Investigating downstream passage of lake sturgeon, *Acipenser fulvescens*, through a Winnipeg River generating station

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A thesis submitted to the Faculty of Graduate Studies of
The University of Manitoba
in partial fulfilment of the requirements of the degree of

MASTER OF SCIENCE

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ABSTRACT

Lake sturgeon, recently recommended to be listed as an endangered species under the Species at Risk Act, inhabit the various impoundments of the Winnipeg River system. Downstream passage through hydroelectric generating stations represents one of the major data gaps in our understanding of how hydroelectric development may be impacting lake sturgeon populations. Acoustic telemetry was used to investigate coarse-scale movements of juveniles, sub-adult and adults throughout the Slave Falls Reservoir, a 10 km long Winnipeg River impoundment, to assess patterns of downstream passage susceptibility and investigate fine-scale movements in the vicinity of the Slave Falls Generating Station. Movements of juveniles and sub-adults were generally restricted to areas of interconnected deep-water habitat, with movements through the shallow river narrows that sub-divide the Slave Falls Reservoir being rare. Adults did move through these narrows, albeit infrequently. Juveniles and sub-adults tagged in the lowermost section of the reservoir, as well as several adults tagged throughout the reservoir, were found to periodically utilize habitat immediately upstream of Slave Falls, where they would be susceptible to entrainment. Mean entrainment rates were estimated at 3.1% per year for adults tagged throughout the reservoir, and 17.9% per year for sub-adults tagged in the lowermost section of the reservoir. Fine-scale movement tracking revealed that three of eleven observed downstream passage events occurred via bottom-draw regulating gates, while another four events were also reasoned to have occurred via this route. The routes of the remaining four could not be determined. Eight of the eleven downstream passage events observed in this study were survived. While the survival of the remaining three fish could not be confirmed, it is highly likely that they also survived. Length-at-age analysis, supported by genetic methods, revealed that 23 of 151 (15.2%) of the lake sturgeon between 525 and 750 mm (fork length) captured in the 6 km stretch of river downstream of Slave Falls were fast-growing outliers, reasoned to have passed downstream through the Slave Falls Generating Station.

ACKNOWLEDGEMENTS

This list of people I would like to acknowledge for helping me complete this endeavour is long. First and foremost, I would like to thank Dr. Gary Anderson, my co-advisor at the University of Manitoba for providing much needed input on a wide variety of issues (both scientific and otherwise), and for guiding and keeping me on track through the graduate student process. You have gone above and beyond what is expected of an academic supervisor. I would also like to thank Dr. Stephan Peake, my co-advisor at the University of New Brunswick, for securing funding for this research.

Dr. Paul Blanchfield, Dr. Margaret Docker, and Dr. Shawn Clark (my advisory committee) are thanked for their suggestions and constructive criticisms over the past two and half years. I have enjoyed working with you all, and hope that we can collaborate on future research endeavours. I wish to acknowledge Dr. Norm Kenkel and Dr. Darren Gillis for their enthusiastic input regarding methodologies for analysing complex telemetry data sets. Dr. Amy Welsh is also thanked for conducting laboratory analysis of DNA samples and for providing initial direction related to genetic methods.

Rob McDougall, who passed up more lucrative summer employment offers to assist me in the field, is thanked for his hard work and dedication. I very much appreciate your willingness to put up with a perfectionist brother (me), and am sorry to have misled you with the lure of a relaxing summer on the water. However, you knew what to expect for the second summer, so I wash my hands of responsibility for that. I would also like to thank many others for field assistance over the course of my research: Jon Peake, Ray Lafantasie, Cheryl Klassen, Claire Hrenchuk, Kelly Sparks, Matt Randell, Karen McDougall (mom) and Tom McDougall (dad).

North/South Consultants deserves significant recognition for providing additional field assistance, lending me a variety of biological sampling and telemetry equipment, providing laboratory space and equipment necessary for ageing structure analysis, and offering insights and preliminary data with regard to lake sturgeon movements. In particular, Mark Gillespie, Mark Blanchard, Darcy Pisiak, Dr. Cam Barth, Don MacDonell, Lee Murray, Ken Ambrose and Dr. Pat Nelson are thanked for their various contributions. I wish to also remember and thank the late Doug Gibson, whom the world was robbed of far too early, for his assistance and friendship. You touched many lives, and you will not be forgotten.

Manitoba Hydro and the National Sciences and Engineering Research Council of Canada are thanked for providing the bulk of the considerable funding necessary to conduct this research. In addition, I would like to thank Doug Krampetz, Shelley Matkowski, Marilynn Kullman, and all the operating staff at the Slave Falls GS for their logistical support, as well as Paul Chanel for generating velocity models.

Last but not least, I would like to thank my lovely wife Chelsey for putting up with me during what has been a trying (but rewarding) graduate student experience. You have provided me with so much support (not to mention field assistance and editorial skills), I can only hope to reciprocate over the course of our life together. The little bundle of joy we have recently welcomed, Logan Douglas McDougall, is also thanked for helping me appreciate the small things in life.

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1.0 BACKGROUND

1.1 Lake sturgeon

1.1.1 Systematics, morphology and general characteristics

The lake sturgeon, *Acipenser fulvescens*, belongs to the Acipenseriformes, an order of primitive fishes that have existed since at least the Lower Jurassic period, some 200 million years ago (Bemis et al. 1997). The sturgeons (Acipenseridae, 25 species) and the paddlefishes (Polyodontidae, 2 species) comprise the order, with the majority displaying anadromous life history strategies (Bemis et al. 1997; Bemis and Kynard 1997). The lake sturgeon is the only potadromous sturgeon found in Canada (Scott and Crossman 1998). Inhabiting lakes and rivers of the Great Lakes, Hudson Bay and Mississippi River drainage basins, lake sturgeon often grow to exceed 1.5 m in length and 50 years of age (Auer 1996a; Scott and Crossman 1998).

Lake sturgeon, like all sturgeons, are externally characterized by a sagittiform body, a large heterocercal tail, scale-less skin, armoured skull, an inferior protactile and toothless mouth, and four barbels (Harkness and Dymond 1961; Houston 1987; Scott and Crossman 1998). As juveniles, the fish is protected from predators by five rows of bony scutes, which are sharp and hook-like (Scott and Crossman 1998). By the time the fish reaches adulthood, the scutes have been reabsorbed (Peterson et al. 2007).

1.1.2 Spawning and early life history

In early spring, adult lake sturgeon congregate at spawning sites in flowing rivers and streams. Spawning sites are predominantly located immediately below an impassable barrier such as a set of falls or rapids (Auer and Baker 2002; Auer 1996a; Harkness and

Dymond 1961; Lahaye et al. 1992; Scott and Crossman 1998). Spawning typically occurs at water temperatures of 9 – 21ºC, (Auer and Baker 2002; Lahaye et al. 1992; Nichols et al. 2003; Scott and Crossman 1998), varying somewhat by system. Eggs are generally deposited over hard substrates such as gravel, cobble, boulder or broken bedrock (Harkness and Dymond 1961; Lahaye et al. 1992; Scott and Crossman 1998).

Fertilized eggs adhere to the substrate on which they were deposited, but many are lost due to dislodging, egg penetration into interstitial spaces, and predation (Johnson et al. 2006; Kempinger 1988). A small percentage of the fertilized eggs hatch 6 – 14 days after deposition, dependent on water temperature (Johnson et al. 2006; Kempinger 1988; Nichols et al. 2003; Scott and Crossman 1998). Larval lake sturgeon are approximately 8 – 10 mm in length when they emerge from the egg (Auer 1982). While the maximum distances larvae drift have rarely been quantified in the literature, Auer and Baker (2002) reported that lake sturgeon larvae drift over 45 km in the Sturgeon River, Michigan. Larval drift is not uniform throughout the river channel, suggesting that larvae may actively select for certain habitats while drifting (Auer and Baker 2002; Smith and King 2005a).

1.1.3 Juvenile life history

Lake sturgeon begin exogenous feeding after reaching approximately 22 – 24 mm (Kempinger 1988; Smith and King 2005a). In Lake Winnebago, Wisconsin, they are able to attain lengths as large as 281 mm before the end of their first year (Kempinger 1996). Rapid growth (length) often continues throughout the early juvenile phase of life (Noakes et al. 1999), decreasing as the fish transition into adults (Harkness and Dymond 1961; Scott and Crossman 1998). Juvenile lake sturgeon diet is primarily made up of invertebrates from a variety of orders, including Ephemeroptera, Diptera, and Trichoptera, small Crustacea, Hirunidae and Mollusca, and as they are benthic generalists, composition can vary considerably by system (Beamish et al. 1998; Chiasson et al. 1997; Kempinger 1996; Mckinley et al. 1993; Nilo et al. 2006). Juvenile lake sturgeon also appear to have a preference for drifting prey items, and there is evidence to suggest that they may sometimes consume prey from the water column (Block 2001; Kempinger 1996; Nilo et al. 2006).

Habitat usage and movement patterns of juvenile lake sturgeon vary considerably by system, but some trends exist. Juvenile lake sturgeon show a strong preference for sand substrates in both field and laboratory investigations (Benson et al. 2005; Chiasson et al. 1997; Holtgren and Auer 2004; Kempinger 1996; Peake 1999; Smith and King 2005b), and will generally utilize deep water when it is available (Barth et al. 2009; Holtgren and Auer 2004; Lord 2007; Smith and King 2005b). In Great Lakes systems, age-0 lake sturgeon are known to spend their first summer in the lower reaches of rivers in which they were spawned, in habitats characterized by shallow, low-velocity water and fine substrates, before descending into the adjacent lake in the fall (Benson et al. 2005; Caroffino et al. 2009; Chiasson et al. 1997; Holtgren and Auer 2004; Kempinger 1996).

1.1.4 Adult life history

Male and female lake sturgeon mature after 10 – 20 and 14 – 33 years, respectively, with male lake sturgeon spawning every 1 – 4 years, and females spawning every 3 – 9 years thereafter (Bruch et al. 2001; Harkness and Dymond 1961; Scott and Crossman 1998). While juvenile sturgeon rapidly grow in length, adult growth is focused more on weight gain, with condition-factor known to increase with size of adult lake sturgeon on almost all systems that it has been studied (Beamish et al. 1996). As juveniles transition into adults, their diet may shift to larger prey items such as clams, snails and small fish, although the small invertebrates which make up the bulk of the juvenile diet are still consumed (Harkness and Dymond 1961; Stelzer et al. 2008; Werner and Hayes 2005).

Because adult lake sturgeon are larger than any potential predators, it is suspected that habitat usage is primarily influenced by feeding habits (Harkness and Dymond 1961; Peterson et al. 2007). In some systems, adult lake sturgeon inhabit the shallows during spring before moving to cooler, deeper water during the summer (Harkness and Dymond 1961; Scott and Crossman 1998). In others, adult lake sturgeon appear to use deeper water year round (Rusak and Mosindy 1997). Adult lake sturgeon often inhabit lacustrine/riverine transition zones, shorelines, reefs and shoals, and are seldom located in the middle of lake and river basins (Block 2001; Harkness and Dymond 1961; Knights et al. 2002; Rusak and Mosindy 1997). Adults are known to migrate over 200 km to reach spawning grounds (Auer 1999; Kempinger 1988). After spawning is complete, adults quickly descend from the spawning grounds to downstream habitats and resume foraging (Bruch and Binkowski 2002; Peterson et al. 2007).

1.1.5 Status

A recommendation by the Committee on the Status of Endangered Wildlife in Canada has recently been made to list lake sturgeon under the Species At Risk Act, with Designatable Units (DUs) accounting for genetic and biogeographical differences between the groups of lake sturgeon (COSEWIC 2006). The following DUs and statuses are proposed: 1) Western Hudson Bay – Endangered, 2) Saskatchewan River –

Endangered, 3) Nelson River – Endangered, 4) Red/Assiniboine Rivers and Lake Winnipeg – Endangered, 5) Winnipeg/English Rivers – Endangered, 6) Lake of the Woods and Rainy River – Special Concern, 7) Southern Hudson Bay and James Bay – Special Concern, and, 8) Great Lakes and Upper St. Lawrence River – Threatened. To understand the status of lake sturgeon populations in Canada, one must look to historical factors.

From approximately 1860 to 1950, fuelled by a demand for smoked meat and caviar, lake sturgeon populations were commercially exploited throughout North America (Harkness and Dymond 1961; Houston 1987). In Ontario, beginning with Lake Erie, a pattern emerged among lake sturgeon fisheries: high initial yields, followed by a sharp decline in production and finally the fishery being closed. From 1885 to 1895, Lake Erie production had declined by 80%, from an annual high of 2,270,000 kg (Carlson 1995; Harkness and Dymond 1961; Houston 1987). As production from one fishery fell, another would rise to take its place, only to succumb to the same fate as the previous. While some fisheries were reopened, prior levels of production were never attained.

Based on the commercial fishing records of the late 1800s, it is certain that the lake sturgeon populations of today generally exist at a small fraction of historic levels. Analysis of these records draws one conclusion: overexploitation was primarily responsible for the drastic and lasting decline in lake sturgeon populations throughout North America (Harkness and Dymond 1961; Houston 1987; Scott and Crossman 1998; Velez-Espino and Koops 2009).

While commercial exploitation of lake sturgeon fisheries has ceased, in some cases for 100 years, there are few signs of natural population recovery (Peterson et al.

2007). This is certainly due in large part to the biology of the species. Late age of maturity and infrequent spawning thereafter means that the generation time for lake sturgeon populations is on a scale of decades, while a meaningful recovery might take centuries (Haxton and Findlay 2008; Peterson et al. 2007; Secor et al. 2002; Velez-Espino and Koops 2009). However, the weakened populations are also currently at risk due to fragmentation by dams, habitat alteration/loss, and pollution (Auer 1996a; Ferguson and Duckworth 1997; Peterson et al. 2007; Secor et al. 2002; Velez-Espino and Koops 2009). For many of the lake sturgeon populations to have a chance at recovery, these threats need to be better understood, and potentially mitigated (Secor et al. 2002; Velez-Espino and Koops 2009).

1.1.6 Hydroelectric development and lake sturgeon

Considering that lake sturgeon inhabit so many of the North American river systems already developed or coveted for future power generation, it is of little surprise that hydroelectric development poses one of the greatest threats to the recovery of lake sturgeon populations (Harkness and Dymond 1961; Scott and Crossman 1998; Secor et al. 2002; Velez-Espino and Koops 2009). As such, research has recently been directed towards understanding the impacts of hydroelectric development on the species.

Hydroelectric generating stations are designed to hold back the rivers and streams on which they are built, so as to harness the energy of flowing water. By raising water levels on the upstream side, dams create the necessary head to generate power. However, head differentials and associated infrastructure of hydroelectric stations, combined with the relatively poor swimming abilities of the lake sturgeon, make hydroelectric generating stations barriers to upstream passage (Auer 1996a; Harkness and Dymond

1961; Peake et al. 1997). Considering the migratory nature of lake sturgeon, this can represent a serious problem (Auer 1996a; Haxton and Findlay 2008).

In many systems, lake sturgeon were historically known to have migrated large distances from lakes up tributaries to spawn, but construction of hydroelectric generating stations in the lower reaches of these tributaries has restricted access to upstream spawning grounds and nursery habitats (Auer 1996a; Harkness and Dymond 1961; Scott and Crossman 1998). As a result, lake sturgeon in hydroelectrically developed systems often spawn downstream of generating stations that restrict upstream passage (Auer 1996b; Harkness and Dymond 1961; Haxton and Findlay 2008; Lahaye et al. 1992). In some cases, unfavourable conditions downstream of hydroelectric generation stations result in limited or lack of spawning success (Auer 1996b). In others, successful deposition, fertilization and larval hatch is known to occur (Bruch and Binkowski 2002; Lahaye et al. 1992).

Hydroelectric development can result in alteration to the natural water flow regime on both long and short-term scales (Petts 2009; Rosenberg et al. 2000). On a long-term scale, some systems are managed to maximize power generation during winter. To achieve this, spring freshets may be held back by dams and large reservoirs to be released when power needs require. As lake sturgeon year class strength has been found to be positively correlated with spring flow volumes (Nilo et al. 1997), this seasonal flow reversal is believed to have a negative effect on juvenile lake sturgeon recruitment.

On a short-term scale, many hydroelectric stations operate on a peaking schedule. These stations pass flow when the need to generate power is high, and hold back water when power production is not needed. As a result, flows and water levels upstream and downstream of peaking stations vary considerably on a scale of hours to days (Jager and Bevelhimer 2007). Auer (1996b) found that peaking operation of the Prickett hydroelectric facility on the Sturgeon River, Michigan, had strong negative impacts on spawning behaviour compared to run-of-the-river operation (stations pass flow as they receive it, and lack a large forebay). More lake sturgeon, including ripe females, were present on spawning grounds immediately downstream of the station, and reproductive readiness was higher in years where the station was operated as run-of-the-river. Additionally, eggs deposited under peaking flow conditions risk exposure to the air, and thus desiccation, when water levels drop (Ferguson and Duckworth 1997). Peaking flow regimes have also been linked to the altered nutritional status of areas downstream of a hydroelectric generating station, resulting in reduced health of the lake sturgeon populations located there (Mckinley et al. 1993).

Backwatering (i.e. water held or pushed back) caused by construction of hydroelectric generating stations alters the character of the river by reducing velocities, increasing depths and rates of sediment deposition and can result in the inundation of rapids and falls previously used for spawning (Ferguson and Duckworth 1997; McKinley et al. 1998). The degree to which these alterations occur varies based on the physical characteristics of the river and the station construction.

Hydroelectric stations do not entirely restrict downstream movement of lake sturgeon like they do upstream movement, and it is acknowledged that all sizes (larval to adult) resident upstream of generating stations could potentially move downstream through powerhouse turbines or over spillways, albeit with an inherent risk of injury or mortality (Secor et al. 2002). On the Mattagami River in northern Ontario, a downstream dispersal pattern of adults to the area immediately upstream of hydroelectric facilities was observed during summer/fall, resulting in susceptibility to entrainment (downstream passage) through a spillway control structure (McKinley et al. 1998). From 1990 to 1995, between 40 and 400 adult lake sturgeon per year were entrained through the Adam Creek control structure, operated as a spillway for the Little Long Generating Station (Seyler et al. 1996). Many of these fish, which were captured and transported back upstream of the station, showed visible injuries. On other river systems, mark-recapture tagging has documented few downstream movements of lake sturgeon over hydroelectric generating stations (Haxton and Findlay 2008; Thuemler 1985; Thuemler 1997).

The topic of downstream passage is a major gap in knowledge of how hydroelectric generating stations impact lake sturgeon (Secor et al. 2002; Velez-Espino and Koops 2009). While there is little specific information available on downstream passage of lake sturgeon, research on other fish species may shed light on the potential consequences of downstream passage on this species.

1.2 Downstream passage of fishes through hydroelectric generating stations

Many species that utilize riverine habitats upstream of hydroelectric generating stations are known to pass downstream through the stations, and thus be at risk to mortality or injury, as well as migratory delays associated with passing (Coutant and Whitney 2000). Downstream passage at a hydroelectric generating station can typically occur via one of two pathways: turbine (powerhouse) or spillway (Schilt 2007). Turbine passage occurs when fish move past trash-racks (metal bars designed to prevent debris from entering a turbine) into and through the penstock (the tube in which water flows towards the turbine) and then the turbine unit, before exiting the generating station in the tailrace. Spillway passage occurs when fish move over the surface of the dam or through gates designed to discharge flows in excess of what the powerhouse can utilize. While downstream passage related studies on migratory species such as shad, eels and anadromous sturgeon exist in the published literature, salmonids have garnered much of the scientific attention due to their economic importance and highly publicized decline in abundance (Schilt 2007).

Many salmonids (e.g. Chinook salmon, *Oncorhynchus tshawytscha*; Coho salmon, *Oncorhynchus kisutch*; rainbow trout, *Oncorhynchus mykiss*; and, Atlantic salmon, *Salmo salar*) migrate large distances from their lacustrine or ocean habitats, moving up rivers to spawn. On developed systems, they encounter hydroelectric generating stations as they move upstream. However, with suitable upstream passage structures installed, these strong swimmers are able to ascend over many of these stations, continue their upstream migration, and successfully reach historic spawning grounds. Eventually, juvenile offspring of these spawning fish attempt to move downstream to lakes or oceans, and thus must pass downstream through any hydroelectric stations on their course. As such, understanding salmonid downstream passage is particularly critical, and thus relatively well-studied (Coutant and Whitney 2000; Schilt 2007).

Turbine passage generally results in the highest rate of fish mortality and injury associated with downstream movements through hydroelectric generating stations, although there is much variation among species, size and age classes, time of year, water temperature, turbine type, and operation mode (Coutant and Whitney 2000; Schilt 2007).

Direct turbine mortality can be caused by a complicated set of interacting factors, including: rapid pressure changes, cavitation, shear stress, turbulence, blade strike and grinding (Cada 2001; Coutant and Whitney 2000). These factors can also be responsible for indirect mortality, particularly when disorientation or changes in buoyancy increase a fish's susceptibility to predation once it leaves the turbine and enters the tailrace below the powerhouse (Cada 2001; Coutant and Whitney 2000; Ferguson et al. 2006). Considering that fish (especially salmonids) may need to pass multiple generating stations on their downstream descents, the cumulative risk of mortality can be quite high (Schilt 2007). Direct mortality rates (i.e. < 48 hour) of 4 – 13% have been reported for juvenile salmonids (Bickford and Skalski 2000; Dedual 2007). To compare with another migratory species, mortality rates of 0 – 66% have been reported for American shad, *Alosa sapidissima* (Bell and Kynard 1985; Dubois and Gloss 1993; Mathur et al. 1994; Taylor and Kynard 1985). At the Hadley Falls Station on the Connecticut River, Massachusetts, USA, downstream passage of adult shortnose sturgeon, *Acipenser brevirostrum,* through turbines (Kaplan) resulted in 100% mortality (Kynard et al. 1999) in (Kynard and Horgan 2001).

Spillway passage mortality rates for juvenile salmonids have ranged from 0 to 2% (Muir et al. 2001; Schoeneman et al. 1961). However, increased levels of dissolved gases downstream of spillways can, in some cases, stress or kill fish (Backman et al. 2002; Backman and Evans 2002; Lutz 1995). Fish concentrated by spillway passage may also be at an increased risk of predation (Schilt 2007), but in general, spillway passage poses a lower mortality risk to downstream moving fish than does turbine passage (Muir et al. 2001; Schilt 2007). However, fish are not able to knowingly select the lowest-risk path when they encounter a generating station during their downstream migration.

While the understanding of downstream passage route selection is incomplete, it is influenced by species behaviour, as well as site specific station configuration and flow characteristics (Coutant and Whitney 2000; Schilt 2007). Juvenile salmonids tend to move downstream with the main river flow, and as a result there is a strong relationship between river flow volumes and the proportion of passage that occurs via the spillway at generating stations (Whitney et al. 1997). Passage route selection in juvenile salmonids is also influenced by their surface oriented behaviour (Giorgi and Stevenson 1995). Spillway gates which discharge surface water (sometimes referred to as sluiceways) tend to be selected for downstream passage more frequently than spillway gates which withdraw water from lower in the water column (Ransom et al. 1988; Raymond and Simms 1980). Similarly, it has been suggested that entry into deep turbine intakes will only occur if juvenile salmonids milling upstream of a hydroelectric station cannot find a more preferred (i.e. higher in the water column) passage route (Coutant and Whitney 2000). On the Columbia and Snake rivers (where most downstream passage related research has been conducted), there is a daily pattern to downstream passage of juvenile salmonids, with surface passage occurring during t daytime and deeper passage occurring at night (Beeman and Maule 2001; Schilt 2007; Thorne and Johnson 1993).

Parsley et al. (2007) investigated passage (both upstream and downstream) of white sturgeon, *Acipenser transmontanus*, over the Dalles Dam, on the Columbia River, Oregon. Acoustic and radio transmitters were implanted in 148 white sturgeon, and eighteen downstream passage events were documented during the March 2004 to November 2005 study period, with some fish making multiple descents (and ascents). Nine downstream passage events occurred over the spillway, and one occurred through either the powerhouse or ice/trash sluiceway. The routes of the remaining eight passage events could not be determined, but they likely occurred either through the spillway or sluiceway since most fish were too large to fit through turbine intake trash-racks. As no mortalities were observed, it was concluded that downstream passage survival at this station was high.

Mechanisms for downstream passage of fish that reside upstream of generating stations for long periods of time are likely very different from those of migratory juvenile salmonids. This is largely because resident species would be adapted to avoid or resist flows that might force them downstream out of their preferred habitat, whereas juvenile salmonids are motivated to move downstream (Coutant and Whitney 2000). Downstream passage of resident species would therefore likely occur when these fish utilized habitat immediately upstream of a generating station and were entrained after coming too close to high flow intake areas upstream of the powerhouse or spillway (Coutant and Whitney 2000). Whereas juvenile salmonids often pass in the middle of a hydroelectric station in relation to the main river flow, passage of non-migratory resident teleosts often occurs in relation to shorelines and sidewalls of intakes, likely a result of resident fish being shoreline or structure oriented (Coutant and Whitney 2000; Federal Energy Regulatory Commission 1995). What little is known about downstream passage of resident species suggests that we cannot necessarily infer too much from published studies of downstream passage by migratory salmonids. However, it is evident that susceptibility of various resident fish species to downstream passage is related to species behaviour, seasonal factors, life stage, and site specific characteristics of the river and hydroelectric station (Coutant and Whitney 2000).

A synthesis of turbine entrainment monitoring studies by the United States Federal Energy Regulatory Commission (1995) suggested that resident teleosts such as smallmouth bass (*Micropterus dolomieu*), walleye (*Sander vitreus*), yellow perch (*Perca flavescens*), black crappie (*Pomoxis nigromaculatus*), alewife (*Alosa pseudoharengus*), white sucker (*Catostomus commersonii*), gizzard shad (*Dorosoma cepedianum*) and threadfin shad (*Dorosoma petenense*) were entrained at various stations, in small numbers throughout the year, although entrainment of schooling species like shad, was found to be very episodic. While large numbers of early life history stages (eggs, larvae, juvenile) may be entrained in certain systems, evidence suggests generally high turbine passage survival of these life stages (Coutant and Whitney 2000; Federal Energy Regulatory Commission 1995). In shad and alewife, high rates of turbine entrainment during fall and winter is thought to be related to deep-water habitat usage, as well as reduced swimming capacity in colder water conditions (Coutant and Whitney 2000).

Efforts to reduce downstream passage mortality, injury and migratory delay of fish (primarily of juvenile salmonids), have investigated and used a wide variety of downstream passage technologies in various combinations (Electric Power Research Institute 1986; Electric Power Research Institute 1998; Schilt 2007). The technologies that are most frequently used and/or are believed to have the greatest promise for future downstream passage application include juvenile turbine bypass systems, surface flow outlets, behavioural deterrents, physical deterrents and “fish-friendly” turbines (Cada 2001; Coutant 2001; Electric Power Research Institute 1986; Electric Power Research Institute 1998; Schilt 2007). However, it is evident that no single technology is appropriate for all species or even all life stages of a single species, and that the biology of the species will dictate which may be effective, should downstream fish protection be required.

