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Cost and relative effectiveness of Lake Sturgeon passage systems in the US and Canada

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ABSTRACT

Sturgeons throughout their circumpolar range comprise one of the most imperiled group of fishes due to their unique life history characteristics, overharvest and habitat changes and loss. Lake Sturgeon, a potamodromous Acipenseridae species, despite showing recent significant signs of recovery in the US and Canada, continue to be impacted in systems throughout its range in part because of dams on rivers in which critical sturgeon spawning and nursery habitat is not available in sufficient quantity and/or quality to maintain adequate long-term recruitment in the population due to fragmentation. There are a small number of fish passage structures and methodologies specifically designed and implemented for Lake Sturgeon in North America, but there has been no general evaluation of their installation and operation costs nor their relative effectiveness. Data were collected on seven different fish passage systems representing the range of options currently being utilized for Lake Sturgeon passage within the species' North American range. Costs per meter of head were $206 060 for nature-like by-pass channel fishways, $305 579 for an upstream projecting pool-weir fishway, $1.1 million for a vertical slot fishway, and $1.6 million for a fish elevator. A capture and transfer operation cost an estimated $11 284 to transfer an average of 110 adult Lake Sturgeon annually. Projected costs per sturgeon passed after 40 years of operation were estimated at $12/fish for the upstream projecting pool-weir fishway, $85/fish for the nature-like by-pass channel fishways, $132 for capture and transfer, $1659 for the vertical slot fishway, and $1680 for the fish elevator. Before Lake Sturgeon passage is pursued, it is important to first determine whether passage would be necessary for restoring, maintaining, or sustaining a LS population and its genetic integrity within the system (above and below the dam); followed then, if passage is warranted, by determining what type of passage methodology might be the most effective, and the most effectively and practically funded, operated, and maintained at the dam in question.

1. Introduction

Sturgeons throughout their natural circumpolar range comprise one of the most imperiled group of fishes due to their unique life history characteristics and anthropogenic factors, primarily overharvest and habitat changes and loss (Birstein et al., 1997; Pikitch et al., 2005). Much of the habitat change has been caused by the construction of dams on rivers in which critical sturgeon spawning and nursery habitat is fragmented and not available in sufficient quantity and/or quality to maintain adequate long-term recruitment in the population. Lake Sturgeon (*Acipenser fulvescens*) (LS), a potamodromous Acipenseridae species, despite showing recent significant signs of recovery within its natural range in the US and Canada, continues to be impacted in systems throughout its range due to loss of access to adequate spawning and/or nursery habitat (Haxton and Findlay, 2008; Haxton et al., 2014, 2015; Bruch et al., 2016). LS were originally widely distributed in North America in the Mississippi River, Hudson Bay, and Great Lakes drainages with populations currently present from Georgia and Tennessee in the southern US to northern Manitoba, Ontario, and Quebec in Canada (Bruch et al., 2016).

The problems caused by dams and fragmentation for LS on river systems in the US and Canada have been recognized for many decades, and various methods have been utilized in attempts to promote recovery of LS populations on some of these systems, including stocking, transfer of wild juveniles and adults, installation of fish passage, and dam removal (Bruch et al., 2016). LS can thrive quite well in totally lotic

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systems, as well as in large lentic-lotic lake-river systems, but, in all cases, like other Acipenseridae species, require lotic river systems for successful spawning and fingerling production (Bemis and Kynard, 1997). Although relatively short sections of fragmented lotic systems have been shown to successfully support LS populations and sustainable fisheries (e.g. 45 km, Scholl, 1986; 10 km (McDougall et al., 2017)), dams on many LS river systems have been targeted for mitigation to provide access to additional critical or historic LS spawning and nursery areas (Haxton and Findlay, 2008; Haxton et al., 2014, 2015). Dam removal is generally always examined in alternatives analyses in LS habitat mitigation efforts (Wippelhauser et al., 2015), but often dams are long established with important social and economic ties to hydro-power production, and other recreational and commercial interests, rendering removal as an unacceptable remedy. Fish passage has been recognized since the early 20th Century as a possible mitigating tool to be used in these situations, especially for salmonid species, on large river systems in the US and Canada, but LS and Salmonid species vary significantly in burst and jumping ability as it relates to moving upstream through a traditional salmonid fish passage system (Peake et al., 1995). The general increase in management and recovery programs targeting LS in the late 1970 s and early 1980 s, following the development of sturgeon aquaculture techniques in North America, led to an increased focus on the understanding and installation of passage systems that would successfully accommodate migrating LS. To date, while there are a small number of fish passage structures and methodologies specifically designed and implemented for LS in the US and Canada (Katopodis et al., 2019; Cooke et al., 2020), there has been no general evaluation of their relative effectiveness nor their installation and operation costs (which likely applies to many other fish species as well). As such, the objective of this study was to review, summarize, and discuss the cost and relative effectiveness of current known LS passage structures and/or methods (i.e., Capture and Transfer).

2. Methods

Information on costs of construction, operation, and/or maintenance of LS passage structures/methods, their respective LS passage effectiveness (i.e., do they facilitate sturgeon passage and at what efficiency), and LS population status and management within their respective water systems was collected through queries made directly to management and research agencies and institutions, as well as from the published and grey literature on six different fish passage structures and five methodologies being employed in the US and Canada. Specifically, information was collected on: a pool-weir ramp extending upstream of a dam (Eureka Fishway, Upper Fox River, Wisconsin); downstream oriented nature-like riffle-pool bypass channels (Winter Fishway, Chippewa River, Wisconsin; and Mequon-Thiensville Fishway, Milwaukee River, Wisconsin; Rupert River KP 223 and KP 209 Fishway, Quebec); a downstream oriented vertical slot fishway with resting/turning basins (Legendre Fishway, Richelieu River, Quebec); a fish elevator (Menominee Fish Elevator, Menominee River, Michigan); and capture and transfer (Wolf River, Wisconsin). These LS passage projects generally represent the range of options currently being utilized for LS passage within the species' North American range (Katopodis et al., 2019; Cooke et al., 2020).

