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A Review of Lake Sturgeon Habitat Requirements and Strategies to Protect and Enhance Sturgeon Habitat

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Cover photo – Lake sturgeon in the St. Clair River. Photo by Chris Napran.

Executive Summary

Lake sturgeon (*Acipenser fulvescens*) have recently been designated by the Committee on the Status of Species at Risk in Ontario (COSSARO) as a threatened species in northwestern Ontario and in the Great Lakes drainage basin. The lake sturgeon receives protection under the *Endangered Species Act* (2007)(ESA), which requires that a recovery strategy be developed within two years of a species being listed as threatened. Habitat provisions are to be included in the recovery strategy as well as implementation goals. This report has been prepared to summarize lake sturgeon habitat requirements, to provide a synopsis of the impacts various activities may have on lake sturgeon habitat, and to review habitat mitigation and enhancement strategies which have been employed in various jurisdictions to date.

Lake sturgeon habitat requirements vary depending on their life stage and the time of year. Sturgeon often make long migrations upstream in rivers to spawn usually below an impassable barrier, such as a waterfall or a dam. Clean, coarse cobble and rubble substrates and a continuing flow of fast water characterize most sturgeon spawning sites. Upon hatching, larval sturgeon drift downstream with the current to shallow bays and slow-moving sections of river having sand or detritus substrates. Juvenile lake sturgeon are found in deeper waters, exceeding 9 m, more often than adults. Habitat selection at this life stage is determined by the availability of food. Adult lake sturgeon generally prefer relatively shallow (< 2-3 m) habitats with a moderate flow of water. They are opportunistic, benthic feeders preferring substrates of sand, gravel and detritus. Lake sturgeon are seldom associated with aquatic vegetation at any life stage. Adult lake sturgeon move to deeper water in lakes and riverine refuge pools during the winter when they are relatively sedentary prior to the spawning season.

The decline in lake sturgeon across much of North America has been attributed initially to unregulated fisheries and, more recently, to habitat alteration and destruction notably by pollution, dredging and channelization, and the construction of dams and hydroelectric facilities. Dredging and channelization can alter lake sturgeon spawning grounds. Sturgeon have been impacted by many forms of pollution which can disrupt olfactory feeding behaviour. Dams and hydroelectric stations can have a negative impact on lake sturgeon by fragmenting their habitat, impeding migrations to spawning grounds and, depending on the type of operation, having a negative impact on egg survival and recruitment. Downstream migrants may also be impinged or entrained at hydroelectric plants.

Attempts to resolve some of these habitat impacts have included construction of fish passes at dams, establishing base flows or “run-or-river” regimes at hydroelectric facilities, creation or enhancement of spawning areas, use of downstream guidance and diversion structures, and improvements to water quality. There has been some success with constructing artificial spawning grounds for lake sturgeon. Sturgeon have also been shown to display a positive response to improvements in water quality and “run-of-river” hydrologic regimes at dams and power stations. The ability to design a fish pass suitable for fish with the body size/shape and swimming capabilities of lake sturgeon has proven difficult, however, and further research is required in this area. Many sturgeon populations are also impacted by “peaking” operations at hydroelectric facilities and the issue of facilitating downstream passage over artificial barriers also needs to be resolved.

The impacts of dams, hydroelectric facilities, and other anthropogenic activities pose significant threats to lake sturgeon in Ontario. A recovery strategy for lake sturgeon in Ontario is currently being developed to provide science-based recommendations on the protection and recovery of this species. Following completion of the recovery strategy under the *Endangered Species Act* (2007), a government response statement will be developed summarizing the Government of Ontario’s intended actions and priorities in response to the recovery strategy.

Sommaire

Le Comité de détermination du statut des espèces en péril en Ontario (CDSEPO) a désigné récemment l'esturgeon jaune (*Acipenser fulvescens*) espèce menacée dans le nord-ouest de la province et dans le bassin hydrographique des Grands Lacs. Cette espèce est protégée en vertu de la *Loi de 2007 sur les espèces en voie de disparition*, qui prescrit l'élaboration d'un programme de rétablissement dans les deux ans suivant la date de la désignation d'une espèce comme espèce menacée. Ce programme de rétablissement doit comprendre des dispositions relatives à l'habitat et des objectifs de mise en œuvre. Le présent rapport a pour objet de résumer les besoins en matière d'habitat de l'esturgeon jaune, de fournir un sommaire des effets possibles de différentes activités sur l'habitat de l'esturgeon jaune et de passer en revue les stratégies d'atténuation et d'amélioration appliquées dans divers territoires de compétence jusqu'à présent.

Les besoins de l'esturgeon jaune en matière d'habitat varient selon l'étape du cycle biologique et le moment de l'année. L'esturgeon effectue souvent de longues migrations vers l'amont jusqu'aux frayères, habituellement situées en aval d'un obstacle infranchissable, comme une chute ou un barrage. La plupart du temps, il choisit pour frayer des zones offrant un substrat de galets et de blocaille grossiers exempt de détritus et un fort débit d'eau constant. À l'éclosion, le courant charrie les larves vers l'aval jusqu'à des baies aux eaux peu profondes et des tronçons des cours d'eau à faible débit, où le substrat est constitué de sable ou de débris de roches. Les jeunes esturgeons jaunes fréquentent les eaux profondes, de plus de 9 m de fond, plus souvent que les adultes. Le choix de l'habitat à ce stade du cycle biologique de l'espèce est déterminé par la disponibilité de la nourriture. En général, les adultes préfèrent les zones relativement peu profondes (moins de 2 ou 3 m) caractérisées par un débit modéré. Ce sont des consommateurs opportunistes benthiques qui accordent leur préférence aux substrats de sable, de gravier et de débris. Durant tout son cycle biologique, l'espèce est rarement associée à la végétation aquatique. Au stade adulte, elle passe l'hiver – période de relative sédentarité précédant l'époque du frai – au fond des lacs et des fosses de refuge le long des rives.

La baisse des effectifs de l'esturgeon jaune dans la majeure partie du continent nord-américain a été attribuée initialement à l'absence de réglementation de la pêche et plus récemment à la transformation et à la destruction de l'habitat, spécialement par la pollution, le dragage et le creusage de canaux, ainsi que par la construction de barrages et d'installations hydroélectriques. Le dragage et le creusage de canaux peuvent transformer les frayères de l'esturgeon jaune. L'espèce a subi les effets de nombreuses formes de pollution pouvant perturber le comportement alimentaire olfactif. Les barrages et les centrales hydroélectriques peuvent avoir une incidence néfaste sur l'esturgeon jaune en fragmentant son habitat, en empêchant les migrations vers les frayères et, selon le type d'exploitation des ouvrages, en nuisant à la survie des œufs et au recrutement. En outre, il est possible que les individus qui migrent vers l'aval soient piégés ou absorbés aux centrales.

On a pris diverses mesures pour tenter de contrer certains des effets sur l'habitat, entre autres la construction de passes migratoires aux barrages, l'établissement de régimes de débit de base ou « au fil de l'eau » aux installations hydroélectriques, l'aménagement ou l'amélioration de frayères, l'utilisation d'ouvrages d'orientation et de dérivation en aval et l'amélioration de la qualité de l'eau. L'aménagement de frayères pour l'esturgeon jaune a donné certains résultats et l'espèce a réagi positivement aux améliorations apportées à la qualité de l'eau et à l'établissement de régimes de débit « au fil de l'eau » aux barrages et installations hydroélectriques. Toutefois, il s'est révélé difficile de concevoir une passe migratoire convenant à un poisson de la taille et de la forme de l'esturgeon jaune et ayant ses capacités natatoires; il faudra pousser les recherches à ce sujet. Par ailleurs, les opérations de production de pointe menées à des installations hydroélectriques

ont eu des effets sur de nombreuses populations d'esturgeons, et il faudra également s'attaquer à la question des mesures à prendre pour faciliter les migrations vers l'aval par-dessus les obstacles artificiels.

Les incidences des barrages, des installations hydroélectriques et d'autres activités anthropiques font peser de grandes menaces sur l'esturgeon jaune dans la province. Un programme de rétablissement de l'espèce en Ontario est en voie d'élaboration et permettra de formuler des recommandations fondées sur des données scientifiques en vue d'assurer sa protection et son rétablissement. À la suite de l'élaboration du programme de rétablissement en vertu de la *Loi de 2007 sur les espèces en voie de disparition*, le gouvernement produira une déclaration résumant les mesures qu'il entend prendre et indiquant ses priorités à l'égard du programme.

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Introduction

The degradation and alteration of habitat has been widely recognized as one of the main causes for the decline of sturgeon *(Acipenser* spp.) worldwide. This report has been prepared to support the development of a recovery plan for lake sturgeon (*Acipenser fulvescens*) in Ontario. More specifically, it reviews lake sturgeon habitat requirements, provides a summary of the impacts of various activities on sturgeon habitat, and outlines measures which have been employed elsewhere to protect, create and enhance sturgeon habitat. Although the provincial review will only involve lake sturgeon (*Acipenser fulvescens*), we have included information on habitat alterations, habitat enhancement techniques, and practices for other sturgeon species which might be applicable for the protection and management of lake sturgeon habitat in Ontario.

Brief History of Lake Sturgeon in Ontario

Prior to 1860 lake sturgeon were largely considered to be a nuisance fish in Ontario (Harkness and Dymond 1961). By 1880, caviar had become a highly valued product and commercial fisheries had been established for lake sturgeon. As early as 1890 many Ontario lake sturgeon were in decline as a result of unregulated exploitation. Several of the lake sturgeon's life history characteristics (e.g., late maturity, fractional spawning, etc.) may have contributed to their decline and prevented their immediate recovery. Subsequent habitat alterations, including pollution, habitat fragmentation, and artificial water manipulation are also believed to have played an important role in the decline of lake sturgeon.

Lake Sturgeon Life History and Habitat Requirements

Lake sturgeon are a long-lived, slow growing species. Their habitat requirements vary according to their life stage and the time of year (Appendix 1). These include: pre-spawning, spawning, incubation, juvenile, adult, and overwintering habitat. Both lake and riverine systems provide important habitats for lake sturgeon. Lake sturgeon are considered a potamodromous species in that they live and move solely within freshwater to forage and breed.

Sturgeon can display both sedentary and migratory characteristics. They can range widely for feeding and spawning or to avoid unfavourable conditions. Annual movements generally involve a spring migration to spawning areas, a post-spawning dispersal to feeding grounds, and a fall migration to overwintering sites (Phoenix 1991, Wilson and McKinley 2004, Shaw 2010). Due to their extensive and widespread movements, sturgeon habitat needs to be considered in terms of broad system-wide conditions which often include diverse and unobstructed habitat. Auer (1996b) suggested that a barrier-free distance of 250-300 km of lake /river range should be considered as a minimum to support self-sustaining sturgeon populations. The presence and availability of suitable habitat is believed to be one of the major factors limiting the abundance of lake sturgeon in the Great Lakes (Auer 1999).

Despite their mobility, sturgeon are generally not as strong swimmers as other species of fish such as salmonids. This has been attributed to having a heterocercal tail, intermediate metabolism, and greater drag due to body size and the presence of scutes.

Maximum sustained swimming speed of lake sturgeon is approximately 30 cm/sec. Prolonged swimming speeds (see Glossary) are in the order of 45-75 cm/sec and burst speeds are 75-85 m/sec (Hoover et al. 2005). Peake et al. (1997) reported that a 130 cm lake sturgeon could maintain its position indefinitely in flow of up to 96.8 cm/sec and could swim for shorter periods at flows of up to 180 cm/sec. The swimming performance of sturgeon increases with temperature and size of fish (Peake et al. 1995, Scruton et al. 1998). Large lake sturgeon can swim longer and at higher speeds than smaller sturgeon. Smith (2006) reported that juvenile lake sturgeon have sustained swimming speeds at velocities up to 45 cm/sec; prolonged swimming at 35-75 cm/sec; and burst swimming at flows of 65-86 cm/sec.

Flow regimes that mimic natural variability are critically important to lake sturgeon. Rapid changes in river flow (increase or decrease) can trigger behaviour patterns, including upstream migration, in sturgeon (Auer 1996a). Although there is some variability among systems, lake sturgeon have shown a tendency to move upstream with increasing discharge and drop back downstream with decreasing discharge (Borkholder et al. 2002). For some sturgeon, the strongest cues for upstream migration occur at night particularly during the autumn (McLeod and DeBruyne 2009). Prior to spawning, adult sturgeon often congregate at river mouths or in deep riverine pools a short distance below the spawning site (Rusak and Mosindy 1997).

Lake sturgeon spawn in the late spring-early summer at water temperatures ranging from 10-20º C, although 12-16º C is generally considered optimal. They select fast water sites having rock-cobble substrate in the upper reaches of large river systems usually at the base of a rapids, waterfalls or dams which prevent further upstream migration (Figures 1 and 2). Feeding ceases during the spawning period (Scott and Crossman 1973). The availability of suitable spawning habitat is critical to reproductive success (Bemis and Kynard 1997). Despite a spawning

Figure 1. Lake sturgeon typically spawn over substrate comprised of clean cobble and rubble.

periodicity of 3-7 years, female sturgeon are in spawning condition for only a short period of time and they re-absorb eggs if no suitable spawning areas are available (T. Haxton pers. comm.). No nest is constructed. Eggs are broadcast and adhere to the substrate during the incubation period. Egg survival rates are optimized at egg densities of approximately 3,500 eggs/m^2 (P. Dumont pers. comm.).

Lake sturgeon can have two separate spawning events during a season (Bruch and Binkowski 2002). This is believed to be primarily influenced by water temperature (Kempinger 1988).

This spawning behaviour has been documented in several locations including the Kaministiquia River where spawning occurs at temperatures of approximately 13º C (usually the last week in May) and then again at 16º C (Friday 2005, 2006a). Adult sturgeon usually move downstream quickly after spawning (Stone 1900, Lyons and Kempinger 1992, Auer 1999, Hayes and Werner 2000).

