analysis for the fuzzy analysis (WLC) of suitable habitat

Factor	Series 1	Series 2	Series 3	Series 4
Velocity	0.45	0.50	0.40	0.40
Substrate	0.45	0.40	0.50	0.40
Depth	0.10	0.10	0.10	0.20

Table 2.2. Summary of mean ($\Delta\ \bar{x}$) and maximum (Δ Max) differences with the 95% confidence interval (CI $\Delta\ \bar{x}$) between velocity and depth with and without sills, where (%) means percent of mean flow depth.

Discharge ($m^3 \cdot s^{-1}$)		**38**			**69**	
Velocity ($m \cdot s^{-1}$)	**$\Delta\ \bar{x}$**	**CI $\Delta\ \bar{x}$**	**Δ Max**	**$\Delta\ \bar{x}$**	**CI $\Delta\ \bar{x}$**	**Δ Max**
Nat. Upstream	0.17	0.03	0.83	0.18	0.04	1.56
Nat. Island	0.02	0.01	0.31	0.02	0.01	0.23
Art. Upstream	0.01	0.00	0.11	0.02	0.00	0.11
Art. Downstream	0.00	0.01	0.25	0.02	0.00	0.06
Depth (m)	**$\Delta\ \bar{x}$ (%)**	**CI $\Delta\ \bar{x}$ (%)**	**Δ Max (%)**	**$\Delta\ \bar{x}$ (%)**	**CI $\Delta\ \bar{x}$ (%)**	**Δ Max (%)**
Nat. Upstream	0.06 (8)	0.01 (1)	0.23 (33)	0.06 (6)	0.01 (1)	0.27 (30)
Nat. Island	0.00 (0)	0.00 (0)	0.03 (6)	0.00 (0)	0.00 (0)	0.02 (2)
Art. upstream	0.01 (3)	0.00 (0)	0.05 (14)	0.02 (4)	0.00 (0)	0.06 (12)
Art. Downstream	0.00 (0)	0.00 (0)	0.03 (1)	0.00 (0)	0.00 (0)	0.00 (0)

Figures

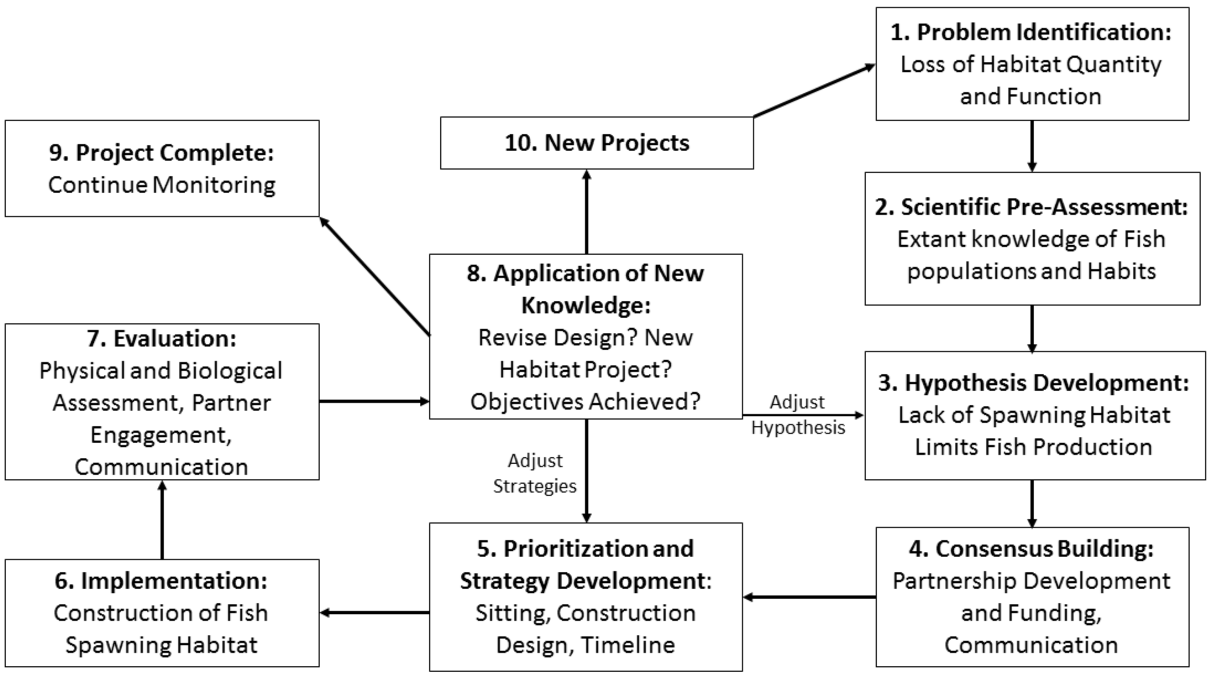

Figure 2.1. Adaptive Management protocol for the restoration of spawning habitat (adapted from Manny et al. 2015).