Information collected and metrics calculated for each structure or methodology and river site were:

- Fishway/passage project name
- Location
- Dam name, type, and height
- Type of upstream passage employed
- Slope of fishway
- Location of fishway entrance
- Average annual stream flow cms (cubic meters per second)
- LS population management objectives above the dam
- Construction/implementation date and years in operation through 2020
- Days per year in operation
- Original construction cost in US dollars (USD)
- Original construction cost in USD 2020 value
- Annual operating costs (including any improvements made over time) in USD 2020 value
- Estimated adult LS abundance within the river system with potential access to the fishway
- Estimated percentage of the adult LS spawners in a given year passed by the various passaged structures/methods
- Average (or estimated average) number of LS passed annually since construction/implementation
- Projected average number of LS to be passed annually post 2020
- Average cost/sturgeon passed (USD) through 2020
- Projected cumulative average cost/sturgeon passed after 40 years of operation
- Potential estimated 2020 cost of fishway construction per meter of dam height
- Potential estimated cost of pool-weir or nature-like riffle-pool bypass channel fishway derived from estimated length of channel needed to accommodate the height of the dam and maintain a 2.5% in-fishway slope

All monetary figures are reported in US dollars (USD). Original costs in Canadian dollars were converted to US dollars using the exchange rate of the time of initial fishway construction. All original construction and operation costs were also converted to USD 2020 values (https://www.usinflationcalculator.com/). All projected costs post 2020 (up through 40 years of operation) were calculated through time using the average annual US inflation rate, 2.41%, 1990–2020 (Statista.com (2021); Usinflationcalculator.com (2021)).

To enhance the information about LS passage structure characteristics, and in order to provide the reader some minimal quantitative water velocity information from a structure which is known to have very successfully passed LS each spring for over 30 years, water velocity measurements were made in the spring of 2020 on the Upper Fox River, Wisconsin at the Eureka Fishway, to document velocities during the period of actual LS movement through the structure during LS migration and spawning. Three measurements were collected within each pool of this pool-weir structure, at the crest, and immediately above the fishway using a General Oceanics Inc Model 2030 R Mechanical Flowmeter. It was not possible to collect water velocities for this study from any of the other structures for which information on costs and passage efficiencies was collected.

LS density estimates received from the various management agencies for their respective rivers with passage systems in place ranged from actual calculated estimates (e.g., Wolf River, WI) to rough numerical or general estimates based on observations and familiarity with the LS population in the respective systems (e.g., Chippewa River, WI "several hundred"; St. Ours, River, Quebec, "abundant"). To provide a coarse yet reasonable estimate of adult abundance for the St. Ours system, the authors, based on over 65 years combined experience working on LS systems, arbitrarily utilized an estimate of a minimum of ~3000 spawning adult LS in a given year in the St Ours River. No measured or general density estimate was provided nor developed for the LS population in the Rupert River System. Specific or general LS density estimates received from the respective system managers (or for the St Ours River, developed) were used to then estimate the number of adult male and adult female, and subsequently the estimated total number of spawning LS utilizing each respective river, and potentially each respective passage system, and ultimately the estimated percentage of the spawning adults in the river that were being passed by the system. Total adult males and females in a population were estimated assuming a 2:1 overall adult sex ratio (Bruch, 1999; Bruch et al., 2016), and total annual spawners by sex were estimated assuming a 4-year spawning

Fig. 1. Eureka Upstream Projecting Pool-Weir Fishway, Upper Fox River, Winnebago Co., Wisconsin, USA. 1a. : aerial view showing upstream fishway alignment (flow moving from top to bottom of photo); 1b: closeup of steps and pools in fishway looking upstream – LS primarily pass through the fishway upstream along the far-right bank of the structure in the lower photo. Photos from WI Department of Natural Resources, Fisheries Management, Oshkosh, WI.

cycle for females, and assuming 75% of the adult males in the population spawned each year (Bruch and Binkowski, 2002; Bruch et al., 2016). The number of LS passed upstream each year were the estimates or direct counts received from the respective passage system managers. These estimates or direct counts were used along with the calculated or best estimates of LS in each respective system received from the system managers to develop a coarse estimate of passage efficiency understanding that not all LS moving up a river system to spawn upon reaching a barrier may elect to move up through a fishway. For clarification, passage efficiency (e.g., 1.0% for the Richelieu River LS population below the St Ours Dam) is the percentage of estimated spawning adult LS in a river system below a dam that move/are moved upstream of each respective dam through the respective passage system on the river. Passage rate (e.g., 36.4% for St Ours Dam fish passage-way) would be the percentage of LS that actually move all the way upstream through a fishway to continue swimming upstream out of all the LS that volitionally enter the fishway from downstream.

Passage Systems Examined.

The seven different LS passage systems examined for this study included:

Eureka Upstream Projecting Plunge-Pool Fishway, Eureka Dam, Upper Fox River, Winnebago System, Eureka, Wisconsin, USA.

The Eureka Fishway (Fig. 1) is a three-step pool-weir rock bed fishway on the upper Fox River, (average annual flow 33.0 cms), Eureka, WI, 27.5 m long with a 3% slope to accommodate LS passage upstream past the 0.9 m head fixed sill dam. The fishway entrance is at the base of the dam and the fishway ramp projects upstream from the dam. The original dam was built in 1877 as part of a series of dams and locks for facilitating commercial barge traffic between Lake Michigan and the Mississippi River drainages in Wisconsin (Bruch, 2008). The Winnebago-Upper Fox-Wolf System is home to one of the largest natural LS populations and sustainable LS fisheries in North America. The upper Fox and Wolf Rivers and tributaries provide over 320 km of spawning and nursery habitat for the LS population (Bruch, 1999; Bruch et al., 2016). The fishway was built in 1988, becoming operational for spring spawning runs of LS and other fish species in 1989. During the spring of 1989 and subsequent years, LS were observed passing through the fishway and spawning at numerous sites up to 35 rkm above the dam. LS have also been observed regularly spawning in the fishway as well (Bruch, 2008). In 1993, a rock-rapids was installed below the face of the dam alongside the fishway, anchored on the fishway side with a wing deflector designed to push attractant flow downstream of the fishway and along the riprapped shoreline below the fishway (Fig. 1). Following the construction of the rapids and the wing deflector, LS continued moving through the fishway to utilize upstream spawning areas, and continued spawning in the fishway, while some LS elected to remain downstream of the fishway to spawn once again on the rip rap below the fishway (Bruch, 2008). An estimated 250 LS migrate upstream through the fishway annually. Not including LS that elected to spawn in the fishway or at sites below the dam, observed passage efficiency of LS through the fishway was 100%, i.e., over a 25-year period, all LS annually observed entering the fishway, and not remaining in the fishway to spawn, successfully moved up through the fishway.