Upon hatching, larval lake sturgeon remain in the substrate until their yolk sac is absorbed (Kempinger 1988). After a relatively short incubation period, larval sturgeon emerge and drift downstream in congregations with the current. Downstream drift occurs predominantly at night (D'Amours et al. 2001), between 1000 hours and 0100 hours, and is often associated with a minimum water temperature of 16º C (Smith and King 2005, Peterson et al. 2007). Declining water temperatures during late summer and fall are believed to initiate downstream movements to a lake environment in some watersheds (Caroffino et al. 2009). Young lake sturgeon are generalist and opportunistic feeders (Jackson et al. 2002, Nilo et al. 2006, Guilbard et al. 2007). Mortality during early life stages is high. For example, in the lower St. Clair River, Nichols et al. (2003) estimated that less than 1% of sturgeon eggs deposited during the spawning run survived to hatch. Forsythe (2010) reported that young sturgeon were highly susceptible to predation by fish and that mortality during out migration was extensive. It is widely accepted that year class strength is directly related to survival during their first year of life (Nilo et al. 1997, Coroffino et al. 2007) and this is probably influenced by climatic and hydraulic factors.

Relatively little is known about habitat requirements of young-of-the-year lake sturgeon. Nursery habitat may vary according to different systems but it is believed to be best described as shallow areas with low current velocity and sandy substrates having an abundance of *Dipteran* larvae (Benson et al. 2005). Despite the ability to adapt to different conditions, it is very likely that the availability of suitable nursery habitat may be a limiting factor in many situations (T. Haxton pers. comm.).

Yearling sturgeon have been observed to congregate in large schools in shallow river mouths or adjacent bays (Peterson et al. 2007). Although little else is known about their juvenile phase, their habitats are believed to be different from adult fish (Hayes and Werner 2000, Huddleston and Wilson 2007).

Juvenile lake sturgeon (young-of-year to 6-7 years of age) grow quickly and are seldom found with adult fish. Gonadal development is believed to start at 7–8 years of age and from this point lake sturgeon may be considered to be sub-adults (L. Mohr pers. comm.). These subadult fish are often captured with adult lake sturgeon. In Ontario, lake sturgeon typically become sexually mature at the ages of 14-20 and 18-25 years of age for males and females, respectively (MNR 2009).

Adult sturgeon are bottom dwellers usually found on productive shoals in lakes or river deltas. There is some evidence of site fidelity in adult sturgeon (Rusak and Mosindy 1997, Auer 1999, Haxton 2002, Dick et al. 2006).

Sturgeon are primarily benthic feeders with opportunistic food habits. They often forage in shallower waters having sand or mud substrate. It is not uncommon, however, for adult lake sturgeon to feed pelagically on dense schools of prey fish or emerging invertebrates (L. Mohr pers. comm.). In the St. Lawrence River, Hayes and Werner (2000) found that zebra mussels comprised a significant proportion of the adult lake sturgeon diet and suggested that mussel densities could be a factor in the selection of preferred habitats by adult sturgeon.

During the winter, adult lake sturgeon move to deeper water (i.e., 6 – 11 m) in lakes and in riverine refuge pools having low water velocity (McKinley et al. 1998, Threader et al. 1998, Aadland and Kuitunen undated). They are often found in aggregations and display sedentary behaviour (Fortin et al. 1993, Environnement Illimité Inc. 2004, Friday and Chase 2005, Snellen 2008). Generally, they do not feed as actively as other times of the year (Werner and Hayes 2005).

Impacts to Sturgeon Habitat

1. Dams and Hydroelectric Facilities

Dams alter the normal pattern of water temperature, flow regime, water chemistry, nutrient transport, fish movement, and community structure in a river system which can affect spawning and recruitment of sturgeon (MacDonell 1995, Bednarek 2001, Threader et al. 2005, Haxton and Findlay 2009, Mora et al. 2009). It has been estimated that 77% of the northern hemisphere's largest rivers are regulated by dams and hydroelectric facilities (Dynesius and Nilsson 1994). Altered hydrologic regimes associated with impoundment operations has been identified as a leading threat to imperilled fish fauna (Richter et al. 1996, World Wildlife Fund 2009). The construction of dams has often preceeded the decline in local sturgeon populations (Granado-Lorencia 1991, Jager 2006a). Dam construction at both extremeties of Lake St. Francis between 1912 and 1958 was attributed as one of the major causes for the collapse of local lake sturgeon stocks (Dick et al. 2006). Similarly, the construction of the Carillon hydroelectric dam on the Ottawa River has contributed to the decline in lake sturgeon in the lower portion of the Ottawa River (Dick et al. 2006). Jager et al. (2001) believed that the amount of free-flowing unobstructed river available often determined its ability to support sturgeon. Haxton and Findlay (2008) concluded that water power management was the primary factor preventing recovery of lake sturgeon in the Ottawa River.

Obstructions, such as dams, which prevent access to spawning grounds are known to have severe impacts on several sturgeon species (Ferguson and Duckworth 1997, Cooke et al. 2004, Dadswell 2006) (Appendix 2). The construction of hydroelectric dams in the Saskatchewan River watershed fragmented one single population into several subpopulations (McLeod et al. 1999). Similary, the lake sturgeon population in the Menominee River, Wisconsin, has been fragmented by hydroelectric dams (Thuemeler 1997). In the Moose River basin, Ontario, it has been estimated that the natural range of lake sturgeon has been reduced by at least 30% as a result of dam construction (MNR 2008).

In addition to blocking upstream access, dams can have other impacts on sturgeon. When blocked by the Pinopolis Dam on the Cooper River, South Carolina, shortnose sturgeon (*Acipenser brevirostrum*) remained below the dam for up to 89 days and eventually spawned under poor

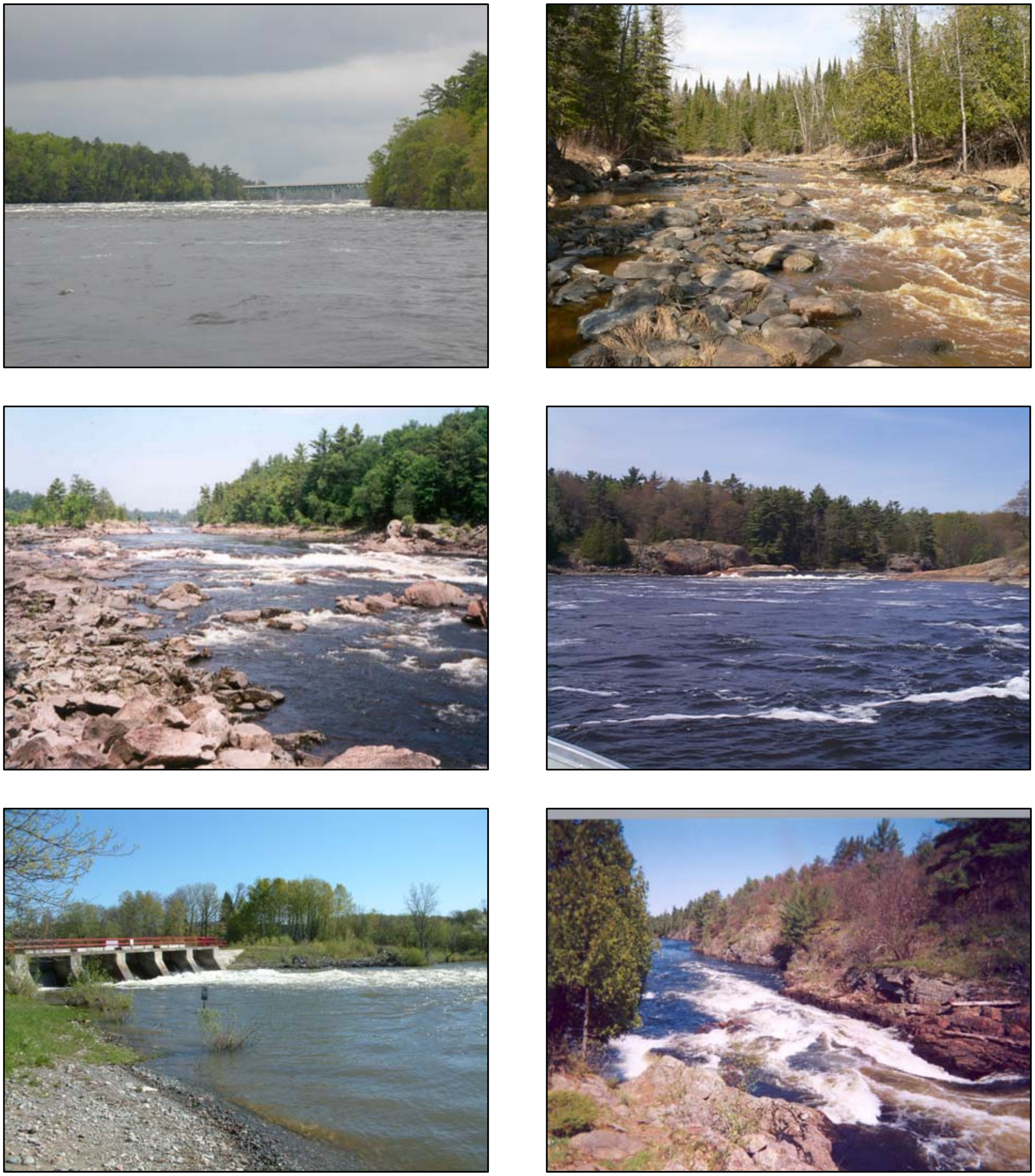

Figure 2. Lake sturgeon spawning sites at selected Ontario locations. Top Left (clockwise): (i) Lost Channel (Ottawa River)(Photo by T. Haxton) (ii) Sturgeon River (Rainy River tributary) (Photo by J. Vandenbroeck), (iii) Mississaugi River (MNR photo), (iv) Thessalon River (MNR photo), (v) Thessalon River (MNR photo), (vi) Coliseum Rapids (Ottawa River)(Photo by T. Haxton).

conditions. As a result, larval survival rates were extremely low (Cooke et al. 2004). Water level manipulation and pollution have also contributed to lake sturgeon declines in Alberta (Earle 2002).

Hydroelectric facilities can have serious impacts on resident fish populations (Cada and Sale 1993, Stokes et al. 1999, Steele and Smokorowski 2000, AECOM Canada Ltd. 2009). Regulated flows can disrupt normal movements and spawning patterns (Veshchev and Novikova 1984, Raspopov et al. 1994). The effects of regulated flow alters the abundance, composition, and diversity of benthic macroinvertebrates which may ultimately affect the diet and nutritional status of lake sturgeon (Fisher and LaVoy 1972, Troelstrup and Hergenrader 1990, Weisberg and Burton 1993, McKinley et al. 1993, Snyder and Minshall 2005). Aquatic habitat upstream of a dam or hydroelectric facility may be degraded or lost. For example, historic lake sturgeon spawning sites were inundated or altered with the construction of the Moses-Saunders dam on the St. Lawrence River (Edwards et al. 1989). Similarly, the construction of the Carillon dam on the lower Ottawa River flooded a historic lake sturgeon spawning site further upstream near Hawkesbury (Haxton and Findley 2008).

Shifts in the timing of naturally occurring peak flows and reductions in these flows below hydroelectric facilities are directly related to sturgeon spawning success and year class strength (Koroshko 1972, Zakharyan 1972, Votinov and Kasyanov 1979, Veshchev 1991). A dewatering event below the Peshtigo River dam, Wisconsin, after sturgeon spawning reduced the size of the 2006 year class of lake sturgeon (Caroffino et al. 2009). Haxton (2007) reported that lake sturgeon abundance was significantly greater in unimpounded reaches of the Ottawa River. A similar observation was made for white sturgeon (*A. transmontanus*) in the Columbia River, Oregon and Washington (Beamesderfer et al. 1995). Population declines of several sturgeon species have coincided with flow regulation associated with hydroelectric development (Khoroshka 1967, Granado-Lorencia 1991, Zhong and Power 1996).

Generally, there are two basic operating regimes at hydroelectric facilities: "peaking" and "run-of-river". A "peaking" operation is one in which water is stored in the reservoir for a period of time and then spilled through the turbines to produce electricity. Typically, water is stored in the reservoir and released through turbines to generate electricity during the day or season when demand for electricity is highest. This results in a dramatic reduction in downstream flows for a period of many hours which has often been attributed to lowered biological diversity downstream of these sites (Cushman 1985, Appendix 2). The reduction or elimination of flow during the night can also impact the downstream drift of larval lake sturgeon. This type of operation is generally believed to impair recruitment in lake sturgeon (Haxton and Findlay 2009).

A "run-of-the-river" operation is based on constant flows through hydroelectric facilities that are equivalent to natural flows being received from upstream. Little or no storage of water is involved in this type of operation. "Run-of-the-river" operations are generally considered to have less impact on aquatic biota (Prosser 1986). When the Prickett hydroelectric facility was converted from a "peaking" to "run-of-the-river" operation, Auer (1996a) reported an increase in the number of spawning sturgeon (including more larger individuals and more fish in a reproductive ready state), and a reduction of time that sturgeon were located at the spawning site.

The alteration of flows outside of natural variability has a pronounced impact on sturgeon. Constant water flows trigger reproductive cues and allow large fish to migrate upstream (Auer 1994, 1996). Fluctuating water velocities were believed to cause a relocation response by spawning white sturgeon in the Kootenai River (Paragamian et al. 2002). Sudden increases in water discharge (both natural and artificial) during the winter can alter behaviour and maturation of gonads in some sturgeon species (Khoroshko 1967, Yelizarov 1968, Pavlov and Slivka 1972). High flows can also create bottom velocities which can preclude spawning or greatly reduce success (Kynard 1997).

