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Potential for reintroduction of lake sturgeon in five northern Lake Michigan tributaries: a habitat suitability perspective

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ABSTRACT

1. Conservation and rehabilitation efforts for lake sturgeon *Acipenser fulvescens* throughout the Great Lakes include the re-establishment of self-sustaining stocks in systems where they have been extirpated.
2. Information on the suitability of potential lake sturgeon habitat in tributaries is important for determining their capacity to support lake sturgeon stocking and to develop system-specific rehabilitation strategies.
3. Geo-referenced habitat information characterizing substrate composition, water depth, and stream gradient were applied to a life-stage specific lake sturgeon habitat suitability index in a geographic information system to produce spatially explicit models of life-stage specific habitat characteristics in five northern Lake Michigan tributaries from which lake sturgeon have been extirpated.
4. Habitat models indicated that high quality lake sturgeon spawning and staging habitat comprised 0 to 23% and 0 to 9% of the available habitat, respectively, whereas high quality juvenile lake sturgeon habitat was relatively ubiquitous throughout each river and comprised 39 to 99%.
5. Comparison of these data to lake sturgeon habitat availability in Lake Michigan tributaries currently supporting populations indicated that spawning and staging habitats may limit the ability of these systems to support spawning. Efforts to re-establish lake sturgeon populations in these systems should consider the creation of spawning and staging habitat to increase reproductive and recruitment potential prior to the initiation of stocking efforts.

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KEY WORDS: *Acipenser fulvescens*; GIS; habitat enhancement; habitat suitability index; juvenile habitat; rehabilitation; spawning habitat; stocking

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INTRODUCTION

Lake sturgeon *Acipenser fulvescens* are an important component of the Laurentian Great Lakes fishery resource. The unique life-history characteristics of this species, including a long life span (up to 154 years), large body size (> 2 m in length), and periodic spawning strategy (males, every 1 to 3 years; females, every 4 to 6 years), represent an important component of biodiversity in the Great Lakes (Hay-Chmielewski and Whelan, 1997). Lake sturgeon were historically one of the most abundant fish species in the basin (Tody, 1974); however, water-quality degradation, overfishing, physical-habitat alteration, and the damming of spawning tributaries significantly reduced their abundance and distribution (Auer, 1999a). Despite improvements in water quality and the closure of most fisheries, many stocks have remained at remnant levels or have been extirpated. As a result, remaining populations are listed as vulnerable or threatened (Ferguson and Duckworth, 1997; Knights *et al.*, 2002).

Management and rehabilitation plans for lake sturgeon have been developed throughout the region, with the goal of maintaining and enhancing remnant populations and the re-establishment of extirpated stocks. Efforts to understand better the biology, ecology, and life-history requirements of remnant lake sturgeon stocks have been initiated throughout the Great Lakes to provide information on current stock status and the potential effects of fishery management and restoration options (Manny and Kennedy, 2002). However, little information exists in systems where lake sturgeon have been extirpated. The importance of available riverine spawning and nursery habitats to the establishment and persistence of sturgeon populations has been well documented (Buckley and Kynard, 1981; Parsley *et al.*, 1993; McCabe and Tracy, 1994; Williot *et al.*, 1997; Paragamian *et al.*, 2001), and is considered one of the major factors limiting the abundance and recovery of lake sturgeon in the Great Lakes (Auer, 1999b). The results of these studies suggest that information on habitat characteristics in tributaries in which stocking efforts will be required to re-establish spawning populations is a critical component in determining the capacity of a system to support lake sturgeon. Therefore, the objectives of this study were to describe the quantity, quality, and spatial distribution of riverine habitats for staging adult, spawning adult, and larval and age-0 juvenile life stages of lake sturgeon in five northern Lake Michigan tributaries. Lake sturgeon are currently not found in these systems, and restoration objectives in Lake Michigan include the re-establishment of spawning populations in these and other Great Lakes tributaries (Hay-Chmielewski and Whelan, 1997; Wisconsin Department of Natural Resources (WDNR), 2004). The results of this research will be used to provide recommendations on rehabilitation strategies for lake sturgeon in these systems and guide restoration efforts in other tributaries throughout the Great Lakes.