Fig. 2. Winter Dam Nature-Like Stepped Riffle-Pool Bypass Channel Fishway, Chippewa River, Winter, Wisconsin, USA. 2a. : Aerial view; 2b Ground view showing detail of nature-like channel. Photos from the WI Department of Natural Resources, Fisheries Management, Park Falls, WI. (WI DNR Photos, Jeff Scheirer, Park Falls, WI).

Fig. 3. Mequon-Thiensville Nature-Like Stepped Riffle-Pool Fishway, Milwaukee River, Thiensville, Wisconsin, USA. Photo from WI Department of Natural Resources, Fisheries Management, Milwaukee, WI.

Construction cost in 1988 was $125000 (WDNR conservation account funds). Operation costs were reported to be zero. (Bruch, 2008; Wisconsin Department of Natural Resources (WDNR), Fisheries Management, Oshkosh, WI, unpubl. data).

Winter Dam Nature-Like Riffle-Pool Bypass Channel Fishway, Chippewa River, Winter, Wisconsin, USA.

The Winter Dam fishway (Fig. 2) on the Chippewa River (average annual flow 11.7 cms) in northwestern Wisconsin was built in 2011 to provide an opportunity for LS to migrate upstream past a 2.1 m head diversion dam located on the river at the start of an adjacent 558 m power canal upstream of a hydro dam located at the lower end of the canal. The diversion dam passes some water into the original river channel below the dam which along with other natural channel areas downstream of the hydro dam support a modest LS population estimated at several hundred adults (WDNR, Fisheries Management, Park Falls, WI, unpubl. data). The 79.0 m long nature-like by-pass channel consists of a series of stepped pools and riffles, with a 2.7 % slope, and an entrance 15.2 m downstream of the base of diversion dam. The channel is operated a total of 61 days/year, April 15-June 1 (47 days) for spring LS spawning migration, and 2 weeks in fall (14 days) for LS fall prespawn upstream migration. An estimated 48 LS utilize the structure to migrate upstream annually, with 70–80 expected post-2020, out of an estimated population of several hundred adults inhabiting the river below the diversion dam. An unknown size but persistent native LS population inhabits the river above the dam. Original 2011 construction cost was $450,000 funded by the US Forest Service and the dam owner. Annual operating costs were reported to be minimal consisting of labor to open and close the gate at the head end of the by-pass channel for periods of operation (Sue Reinecke, US Forest Service, Park Falls, WI, pers. comm).

Fig. 4. Rupert River Nature-Like Weir and Fishway KP 290, Rupert River, Quebec, Canada. Photo credit: Environnement Illimité inc (2012).

Mequon-Thiensville Nature-Like Riffle-Pool Bypass Channel Fishway, Milwaukee River, Thiensville, Wisconsin, USA.

The Mequon-Thiensville Fishway (Fig. 3) was built on the Milwaukee River (average annual flow 13.1 cms) at the 3.9 m head Thiensville Dam (fixed sill) in 2011 to provide an opportunity for migrating fish species to have access to 27.5 km of high-quality spawning and nursery habitat upstream of the dam. The fishway has a 1.1% slope and consists of a 360 m long nature-like bypass channel with stepped riffles and pools 36.6 m apart and an entrance 12.2 m below base of dam (Will Wawrzyn, WDNR, Milwaukee, pers. comm.). The Milwaukee River basin has been the target of numerous habitat and fisheries improvement actions including the mitigation of barriers beginning in 1997 and the annual stocking of LS for population restoration beginning in 2003. Adult LS have been observed migrating up the Milwaukee River beginning in 2019 although none have been observed traversing the Mequon-Thiensville fishway as of that date (Brad Eggold, WDNR, Milwaukee, pers. comm). A forward projecting stochastic LS population recovery model predicts that increases in adult densities, along with planned final mitigation of two man-made intermittent barriers in the river downstream of the fishway, may result in up to 1100 adult LS potentially

Fig. 5. Vianney-Legendre Vertical Slot Fishway, St. Ours Dam, Richelieu River, Quebec, Canada. Photo credit: www.lakestolocks.org.

utilizing the fishway annually by the early 2030 s (Bruch et al., 2021). While it is impossible at this time to know exactly how many LS will eventually utilize this fishway in coming years, earnest efforts are currently underway to mitigate the two remaining intermittent barriers on the system, and to date, adult LS returns from stocked fish indicate numbers could potentially increase as predicted by the model from Bruch et al. (2021). Original construction cost was $600 000 funded by Ozaukee County, the USFWS, and the WDNR (Brad Eggold, WDNR, Milwaukee, pers. comm).

Rupert River Nature-Like Bypass Channel Fishway with Weir, Quebec, Canada.

A diversion was created in the Rupert River as part of the La Grande Hydroelectric project in mid-northern Quebec in 2007. The Rupert River flows approximately 600 km from a large lake in Quebec westerly to James Bay and has a drainage area of approximately 43 400 km^2 (D'Amours and Dion, 2019). Approximately 29 % of the historical flows remain with the Rupert River after the diversion, with a targeted flow of 127 cms during winter and summer months, and a flow of 416 cms during the freshet for a 45-day period (D'Amours and Dion, 2019). Hydraulic structures were constructed in the Rupert River to ensure water levels were maintained downstream of the diversion dam for at least half the length of the river. Spawning areas were created downstream of the weirs (McAdam et al., 2017; D'Amours and Dion, 2019) and by-passes (fishways) were constructed in the weirs to maintain connectivity up to the diversion dams. Two fishways were constructed at rkm 223 and 290 (known as KP 223 and KP 290) to facilitate passage and to accommodate natural constraints at each site prior to the construction of the diversion dam. At site KP 290, a natural fishway (Fig. 4) constructed on an island separating the two weirs, is 10 m wide, 155 m long with a 1.7 % longitudinal slope and 10 % transverse slope to concentrate flows one side during low flow periods. Large derrick stones were placed in the fishway as shelter resting areas for fish during migration. The fishway was initially designed through 3D modeling (AECOM, 2011) and became operational in 2009. The initial cost for the planning and construction of the two fishways at rkm 223 and 290 in 2009 was $310 360 (2009 US dollar value) which did not include the construction of the weir. Original cost of fishway KP 290 with the weir construction totaled $760 966 (2009 US dollar value). Flows through the fishways are maintained at less than 1.2 m/s to facilitate upstream passage. Monitoring of passage efficacy was based on hydraulic flows strictly under the premise that if the flows were suitable, then sturgeon would use the channels as a fishway. Limited telemetry data indicated that a LS passage rate of 2.5 % (Environnement Illimité inc, 2012). Modifications were made to both channels in 2010 and 2011 to reduce the flows at a cost of $418 464. Annual operational costs were reported to be zero for these nature-like fishways.