Decreased water levels and flows in the spring can delay the upstream spawning migration of sturgeon (Friday and Chase 2005). Periodic high water flows can attract sturgeon into pools at the base of dams and spillways, thereby trapping them when water levels subside (Young and Love 1971, Brousseau and Goodchild 1989, Friday 2004). The rate at which flows are decreased (i.e., ramping) may not provide sufficient protection from trapping or stranding fish during flow reductions (Higgins and Bradford 1996). Climate and water flows during the spawning and incubation period are widely believed to influence year class strength (Votinov and Kasyanov 1978, Nilo et al. 1997, Jager et al. 2002, Randall and Sulak 2007). Highly variable flows from peaking operations can dislodge sturgeon eggs and larvae from their incubation sites (Swanson et al. 1990). Regulated flows, involving both lowering and raising of water levels, on the Wolf River, Wisconsin, following lake sturgeon spawning resulted in dessication of lake sturgeon embryos after being dislodged from the substrate and subject to air exposure (Kempinger 1988). Nocturnal flows are also required to ensure the downstream drift of sturgeon larvae which occurs predominantly at night. There is the need to develop flow enhancement and/or supplementation strategies below hydroelectric facilities especially during the spawning, incubation, and drifting periods of migratory fishes (Schilt 2007).

In addition to obstructing upstream fish movements, dams and hydroelectric facilities also represent barriers to downstream migration. Downstream migrants basically have three options when arriving at a dam or hydroelectric site: spill over the dam; entrain through the turbine; or utilize a turbine bypass system (when available). Most juvenile fish will pass downstream through spillways if outlet flow is sufficient. At the Dalles Dam on the Columbia River, larger (i.e., ≥95 cm total length) sturgeon have been recorded passing over the spillway with relatively low mortality (Parsley et al. 2007). Fish passing over spillways can be injured by rapid deceleration and pressure changes, abrasion, and impact from hitting the water. Small sturgeon are especially poor swimmers and are often unable to escape from an undertow below a dam. Water below spillways at high relief dams can become supersaturated and fish can sometimes develop gas bubble disease (Ruggles and Murray 1983, Counihan et al. 1998).

Mortality of downstream migrants is usually greatest during years of low flow when most of the river flow is passed through turbines (Prosser 1986). When fish pass through turbines, injuries and mortality result from pressure changes, mechanical contact with a turbine blade, or through shear forces and turbulence (Cada 1990). Small, juvenile fish seem especially prone to entrainment in turbines (Coutant and Whitney 2000). Killgore et al. (2001) reported mortality from shear stress was greater (> 75%) for smaller larvae (lake sturgeon and blue suckers, *Cycleptus elongatus*) than larger larvae (shovelnose sturgeon (*Scaphirhynchus platornchus*) and paddlefish (*Polyodon spathula*).

In some instances, such as the Mattagami River in northeastern Ontario, post-spawn sturgeon are drawn downstream through a spillway where they often become entrained in pools in the dewatered diversion channel below the dam (McCormick et al. 1990, Sheehan 1992, Seyler et al. 1996).

Figure 3. Dewatered lake sturgeon spawning bed below a dam on the Spanish River (MNR photo).

Figure 4. Sturgeon mortality resulting from dewatering below hydroelectric stations on a northeastern Ontario river (left, MNR photo) and the Kaministiquia River (right, Photo by M. Friday).

Since 1990, over 5,000 lake sturgeon have been relocated from the Adams Creek site (Bruch et al. 2009)(Table 1).

Table 1. Stranded lake sturgeon which have been relocated from the Adams Creek spillway, 1990-2008.

Year	No. Sturgeon Relocated	Year	No. Sturgeon Relocated
1990	959	2000	272
1991	100	2001	19
1992	51	2002	-
1993	496	2003	148
1994	400	2004	160
1995	124	2005	63
1996	441	2006	95
1997	367	2007	472
1998	18	2008	226
1999	487		

Several alternate strategies have been considered to address this problem but, to date, physical relocation of stranded sturgeon has proven to be the most viable option (Evans et al. 1993, D. Barbour pers. comm.).

Under the federal *Fisheries Act*, the impacts of dams and hydroelectric facilities can be grouped into three broad categories: fish passage, fish mortality, and fish habitat (DFO 2011). Section 20(1) of the Fisheries Act provides the Minister of Fisheries and Oceans with the power to order the owner or occupier of an obstruction to provide for the free passage of fish. Section 22 provides the authority to regulate downstream water flows at an obstruction to provide for the safe and unimpeded descent of fish and for the free passage of both ascending and descending migratory fish during the period of construction. Section 30 of the Fisheries Act requires that any water intake must have a fish guard, screen, or covering to prevent fish from sustaining injury leading to death. This is particularly relevant to juvenile fish migrating downstream through the turbines of a hydroelectric facility.

Finally, Section 35(1) is a prohibition against the harmful alteration, disruption or disruption (HADD) of fish habitat. Under this section, an obstruction of fish passage could be considered a HADD of fish habitat.

Under Ontario's *Species at Risk Act* (ESA), Regulation 242/08 stipulates that persons operating existing hydroelectric generating stations are exempt from sections of the ESA (killing, harming, harassing, capturing, taking, possessing, or transporting species and from damaging and destroying their habitat) provided the person operating the station enters into an agreement with the Minister. If the construction of the hydroelectric station began or if all of the required approvals for construction were obtained before the species was included on the COSSARO list, or before the species came to exist at the station, the operator may rely on the exemption for three years to continue with their operations while negotiating an agreement. After three years have passed the operator must have entered into an agreement with the Minister. Agreements must indicate the species, require reasonable steps to minimize adverse effects on the species, provide for monitoring the effects of the station's operation on the species, and must not conflict with any actions the Ministry is required to implement in response to a recovery strategy. The operation of the station must not jeopardize the survival or recovery of the species in Ontario.

If the construction of the hydroelectric station has not begun or if all of the required approvals for construction were not obtained before the species was included on the COSSARO list as threatened, then the construction of a new hydroelectric project would need to avoid contraveining section 9 (species protection) or 10 (habitat protection) of the ESA. If the construction of a new hydroelectric station would contravene section 9 or 10 of the ESA, than an ESA permit would need to be requested and obtained prior to the construction work proceeding.

2. Pollution and Contaminants

Sturgeon have been impacted by many forms of pollution. Many effluents and pollutants have the potential to disrupt the olfactory feeding behaviour of sturgeon (Hay-Chmielewski and Whelan 1997). Pollution has been identified as the reason for the decline or loss of sturgeon in the St. Lawrence River (Caron 1998), the Delaware estuary and Chesapeake Bay (Dadswell 2006), the Danube River (Hensel and Holcik 1997, Lenhardt et al. 2006) and the Volga River (Khodorevskaya et al. 1997, Lenhardt et al. 2006). Pollution and loss of spawning habitat in the Rainy River, Ontario, and it's tributaries resulting from paper mill construction and operation as well as agricultural development were identified as contributing factors in the decline of lake sturgeon (Mosindy 1987).

Logging and lumber operations, which occurred across Ontario during the 1800s, used every waterway available to move wood to mills and factories. Massive log drives and log jams changed the landscape, particularly in larger rivers and their tributaries. Most log movement occurred during the spring and it is highly likely that these log drives had an impact on sturgeon spawning activity. Log drives probably scoured lake sturgeon spawning habitat, destroyed sandbars, and removed soft substrates which are important habitat for juvenile lake sturgeon.

The accumulation of bark and wood fibre during the period of log drives on the Ottawa River altered the river bed and water chemistry of the river (Haxton 2008). The relative density of macroinvertebrates, the predominant food source for juvenile lake sturgeon, was found to be significantly reduced in rivers whose substrate was covered with wood chips (Beamish et al. 1998). This wood fibre often accumulated over large areas (in some cases more than 30 km downstream) blanketing spawning and larval habitat (Harkness and Dymond 1961). Brousseau and Goodchild (1989) reported that log drives and pulp and paper mill effluents severely degraded habitat for fish, including lake sturgeon, in several areas of the Moose river basin. Log drives and deforestation on the Goulais River watershed, Ontario, increased sedimentation and covered the substrate with bark and debris which had detrimental effects on lake sturgeon habitat (Friday 2002). A reduction in lake sturgeon spawning activity in the Sturgeon River, a Lake Nipissing tributary, was attributed to the accumulation of large amounts of pulp and wood fiber on the substrate below the mill (Young and Love 1971). Several river deltas on the Great Lakes are covered in decaying bark and woody debris left from pulp and paper mill operations (L. Mohr pers. comm.). While not the primary cause of decline, pollution of spawning and nursery habitat in the Rainy river by toxic effluents and wood fiber from pulp and paper mills impeded the subsequent recovery of lake sturgeon in the river and Lake of the Woods (Mosindy and Rusak 1991).

In Lac des Deux Montagnes, the lake sturgeon population, which had not been exploited commercially since 1950, was decimated following a prolonged period of winter anoxia caused by the discharge of untreated domestic sewage and pulp and paper effluent in the Ottawa River watershed (P. Dumont, pers. comm.).

Although the influence of pollution on sturgeon populations is not well understood, sturgeon are known to be among the most sensitive of all aquatic organisms to a wide range of substances including ammonia (Fontenot et al. 1998), chlorine (Kajiwara and Ueno 2003, Little and Calfee 2008b, Williams 2009), copper (Little and Calfee 2008b, Williams 2009), herbicides (Little and Calfee 2008a), nitrite (Fontenot et al. 1998, Huertas et al. 2002), pesticides (Markov 1990), polychlorinated biphenyls (Bosely and Gately 1981), and heavy metals (Andreev et al. 1989).

Elevated concentrations of copper were considered a threat to white sturgeon (*Acipenser transmontanus*) egg viability in the Kootenai River (Duke 1993). In the Columbia River, Feist et al. (2005) concluded that exposure of white sturgeon to contaminants could be affecting both growth and reproductive physiology. Young-of-the-year lake sturgeon are also known to be very sensitive to the lampricide TFM (Johnson et al. 1999, Boogaard et al. 2003, Williams 2009).

The production of methylmercury often increases after impoundment of a river in response to the flooding of naturalized terrestrial areas and subsequent decomposition of organic matter (Grondin et al. 1995, Stokes and Wren 1987). Mercury contamination in fish can also extend downstream from impoundments (Zhong and Power 1996b). Methylmercury can be absorbed directly through the gills or indirectly through their diet (Hall et al. 1997). Long-lived benthivores, such as sturgeon, are particularly susceptible to increases in mercury concentrations (Headon and Pope 1990). The effect of contaminants can vary from acute to chronic. Heavy metals and other contaminants accumulate in the fatty tissues of sturgeon. The accumulation of mercury in the tissues of white sturgeon is believed to have an effect on reproduction (Feist et al. 2005, Webb et al. 2006). Haxton (2007) identified contaminants as one of three main stressors which explained the difference in lake sturgeon abundance among various reaches of the Ottawa River. However, neither growth or condition of the sturgeon could be related to increased contaminant levels (Haxton and Findlay 2008).

3. Siltation and Sedimentation

Benthic organisms, including larval sturgeon, can become smothered by silt and sediment. At high sediment loads, gas exchange through the gills is reduced and benthic organisms may become smothered. Mortality under sediment cover is generally attributed to restricted water circulation around incubating embryos which results in reduced exchange of respiratory gases such as oxygen and carbon dioxide.

In some instances, the reservoir behind some dams and hydro facilities is flushed to prevent an accumulation of sediment (Doeg and Koehn 1994). This can cause dramatic alterations to water quality and habitat downstream, often resulting in fish kills (Nesse and Newcombe 1982).

Sedimentation of critical habitat was identified as the cause of a reduction in white sturgeon recruitment in the Nechaka River, British Columbia (McAdam et al. 2005). In the Kootenai River, Idaho, sediment cover at a spawning site resulted in delayed hatching, small size at emergence, and reduced survival of white sturgeon (Kock et al. 2006). Nichols et al. (2003) attributed a heavy silt load on lake sturgeon spawning grounds in the St. Clair River, Michigan, as the cause of a poor sturgeon year class in 1999. Sturgeon habitat in the lower reaches of the Assiniboine River, Manitoba, has declined due to erosion, sedimentation, and an influx of sewage effluent (Dick et al. 2006). In northeastern Ontario, erosion and sedimentation resulting from construction of logging roads was identified as an activity which impaired water quality in sturgeon habitat (Ferguson and Duckworth 1997).

4. Dredging and Channelization

Dredging can result in the removal of spawning substrate and other underwater cover required by sturgeon. Dredge and fill activities can result in increased turbidity, reduced light penetration, altered water circulation patterns, and decreased levels of dissolved oxygen (Jeane and Pine 1975, Johnston 1981). Due to their relatively poor swimming abilities, sturgeon can be subject to entrainment during dredging activities (Hatfield et al. 2004, Smith 2006, Boysen and Hoover 2009). Small (i.e., young-of-year) sturgeon are believed to be particularly susceptible (Hoover et al. 2005, 2009). Correspondingly, channelization reduces river width, alters water velocity, eliminates eddies and pools, and prevents flow into backwater areas.

Dredging and channelization for navigation has resulted in the destruction of lake sturgeon habitat throughout the St. Lawrence River and several of the connecting waterways in the Great Lakes (Edwards et al. 1989, MNR 2009). Since the late 18th century, several portions of the St. Marys River have been altered by dredging, blasting and construction of docks and canals to improve navigation and develop hydroelectric power (Kauss 1991). In the St. Clair River, dredging has historically been conducted for navigational improvement and for commercial gravel removal (Derecki 1985). Since 1900, the Detroit River has been excavated and channelized to facilitate commercial shipping (Manny et al. 2006). Dredging was implicated as the cause for loss of a lake sturgeon spawning shoal in the upper Niagara River near Buffalo Harbour (Carlson 1995). In the lower St. Lawrence River, annual dredging operations are required for maintenance of navigational channels. The disposal of dredgeate has been observed to modify the existing substrate causing a reduction in food organisms for sturgeon (Munro 2000, Drapeau et al. 2003, Nellis et al. 2007, Hatin et al. 2009). Post-dumping observations indicated direct avoidance of the dredgeate disposal sites by Atlantic sturgeon (*A. oxyrinchus*) (Hatin et al. 2007).