1.3 The Winnipeg River

The Winnipeg River originates at the outlets of Lake of the Woods, Ontario, and flows 260 km prior to emptying into the south basin of Lake Winnipeg, Manitoba. Its drainage basin covers over 150,000 km^2 of predominantly Precambrian Shield, stretching into Minnesota and across north-western Ontario, almost to the shores of Lake Superior (Lake of the Woods Control Board 2002; Rosenberg et al. 2005). Historically, the Winnipeg River consisted of a series of lakes separated by rapids and falls, plunging 105 m over its course (Rosenberg et al. 2005; St. George 2007). Downstream of Lake of the Woods, the Winnipeg River carries an average flow of 460 m^3/s (Lake of the Woods Control Board 2002). Flow is soon supplemented by the English River, which contributes an average of 260 m^3/s. Near the end of its course, the Winnipeg River carries an average flow of 967 m^3/s (range: 135 to 2990 m^3/s) (Environment Canada 2010).

The Winnipeg River has been highly developed for hydroelectric power generation, with the first station (Pinawa Dam) going into service in 1906, over 100 years ago (Bateman 2005). All six active Winnipeg River hydroelectric generating stations in Manitoba operate as run-of-the-river (Bateman 2005; St. George 2007) with little daily fluctuation in flows, but river discharge is regulated at the Lake of the Woods outlets, as well on the English River (Lake of the Woods Control Board 2002).

The Winnipeg River watershed supports a rich assemblage of 61 native fish species as well as eleven transplanted or introduced species (Stewart and Watkinson 2004). But perhaps most notably, the Winnipeg River is inhabited by Canada's largest and longest-lived freshwater fish, the lake sturgeon (Scott and Crossman 1998). Historically, the lakes located at either end of the Winnipeg River, Lake of the Woods and Lake Winnipeg, supported large (but brief) commercial lake sturgeon fisheries in the early 1900s (Harkness and Dymond 1961; Houston 1987; Sunde 1959). Lac du Bonnet, one of the lacustrine widenings of the Winnipeg River, also supported a short-lived commercial fishery (Harkness 1980; Sunde 1959). While Lac du Bonnet is the only location on the Winnipeg River mentioned in commercial harvest records, although it is assumed that the adjacent sections of river would also have been targeted to some degree.

1.4 Hypotheses and objectives

Some of the negative effects that hydroelectric development can have on lake sturgeon populations, as described in Section 1.1.6, relate to how generating stations restrict movements and fragment habitats. Considering the relatively poor swimming abilities of lake sturgeon (Peake et al. 1997; Webb 1986), it is assumed that upstream passage cannot occur over Winnipeg River generating stations due to large head differentials (7 – 18.6 m) and associated infrastructure of the stations. Still, the notion that Winnipeg River stations have artificially restricted upstream passage is questionable, since many were built at or near the sites of falls/rapids, which may have been natural barriers to upstream movement (Appendix 1). Conversely, downstream passage of lake sturgeon can certainly occur over Winnipeg River generating stations, but we know little about the frequency, mechanisms and success rate of passage events. Trash-racks on Winnipeg River powerhouses (5 – 10 cm spacing, varying by station) should prevent adult lake sturgeon from entering penstocks and passing via turbines, but smaller fish (larval to juvenile) could fit through the openings between trash-racks and thus pass downstream. Downstream passage of all sizes of lake sturgeon over the spillways at each generating station on the Winnipeg River is also possible, particularly during high-flow periods.

Recent research conducted on lake sturgeon on the Winnipeg River has led to several observations related to downstream passage over hydroelectric generating stations. As part of a mark-recapture study, three of approximately 1300 (0.27%) lake sturgeon marked with Floy tags (uniquely numbered external markers anchored between the basal pterygiophores of the dorsal fin) in the Slave Falls Reservoir from 2006 to 2008 have been recaptured downstream of the Slave Falls Generating Station (GS) (North/South Consultants unpublished data). These mark-recapture data obviously indicate that downstream passage (and survival) of lake sturgeon over the Slave Falls GS does occur, but they reveal little about the frequency or mechanisms of downstream passage events.

Similarly, one out of the sixteen (6.3%) lake sturgeon marked with Floy tags in the Pointe du Bois GS forebay from 2006 – 2008 has been recaptured downstream of Pointe du Bois (North/South Consultants unpublished data). Furthermore, some data suggests that flow conditions may influence distribution patterns upstream of Winnipeg River generating stations. In 2006 and 2007, under low and average flow conditions, no lake sturgeon were captured immediately upstream (within 1 km) of Pointe du Bois. In 2008, under high-flow conditions, seven lake sturgeon were captured immediately upstream of Pointe du Bois, with less gillnet effort. While set locations and timing were not consistent between years, it is possible that the relative abundance of lake sturgeon immediately upstream of the Pointe du Bois GS in 2008 may have been influenced by high-flow conditions.

This thesis examines downstream passage of lake sturgeon over the Slave Falls GS. Specific objectives include determining how movement patterns of lake sturgeon in the Slave Falls Reservoir result in susceptibility to downstream passage; assessing the frequency, route of passage, and survivability of passage events; and finally examination of the relationship between downstream passage and life history stage.

In examining the interaction between movements of lake sturgeon and the Slave Falls GS, I hypothesise that abiotic factors may influence the frequency of downstream passage. Specifically, I hypothesise that movements of lake sturgeon within the Slave Falls Reservoir are influenced by seasonality and flow conditions, and that high flows during the summer/fall period would correlate with relatively higher concentrations of adult and sub-adult fish immediately upstream of the Slave Falls GS. Furthermore, I hypothesise that downstream passage of lake sturgeon would occur both through the Slave Falls GS powerhouse and over the spillway, however, with passage being largely attributable to random movements within a fishes home range. Finally, given the combined potential for downstream movement of larval, juvenile, sub-adult and adult life stages, I hypothesise that, despite the presence of the Slave Falls GS, the Slave Falls Reservoir lake sturgeon population contributes to the genetic mix of the lake sturgeon population downstream of Slave Falls.

Chapter 2 investigates the coarse-scale movements of adult, sub-adult and juvenile lake sturgeon throughout the Slave Falls Reservoir using acoustic telemetry. Chapter 3 focuses on downstream passage route determination and assessing survival of fish following downstream passage events, as well as investigating fine-scale movements of lake sturgeon in the immediate vicinity of the Slave Falls Generating Station, also using acoustic telemetry. Chapter 4 investigates the genetic contribution of the Slave Falls Reservoir population to the population downstream of Slave Falls using microsatellite DNA analysis.

2.0 COARSE-SCALE MOVEMENTS OF LAKE STURGEON IN THE SLAVE FALLS RESERVOIR

2.1 Introduction

Movement patterns of lake sturgeon have been studied in some detail (Auer 1999; Fortin et al. 1993; Haxton 2003; Holtgren and Auer 2004; Knights et al. 2002; Rusak and Mosindy 1997), and it is apparent that they can vary considerably by river system, life stage, and amongst individuals. Adults may use well-defined core areas, and even in the absence of physical or hydraulic barriers, seldom stray except perhaps to spawn (Borkholder et al. 2002; Harkness and Dymond 1961; Haxton and Findlay 2008). Even within a given system, some may show affinity to core areas while others may exhibit long range and complex movement patterns (Knights et al. 2002). Seasonal migration patterns, characterized by upstream movements towards spawning grounds in spring, followed by downstream movement to foraging areas after spawning are also well known (Auer 1996a; Bruch and Binkowski 2002; McKinley et al. 1998; Rusak and Mosindy 1997). Movements of adult lake sturgeon have also been correlated to flow conditions, with upstream movements coinciding with increasing flow conditions and downstream movements coinciding with decreasing flow conditions (Borkholder et al. 2002). Juveniles have been found to utilize small home ranges in the Great Lakes region (Holtgren and Auer 2004; Kempinger 1996; Lord 2007; Smith and King 2005b), and in a large northern river (Barth et al. 2011).

Many river systems inhabited by lake sturgeon are hydroelectrically developed, and on some, seasonal movement patterns of adults can result in fish utilizing areas immediately upstream of hydroelectric facilities, where they may be vulnerable to entrainment (downstream passage) and subsequent mortality or injury (McKinley et al. 1998; Secor et al. 2002; Seyler et al. 1996). The frequency of entrainment at hydroelectric facilities may be related to the amount of time lake sturgeon spend in the immediate vicinity of the station, and as such, populations occurring in small impoundments could be highly susceptible. In order to assess the potential impact that entrainment at hydroelectric facilities might be having on lake sturgeon populations resident in small impoundments, the movement patterns of these fish need to be better understood.

In this study, acoustic telemetry was used to investigate the coarse-scale movement patterns of adult, sub-adult and juvenile lake sturgeon in the Slave Falls Reservoir, a small impoundment located on the Winnipeg River, Manitoba. The primary objective was to determine how movements resulted in susceptibility to entrainment through the Slave Falls Generating Station (GS), located at the lower end of the reservoir. It was hypothesized that entrainment would primarily occur as a result of random movements within a lake sturgeon’s home range, and in this regard, that fish tagged closer to Slave Falls would spend more time in the vicinity of hydroelectric facilities than would those tagged further upstream. Furthermore, it was hypothesised that movements of lake sturgeon within the Slave Falls Reservoir would be influenced by seasonality and flow conditions, and that high flows during the summer/fall period would be correlated with increased concentrations of adult and sub-adult fish immediately upstream of the Slave Falls GS.

2.2 Materials and methods

2.2.1 Study area

The study area for research presented in this chapter is the ~10 km stretch of the Winnipeg River located between the Pointe du Bois GS (est. 1909, 50º17’52N, 95º32’51W) at the upstream end and the Slave Falls GS (est. 1931, 50º13’39N, 95º37’51W) at the downstream end, hereon referred to as the Slave Falls Reservoir (Block 2001; Tremblay et al. 2004) (Figure 2.1). Winnipeg River flows here average 869 m^3/s (range: 100 – 2600) (St. George 2007), and this stretch is generally characterized by deep water (15 – 50+ m) and a variety of coarse and fine inorganic substrates (North/South Consultants Inc. unpublished data). Water level fluctuation is minimal, and the reservoir does not stratify.

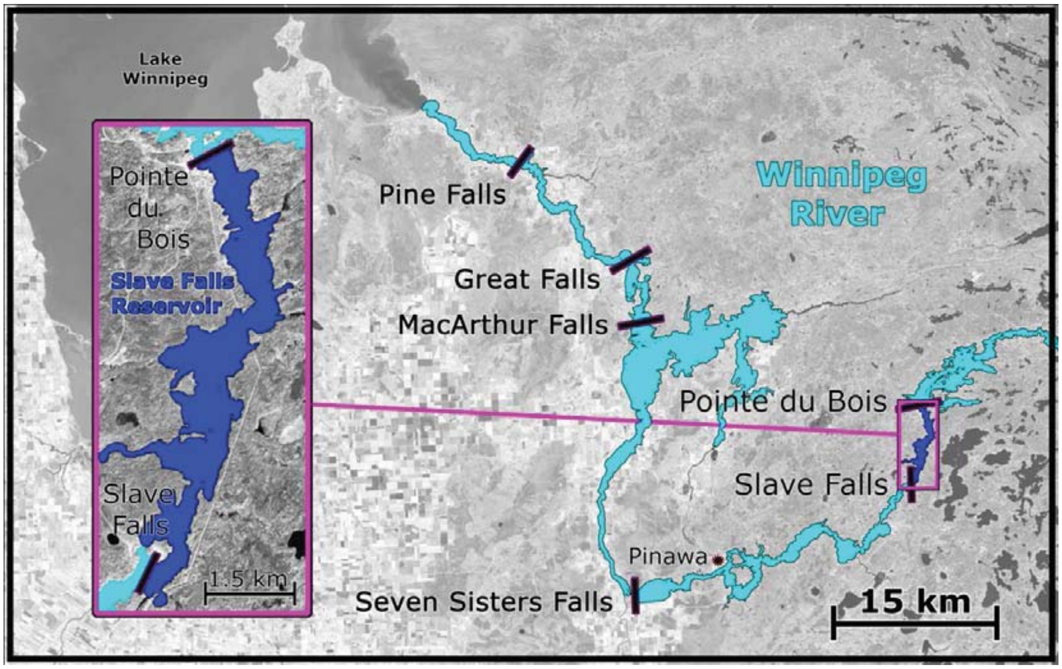

Figure 2.1. The Winnipeg River from the Manitoba/Ontario Border to Lake Winnipeg, with generating stations labelled, and study area inset.

Considering its small size, the Slave Falls Reservoir supports a relatively strong lake sturgeon population, estimated at 3273 adults in 2010 (North/South Consultants Inc. unpublished data). Spawning is known to occur at the base of the Pointe du Bois powerhouse and spillway, located at the upper end of the reservoir, during May/June, at water temperatures of 9 – 14°C (McDougall et al. 2008a; McDougall et al. 2008b). For the purpose of acoustic tagging, the Slave Falls Reservoir was divided into five sections relative to the primary flow axis of the Winnipeg River (Figure 2.2). The lowermost (i.e. closest to Slave Falls) is referred to as Section 1, while the uppermost (i.e. immediately downstream of Pointe du Bois) is referred to as Section 5.

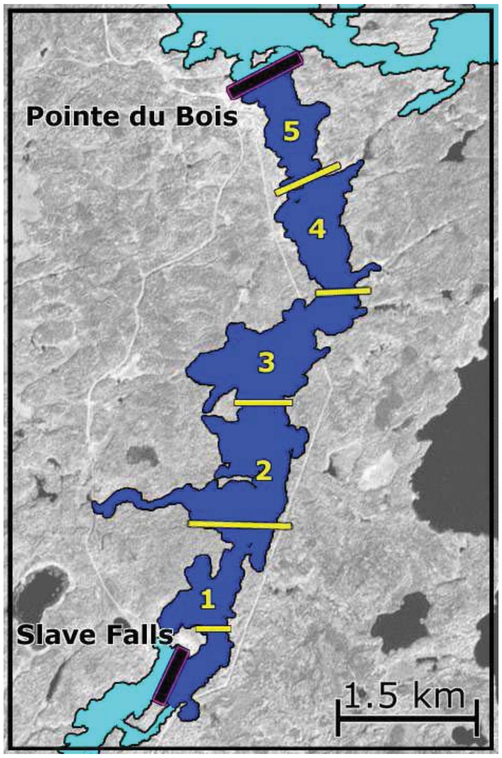

Figure 2.2. The Slave Falls Reservoir, divided into five sections for acoustic tagging of lake sturgeon.

2.2.2 Acoustic transmitters

Vemco V16TP-4L, V13TP-1L and V9TP-2L (Vemco, Shady Bay, Nova Scotia) 69 kHz acoustic transmitters were used in this study. V16TP-4L transmitters were 71 mm in length, 16 mm in diameter, had a mass of 25 g (in air) and a life expectancy of 1350 days. V13TP-1L transmitters were 45 mm long, 13 mm in diameter, had a mass of 12 g and a life expectancy of 520 days. V9TP-2L transmitters were 47 mm long, 9 mm in diameter, and had a mass of 6.4 grams. V9 transmitters were of two varieties: "on" transmitters which were set to start pinging immediately after activation, and "delayed" transmitters were set to start pinging 237 days after activation. Once activated, V9TP-2L transmitters had a life expectancy of 250 days. Delayed transmitters were required as the 250 day life expectancy of only V9TP-2L "on" transmitters would not cover the entire study period. All Vemco acoustic transmitters used in this study were programmed to randomly transmit once every 30 – 90 seconds. V9TP-2L and V13TP-1L were equipped with a -5 to +35ºC (+/- 0.5ºC) temperature sensor and a 0 – 50 m (+/- 2.5 m) depth (pressure) sensor. V16TP-4L were equipped with a -5 to +35ºC temperature sensor and a 0 – 34 m (+/- 1.7 m) pressure sensor. Temperature and pressure data were transmitted in alternating succession, so that ~50% of all detections were accompanied with temperature data while the remaining would have depth.

Acoustic tagging was stratified by reservoir sections (1 – 5) described in Section 2.1.1 and fish size (juvenile, sub-adult and adult). Fish between 330 and 510 mm (fork length) were considered juveniles, those between 511 and 800 mm were considered sub-adults, and those >800 mm were considered adults. While these criteria were somewhat subjective, Barth et al. (2009), working on an adjacent stretch of Winnipeg River, classified lake sturgeon <530 mm as juveniles. Similarly, lake sturgeon from the Slave Falls Reservoir >800 mm are considered adults for the purpose of population estimates (North/South Consultants unpublished data). The distinction “sub-adult” refers to a fish that has developed many but not all adult characteristics and has yet to spawn for the first time.

Lake sturgeon were captured using overnight gillnet sets. Following capture, each suitable lake sturgeon was measured for fork length, total length and body mass. A uniquely numbered Floy tag (Floy Tag and Manufacturing Inc, Seattle, Washington) was anchored between the basal pterygiophores of the dorsal fin of previously unmarked fish, while identification numbers of previously marked fish were recorded. Each lake sturgeon was then anaesthetized in a fish tub containing approximately 30 L of a 40 mg/L clove oil/water solution, adapted from Anderson et al. (1997). Once the fish began to lose its equilibrium, it was removed from the solution and placed ventral side up on a v-shaped surgery table. Throughout the surgery, river water was irrigated over the fish’s gills using a submersible pump. A 2 – 3 cm incision was made through the body wall in the middle of the abdomen, parallel to the midline. The presence of eggs was noted, but sex/maturity was not otherwise assessed. The transmitter, previously sterilized in ethanol, was inserted into the body cavity of the fish, and pushed towards the rear of the fish to reduce pressure on the incision. Three chromic gut sutures (#2 for juveniles and sub-adults, #1 for adults) were used to close the incision. The fish was placed in a recovery tub and monitored until equilibrium was re-established, prior to being released in an off-current area in close proximity to its capture location.

A total of 99 lake sturgeon were implanted with Vemco acoustic transmitters: 25 adults (853 – 1357 mm), 30 sub-adults (516 – 711 mm), and 44 juveniles (339 – 509 mm) (Appendix 2). In general, adults received V16TP-4L transmitters, sub-adults received V13TP-1L transmitters, and juveniles received V9TP-2L transmitters. The only exception to this occurred in Section 1, located upstream of the Slave Falls GS, where only four juveniles could be captured. As such, six additional sub-adults were implanted with V9TP-2L transmitters previously allocated for juveniles from this area. Acoustic tags applied to adults and sub-adults were a maximum of 1.9% of body mass, while those applied to juveniles were a maximum of 3.5%, well below the maximum recommendations of 5.5 – 8% (Brown et al. 2006; Chittenden et al. 2009; Lacroix et al. 2004). Adults and V13 sub-adults were tagged between 5 and 21 May, 2009 while juveniles and V9 sub-adults were tagged between 6 May and 22 June, 2009.

2.2.3 Acoustic receivers

Vemco VR2W receivers were used to record detections of nearby acoustically tagged lake sturgeon throughout the Slave Falls Reservoir. Each VR2W receiver consisted of an omni-directional hydrophone, internal data-logger and lithium-ion battery, enclosed in a watertight PVC casing. When a transmitter emitted its unique coded pulse train, any VR2W receivers within range would record the unique transmitter number, the date and time of detection, and the temperature or pressure (depth) data associated with the detection. Maximum efficient detection ranges for the V9TP-2L, V13TP-1L and V16TP-4L transmitters were found to be 550, 1000 and 1200 m, respectively, as determined via stationary tag trials in a low flow area of the Winnipeg River. Detection ranges of tagged fish were expected to be slightly lower since tags were implanted internally. Detection range was also expected to be reduced in areas with higher flows, due to environmental noise.

Between 20 and 25 Vemco VR2W receivers were deployed in off-current locations on the edges of the main river channel throughout the Slave Falls Reservoir from 2 May, 2009 to 17 October, 2010 (Figure 2.3a – c), adapted from methodologies used to monitor movements of green sturgeon, *Acipenser medirostris* (Heublein et al. 2009). Receivers were separated by 200 – 1000 m, as dictated by varying bathymetric and hydraulic conditions, as well as the number of VR2W receivers available. Locations were recorded using a Garmin 76Cx (Garmin Limited, Olathe, Kansas) handheld GPS receiver. During the open-water season, receivers were downloaded monthly.

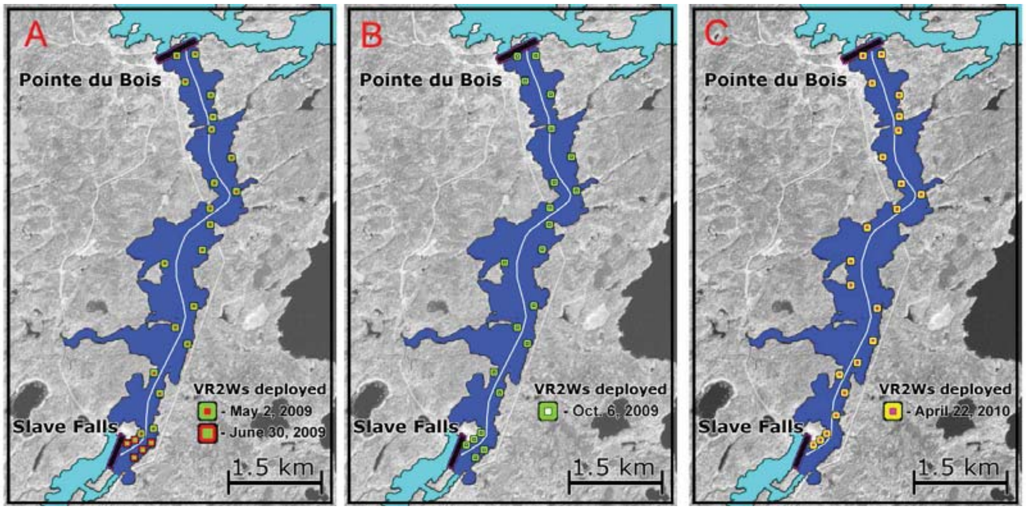

Figure 2.3. Locations of VR2W receivers deployed in the Slave Falls Reservoir during: a) 2009 open-water; b winter 2009 – 2010, and; c) 2010 open-water season.

Supplemental monitoring of movements immediately upstream of the Slave Falls spillway was provided first by a Vemco Radio Acoustic Positioning (VRAP) system and later a Vemco VR2W Positioning System (VPS). The VRAP receiver system consists of three radio-linked buoys deployed on the water surface. Each is comprised of a buoyant exterior, omni-directional hydrophone, rechargeable battery (10 – 14 day life) and a radio transmitter/receiver. Data collected by each VRAP buoy is transmitted back to the base station computer, where Vemco's VRAP5 software processes and triangulates detections. The VPS receiver system consists of VR2W receivers, deployed in combination with time synchronization tags, allowing for triangulation of detections.

The VRAP telemetry system was installed in a triangular configuration immediately upstream of the Slave Falls spillway from 6 May to 6 October, 2009. Each VRAP buoy was attached to aircraft cable and moored to a 75 kg concrete anchor. Buoy locations were recorded with a Garmin 76Cx GPS. The VRAP system was removed from the water for approximately 12 hours every 10 – 14 days for recharging, although logistical issues necessitated 4 day removals of the system on two occasions. On 6 October 2009, the VRAP system was removed and a four receiver VPS system was installed in a square configuration immediately upstream of the Slave Falls GS spillway. The VPS system was removed on 20 April, 2010, for downloading, and was redeployed on 7 May, 2010, for the remainder of the 2010 open water season.

2.2.4 Data analysis

VR2W data for each individual fish were exported from Vemco Vue software into Microsoft Excel 2007 for processing. Due to the large number of pinging transmitters located in the Slave Falls Reservoir, false detections generated by colliding pulse trains of multiple transmitters occurred frequently. To filter out false detections, a unique transmitter was required to be detected twice by a given receiver within a 30 minute interval in order for detections to be deemed "valid," as suggested by the manufacturer (Pincock 2008). The probability of two false detections for a particular code occurring within a 30 minute time period is very low, but it can occur (Pincock 2008). As such, it was necessary to further filter a small number of suspicious “valid” detections manually, and re-classify them as either “valid” or “false” considering all other spatiotemporal data available.

River kilometre (rkm) distance of each VR2W receiver from Slave Falls, relative to the primary flow axis of the Winnipeg River, was measured using Garmin Mapsource software. A translation table was then generated in Excel to assign the measured distances to all transmitter detections. Next, a simplification of the centre-of-activity algorithm used by Simpfendorfer (2002) was used to calculate the average detection distance for each lake sturgeon in terms of linear river kilometre distance from Slave Falls, for defined time intervals of 2 and 4 hours:

$$\overline{D}_{\Delta t} = \frac{\sum_{i=1}^{n} R_i D_i}{\sum_{i=1}^{n} R_i}$$

> where n = the number of receivers in the array, R_i = the number of detections at the i^{th} receiver during the ΔT time period, and D_i = the linear river kilometre distance of the i^{th} receiver from Slave Falls. For V16 and V13 tagged fish, receivers found to be highly redundant were omitted from algorithm calculations.

Detection distance from Slave Falls was used as the measure of a fish’s position to investigate coarse-scale movement patterns in the reservoir. Algorithm positioning error was theoretically estimated to be <0.5 rkm most of the time, based on overlapping receiver coverage, but occasionally positioning error might approach the detection ranges of the tags used.

Range estimates were calculated and plotted for each tagged lake sturgeon based on 4-hour algorithm intervals, supplemented by VRAP or VPS triangulated positions for fish located in the area immediately upstream of Slave Falls. Monthly trends in movement range of adults and V13 tagged sub-adults were analyzed using repeated-measures Analysis of Variance (RMANOVA), with study month entered as the treatment, and individual fish entered as a random effect.

Linear river utilization distributions were calculated for adult and V13 tagged sub-adult lake sturgeon using histograms binned at intervals of approximately 1 rkm, excluding the winter period (defined as 16 November, 2009 – 31 March, 2010). For this analysis, interpolation of positions was conducted based on the Last Observation Carried Forward (LOCF) assumption (Shao and Zhong 2003), which assumes that a fish had remained in the bin section it was last positioned in until it was next positioned. A 4-hour algorithm interval was generally used, except when additional temporal detail was deemed necessary to capture rapid movements. In these rare cases, a 2-hour interval was used. As detection efficiency of V9 tagged lake sturgeon was found to be low in some areas of the Slave Falls Reservoir, this analysis was not conducted for juveniles and V9 tagged sub-adults.

The proportion of time a tagged lake sturgeon was positioned in the lowermost 0.9 rkm of the reservoir (i.e. the area immediately upstream of Slave Falls), relative to its total open-water (i.e. excluding the winter period) time tracked in the reservoir, was calculated. Fish were defined as being “present” if they were ever positioned between rkm 0 and 0.9, and “absent” if they were never positioned here during the time their tag was active. A chi-squared (χ^2) test was used to assess the statistical significance of presence/absence data between tagging sections. Analysis of variance (ANOVA) on the arcsine transformed proportion of time data was conducted to further quantify differences between tagging sections.