Vianney-Legendre Vertical Slot Fishway, St. Ours Dam, Richelieu River, Quebec, Canada.

The Vianney-Legendre Fishway (Fig. 5) at the St. Ours Dam on the Richelieu River (average annual flow of 362.0 cms), flowing north from Lake Champlain to the St. Lawrence River in Quebec, Canada was constructed and operational in 2001 after previous reconstruction of the St. Ours and Chambly Dams was suspected of contributing to the decline of the copper redhorse and American eel populations in the river (Parks Canada, 2021). LS are considered "abundant" in the river system and considered another key fish species to utilize the fishway (Parks Canada, 2021; Thiem et al., 2016). The 185 m long fishway has an internal slope of 4.0% accommodating a 3.4 m head at the dam, and consisting of 16 vertical slots 0.6 m wide, 2.3 – 4.0 m high, 17 pools, two turning basins with a 2.75 m radius, and which passes approximately 1 cms with capacity of 6.5 cms attraction flow. Passage efficiency of LS observed entering the fishway was measured at 36.4 % (Thiem et al., 2016). Construction cost in 2001 was $3.1 million (USD; funded by Parks Canada). Since first operation in 2001 the fishway has passed an average of 28 LS upstream per year with numbers expected to grow to 70/year post 2020 (Audrey Godin-Champagne, Parks Canada, pers. comm.).

Menominee Fish Elevator, Menominee River, Menominee, Michigan, USA.

The fish elevator at the 7.6 m head Menominee Hydro Dam (Fig. 6) on the Menominee River (average annual flow 93.7 cms) on the Wisconsin-Michigan border was constructed in 2014–2015 becoming operational in 2015 for the primary purpose of capturing LS migrating upstream out of Green Bay (to spawn below the dam), then transporting them by truck for release above a second dam, the Park Mill Dam 1.6 km upstream of the Menominee Dam. The population estimate of adult LS potentially utilizing the lower Menominee River below the dam for spawning was 3000 (Robert Elliot, USFWS, New Franken, WI, pers. comm.). Above the Park Mill dam, the transferred LS have access to 35.4 km of open river containing high quality LS spawning and nursery habitat, in which though also resides a stable native riverine LS population. During 2015–2020, an average of 90 LS were captured in the elevator and trucked upstream annually for release with a post-2020 goal of capturing and trucking 200 LS/year with a 2:1 male to female sex ratio (Donofrio, 2017, 2018, 2019; Donofrio and Kramer, 2019; Robert Elliot, USFWS, New Franken, WI, pers. comm.). Capture efficiency of LS near the entrance to the elevator was found to be 7.1 %– 7.9 % during spring spawning migration and 0 %– 4.3 % during fall pre-spawn migration (Porter, 2019). The original construction cost for the elevator was $11.0 million, funded by Great Lakes Restoration Initiative and the dam owner, with average annual operating costs (2020) of $22 000 (Robert Elliot, USFWS, New Franken, WI, pers. comm.).

Lake Sturgeon Capture and Transfer, Wolf River, Shawano, Wisconsin, USA.

The LS capture and transfer program on the Wolf River (Fig. 7) is possible as the river contains the primary spawning and nursery grounds for LS of the Winnebago System in east central Wisconsin which, as referenced earlier, is home to one of the largest and healthiest native LS populations in North America. Two hundred and one km of the original

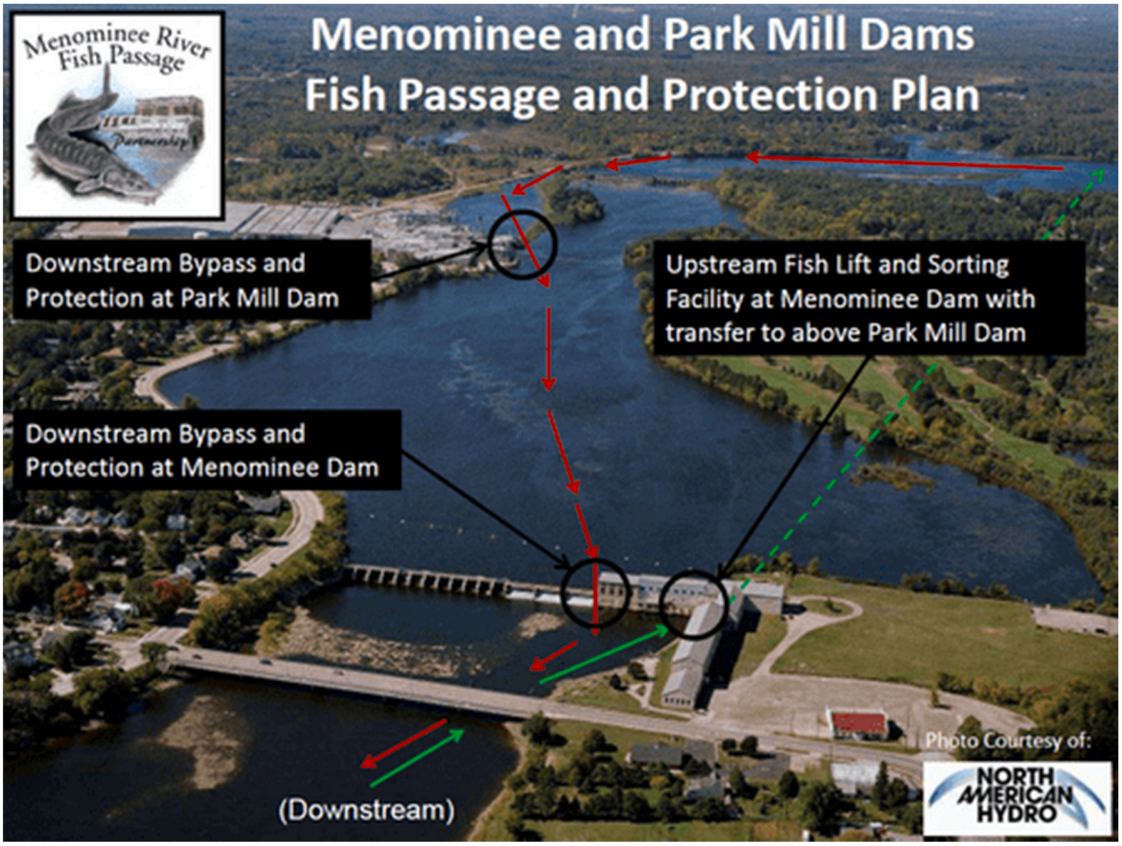

Fig. 6. Menominee Fish Elevator, Menominee River, Menominee, Michigan, USA. 6a: illustrated aerial showing passage schematic; 6b: view of elevator operation and holding tank. Photos credit www.menomineewatershed.com.