METHODS

Field data collections

Habitat assessments were conducted in the Pensaukee, Suamico, and Little Suamico rivers, and Duck Creek, Wisconsin, and the Ford River, Michigan, from June to August 2004 and 2005 (Figure 1). These tributaries have been identified as potential candidate systems for lake sturgeon stocking efforts in the Lake Michigan basin. Because no remnant lake sturgeon populations or historical records of spawning locations in these systems exist (P. Cochran, St. Mary's University, personal communication), each tributary was sampled in an upstream direction beginning at the river mouth until potential spawning habitat was identified.

Characterization of stream habitats within each system was accomplished following a stratified random sampling design. Sampling reaches within each tributary were divided into generalized stream channel units (i.e. homogeneous areas of the channel that differ in depth, current velocity, and substrate characteristics

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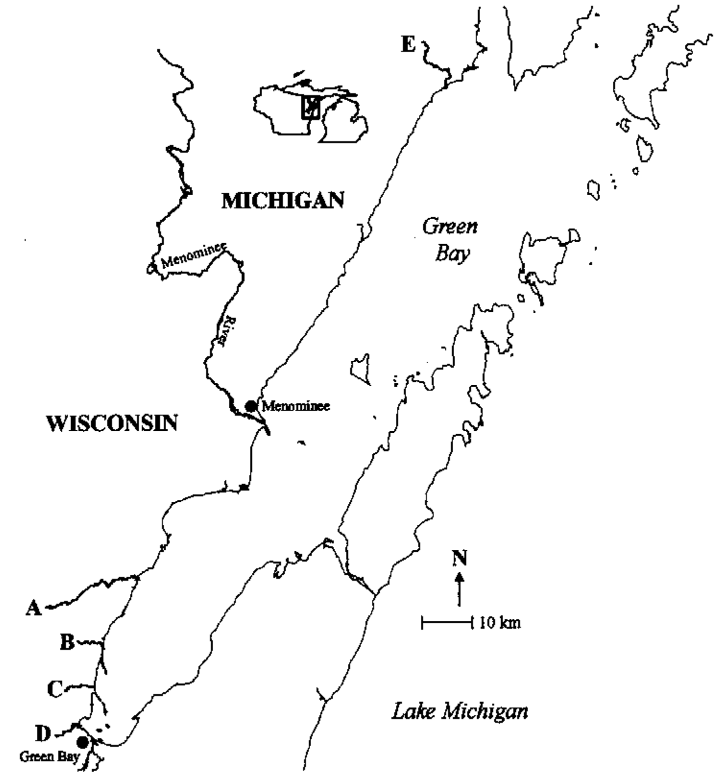

Figure 1. Map of the study region illustrating the location of each tributary. Letters correspond to each system as follows: Pensaukee River (A), Little Suamico River (B), Suamico River (C), Duck Creek (D), and Ford River (E).

from adjacent areas upstream or downstream of a given location; Armantrout, 1998). Stream channel units used in this study were based on field measures at each transect and defined as follows: runs (areas associated with water depths ranging between 0.5 and 1.0 m in depth and flow rates less than 0.3 $m\,s^{-1}$); riffles (areas with water depths less than 0.5 m and flow rates greater than 0.3 $m\,s^{-1}$); and pools (areas greater than 1.0 m in depth and flow rates less than 0.3 $m\,s^{-1}$).