The relationship of adult and V13 tagged sub-adult movements with abiotic factors was investigated based on a 4-hour algorithm interval and the LOCF assumption (Shao and Zhong 2003). As autocorrelation of movements can cause statistical problems (De Solla et al. 1999; Dray et al. 2010; Otis and White 1999), it has been suggested that locations can be considered spatially independent if the temporal interval used for analysis is greater than the time it takes a fish to move across its entire home range (White and Garrott 1990). Adult lake sturgeon have been documented to move as far as 17 km during a single day (Knights et al. 2002); however such movements were infrequent in the present study. Therefore, as a conservative approach to account for spatial autocorrelation, weekly intervals were used for analysis. Weekly median locations (i.e. binned reservoir section in terms of distance from Slave Falls) of individual fish were compared to weekly means of abiotic variables using Spearman’s ρ. Abiotic variables included: flow, change in flow (current minus previous weekly period), water temperature, change in water temperature, air temperature, change in air temperature, daylight hours and moon phase. Winnipeg River flow, as measured by mean daily discharge at the Slave Falls GS, was provided by Manitoba Hydro. Mean daily water temperature in the Slave Falls Reservoir was calculated by averaging the mean daily temperature recorded by five of the most frequently detected adult lake sturgeon. Daylight hours and moon phase (sine transformed) data were generated using the United

States Naval Observatory's online calculator, based on the latitude and longitude of Slave Falls. Mean daily air temperature data, measured at Pinawa, Manitoba (50º9'7N, 95º52'56W, located 24 km from Slave Falls, Figure 2.1) were acquired from Environment Canada's online archive. As lake sturgeon moved very little during the winter, this period was excluded from analysis.

Changes in proportional usage of the reservoir by adults and V13 tagged sub-adults over the course of the study were also investigated. Data were plotted based on a 4-hour algorithm interval and the LOCF assumption, with the reservoir binned at approximately 1 rkm intervals. Winnipeg River flow and water temperature were overlaid for visualization purposes. Multiple regression analysis (stepwise inclusion) of abiotic variables on proportional usage of the lowermost 4.0 rkm by adults was conducted to quantify patterns. Here again, the data were averaged over weekly intervals, and the winter period was excluded.

Statistical analyses were conducted using JMP 8.0 (SAS Software, Cary, North Carolina) to a significance level of 0.05. All tests for multiple comparisons were made using Tukey's Honestly Significant Difference (HSD). To account for potential changes in behaviour due to stress caused by capture, handling and/or tagging, data from the first 14 days after a fish was implanted with an acoustic transmitter were omitted from all analyses. Data from mortalities (i.e. no change in horizontal or vertical position, n=2) were altogether excluded from analysis. In addition, fish which left the reservoir prior to the conclusion of the study (n=5) were excluded from some analyses, since these would present a temporal bias.

2.3 Results

Three primary zones of movement were identified for lake sturgeon in the Slave Falls Reservoir and are referred to as: Zone A, located between rkm 0 and 2.1; Zone B, located between rkm 2.1 and rkm 8.1; and Zone C, located between rkm 8.1 and 9.8. Two narrow, typically fast-flowing sections of river at Old Slave Falls and Eight Foot Falls, whose names reflect pre-impoundment conditions, separate Zone A from B and Zone B from C, respectively (Figure 2.4). Section 1 is principally associated with Zone A (and the lowermost portion of Zone B), sections 2, 3 and 4 are within Zone B, and Section 5 is synonymous with Zone C.

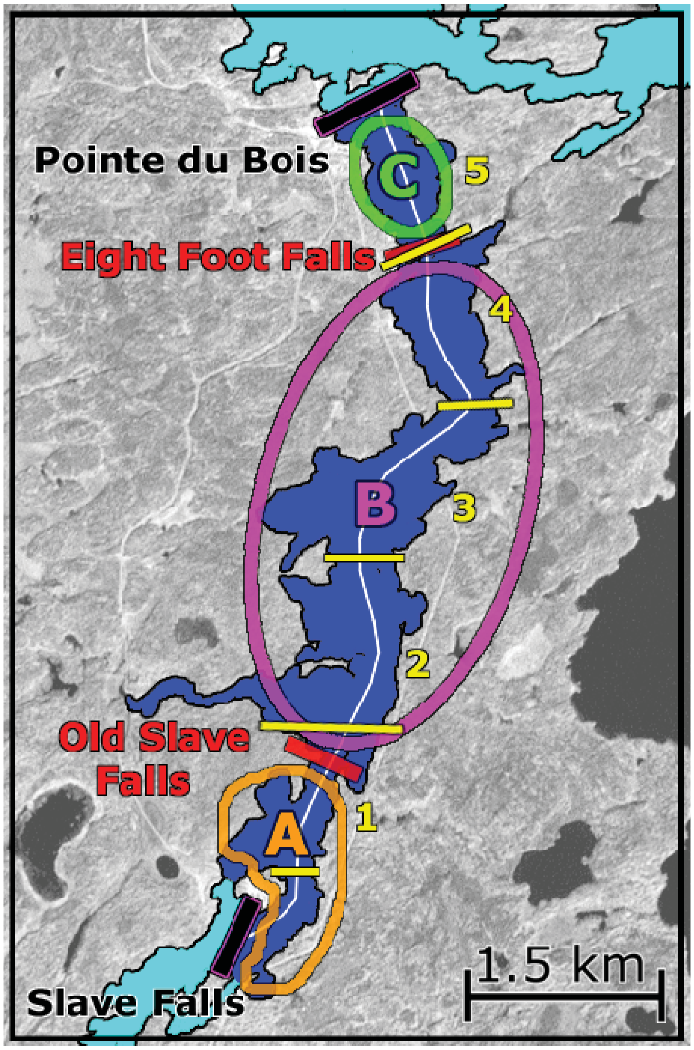

Figure 2.4. Primary zones of lake sturgeon movement identified in the Slave Falls Reservoir, separated by the Eight Foot Falls and Old Slave Falls narrows. Tagging sections (1 – 5) are overlaid.

2.3.1 Adults

Adult lake sturgeon were frequently and consistently detected throughout the study. The median number of total detections recorded for adult lake sturgeon tracked for the study duration, after filtering, was 252,503 (range: 139,992 – 304,173, n=21). Adults #239 and 249 died in July 2009 and January 2010, respectively. Two others (#223 and 237) left the Slave Falls Reservoir, downstream over or through the Slave Falls GS, prior to the conclusion of the study. Algorithm output for individual fish (calculated based on a 4 hour interval) is presented in Appendix 3.

Range in movement distance by adult lake sturgeon was highly variable. At one extreme, three fish (#209, 217 and 225) moved throughout the entire reservoir, while three others (#247, 253 and 255) did not move further than 1.7 rkm (Figure 2.5). Mean total range estimates for adults tagged in sections 1 – 5 and tracked for the study duration varied by tagging section (ANOVA, $F_{4,16} = 4.72$, $p = 0.011$). Tukey's HSD indicated that range estimates for Section 5 tagged adults (M = 2.65 rkm, SD = 3.32, n=4) was less than those tagged in sections 1 (M = 7.04 rkm, SD = 1.98, n=5) and 2 (M = 8.25 rkm, SD = 1.45, n=4) but not significantly different from those tagged in sections 3 (M = 6.35 rkm, SD = 0.94, n=4) and 4 (M = 6.41 rkm, SD = 0.92, n=5). Estimates of total winter range were < 3.3 rkm for all tagged adults, with the exception of one fish (#235) which had an estimated winter range of 4.2 rkm. It should be noted that in the 2009 open-water and winter period, the area between rkm 2.1 and 2.8 was only covered by a single receiver located at rkm 2.8, and that the apparent lack of fish using this area (Figure 2.5) is almost certainly a result of the algorithm positioning all fish in this area at rkm 2.8. In 2010, an additional receiver was deployed at rkm 2.4.

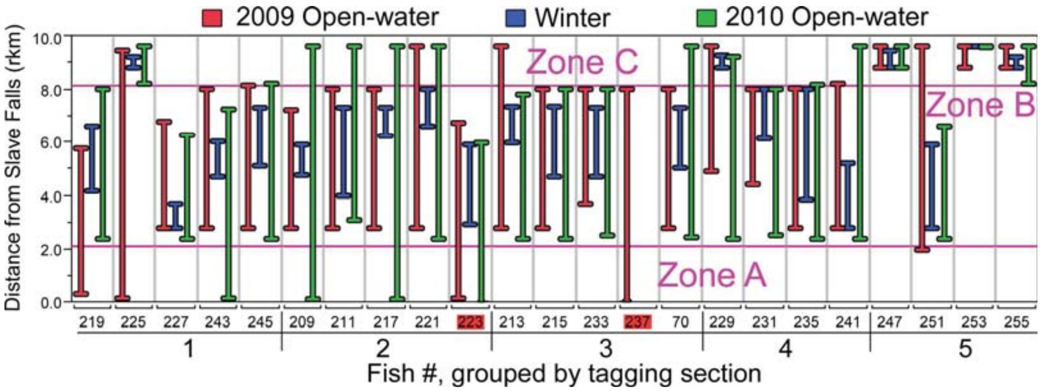

Figure 2.5. Range estimates for adult lake sturgeon in the Slave Falls Reservoir, separated by season. Red highlights indicate fish which passed downstream through the Slave Falls GS during of the study.

When investigated on a monthly basis, adult range estimates were found to vary significantly by month (RMANOVA, $F_{15} = 17.2$, $p < 0.0001$), with range estimates for winter months being considerably less than for summer months (Figure 2.6).

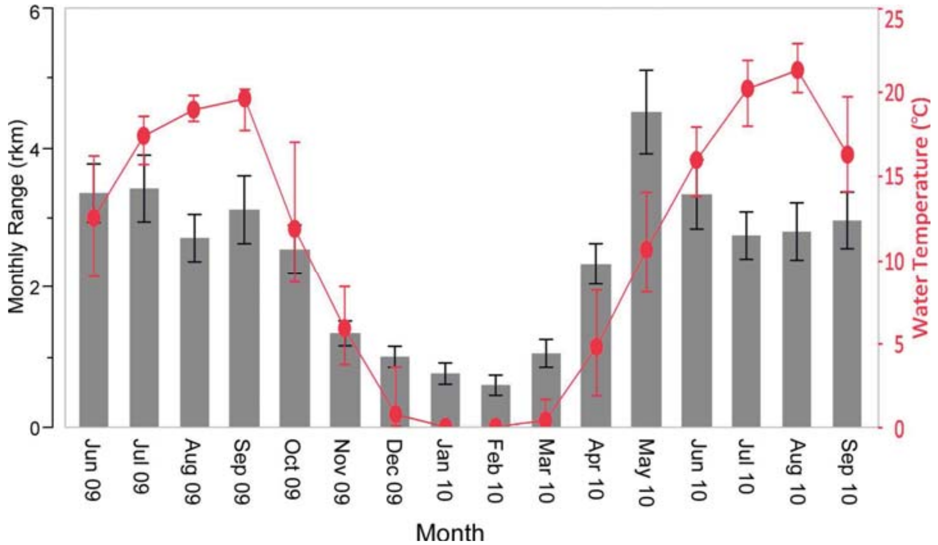

Figure 2.6. Monthly range estimates for adult lake sturgeon in the Slave Falls Reservoir (all fish pooled, n=21), indicating reduced movement extent during winter months. Bars represent means +/- standard error. Mean monthly water temperature data is overlaid, with error bars indicating monthly temperature range.

Open-water utilization distributions of adult lake sturgeon also varied considerably by individual. Twelve of the adults tracked for the study duration spent >40% of their open-water time within one of the ten ~1 rkm binned sections of the reservoir, while the distribution of the others was considerably more spread out (Figure 2.7). Overall, eight adult lake sturgeon were located in Zone A, and seven of these were located, at least for a short duration, in the lowermost 0.9 rkm. It was also notable that despite limited use of Zone A (i.e. rkm 0 – 2.1), the section of river immediately upstream of Old Slave Falls (i.e. rkm 2.1 – 3) was often utilized, with twelve adults spending >20% of their open-water time in that section.

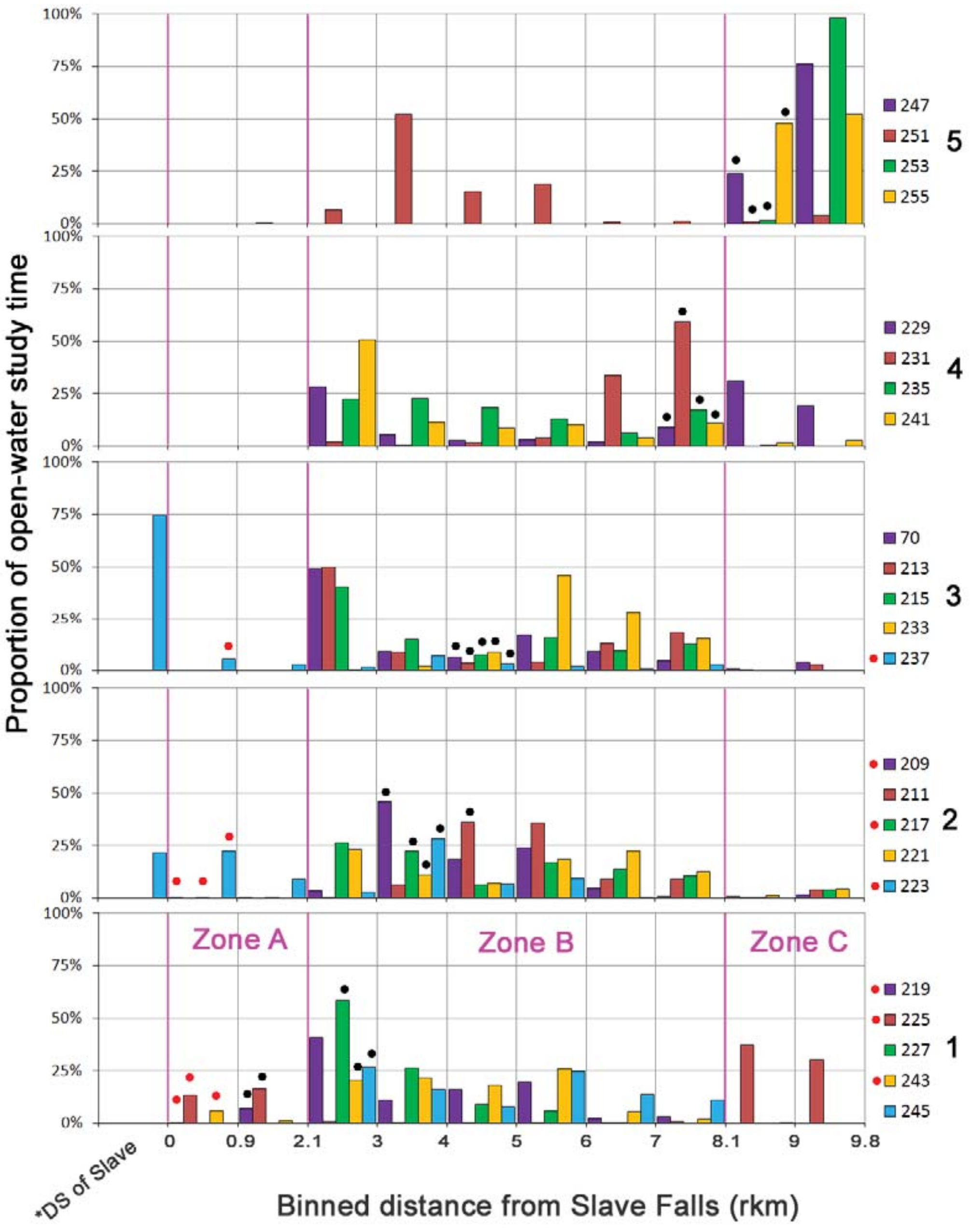

Figure 2.7. Open-water utilization distribution of the Slave Falls Reservoir by adult lake sturgeon, binned at ~1 rkm intervals from Slave Falls. Individual fish are grouped by tagging section (1 – 5). Red dots indicate fish which were located in the lowermost 0.9 rkm. Black dots indicate the binned section a fish was tagged in. *DS of Slave refers to the proportion of open-water study time a fish spent downstream of Slave Falls following entrainment.

Movements of nine adult lake sturgeon were essentially confined to the zones they were initially tagged in. Three of four adult lake sturgeon tagged in Zone C (omitting a mortality) remained within that zone, and six of seventeen tagged in Zone B (omitting a morality) essentially remained within Zone B throughout the 18 month study (Figure 2.5). The remaining 14 adults (1/4 tagged in Zone C, 11/17 tagged in Zone B and 2/2 tagged in Zone A) made infrequent, and generally asynchronous inter-zone movements through the Old Slave Falls and/or Eight Foot Falls narrows during the open-water portion of the study. No adults moved between zones in the winter.

Adult #251, a female with developed eggs when tagged in Zone C (Section 5), moved downstream out of this area in June 2009, and never returned. Nine of 20 adults tagged downstream of Eight Foot Falls (sections 1 – 4) made definite upstream movements into Zone C, while two others (#245 and 235) were briefly positioned at Eight Foot Falls but did not appear to move past it. Five adults (#70, 209, 211, 217 and 221) moved upstream into Zone C during May 2010, where they resided for less than 30 days. Two of these fish (#209 and 217) moved in and out of Zone C multiple times during this time period. In addition, adult #221 moved into and then out of Zone C in July 2009 and August 2010, both times residing there for less than one week before moving back downstream into Zone B. Adult #213 moved upstream into Zone C in late May 2009 and again in late June 2009, both times residing there for less than a week. Adult #229 moved upstream into Zone C during June 2009, remaining there until May 2010. Adult #241 moved into Zone C during August 2010, residing there for less than a week. After residing in Zone A for the first four months of the study, adult #225 moved upstream into Zone C during September 2009, where it remained for the study duration.

The only adult (#251) which utilized Zone A, but not the lowermost 0.9 rkm, entered the zone following a rapid downstream movement originating in Zone C during June 2009, remaining near rkm 2.0 for < 1 day, before moving back upstream into Zone B where it remained for the study duration. Three adults (#209, 217 and 219) utilized the lowermost 0.9 rkm only briefly, spending 0.18, 0.02, and 0.49%, respectively, of their open-water time there. Adult #219, tagged in Zone A (Section 1), used the lowermost 0.9 rkm for only a few days in early June 2009, before moving upstream into Zone B where it remained for the study duration. Movements of adults #209 and 217 into the lowermost 0.9 rkm during May 2010 were precluded by a rapid downstream movement from Zone C. Adult #209 moved in and out of the lowermost 0.9 rkm three times between 24 and 25 May, 2010, before moving back upstream where it continued to make erratic, wide ranging movements for ~10 days (Figure 2.8a). Adult #217 moved downstream to the area near Slave Falls on 19 May 2010, but remained in the area only for ~2 hours before moving back upstream (Figure 2.8b). Both of these fish were positioned by the VPS system less than 150 m from the Slave Falls spillway, which was not operational at the time.

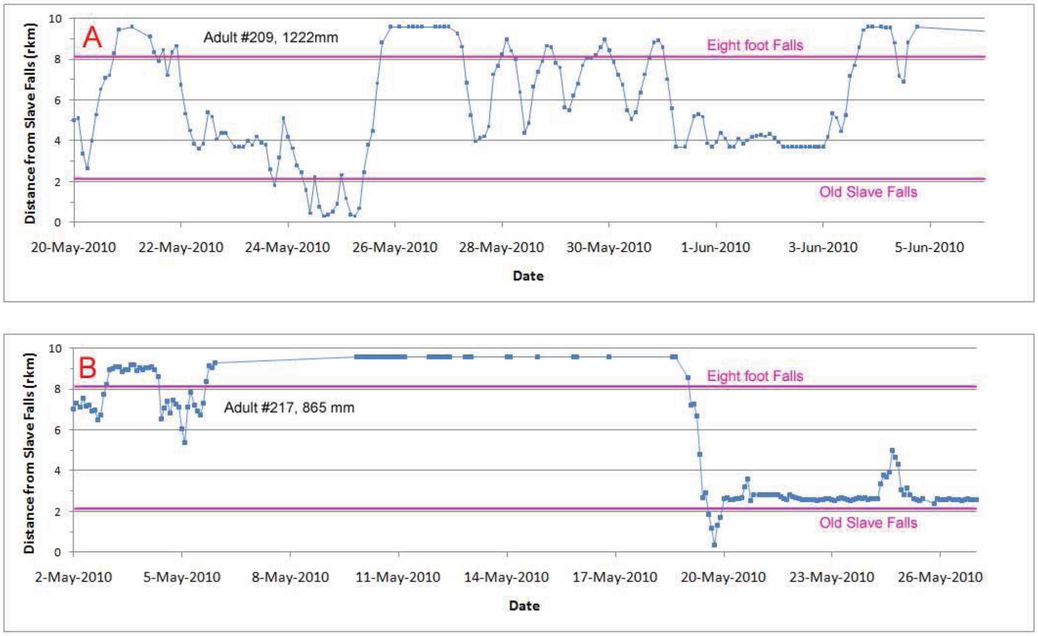

Figure 2.8. Rapid downstream movements of adult lake sturgeon #209 (a) and 217 (b) towards Slave Falls, occurring in May 2010. Data shown is generated with a 2-hour algorithm interval.

Four adults (#223, 225, 237 and 243) resided in the lowermost 0.9 rkm for considerably longer, where they spent 28.4, 13.2, 21.1 and 5.7%, respectively, of their open-water time in the Slave Falls Reservoir. Adult #223 moved downstream from Zone B into Zone A in late July 2009, and frequently used the lowermost 0.9 rkm until mid-September, when it moved back upstream into Zone B. Then, between mid-May and mid-June 2010, it moved in and out of Zone A several times, before residing in the lowermost 0.9 rkm until it was last detected on July 28, 2010, prior to entrainment at Slave Falls. After tagging, adult #225 remained in Zone A until early-September 2009, periodically using the lowermost 0.9 rkm. Over a period of ~2 weeks, this fish then made a series of pronounced movements, first upstream into the upper portion of Zone B, then back to the Slave Falls area, and then upstream into Zone C where it remained for the study duration. Adult #237 moved downstream into Zone C in late July 2009, thereafter periodically utilizing the lowermost 0.9 rkm until it was last detected on 26 August, 2009, prior to being entrained at Slave Falls. Lastly, adult #243 moved downstream into Zone A during late May 2010, and with the exception of one brief foray into Zone B, resided in Zone A for almost a month. During this time, this fish periodically utilized the lowermost 0.9 rkm. It then moved back upstream into Zone B and remained there for the study duration.

Adult lake sturgeon presence in the lowermost 0.9 rkm was not found to be significantly different amongst tagging sections ($\chi^2[4, n=23] = 7.89$, $p = 0.096$), although it should be noted that this analysis was flagged as suspect due to low expected cell counts. Similarly, the proportion of open-water time spent in the lowermost 0.9 rkm (arcsine transformed) did not vary significantly by tagging section (ANOVA, $F_{4,18} = 0.66$, $p = 0.63$). No adults were located in the lowermost 0.9 rkm, or the rest of Zone A, during winter.

Spearman's ρ revealed that the movements of adult lake sturgeon were correlated with several abiotic variables. Water temperature, air temperature, change in water temperature, daylight hours, flow and change in flow all yielded statistically significant ($p < 0.05$) correlations for multiple fish. No significant correlations were observed between movements of individual fish with the change in air temperature or moon phase variables. But it should first be noted that there was a high degree of redundancy between several pairs of seasonal abiotic variables included in the analysis (Table 2.1). As expected, water temperature and air temperature were highly correlated ($r = 0.782$), as were change in water temperature and daylight hours ($r = 0.722$). Air temperature was also highly correlated with both change in water temperature ($r = 0.588$) and daylight hours ($r = 0.656$). Flow was moderately correlated with water temperature ($r = 0.353$) and air temperature (r = 0.294), while daylight hours was moderately correlated with water temperature (r = 0.362).

Table 2.1. Pearson's correlation between abiotic variables (weekly average). Only variables which yielded statistically significant correlations to movements of individual fish are included.

Variable	Water Temp.	Air Temp.	Δ Water Temp.	Daylight Hours	Flow	Δ Flow
Water Temp.	1					
Air Temp.	0.782	1				
Δ Water Temp.	0.027	0.588	1			
Daylight Hours	0.362	0.656	0.722	1		
Flow	0.353	0.294	0.031	0.210	1	
Δ Flow	0.163	0.222	0.132	0.171	-0.003	1

Although there was much variation amongst individual fish, movements of many adults were negatively correlated with variables associated with seasonality (water temperature, air temperature, change in water temperature and daylight hours) (Table 2.2). Movements of other adults were uncorrelated to seasonal abiotic variables, while two (#247 and 231) showed significant positive correlations to seasonal variables.

Table 2.2. Spearman's ρ for the rank-order relationship between weekly median binned reservoir section utilized by individual adult lake sturgeon and the weekly mean of abiotic variables, based on pooled 2009 and 2010 open-water data. Only fish tracked for the study duration (n=21) were analyzed, and only variables which yielded statistically significant correlations are included in this table.

Fish #	Fork Length (mm)	Tagging Section	Water Temp.	Air Temp.	Δ Water Temp.	Daylight Hours	Flow	Δ Flow
247	1105	5	0.221	0.245	0.352	0.451	-0.003	0.030
251	1208	5	0.004	0.048	0.101	0.149	0.288	-0.266
253	1357	5	-	-	-	-	-	-
255	985	5	-0.667	-0.424	0.222	0.077	-0.611	0.011
229	926	4	-0.199	-0.244	-0.175	-0.305	0.252	-0.422
231	1109	4	0.646	0.442	-0.063	0.115	0.423	-0.004
235	985	4	-0.211	-0.322	-0.168	-0.241	-0.059	-0.308
241	943	4	0.240	0.172	-0.038	0.153	0.331	-0.228
70	968	3	-0.488	-0.452	-0.089	-0.232	-0.400	-0.261
213	1174	3	-0.596	-0.547	-0.297	-0.386	-0.056	-0.231
215	1197	3	-0.256	-0.323	-0.248	-0.260	-0.043	-0.360
233	963	3	-0.130	-0.353	-0.380	-0.344	0.031	-0.322
209	1222	2	-0.443	-0.490	-0.279	-0.498	-0.529	-0.244
211	1278	2	-0.110	0.003	0.080	-0.075	-0.154	-0.250
217	865	2	-0.174	-0.158	0.022	-0.064	-0.342	-0.166
221	978	2	-0.490	-0.445	-0.175	-0.262	0.072	-0.370
219	1130	1	-0.312	-0.403	-0.275	-0.541	-0.529	-0.085
225	1160	1	-0.218	-0.228	-0.056	-0.069	-0.785	0.012
227	1067	1	-0.183	-0.236	-0.264	-0.304	-0.182	-0.179
243	853	1	-0.332	-0.259	-0.128	-0.378	-0.083	-0.252
245	896	1	-0.090	0.054	0.109	-0.104	0.033	-0.071

Correlation and probability
positive, |ρ|<0.05
positive,|ρ|<0.15
close to 0, |ρ|>0.15
negative,|ρ|<0.15
negative,|ρ|<0.05

Movements of some adults were significantly correlated with Winnipeg River flow, either positively (n=3) or negatively (n=6) (Table 2.2). All significant correlations (n=5) between movements of adults with change in flow were negative, while many others (n=7) showed a weak negative correlation ($p < 0.15$) to this variable.