Based on a four year study, Veshchev (1981) reported that 68-77% of migrating sturgeon larvae were destroyed by dredging activities on the Volga River. In addition to direct effects, dredging can destroy benthic feeding areas. Disposal of dredgeate can also cover important sturgeon habitat (Hatten and Parsley 2009).

Approximately 51% of the pallid sturgeon's (*Scaphirhynchus albus*) 5,390 km range in the Missouri and Mississippi rivers has been channelized (National Wildlife Federation – www.nwf.org/endangered/pdfs/UM-PallidSturgeonpdf). Across the United States, it has been estimated that 40% of pallid sturgeon habitat has been channelized.

Mitigation and Enhancement Measures

The following sections provide a review of habitat creation and enhancement strategies which have been employed in various jurisdictions to date

1. Spawning Bed Creation and Enhancement

The availability of spawning and nursery habitat is crucial for the perpetuation of any fish species. Limited habitat for various life stages of lake sturgeon could prevent the establishment of self-sustaining populations (Daughterty et al. 2007). In some instances, the creation or enhancement of spawning grounds for sturgeon increased reproductive success where substrates were poor or when egg densities were high (Daugherty et al. 2008).

New spawning grounds should provide a range of suitable conditions for spawning under varying seasonal conditions of water discharge. Some key considerations for the construction of spawning grounds for sturgeon include:

- Current velocities ranging from 0.1 – 1.5 m/sec;
- Substrate composed of coarse cobble and rubble;
- Water depths ranging from 0.1 – 5.0 m;
- Substrate thickness of at least 0.3 m;
- Maintenance of sediment-free interstitial spaces;
- Distance of staging areas from spawning site should be minimized (e.g., < 3 km); and
- Current breaks (e.g., boulders) are important.

Several sturgeon spawning site creation and enhancement projects have been undertaken. These include:

(a) Detroit River - This binational project involved the creation of three large (each bed measured 371.5 m^2) spawning beds for lake sturgeon in the Detroit River during June, 2004 (Manny et al. 2004, Read et al. 2006). The beds were created in 7 – 9 m of water where current velocities were 0.6 – 0.9 m/sec. Three different types of material were used: broken limestone 40-60 cm in diameter; 15-25 cm rounded metamorphic cobble; and 2-7 cm coal cinders. Initially, the sites were used by at least six other fish species for spawning (Boase et al. 2006, Kennedy et al. 2006). In 2008, twelve additional shoals were constructed downstream (Kennedy et al. 2009). Successful reproduction by lake sturgeon was documented at one shoal (Fighting Island) in 2009. The shoal has also been used for spawning by several non-target species including lake whitefish (*Coregonus clupeaformis*), walleye (*Sander vitreus*), white bass (*Morone chrysops*) and suckers (*Catastomus* spp.)(Allan et al. 2008).

(b) Eastmain River - The project involved the creation of three artificial spawning grounds to compensate for loss of an 890 m^2 lake sturgeon spawning site due to decreased water levels below a dam (Environnement Illimité Inc. 2009). Sites were strategically selected to be accessible during low water periods. Large boulders were also placed in the river to maintain higher water levels for overwintering habitat.

(c) Kuban River - Two large spawning beds were constructed (Vlasenko 1974). A bed of approximately 5 ha in area was constructed 300 m below the Krasnodar

Dam. A second spawning bed, approximately 7.5 ha in area, was constructed 1,500 m below the Fedorovsk Dam (Chebanov et al. 2008). Materials used included gravel and small aggregate placed directly on the river bed. During the first three years after construction these spawning sites were well used by stellate sturgeon (*Acipenser stellatus*). Egg densities were as high as 7,000 m^2 with pre-larvae estimated at 48 million fish in 1969. By the mid 1970's, the spawning grounds had deteriorated due to siltation and deposition of sand. It was concluded that artificial spawning grounds can be created but design must account for erosion and sedimentation.

(d) Manistee River - A bank stabilization project at Suicide Bend, a short distance below a known spawning site (Tippy Dam), also increased available spawning habitat for lake sturgeon. Spawning at the site was subsequently confirmed by the presence of sturgeon eggs (Chiotti 2004).

(e) Ottawa River - Rock-rubble was deposited in the Ottawa River, immediately below the Chenaux Generating Station in 2008. Drift net surveys are planned for 2011 to evaluate success (R. Threader, pers. comm.)

(f) Riviere des Prairies - Artificial sturgeon spawning grounds were constructed by Hydro Québec near an existing spawning site in 1985 (5,000 m^2) and again in 1996 (8,000 m^2). The location was approximately 250 m downstream of a hydroelectric station which had been constructed in 1928 (Verdon and Gendron 1991). Gravel and cobble (20-30 cm in diameter) was deposited to a depth of approximately 30 cm. This was encircled with a strip of 30-50 cm rock. Water depths at the site ranged from 1.5 – 3.0 m and current velocity was 1.0 m/sec (Dumont et al. 2009). Pre- and post-project monitoring indicated that egg-larvae survival increased from 0.88% and 0.81%, respectively, in 1995 and 1996 (pre-treatment) to 5.43% in 1997, 3.65% in 1998, and 2.4% in 1999 (LaHaye et al. 1992. Dubuc et al. 1997). Average larval production also increased from 3.9 million (1994-1996) to 7.0 million (1997-2003).

Results from this project indicated that the best egg-larval survival rates corresponded with an average spawning bed area of 13 m^2 per female. Low egg deposition in 1998 was attributed to a decrease in water flows to less than 1,000 m^3/sec (Thibodeau et al. 1998). It was concluded that the new section of spawning ground had a positive impact on the reproduction of lake sturgeon in the Des Prairies River (Fortin et al. 2002, Garceau and Bilodeau 2004).

Figure 5. Artificial lake sturgeon spawning area which was created on the Riviere des Prairies (Photo by L. Bouthillier, Québec Ministère des Ressources Naturelles et de la faune du Québec).

(g) Riviere Ouareau - A major landslide occurred at the sole lake sturgeon spawning site in the Riviere Ouareau, Québec, in March, 1990. Approximately two-thirds of the spawning substrate was covered by a thick layer of clay and the river's flow regime was substantially altered. During the winter of 2007 and 2008, a total of 18,000 m^2 of new substrate was added to the site. In addition, two low level rock dams were constructed in an attempt to prevent dessication of eggs and fry during periods of extreme variation in water flow. Post-project assessment indicated that sturgeon used both the natural and artificial sites in 2007 and 2008 (LaHaye et al. 1990).

(h) Riviere Saint-Maurice - In August 1999, an artificial lake sturgeon spawning area (2,100 m^2) was created downstream of the La Gabelle dam and adjacent to an existing spawning site. The project involved construction of 30 small artificial spawning sites for sturgeon. Each series of spawning sites measured 1 m in height and 3 m in width and consisted of several large boulders with finer materials (30-400 mm diameter) placed immediately downstream. Most of the sites were situated in the center of the river. In total, 2,100 m^2 of new spawning habitat was created to supplement existing sturgeon spawning grounds (Faucher 1999, 2001). This project was intended to compensate for fish habitat alterations associated with renovations to a Hydro Québec hydroelectric facility. Assessments conducted in 2000 and 2001 indicated that the spawning grounds were used by lake sturgeon (and seven other fish species) under a wide range of water flows (GDG Conseil Inc. 2001). In fact, lake sturgeon egg densities were greater on the new shoal than on the existing spawning shoal.

(i) St. Lawrence River - There have been several lake sturgeon spawning bed creation and enhancement projects on the St. Lawrence River:

Odgensburg - This project involved the creation of a spawning ground for lake sturgeon in the St. Lawrence River near Odgensburg, New York. A total of 405 m^3 of clean limestone was placed in 4-5 m of water and at a thickness of 30 cm to create a spawning ground measuring 36 m^2 in area. Successful spawning was documented at the artificial site for three successive years (Lapan et al. 1997). In one assessment study, it was estimated that 275,000 lake sturgeon eggs were present on one 0.075 ha site (Johnson et al. 2006). Subsequently, excessive growths of cladophora developed, the site became silted, and infested with zebra mussels. Despite efforts to clean the substrate there was no evidence of continued use after that point.

Iroquois – In October 2007, two spawning grounds for lake sturgeon were constructed at the Iroquois water control structure (one upstream and one downstream). Sites were based on egg trapping assessments which had been conducted in 2004. Each spawning ground consisted of gravel 5-10 cm in diameter deposited at a thickness of approximately 0.3 m. Ten large boulders, each measuring 1 m in diameter, were placed immediately downstream of the spawning ground to serve as a current break. The sites were in 10-12 m of water with current velocities of 0.6-0.7 m/sec. Each spawning ground covered an area of approximately 929 m^2. Successful spawning activity and hatching was documented in 2008 (McGrath 2009).

Beauharnois – In the fall of 1998, an artificial lake sturgeon spawning ground, measuring 2,000 m^2 in area, was created in the St. Lawrence River downstream of the Beauharnois power dam. The site was near a location where lake sturgeon were known to concentrate. Post-project monitoring for three subsequent years indicated that the site was not being used by sturgeon. Failure was attributed to substrate siltation, presence of aquatic vegetation, and altered flows which limited the attraction to sturgeon (Gendron et al. 2002). Despite efforts to clean the substrate the project was deemed to be unsuccessful and it was recommended that future efforts be directed to other sites.

(j) St. Louis River – This cooperative project, involving the Wisconsin and Minnesota Departments of Natural Resources and the Nature Conservancy, was completed in 2009. It involved the deposition of approximately 1,500 tons (200 truckloads) of rock and boulders to create riffles and pools for lake sturgeon spawning below the Fond du Lac dam on the main channel of the St. Louis River, a Lake Superior tributary. Material was hauled to the site during the winter and placed into the channel during the summer.

Figure 6. Lake sturgeon spawning ground enhancement below the Fond du Lac dam on the St. Louis River (left). Placement of rock and boulders (right). (Photos courtesy of Clint Austin, Duluth News Tribune).

(k) Upper Black River – In 1972, four artificial spawning reefs, comprised of rip-rap cobble, were constructed in the Upper Black River, Michigan, for lake sturgeon. In subsequent years much of the reefs have become covered with sediment which has greatly reduced its effectiveness (Smith and Baker 2005).

(l) Volga River – A spawning bed for lake sturgeon was constructed 380 km downstream of the Volgograd hydroelectric station. Medium-sized (5-10 cm) gravel was used to create a submerged bank ridge on the bottom of the river. The spawning site measured 10-12 m in width and 1 km in length (Khoroshko and Vlasenko 1970). The site was located in 3 - 4 m of water with flows ranging from 0.5 – 1.0 m/sec. Subsequent evaluation indicated that the site was hardly ever used by spawning sturgeon. It was concluded that the location was too far downstream from the existing spawning site at the base of the hydroelectric station.

(m) Wolf and Fox Rivers – Rip rap was placed along the banks at a number of sites on both the Wolf and Fox Rivers, Wisconsin. Material was deposited on the outside bends of the rivers along the entire slope of the bank to below the water line. These areas were exposed to currents exceeding 5 m/sec. These sites have been utilized by spawning lake sturgeon for many years (Folz and Meyers 1985). Use of rock 15-45 cm in diameter was recommended for future projects.

While the construction of new or enhanced spawning grounds has proven somewhat successful, their use by sturgeon depends on a suitable water discharge regime to not only provide suitable incubation conditions but also to keep the substrate clean of silt and sediment.

There are isolated instances of lake sturgeon using spawning areas created for other fish species. For example, a spawning area originally created for American shad (*Alosa sapidissima*) on the Ottawa River at Carillon has been used by lake sturgeon (Provost et al. 1984, Rochard et al. 1990). The artificial spawning grounds were comprised of gravel and boulders with a current velocity of approximately 1.0 m/sec.

Other habitat types are also important to maintain self-sustaining sturgeon populations. For example, pre-spawn staging habitats in proximity (i.e., < 3 km) to spawning sites are believed to be essential in many Great Lakes tributaries. Daughtery et al. (2007) concluded that a lack of high quality staging habitat could have a negative effect on the potential to sustain a lake sturgeon population. In some instances the installation of current deflectors (e.g., wing dams and tree revetments) could be used to create sturgeon staging areas near spawning sites.

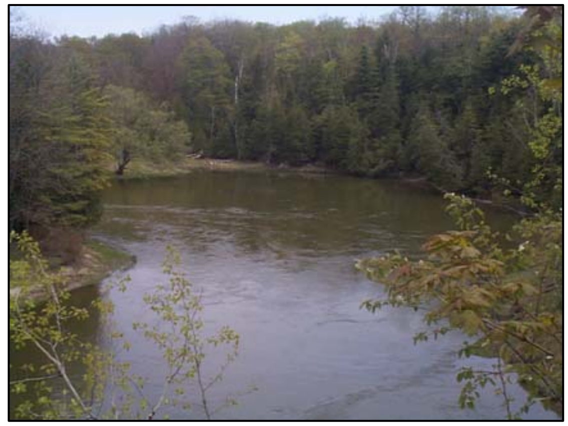

Figure 7. Large, deep pool on the Nottawasaga River, Ontario, below a lake sturgeon spawning site. This pool is used by staging lake sturgeon prior to spawning and by fish moving downstream after spawning (MNR photo).

Although there has been some success in spawning bed creation and enhancement, maintenance of existing sturgeon habitat may provide the greatest protection to the species. This may involve the identification and protection of important sturgeon habitat as well as enhancement and remediation. Evaluating a river system from a habitat availability perspective allows for the assurance that habitats exist for all life history phases of lake sturgeon.

2. Fish Passage

Restoring connectivity is believed to be an important recovery strategy in river systems which have been fragmented by dams (Jager 2006b, Wozney et al. 2011). Auer (1996b) recommended that fisheries managers give fish passage over barriers a higher priority than habitat enhancement for populations restricted in range. Prior to facilitating passage, consideration needs to be given to water quality conditions and habitat suitability in the reservoir and river upstream and what measures exist to prevent mortality during downstream migration over hydroelectric facilities (Y. Jager pers. comm.).