Within each stream channel unit, data describing substrate composition, water depth, and water velocity were collected from three equidistantly spaced channel segments (left, middle, and right channel) located across randomly spaced transects perpendicular to the stream flow. Additional point samples were collected along transects delineating the upstream and downstream boundaries of each channel segment. Because run habitats typically comprise most of the available habitat in low-velocity streams (Hynes, 1970), transects were spaced at random intervals between 100 and 200 m. Pool and riffle channel units represented by shorter stream reaches were sampled at 10 to 50 m intervals in order to provide more detailed characterization of these habitat types. At each sample location, latitude and longitude were recorded using a wide-angle augmentation system (WAAS) enabled global positioning system (GPS) receiver, and water depth was measured to the nearest 0.01 m using a boat-mounted sonar unit. Water velocity at each sampling location was measured to the nearest 0.01 $m\,s^{-1}$ at approximately 0.3 m above the river bottom using a mechanical flow meter (Model 2030; General Oceanics, Miami, FL). The substrate at each sampling location was determined using a 2.5 cm diameter aluminium wading pole (3 m in length) in wadeable areas as described by Hamilton and Bergersen (1984) or a petite ponar grab sampler (225 cm^2 sample area) at water depths > 1 m. Substrate type was determined based on median particle size as defined by Threader *et al.* (1998, Table 1). All habitat data were collected during baseline summer flow conditions based on US Geological Survey (USGS) gauging station mean annual discharge data.

Although water-depth and flow-rate data collected during baseline summer flow regimes accurately represent river habitats experienced by age-0 juvenile life stages of lake sturgeon, these data are not representative of conditions experienced by spawning adults. This life stage is present in rivers from March to May (Scott and Crossman, 1973; Auer, 1999a), which coincides with increased discharge levels due to freshets caused by spring snowmelt and rain events. Therefore, data collected during summer flow regimes will underestimate water depths and flow rates experienced by spawning adult lake sturgeon during spring months. Although water depth has low importance to spawning lake sturgeon (0.6 to 5 m, Scott and Crossman, 1973; up to 18 m, Threader *et al.*, 1998; up to 11 m, Caswell *et al.*, 2004), water velocity at spawning locations is an important criterion for spawning-site selection (LaHaye *et al.*, 1992). As a result, stream channel slope, a measure of the gradient of the river channel which remains constant regardless of temporal charges in discharge, was calculated as a measure of stream-flow potential. Channel gradient was estimated at each transect location using Manning's equation:

$$S = \left(\frac{U}{\left(\frac{1}{n}\right)(Rh)^{2/3}} \right)^2$$

where S is stream channel slope (m m^{-1}), U is water velocity, n is Manning's coefficient, and R_h is the hydraulic radius (in m; Chaudhry, 1993). Hydraulic radius, defined as the cross-sectional area of the stream divided by the wetted perimeter, was estimated based on stream-width and water-depth measurements recorded at each transect. Manning's coefficient, a unitless measure of streambed roughness characterizing the resistance of the channel to flow, was determined based on the dominant substrate type at each transect (Chaudhry, 1993; Table 1).

Habitat modeling

Spatially explicit models of each habitat variable were constructed using ArcGIS® 9.1 (Environmental Systems Research Institute (ESRI), Redlands, CA). A base layer delineating the river channel boundaries and features (points, islands, etc.) for each system was digitized manually as a polygon feature class using USGS 1 m resolution digital orthophoto quadrangle aerial photographs.

The geographic coordinates and associated point-sample habitat data from each tributary were plotted as point-feature classes. Raster data models for each habitat variable were then interpolated using the inverse

Table 1. Substrate particle-size statistics as reported by Threader *et al.* (1998) and Manning's *n* coefficients as reported by Chaudhry (1993) utilized in substrate and stream-channel slope interpolation models

Substrate class	Particle size range (mm)	Median particle size (mm)	Manning's *n* coefficient
Clay	—	0	0.022
Silt	< 1	0.5	0.022
Sand	1 to 2	1.5	0.022
Gravel	2.1 to 80	41.1	0.025
Cobble	81 to 250	166.5	0.035
Boulder	> 250	250	0.035
Bedrock	—	500	0.022

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distance weighted (IDW) method. For each habitat variable, the IDW interpolation was parameterized using the polygon base layer as an analysis mask and to define the analysis extent, a variable search radius with four nearest-neighbour point samples, a power of 0.5, and an output cell size of 5 m^2. A power of 0.5 was used to minimize the local influence of nearest-neighbour sampling points and create the smoothest possible raster surfaces (Bolstad, 2002). In reaches containing islands or where a highly sinuous or braided channel was present, a polyline barrier layer was created and utilized to prevent the interpolation of neighbouring points across land (Rubec *et al.*, 1999).