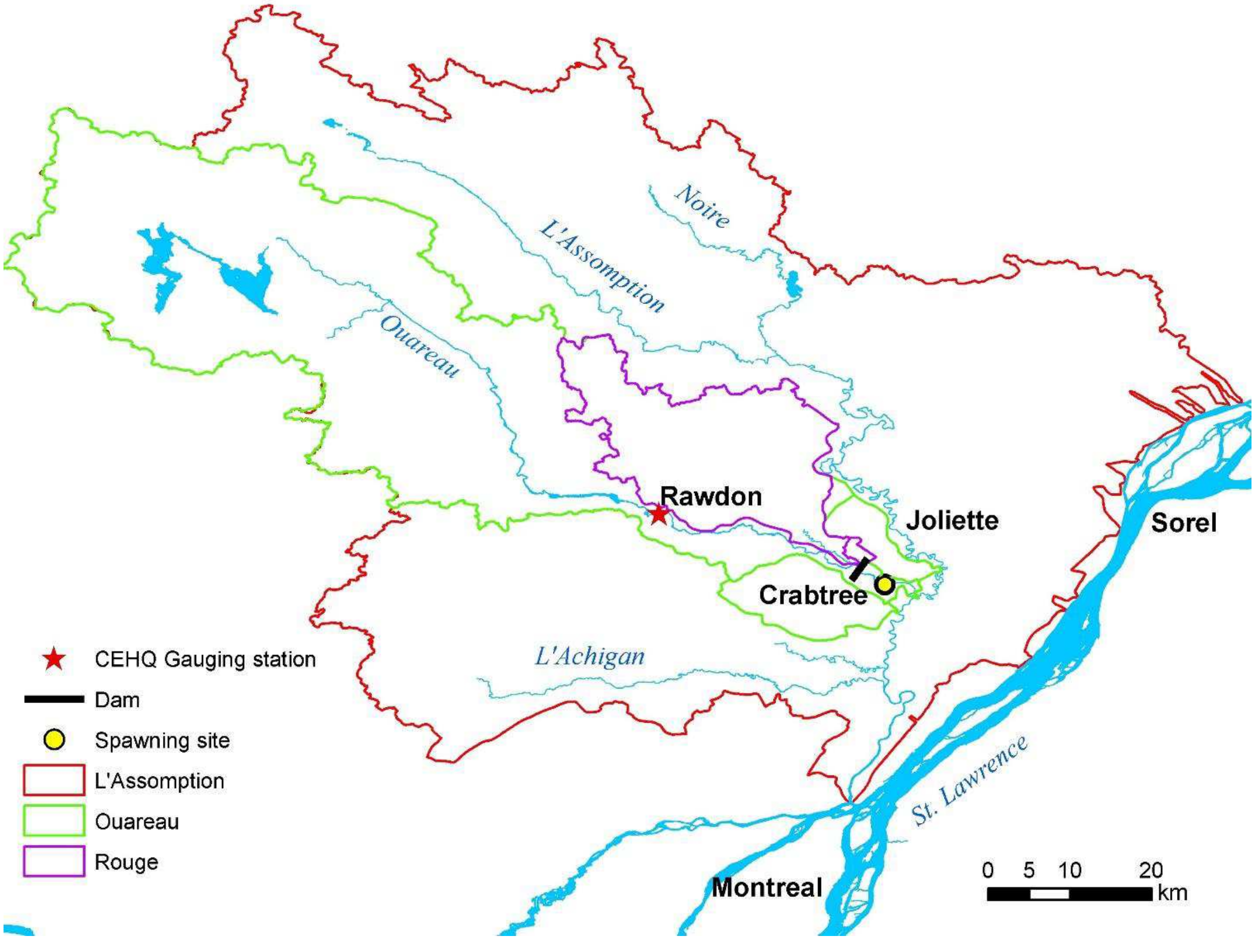

Figure 2.2. Watershed limits of the Ouareau River, a tributary of the L'Assomption River, also indicating the Rouge River subwatershed and the spawning site restoration project downstream of the dam in Crabtree. The gauging station (Centre d'Expertise Hydrique du Québec, CEHQ, ID 052212) is located upstream of the confluence with the Rouge River (red star).