Despite considerable variation and asynchronicity of movements by individual adults, trends in coarse-scale distribution of the sample population were apparent. In general, proportional usage of Zone C was relatively constant, with between 13 and 23% (weekly averages) of tagged adults present in the Slave Falls Reservoir typically utilizing this area (n=23, decreasing to 21 following downstream passage events). However, during May 2010, when water temperatures were increasing from 8 to 15 °C and lake sturgeon staging/spawning was known to be occurring at the base of the Pointe du Bois GS (located in Zone C), weekly average usage reached a high of 37% (n=22) (Figure 2.9).

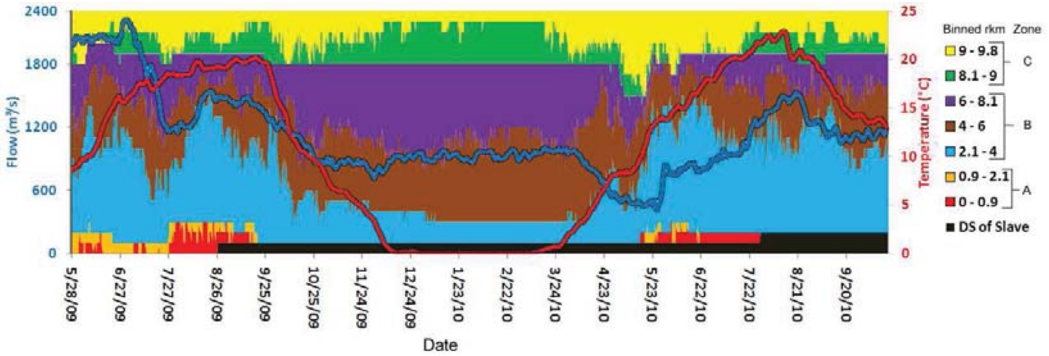

Figure 2.9. Proportional distribution of acoustically tagged adult lake sturgeon (n=23) in the Slave Falls Reservoir throughout the study period, based on a 4-hour algorithm interval, and divided into the binned sections indicated. Winnipeg River flow and water temperature data is overlaid. Fish located downstream of Slave Falls (black shaded area) following entrainment were not included in analysis.

Proportional usage of rkm 2.1 – 4.0 was generally high from May to September 2009 with 23 – 51% (weekly averages) of the tagged adults being located there during this time period (Figure 2.9). During October and November 2009, proportional usage of rkm 2.1 – 4.0 slowly decreased as adults moved upstream into the upper and middle portions of Zone B (rkm 4 – 6 and 6 – 8.1). By mid January 2010, only 9.0% (n=22) of the adults were located between rkm 2.1 and 4.0. In early April 2010, proportional usage of rkm 2.1 – 4.0 increased, and ranged from 25 to 53% (weekly averages) from May to October 2010. Proportional usage of Zone A was generally low, with a maximum of 13% of the tagged adults (n=23) being located here during the 2009 open-water season, and 8.7% (n=22) being located here during the 2010 open-water season (Figure 2.9).

When examined on a weekly interval (omitting the winter period), proportional usage of the lower 4 rkm of the reservoir was well explained ($r^2_{adj} = 0.61$) by a multiple regression (as determined by stepwise inclusion) which included water temperature, change in flow, and daylight hours as factors ($F_{3,47} = 27$, $p < 0.0001$) (Table 2.3). These three variables were all positively related to proportional usage of the lower 4 rkm, and statistically significant when considered individually.

Table 2.3. Statistical output for a multiple regression (stepwise inclusion) analysis of abiotic variables versus proportional usage of the lower 4 rkm of the Slave Falls Reservoir. Data were averaged over a weekly interval, and excludes the winter period.

Summary of Fit	
RSquare	0.632959
RSquare Adj	0.609531
Root Mean Square Error	0.079322
Mean of Response	0.401643
Observations (or Sum Wgts)	51

Analysis of Variance				
Source	**DF**	**Sum of Squares**	**Mean Square**	**F Ratio**
Model	3	0.50996889	0.16999	27.0171
Error	47	0.29572081	0.006292	**Prob > F**
C. Total	50	0.8056897		<.0001

Parameter Estimates				
Term	**Estimate**	**Std Error**	**t Ratio**	**Prob>|t|**
Intercept	-0.07932	0.073867	-1.07	0.2884
Water Temp	0.011792	0.002578	4.57	<.0001
Δ Flow	0.000326	9.68E-05	3.37	0.0015
Daylight Hours	0.021746	0.005431	4	0.0002

2.3.2 Sub-adults

The median number of total detections recorded for V13 tagged sub-adults tracked for the study duration, after filtering, was 179,815 (range: 69,678 – 358,993, n=22). Two V13 tagged sub-adults (#177 and 187) left the Slave Falls Reservoir, downstream over or through the Slave Falls GS, during the study. With the exception of three fish from Section 1 which were rarely detected during the winter period, V13 tagged sub-adults tended to be frequently and consistently detected throughout the study. Of the six additional sub-adults from Section 1 which received V9 "on" (n=2) or V9 "delayed" (n=4) tags, five were detected a median of 3,846 times (range: 79 – 6,243) during the respective halves of the study their tags were active for. One V9 "delayed" tagged sub-adult (#142) was never detected in the Slave Falls Reservoir. Algorithm output for individual fish (calculated based on a 4 hour interval) is presented in Appendix 4.

Mean total range (rkm) estimates for V13 tagged sub-adults tracked for the study duration varied by tagging section (ANOVA, $F_{4,17} = 5.10$, $p = 0.0069$) (Figure 2.10). Tukey's HSD indicated that total range estimates for Section 5 tagged sub-adults (M = 2.46 rkm, SD = 2.65, n=5) was less than for those tagged in sections 1 (M = 6.77 rkm, SD = 0.99, n=3) and 4 (M = 5.20 rkm, SD = 0.50, n=5) but not significantly different from those tagged in sections 2 (M = 5.12 rkm, SD = 0.30, n=5) and 3 (M = 5.01 rkm, SD = 0.83, n=5). Total estimated winter range was < 3.4 rkm for all V13 tagged sub-adults. Of the detected sub-adults implanted with V9 tags in Section 1, which were each only active for ~half of the study, sub-adult #113 had an estimated range of 3.9 rkm, while the remaining four had estimated ranges of < 2 rkm.

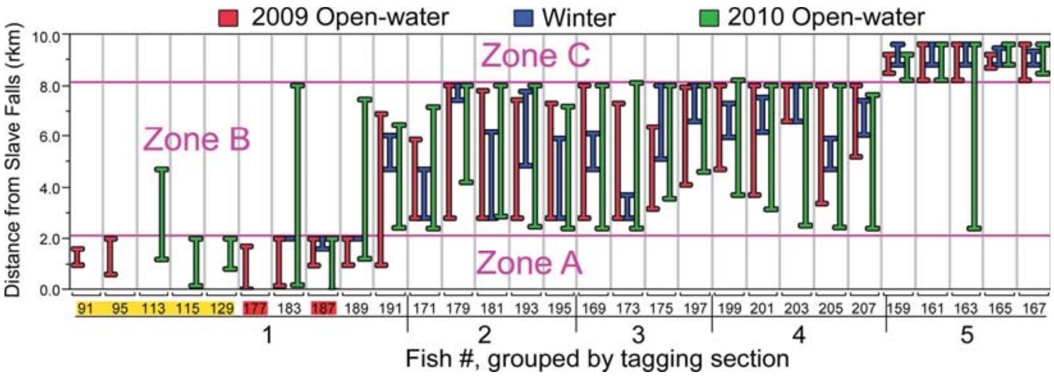

Figure 2.10. Range estimates for sub-adult lake sturgeon in the Slave Falls Reservoir, separated by season. Red highlights indicate fish which passed downstream through the Slave Falls GS during the study, while yellow highlights indicate fish implanted with V9 tags.

When investigated on a monthly basis, V13 tagged sub-adult range was found to vary significantly by month (RMANOVA, $F_{15} = 12.8$, $p < 0.0001$), with range estimates for winter months being considerably less than for summer months (Figure 2.11).

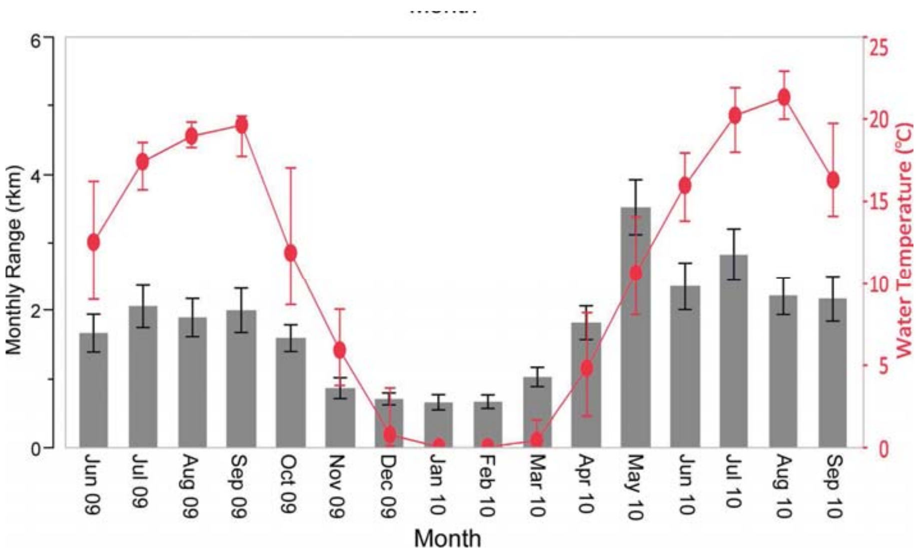

Figure 2.11. Monthly range estimates for V13 tagged sub-adult lake sturgeon in the Slave Falls Reservoir (all fish pooled, n=22), indicating reduced movement extent during winter months. Bars represent means +/- standard error. Mean monthly water temperature data is overlaid, with error bars indicating monthly temperature range.

Movements of most tracked sub-adults were confined to the zones in which they were initially tagged in. Four of the five sub-adults tagged in Zone C (Section 5) remained within that zone for the study duration (Figure 2.10). The other sub-adult (#163) descended into Zone B in late May 2010, traversing the zone several times during June and July 2010 before residing in the lower portion of Zone B for the remainder of the study.

Movements of sub-adults tagged in Zone B (Sections 2 – 4, n=14) were essentially confined to this ~6 rkm zone (Figure 2.10). Two fish (#173 and 199) were briefly positioned at Eight Foot Falls, but did not appear to actually move into Zone C.

While many sub-adults moved throughout Zone B, utilization distributions were often indicative of affinity to the area in which a fish was tagged (Figure 2.12). Sub-adults tagged in the upper portion of Zone B (i.e. Section 4, n=5) utilized this area more so than the middle and lower portions of the zone. Similarly, for the majority of fish from the middle and lower portions of Zone B (i.e. Section 3, n=4, and Section 2, n=5) showed affinity to the areas from which they were captured for tagging, but other fish (i.e. #173, 179 and 193) deviated from this trend, spending considerably more time in other areas (Figure 2.12).

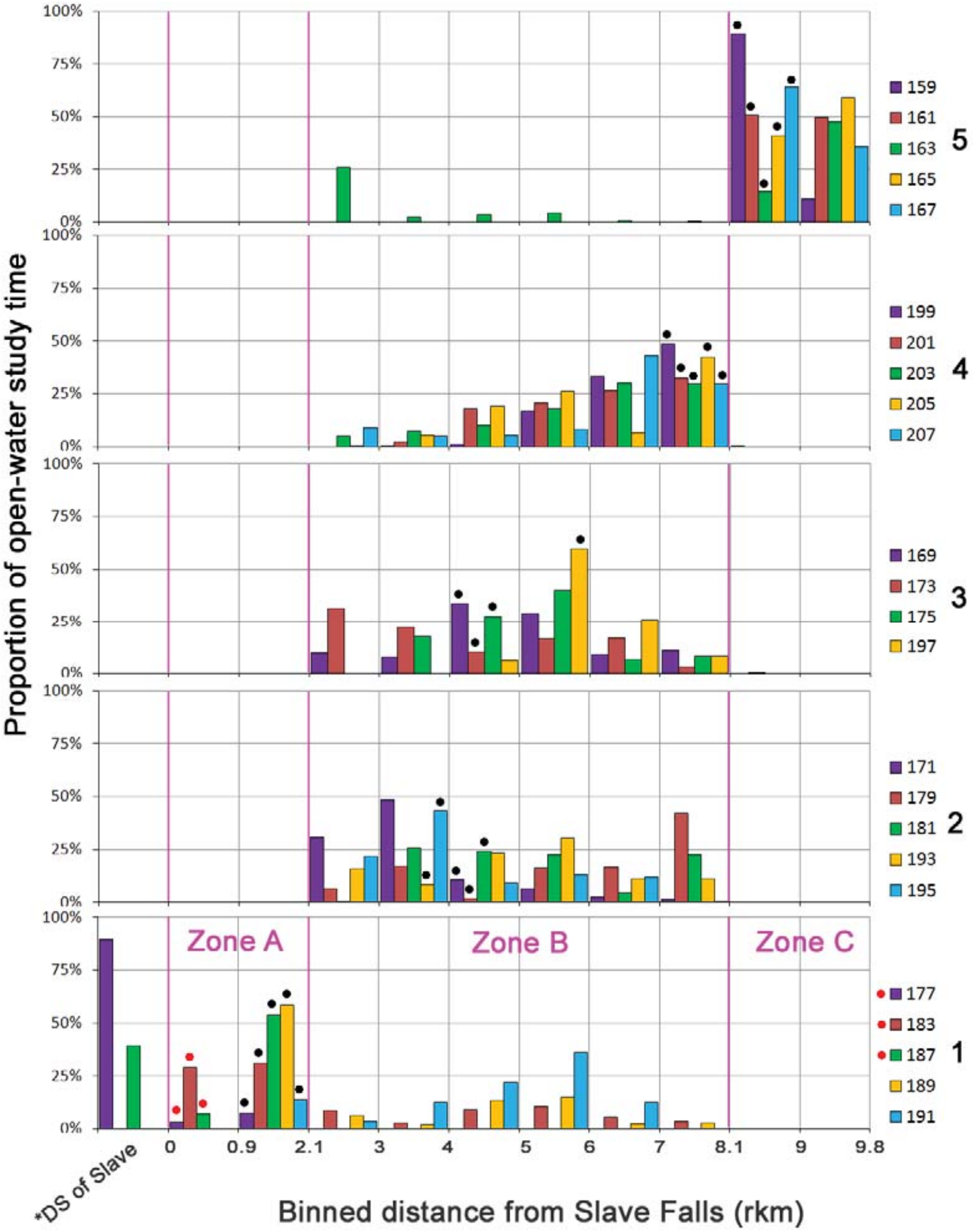

Figure 2.12. Open-water utilization distribution of the Slave Falls Reservoir by V13 tagged sub-adult lake sturgeon, binned at ~1 rkm intervals from Slave Falls. Individual fish are grouped by tagging section (1 – 5). Red dots indicate fish which were located in the lowermost 0.9 rkm. Black dots indicate the binned section a fish was tagged in. *DS of Slave refers to the proportion of open-water study time a fish spent downstream of Slave Falls following entrainment.

Of the sub-adults implanted with V13 tags in Zone A, two (#191 and 189) moved upstream into Zone B in mid July 2009 and mid May 2010, respectively, wherein they remained for the study duration. Sub-adult #183 moved upstream into Zone B on 22 May 2010, but made a brief downstream movement into the Old Slave Falls narrows (positioned at rkm 2.0) on 29 May 2010 before moving back upstream into Zone B, where it remained thereafter. The other two (#177 and 187) remained in Zone A until they were last located on 6 July 2009 and 24 May 2010, respectively, prior to entrainment at Slave Falls. The two V9 "on" tagged sub-adults (#91 and 95), which were monitored during 2009, remained in Zone A throughout this period. Two of the detected V9 "delayed" tagged sub-adults (#115 and 129), which were monitored during 2010, were only located in Zone A, while sub-adult #113 moved upstream into Zone B in late July 2010, and remained there. Sub-adults which over-wintered in Zone A were rarely (if ever) located during that period, and it was reasoned that they must have remained in the off-current bay located in the middle of the zone, out of receiver detection range.

Six of ten tracked sub-adults tagged in Section 1 (Zone A) periodically utilized the lowermost 0.9 rkm during the open-water season. Percentage of open-water time spent in the lowermost 0.9 rkm by sub-adults tagged in Section 1 ranged from 3.3 to 29.9%. Two tracked sub-adults (#177 and 187) that passed downstream had spent 29.9 and 11.5% of their open-water time, respectively, in this area prior to entrainment. As a result of no sub-adults tagged in sections 2 – 5 being positioned in the lowermost 0.9 rkm, presence in this area was found to be significantly higher for sub-adults from Section 1 ($\chi^2[4, n=29] = 14.37$, $p = 0.0062$), although it should be noted that this analysis was flagged as suspect due to low expected cell counts. Similarly, proportion of open-water time spent in the lowermost 0.9 rkm (arcsine transformed) by fish tagged in Section

1 varied significantly compared to that of fish tagged in other sections (ANOVA, $F_{4,24}$ = 4.62, $p = 0.0065$). No sub-adults were located in the lowermost 0.9 rkm during the winter period.

The lone undetected sub-adult (#142), implanted with a V9 “delayed” tag in Section 1, was incidentally captured in a gillnet downstream of Slave Falls on 13 August 2010. It was reasoned that this fish passed downstream through the Slave Falls GS prior to tag activation, which should have occurred in February 2010.

Spearman’s ρ revealed that movements of V13 tagged sub-adult lake sturgeon were correlated with the abiotic variables included in analysis. Water temperature, change in water temperature, air temperature, daylight hours, flow and change in flow all yielded statistically significant ($p < 0.05$) correlations for multiple fish (Table 2.4). No significant correlations were observed between movements of individual fish with change in air temperature or moon phase. While significant correlations were found, there was little consistency in the directionality of the relationship (i.e. positive or negative correlation) between the movements of individual sub-adults and abiotic variables investigated, and no pattern to explain differences amongst individuals could be discerned.

Table 2.4. Spearman's ρ for the rank-order relationship between weekly median binned reservoir section utilized by individual sub-adults and the weekly mean of abiotic variables, based on pooled 2009 and 2010 open-water data. Only fish tracked for the study duration (n=22) were analyzed, and only variables which yielded statistically significant correlations are included in this table.

Fish #	Fork Length (mm)	Tagging Section	Water Temp.	Air Temp.	Δ Water Temp.	Daylight Hours	Flow	Δ Flow
159	553	5	-0.185	0.027	0.302	0.141	0.007	-0.137
161	627	5	0.313	0.008	-0.581	-0.683	0.163	0.120
163	709	5	-0.375	-0.281	0.003	-0.237	-0.079	-0.361
165	606	5	0.162	-0.011	-0.208	-0.084	-0.444	0.125
167	584	5	-0.079	-0.047	0.057	-0.077	-0.024	-0.183
199	516	4	0.065	0.109	0.178	0.231	-0.242	0.048
201	564	4	-0.411	-0.332	-0.085	-0.252	0.092	-0.390
203	589	4	-0.302	-0.287	-0.139	-0.296	0.161	-0.390
205	565	4	-0.354	0.034	0.670	0.682	-0.322	-0.005
207	659	4	0.302	0.354	0.005	-0.091	0.435	0.363
169	640	3	-0.126	-0.049	-0.032	-0.107	0.284	-0.188
173	660	3	0.304	0.426	0.341	0.480	0.570	0.256
175	631	3	-0.630	-0.456	0.044	-0.169	-0.629	-0.039
197	652	3	-0.568	-0.549	-0.201	-0.499	-0.455	-0.306
171	585	2	-0.393	-0.209	0.243	0.169	-0.235	0.046
179	554	2	-0.578	-0.530	-0.045	-0.173	-0.691	-0.118
181	572	2	0.192	0.301	0.434	0.505	-0.224	-0.012
193	632	2	-0.181	-0.071	0.123	-0.147	-0.342	0.122
195	552	2	-0.488	-0.219	0.387	0.187	0.014	-0.018
183	620	1	0.168	0.119	-0.032	0.143	-0.148	0.289
189	634	1	0.260	0.267	0.111	0.210	-0.359	0.401
191	570	1	0.028	-0.154	-0.387	-0.367	-0.331	0.095

Correlation and probability
positive, |ρ|<0.05
positive, |ρ|<0.15
close to 0, |ρ|>0.15
negative, |ρ|<0.15
negative, |ρ|<0.05

The overall distribution of V13 tagged sub-adult lake sturgeon changed somewhat over the course of the study. Usage of Zone C was relatively constant (range: 18 – 22%, n=24 decreasing to 22 following downstream passage events), as only one sub-adult moved downstream out of this zone (Figure 2.13). Proportional distribution of V13 tagged sub-adults located in Zone A decreased from 21% (n=24) to 0% (n=22) over the course of the study, as individuals moved upstream into Zone B, or were entrained at Slave Falls. There was no pronounced peak in usage of the lowermost 0.9 rkm, and data did not suggest a significant relationship between abiotic variables and proportional usage, although the absence of sub-adults from this area during winter may be indicative of a temperature related threshold.

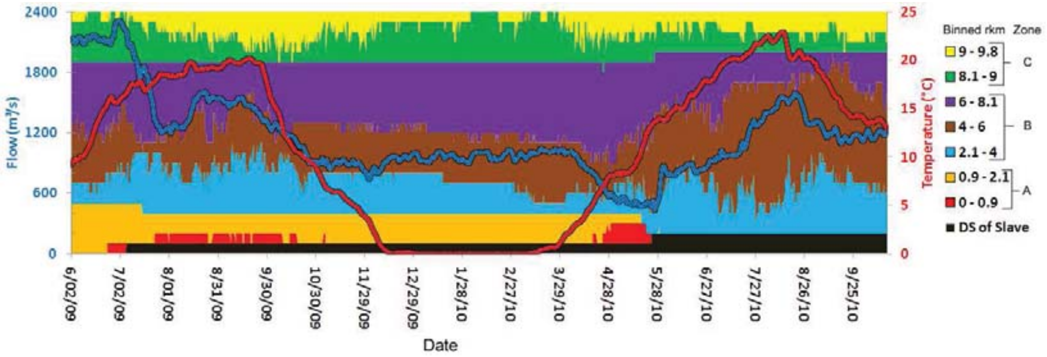

Figure 2.13. Proportional distribution of acoustically tagged sub-adult lake sturgeon in the Slave Falls Reservoir throughout the study period, based on a 4-hour algorithm interval, and divided into the binned sections indicated. Winnipeg River flow and water temperature data is overlaid. Fish located downstream of Slave Falls (black shaded area) following entrainment were not included in analysis.

Proportional distribution in the Zone B rkm sections fluctuated somewhat (Figure 2.13), but these changes did not appear to be correlated with abiotic variables. Focusing on rkm 4 – 6, between June 2009 and April 2010, proportional usage typically ranged from 15 to 25% (weekly averages). After May 2010, usage of rkm 4 – 6 increased considerably, with proportional weekly usage ranging from 29 to 56% (weekly averages).

2.3.3 Juveniles

The median number of detections recorded per juvenile lake sturgeon after filtering was 9,321 (range: 28 – 149,516). Twenty-three of the 44 juvenile tags applied were active during the 2009 open water season (V9 “on”), while the remainder were active during the 2010 open water season (V9 “delayed”), with some winter overlap occurring. One V9 “on” and ten V9 “delayed” tagged juveniles were last detected several months before their tags were programmed to cease activation (Appendix 2). It is unclear if these were mortalities, if these fish simply remained out of receiver detection range for the remainder of the tag’s life, or if these tags became inactive prematurely. Considering spatial coverage of the receiver array, the latter seems most likely. For consistency, these fish were excluded from range analyses. Algorithm output for individual fish (calculated based on a 4 hour interval) is presented in Appendix 5.

Mean total range (rkm) estimates for juveniles tagged in sections 2 – 5 varied by tagging section (ANOVA, $F_{3,27} = 10.65$, $p < 0.001$) (Figure 2.14). Tukey’s HSD indicated that total range estimates for Section 5 (M = 0.40 rkm, SD = 0, n=5) juveniles was less than for those tagged in sections 2 (M = 3.44 rkm, SD = 1.18, n=10), 3 (M = 3.20 rkm, SD = 1.26, n=10) and 4 (M = 2.18 rkm, SD = 0.84, n=6). The two juveniles tagged in Section 1 that were tracked for the duration of their anticipated tag life (#64 and 101) had estimated ranges of 2.1 and 4.6 rkm.

For the duration their tags were active, movements of 42 of 44 juvenile lake sturgeon were confined to the zone in which the fish were originally captured and tagged. All fish tagged in Zone C (Section 5, n=10) remained within this zone; furthermore, none of these fish were ever positioned outside of rkm 8.8 – 9.2 (Figure 2.14).

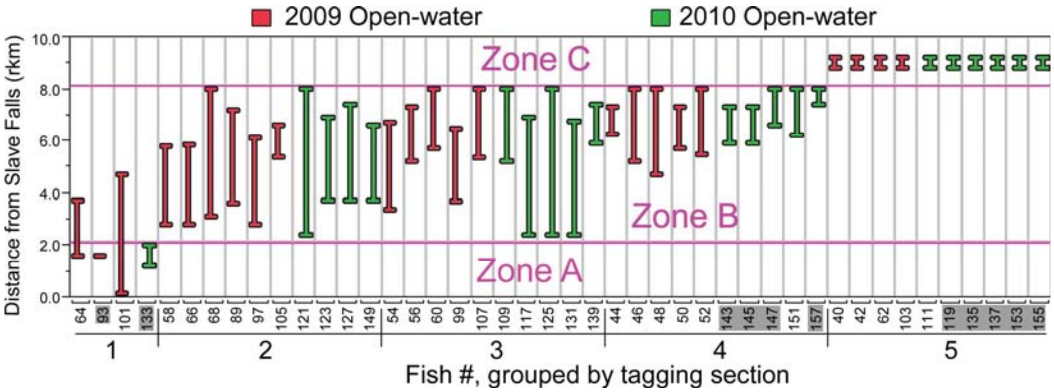

Figure 2.14. Range estimates for juvenile lake sturgeon in the Slave Falls Reservoir. Grey highlights indicate fish that were last detected several months before their tags were programmed to cease activation, and were thus excluded from range analysis. See Appendix 2 for further details.

All juveniles tagged in Zone B (sections 2 – 4) remained within that zone during the time in which their tags were active. Fish tagged in the upper portion of Zone B (Section 4, n=10) moved primarily in the upper half of the zone, while those tagged in the middle and lower portions (Section 3, n=10 and Section 2, n=10) showed more variation in their movement ranges (Figure 2.14).

Two of four juveniles (#93 and 133) tagged in Zone A (Section 1) remained in this zone for the duration their tags were known to be active. Juvenile #64 moved upstream into Zone B in mid October 2009, where it remained for the duration its tag was active. Only juvenile #101 was located in the lowermost 0.9 rkm, utilizing this area exclusively from mid September to early November 2009, thereafter ascending into Zone B where it remained for the duration its tag was active. This fish spent 37.4% of its open-water time in the lowermost 0.9 rkm.