219 km of mainstem Wolf River remain open to spawning migrations of LS out of Lake Winnebago and its connecting waters upstream (Bruch, 1999; Bruch and Binkowski, 2002). The Shawano Paper Mill Dam (3.2 m head) at rkm 201 has been the upstream LS migration endpoint since 1892 when the dam was built. Prior to the dam being installed, the original LS migration endpoint was a natural 0.9 m waterfall, Keshena Falls, 19.6 km upstream of the dam and within the Menominee Indian Reservation. Above the Shawano Paper Mill Dam 9.4 km, and 10.2 km below Keshena Falls, another dam, Balsam Row Dam (4.3 m head), was built in 1926 (WDNR, 2020). The area below the Shawano Paper Mill Dam is the largest and most heavily utilized LS spawning site on the river as the dam was built directly on a large rapids that was historically extensively used by LS for spawning, and a site the Menominee Indians used as a key spring LS harvest area prior to construction of the dam (Schmitt-Klein et al., 2009). Currently, in addition to spawning below the Shawano Paper Mill Dam, LS spawn at several other natural sites and over 50 man-made sites in the Wolf River and other tributaries to the Wolf River 0.1–150 river km downstream of dam (Bruch, 1999; Bruch and Binkowski, 2002; Koenigs et al., 2019). The Winnebago-Wolf LS population is thriving close to carrying capacity and supports a robust winter spear fishery with an average annual sustainable harvest of over 1500 fish through natural recruitment from spawning activity at Shawano Paper Mill Dam and the numerous other sites downstream. The Menominee Indian Tribe of Wisconsin (MITW) expressed an interest in seeing LS migrate once again to the historic spawning areas on the Reservation below Keshena Falls although neither the Shawano Paper Mill Dam nor the Balsam Row Dam are within the MITW Reservation and the MITW have no off-reservation Treaty Rights. Subsequently, in

Fig. 7. Lake Sturgeon Capture and Transfer, Wolf River, Shawano, Wisconsin, USA. 7a. : Electrofishing to capture lake sturgeon; 7b: placing lake sturgeon from tank truck into a stretcher for movement to release point on Wolf River in the Menominee Indian Reservation. Photos from WI Department of Natural Resources, Fisheries Management, Oshkosh, WI.

2011, the WDNR developed and entered into a 10-year agreement (perpetually renewable) with MITW to capture (via electrofishing) a minimum of 100 (average 2012–2016 of 124) adult LS each year from the Wolf River zero to 16 km below the Shawano Paper Mill Dam (average annual flow 39.0 cms) and transfer them by truck for release upstream below Keshena Falls. Fall and spring migrant gravid adults (primarily from Lake Winnebago), as well as some late summer river resident adult LS were captured, transferred, and released in the Wolf River 243 m below Keshena Falls during 2011–2019 resulting in LS spawning directly below the falls each spring of the project and natural recruitment from this spawning activity (Koenigs et al., 2019). In the first several years of the project, 245 transferred LS were fitted with internal 10-year Vemco sonic tags to track post release movement via an extensive array of 36 stationary Vemco VR2W sonic receivers. Resultant tracking data showed that within a year after being transferred and released below Keshena Falls, 75% went back safely through the gates of both dams to Lake Winnebago after the spawning season, 7% remained between Keshena Falls and Balsam Row Dam, and 15% moved safely through the gates at Balsam Row Dam and remained between Balsam Row Dam and Shawano Paper Mill Dam (with 3% undetected). None of the 245 telemetered LS were detected on a stationary Vemco VR2W receiver located immediately above Keshena Falls indicating that LS that migrated up to and were observed spawning below the falls were unable to swim upstream over the 0.9 m falls during the three years of telemetry data collection (Koenigs et al., 2019; WDNR, 2020). The WDNR is promoting capture and transfer of LS at these dam sites in lieu of volitional fishways in part due to aquatic invasive species concerns (i.e., zebra mussels, VHS virus, common carp) in the Wolf River below the dams (WDNR, 2020). Total costs calculated in 2019 were $91 per fish (not including sonic tags) for an average annual cost of approximately $11 284 (Koenigs et al., 2019) (funded by the WDNR sturgeon spearing license sales revenues).

3. Results

Below, we present the estimated costs per fish of passing LS within the limited number of systems where passage has been implemented for the species. Despite the variation in LS population sizes, the quality and availability of LS population and passage data across river systems, and the challenges these differences present in making comparisons across the passage systems described below, we nonetheless, present this material to provide some insight into the cost and relative efficiency of LS passage systems.

Table 1 lists the information received from the various agencies, reports, and system managers; and the estimates developed and utilized for this study. Construction costs (for hardened structural fishways) ranged in 2020 USD values from $275 021 for the upstream projecting pool-weir fishway to $12.1 million for the fish elevator. Costs per meter of head (least to most) were $183 601 for the nature-like bypass channel fishway including adjoining weir; $217 289 (average) for the two Wisconsin nature-like bypass channel fishways; $305 579 for the upstream projecting pool-weir fishway, $1.1 million for the vertical slot fishway, and $1.6 million for the fish elevator. Annual operating costs were reported to be $0 for the three nature-like bypass channel fishways, $0 for the upstream projecting pool-weir fishway, $7824 for the vertical slot fishway, and $22 507 for the fish elevator. The capture and transfer operation evaluated had zero infrastructure cost (aside from electrofishing equipment used) and an operating cost estimated at $11 284 covering labor, expenses, and supplies needed to transfer an average of 110 adult LS annually.

Estimates of LS densities received from the various managers for the systems examined, in addition to the estimates of the number of LS adult spawners, and percentage of LS adult spawners passed upstream annually by the various structures/methods, along with the number of LS projected by the respective management agencies to be passed in the future are listed in Table 2. The percentages of adult LS spawners in the respective river systems passed annually by the various passage structures/methods were roughly estimated at 1 % for the St Ours River vertical slot fishway and Wolf River capture and transfer, 5 % for the Menominee River fish elevator, 27 % for the Chippewa River nature-like bypass channel, and 50 % for the Upper Fox River upstream projecting pool-weir fishway. Environnement Illimité (2012) provided a passage efficiency estimate of 2.5 % for LS using the nature-like weir bypass on the Rupert River, although it could not be determined specifically how this estimate was developed nor exactly what it represented.