Lake sturgeon habitat suitability modelling

The raster data models for each habitat variable were reclassified into habitat suitability index (HSI) values for each riverine life stage of lake sturgeon (i.e. staging adult, eggs and spawning adult, and juvenile life stages) based on the suitability criteria developed by Threader *et al.* (1998, Table 2). Habitat suitability index models have not been developed for all habitat variables and lake sturgeon life stages examined in this study (i.e. stream gradient and staging adult life stage). As a result, habitat suitability criteria were developed based on a review of the available literature and scaled as defined above (Table 2).

The geometric mean of the reclassified raster data models of each habitat variable and life stage was calculated to provide a composite model of habitat suitability at each location within each study reach (Li *et al.*, 1984; Threader *et al.*, 1998; Rubec *et al.*, 1999). Because previous studies have indicated that some habitat characteristics do not appear to be limiting factors for certain life stages of lake sturgeon, not all habitat variables measured during this study were utilized to model habitat suitability for all life stages (Table 2). Cells of the composite model with a value of 0 were defined as unsuitable habitat, whereas cell values ranging between 0 and 0.79 were defined as marginal habitat (Threader *et al.*, 1998). Raster cells in the composite models with a value of 0.8 to 1 were considered to provide high-quality habitat for the respective life stage.

The resultant composite raster data models of habitat suitability for each life stage were subsequently converted to polygon feature classes. Areas within each suitability model representing unsuitable habitat were omitted from the models using a select by attribute routine (ESRI, 2005). Additional select-by-attribute and select-by-location routines were conducted on the larval and juvenile and staging adult suitability models in order to meet geometric or geographic (i.e. patch size or locational, respectively) habitat requirements as suggested by Benson *et al.* (2005) for juvenile lake sturgeon and McKinley *et al.* (1998) and Bruch and Binkowski (2002) for staging adult lake sturgeon (Table 2).

Data analyses

The life-stage specific habitat suitability models were used to determine the total availability, relative availability, and quality characteristics of lake sturgeon habitats within each system. The raster models of habitat suitability for each life stage were converted to polygon feature classes and the total area (m^2) of all habitat patches were calculated. The habitat characteristics in these systems were then compared with other Lake Michigan tributaries currently supporting lake sturgeon populations to determine the most appropriate lake sturgeon restoration strategy in each system.

RESULTS

Pensaukee River

A total of 1220 habitat samples were collected from the Pensaukee River during June 2005 (Table 3). Models of spawning habitat indicated that high quality lake sturgeon spawning habitat did not exist in the

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Table 2. Input values for the identification of optimal, marginal, and unsuitable habitats for riverine life stages of lake sturgeon