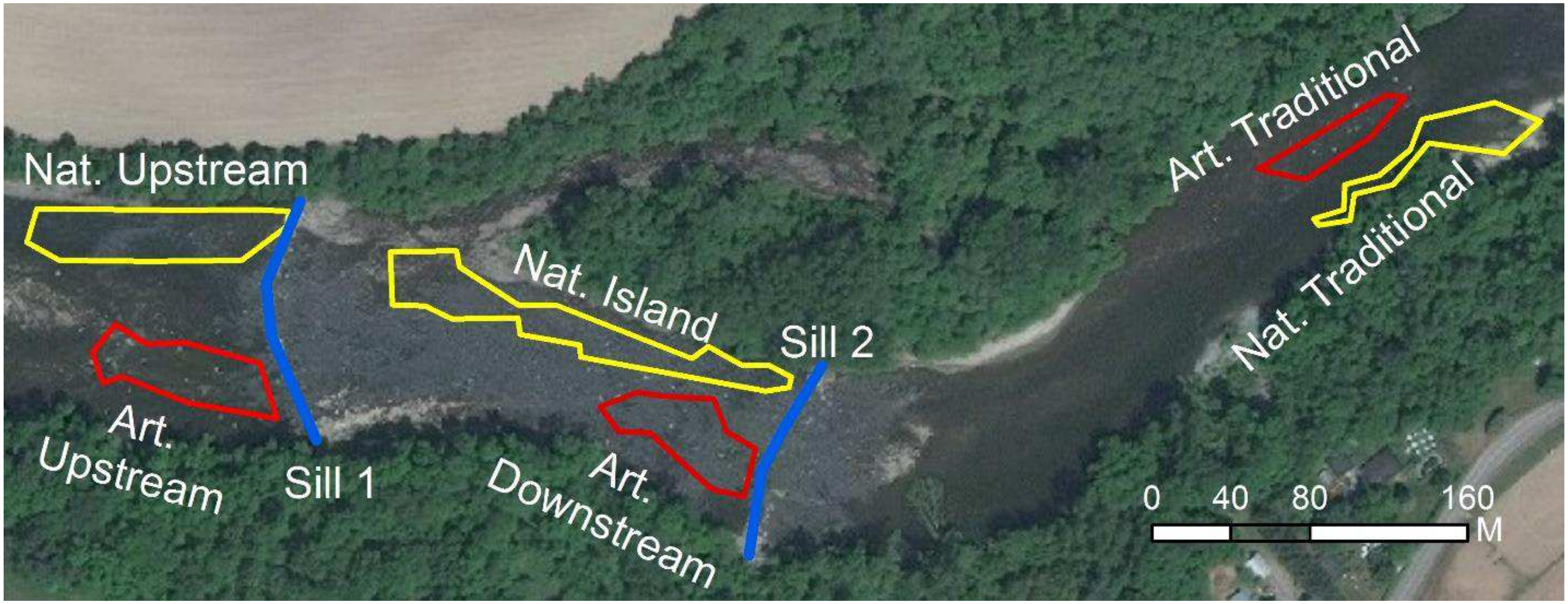

Figure 2.3. Ouareau River with artificial (red) and natural (yellow) spawning sites. This study focuses on the section including the two sills, and does not include the two downstream spawning sites.