Projected costs per sturgeon passed after 40 years of operation (using original construction cost and annual operations costs, and the number of LS projected to be passed via each system through 40 years) were roughly estimated at $12/fish for the upstream projecting pool-weir fishway (Fox River, Wisconsin), $85/fish (average) for the two Wisconsin nature-like bypass channel fishways (Chippewa and Milwaukee Rivers, Wisconsin), $132 for capture and transfer (Wolf River, Wisconsin), $1659 for the vertical slot fishway (Richelieu River, Quebec), and $1680 for the fish elevator (Menominee River, Michigan) (an estimate could not be developed for the Quebec bypass channel fishway with weir; Table 1).

Water velocity measurements of the Eureka Dam Upstream Projecting pool-weir fishway during LS migration and spawning in 2020 averaged 1.10 m/s (0.04 SD) in the lower pool, 1.21 m/s (0.05 SD) in the middle pool, 0.60 m/s (SD=0.06) in the upper pool, 2.15 m/s (0.07 SD) at the fishway crest, and 1.22 m/s (0.02 SD) immediately above the fishway.

4. Discussion

To date, little to no information on the relative cost and effectiveness of passage methodologies for lake sturgeon can be found in the published or grey literature. Available LS passage literature focusses

Table 1
Location, characteristics, costs; and LS population characteristics of examined LS passage systems and rivers.

Fishway Passage Project	Eureka Fishway	Winter Dam Fishway	Mequon-Thiensville Fishway	Rupert River Fishway KP290	Vianney-Legendre Fishway	Menominee River Fish Elevator	Wolf River Capture and Transfer
Location	Upper Fox River, Eureka, WI, USA	Chippewa River, Winter, WI, USA	Milwaukee River, Thiensville, WI, USA	Rupert River, Mid-Northern Quebec, Canada	Richelieu River, Southern Quebec, Canada	Menominee River, Menominee, MI, USA	Wolf River, Shawano, WI, USA
Dam(s)	Eureka Dam	Winter Dam	Thiensville Dam	Rupert River Diversion Dam	St. Ours Dam	Menominee Dam	Balsam Row Dam (BRD) and Shawano Paper Mill Dam (SPMD)
Dam Type	Navigation, Fixed Sill	Diversion	Fixed Sill	Diversion – rock weirs	Navigation, submersible gates	Hydro	Hydro
Dam Height (m)	0.9	2.1	3.9	5	3.4	7.6	4.3 (BRD), 3.2 (SPMD)
Type of Upstream Passage Employed	31.3 m long pool-weir ramp	79.2 m long nature-like bypass channel with stepped riffles and pools	359.7 m long nature-like bypass channel; stepped riffles and pools 36.58 m apart	155 m long, 10 m wide nature-like channel with islands of large rocks	vertical slots, 17 pools, 2 turning basins	Volitional (spring and fall) movement with attractant flow into elevator/then truck transport LS 1.6 km for release above next dam upstream (Park Mill Dam)	Electrofishing capture (early fall, late fall, spring) and truck transport for release above dams
Slope of Fishway	3.3 %	2.7 %	1.1 %	1.7% longitudinal slope and a 10% transverse slope in order to concentrate the flow on the left side during low-flow summer conditions	2.5%	NA	NA
Location of Fishway Entrance	0 m below dam (at the base of the dam with fishway projecting upstream)	15.2 m below base of dam	12.2 m below base of dam	90 m below base of dam	32.0 m below the base of the dam	entrance to elevator carriage trap ~6 m below dam along power house	NA
Average Annual Stream Cubic Meters per Second (cms)	33.0	11.7	13.1	127 cms during winter and summer months, and a flow of 416 cms during the freshet for a 45-day period	362.0	93.7	39.0
LS Population Management Objectives	Expand native LS spawning stock in Upper Fox River	restore adult migration, spawning and recruitment above dam	restore adult migration, spawning and recruitment above the dams	Maintain historic LS migration connectivity	provide access for LS to upstream spawning sites	restore adult migration, from Green Bay, spawning and recruitment above dams; transferred LS released into existing stable riverine LS population	restore adult spawning in the Wolf River in the Menominee Indian Reservation
1st Year of Operation	1988	2011	2011	2009	2001	2014	2011
Days/Year in Operation	365	Total 61 days/yr. April 15-June 1 (47 days); 2 weeks in fall (14 days)	365	365	92 days (May 1-July 31)	Total 105 days/yr. March 15-May 31, 49 days in spring; 8 weeks, 56 days, in fall	3
Original Construction Cost (USD)	$150 000	$450 000	$600 000	$760 966	$3 096 000	$11 000 000	$0
Original Construction Cost in 2020 USD	$275 021	$520 650	$727 930	$918 009	$358 2072	$12 093 978	$0
Annual (USD) Operating Costs in 2020	$0	$0	$0	$0	$7824	$22 507	$11 284
Cost (USD) per meter of Head	$305 579	$247 929	$186 649	$183 601	$1 053 551	$1 591 313	NA
Estimated Annual Number of Spawning Adults (2020)	500	175	360	"high" densities below, "low" densities above	3000	1750	25250
Estimated Average	250	48	0	unknown	28	90	124

(*continued on next page*)

Table 1 (*continued*)

Fishway Passage Project	Eureka Fishway	Winter Dam Fishway	Mequon-Thiensville Fishway	Rupert River Fishway KP290	Vianney-Legendre Fishway	Menominee River Fish Elevator	Wolf River Capture and Transfer
Number of LS Passed Annually Upstream (through 2020)							
Projected Average Number of LS to be Passed Upstream Annually post 2020	300	78	1100 (by 2030 s)	unknown	70	140	110
Estimated % Spawning Adults Passed Upstream/Yr (2020)	50%	27%	NA	2.5% (reported byEnvironnement Illimité inc inc, 2012)	1%	5%	1%
Average Cost/ Sturgeon Passed (through 2020)	$16	$938	NA	Unknown	$5808	$20 620	$91
Projected Average Cost/ Sturgeon Passed after 40 Years of Operation	$12	$159	$11	Unknown	$1659	$1680	$132

Table 2
Reported 2020 estimated abundance of LS adults, and coarsely estimated abundance of annual LS adult spawners and passage efficiency in examined river and passage systems (not including Rupert R, Quebec as no LS population data were provided); and projected number of LS adults projected to be passed upstream post 2020.