Most measures to facilitate upstream access fall within three general categories: trap and transfer; fishways; and fish lifts. Fishways in North America have been designed primarily for salmonids and are not well suited for sturgeon. In comparison with other fish species, lake sturgeon are relatively poor swimmers. As a result of their body shape, sturgeon have less thrust and greater drag than salmonids so elevated swimming speeds impose a high energetic cost (Webb 1986, Peake et al. 1997) Fishway designs requiring fish to jump from one step to the next are generally not appropriate for the passage of sturgeon (Webb 1986, Peake et al. 1997). Fishway design considerations for sturgeon are summarized in Appendix 3 and a listing of fishways which have been designed and constructed to pass sturgeon is presented in Appendix 4.

Although there are some instances of subadult sturgeon using vertical slot fishways (Hay-Chmielewski and Whelan 1997, Anderson et al. 2007), most structures do not meet the requirements of sturgeon (Rosenthal 2008). With the exception of the low head Eureka fishway on the Fox River, most fish passes which have been constructed with the intention of facilitating upstream access of sturgeon have been unsuccessful (Warren and Beckman 1993, Chebanov et al. 2008).

Kynard et al. (2003) experimented with a spiral-side baffle fish ladder for juvenile lake sturgeon. Gravity fed water was regulated by a control valve at the upper end so that velocity did not change from the top to the bottom of the ladder. Slope of the ladder was 6% and side baffles alternated on the inside and outside walls of the flume. This provided the opportunity for fish to swim continuously or rest in an eddy behind a baffle. Overall, this type of fish ladder showed that both lake sturgeon and several other riverine fish species were able to move upstream. The repeated testing of lake sturgeon demonstrated great variability among individual fish for passage performance. Tests were done using both a single and double loop fish ladder but little difference in success between the two was observed.

Fish lifts operate on the concept of attracting fish into a collecting device. When the collecting device is filled with fish it is lifted to the level of the head pond where they are released. This process is repeated many times during the spawning period. The success and efficiency of fish lifts has generally been poor for sturgeon. This has been attributed to the inability to attract sturgeon into the lifting device.

Figure 8. Attracting sturgeon to the fishway entrance is a key consideration for any upstream fish passage structure (Photo by T. Haxton).

Gertsev and Gertseva (1999) reported that, in the Volga River system, only

10% of the sturgeon were successfully lifted above dams. Over a twenty-two year period, Kynard (1998) reported the ascent of only 97 shortnose sturgeon from a fish lift at the Holyoke Dam on the Connecticutt River. He found that the number of sturgeon passed annually was only a small portion of the number of fish present below the dam. One of the reasons for poor passage was attributed to an insufficient amount of flow and depth of water to attract sturgeon to the entrance of the fishlift.

Where fish passage strategies are inappropriate or unsuccessful, physical relocation may provide a viable option to support fish passage. These activities are most successful when suitable spawning habitat is available upstream and where measures to ensure safe downstream migration (by adult and young-of-year sturgeon) are addressed.

Lake sturgeon have the ability to move upstream in water velocities exceeding 1.5 m/sec by moving into shallower water and staying close to the bottom where the current is slower (Aadland 2007). Sturgeon and paddlefish have been found to have the capability to negotiate dams under open gate conditions during periods of high water (Brooks et al. 2009). Sturgeon can also successfully ascend a barrier if provided with a series of small elevation changes. McLeod and Debruyne (2009) reported that lake sturgeon were able to move upstream beyond a 7 m high barrier by utilizing a series of numerous shallow rapids spread out over a distance of approximately 2 km. With some low head barriers, natural bypass channels have been created to successfully allow upstream and downstream passage of several fish species including lake sturgeon (White and Mefford 2002, Aadland et al. 2005).

Effective passage of sturgeon around hydroelectric facilities and other high relief structures remains problematic (Ead et al. 2004, Lagutov and Lagutov 2008). The key to passage success seems to depend on letting the behaviour and characteristics of the target species guide all aspects (i.e., entrance type and location, access route, size of facility, attractant flows, etc.) of passage development (Rodriguez et al. 2006). There is a definite need for research into the design of safe and effective upstream passage for sturgeon (Holey et al. 2000, Galarowicz 2003).

Figure 9. Sturgeon often negotiate strong currents by moving to shallow, lower velocity waters near the shoreline (MNR photo).

3. Dam Modification or Removal

In some situations, low head dams may be modified to improve upstream fish access. In 2002, the Heiberg Dam on the Wild Rice River, Wisconsin, was breached after heavy rain. After repairing the breach, the low head dam was modified by cutting a six foot notch intended to provide upstream passage for species including walleye, bass (*Micropterus* spp.), channel catfish (*Ictalurus punctatus*), and lake sturgeon

(Abraham 2008). Large rocks were also added to provide refuge when moving upstream. There have been several dam modification and removal projects on the Red River, Minnesota, and its tributaries to improve upstream access for lake sturgeon (Abraham 2008). These have included the construction of low velocity bypass-type fishways and natural-type fishways created by installing rock and rip-rap below several small impoundments to form step pools and rapids similar to natural spawning areas (Aadland 2007).

Dam removal can restore many ecological benefits. These include unimpeded flow (i.e., return to natural flows) and fish movement, improved water quality, decreased water temperatures, restoration of the river channel, and an increase in biodiversity (see review by Bednarek 2001). The removal of the Sandstone dam on the Kettle River, Minnesota, created new spawning habitat in a portion of the former reservoir (Morse et al. 1997).

Wentworth (2001) concluded that dam removal would increase sturgeon spawning habitat and restore riverine habitat for juvenile sturgeon in the Lamoille River, Vermont. Kanehl et al. (1997) found that dam removal benefited habitat, fisheries potential and biotic integrity in the Milwaukee River, Wisconsin. Auer (1996b) concluded that fisheries managers should give barrier removal higher priority than habitat enhancement for sturgeon populations which are isolated or restricted in range.

There are a number of factors to be considered when assessing dam removal as an option for river restoration (Shuman 1995). Many dams serve as a means to prevent flooding and to generate power. In the Great Lakes basin, many dams which impede sturgeon movements also serve to block spawning migrations of the parasitic, non-native sea lamprey (*Petromyzon marinus*).

Sediment transport and channel stability after dam removal also need to be evaluated (Bednarek 2001). Short term impacts often include an immediate increase in sediment load downstream. Removal of the Sandstone dam on the Kettle River, Minnesota, resulted in sedimentation and loss of a lake sturgeon spawning site and deep pool habitat immediately downstream (Morse et al. 1997).

Dam removal has the potential to alter downstream habitat some of which may be rehabilitated habitat. Dam removal also means the loss of reservoir habitat and the fisheries it supported. Finally, the impacts of dam removal on other aquatic and terrestrial biota requires consideration.

4. Upstream Passage Through Navigation Locks

Relatively low head navigation dams also represent barriers to sturgeon movement (Knights et al. 2002, Cech and Doroshov 2004). In some cases, fish locks, operating on the same principle as navigation locks, have been constructed to facilitate fish passage. Due to their limited capacity, discontinuous operation, and problems of attraction, they have generally been considered ineffective (Larinier 2001). In many cases, the required method of operation is incompatible with navigation requirements. In a fish passage study on the upper Mississippi River, Brooks et al. (2009) found that, although fish including lake sturgeon frequented and occasionally used lock chambers for movements, lock chambers were not routinely used for passage.

During a five year study, few, if any, shortnose sturgeon passed through a navigation lock system on the Cooper River, South Carolina (Cooke et al. 2002, Cooke and Leach 2004). Similarly, Monan et al. (1970) found that less than 1.5% of migrating fish used the navigation lock at the Bonneville dam on the Columbia River. Moser et al. (2000) reported techniques to improve the passage of American shad (*Alosa sapidissima*) through low elevation dams with navigation locks on the Cape Fear River, North Carolina. Operating techniques to improve sturgeon through navigation locks might include:

- Operating the locks at night when sturgeon are often more active;
- Ensuring there is sufficient flow to attract fish into the lock as well as proceed upstream;
- Filling the lock slowly with water to minimize turbulence;
- Leaving the upper gates open for an extended period of time to allow sturgeon to exit the lock upstream; and
- Extending the operation of locks to accommodate sturgeon passage.

5. Water Quality Improvements

Pollution and degraded water quality has been identified as a factor limiting sturgeon abundance in many locations (Harkness and Dymond 1961, Dick et al. 2006). In the Riviere L'Assomption, lake sturgeon spawning beds were exposed to discharges of raw sewage. Based on a five year study of the effects on sturgeon larval production, it was concluded that there was massive egg and larval mortality attributed to raw sewage. After sewage treatment facilities were finally constructed, there was a ten fold improvement in larval production. The spawning site has now been recognized as a key site for biodiversity and management plans have been developed to ensure its protection and restoration (Dumas et al. 2003).

A dramatic recovery in lake sturgeon abundance in Rainy River and Lake of the Woods followed improvements in water quality in the Rainy River resulting from substantial reductions in the amount of wood fiber and untreated chemical wastes discharged by upstream pulp and paper mills (Mosindy and Rusak 1991). Similar improvements in water quality of the Genesee River, New York, contributed to the restoration of lake sturgeon (Dittman and Lowie 2001).

Activities contributing to siltation in sensitive areas, such as spawning sites, can limit lake sturgeon abundance. As such, avoiding or mitigating the factors contributing to siltation can reduce sedimentation of and damage to aquatic ecosystems, including essential habitat required by lake sturgeon. On the Upper Black River, Michigan, erosion control measures were initiated at three sites adjacent to known lake sturgeon spawning areas. The projects involved stabilizing the shoreline using bioengineering techniques including the use of large woody debris, installation of coconut fiber logs, terracing, and plantings of several thousand native plants. This served to prevent further erosion and reduce the input of sediment into the stream www.sturgeon fortomorrow.org/habitat.php).

6. Timing of Water-Related Activities

Water related projects that potentially impact sturgeon habitat can sometimes be modified to reduce or eliminate their impact. Auer and Baker (2002) recommended that sea lamprey chemical treatments, road and streambank construction projects and stocking programs involving predatory fish species should be delayed below sturgeon spawning sites to allow drifting larvae the opportunity to reach nursery areas in the lower river. Lampricide treatments should be scheduled to avoid sensitive sturgeon life history periods and be applied at concentrations that minimize risk to larval and juvenile sturgeon.

Dredging of river channels can result in substantial mortality to sturgeon larvae (Veschev 1981). Dredging projects involving navigation in channels and harbours in proximity to sturgeon habitat are best timed to avoid the critical spawning and larval period, Similarly, the alteration or removal of rock and gravel from known sturgeon spawning sites is best avoided in order to maintain reproductive success.

7. Downstream Guidance or Diversion

Lake sturgeon have been noted to display a relaxed downstream drifting behaviour with fish oriented tail first (Kynard et al. 2003). There appears to be limited body movement with the exception of fin movements for body orientation.

Lake sturgeon have demonstrated the ability to move downstream over natural barriers. McLeod and Debryune (2009) recorded downstream movements of five individual sturgeon over High Falls on the Namakan River, Ontario - an elevation drop of 6.8 m. Similary, some lake sturgeon have been known to move downstream over dams (Priegel 1973, Thuemler 1985).

Generally, downstream fish passage technology is less advanced than that for upstream passage (Larinier 2001). The effectiveness of mechanisms to bypass fish away from turbine intakes depends upon the ability to predict fish movements and behaviour (Davies 1988). Juvenile shortnose sturgeon have been observed to display extensive periods of complex movement as well as prolonged periods of inactivity in the presence of angled louvers (EPRI et al. 2006). The ability to guide fish away from turbine intakes seems to improve with size of fish (Coutant and Whitney 2000). There is also some evidence to indicate that intakes which are situated further from shore or at greater depth may be less likely to entrap downstream migrants (Pavlov 1989).

Mechanical barriers (e.g., screens, louvers, etc.) and behavioural barriers (e.g., air bubbles, acoustics, lights, etc.) have been used in an attempt to divert downstream migrating fish from water intakes (Marshall, Macklin and Monaghan 2007). Many of these diversionary options have been found to be ineffective at preventing entrainment of lake sturgeon (see reviews by Pavlov 1989, Zhong et al. 1995 and Schilt 2007). The guidance efficiency of angled bar racks and louvers for lake and shortnose sturgeon has been found to be low for small (< 200 mm) sturgeon but more effective for larger fish (Kynard and Horgan 2001, Amaral et al. 2002). Turbine bypass systems, designed for Pacific salmon at hydro facilities have achieved only varying degrees of success. Similarly, barrier nets have been used with some success (Hutchinson and Matousek 1988). All of these bypass systems incurred some amount of descaling, injury, and direct/indirect mortality (Ferguson 1992). Ontario Power Generation (formerly

Ontario Hydro) examined a number of physical barriers and behavioural technologies to prevent the downstream passage of lake sturgeon in the Adam Creek diversion. They concluded there was no practical or economically viable means of diversion and, since 1990, have physically relocated sturgeon which became entrained below the Little Long Generating Station reservoir (Barbour 2008).

Many hydroelectric dams do not have facilities to enable downstream fish passage. Risks for downstream passage of sturgeon need to be minimized before efforts are undertaken to provide upstream access for sturgeon (Jager 2006). Appropriate measures taken to prevent sturgeon entrainment at intakes of hydroelectric facilities can support downstream fish passage and help maintain connectivity. Despite the fact that little research has been done with respect to sturgeon, there are structural modifications and alternative techniques (see Ruggles and Murray 1983) which should be reviewed for effectiveness.

8. Operation of Hydroelectric Facilities

Best management practices have been developed to provide guidance to proponents and practioners with regard to minimizing impacts of new and existing hydroelectric projects on lake sturgeon (AECOM 2009). The establishment of base (minimum) flow releases or simulated "run-of-river" regimes at hydroelectric facilities can enhance conditions for aquatic biota, including sturgeon, downstream of the dam (Weisberg et al. 1990, Travnichek et al. 1995, Metcalfe et al. 2003, Fernandez and Metcalfe 2004). Flow management plans for regulated rivers based on minimum flows may be most effective when implemented in conjunction with plans that reduce the spatial and temporal variability of habitat availability particularly in shallow, slow-flowing habitats (Stanford et al. 1996, Shea and Peterson 2007).