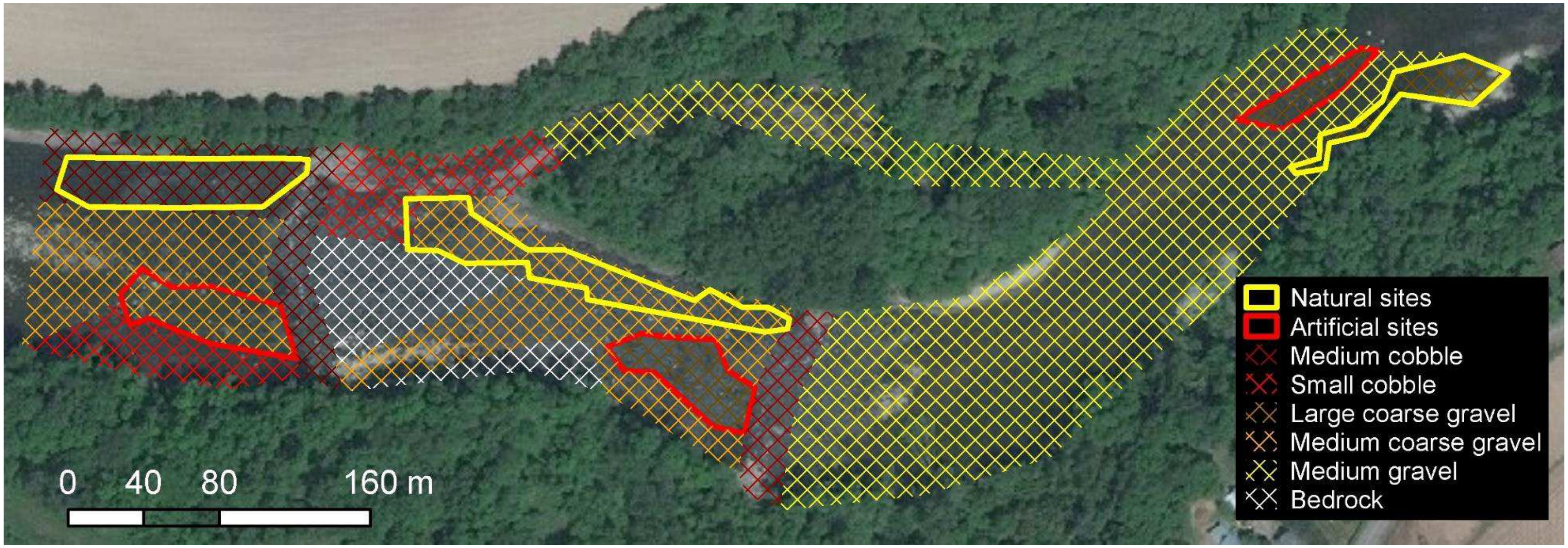

Figure 2.4. Substrate size, classified using the Wentworth scale (1922) at the Ouareau study site.

Figure 2.5. Results for the fuzzy habitat suitability model for lake sturgeon spawning at discharges of A. 38 m3/s, B. 55 m3/s, C. 69 m3/s and D. 87 m3/s.