River System	Estimated Total Adults in Population	Estimated Total Adult Males	Estimated Total Adult Females	Estimated Total Annual Male Spawners	Estimated Total Annual Female Spawners	Estimated Total Spawners per Year	Number LS Passed per Year	Estimated % of Adult Spawners Passed Upstream	Projected Number of LS to be passed annually post 2020
Upper Fox R[a]	850	570	281	427	70	497	250	50%	300
Wolf R[b]	43 150	28 911	14 240	21 683	3560	25 243	124	1%	110
Menominee R[c]	3000	2010	990	1508	248	1755	90	5%	140
Milwaukee R[d]	364	244	120	183	30	213	NA	NA	1100 (by 2030 s)
Chippewa R[e]	300	201	99	151	25	176	48	27%	78
St Ours R[f,g]	5000	3350	1650	2513	413	2925	28	1%	70

[a] WDNR, Oshkosh, WI, unpubl. data (upstream projecting pool-step fishway)
[b] WDNR, Oshkosh, WI, unpubl. data (capture and transfer)
[c] USFWS, New Franken, WI, unpubl. data (fish elevator)
[d] Bruch et al. (2021) (natural-like riffle pool bypass channel
[e] US Park Service, Park Falls, WI, unpubl. data (natural-like riffle pool bypass channel)
[f] Audrey Godin-Champagne, Parks Canada, Chambly, Québec, pers. comm. (vertical slot fishway); Thiem et al. (2016)
[g] Author's estimate of ~3000adult LS spawners per year based on relative abundance information received from Parks Canada, and 65 + years combined experience working on LS systems in US and Canada

primarily on the need for barrier mitigation (e.g., Auer, 1996; Jager et al., 2016), and sturgeon swimming performance as it relates to passage (e.g., Peake, 1995; Kynard et al., 2011; Katopodis et al., 2019). The question of the need for passage for LS on various systems can be quite complicated as LS have shown they can reproduce and persist quite well in some waters with dams (DFO, 2010; Scholl, 1986; McDougall et al., 2017) while on other waters there is obvious need for barrier mitigation (Bruch et al., 2021; Haxton and Findlay, 2008; Haxton et al., 2014, 2015). In fragmented systems, LS populations can rely on production from spawning that occurs at critical natural or man-made habitat located directly below dams (Bruch, 1999; Dumont et al., 2011), which in some cases could be negatively impacted by dam modifications or operations (DFO, 2010; Friday and Haxton, 2021).

The efficiency of various structures in facilitating upstream passage of LS has not been extensively researched. The rough estimates of efficiency developed from this effort should be viewed as that – rough estimates that provide some insight into the general efficiency of the various types of passage systems that have been installed or implemented to date for LS in North America. The limited reported data (Porter, 2019) along with the rough estimates developed for this study suggest a wide range of efficiencies which emphasizes the need not only for further research but also for the need for thoughtful and practical planning when LS passage is being required or proposed. While the true efficiency of any LS passage system will of course be affected to some extent by the size of the LS population inhabiting a particular river, there undoubtedly are differences in the efficiencies among LS passage systems due to the design and type of system built, and by other factors such as fishway entrance location and slope. Although the number of existing LS passage systems in the US and Canada is quite small providing a relatively limited field of systems to examine for this evaluation, the results of this evaluation provide useful information that can contribute to further needed research and the development of a successful approach for cost efficient and effective LS passage at dams and rivers within the lake sturgeon range in North America.

The evaluation and comparison of existing LS passage methodologies in the current evaluation raises important questions in key areas of relative effectiveness and cost. Many biologists and fisheries managers in various institutions and regulatory agencies likely desire to see dams removed to facilitate the return of rivers to a natural free flowing condition. While there are likely many dams within the LS range that may have outlived their life expectancy, original intent, and/or usefulness, there are likely many more that continue to efficiently function to create hydropower, as well as maintain impoundments that support important recreational and commercial fisheries, important aquatic habitats, water recreation, flood control, waterfront properties and infrastructure, and local economies. Also, there are likely many river systems where a dam was originally placed at the site of a natural bedrock break or waterfall - which originally acted as a natural fish migration barrier – to take advantage of the natural head for hydropower production. If dam removal is not an option, it is important that before LS passage at a dam is pursued, the following factors are considered:

- the presence of any pre-dam natural migration barriers;
- the LS population status (densities, recruitment, genetic integrity) above and below the dam;
- the presence or absence, quantity and quality of LS spawning and nursery habitat above and below the dam;
- LS management objectives for the river system;
- the role the impoundment does or might play in long-term LS population viability (e.g., overwintering habitat, grow-out areas);
- the potential for passage to facilitate the expansion of Aquatic Invasive Species;
- the value of the fisheries and infrastructure on the impoundment and impacted river reaches;
- the presence and status of the dam's government license;
- the function of and physical condition the dam;
- public opinion on the dam, river, and impoundment and related aquatic resources and resource use.
- Estimated cost of the lake sturgeon passage system(s) being proposed or considered; and
- Potential relative efficiency of the lake sturgeon passage system(s) being proposed or considered

Each dam needs to be dealt with on a case-by-case or context-specific basis thoroughly considering potential cost, potential relative passage effectiveness, and the remaining previously listed factors before a conclusion is reached that passage (or even dam removal) is necessary at the dam.

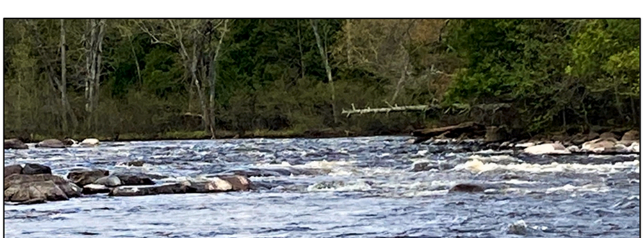

Fig. 8. Quinn's Rapids, North Fork of the Flambeau River, Ashland Co, WI. One of more than a dozen high gradient rapids within a 45 km reach of river between dams that LS traverse each year to migrate upstream to spawning areas below the Turtle Flambeau Flowage Dam. Photo by Ron Bruch, May 2021.