The Prickett hydro facility on the Sturgeon River, Michigan, began as a "run-of-river" operation in 1990 after almost sixty years as a peaking facility. As part of the operating agreement, once water temperatures reached 8˚C for two consecutive days, specified minimal flows were required to be released for a period of 54 days in order to ensure spawning, hatch and drift of lake sturgeon (N. Auer pers. comm.). The hydro company also conducted physical manipulation of the river channel below the spillway to concentrate flow in areas suitable for spawning. This change in operating regime has resulted in a positive response in lake sturgeon spawning activity (Auer 1996a).

Thermal profiles downstream from a dam can be dramatically altered depending on where the upstream water is drawn from (Ruane et al. 1986). Kappenman et al. (2009) concluded that decreases in the natural temperature regime (from hypolimnetic releases) outside the preferred temperature ranges of sturgeon could result in decreased growth rates, increased mortality and decreased production of sturgeon. The development and implementation of downstream temperature regimes standards can ensure appropriate downstream conditions for sturgeon.

Hydrologic manipulation of river systems can be planned in a way to minimize the risk of entrainment, prevent disruptions to habitat and food availability and accommodate life history requirements of resident lake sturgeon. Hydroelectric operations conducted in a fashion so as to provide adequate flows and timing of flows to accommodate the upstream and downstream migration of spawning adults, egg incubation and larval drift can reduce impacts to lake sturgeon associated with the operation of the facility. Water management plans for individual facilities have been beneficial in mitigating impacts of hydroelectric operations in the past. There have also been instances (e.g., Lachine Rapids and Courant Sainte-Marie, St. Lawrence River) where proposals for new hydroelectric development have not proceeded because of environmental concerns including the desire to maintain free movements of migratory fish species such as lake sturgeon (Dumont et al. 2005).

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Glossary

Biodiversity – The variation of life forms within a particular ecosystem which is often used to measure the health of biological systems. The biodiversity found on earth today consists of many millions of distinct species which is the product of nearly 3.5 billion years of evolution.

Brackish – Water whose salinity is intermediate between freshwater and seawater.

Burst swimming speed – Swimming used for prey capture or predator avoidance (< 30 sec). This type of activity depends on anaerobic metabolism and quickly depletes short term energy reserves.

Channelization – The process of changing and straightening the natural path of a waterway.

Dredging – An excavation activity usually carried out at least partly underwater with the purpose of gathering up bottom sediments and disposing of them at a different location.

Entrainment – Involuntary capture and downstream passage of fish at a dam. Mortality due to entrainment varies according to the life stage and species of fish as well as physical parameters of water flow.

Erosion – The wearing away and transportation of soil, rocks, and dissolved minerals from the land surface or along shorelines by rainfall, running water, wind, wave and current action.

Fishway – A device or structure which allows a fish to pass around a barrier.

Habitat – The environment in which an organism lives and grows. For fish this includes spawning grounds and nursery, rearing, food supply and migration areas on which fish depend directly or indirectly in order to carry out their life processes.

Heterocercal tail – In fish, a tail in which the tip of the vertebral column turns upward, extending into the dorsal lobe of the tail fin; the dorsal lobe is often larger than the ventral lobe. The heterocercal tail is present in many fossil fish, in the sharks (*Condrichthyes*) and in the more primitive bony fish (e.g., the families *Acipenseridae* and *Polyodontidae*).

Home range – A term which describes the phenomena that a fish (or other organism) live and carry out many of their life processes within a relatively small restricted area.

Impingement – Fish which are pinned against the intake screens of a hydroelectric facility by the force of the intake water flow.

Lampricide – A chemical which is designed to target and kill larval lamprey in river systems before their recruitment to parasitic adults.

Littoral area – The shallow nearshore waters where light can penetrate to the bottom and where aquatic vegetation is present.

Methylmercury – An organometallic cation (CH_3Hg) which is a bioaccumulative environmental toxicant.

Peaking operation – Hydroelectric operation in which water is stored in a reservoir for a period of time and then spilled through the turbines to generate electricity when demand is highest.

Potamodromous – Fish which lives and moves solely within freshwater to forage and spawn.

Prolonged swimming speed – Swimming from 30 sec – 200 min in duration which utilizes both aerobic and anaerobic metabolism thereby resulting in fatigue.

Run-of river – Flows past hydroelectric facilities that are equivalent to flows being received from upstream (i.e., little or no storage of water).

Scute – A bony external plate or scale.

Sedentary behaviour – A type of lifestyle or behaviour characterized by being relatively inactive with little exercise and few, if any, significant movements.

Sedimentation – The removal, transport, and deposition of detached soil particles by flowing water or wind resulting in the accumulation of organic and inorganic matter of the lake/river bottom.

Substrate heterogeneity – A diversity in the size and types of materials comprising the substrate.

Sustained swimming speed – Swimming which depends on aerobic metabolism and does not result in muscular fatigue. This type of movement (> 200 min in duration) is used in migrations, foraging, and other routine activities.

Thalweg – A term which signifies the deepest continuous line along a valley or watercourse which marks the natural direction (or profile) of a watercourse. The thalweg is almost always the line of fastest flow in any river.

Vertical slot fishway – A series of small dams and pools of regular length to create a long, sloping channel for fish to travel around an obstruction. Each "dam" has a narrow slot in it near the channel wall. This allows fish to swim upstream without leaping over an obstacle. Vertical-slot fish passages also tend to handle reasonably well the seasonal fluctuation in water levels on each side of the barrier.

Appendix 1. A summary of habitat conditions for various life stages of lake sturgeon.

Life History Stage	Habitat Requirements
Spawning Habitat	
Staging areas	• Water > 2 m deep in proximity to spawning site (Daugherty et al. 2008). • Pools 2-10 m in depth (Bruch and Binkowski 2002). • Situated < 3 km from spawning habitat (Daugherty et al. 2007).
General spawning location	• Rivers with fast flowing water. • Below barriers in rivers (Billard and Lecointre 2001). • Outside of river bends or meanders. • Rocky, wave-exposed shoals or ledges in lakes (Wilson and McKinley 2004, Peterson et al. 2007). • Former spawning sites in Lake Erie were over rocky substrate located 13-19 km offshore (Carlson 1995). • Lake sturgeon display a high degree of fidelity to the river of their origin (Auer 1999, Bemis and Kynard 1997, Elliott 2005, Folz and Meyers 1985, Priegel and Wirth 1978).
Spawning substrate	• Cobble and boulders (> 15 cm in diameter)(Threader et al. 1998). • Coarse (≥ 2.1 mm) substrates (Daugherty et al. 2008, Peterson et al. 2007). • Strong association with boulder, cobble, rubble, gravel, sand and clay substrates (Lane et al. 1996a). • Gravel substrate (Billard and Lecointre 2001). • Silt and algae free (Environnement Illimité 2004). • Substrate heterogeneity is important (Chiotti et al. 2008). • Zebra mussels not found at any Detroit River spawning sites (Caswell et al. 2002). • Void of aquatic vegetation (LaHaye et al. 2003, Desloges et al. 2004). • Fine – coarse gravel interspersed with boulders and large rocks (LaHay et al. 1992, Desloges et al. 2004). • Medium grain substrates (gravel and cobble)(Shaw 2010). • Substrates with an abundance of interstitial spaces provide greatest incubation and hatch success (Caroffin et al. 2010).
Depth of spawning	• 0.3 – 6.0 m (Scott and Crossman 1973). • 0.6 – 9.0 m (FAO 2009). • 9 - 12 m (Manny and Kennedy 2002). • 0.6 – 4.7 m (Wilson and McKinley 2004). • < 10 m (McGrath 2009). • 1 – 5+ m (Lane et al. 1996a). • 1.5 – 3.0 m (LaHay et al. 2003, Chiotti et al. 2008, Aadland and Kuitunen undated). • 0.1 – 1.5 m (LaHaye et al. 1992). • 0.5 – 6.0 m (Dick et al. 2006). • 0.5 – 2.5 m in the Genessee River (Dittman et al. 2000). • 1.0 – 3.0 m (Threader et al. 1998). • < 3.5 m (Billard and Lecointre 2001). • Deep (2 – 10 m) lake shoals having strong lake currents (L. Mohr pers. comm.). • 1 – 5 m (Shaw (2010).

Life History Stage	Habitat Requirements
Water velocities	• Sturgeon moved onto spawning sites at flows of at least 14-23 m^3/sec (Friday and Chase 2005, Friday 2006a). • 0.6 – 2.5 m/sec (Thuemler 1991). • 0.46 – 0.6 m/sec or higher (Johnson et al. 2006). • 0.15 – 0.70 m/sec (Threader et al. 1988). • 0.5 – 2.0 m/sec (Bruch et al. 2009). • 1.7 – 5.5 m/sec (Shaw 2010) • Flow rate between 1.02 – 1.91 m/sec (LaHaye et al. 2003). • > 0.1 m/sec (Kempinger 1988). • 0.4 – 1.8 m/sec (Billard and Lecointre 2001). • 0.34 – 1.32 m/sec (Chiotti et al. 2008). • > 0.5 m/sec (McKinley et al. 1998, Bruch and Binkowksi 2002). • 0.3 – 2.0 m/sec optimal (Threader et al. 1998). • 37 – 84 cm/sec (LaHaye et al. 1992). • 0.4 – 1.0 m/sec in the Detroit River (Caswell et al. 2004). • 0.5 – 1.3 m/sec (Peterson et al. 2007). • No lake sturgeon eggs found in areas with currents exceeding 2 m/sec (LaHay and Fortin 1990).
River gradient	• Moderate to high (≥ 0.6 m/km)(Daugherty et al. 2008). • >5 feet/mile (Hay-Chmielewski and Whelan 1997).
Water quality	• Dissolved oxygen levels for incubating sturgeon larvae optimal at > 7.5 mg/l (Yurovitskii 1964). • Abnormally high (supersaturation) oxygen levels have adverse or lethal effects on sturgeon embryos and larvae (Yurovitskii 1964).
Water temperatures (˚C)	• Sturgeon arrive at spawning site at water temperatures of 8.0 – 10.0˚C (McKinley et al. 1998). • Spawning commences at 14 - 15˚C (Johnson et al. 2006). • Spawning begins at 11.7˚C (Folz and Meyers 1985). • Spawning commences between 11.0 – 11.6˚C (LaHaye et al. 1992). • Egg deposition at 14.0º C in the Detroit River (Caswell et al. 2002). • Optimal water temperatures are 13 - 18˚C (Scott and Crossman 1973). • 10.0 - 20.0˚ C; optimal 14 - 16˚C (MNR 2009). • 11.1 – 14.8˚ C (Chiotti et al. 2008). • 16.0 – 18.0˚ C (Haxton 2008). • 13.0 – 21.0º C (Lane et al. 1996a). • 10.0 – 15.0˚ C (Auer 1996b, Kempinger 1988). • 13.0 – 18.0˚ C (Nichols et al. (2003). • Peak spawning at 11.0 – 12.0º C (Scholl 1986). • Peak spawning at 12.0 – 15.0º C (Verdon and Gendron 1991). • Spawning at 13˚ C (Phoenix and Rich 1988). • Greatest spawning activity at temperatures from 11.5 -16.0˚ C (Bruch and Binkowski 2002). • 12.0 – 16.0˚ C optimal (Threader et al. 1998). • 11.5 – 15.0º C in the Eastmain River (Environnement Illimité 2004). • 11.0 – 17.0º C in the Lower Nelson River (MacDonell 1995). • 12.2 – 14.2º C in the des Prairies River (Dubuc et al. 1997). • 12.0 – 15.0º C optimal (Bruch et al. 2009). • Optimal egg survival at temperatures of 14.0 – 17.0˚ C (Wang et al. 1985).

Life History Stage	Habitat Requirements
<u>Young-of-the-Year Habitat</u>	
Substrate	• Shallow, sandy substrates devoid of vegetation (Kempinger 1996, Peake 1999, Benson et al. 2005). • Abundance of food especially *Diptera* larvae (Benson et al. 2005). • Sand substrates (Benson et al. 2005). • Substrates devoid of aquatic vegetation (Kempinger 1996). • Young-of-year sturgeon observed in areas of sand and pea gravel immediately below woody debris (Holtgren and Auer 2004).
Depth	• Young-of-year in water 0.75 m deep (Kempinger 1996). • 20 - 55 cm in Kaministiquia River (Friday 2006a) • Relatively shallow (< 2m) water (Benson et al. 2005).Shallow (< 0.5 m in depth) bays in the Kenogami River system (Ecologistics Ltd. 1987). • Lake sturgeon larvae were found throughout the water column when drifting downstream but usually were found nearer to the surface than to the substrate (Caroffino et al. 2009). • Distribution of drifting lake sturgeon larvae is neither benthic or uniform (Carofinno et al. 2009).
Water quality	• Dissolved oxygen levels of > 3 mg/l (Doudoroff and Shumway 1970). • Growth of larvae and young fry of stellate sturgeon was depressed when dissolved oxygen levels decreased from 7.0 to 6.3 mg/l (Oliphan 1940).
Water temperatures (º C)	• 14.0 – 17.0º C optimal for egg/larval development (Wang et al. 1985, Cech and Doroshov 2004). • Hatching rates decrease at temperatures > 20º C. • Mortality occurs starting at 20.0º C (Wang et al. 1985).
Water velocities	• Reduced current velocity and lower stream gradients often found in the lower reaches of the river (Auer and Baker 2002, Daugherty et al. 2008). • Detectable current (Kempinger 1996). • 8.4 cm/sec is the maximum velocity that lake sturgeon larvae can sustain without drifting downstream (Scheidegger and Bain 1995). • Low velocity (< 30 m^3/sec) areas (Friday 2006b). • Low (< 0.6 m/sec) current velocity (Benson et al. 2005). • Low flow areas in river bends (L. Mohr pers. comm.).
<u>Juvenile (Subadult) Habitat</u>	
General	• High site fidelity with very little movement (Lord 2007). • Juveniles and adults inhabit different areas (Ecologistics Ltd. 1987). • Prefer nearshore, slow water currents in the lower Niagara River (Hughes and Haynes 1999).
Substrate	• Habitat preferences determined largely by food abundance (Beamish et al. 1998). • Sand, gravel and organic substrates (Smith and King 2005, McCabe et al. 2006).