Life stage	Habitat variable	Suitability index value	Source
Egg/Spawning adult			
	Substrate type		
	Clay	0	Threader *et al.* (1998)
	Silt	0	Threader *et al.* (1998)
	Sand	0	Adapted from Threader *et al.* (1998)
	Gravel	0.5	Threader *et al.* (1998)
	Cobble	1	Threader *et al.* (1998)
	Boulder	1	Threader *et al.* (1998)
	Bedrock	0.3	Threader *et al.* (1998)
	Stream gradient (m km^{-1})		
	>1.0	1	Hay-Chmielewski and Whelan (1997)
	0.6 to 1.0	1	Hay-Chmielewski and Whelan (1997)
	0.3 to 0.59	0.5	Hay-Chmielewski and Whelan (1997)
	<0.3	0	Hay-Chmielewski and Whelan (1997)
Staging adult			
	Water Depth (m)		
	<2.0	0	Bruch and Binkowski (2002)
	>2.0	1	McKinley *et al.* (1998); Bruch and Binkowski (2002)
	Geographic constraint		
	<3 km from potential spawning habitat	1	Bruch and Binkowski (2002)
	>3 km from potential spawning habitat	0	Bruch and Binkowski (2002)
Larval/juvenile			
	Substrate type		
	Clay	0.2	Threader *et al.* (1998)
	Silt	1	Threader *et al.* (1998)
	Sand	1	Threader *et al.* (1998)
	Gravel	1	Threader *et al.* (1998)
	Cobble	0.8	Threader *et al.* (1998)
	Boulder	0.5	Threader *et al.* (1998)
	Bedrock	0.2	Threader *et al.* (1998)
	Stream gradient (m km^{-1})		
	>1.0	0	Benson *et al.* (2005)
	0.6 to 1.0	1	Benson *et al.* (2005)
	0.3 to 0.59	0.9	Benson *et al.* (2005)
	<0.3	0.5	Benson *et al.* (2005)
	Water Depth (m)		
	<0.5	0	Threader *et al.* (1998)
	0.5 to 1.9	0.8	Threader *et al.* (1998)
	2.0 to 4.0	0.9	Threader *et al.* (1998)
	4.1 to 7.9	1	Threader *et al.* (1998)
	8.0 to 14.0	0.5	Threader *et al.* (1998)
	>14.0	0	Threader *et al.* (1998)
	Geographic constraint <0.5 rkm of contiguous habitat	1	Benson *et al.* (2005)
	>0.5 rkm from contiguous habitat	0.9	Benson *et al.* (2005)

Table 3. Summary statistics of habitat samples collected in each river June to August 2005

River	Reach length (km)	Number of point samples
Pensaukee	26	1220
Little Suamico	20.1	320
Suamico	17.9	318
Duck Creek	5	202
Ford	25.6	626

Table 4. Summary statistics of high-quality lake sturgeon habitat in each river

Habitat type	River	Habitat (m^2)	Availability (%)
Spawning	Pensaukee	0	0
	Little Suamico	2321	0.6
	Suamico	0	0
	Duck Creek	18 839	3.2
	Ford	211 923	22.9
Staging	Pensaukee	0	0
	Little Suamico	0	0
	Suamico	19 866	8.9
	Duck Creek	0	0
	Ford	0	0
Juvenile	Pensaukee	300 488	44.8
	Little Suamico	154 100	63.3
	Suamico	174 516	77.8
	Duck Creek	572 917	99.8
	Ford	340 449	36.7

study reach. However, 91% of the river was classified as marginal (poor to good) spawning habitat. Staging habitat was also not found in the study reach (Table 4). Analyses of models characterizing juvenile lake sturgeon habitat indicated that 45% of the Pensaukee River provided high quality habitat (Table 4).

Little Suamico River

Analysis of 320 habitat samples collected from the Little Suamico River during July 2005 indicated that high quality lake sturgeon spawning habitat is limited and accounted for less than 1% of the study reach (Table 4). However, marginal spawning habitat comprised 35% of the available lake sturgeon habitat. Similar to the results of staging habitat models in the Pensaukee River, no suitable staging habitat existed in the study reach. Models of juvenile habitat suitability indicated that a large proportion (63%) of the study reach provides high quality juvenile lake sturgeon habitat.

Suamico River

Habitat models constructed based on the collection of 318 habitat samples from the Suamico River during July 2005 did not identify the presence of high quality spawning habitat (Table 4). However, 24% of the study reach was classified as marginal spawning habitat. Staging habitat associated with potential spawning habitats accounted for 9% of the available habitat (Table 4). Similar to the juvenile habitat suitability models constructed for the other rivers examined in this study, high quality juvenile habitat was relatively ubiquitous throughout the study reach and comprised 78% of the available habitat (Table 4).