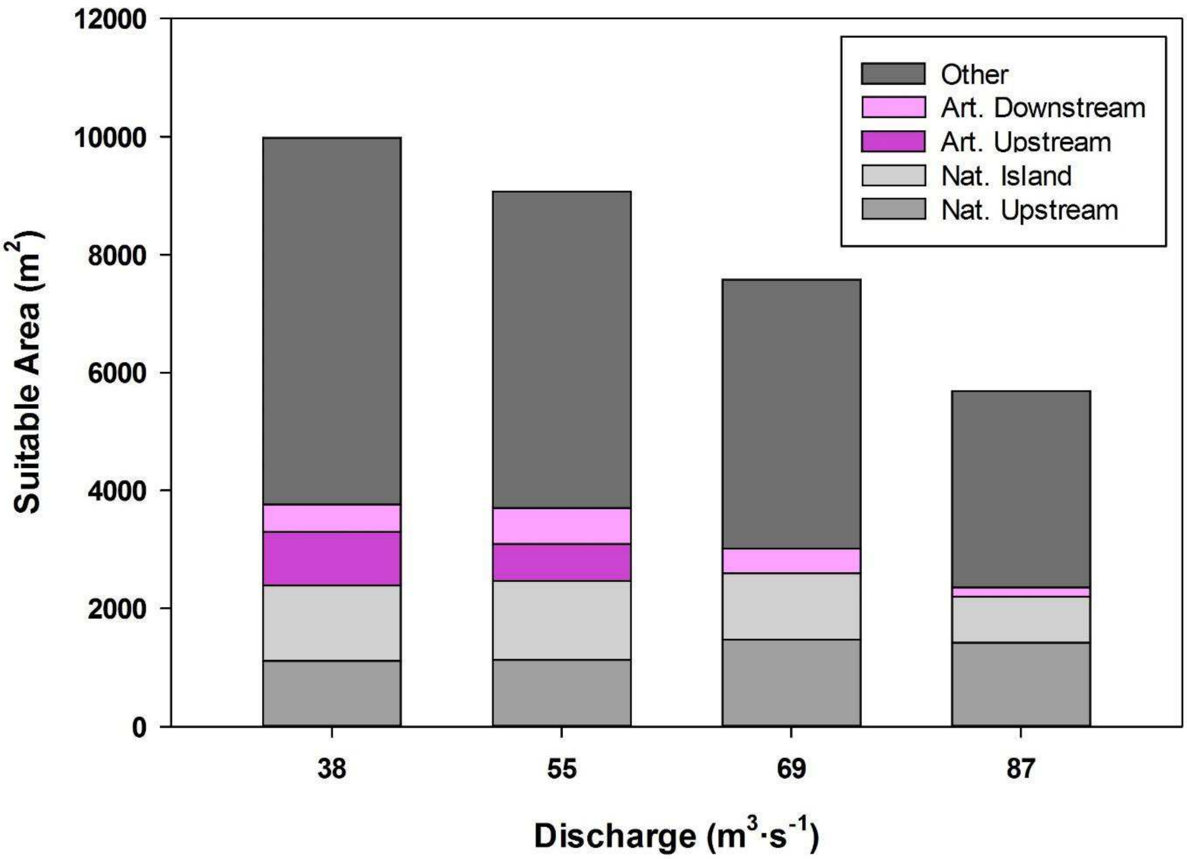

Figure 2.6. The post restoration amount of suitable spawning area (m^2) within and outside known spawning sites within the Ouareau spawning area for lake four representative discharges.

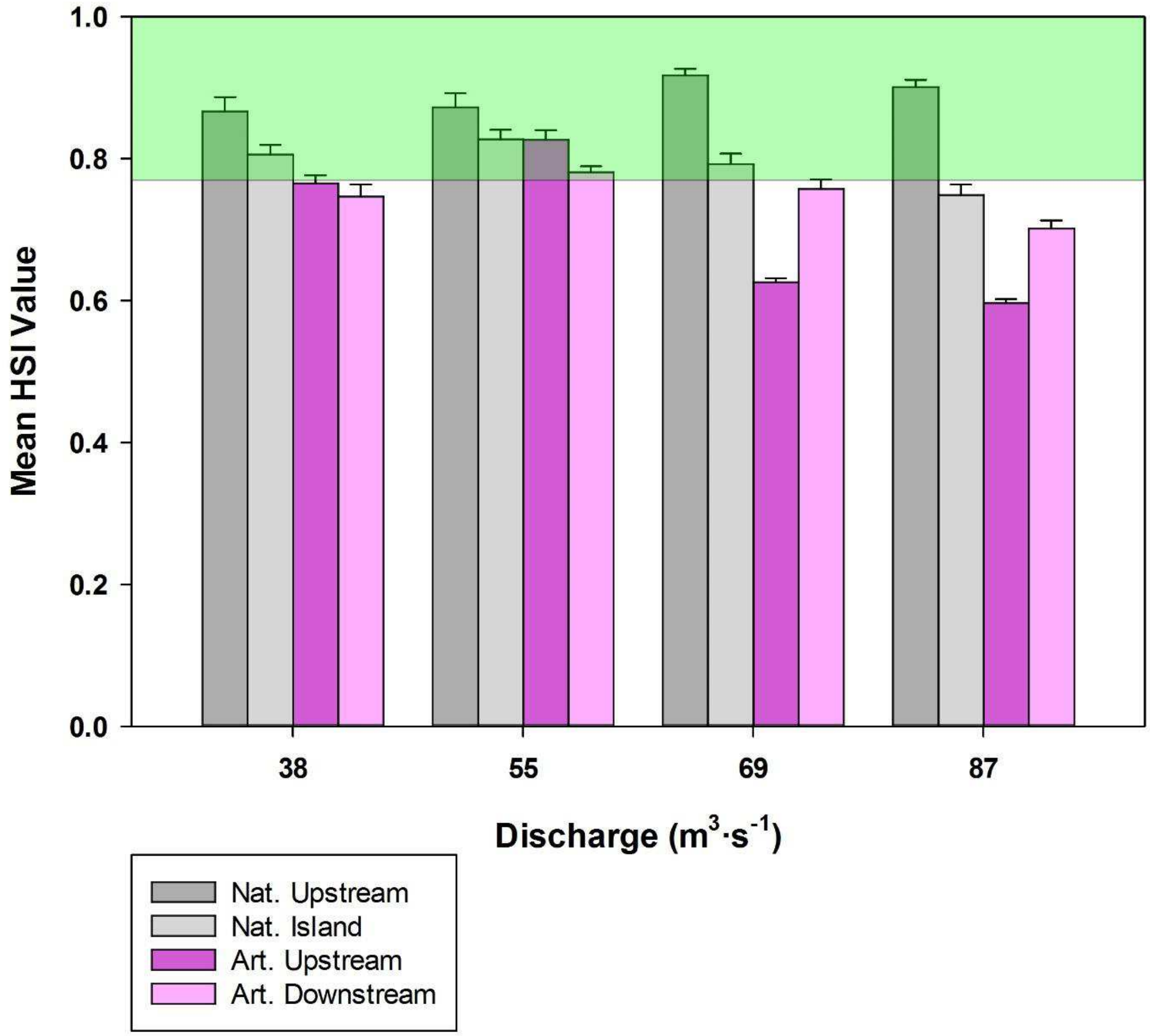

Figure 2.7. Mean habitat suitability index score for documented spawning sites on the Ouareau River. The green zone represents HSI values above the minimum threshold.