Life History Stage	Habitat Requirements
<u>Juvenile/Subadult Habitat (cont'd)</u>	
Substrate	• Flat areas selected – uneven substrates avoided (Sbikin and Bibikov 1988). • Sections of river having sandy substrate (Benson et al. 2005, Nilo et al. 2006). • Sand bottom near the mouth of the Rainy River in Lake of the Woods (Mosindy and Rusak 1991). • Clean sand and gravel substrates (Boase et al. 2009). • Gravel substrate (Lord 2007). • Greatest numbers of juvenile lake sturgeon were found over clay substrate in the des Prairies and l'Assomption rivers (LaHaye 1982). • Clay and sand substrates (Chiasson et al. 1997). • Pea gravel and sand (Bruch et al. 2009). • Always found over sand substrate in the Mississippi River (Spier et al. 2009). • Substrates dominated by sand in the Missouri River (Ridenour et al. (2009). • High affinity for sand and silt; medium affinity for gravel and rubble (Lane et al. 1996b). • Various substrate types (Barth et al. 2009).
Depth	• 4 – 6 m near bends of rivers with associated rock bluffs in the upper Tennessee River (Huddleston and Wilson 2007). • Most juvenile sturgeon were deeper than 9m – most common at 12-18 m in the St. Clair River (Lord 2007). • 2 – 5+ m (Lane et al. 1996b). • Juveniles and adults may occupy similar depths in the lower • Ranges from 4-17 m during the day; frequently > 10m (Holtgren and Auer 2004). • Predominantly found at 3.0 – 4.5 m in Lake Nipigon (Harkness and Dymond 1961). • 3 - 12 m in the St. Louis River (Schram et al. 1999). • Water depths > 13.7 m (Barth et al. 2009). • 1 - 7 m in the Genessee River (Dittman and Zollweg undated). • > 10 m in depth (Boase et al. 2009). • > 2 m in Lake St. Clair (Thomas and Haas 2002). • 12 – 20 m in the Ottawa River (Haxton 2009). • Highest densities at depths > 13.7 m (Barth et al. 2009) • Broad range of depths (Daugherty et al. 2008). • Shallow (<5 m) at night and deeper (>7.5 m) offshore areas during the day (Holtgren and Auer 2004). • Offshore habitat (deeper than adults) (Holtgren and Auer 2004, Smith and King 2005). • Water 3-6 m in depth (Nilo et al. 2006). • 3 – 8 m near the mouth of the Rainy River in Lake of the Woods (Mosindy and Rusak 1991). • Juveniles and adults may occupy similar depths in the lower Niagara River. • Stocked lake sturgeon generally inhabited waters <30 m deep but were captured as deep as 60 m in Lake Superior (Schram 2007). • Depths > 13.7 m (Barth et al. 2009).
Water quality	• Carbon dioxide levels as high as 50 mg/l can impair appetite and growth of young sturgeon (Lozinov 1953).

Life History Stage	Habitat Requirements
Juvenile (Subadult) Habitat (cont'd)	
Water velocities	• Flow rates of 40 – 75 cm/sec preferred (Threader et al. 1998). • Moderate current of 0.25 – 0.5 m/sec (Nilo 1996). • 10-40 cm/sec (Dittman and Zollweg undated). • Detectable (> 0.20 m/sec) water velocities (Barth et al. 2009). • Rarely found at water velocities exceeding 70 cm/sec (Billard and Lecointre 2001). • Areas with detectable (> 0.20 m/sec) water velocities (Barth et al. 2009). • Detectable water velocities (> 0.20 m/sec) (Barth et al. 2009)
Home range	• 0.8 – 10.8 km^2 with a high degree of home range overlap (Lord 2007).
Water quality	• Active at water temperatures of 19.0º C (Cech and Doroshov 2004). • Optimal water temperatures below 25.0º C (Chech and Doroshov 2004). • Can tolerate salinity < 23 ppt salinity. • Sensitive to decreases in dissolved oxygen (Klyashtorin 1976).
Adult Habitat	
General	• After spawning, return to home areas and/or feeding areas followed by late summer migration to wintering areas (Rusak and Mosindy 1997, Thuemler 1997, Block 2001, Adams et al. 2006). • Highly productive shoal areas of lakes and rivers (Wilson and McKinley 2004). • Open water and embayments of the St. Marys River (Kauss 1991). • Sedentary behaviour during the summer and winter (Fortin et al. 1993, Friday and Chase 2005). • Deep (4-7 m), slow velocity pools along river bends (McLeod et al. 1999). • Habitat preferences largely based on prey availability (Hay-Chmielewski 1987, Mosindy and Rusak 1991, Werner and Hayes 2005). • Unrestricted access upstream and downstream. • Absence of aquatic vegetation (Ecologistics Ltd. 1987). • Sometimes found in dense aggregations in Lake St. Clair (Thomas and Haas 2004). • Avoid shallow rapids in the winter (McLeod and Debruyne 2009).
Substrate	• Feeding areas are flat with sand, mud and gravel substrate. • Presence of boulders is important (Werner and Hayes 2005). • Sand substrate utilized most (Morse et al. 1997). • Silt and silt-sand more preferred (Haugen 1970, Knights et al. 2002). • Muck was the preferred substrate in Black Lake, Michigan (Hay-Chmielewski 1987). • High proportion of sand and silt (Haugen 1970). • Sections of river having muddy substrate (Nilo et al. 2006). • Sand and clay (Chiason et al. 1997, Haxton 2002). • Overwintering sites dominated by fine substrates (Shaw 2010).

Life History Stage	Habitat Requirements
<u>Adult Habitat (cont'd)</u> Depth	• Refuge pools (6 – 11 m in depth) required for overwintering (McKinley et al. 1998, Threader et al. 1998, Aadland and Kuitunen undated). • Shallow (2-6 m) littoral areas (Seyler 1997). • > 2 m (Haugen 1970, Thomas and Haas 2002). • 4.6 – 9.2 m (USFWS 2008). • Usually 5 – 10 m but consitently at depths of greater than 10 m in the Winnipeg River (Dick et al. 2006). • 2 – 7 m in the Genessee River (Dittman et al. 2000). • 4 – 9 m (Houston 1987, Wilson and McKinley 2004). • Optimal depth (day and night) was 3.2 m (Morse et al. 1997). • Depths of 3 - 5 m most common (Knights et al. 2002). • 10.3 m in summer and 7.1 m in winter in Black Lake, Michigan (Hay-Chmielewski 1988). • Mean depth of 3.5 m (maximum 12 m) in the Ottawa River (Haxton 2003). • > 2.5 m in the Mattagami River (McKinley et al. 1998). • Overwinter at depths > 6 - 7 m; rarely deeper than 10 m in Lake of the Woods (Rusak and Mosindy 1997). • 10.3 m in summer and 7.1 m in winter (Hay-Chmielewski 1987). • Thalweg depths of > 2 m in the South Saskatchewan River (Haugen 1970). • Depths ranging from 2.4 – 9.8 m (average 4.5 m) in Chipman Lake (Goddard 1963). • Prefer depths < 9 m during cooler months (Peterson et al. 2007). • Rarely found in waters greater than 6 - 7 m in depth (Harkness 1980). • Overwintering sites had depths ranging from 1 - 40 m (Shaw 2010).
Water velocities	• Moderate flow (e.g., < 6 m/sec) in rivers; island and mainland shorelines with water movement in lakes (MNR 2009). • Water velocities ranging from 15-50 cm/sec (Seyler 1997). • Water velocities ranging from 0 – 75 cm/sec; median 13-22 cm/sec (Knights et al. 2002). • < 80 cm/sec (Haugen 1970). • 0 – 25 cm/sec in the Genessee River (Dittman et al. 2000). • Velocities < 80 cm/sec in the South Saskatchewan River (Haugen 1970). • Adults seem to prefer the faster currents of the Niagara River and its confluence with Lake Ontario (Hughes and Haynes 1999) • 3.0 – 12.0 cm/sec (Morse et al. 1997). • Areas where water velocities do not exceed 70 cm/sec (Dick et al. 2006).
Water quality	• Some tolerance to brackish water (Dick et al. 2006). • Adapted to water temperatures ranging from 3 - 24º C (Dick et al. 2006). • Dimly lit, moderately turbid waters generally preferred (Cech and Dorosov 2004). • Generally prefer cool (< 25º C) water temperatures (Cech and Doroshov 2004). • Prefer water temperatures in the 11 - 18º C range (USFWS 2008).

Life History Stage	Habitat Requirements
<u>Adult Habitat (cont'd)</u>	
Home range	• Spatially extensive but adults frequent core areas (Knights et al. 2002, Smith and King 2005). • Mean home range size of 4,625 ha in Rainy Lake (Adams et al. 2006). • Mean home range was 1,528 ha for four Ottawa River sturgeon (Haxton 2003). • Individual home range ranges from 0.4 – 16.1 ha in rivers and up to 20x larger in lakes (Randall 2008). • Home area was a 10 - 12 km stretch of the Detroit River (Caswell et al. 2002). • Home range location varied with season in the Mississippi River (Snellen 2008). • Large movements within and between pools in the Mississippi River (Bruch et al. 2009).

Appendix 2. Ecological effects of dams and hydroelectric facilities on sturgeon and other aquatic biota.

Effect	References
Spring floodwater discharges reduced or altered.	B.C. Environment (1997), Clay (1995), Haxton (2002), Khoroshko (1972), Larinier (2001), Liu and Yu (1992), McLeod et al. (1999), Paragamian et al. (2002), Rosenberg et al. (1997), Shuman (1995), Zhong and Power (1996b)
Reduction in sturgeon spawning effectiveness and recruitment.	Caroffino et al. (2010), Chebanov et al. (2002), Ferguson and Duckworth (1997), Flowers et al. (2009), Gao et al. 2009, Khoroshko (1972), Liu and Yu (1992), Lukens (1981), National Marine Fisheries Service (1998), Poff and Zimmerman (2009), Prosser (1986), Tyus and Winter (1992), Veshchev (1991), Veshchev and Novikova (1984), Votinov and Kasyanov (1979)
Altered thermal regime downstream.	Baxter (1977), Casado et al. (1989), Clarke et al. (2008), Clarkson and Childs (2000), Clay (1995), Graham (1985), Grizzle (1981), Hauer and Stanford (1982), Horne et al. (2004), Kappenman et al. 2009, Khodorevskaya et al. (2009), Koroshko (1972), Larinier (2001), Ligon (1995), Liu and Yu (1992), Olden and Naiman (2009), Paragamian et al. (2001), Penaz et al. (1999), Peters (1982), Saila et al. (2005), Spence and Hynes (1971), Tyus and Winter (1992), Zhong and Power (1996b)
Sturgeon behaviour affected.	Khodorevskaya (1980), Koroshko (1972), Modde and Schmulbach (1977), Poddubnuy et al. (1974), National Marine Fisheries Service (1998), Veshchev and Novikova (1984), Zakharyan (1971), T. Haxton (pers. comm.)
Reduction in biodiversity/productivity downstream.	Beamesderfer et al. (1995), Bednarek (2001), Casado et al. (1989), Cushman (1985), Edwards (1978), Englund and Malmqvist (1996), Fiset (1998), Fisher and Lavoy (1972), Gersich and Brusven (1981), Gislason (1985), Hesse and Newcomb (1982), Hunt and Jones (1972), Jalon et al. (1994), McAllister et al. (2000), McKinley et al. (1998), Munn and Brusven (1991), AECOM Canada Ltd. (2009), Peters (1986), Poddubny and Galat (1995), Poff and Zimmerman (2009), Renofalt et al. (2009), Rosenberg et al. (1997), Smokorowski (2008), Snyder and Minshall (2005), Stanford et al. (1996), Travnichek et al. (1995), Tyus and Winter (1992), Ward (1974).
Displaced sturgeon spawning activity to less desirable habitat.	Cooke and Leach (2004), Paragamian et al. (2002)
Increased densities of other fishes resulting from change in hydraulic conditions – increased predation on sturgeon eggs.	Ginzburg (1967), Khoroshko (1972), Larinier (2001), Poff and Zimmerman (2009)

Effect	References
Crowding and increased vulnerability of sturgeon above/below dams in shallow water.	AECOM Canada (2009), Higgs (2002), Larinier (2001), Messier and Roy (1987), North et al. (1993), Peters (1982), Richards et al. (1986), Ruggles and Murray (1983), Schilt (2007).
Spawning migrations impeded or delayed.	B.C. Environment (1997), Beamesderfer et al. (1995), Cooke et al. (2002), Dick et al. (2006), Ferguson and Duckworth (1997), Edwards et al. (1989), Friday (2002), Galarowicz (2003), Gao et al. (2009), Geen (1974), Gessner and Bartel (2000), Graham (1985), Haxton (2002), Jager et al. (2001), Knights et al. (2002), Kynard (1997), Kynard et al. (1998), Larinier (2001), Lenhardt et al. (2006), Ligon (1995), Lyttle (undated), McAllister et al. (2000), McLeod et al. (1999), Mora et al. (2009), North et al. (1993), Pavlov (1971, 1989), Peters (1982, 1986), Renofalt et al. (2009), Richards et al. (1986), Rosenberg et al. (1997), Ruggles and Watt (1975), Runstrom et al. (2002), Saenko (2009), Schilt (2007), Shuman (1995), Smith (1985), Zhong and Power (1996a, 1996b)
Alteration or deterioration of water quality.	Baxter and Glaude (1980), Beiningen and Ebel (1970), Clay (1995), Collier et al. (1996), Fiset (1998), Gerritsen et al. (2008), Grizzle (1981), Hesse and Newcomb (1982), Ligon (1995), Liu and Yu (1992), Mackie et al. (1983), McAllister et al. (2000), Peters (1986), Renofalt et al. (2009), Richards et al. (1986), Rosenberg et al. (1997), Ruane et al. (1986), Ruggles and Watt (1975), Zhong and Power (1996b)
Reduced nutritional state of sturgeon.	McKinley et al. (1993)
Entrainment or impingment/mortality of downstream migrants.	Adams et al. (1993), Boysen et al. (2009), Department of Fisheries and Oceans (2008), Graham (1985), Jager (2000), Kelso and Milburn (1979), Larinier (2001), McCormick et al. (1990), McKinley and Kowalyk (1991), Peters (1986), Prosser (1986), Richards et al. (1986), Ruggles and Watt (1983), Seyler et al. (1996)
Impacts to genetic integrity of the sturgeon population.	Ferguson et al. (1993),Ferguson and Duckworth (1997), Gerritsen et al. (2008), North et al. (1993)
Decreased abundance/diversity of benthic invertebrates.	Blinn et al. (1995), Boon (1993), Ceereghino and Lavandier (1998), Chiasson et al. (1997), Fisher and LaVoy (1972), Fjellheim et al. (1993), Gislason (1985), Haxton (2007), Irving (1985), Kraft and Mundahl (1984), Lauters et al. (1996), Moog (1993), Nyman (1995), Peters (1982), Radford and Harland-Rowe (1971), Spence and Hynes (1971), Trotzky and Gregory (1974), Valentin et al. (1995)

Appendix 3. Fishway design considerations for passing sturgeon (*Acipenseridae*).