Duck Creek

Habitat suitability models of Duck Creek were constructed based on 202 habitat samples collected during June 2005 (Table 3). High quality spawning habitat accounted for approximately 3% of the total habitat available in the study reach (Table 4). Staging areas associated with the potential lake sturgeon spawning habitat were not identified in the habitat suitability model. Analysis of juvenile lake sturgeon habitat indicated that highly suitable habitat is ubiquitous throughout the study reach, with greater than 99% of the available habitat classified as high quality juvenile habitat (Table 4).

Ford River

A total of 626 habitat samples were collected from the Ford River during August 2005 (Table 3). In contrast to the other systems examined in this study, high quality spawning habitat comprised a large proportion (23%) of the available habitat. An additional 45% of the available habitat was classified as marginal spawning habitat. However, the presence of staging habitats associated with the potential spawning areas was not identified in the study reach. High quality juvenile lake sturgeon habitat comprised 37% of the available habitat (Table 4).

DISCUSSION

A long-term goal of lake sturgeon rehabilitation in the Great Lakes includes the establishment of self-sustaining spawning populations throughout the basin (Holey *et al.*, 2000). Natural reproduction must occur for a population to be self-sustaining, which is dependent on successful spawning. Because lake sturgeon exhibit slow growth, late age-at-reproductive maturity, a periodic spawning strategy, and high spawning-site fidelity to their natal stream, natural recolonization of lake sturgeon populations in systems with extirpated populations may require centuries (Schram *et al.*, 1999). As a result, lake sturgeon management plans for the Lake Michigan basin include the development of stocking programmes to accelerate or initiate the establishment of spawning populations (Hay-Chmielewski and Whelan, 1997; WDNR, 2004). However, tributaries in which lake sturgeon are stocked must provide adequate, high-quality juvenile habitat to support the survival and recruitment of stocked individuals as well as potential spawning habitat for returning adults. The results of this study suggest that limited habitat availability for all riverine life stages may inhibit the establishment of self-sustaining lake sturgeon populations in the systems examined in this study.

Spawning habitat availability in Lake Michigan tributaries currently known to support remnant populations of lake sturgeon typically ranges from 1 to 10% of the available habitat in each system (Table 5). The lack of high quality spawning habitat currently available in the Pensaukee and Suamico rivers suggests that these systems have a limited capacity to support lake sturgeon spawning. These results suggest that lake sturgeon rehabilitation efforts in these systems should focus on the restoration or creation of spawning habitat. The addition of gravel and cobble substrates has been successfully utilized in other systems to increase spawning habitat availability. Successful spawning efforts by lake sturgeon have been documented over coal cinder deposits (0.5–12 cm in diameter) in the Detroit and St. Clair rivers, Michigan (Manny and Kennedy, 2002; Caswell *et al.*, 2004). Increasing abundance of lake sturgeon in the Wolf River system, WI, has been attributed to increased spawning habitat availability resulting from the stabilization of stream banks with large cobble and boulder rip-rap (Folz and Meyers, 1985; Kempinger, 1996; Bruch and Binkowski, 2002). These study results suggest that enhancing existing habitat or providing newly

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Table 5. Summary statistics of high-quality lake sturgeon habitat in Great Lakes tributaries currently supporting lake sturgeon populations*

Habitat type	River and reach	Habitat (m^2)	Availability (%)
Spawning	Menominee (MI)	104 396–405 283	9.8–38.3
	Peshtigo (WI)	8661	0.5
	Oconto (WI)	25 589	1.5
	Lower Fox (WI)	152 089	2.7
	Manistique (MI)	20 270	6.3
Staging	Menominee (MI)	744 884–3 217 165	49–71
	Peshtigo (WI)	560	<1
	Oconto (WI)	4571	0.3
	Lower Fox (WI)	2 086 018	38
	Manistique (MI)	164 833	51
Juvenile	Menominee (MI)	858 063–6 514 534	82–91
	Peshtigo (WI)	1 749 467	81
	Oconto (WI)	1 690 652	100
	Lower Fox (WI)	5 411 942	99
	Manistique (MI)	221 451	69