Based on the 33 juveniles whose tags provided the best data (i.e. omitting the eleven fish whose tags may have expired prematurely), presence in the lowermost 0.9 rkm was found to be significantly higher for juveniles from Section 1 (χ^2[4, n=33] =

15.98, $p = 0.030$). It should be noted that this analysis was flagged as suspect due to low expected cell counts. Similarly, the proportion of open-water time spent in the lowermost 0.9 rkm (arcsine transformed) varied significantly by tagging section (ANOVA, $F_{4,28} = 6.58$, $p = 0.0007$). The same patterns were observed when all juveniles (n=44) were included in analyses.

Formal analysis of juvenile movements during winter was not conducted due to tags becoming inactive/active at various times throughout the period, but no juveniles moved between zones during the winter period, and data indicated reduced movement extents (Appendix 5).

2.4 Discussion

Through the use of acoustic telemetry, movement patterns of adult, sub-adult and juvenile lake sturgeon in the Slave Falls Reservoir were investigated, with particular focus on how movements resulted in fish utilizing habitat immediately upstream of the Slave Falls GS, and thus susceptibility to entrainment. Juveniles and sub-adult lake sturgeon tagged closer to the Slave Falls GS (i.e. Section 1) were more likely to be present and spend a greater proportion of time in the area immediately upstream of the station compared with those tagged further upstream. Furthermore, the results of this study indicate that sub-adults and juveniles found upstream of the Old Slave Falls narrows (Zones B and C) would rarely (if ever) be susceptible to entrainment through the Slave Falls GS, since these fish do not appear to move downstream through the Old Slave Falls narrows. Open-water utilization distributions of these fish were often indicative of affinity to core areas, as has been observed elsewhere (Holtgren and Auer 2004; Kempinger 1996; Lord 2007; Smith and King 2005b). But considering that many sub-adults and juveniles had movement ranges approaching the size of the zones in which they were tagged, it also appeared that the Eight Foot Falls and Old Slave Falls narrows restricted movements of these fish. One would expect that if movements were entirely random, or even randomly distributed around a core area, chance would have resulted in more fish moving upstream or downstream through these narrows over the course of the 18 month study. As such, it seems likely that a biological mechanism is involved.

One hypothesis is that movements in this impoundment are generally confined to areas of contiguous suitable foraging habitat, as has been observed in various species of marine fishes (Lowe et al. 2003; Meyer et al. 2010). The Slave Falls Reservoir contains a plethora of deep water (15 – 50+ m), typically dominated by sand and gravel substrates (Manitoba Hydro unpublished data). This type of habitat is contiguous throughout the stretches of river from Slave Falls to Old Slave Falls (Zone A, rkm 0 – 2.1) and from Old Slave Falls to Eight Foot Falls (Zone B, rkm 2.1 – 8.1). A small patch of deep water (15 – 25 m) is also found between Eight Foot Falls and the Pointe du Bois GS (Zone C, rkm 8.1 – 9.8). Eight Foot Falls and Old Slave Falls appear to be habitat breaks, being considerably shallower (< 10 m) and bedrock dominated. Sand and gravel substrates are known to be preferred by juvenile lake sturgeon (Benson et al. 2005; Chiasson et al. 1997; Holtgren and Auer 2004; Kempinger 1996; Peake 1999; Smith and King 2005b), and while rigorous analysis of the vertical usage patterns of lake sturgeon in the Slave Falls Reservoir is beyond the scope of this thesis, preliminary analysis indicates that juveniles and sub-adults in this impoundment primarily utilize deep-water habitat (>15 m) (C. McDougall unpublished data). Indeed, when deep water habitat is available, it tends to be preferentially selected by juvenile lake sturgeon (Barth et al. 2009; Holtgren and Auer 2004; Lord 2007; Smith and King 2005b).

The restriction of juvenile and sub-adult movement at Eight Foot Falls and Old Slave Falls could also be due to these fish having an aversion to the narrows because of the relatively high-flow conditions that persist there (column averaged velocities range from 0.5 – >3 m/s for 50% to 95% Winnipeg River flow scenarios, Manitoba Hydro unpublished data). Depending on Winnipeg River flow conditions, moving upstream through these narrows might be difficult or even impossible for lake sturgeon, which are perceived as weak swimmers (Peake et al. 1997; Webb 1986). At a stage when a lake sturgeon's life history strategy focuses on growth (Noakes et al. 1999; Scott and Crossman 1998), there might be little reason for these fish to attempt an upstream movement through a high-velocity area should they already have access to sufficient resources. Similarly, like many river resident species, lake sturgeon may be adapted to resist downstream movement through river narrows (Coutant and Whitney 2000), which would carry a risk of mortality, injury, or permanent displacement into potentially unsuitable habitat depending on the severity of the hydraulic gradient encountered. Often studied juvenile salmonids are known to elicit an avoidance response when they encounter accelerating flow conditions as they move downstream (Enders et al. 2009; Kemp et al. 2005), and it is possible that lake sturgeon do the same. However, to the knowledge of the author, this response has yet to be formally investigated in sturgeon. Fine-scale tracking of movements in and near river narrows, in corroboration with high-detail habitat and velocity mapping would shed more light on why juveniles and sub-adults rarely move upstream or downstream through these areas.

Recently, Barth et al. (2011) also found movements of juvenile lake sturgeon in an adjacent stretch of the Winnipeg River to be restricted by habitat transitions occurring at river narrows. It was suggested that home range size of these fish is related to the length of continuous deep-water habitat available (i.e. between river narrows). Results of the present study strengthen this hypothesis, extending the pattern into the sub-adult size class. The results of Barth et al. (2011) also indicated that juvenile lake sturgeon can exist in relatively short sections of river (<1.5 rkm) year-round. In the current study, juveniles tagged in Section 5 (Zone C) were never positioned outside rkm 8.8 – 9.2, which suggests an even lower limit to the habitat quantity requirements of juveniles in the Winnipeg River.

While sub-adults and juveniles tagged upstream of the Old Slave Falls narrows (sections 2 – 5) never moved near to the Slave Falls GS, many of those tagged in Zone A (Section 1) utilized the area immediately upstream of the Slave Falls GS for periods of days to months, indicative of home range usage. This narrow immediate forebay likely provides good open water foraging habitat, since it is dominated by deep water (15 – 30 m) and sand/gravel substrates (Manitoba Hydro unpublished data). Downstream passage of three of eleven (27%) tagged sub-adults suggests that when these fish do utilize this area as part of their home range, the frequency of entrainment is considerable.

Juvenile and sub-adult lake sturgeon from Zone A also showed a tendency to leave this area via upstream movement into Zone B, but the reasons behind what seem to be permanent emigrations are unclear. Zone A contains much of the same type of deep-water habitat found in Zone B, which should be suitable for juvenile and sub-adult lake sturgeon. Indeed, condition factor (K) for sub-adults captured in Zone A was generally higher than for those captured in Zone B (see Chapter 4), suggesting that adequate resources are available to sustain growth. Still, it may be that some unknown aspect of the habitat in Zone A is less than ideal, prompting upstream emigration. It is also perhaps notable that based on 2010 gillnetting effort (see Chapter 4) and recent technical documents (McDougall et al. 2008a; McDougall et al. 2008b), relative densities of juvenile and sub-adult lake sturgeon in Zone A appear to be much lower than in Zone B. Barth et al. (2009) suggested that juvenile lake sturgeon in the Winnipeg River may congregate in high densities because of a net social benefit relating to a shortened stress response (Allen et al. 2009) or group-size influenced survival (Hager and Helfman 1991; Pitcher et al. 1982). Considering that population thinning in Zone A seems to be occurring due to a combination of entrainment at Slave Falls as well as upstream emigration, it may be that juvenile and sub-adult lake sturgeon occurring in low or decreasing densities are motivated to search for larger congregations of conspecifics.

Absence of downstream movements of juveniles or sub-adults into Zone A during this study begs the question as to how these fish come to arrive in this area. It may be that a small proportion of juvenile/sub-adult lake sturgeon in the upper/middle portions of this impoundment do move downstream through the Old Slave Falls narrows. However, results from this study and that of Barth et al. (2011) suggest that this proportion would be very small. As such, significant recruitment into Zone A is suspected to occur during early life stages. Larval lake sturgeon are known to drift long distances (Auer and Baker 2002), and at least some lake sturgeon enter Zone A during this stage. In 2007, under low-flow conditions, no larval lake sturgeon were captured in larval drift traps set at the Old Slave Falls narrows and upstream of Slave Falls (rkm 1.0), but in 2009 under high-flow conditions, larval lake sturgeon (n=27) were captured in these areas (North/South Consultants unpublished data). Incidental captures of this 2009 cohort in Zone A occurred during gillnetting effort in 2010 (C. McDougall unpublished data). Considering that Winnipeg River flow conditions vary considerably from year-to-year (St. George

2007), recruitment of lake sturgeon into this zone is probably intermittent. Therefore, the degree of juvenile/sub-adult entrainment at Slave Falls may vary considerably from year-to-year, following a lagged response to flow conditions of years prior.

In other river systems, movement patterns of adult lake sturgeon have been found to be highly variable, and often asynchronous (Knights et al. 2002; Rusak and Mosindy 1997). Despite the small size of the Slave Falls Reservoir (~10 rkm), these observations were certainly echoed in the present study. Some adults traversed the entire length of the reservoir, while others never moved out of the zone they were initially tagged in. Utilization distributions of many adults were indicative of affinity to core areas, as observed elsewhere (Borkholder et al. 2002; Harkness and Dymond 1961; Haxton and Findlay 2008). Fourteen adults made upstream or downstream movements between zones during this study, but the infrequency of these movements seems to indicate that the Eight Foot Falls and Old Slave Falls narrows also restrict adult movements. However, as is the case for juveniles and sub-adults, the mechanism for this restriction is yet unknown and warrants further research.

Contrary to the results for juveniles and sub-adults, data did not support the hypothesis that adults tagged closer to the Slave Falls GS were more likely to be present or spend a greater proportion of time in the area immediately upstream of the station compared with those tagged further upstream. Based on the results of this study, one might wonder if certain adults are predisposed to utilizing the area immediately upstream of the Slave Falls GS, or if all adults in the Slave Falls Reservoir might potentially move into that area over the course of their mature life. Only one of seven adults (14%) located near to Slave Falls utilized this area in both 2009 and 2010. However, one of the two adults which passed downstream did so during 2009, thereby precluding it from using the area in 2010. This lack of annual consistency seems to suggest that the latter is a possibility, but addressing this question is logistically difficult because lengthy monitoring would be required. Variation in movement patterns among adults is probably at least in part due to sex specific differences, spawning periodicity, and the stage of an adult's reproductive cycle (Auer 1996a; Knights et al. 2002), which could not be accounted for in this study. Furthermore, even if sex and reproductive stage were determined at time of tagging, because spawning periodicity in lake sturgeon is variable (Bruch et al. 2001; Harkness and Dymond 1961; Scott and Crossman 1998), it would be problematic to infer reproductive stage of tracked adults in years subsequent to acoustic tagging.

Mark-recapture studies (predominantly of adults) on several river systems have documented relatively few instances of downstream passage over hydroelectric facilities (Haxton and Findlay 2008; Thuemler 1985; Thuemler 1997). However, on the Mattagami River, Ontario, between 40 and 400 adult lake sturgeon per year were entrained through the Adam Creek Control Structure (operated as a spillway for the Little Long GS) from 1990 to 1995 (Seyler et al. 1996), attributed to fish utilizing foraging habitat immediately upstream of the hydroelectric facilities (McKinley et al. 1998). In the current study, four adults utilized the area immediately upstream of Slave Falls for periods of days to months during the open-water season, patterns characteristic of home range use. Downstream passage of two of these adults suggests that when this area is used as part of their home range, the frequency of entrainment may be considerable. If one assumes that, in the current study, tagging location had no bearing on the probability of an adult moving to the vicinity of Slave Falls, entrainment rates for the adult population could be estimated at 4.3% (one out of 23 fish passed downstream) in 2009, and 4.5% (one out of 22) in 2010. These preliminary estimates suggest that entrainment of adults at the Slave Falls GS is relatively common.

It is perhaps useful to consider the adult life history stage in the Slave Falls Reservoir from a different perspective. Elsewhere, adult lake sturgeon are known to grow to considerable size, frequently exceeding 1.5 m in total length and 50 years of age (Auer 1996a; Scott and Crossman 1998). In the Slave Falls Reservoir, despite considerable large mesh (203 – 305 mm) gillnet effort between 2006 and 2011 and a lack of recent commercial harvest, only four out of the 991 adults captured (0.4%) exceeded 1.5 m in length (North/South Consultants unpublished data). Entrainment at the Slave Falls GS could be a factor explaining why so few large lake sturgeon are present in the Slave Falls Reservoir. While the probability of an individual adult lake sturgeon being entrained during a given year is likely low, as suggested by this study, the cumulative risk over each individual lake sturgeon’s long lifespan could be high. As such, it may be that many Slave Falls Reservoir adults are entrained prior to attaining the body sizes described in the literature (Auer 1996a; Bruch 1999; Harkness and Dymond 1961; Scott and Crossman 1998). However, in sturgeons there is a positive correlation between body size and the length of spawning migration (Auer 1996a), and it could also be that small body size in the Slave Falls Reservoir is a historical adaptation to confinement in a small stretch of river (i.e. pre-hydroelectric development). Lengthy migrations would not be necessary because of proximity to spawning habitat. In Ontario, a review of size at maturity data suggested that female lake sturgeon do not mature until at least 1.2 m (Ontario Ministry of Natural Resources 2006). In the well-studied Lake Winnebago system, 50% maturity for females and males was reached at 1.4 and 1.2 m, respectively

(Bruch 2008). Conversely, in the Slave Falls Reservoir, female lake sturgeon between 1 and 1.2 m in length are frequently mature (North/South Consultants unpublished data), perhaps indicative of such an adaptation. The recent capture of several ripe males measuring 642 – 720 mm (fork length) and as young as 8 years old (C. McDougall unpublished data) is unknown in the literature, and perhaps also supportive of this hypothesis. Further research would be required to determine if entrainment at Slave Falls is a factor limiting the size of adults in the Slave Falls Reservoir, or if small body size (and younger age of maturity) is an adaptation to historical confinement.

Rapid downstream movements of three adults observed in this study, considering their timing (May) and origin at the extreme upper end of the reservoir, were probably related to post-spawn behaviour, as lake sturgeon are known to quickly descend to foraging habitats following spawning (Bruch and Binkowski 2002; McKinley et al. 1998). While one adult ceased its descent upon reaching the Old Slave Falls narrows, the other two were briefly located immediately upstream of Slave Falls before returning to Zone B. What would have happened if the spillway was operational when these descents occurred is unknown, but it seems that this type of behaviour could also potentially result in entrainment. The rapidity of downstream movements of adults to the vicinity of the Slave Falls GS highlights the utility of passive acoustic telemetry arrays for monitoring movements of lake sturgeon, as it would be near impossible to document these types of movements via mark-recapture, or active tracking methods.

It is well known that fish movements are influenced by abiotic factors (Beitinger and Fitzpatrick 1979; Childs et al. 2008; Paukert and Fisher 2000; Saulamo and Lappalainen 2007; Zimmer et al. 2010), although these relationships can be difficult to identify in field investigations. With regards to comparisons of movement extent between study months, the data demonstrate markedly reduced movement extents for both sub-adult and adult lake sturgeon during winter, consistent with results of other studies that examined winter movements of adults (Borkholder et al. 2002; Rusak and Mosindy 1997). In the Slave Falls Reservoir, the effect of cold water periods on the extent of lake sturgeon movement was pronounced. As the positioning algorithm used tends to maximize range calculations over time, it is likely that many of the tracked fish remained essentially stationary for lengthy intervals (days to weeks) during the winter period, as observed in the closely related shortnose sturgeon, *Acipenser brevirostrum* (Li et al. 2007). It was also notable that no tagged lake sturgeon (from any of the three size classes) moved through either Old Slave Falls or Eight Foot Falls, and none utilized the area immediately upstream of the Slave Falls GS during the winter months. Since moderate flow conditions persist in this area, it is suspected that it provides relatively poor overwintering habitat.

While there was considerable variation amongst individuals, the adult lake sturgeon sample population tended to be located further downstream when water temperature and air temperature was high, when days were long, and when flow and water temperature was increasing. With entrainment susceptibility in mind, investigation of the data focused on the lower portion of the reservoir. Through multiple regression analysis, it was determined that proportional utilization of the lowermost 4 rkm of the reservoir was well explained by, in order, water temperature (+), change in flow (+), and daylight hours (+). The adult population level response in the Slave Falls Reservoir is similar to that observed by McKinley et al. (1998) on the Mattagami River, Ontario, where adult lake sturgeon tended to utilize the lower end of the study area (upstream of hydroelectric facilities) during summer, before moving back upstream in fall to overwintering locations. While the lower portion of the Slave Falls Reservoir was used extensively by adults, the area between rkm 2.1 and 4 was used far more than the area from rkm 0 to 2.1 (Figure 2.7, Figure 2.9). Again, this result is quite similar to the findings of McKinley et al. (1998) who found comparably higher densities of lake sturgeon located several kilometres upstream of the station versus in the immediate vicinity of the station during the summer period. Of course, this could in part be a function of fish utilizing habitat immediately upstream of the station being entrained before they could be sampled, thereby biasing proportional estimates. In the Slave Falls Reservoir, the Old Slave Falls narrows appears to somewhat restrict the movements of adult lake sturgeon into the lowermost 2.1 rkm. Considering that the frequency of entrainment is potentially high when these fish do utilize the area upstream of the GS, the presence of the Old Slave Falls narrows may effectively reduce entrainment of adults that make seasonal downstream movements.

Also, the seasonal movement pattern in the Slave Falls Reservoir is somewhat muted, in the sense that not all adults adhere to the pattern. On the Mattagami River, adult lake sturgeon vacated the upper sections of the study area during summer (McKinley et al. 1998). In the current study, outside of the 2010 spawning period, between 13 and 23% of the tagged adults in the current study were located in the uppermost section (Zone C) throughout the study period. It has been reasoned that lake sturgeon move towards optimal foraging habitats following the spawning period (McKinley et al. 1998; Rusak and Mosindy 1997). As such, sedentary behaviour of some adults observed in the current study indicates that the upper section of the Slave Falls Reservoir also provides suitable foraging habitat, as well as overwintering habitat.

Indeed, proportional distribution and movement patterns of the three size classes of lake sturgeon within the Slave Falls Reservoir indicate that on a coarse scale, suitable habitat for all three size classes exists throughout the impoundment.

For sub-adults, there was little consistency in the correlation of movements to abiotic variables. Some individuals showed positive correlations to seasonal variables (water temperature, change in water temperature, air temperature or daylight hours) as well as flow and change in flow, others showed lack of correlation, and still others showed negative correlations to the same variables. Similarly, changes in the proportional distribution of the tagged sub-adults appeared to be uncorrelated with abiotic variables, assumed to be because a roughly equal proportion of fish were moving in opposite directions in response to the same environmental conditions. It is unclear why there was a relatively high degree of consistency in the directionality of correlations for adults, yet a lack of consistency for sub-adults. It may be that genetic variation plays a role, and that sub-adults which adhere to the positive correlation pattern are more likely to survive to adulthood than fish which behave in the opposite manner. Alternatively, the difference might reflect a behaviour increasingly exhibited or perhaps learned over the course of a long lifespan. Clearly further research would be required in order to understand the differing relationships of lake sturgeon movements to abiotic variables, both between size-classes and across individuals.

The observation that the proportional distribution of sub-adult lake sturgeon became skewed towards the middle of the reservoir after May 2010 is also interesting. While this result is partially a function of Zone A (n=3) and Zone C (n=1) sub-adults immigrating into Zone B, there was also a tendency for fish from Zone B to increasingly utilize the middle rkm 4 – 6 section. Indeed, post-May 2010 proportional usage of this section was essentially double pre-May 2010 levels. This pattern may be indicative of a tendency for these fish to actively coalesce, which if so, might partially explain the dense congregations observed in the Slave Falls Reservoir (McDougall et al. 2008a; McDougall et al. 2008b) and elsewhere in the Winnipeg River (Barth et al. 2009). However, because of the rather sudden change in distribution, it may also be that the pattern is the result of a change in forage density, perhaps an invertebrate hatch.

Analysis of the relationship of movements to abiotic variables was certainly complicated by the multi-basin nature of the Slave Falls Reservoir, as well as considerable individual variation. While flow and change in flow conditions were correlated with movements of many individual adults and sub-adults, the hypothesis that high flows during the summer/fall period would result in increased concentrations of these fish immediately upstream of Slave Falls was not supported. However, the observation that upstream movements of adults tended to be correlated with decreasing flow conditions is interesting in itself, since it is contrary to the trend observed by Borkholder (2002) in a small river, highlighting how differently lake sturgeon may behave in a small impoundment on a large shield river. Indeed, as lake sturgeon of various life stages and from different river systems are increasingly studied, the more apparent the differences become.

Because lake sturgeon frequently utilized habitat immediately upstream of the Slave Falls GS, coupled with the fact that entrainment of adult (n=2) and sub-adult (n=3) lake sturgeon was observed in the current study, there is considerable merit in investigating the downstream passage phenomenon in more detail. The following chapter will investigate if downstream passage occurs through powerhouse turbines or spillway gates, how abiotic factors such as water velocity and bathymetric features influence downstream passage, and how frequently lake sturgeon survive downstream passage events.

3.0 DOWNSTREAM PASSAGE THROUGH THE SLAVE FALLS GENERATING STATION: PASSAGE ROUTE DETERMINATION, SURVIVAL AND FINE-SCALE MOVEMENTS

3.1 Introduction

Sturgeon species occurring upstream of hydroelectric generating stations may be vulnerable to mortality or injury, should they pass downstream through turbines or spillway gates (Secor et al. 2002). Direct turbine mortality in fishes has been attributed to a variety of factors, including rapid pressure changes, cavitation, shear stress, turbulence, blade strike and grinding, while indirect mortality resulting from disorientation or changes in buoyancy resulting in heightened susceptibility to predation can also occur (Cada 2001; Coutant and Whitney 2000; Ferguson et al. 2006). In juvenile salmonids, mortality rates of 4 – 13% associated with downstream passage through turbines have been reported (Bickford and Skalski 2000; Dedual 2007). Spillway passage is broadly considered to pose less of a mortality risk to fishes than does turbine passage, with salmonid mortality rates of 0 – 2% having been reported (Cada 2001; Coutant and Whitney 2000; Muir et al. 2001; Schilt 2007). Investigation of downstream passage related mortality in sturgeon species is rare in the literature, but at the Hadley Falls Station on the Connecticut River, Massachusetts, mortality rates of 100% were observed for adult shortnose sturgeon, *Acipenser brevirostrum,* which passed through Kaplan turbines (Kynard et al. 1999) in (Kynard and Horgan 2001). Conversely, at the Dalles Dam on the Columbia River, Oregon, all eighteen white sturgeon, *Acipenser transmontanus*, downstream passage events, which primarily occurred via open spillway gates, were survived. As such, it can be reasoned that downstream passage route likely governs mortality of lake sturgeon at any given hydroelectric generating station.

Downstream passage of river resident lake sturgeon through hydroelectric facilities is thought to occur infrequently on some systems (Haxton and Findlay 2008; Thuemler 1985; Thuemler 1997). In contrast, adult lake sturgeon were found to be frequently entrained through the Adam Creek Control Structure, operated as the spillway for the Little Long GS on the Mattagami River, Ontario (McKinley et al. 1998; Seyler et al. 1996). In this system, a seasonal downstream migration pattern to the area immediately upstream of the control structure was apparent (McKinley et al. 1998), resulting in between 40 and 400 lake sturgeon being entrained per year between 1991 and 1995, many having sustained injuries (Seyler et al. 1996). The results of Chapter 2 indicate lake sturgeon frequently utilize the area immediately upstream of the Slave Falls GS. Since 27% (3 of 11) of sub-adults tagged in the lowermost section and 8.7% (2 of 23) adults tagged throughout the reservoir were entrained, it appears that downstream passage at this station is a rather common occurrence. Because of the risk of mortality and injury, or at least permanent displacement following downstream passage, there is considerable merit in investigating this phenomenon in more detail. Determining if passage at the Slave Falls GS occurs via turbines or spillway gates and assessing survival are of particular interest. Furthermore, because of the relatively high interaction frequency of individual fish with the Slave Falls GS, coupled with a large lake sturgeon population size, this study site provides an excellent opportunity to investigate fine-scale movements of juveniles, sub-adults and adults as they approach hydroelectric facilities, providing baseline data needed for the direction of future fish protection initiatives. In this study, acoustic telemetry was used to determine downstream passage routes, assess downstream passage survival, and investigate fine-scale movements of adult, sub-adult and juvenile lake sturgeon in the immediate vicinity of the Slave Falls GS.

3.2 Materials and methods

3.2.1 Study area

The study area for this chapter encompassed the lowermost section of the Slave Falls Reservoir (see Section 2.2.1), from the interface with the Slave Falls GS to approximately 500 m upstream, as well as the 10 rkm stretch of Winnipeg River located downstream (Figure 3.1). The Slave Falls GS immediate forebay is dominated by moderately deep water (10 – 30 m) and bedrock, gravel and sand substrates (Manitoba Hydro unpublished data). The Slave Falls GS powerhouse stretches 180 m from the southwest shore (Figure 3.2), operating with a head of 9.5 m. At peak capacity the powerhouse can pass approximately 950 m^3/s through its eight vertical propeller-type turbine units (Manitoba Hydro 2010). Trash-rack spacing on the powerhouse units at Slave Falls is ~10 cm. Spill is discharged through seven main gates located on the north-eastern side of the 280 m long spillway (Figure 3.3), and from two regulating gates located inside the north end of the powerhouse. When Winnipeg River flow is relatively low, main spillway gates are not utilized while regulating gates are typically operated intermittently to maintain a consistent forebay level. Winnipeg River flow at Slave Falls averages 869 m^3/s (range: 100 – 2600) (St. George 2007), and spill is common during the open water season. Water velocities are typically low to moderate (0.0 – 0.5 m/s) throughout the immediate forebay, but are generally higher (0.5 – 1.0 m/s) in front of the powerhouse, and can reach as high as 1.4 m/s immediately upstream of intakes during high flow conditions (Manitoba Hydro unpublished data).

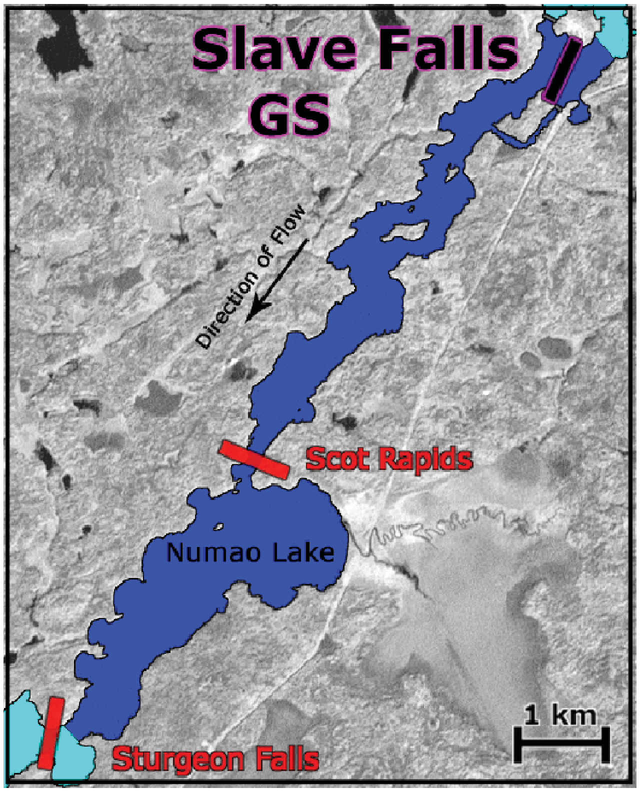

Figure 3.1. Study area for Chapter 3 (in dark blue): the Winnipeg River 500 m from the upstream interface of the Slave Falls GS, to Sturgeon Falls, located ~10 rkm downstream.