Design Consideration	Recommendation	Reference(s)
Entrance to fishway	• 0.30 – 0.91 m/sec attractant flow.	Anderson et al. (2007), Cheong et al. (2006)
	• Attractant flow should be 3% of maximum flow.	G. Madison (pers. comm.)
	• Attractant flow should be 2-5% of the main river flow.	Larinier (2008)
	• Entrance diagonal to main water flow.	Pavlov and Ya Vilenkin (1989)
	• Entrance should be at or near the face of dam at level of river bed.	Larinier (2001), R. Bruch (pers. comm.)
	• Multiple entrances may increase useage.	
	• Water depths at entrance should be relatively shallow (e.g., 2 m).	
	• Reduce or eliminate flow from other sources (e.g., spillways, hydroelectric generators) so that most, if not all, flow is through fishway.	Gertsev and Gertseva (1999)
	• Fishway entrance must be as close as possible to the fish`s zone of search.	Clay (1995)
	• Need to consider bottom topography and current velocities which determine sturgeon movement patterns.	Pavlov (1989)
	• Velocity barriers from spillway or tailwater discharge should not compromise access to fishway entrance.	Bunt (2001)
Slope of fishway	• Slopes ranging from 1:8 to 1:10 generally conducive for passing sturgeon.	G. Madison (pers. comm.)
	• 4% slope.	Anderson et al. (2007)
Fishway water velocities	• Rapid (e.g., 0.84 - 2.52 m/sec) water velocities to intiate movement and slower (e.g., 0.51 - 0.60 m/sec) water velocities for resting.	Webber et al. (2007)
	• Highest guidance efficiency at water velocity of 0.33 m/sec.	Cheong et al. (2006)
	• Attractant velocities ranging from 0.6 – 2.0 m/sec.	Pavlov (1989)
	• Range of velocities to accommodate variety of ages/sizes of sturgeon.	Peake et al. (1997), Bruch (2008)
	• Operate fishway intensively after peak natural discharge.	Kynard (1998)
	• Water velocities must be within the swimming capability of sturgeon.	Peake et al. (1995), Cada (1997)
	• Velocities in the general range of 0.6 – 0.8 of the critical velocity for the species.	Pavlov (1989)
	• Current velocity in the fishway should approximate the cruising speed of the fish.	Pavlov (1989)
	• Passage structures for sturgeon need to incorporate rapid velocity (0.8 – 2.5 m/sec) sections to induce movements as well as slower velocity (0.5 – 0.7 m/sec) sections for rest and recovery.	Webber et al. (2007)
	• Velocity more important that depth – best orientation at velocities of 7.6 m/sec	(White and Mefford 2002).

Design Consideration	Recommendation	Reference(s)
Weirs and pools	• Passage structure minimum width 2.1 m.	Anderson et al. (2008)
	• Resting pools should have a depressed bottom section.	Anderson et al. (2008)
	• 30 m of fishway length for each 1 m of head.	Bruch (2008)
	• Eddies behind baffles often used by sturgeon to rest while moving upstream.	Kynard et al. (2008)
	• Minimum tail pool water depth of 1.0 m.	Anderson et al. (2008), UMRS (2009)
	• Weir height of not greater than 0.61 m.	Anderson et al. (2008)
	• As the size of vertical eddies increase, success in passage decreases	White and Mefford (2002)
Slots and orifices	• Space requirements are important - large horizontal orifices preferred to vertical slots.	Parsley et al. (2007)
	• Fish should be able to move through orifices at the surface or at the bottom of the fishway.	Anderson et al. (2008)
	• Slot opening of at least 0.61 m.	Anderson et al. (2008)
	• Physical dimensions are important – pool dimensions must be large enough for adult sturgeon	Larinier (2001), Peake et al. (1997)
Misc. considerations	• Flow lines should be straight and horizontal – vertical eddies may confuse fish.	Anderson et al. (2008)
	• Substrate roughness may increase sturgeon passage through ladder.	Anderson et al. (2008)
	• No sharp edges on any structures.	Anderson et al. (2008)
	• Fish should be able to ascend the fishway quickly.	Kynard et al. (2005)
	• Movements of lake sturgeon vary among individual fish and their motivational drive.	Cada (1997)
	• Fishway exits should not be located near spillways or turbine intakes.	Clay (1995)
	• Lake sturgeon have been found to move upstream during both day and night. Fishways designed for lake sturgeon should be operated on a 24 hour basis.	
	• Poorest movement success over cobble substrate.	White and Mefford (2002).

Appendix 4. A summary of fishways designed for species including sturgeon (*Acipenseridae*).

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Waterbody	Stugeon Species	Description of Barrier	Fishway Design	Evaluation of Effectiveness	Source of Information
Columbia River (USA)	White sturgeon	Dalles Dam	• Dam has two fish ladders (east and north). • Fishway design includes overflow weirs with submerged orifices. • East fish ladder is 1.82 m wider with larger orifices.	• In 1995, 943 white sturgeon ascenced the east ladder and 104 ascended the north ladder.	Parsley et al. (2007), USGS (2008)
Connecticut River (USA)	Shortnose sturgeon	Holyoke Dam	• Fish Lift	• Relatively inefficient – only 22 sturgeon lifted over a 22 year operating period.	Kynard (1998)
Don River (USSR)	Several sturgeon species	Tsimlyanskiy Dam	• Hydraulic fish lift constructed in 1955. • Includes a fish collection gallery (110 m long, 6 m wide and 6.5 - 13.6 m deep), a fish pool (5 x 18 m and 4.2 – 11.6 m deep), a vertical shaft (7 x 5 m, height 36.8 m) and an upper outlet chute (6 m wide, 65 m long, water depth 2 – 7 m). • Operated on 2.5 – 3.0 hour cycles from April until November each year. • Reconstructed in 1972 to increase efficiency by improving the fish collection gallery.	• Moderate success in moving sturgeon and some other fish species.	Pavlov (1989)
	Russian sturgeon, Starry sturgeon, Sterlet sturgeon, Beluga sturgeon	Kochetovskiy dam	• Sluice fish pass which operates by means of locks. • Includes a collection gallery (68 m long and 10 m wide), an operation chamber with gates at both ends and an upper outlet chute.	• It has been estimated that up to 67% of the *Acipenseridae* approaching the dam successfully negotiate the fishway.	Pavlov (1989)

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Waterbody	Stugeon Species	Description of Barrier	Fishway Design	Evaluation of Effectiveness	Source of Information
Don River (cont`d)			• Fish are attracted with water velocities of 0.8 – 1.8 m/sec. • Similar devices have also been constructed at the Nikolaevskiy and Konstantinovskiy stations on the Don River.		
	Various fish species including sturgeon	Kochetovskiy dam	• Collection barge which is a vessel which uses submerged pumps to attract fish into the device (1.5 – 2.0 hours). A crowding screen is used to move fish from the fish collector to the transport vessel which then takes fish through navigational locks and release them in the reservoir. • Similar devices have been used on the Don, Kuban, Volga and Daugava rivers.	• Some success with moving fish upstream.	Pavlov (1989), Lagutov and Lagutov (2008)
Eastmain River (Québec)	Lake sturgeon	Eastmain 1 dam	• Rock ramp with alternate pools/weirs created with rocks and cement blocks. • 180 m long and 15 m wide. • 18 pools with a 15 cm drop over 10 m. • 6-7% slope. • Construction cost was ~$1 million with $100,000 in recent alterations.	• Only 2-3 sturgeon used the fishway in 2008. • Fish concentrated at the weir and did not pass through the fishway.	Burton et al. (2008)
Fox River (USA)	Lake sturgeon	Eureka dam (low head structure)	• Sluice gate fishway (1962-87) • Three step plunge pool fishway (1988-91)	• Ineffective except under extreme flood events. • Provided upstream passage but not downstream due to undertow at dam.	Bruch (2008), Bruch and Endris (1990)

Waterbody	Stugeon Species	Description of Barrier	Fishway Design	Evaluation of Effectiveness	Source of Information
Fox River (cont'd)			• Natural channel (1992-present). In 1993, the face of the dam was backfilled with rock.	• Successful for both upstream and downstream migration.	
Kuban River (Russia)	Various sturgeon species	Krasnodarskiy Dam	• Mechnical fish lift involves collection gallery where fish are crowded into a collection chamber and lifted to the reservoir by a crane.	• Approximately one million fish (several species) pass through this lift annually. • Ineffective (<0.5% of sturgeon migrants lifted between 1976-1995).	Chebanov et al. (2008), Pavlov (1989)
	Russian sturgeon and Starry sturgeon	Fedorovskiy station	• Sluice fish pass constructed in 1982.	• Up to 1,000 sturgeon spawners (and other species) pass upstream each year.	Pavlov (1989)
Otter River (USA)	Lake sturgeon		• Pool-weir which has a streaming flow system that allows sturgeon passage at different flows.	• Some sturgeon have been observed using the fishway.	Hay-Chmielewski and Whelan (1997)
Po River (Italy)	-	Isola Serafini dam and hydrogenerating station		• Unknown.	Telo et al. (2008)
Red River watershed (Manitoba)	Lake sturgeon	-	• Dams converted to nature-like fishways with rapids at nine sites.	-	Aadland et al. (2005)
Richelieu River (Québec)	Lake sturgeon	Saint-Ours dam (Vianney-Legendre Fish Ladder)	• Entrance basin (diagonal to river flow) with 16 successive basins (each 3m x 3.5 m). • Entrance has two openings – one near bottom of river and second at the surface. • 15 cm difference in elevation between each basin.	• Record catch of 47 lake sturgeon captured in fishway during 2007 (most years < 40 large sturgeon). • Fishway used by a number of different fish species.	Dumont et al. (1997), Fleury and Desroches (2004), Paradis and Malo (2003)

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Waterbody	Stugeon Species	Description of Barrier	Fishway Design	Evaluation of Effectiveness	Source of Information
Richelieu River (cont'd)			• Bottom is covered with gravel. • Attractant flow is ~ 5 m^3 sec^{-1}; fishway flow ~ 1$m^3$$sec^{-1.}$		
Santee-Cooper rivers (South Carolina)	Shortnose Sturgeon	Santee River Dam (St. Stephen fish lift)	• Fish lift	• Some shortnose sturgeon have successfully been moved upstream.	South Carolina et al. (undated)
Volga River	Beluga sturgeon, Russian sturgeon and Stellate sturgeon	Volgograd Hydroelectric Dam	• Hydraulic fish lift constructed in 1961. • Facility consists of a two-stream collection gallery (width 8.5 m, length 82 m, water depth 5.7 – 14.4 m), two vertical shafts (8.5 m x 8.5 m x 36.9 m) with horizontal and vertical metallic crowding screens, and an upper one-stream chute (100 m x 12 m x 8 m) with three openings (4.8 m x 8.5 m) in the longitudinal wall at the side of the weir. • Operated on 1.5 – 2.0 hour cycles	• Successful but inefficient – used by up to 23,000 adult sturgeon per year (10-20% of migrating fish). • Fish lift not used by beluga sturgeon. • In total, fish lift passes approximately one million fish (various species) each year.	Rochard et al. (1990)
	Several sturgeon species	Volzhskaya Hydroelectric Dam	• Saratovskiy mechanical fish lift constructed in 1969. • Consists of a bypass gate which directs flow into the entry port to attract fish. A crowding screen concentrates fish at one end of the chute. Fish then leave the collection gallery and move through the locks into containers which are transferred to the reservoir.	• ~ 60,000 sturgeon passed in 1967. • Up to one million fish (different species) are transferred annually.	Clay (1995) Pavlov (1989)

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Waterbody	Stugeon Species	Description of Barrier	Fishway Design	Evaluation of Effectiveness	Source of Information
Volga River (cont'd)	Russian sturgeon, Starry sturgeon, and Beluga sturgeon	Volga River Flow Divider	• Two stream sluice fish pass on the flow divider between the eastern and western deltas of the Volga River. • Only operated in years of low water when gates of control dams are closed.	• Facilitates passage of three sturgeon species.	Pavlov (1989)
Volkhov River (USSR)	Several sturgeon species	Volkhovskiy Dam	• Hydraulic fish lift built in 1967 based on design of the Volgogradskiy fish lift.	• Facilitates the passage of whitefish and some other species.	Pavlov (1989)

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