**Source*: Daugherty (2006).

created spawning habitat through the addition of large gravel, cobble, and boulder complexes (size range = 8 and 250 cm; Threader *et al.*, 1998) would increase potential spawning habitat availability. Habitat restoration efforts in these systems should aim to provide a similar proportion of high quality spawning habitat to that found in the aforementioned systems currently supporting lake sturgeon populations.

Spawning habitat abundance in the Little Suamico, Duck Creek, and Ford rivers was similar to or exceeded that found in systems currently supporting spawning populations of lake sturgeon. However, staging habitat associated with potential spawning areas (i.e. within 3 river kilometres (rkm) of potential spawning habitat; Bruch and Binkowski, 2002) was not available. Lake sturgeon are known to undergo pre-spawn migrations out of the lake to occupy river staging habitats during autumn and early winter (October to December; Scott and Crossman, 1973; Bruch and Binkowski, 2002), which may be important for the optimum maturation of gametes (Auer, 1996). Bruch and Binkowski (2002) reported that over 90% of pre-spawn lake sturgeon in Lake Winnebago, WI, entered the Wolf River to stage during winter months. Staging habitats are known to comprise 1 to 70% of the available habitat in Great Lakes tributaries currently supporting lake sturgeon populations (Table 5). The results of these studies, coupled with the relatively small size of the rivers examined in this research, suggest that a lack of high quality staging habitat may negatively affect the potential of these systems to support lake sturgeon spawning efforts. As a result, lake sturgeon habitat availability data in these systems indicates that rehabilitation efforts should focus on the creation of staging habitat. The installation of current deflectors, such as tree revetments and wing dams, may be used in the vicinity of high quality lake sturgeon spawning areas to create staging habitats.

Age-0 juvenile lake sturgeon habitat comprised the greatest proportion of available habitat in each system. Previous studies investigating the habitat use of juveniles have indicated a preference for low current velocities and sand substrates (Kempinger, 1996; Peake, 1999; Benson *et al.*, 2005), which comprised a large proportion of the habitat in this study (67 to 94% of habitat samples collected). These results suggest a potential for these systems to support early life stages of lake sturgeon. High-quality juvenile lake sturgeon habitat in Great Lakes tributaries currently supporting populations of lake sturgeon range from 70 to 100% of the available habitat (Table 5). Juvenile habitat availability in the systems examined in this study ranged from 37 to 99%, suggesting a lower relative availability of juvenile habitat

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when compared with systems with existing populations. However, relationships between lake sturgeon habitat availability and density-dependent factors which determine carrying capacity, such as prey availability, have not been investigated (Zollweg *et al.*, 2003). Future studies are required to determine relationships between habitat availability and population size in order to identify life-stage specific habitat availability thresholds in relation to system-specific management objectives.

Lake sturgeon are an important component of the native Great Lakes fish community. Rehabilitation of this species will aid in the maintenance of biological integrity and diversity throughout the Great Lakes. Although this study provides an understanding of the current and potential ability of these systems to support lake sturgeon spawning and recruitment, future research is required to define further the biological and ecological mechanisms that structure lake sturgeon populations. Efforts to understand lake sturgeon habitat use at both smaller (e.g. microhabitat) and larger (e.g. catchment) geographic scales, determine life-stage specific minimum habitat areas, the influence of habitat patch dynamics and spatial ecology, and the relative importance of various habitat characteristics are needed to provide a better understanding of lake sturgeon habitat. The results of such studies should be incorporated into future evaluations of lake sturgeon habitat availability and quality to promote the restoration of lake sturgeon in the Great Lakes.

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