Figure 3.2. The Slave Falls GS powerhouse, as seen from the upstream side looking west. Photo taken on 21 May, 2010.

Figure 3.3. The Slave Falls GS spillway, as seen from the downstream side looking south. Photo taken 26 August, 2010, when spillway discharge was approximately 430 m^3/s.

Downstream of the Slave Falls, the Winnipeg River flows swiftly south as a single channel, and is characterized by variable water depths (0 – 30 m) and a variety of coarse substrates (cobble/gravel, bedrock and sand) (Barth 2011). The river narrows and accelerates considerably at Scot Rapids, prior to widening to form Numao Lake. Flow is still evident here and water depth and substrates are similar to that upstream of Scot Rapids. The river narrows again at Sturgeon Falls, marking the lower end of the study area.

3.2.2 Physical data and modelling

During spring 2011, bathymetry of the Slave Falls GS immediate forebay was surveyed and logged using a Lowrance HDS-5 Sonar/GPS (Lowrance Electronics Inc., Tulsa, Oklahoma). From this data, a model was generated in DrDepth version 4.1 (Prefix Elektronik, Gothenburg, Sweden), based on interpolation and extrapolation limits of 25 and 50 m, respectively. Water level fluctuation in the vicinity of Slave Falls is minimal

(<0.3 m) irrespective of flow conditions (Manitoba Hydro unpublished data), so only one model was generated and assumed to be representative throughout the study period.

Velocity models were generated by Manitoba Hydro hydraulic engineers using FLOW 3D software (Flow Science, Santa Fe, New Mexico), which is capable of simulating dynamic and steady state behaviour of liquids and gases in one, two, or three dimensions. The software operates via solution of the complete Navier Stokes equations of fluid dynamics, and is applicable to almost any type of flow process and is capable of simulating free surface flow. The program utilizes specialized algorithms to track the location of the water surface over large and small spatial and temporal variations. These capabilities make the FLOW 3D software well suited for simulating varied and complex flow conditions, which typically occur near hydroelectric generating stations. Models were generated for historical 50%, 75% and 95% flow scenarios. Historical data is unavailable to assess typical regulating gate flows under different percentile flow conditions, so regulating gates are assumed to be inoperative for the three percentile flow scenarios. A model scenario (referred to as July25Model) was also created based on specific flow conditions and gates in operation (including known regulating gate status) to model velocities at the time a tracked downstream passage event occurred. Since sturgeon are typically regarded as benthic (Kynard and Horgan 2001; Parsley et al. 2007) and thus bottom oriented, near-bottom (i.e. 1 m above river bed) velocities were extracted from the Flow 3D model. For comparative purposes, mid-column velocities are also presented.

3.2.3 Acoustic telemetry

Hydroacoustic Technologies Inc. (HTI) Model 795 Series Z, X and G Acoustic Tags (Hydroacoustic Tehcnologies Inc., Seattle, Washington) were used in this study. These tags operate at a frequency of 307 Hz, and as such, are particularly suitable for high noise environments such as near hydroelectric generating stations. Series Z tags were 65 mm long, had a maximum diameter of 15 mm, a weight of 24 g, and a life expectancy of ~1095 days. Series X tags were 45 mm long, had a maximum diameter of 15 mm, a weight of 13 g, and a life expectancy of ~180 days. Series G tags were 30 mm long, had a maximum diameter of 9 mm, a weight of 4.5 g, and a life expectancy of ~90 days. Individual HTI acoustic tags are programmed to ping at a constant rate, and the interval between pings, or Pulse Rate Interval (PRI), is used to identify the tag present. In this study, PRI of individual tags ranged from 1895 to 5253 msec. Life expectancy for each individual tag was expected to vary somewhat since it is influenced by the tag's PRI.

Based on 2009 preliminary coarse-scale movement data (Chapter 2), it was observed that juveniles and sub-adults tagged upstream of the Old Slave Falls narrows never descended through this narrows, and were thus never located in the vicinity of the Slave Falls GS. Conversely, adults were observed to make movements (albeit infrequently) through the Old Slave Falls narrows and into the area immediately upstream of the GS. Therefore, HTI acoustic tags were applied to juveniles and sub-adults captured only in the lower 2 km of the Slave Falls Reservoir (i.e. between Old Slave Falls and the Slave Falls GS), but to adults captured throughout the lower 6 km of the reservoir. A total of 12 juveniles (426 – 501 mm, fork length), 34 sub-adults (530 – 732 mm) and 56 adults

(841 – 1500 mm) were surgically implanted with HTI acoustic transmitters and externally marked with Floy tags using methods previously described in Section 2.2.3, with the exception that body mass was not determined for adults. Adults were implanted with Model 795Z or 795X transmitters between 23 April and 21 May, 2010 (Appendix 6). Sub-adults were implanted with 795X or 795G transmitters between 12 May and 25 August, 2010. Juveniles were implanted with 795G transmitters between 14 July and 24 August 2010, with the exception that one juvenile was tagged on 21 May. HTI acoustic transmitters applied to juveniles and sub-adults were a maximum 1.2% of body mass. Based on conservative estimates from length-weight regressions generated previously for Slave Falls Reservoir (North/South Consultants unpublished data), transmitters applied to adults would have been <0.7% of body mass. Five lake sturgeon previously implanted with Vemco acoustic transmitters (Chapter 2) also received an HTI transmitter, and for these fish transmitters (Vemco + HTI) were a maximum of 1.4%.

Unfortunately, duplicate PRI identifications were accidently assigned to eight pairs of lake sturgeon. As such, it was occasionally impossible to definitively determine which of the two fish was being detected (seven pairs were sub-adult + adult, the remaining was adult + adult). However, in all cases, one of each pair received a Model 795Z tag (life expectancy of ~1095 days) and the other received a Model 795X tag (~180 days). So in cases where downstream passage of one of these fish occurred, it was possible to determine which of the two fish had passed since only one of the two tags would still be active in spring 2011, when manual tracking was conducted throughout the Slave Falls Reservoir.

HTI Model 291 and 290 Tracking Systems were used to track the fine scale movements of HTI acoustically tagged lake sturgeon in the vicinity of the Slave Falls GS spillway and powerhouse, respectively. The Model 291 system consists of a base station attached to a maximum four cabled hydrophones deployed in a grid surrounding the area of interest. Data received from the hydrophones is transmitted back to the base station and then to a laptop computer, which logs raw detection data using HTIs AcousticTag software. The Model 290 system is similar, except that it can be attached to a maximum of 16 cabled hydrophones. Tag detection range for both systems are effectively determined by the “gain” settings applied to individual hydrophones, with manufacturer’s specifications indicating an upper limit approaching 1 km.

An HTI Model 291 four hydrophone Tracking System was installed in a square arrangement immediately upstream of the Slave Falls GS spillway on 7 May 2010 (Figure 3.4). Hydrophones were either hard-mounted to the concrete surface of the spillway (H1), hard-mounted to 75 kg concrete anchors (H2 and H3), or suspended under foam floats attached to aircraft cable and moored to a 75 kg concrete anchor (H4). Cables were run back to the base station located on shore. Following initial setup and slight modifications to hydrophone locations, approximate locations and depths were recorded using a Lowrance HDS-5 Sonar/GPS. A ping-around was later conducted to accurately determine hydrophone locations based on the time it took pulses transmitted by each hydrophone to reach the remaining hydrophones in the grid, as described by the manufacturer. Stationary tag trials indicated detection ranges of >300 m for all hydrophones in the grid, so long as there was a line of sight.

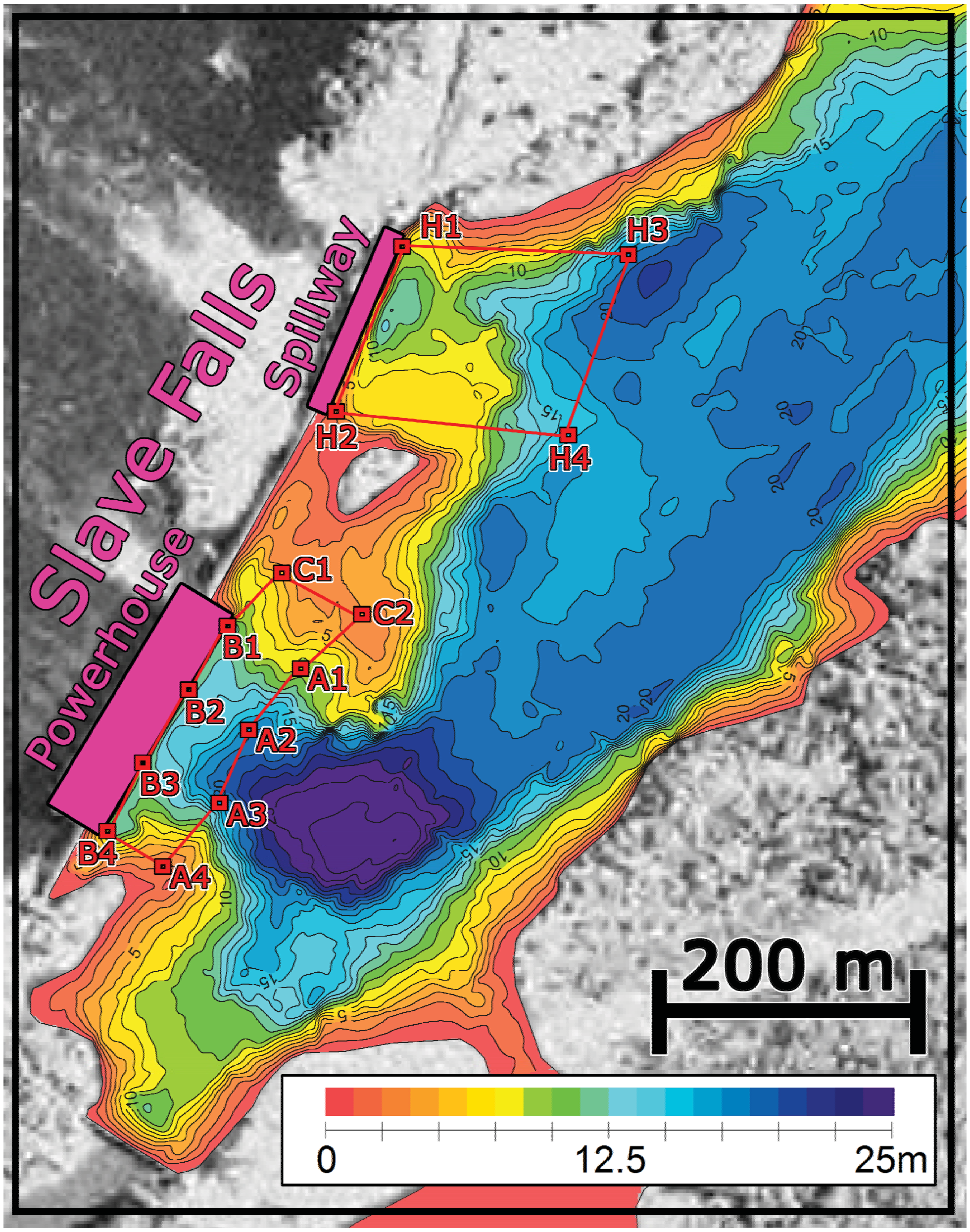

Figure 3.4. Location of HTI hydrophones (labelled) monitoring the Slave Falls powerhouse and spillway, overlaid on model generated bathymetry. Water depths (m) are colour coded as indicated by the scale bar.

An HTI Model 290 Tracking System was installed immediately upstream of the Slave Falls GS powerhouse on 8 July 2010 (Figure 3.4). Initially, eight hydrophones were installed (A1 – A4 and B1 – B4) in a rectangular grid using deployment methods previously described. Tag detection ranges of the hydrophones varied considerably, because gain settings needed to be optimized to contend with dynamic noise conditions. But in general, stationary tag trials indicated detection ranges of >150 m so long as there was a line of sight, and as such there was a high degree of coverage overlap. Several operational issues occurred. Hydrophone A2 ceased functioning on 30 July, 2010, and could not be replaced due to dangerous flow conditions in front of the powerhouse. On 7 August, 2010, two additional hydrophones (C1 and C2) were added in locations to the north of the powerhouse to supplement the existing installation, but between 1 and 10 September, hydrophones C1 and C2, as well as A1 ceased functioning, apparently as a result of large debris snagging and breaking the cables to which they were attached. These hydrophones were not replaced.

Various system outages also occurred. The powerhouse system was not operational from 7 October to 30 November, 2010, 11 – 17 February, 2011, and 25 May – 1 June, 2011. The spillway system was not operational from 24 March to 21 April, 2011, and 28 May – 1 June, 2011. For the purposes of this thesis, monitoring concluded on 7 July, 2011.

3.2.4 Fine-scale movements upstream of the Slave Falls GS spillway and powerhouse

Post-processing of raw acoustic data was conducted in HTI's MarkTags and AcousticTag software. Data were initially batch processed to generate presence/absence data. If a fish was detected by multiple hydrophones, preliminary 2D positional data were also generated. Whenever a tagged lake sturgeon was preliminarily positioned within 150 m of the spillway, raw data were re-examined and the pulses received by each individual hydrophone were filtered manually, so as to generate final 2D positional data (< 5 m accuracy within the array). Positional data were exported into ArcGIS 9 (Environmental Systems Research Institute, Redlands, California) for analysis. To account for potential changes in behaviour due to stress caused by capture, handling and/or tagging, data from the first 48 hours after a fish was implanted with an acoustic transmitter were omitted from all analysis.

Movements into the area within 80 m of the spillway were primarily investigated in terms of bathymetry. Telemetry tracks were overlaid on top of the bathymetric model to determine the water depth at the point in which lake sturgeon crossed the 80 m threshold line when entering the area (Figure 3.5). Entrance depth was then classified as follows: 0 – 6 m (class A), 6 – 9 m (B), and 9 – 13 m (C). A fish needed to move at least 10 m past the 80 m threshold for a movement to be included in analysis, and similarly, individual movement events were considered to conclude after the fish had moved 5 m outside of the 80 m threshold line. Entrance depth comparisons between size classes were analyzed using a mixed model least squares regression, with individual fish entered as a random effect.

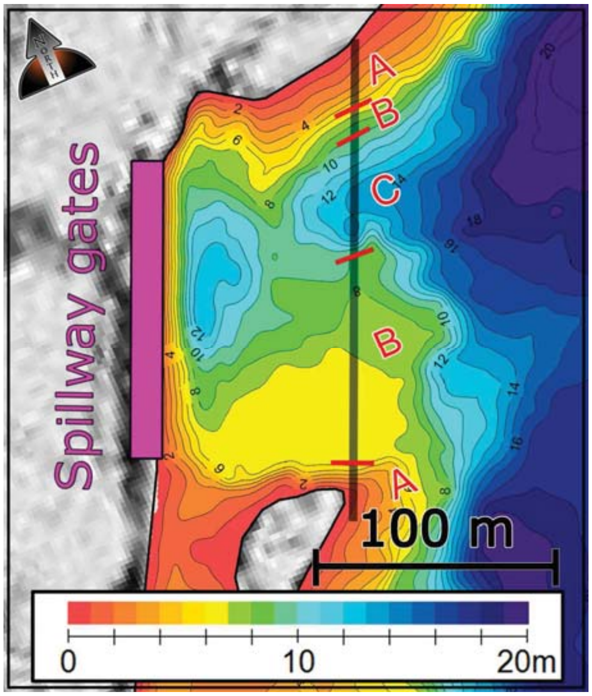

Figure 3.5. Bathymetric model depicting the area immediately upstream of the Slave Falls GS spillway, with grey line drawn at the 80 m threshold used for movement analysis. Depth class zones of 0 – 6 m (A), 6 – 9 m (B), and 9 – 13 m (C) along the threshold line are shown in red. Water depths (m) are colour coded as indicated by the scale bar.

The effects of size-class and entrance depth class on residence time (i.e. time spent inside of the 80 m threshold line during a given movement, in decimal hours), and minimum proximity (Prox_{MIN}) to the spillway (i.e. the closest a fish came to spillway infrastructure during a movement past the 80 m threshold, in metres) were also investigated using a mixed model, again with individual fish entered as a random effect. Tukey's HSD was used for all multiple comparisons. To see if there was a statistically significant diel influence on movements past the 80 m threshold, entrance timing, in terms of temporal distance from high noon (12:00) was analyzed with size-class and entrance depth class entered as potential effects, and individual fish entered as a random effect. For example entrances that occurred at 10:00 and 14:00 would both have a temporal distance of 2.0 hours from high noon. Additionally, for visual presentation, timing of movement events were classified as follows: midnight (21:00 – 3:00), morning (3:00 – 9:00), noon (9:00 – 15:00), and evening (15:00 – 21:00).

Processing of data collected by the powerhouse array was conducted in similar fashion. Second iteration tracks (i.e. after manual filtering) generated for movements into the area immediately upstream of the Slave Falls GS powerhouse are presented graphically. Because the complexity of triangulating precise positions based on detections made by a variable number hydrophones was beyond the knowledge of the author, with the exception of downstream passage tracks, tracks in the vicinity of the powerhouse should be regarded as preliminary. In cases where downstream passage occurred, data were processed in detail and tracks confirmed via correspondence with Hydroacoustic Technologies Inc.

3.2.5 Downstream passage route determination and survival

Downstream passage routes for HTI tagged fish (spillway, turbines or regulating gates) were determined via 2D tracking. If tracks were unavailable due to either the powerhouse or spillway not being monitored at the time of passage, routes were narrowed down as far as possible. For example, if passage occurred at a time when only the spillway was monitored, and passage was known not to have occurred through the spillway, it could be reasoned that passage occurred through the powerhouse. However, in this case it would be uncertain if passage occurred via turbines or regulating gates.

Success of downstream passage for HTI tagged fish, as well as Vemco tagged fish which passed downstream during the coarse-scale movement study (Chapter 2) was assessed through a combination of methods. For Vemco tagged fish which passed downstream over the Slave Falls GS (Chapter 2), four VR2W receivers, as described in Section 2.2.3, were deployed, at rkm 0.8, 3.0, 5.0 and 9.0, downstream of the Slave Falls GS from 1 September – 12 October 2010. Changes in vertical position (i.e. via pressure sensor data) were analyzed to determine if fish that had passed downstream were moving at their own volition. In order to account for potential delayed mortality, data needed to definitively indicate a >5 m change in vertical position (depth) or an upstream movement 30+ days after downstream passage for it to be deemed successful.

For HTI tagged fish, manual tracking was conducted using an HTI Model 295-X data logger. This system is capable of resolving sub-metre changes in distance between the hydrophone and pinging tag, and was configured so that it had a detection range of ~500 m. Its cabled hydrophone was lowered over the side of the boat, and the boat was back trolled throughout the area from immediately below the Slave Falls GS to 6 km downstream, and occasionally as far as 10 km downstream, while positional data were logged to a Garmin (Garmin Limited, Olathe, Kansas) 76Cx handheld GPS. Data were analyzed in MarkTags software, with the time signature associated with the apex of the detection arc (i.e. strongest and closest signal) being compared to that logged by the GPS to determine the approximate location of the fish. Locations were plotted in Garmin Mapsource software. For a fish to be deemed alive, it needed to have made a 1 km or greater upstream movement 30+ days after passage. For tagged fish which were not observed to have made significant upstream movements following downstream passage, an additional method was used to determine if the tag was stationary (and the fish assumed dead). Upon returning to the approximate location of the fish 30+ days after downstream passage, the boat was anchored off-current from the bow and stern, so that the boat remained stationary. A hydrophone was lowered over the side of the boat and acoustic data were logged for 10-30 minutes. Data were analyzed in MarkTags, with changes in Pulse Rate Intervals indicating that the tag was moving either nearer to or further from the stationary hydrophone, and a constant Pulse Rate Interval indicating that the tag was not moving. HTI tagged fish which were not documented to have made upstream movements of 1 km or greater, yet whose tags were still observed to be moving 30+ days after passage, could not definitively be determined as alive or dead. Manual tracking surveys were conducted eleven times between 5 August and 12 October, 2010. One additional stationary manual track was conducted on 18 October, 2010.

3.3 Results

3.3.1 Physical data and monitoring

Differences in near-bottom (i.e. 1 m above river bed) velocities generated for 50% (810 m^3/s total flow), 75% (1064 m^3/s) and 95% (1623 m^3/s) flow as well as July25Model (1281 m^3/s) are most pronounced in the vicinity of the Slave Falls GS spillway, where under 50% and 75% flow conditions, velocities are generally <0.25 m/s. (Figure 3.6). Under 95% flow conditions, near-bottom flows in the immediate vicinity of open spillway gates (gate 4 passing 425 m^3/s and gate 5 passing 278 m^3/s) are in the 0.5 – 1 m/s range. A notable difference between the historical 75% flow model and the July25Model conditions is that regulating gate flows of 132 m^3/s are included in the latter. In this model scenario, near-bottom velocities between 0.5 – 1 m/s occur <5 m away from the dam face in the vicinity of regulating gate intakes. Mid-column velocities tend to be slightly higher than near-bottom velocities, but only under 95% flow conditions do mid-column velocities exceed 1.0 m/s, immediately upstream of spillway gates. Specific Flow 3D boundary conditions from which the models are derived are included in Appendix 7.

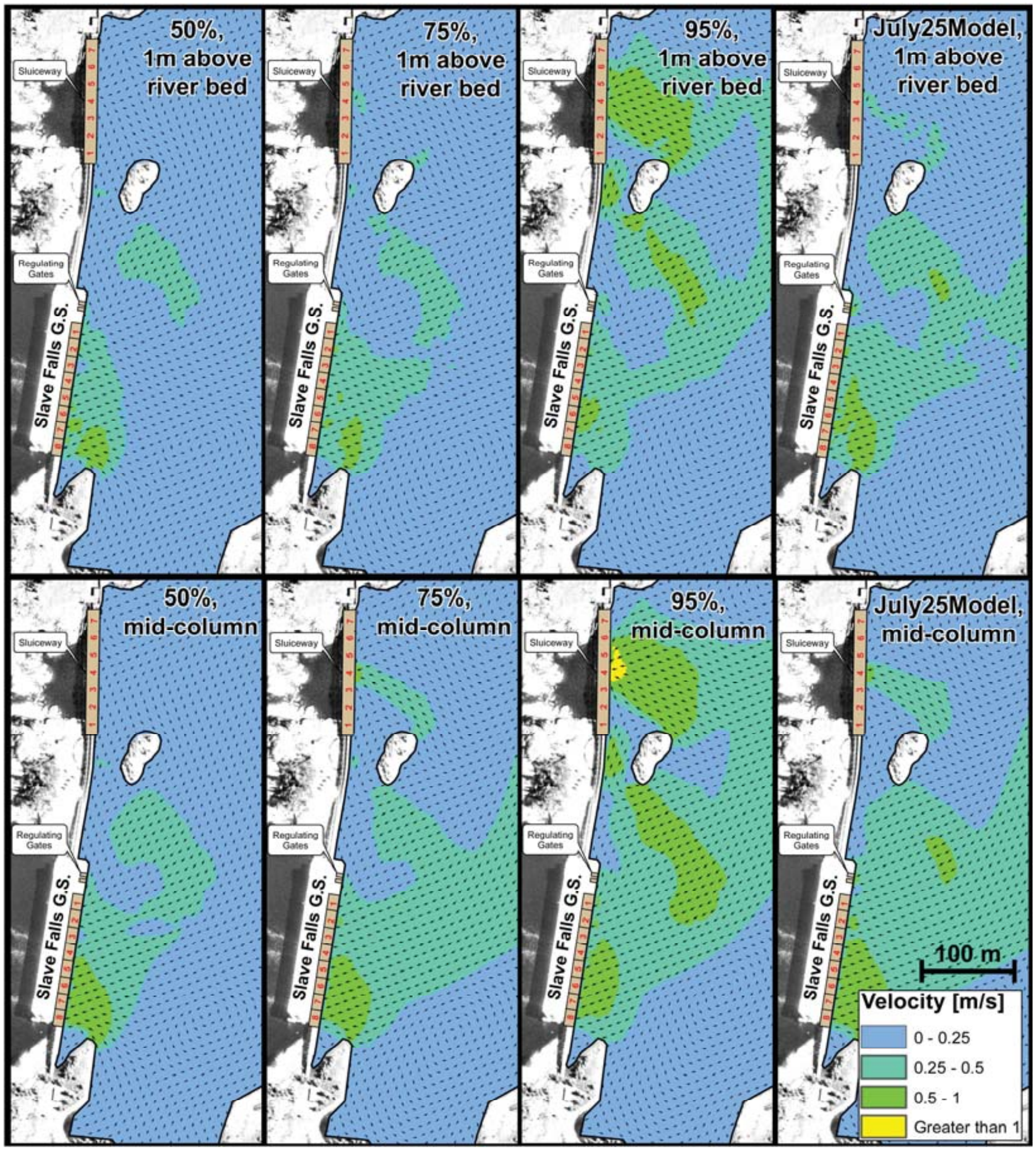

Figure 3.6 Near-bottom and mid-column water velocities in the area immediately upstream of the Slave Falls GS, based on 50%, 75% and 95% historical and July25Model flow scenarios, extracted from Flow3D model created by Manitoba Hydro. Locations of individual spillway gates (referred to in this figure as sluiceway gates), regulating gates and turbine units are labelled.

Differences in near-bottom (i.e. 1 m above river bed) velocities generated for 50%, 75% and 95% flow as well as July25Model are most pronounced in the vicinity of the Slave Falls GS spillway (Figure 3.6). Under 50% and 75% flow conditions, velocities are generally <0.25 m/s, whereas under 95% flow conditions, near-bottom flows in the immediate vicinity of open spillway gates (gate 4 passing 425 m^3/s and gate 5 passing 278 m^3/s) are in the 0.5 – 1 m/s range.

The 2009 open-water season was characterized by high Winnipeg River flow volumes, which reached as high as 2321 m^3/s on 1 July 2009, before rapidly declining to 1196 m^3/s on 2 August 2009 (Figure 3.7). Following a brief increase in late September, flow levels gradually declined to 997 m^3/s by 24 October, 2009. Throughout the 2009 open-water season, only four of eight turbine units were typically operational, and as such an uncharacteristically high proportion of total flow was directed over the spillway and/or regulating gates located at the north end of the powerhouse. From November 2009 to April 2010, Winnipeg River Flows were quite consistent, ranging from 740 to 1010 m^3/s. Over the course of this interval a decreasing amount of water was spilled, as additional turbine units were brought back online.