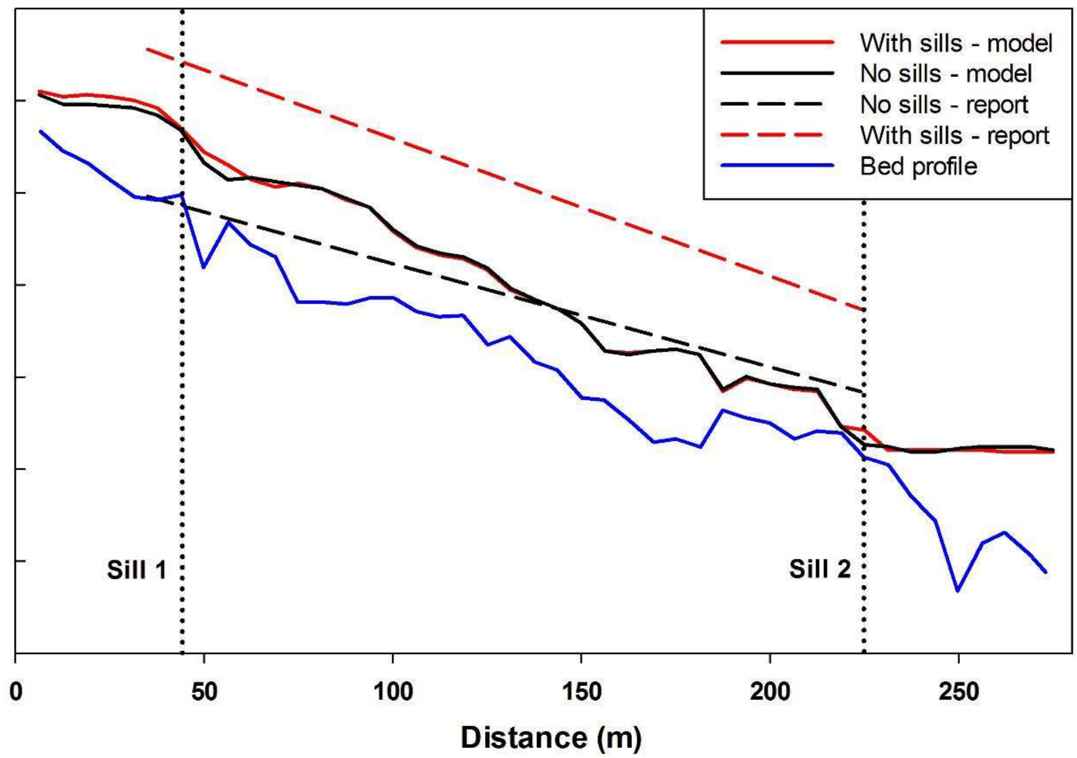

Figure 2.8. Ouareau longitudinal profile for conditions with and without sills at 38 m^3/s for water surface elevation from the hydrodynamic model, the Beaulieu report (2011), and bed elevation from the longitudinal bed profile (Beaulieu 2005).