Once a decision is reached that the presence of an established dam on a LS river system fragments the river in a manner that disrupts sufficient recruitment to prevent the LS population from reaching or sustaining population management objectives, the second phase of the decision-making process is determining the best passage methodology to employ. If a hardened structure is deemed the best passage solution, the results from this evaluation suggest that an upstream projecting pool-weir ramp or a nature-like by-pass channel may be the most cost effective and most efficient choice, providing sufficient land or space is available adjacent to the dam to accommodate the channel whether above or below the dam at estimated costs of $186 649 to $305 579 per meter of head to construct. Potentially up to 50% or more of the spawning adult LS in the system could be passed in a given year through a nature-like bypass channel although these percentages could vary depending upon the quantity and quality of LS spawning habitat above the dam vs below the dam, location of the fishway entrance, as well as other factors. At the Eureka fishway on the upper Fox River in Wisconsin, in operation since 1989, 100% of the LS observed in the fishway during annual LS spawning assessment operations there passed through the fishway (with some simply spawning in the fishway as they passed up and down through the fishway), but the number of LS spawning below the dam and the fishway varied significantly from year to year depending on factors suspected to include flows and rate of spring water temperature warm-up (Bruch, 2008; R. Bruch, Observations at the fishway, 1988–2012). In our experience gravid lake sturgeon are generally always motivated to go somewhere to spawn - usually upstream, although there are some reports in the literature documenting shoal spawning of lake sturgeon (Nevin, 1919), but the occurrence is generally rare. Lake sturgeon ready to spawn often migrate as far upstream as possible bypassing seemingly ideal spawning habitat, but not always and their spawning migration "destinations" will vary from one spawning year to the next within systems. This has been well documented and may be one of the covariates affecting the % of population attempting to use fish passages (Bruch and Binkowski, 2002; Bruch et al., 2016; Ecclestone et al., 2020).

A critical factor affecting the effectiveness of a nature-like bypass channel or upstream projecting ramp appears to be the placement of the entrance of the fishway as close as possible to the base of the dam, and then also assuring there is sufficient attraction flow, with water velocities > 0.5 m/s up to 2.1 m/s (Eureka Fishway data, current study; Bruch and Binkowski, 2002). The overwhelming success of the Eureka Fishway in attracting and passing LS, after 30 + years of observations, appears to be due, in large part, to the location of the entrance which is literally at the base of the dam where migrating LS concentrate and, after finding the attractive flow and entrance to the fishway, readily continue moving upstream. The velocities in the Eureka Fishway allow LS to move through easily, as well as to hold in the fishway, and are sufficient enough to facilitate some spawning as well within the fishway in many years. LS in the Rupert River, Quebec, were found to have little interest in passing through a pool step bypass fishway due, it was suspected, to the placement of the fishway entrance 90 m below the dam (Environnement Illimité inc, 2012).

The other important factor favoring a nature-like bypass or upstream projecting channel are relatively low operating costs. The responses received from the various fishway managers indicated that if designed and constructed properly, these fishways cost very little to operate and maintain. If the fishway is only operated seasonally, the primary expense was for staff time that would be needed to open and close the head gates at the start and the end of the operating season. Slopes and channel configuration in the by-pass fishways are also likely keys to their success in passing LS. Slopes of the four bypass channel fishway structures examined, Eureka Dam, Winter Dam, Mequon-Thiensville Dam, and Rupert River are 3.3 %, 2.7 %, 1.1 %, and 1.7 % respectively. All four are made up of some configuration of stepped pools and/or riffle runs which simulate very well the slope and configuration of natural high gradient rapids in the LS rivers in northern Wisconsin, e.g., Quinn's Rapids, North Fork of the Flambeau River (Fig. 7).

The vertical slot fishway and the fish ladder as hardened structures were substantially more costly and relatively less efficient at passing LS upstream. The vertical slot fishway at the St. Ours Dam on the Richelieu River, Quebec cost $1.1 million per meter of head to design and construct while the Menominee River Fish Elevator at the Menominee Dam, Michigan cost $1.6 million per meter of head to design and construct. In addition, these structures in 2020 had $7824 and $22 507 annual operating costs while passing only an estimated 5% and 1% of the adult LS making the spawning run in the respective rivers. The Vianney-Legendre fishway is operated 92 days per year while the Menominee Fish Elevator is operated 105 days per year. In addition, the LS captured in the Menominee Fish Elevator need to be placed in a tank and trucked by road for release 1.6 km upstream above the next dam. Fig. 8.

The Capture and Transfer (C&T) operation on the Wolf River in Wisconsin has been highly successful re-establishing within the program's 1st year a successfully spawning LS population in a reach of the river where LS sturgeon had not spawned in likely over 100 years (Koenigs et al., 2019). The moderate size of Wolf River (ave. annual flow 39.0 cms), its high seasonal abundance of migrant adult LS, and its good access by boat, creates an optimal situation for successfully capturing large numbers of LS within 2–3 weeks pre-spawn via electrofishing for truck transport for release 16 km upstream within the Menominee Reservation below the original natural migration barrier, Keshena Falls. The high costs of hardened passage structures are eliminated with C&T, and the long-term projected costs are quite low ($1 M to build a hardened fishway would fund a C&T program similar to the one on the Wolf River for almost 100 years). Conditions for efficiently capturing pre-spawn LS via electrofishing (or other gear) may not be as optimal though on other LS river systems in the US and/or Canada due to lower LS abundance, remoteness of and difficult access to the LS pre-spawn staging and spawning areas, and size of the LS rivers (too big or too small to sample effectively).

Upstream LS passage has been successfully accomplished at dams in the US and Canada however the relative passage efficiency and the numbers passed each year is neither fully understood nor fully documented. Based on the information gathered for this evaluation, forty year long-term projected costs may be relatively low, approximately $10 per LS, to quite high, approximately $1700 per LS, depending on the structure or method employed, and the size of the LS population in question. The first important step is to determine whether LS passage is actually needed to restore, maintain, or sustain a LS population at its historic or desired abundance level in a system (above and below the dam); followed then, if passage is needed, by determining what type of passage methodology might be the most effective, and the most effectively and practically funded, operated, and maintained at the dam in question.

While this paper summarizes the experiences with upstream passage systems for LS, little information has been reported on the downstream passage systems for LS. The information provided herein, specifically the details about the movement of LS downstream through two dams on the Wolf River following sonic tagging and release through the LS Capture and Transfer Program there, provide some clear indication that LS can and will very successfully move downstream through tainter gates of dams without suffering ill effects, and without the presence of, and perhaps need for, any specialized downstream LS movement structure in place (Koenigs et al., 2019; WDNR, 2020).

CRediT authorship contribution statement

Ronald Bruch: Conceptualization, Methodology, Data collection, Analysis, Writing – original draft preparation, Writing – review & editing. **Tim Haxton:** Conceptualization, Methodology, Data collection, Analysis, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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