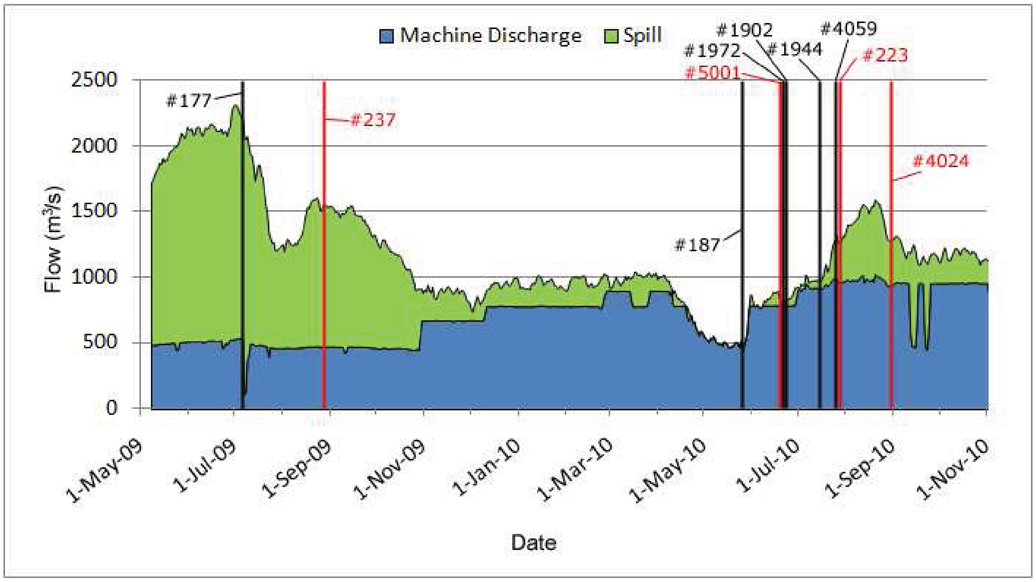

Figure 3.7. Winnipeg River flows as measured at the Slave Falls GS, separated into machine discharge and spill, from May 2009 to November 2010. Downstream passage events with fish numbers overlaid in black (sub-adults) and red (adults).

In April 2010, Winnipeg River flows decreased, falling to 431 m^3/s on 26 May, 2010. From 23 April to 8 June, 2010, the daily average spill was only 3 m^3/s (leakage). From 9 June to 20 August, 2010, flows increased considerably to 1596 m^3/s, before declining and fluctuating between 1196 and 1321 m^3/s from 28 August to 26 October, 2010. During the 2010 open-water season, the bulk of Winnipeg River flow was passed through the Slave Falls GS powerhouse turbines.

3.3.2 Presence/absence telemetry

Over the course of the study, omitting the 48 hour interval after individual fish were tagged, a total of 33 different HTI tag IDs were detected by the arrays deployed on the Slave Falls GS spillway and powerhouse (Figure 3.8). No HTI tagged fish were detected by the spillway or powerhouse arrays after 26 October, 2010. All HTI Model 795X and G tags implanted were scheduled to expire prior to December 2010, but many adults (n=37) received Model 795Z tags that should have remained active into early 2012 (Appendix 6). The vast majority of these fish (35 of 37) were detected between the Pointe du Bois GS and Old Slave Falls during manual tracking conducted in spring 2011, confirming that the 795Z tags were indeed still active.

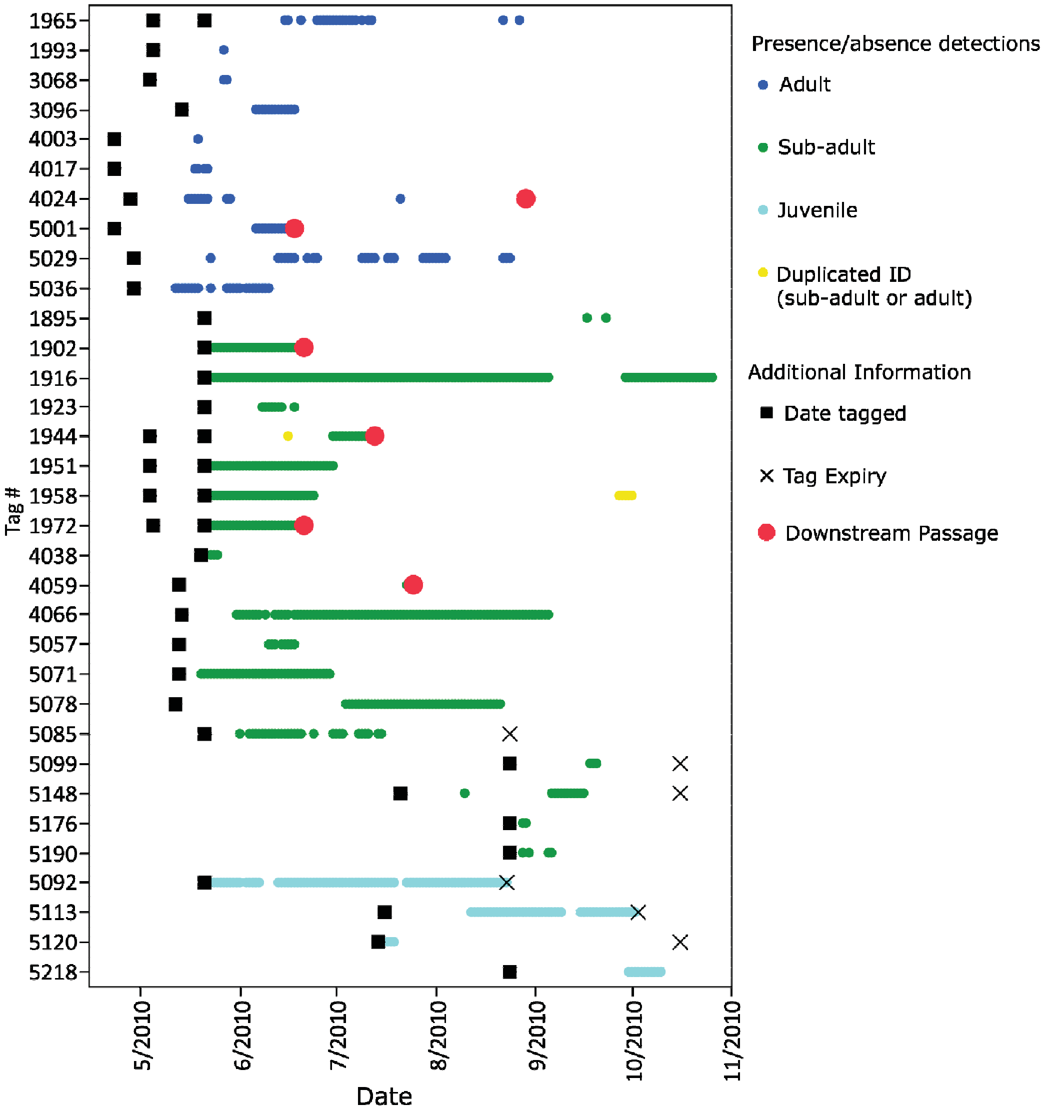

Figure 3.8. Presence/absence detection data for HTI tagged lake sturgeon at the Slave Falls GS spillway and powerhouse HTI acoustic arrays, with supplemental tagging dates, tag expiry dates, and downstream passage events indicated.

3.3.3 Downstream passage route determination

Between the coarse-scale study (Chapter 2) and the current study, a total of eleven downstream passage events occurred (Table 3.1, Figure 3.7). Six were HTI tagged fish and five were Vemco tagged fish. Of the five Vemco tagged fish that passed downstream, two adults (#237, 1065 mm and #223, 1287 mm) (Appendix 2), were last located upstream of Slave Falls on 26 August, 2009 and 28 July, 2010, respectively. Two sub-adults (#177, 608 mm and #187, 609 mm) were last located upstream of Slave Falls on 6 July, 2009 and 24 May, 2010, respectively. One additional sub-adult (#141, 554 mm), which was implanted with a V9 delayed activation tag during the coarse-scale movement study but was never detected upstream of Slave Falls, was incidentally captured in a gillnet downstream of Slave Falls on 13 August, 2010. This fish was identified by its external Floy tag and a well-healed acoustic tagging scar. As this acoustic tag should have activated in February 2010, it was reasoned that this fish passed downstream prior to that time. Because sub-adult #187 passed downstream at a time when no flow was being directed through the spillway (average daily spill of 3 m^3/s, Figure 3.7), it was concluded that this fish must have passed downstream through the powerhouse (either through turbines or regulating gates). Passage routes for the other four Vemco tagged fish could not be determined.

Table 3.1. Summary of tagging and survival assessment information for acoustic tagged lake sturgeon which passed downstream through the Slave Falls GS.

Tagging information						Downstream passage information					Survival information			
Tag #	Tag type	Size class	Fork length (mm)	Capture distance from Slave Falls (rkm)	Date tagged	Last detected upstream	Days after tagging	Powerhouse flow (m^3/s)	Spillway flow (m^3/s)	Passage route	Survival	Survival confirmation method	Last confirmation	Days since passage
223	V16	Adult	1287	4.0	05/11/09	07/28/10	443	961	311	Unknown	Yes	Vertical position (+US move)	05-Oct-10	69
237	V16	Adult	1065	4.9	05/09/09	08/26/09	109	470	1044	Unknown	Yes	Vertical position	10-Oct-10	410
177	V13	Sub-adult	608	1.6	05/13/09	07/06/09	54	538	1670	Unknown	Yes	Vertical position	10-Oct-10	461
187	V13	Sub-adult	609	1.6	05/13/09	05/24/10	376	468	3	Powerhouse (assumed)[a]	Yes	Vertical position (+US move)	11-Oct-10	140
141	V9d	Sub-adult	554	1.3	06/20/09	Never	-	-	-	Unknown	Yes	Gillnet capture	13-Aug-10	>195[d]
4024	HTI-X	Adult	1010	1.8	04/28/10	08/29/10	123	934	349	Regulating gates (track)	-	Moving Tag[c]	18-Oct-10	50
5001	HTI-X	Adult	878	5.5	04/23/10	06/18/10	56	786	110	Powerhouse (assumed)[b]	-	Moving Tag[c]	20-Aug-10	63
1902	HTI-X	Sub-adult	600	0.3	05/21/10	06/21/10	31	791	12	Powerhouse (assumed)[b]	Yes	Upstream movement	28-Sep-10	99
1944	HTI-X	Sub-adult	649	0.3	05/21/10	07/13/10	53	924	57	Regulating gates (track)	Yes	Upstream movement	12-Oct-10	91
1972	HTI-X	Sub-adult	673	0.3	05/21/10	06/20/10	30	790	23	Powerhouse (assumed)[b]	Yes	Upstream movement	01-Sep-10	73
4059	HTI-X	Sub-adult	706	1.1	05/13/10	07/25/10	73	999	283	Regulating gates (track)	-	Moving Tag[c]	28-Aug-10	34

a - Powerhouse passage route assumed because only spillway leakage occuring.

b - Powerhouse passage route assumed because passage did not occur through the spillway, which was monitored at this time.

c - Because fish never made a pronounced upstream movement, it could not be definitevly ascertained as alive.

d -Vemco tagged fish #141, implanted with a delayed activation tag was never located upstream of Slave Falls. Therefore it was assumed that it passed downstream prior to scheduled tag activation, which should have occurred in February 2010.

Of the six HTI tagged fish which passed downstream, adult #5001 (878 mm), sub-adult #1972 (673 mm), and sub-adult #1902 (600 mm) were last located upstream of the Slave Falls GS on 18, 20 and 21 June, 2011, respectively, prior to the powerhouse HTI tracking system being installed (Table 3.1, Figure 3.7). Since these passage events did not occur through the spillway (which was consistently monitored at this time), it was narrowed down that passage occurred through the powerhouse (either turbines or regulating gates). The powerhouse HTI tracking system was in place for the remaining three HTI downstream passage events. Sub-adult #1944 (649 mm), sub-adult #4059 (706 mm), and adult #4024 (1010 mm) were last located upstream of the Slave Falls GS on 13 July, 25 July and 29 August, 2010, respectively. In all cases, fish were positioned immediately upstream of the powerhouse for only brief periods of time (0.35 – 1.13 hours) before approaching the powerhouse and never being detected in the Slave Falls Reservoir again. Based on 2D tracks, it was concluded that these three fish passed downstream through the regulating gates located at the north end of the powerhouse (Figure 3.9).

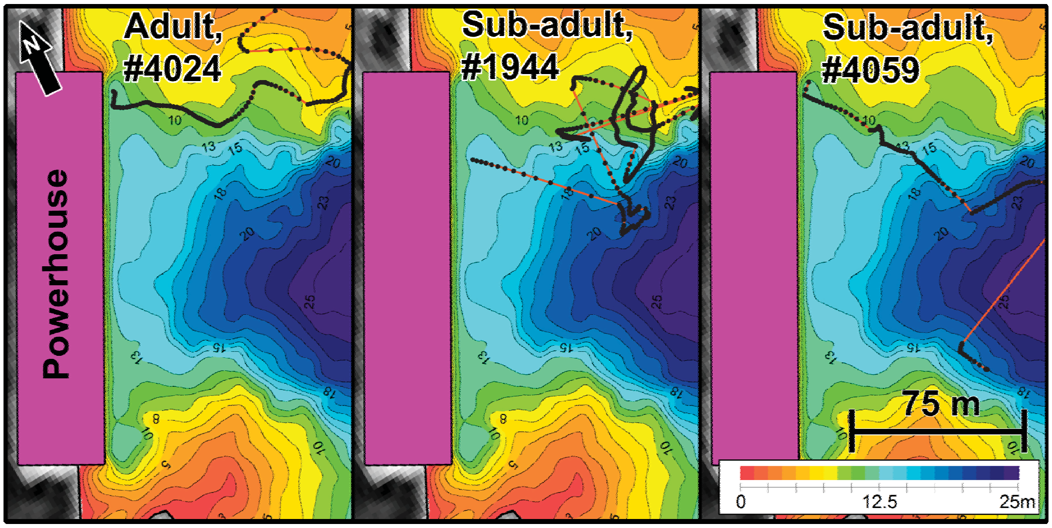

Figure 3.9. Downstream passage tracks for three HTI tagged lake sturgeon overlaid on top of the bathymetric model. Water depths (m) are colour coded as indicated by the scale bar.

In summary, of the eleven downstream passage events documented in this study, it was concluded that three occurred through regulating gates (Figure 3.1). Four more occurred through the powerhouse, but it is uncertain if these fish passed via turbines or regulating gates. Nothing could be determined about the passage routes of the remaining four fish.

3.3.4 Downstream passage survival

Four of the Vemco tagged fish (adults #223 and 237, sub-adults #177 and 187) were detected frequently (range: 4,133 – 12,598 detections) on Vemco VR2W receivers deployed between the Slave Falls GS and Sturgeon Falls from 1 September to 12 October, 2010. All four were determined to be alive 30+ days after downstream passage occurred, based on changes in vertical position (depth) (Figure 3.10). In addition, both Vemco tagged fish that passed downstream during 2010 (#187 and 223) made sufficient horizontal movements so as to be detected on multiple receivers 30+ days after downstream passage. It was concluded that sub-adult #141 also survived downstream passage since it was in perfect external condition when recaptured downstream of Slave Falls.

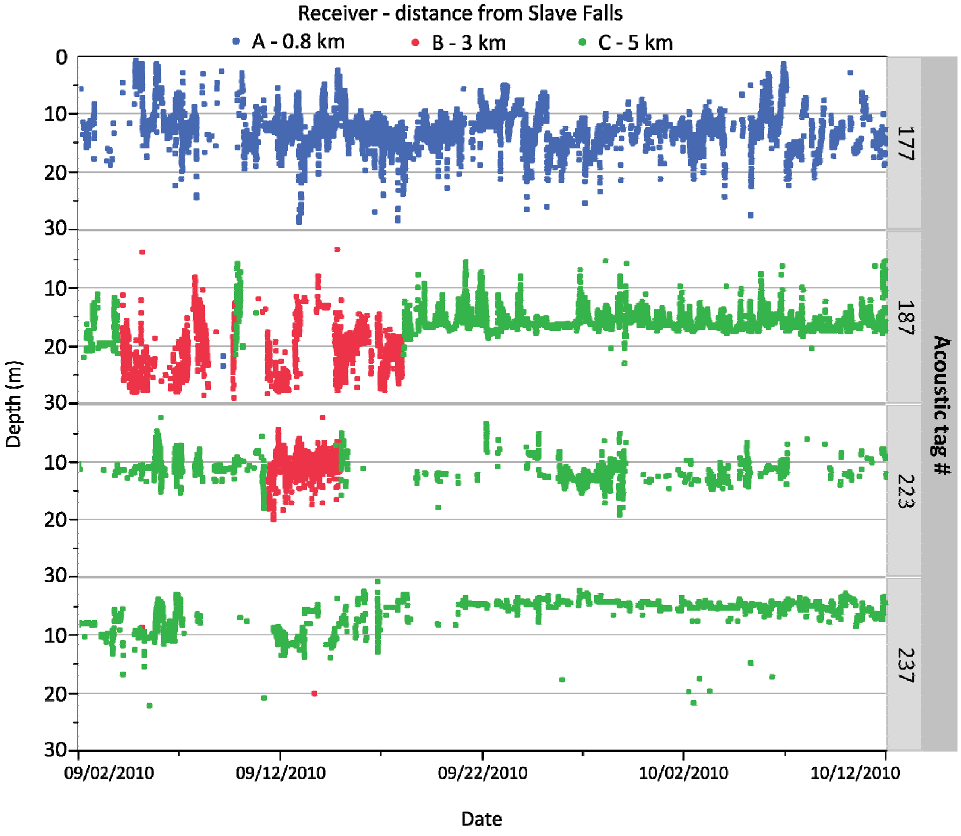

Figure 3.10. Vertical position of Vemco tagged lake sturgeon which previously passed downstream over the Slave Falls GS, indicating that these fish are moving vertically at their own volition, and have therefore survived downstream passage. Note that obvious outliers are almost certainly false detections, which were not filtered from this figure.

All six HTI fish which passed downstream during the study were located multiple times during manual tracking. Three sub-adults (#1902, 1944 and 1972) were documented to have made pronounced upstream movements (>1 km) 30+ days after downstream passage. Therefore, it was concluded that they had survived downstream passage. Stationary manual tracking indicated that the remaining three tags were moving 30+ days after downstream passage, but due to the possibility that the fish's carcass might simply be drifting in the current, it could not be definitively concluded if they had survived downstream passage (Table 3.1).

To summarize, it was concluded that eight of the 11 downstream passage events observed were survived, while survival of the remaining three events could not be ascertained. Following downstream passage, five of six HTI tagged lake sturgeon were consistently located in the stretch of river between Slave Falls and Scot Rapids when manual tracking was conducted. Only adult #5001, which was located on 5 and 20 August, 2010, near the base of the Slave Falls GS (tag observed to be moving on both occasions), was never located during subsequent manual tracking. All Vemco tagged fish which passed downstream were located between the Slave Falls GS and the next significant habitat transition, Scot Rapids, during survival assessments, despite two of them having passed downstream >400 days prior. In addition, since maximum efficient detection range was estimated at 1200 m for adults and 1000 m for sub-adults (Chapter 2), data indicated a tendency for these fish to remain in a relatively small area for lengthy intervals (up to several weeks).

3.3.5 Fine-scale movements

Nine different HTI tagged lake sturgeon made movements within 80 m of the Slave Falls GS spillway throughout the course of the study. Five adults made a total of 17 movements, three sub-adults made a total of 20 movements, and one juvenile made three movements into this area (Figure 3.11). Movements occurred when total spill ranged from 0 to 748 m^3/s. However, these data also include flow directed through regulating gates located in the north end of the Slave Falls GS powerhouse, and is therefore likely to be somewhat inflated. Because of small samples sizes, statistical comparisons involving juveniles were not made.

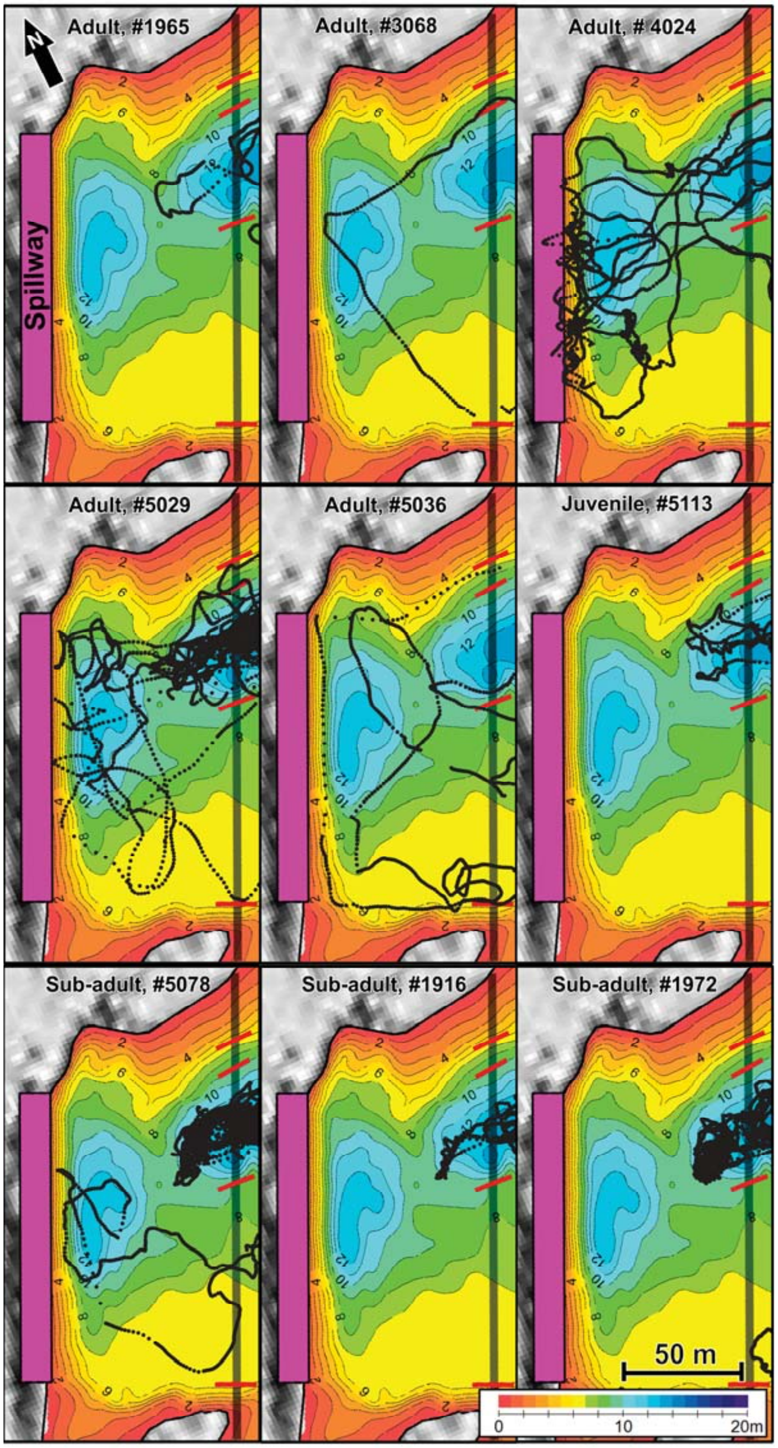

Figure 3.11. Graphical summary of fine-scale movements of HTI tagged lake sturgeon near the Slave Falls GS spillway over the course of the study. Movements are separated by individual fish. Water depths (m) are colour coded as indicated by the scale bar.

Entrance crossings of the 80 m threshold line occurred most frequently through the relatively deep (9 – 13 m, depth class C) channel leading towards the spillway, less frequently over the mid-depth shelf extending from the small island located upstream of the spillway and break extending from the north shoreline (6 – 9 m, depth class B) and never via near-shore areas with depths < 6 m (depth class A) (Figure 3.11.). For adults, 11 of 17 entrance crossings occurred at depth class C, while the remaining six occurred at depth class B. For sub-adults, 19 entrances occurred at depth class C, while one occurred at depth class B. However, mixed model analysis did not reveal any statistically significant differences in entrance depth between size classes (MIXED MODEL, $F_{1,4.34} = 4.15$, $p = 0.11$), perhaps a function of low statistical sample size (i.e. number of individual fish). For the lone juvenile which crossed the 80 m threshold, all three entrances occurred at depth class C.

Mean residence time inside the 80 m threshold was 0.45 hours (range: 0.03 – 3.16). Residence time did not vary significantly by size class (MIXED MODEL, $F_{1,12.84} = 0.384$, $p = 0.55$) or entrance depth class (MIXED MODEL, $F_{1,32.6} = 0.237$, $p = 0.63$). No significant interaction between the two variables were observed (MIXED MODEL, $F_{1,32.6} = 0.2864$, $p = 0.60$). Mean $\mathrm{Prox}_{\mathrm{MIN}}$ to spillway infrastructure for sub-adult movements that began with an entrance crossing at depth class C was 57.9 m (range: 53 – 70), while the only sub-adult movement with an entrance crossing at depth class B had a $\mathrm{Prox}_{\mathrm{MIN}}$ of 3 m. Mean $\mathrm{Prox}_{\mathrm{MIN}}$ for adult movements that began with an entrance crossing at depth class C was 32.0 m (range: 0 – 64), while mean $\mathrm{Prox}_{\mathrm{MIN}}$ for adults that began with an entrance crossing at depth class B was 16.8 m (range: 0 – 52) (Figure 3.12). In total, ten adult movements and one sub-adult movement resulted in fish being located within 25 m of spillway infrastructure. $\mathrm{Prox}_{\mathrm{MIN}}$ did not vary by size class (MIXED MODEL, $F_{1,10.16} =$

0.3151, p = 0.59) but did vary by entrance zone, with movements associated with entrance depth class B typically resulting in fish being located closer to spillway infrastructure (MIXED MODEL, $F_{1,32.2} = 12.96$, p = 0.0011). In addition, analysis revealed an interaction effect between size class and entrance depth class (MIXED MODEL, $F_{1,32.2} = 4.62$, p = 0.034). Tukey's HSD indicated that sub-adult movements that began with an entrance crossing at depth class C resulted in a significantly greater $\mathrm{Prox_{MIN}}$ distance from the Slave Falls GS spillway than sub-adult and adult movements that began with an entrance crossing at depth class B. In other words, sub-adults which crossed the 80 m threshold at water depths of 9 – 13 m (depth class C) tended to remain further away from spillway infrastructure during movements. No other significant differences were observed.