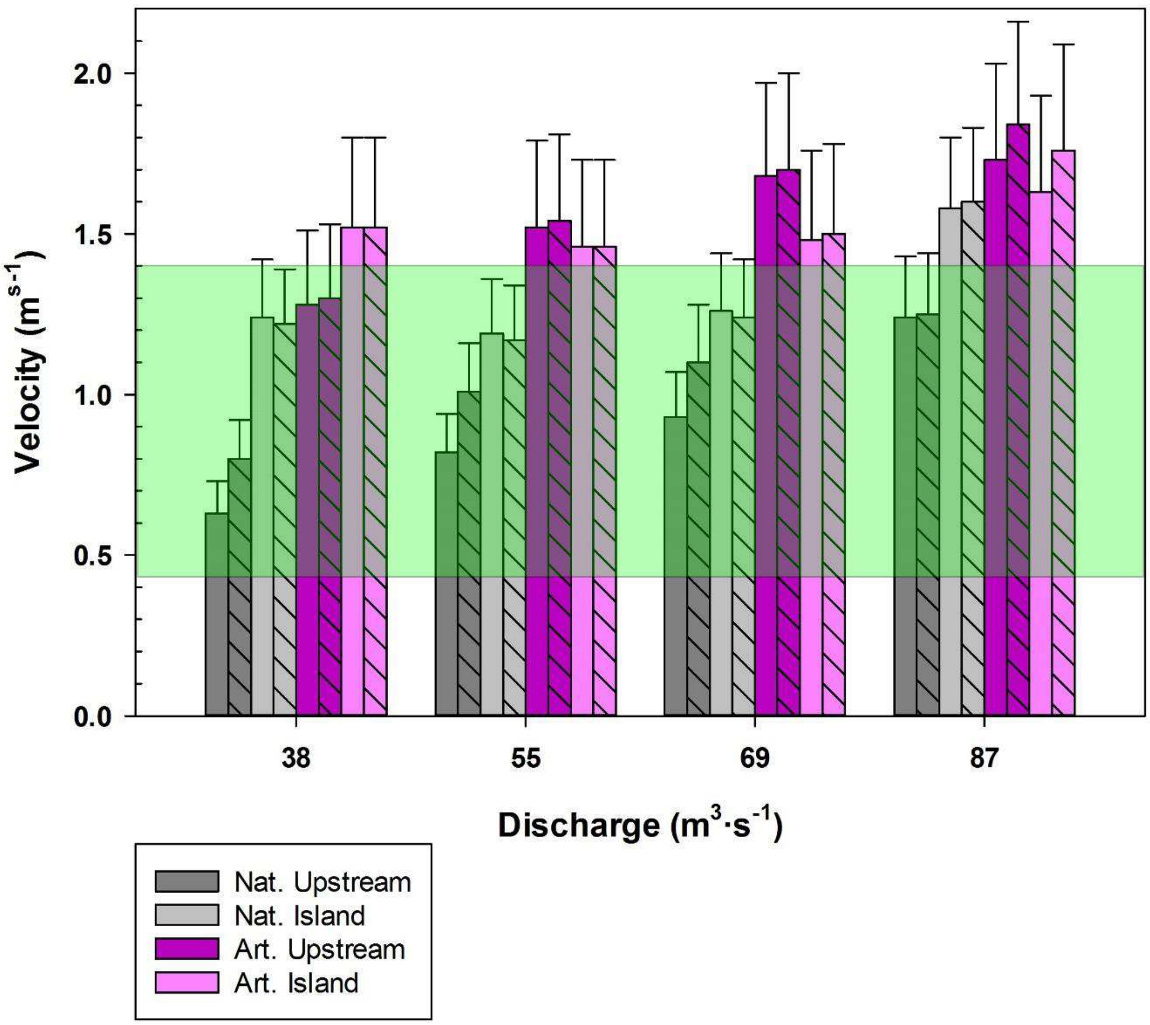

Figure 2.9. Depth-averaged velocity at the Ouareau spawning sites with (solid colour) and without (hatched) sills. The mean range of depth-averaged velocity from habitat suitability index is indicated in green fill for four discharges known to occur during spawning.

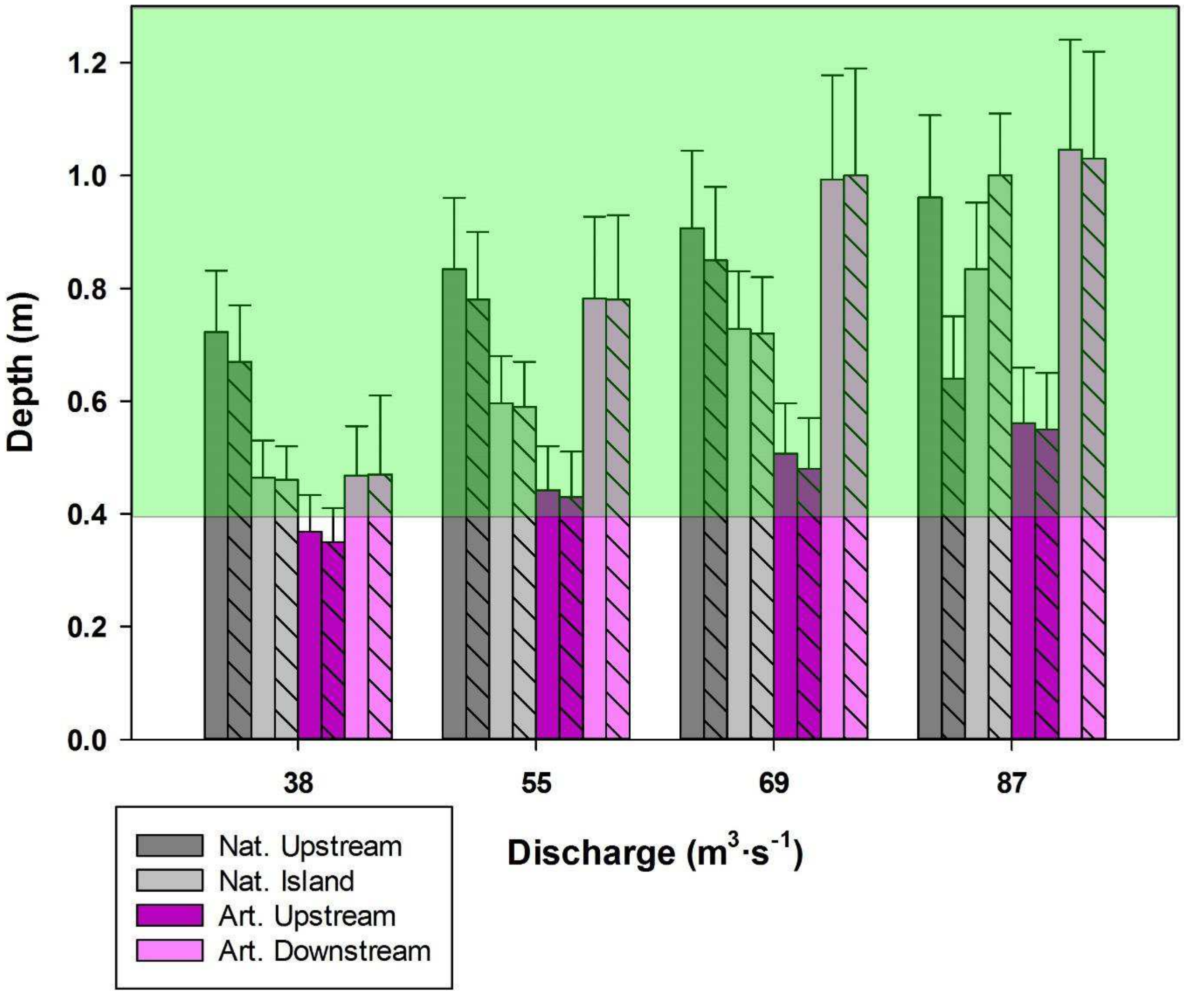

Figure 2.10. Depth at the Ouareau River spawning sites for conditions with (solid colour) and without (hatched) sills. The mean range of depth from habitat suitability index is indicated with the green fill for four discharges known to occur during spawning.

General Conclusions

Based on the persistence of the species through geologic time and the large and diverse range it occupies in North America, it is clear that lake sturgeon are a resilient and adaptive species (Secor et al. 2002). Interestingly, in spite of spawning in rivers ranging from the largest on the continent (Mississippi) to tributaries with annual average discharges below 15 $m^3 \cdot s^{-1}$ (Yellow), the habitat conditions in which they spawn are consistently similar, with some small, intuitive, exceptions; water temperature at which spawning occurs, which tends to decrease as latitude increases; and the differences in the depths of spawning sites between large (>100 $m^3 \cdot s^{-1}$) or small (< 100 $m^3 \cdot s^{-1}$) rivers. While this does not mean that lake sturgeon population recovery programs targeting critical reproductive habitat can take a one size fits all approach, it does allow for the implementation of the general knowledge in Chapter 1 to locate potential habitat for protection. To address local concerns over the loss of spawning habitat, it is important to understand the environmental, human and biological context causing the perceived loss of habitat, and assess the state of not just a specific site, but that of all of the basin wide system (Palmer et al. 2005). By using an AMP, ensuring inter-disciplinary collaboration, and adopting tools such as habitat suitability or 2D or 3D hydrodynamic modelling, restoration plans can take into account issues which extend beyond the scale of the specific site and the limits of one scientific field. Moreover, by undertaking thorough pre-restoration assessments, the limited funds available to restoring or augmenting habitat can be allocated more responsibly, allowing for a greater impact on threatened or endangered species which need protection. We therefore recommend rigorous scientific AMPs being in place to guide restoration decisions, and stress the need for inter-disciplinary participation in planning for and implementing habitat restoration projects, including hydrogeomorphology. In particular, the impact on flow dynamics and habitat of instream structures such as the sills used in the Ouareau

River project should be thoroughly examined prior to their implementation based on the biological, hydrogeomorphological and engineering scientific literature. Given the lack of evidence that the costs of addition of instream structures are offset by biological recovery (Palmer et al. 2010), their use in the future should be restricted only to exceptional cases, for example with demonstrated evidence that it is the only solution for a species at risk of extinction.

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