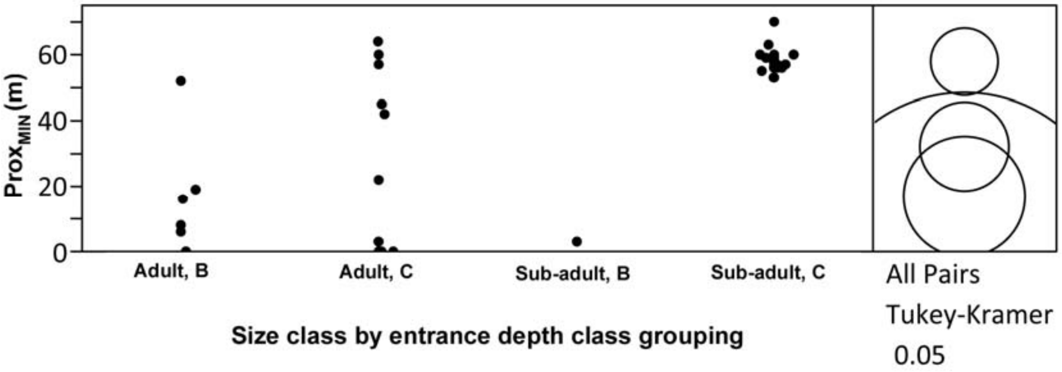

Figure 3.12. Comparison of minimum distance to spillway infrastructure ($\mathrm{Prox_{MIN}}$) during movement, by size class and entrance depth class combinations. As indicated by Tukey's HSD, sub-adult movements associated with entrance depth class C tended to have higher $\mathrm{Prox_{MIN}}$ distances than sub-adult and adult movements associated with entrance depth class B. It should be noted that this figure does not reflect that individual fish were entered as a random effect for the purposes of statistical testing.

For adults, timing of entrances past the 80 m threshold varied between entrance depth classes. All six entrances at depth class B occurred during the "midnight" (21:00 –

3:00) interval (Figure 3.13). For sub-adults, the only entrance at depth class B also occurred during the “midnight” interval. For both adult and sub-adult size classes, entrances that occurred at depth class C tended to be well distributed throughout the day. All three juvenile movements occurred during the “midnight” interval.

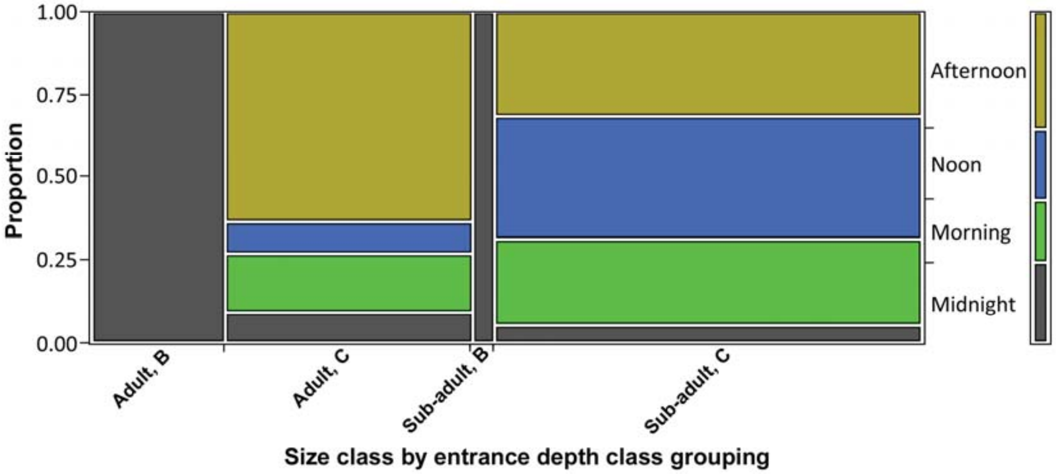

Figure 3.13. Temporal distribution of entrances past the 80 m threshold into the area immediately upstream of the Slave Falls GS spillway. Movement events are grouped by size (adult, sub-adult) and entrance location depth class (B, C) across temporal intervals of 21:00 – 3:00 (midnight), 3:00 – 9:00 (morning), 9:00 – 15:00 (noon), and 15:00 – 21:00 (afternoon). It should be noted that this figure does not reflect that individuals were entered as a random effect for the purposes of statistical testing.

Entrance timing, in terms of temporal distance from 12:00 (noon), was not found to vary by size class (MIXED MODEL, $F_{1,9.95} = 1.80$, $p = 0.21$). Conversely, entrance timing varied by entrance depth class (MIXED MODEL, $F_{1,32.98} = 9.57$, $p = 0.004$). Movements associated with entrance depth class C (9 – 13 m) occurred an average of 5.2 hours from noon (range: 0.9 – 11.4, n=30) while those associated with entrance depth class B (6 – 9 m) occurred an average of 11.0 hours from noon (range: 9.1 – 11.8, n=7). No interaction between size class and entrance depth class was found (MIXED MODEL, $F_{1,32.98} = 0.11$, $p = 0.74$).

From 7 July to 7 October, 2010, in addition to the three lake sturgeon which passed downstream through the regulating gates, eight other HTI tagged lake sturgeon were located in the immediate vicinity of the Slave Falls GS (Figure 3.14). While tracks presented are to be treated as preliminary, it appears that only three movements by one sub-adult (#4066) resulted in fish being located within 25 m of the powerhouse. One of these movements appears to have resulted in this fish being located slightly inside the face of the powerhouse before it swam back upstream. Two sub-adults (#1916 and #4066) sometimes remained within 100 m of the powerhouse for intervals of hours to days, while movements of the others tended to consist of brief forays (<2 hours) into the area.

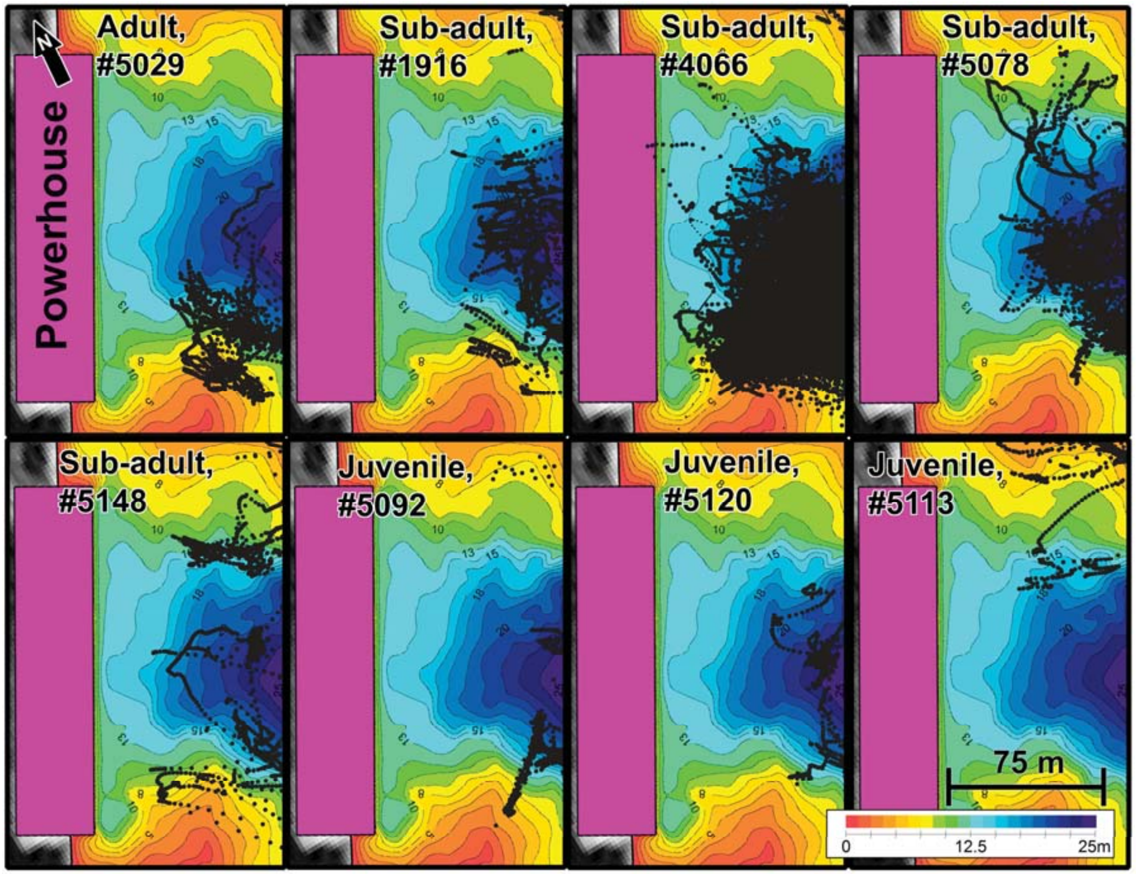

Figure 3.14. Graphical summary of fine-scale movements of HTI tagged lake sturgeon near the Slave Falls GS powerhouse over the course of the study, based on 2nd iteration tracks. Movements are separated by individual fish. Water depths (m) are colour coded as indicated by the scale bar. This data should be treated as preliminary.

3.4 Discussion

First and foremost, the results of this study further support the notion that downstream passage of adult and sub-adult lake sturgeon through the Slave Falls GS is a regular occurrence, a phenomenon only thus far documented in adult lake sturgeon in one other river system (McKinley et al. 1998). Based on the observation that eight of 11 fish which passed downstream over the course of the study were definitively alive, downstream passage at the Slave Falls GS appears to be frequently survived. While stationary manual tracking results indicated that the tags of the three questionable fish were moving 30+ days after downstream passage, the possibility of a carcass drifting in the current precluded making a definitive survival assessment. However, given the swiftly flowing nature of the Winnipeg River between the Slave Falls GS and Scot Rapids, it is likely that a tag moving as a result of this phenomenon would tend to drift downstream over time.

Of the three fish of questionable status, sub-adult #4059 was consistently located approximately 1.5 rkm downstream of the Slave Falls GS, on eight manual tracking surveys conducted from 20 August to 12 October, 2010 and was last confirmed to be moving via stationary manual tracking on 28 August, 2010. Adult #4024 was located approximately 1.5 rkm downstream of the Slave Falls GS on 1 September, 2010, then approximately 6 rkm downstream (immediately upstream of the high velocity Scot Rapids) on four occasions between 28 September and 12 October, 2010. It was again located at approximately rkm 6 and again confirmed to be moving on 18 October, 2010, via stationary manual tracking. Based on these observations, it is highly likely that sub-adult #4059 and adult #4024 also survived downstream passage. The fate of adult #5001 is less certain.

No HTI tagged adults were detected by the Slave Falls arrays during winter (November 2010 – April 2011), consistent with the hypothesis that these fish do not utilize the area immediately upstream of the generating station during winter months. However, the absence of the 37 adults with active HTI tags in or near HTI arrays between May and July, 2011, was unexpected. By comparison, four out of 23 and four out of 22 Vemco tagged adults were located near Slave Falls in the 2009 and 2010 open-water season, respectively. Due to duplicated tag IDs, it could only be concluded that at least 10 (and possibly up to 13) out of a total of 56 HTI tagged adults were present near Slave Falls at some point during 2010. Why a similar proportion of the 37 HTI tagged adults were not located in 2011 is unclear. However, re-examination of Chapter 2 data revealed that downstream movements of Vemco tagged adults through the Old Slave Falls narrows (six fish, 14 total downstream movements) only occurred when flows were <1300 m^3/s. One Vemco tagged adult (#251) did move downstream into the narrows when flows were ~2100 m^3/s, but moved back upstream without being detected further downstream than rkm 2.0, perhaps indicative of an avoidance response. From 1 May to 27 June, 2011, flows varied from ~1400 to 1775 m^3/s. As such, it may be that the frequency of adult downstream movement through the Old Slave Falls narrows is related to Winnipeg River flow volumes, perhaps due to the increased velocities that would be present at this river bottleneck.

Fine-scale telemetry tracks indicated that downstream passage of three HTI tagged lake sturgeon during 2010 occurred through regulating gates located at the north end of the Slave Falls GS powerhouse. It was also determined that downstream passage of three other HTI tagged and one Vemco tagged fish must have occurred via the powerhouse, since these events did not occur via the spillway. Because trash-racks (~10 cm spacing) should prevent adult and sub-adult lake sturgeon from entering turbine units, and since three of these four downstream passage events were survived, it is highly likely that they also occurred via the regulating gates. Downstream passage events occurred during both high flow conditions in 2009, and low to moderate conditions in 2010. While more downstream passage events occurred in 2010, far more fish were tracked during this time period. As such, data did not indicate that flow conditions had any direct effect on downstream passage event frequency.

Movements into the area immediately upstream of the Slave Falls GS spillway appear to be non-random, and are apparently influenced by bathymetric features of the area. Notably, lake sturgeon entering the area (i.e. moving past the 80 m threshold line) via the deep water channel (9 – 13 m) tended to remain further away from the spillway than those which entered at mid depth (6 – 9 m) areas. No fish crossed the 80 m threshold via shallow water (<6 m), or utilized shallow water to any significant degree. Results indicate that the bathymetry of the area immediately upstream of the Slave Falls GS spillway may influence downstream passage susceptibility since fish approaching the spillway via the deep-water channel often turn around at or before they reach the top of the bedrock saddle (~10 m depth), ~45 m away from spillway infrastructure. Entrances into the immediate vicinity of the spillway at moderate depths (6 – 9 m) only occurred during the middle of the night, perhaps indicative of a diel influence on lake sturgeon movement patterns. This pattern has yet to be explored in the Winnipeg River, but has been observed elsewhere (Holtgren and Auer 2004).

Given that flow through the Slave Falls GS spillway was relatively low during 2010, it is unclear if this played a role in the lack of spillway passage observed during 2010. Unfortunately, the influence of spillway flow on variables such as residence time, proximity and entrance depth class could not really be analyzed, because regulating gates can conceivably pass up to 400 m^3/s (although this occurs rarely), yet the available spill data typically represents spillway gate and regulating gate spill combined. It is important to note that the Slave Falls GS spillway gates draw from the mid to upper portion of the water column, and it may be that the lake sturgeon's tendency to be bottom oriented protects them from entrainment through this spillway. Velocity modelling indicates that even at 95% flow conditions, near-bottom velocities immediately upstream of open spillway gates range from 0.5 to 1.0 m/s. Since adult lake sturgeon (~1200 mm total length) are able to sustain swimming speeds of 1.0 – 1.7 m/s for short durations at water temperatures of ~14°C (Peake et al. 1997), they may be able to come quite close to spillway infrastructure without significant risk of entrainment. Observation of several movements within 25 m of spillway infrastructure when spillway gates were operational, with no downstream passage resulting, support this rationale.

While eleven different lake sturgeon were located within 100 m of the Slave Falls GS powerhouse, with the exception of the three fish which passed downstream via regulating gates, fine-scale positioning indicated that movements within 25 m of the powerhouse were rare, with one sub-adult (#4066) making all of the three documented movements within this threshold (Figure 3.14). On one particular movement, this fish may have actually entered the upstream end of a turbine intake prior to swimming back upstream, which is conceivable because trash-racks at the Slave Falls GS are located ~10 m inside of the powerhouse exterior wall. That being said, additional processing is required before these tracks can be finalized. It is extremely interesting to note that at the Slave Falls GS, turbine unit intakes sit on top of a vertical concrete sill that extends ~3.3m off the river bottom, and as such draw water from the middle of the water column. Conversely, regulating gate intakes lack a concrete sill, and draw from the lower 4 m of the water column. Furthermore, these gates open upward, meaning that even when they are partially open, they draw water explicitly from the river bottom. Given that sturgeon tend to be bottom oriented, this configuration very likely influenced both the high rate and frequent survival of downstream passage events observed in this study.

As noted in Chapter 2, one of 23 adults (4.3%) and one of 22 adults (4.5%) in the Slave Falls Reservoir tracked with Vemco tags passed downstream over the Slave Falls GS in 2009 and 2010, respectively. Excluding one adult which was tracked with both a Vemco and an HTI tag in 2010, two of 55 (3.6%) HTI tagged adults passed downstream in 2010, while zero of 37 (0%) passed downstream in 2011. Taking a mean of these four proportions, an estimated 3.1% (range: 0 – 4.5) of the Slave Falls Reservoir adult population might be expected to pass downstream during a given year. Even if downstream passage survival rates for adults are a pessimistic 50% (two out of four events definitively survived in this study), given an estimated upstream population of 3273 adults (North/South Consultants unpublished data), this represents an annual influx of ~50 adults into the downstream population. Based on a similar mathematical rationale and the data collected in this thesis, it was estimated that 17.9% (range: 13.3 – 20%) of the sub-adults in Zone A might be expected to pass downstream during any given year. Considering that six of seven (85.7%) sub-adult downstream passage events observed in this study were definitively survived, this too could equate to a considerable influx into the downstream population. This is of course dependent on the total number of sub-adults located in Zone A, which probably varies considerably over time and was not explicitly quantified. It is also notable that the rate of sub-adult entrainment at Slave Falls seems to exceed the rate of downstream movements of sub-adults through natural river narrows. In 2009, zero of 19 (0%) tracked sub-adults tagged upstream of Old Slave Falls made downstream movements through either the Eight Foot Falls or Old Slave Falls narrows, while in 2010, one of the same 19 fish (5.2%) made a downstream movement through the Eight Foot Falls narrows, for an average annual rate of 2.6%.

Telemetry data collected on juveniles from Zone A in this chapter as well as Chapter 2 was relatively sparse in terms of numbers of fish tagged. In addition, the monitoring duration of tagged juveniles was less than for other size classes, a function of transmitter battery life. None of the 16 juveniles from Zone A implanted with Vemco or HTI tags passed downstream, and while three HTI tagged juveniles were located in relatively close proximity to the Slave Falls GS powerhouse and/or spillway, no data were collected that indicates downstream passage of juveniles is a concern.

Survivable downstream passage over hydroelectric generating stations results in a quantity loss to upstream populations, but also a quantity gain to downstream populations (Parsley et al. 2007). In terms of the overall Winnipeg River metapopulation, this pattern might seem rather trivial. However, Parsley et al. (2007) noted, in the context of downstream passage of white sturgeon over the Dalles Dam on the Columbia River, Oregon, if density is a factor limiting growth in downstream populations, this quantity gain has the potential to heighten density related problems. In the Winnipeg River, juvenile and sub-adult lake sturgeon located in the 15 rkm downstream of the Slave Falls GS have recently been found to be densely aggregated and growing very slowly relative to other lake sturgeon populations (Barth 2011). As such, it was notable that the vast majority of downstream passers were consistently located in the stretch of river between the Slave Falls GS and Scot Rapids during survival assessments. The observation that sub-adults did not disperse to areas further downstream was not unexpected, because movements of juvenile and sub-adult lake sturgeon in the Winnipeg River have been found to be primarily restricted to areas of interconnected deep-water habitat, with movements through shallow river narrows being rare (Chapter 2, Barth 2011). Because juveniles and sub-adults in the stretch of Winnipeg River downstream of Slave Falls occupy similar habitats and forage on similar food items (Barth 2011), it can be reasoned that a considerable influx of sub-adults into the downstream population could potentially influence population growth parameters of not only resident sub-adults, but also resident juveniles. Since sturgeon population structure trajectories are thought to be defined during early life stages (Gross et al. 2002), the importance of this relationship certainly warrants further investigation.

Considering the number of survived downstream passage events observed in this study, there is certainly merit in examining the phenomenon in the context of the downstream population. While Chapters 2 and 3 have utilized acoustic telemetry to investigate downstream passage, Chapter 4 takes a different approach, investigating downstream gene flow and the demographic contribution of the upstream population to the downstream population via genetic methods.

4.0 GENETIC CONTRIBUTIONS OF THE SLAVE FALLS RESERVOIR LAKE STURGEON POPULATION TO A POPULATION DOWNSTREAM OF SLAVE FALLS

4.1 Introduction

Hydroelectric development has fragmented rivers (Nilsson et al. 2005; Rosenberg et al. 2000), separating formerly panmictic sturgeon populations into distinct segments defined by dams, with little or no known gene flow occurring between them (Jager et al. 2001; Thuemler 1997; Wozney et al. 2011). In the heavily developed Ottawa River, it is believed that downstream gene flow over hydroelectric generating stations might now occur, at best, via larval drift (Haxton and Findlay 2008; Wozney et al. 2011). Little is known about downstream gene flow in the Winnipeg River, but elsewhere, larval lake sturgeon have been documented to drift over 45 km following emergence (Auer and Baker 2002), distances which exceed dam separation on the Manitoba portion of the Winnipeg River. Drifting lake sturgeon larvae have been captured <1 km upstream of the Slave Falls GS during a high flow year (North/South Consultants unpublished data), and it is therefore likely that larvae are periodically entrained at Slave Falls. As early life stages of other fish species frequently survive downstream passage through hydroelectric stations (Coutant and Whitney 2000; Federal Energy Regulatory Commission 1995), it is assumed that survival of larval lake sturgeon would also be high. In addition, downstream gene flow could occur via downstream passage of older life stages through dams. Downstream passage of river resident adults is thought to occur infrequently on many other river systems (Haxton and Findlay 2008; Thuemler 1985; Thuemler 1997), however, it appears that survivable downstream passage of sub-adults and adults is common at the Slave Falls GS (as shown in Chapters 2 and 3).

Considering the various life stages at which survivable downstream passage could occur, it was hypothesized that contribution by the Slave Falls Reservoir population to the population downstream of Slave Falls would be significant from both a genetic and a demographic perspective. In this study, genetic methods based on microsatellite data were used to address this hypothesis. Traditional population metrics such as F_{ST}, genotypic differentiation, heterozygosity, and allelic richness, which have been used for lake sturgeon populations to assess connectivity in natural and hydroelectrically developed rivers (Welsh and McLeod 2010; Wozney et al. 2011), were employed to quantify population structure upstream and downstream of the Slave Falls GS. Sibship inference based on maximum likelihood routines has been used to assess family structure and examine dispersal in salmonids (Kanno et al. 2011; Sanz et al. 2011), but has yet to be utilized in lake sturgeon populations which tend to exhibit relatively low levels of microsatellite polymorphism (DeHaan et al. 2006; Welsh et al. 2008; Welsh and McLeod 2010; Wozney et al. 2011). In the current study, sibship inference was utilized in an attempt to identify downstream fish with siblings located upstream of Slave Falls, which would indicate that some of the downstream individuals were there due to downstream passage through the Slave Falls GS. Accuracy of maximum likelihood based sibship inference was assessed using hatchery reared control samples of known relatedness (full-sibling, half-sibling, unrelated at the 1st generation). Pairwise relatedness methods have also been utilized in a variety of applications, including quantifying inbreeding and dispersal (Sweigart et al. 1999), assessing kin association (Piyapong et al. 2011), and investigating the presence of structure in a genetically homogenous population (Bergek et al. 2010). Many pairwise estimators exist (Lynch 1988; Lynch and Ritland 1999; Milligan 2003; Queller and Goodnight 1989; Ritland 1996; Wang 2007; Wang 2002), and in this study, these were used in combination with basic biological data as an alternative means of identifying fish which had passed downstream over Slave Falls. In order to maximize the potential for relatedness (i.e. siblings), efforts focused on juvenile/sub-adult lake sturgeon of a narrow age range.

4.2 Materials and methods

4.2.1 Study area

The study area for research presented in this chapter is the lower 3 rkm of the Slave Falls Reservoir (Zone A and the lower portion of Zone B, as described in Sections 2.2.1 and 3.2.1), and the 6 rkm stretch of Winnipeg River located between the Slave Falls GS and Scot Rapids (Zone DS) (Figure 4.1). The downstream section is considerably more riverine than the Slave Falls Reservoir, variable in depth (0-30 m) and is dominated by cobble/gravel, bedrock and sand substrates (Barth et al. 2009). Lake sturgeon are known to spawn at the base of the Slave Falls GS and spillway (North/South Consultants unpublished data), and the downstream section of the study area is known to support a dense, slow-growing population of juvenile lake sturgeon (Barth 2011).

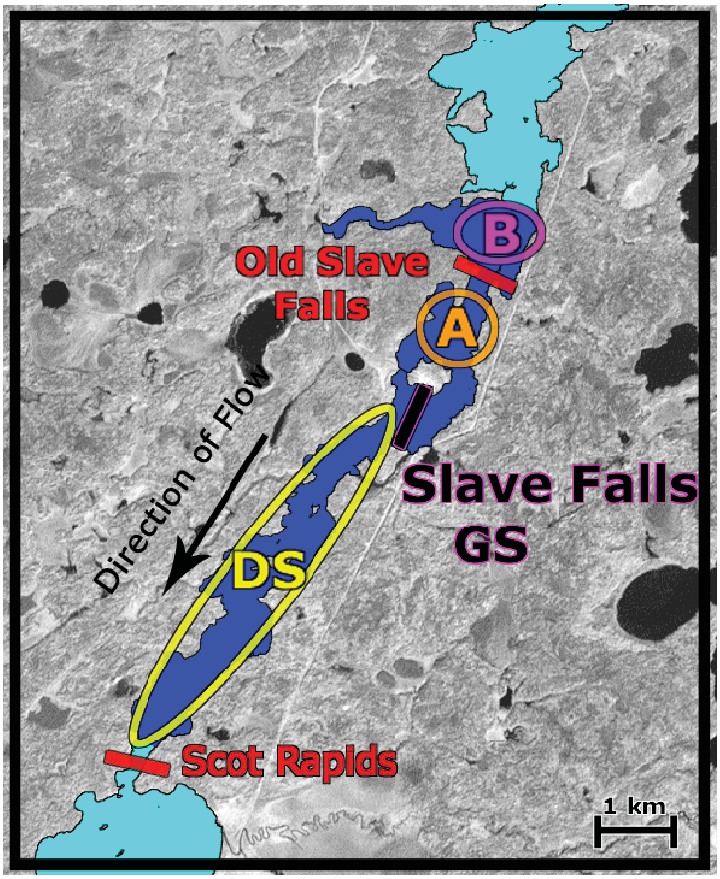

Figure 4.1. Chapter 4 study area, divided into sampling zones A and B, located upstream of the Slave Falls GS, and Zone DS, located downstream of the Slave Falls GS.

4.2.2 Tissue sample collection

Upstream of the Slave Falls GS, lake sturgeon between 550 and 750 mm (fork length) were captured from Zone A and lower portion of portion of Zone B, as described in Chapter 2 (Figure 4.1). Gillnets (91.6 m long x 1.8 m deep, 127 mm stretched nylon mesh) were set overnight between 19 May and 21 July, 2010, in deep water habitats (15 – 50 m) known to be utilized by this size-class in the Slave Falls Reservoir (C. McDougall unpublished data). Lake sturgeon of appropriate size were measured for fork length, total length, and body mass. Approximately 50% of the upstream fish sampled were marked with an individually numbered Floy tag, as described in Section 2.2.4, prior to being released. Tag numbers of previously marked fish were also recorded. A 2 cm^2 fin clip was removed from the lower lobe of the caudal fin and placed into an individually labelled vial filled with biological grade (95%) ethyl alcohol. The first ray of the right pectoral fin, immediately distal to the fin articulation, was then removed for aging and placed in an individually labelled envelope, prior to the fish being released. Upon returning from the field, samples for genetic analysis were stored in a -20°C freezer and fin rays were dried at room temperature prior to preparation for the determination of fish age.

Downstream of the Slave Falls GS, lake sturgeon between 450 and 750 mm (fork length) were targeted, because previous data from this stretch (Barth 2011) suggested that the growth rate of lake sturgeon was lower than upstream of the station (McDougall et al. 2008b). Lake sturgeon were captured in overnight gillnet sets between 4 and 20 August, 2010, in habitats containing water depths >13.9 m, as suggested by Barth et al. (2009). Gillnetting was conducted between the Slave Falls GS and Scot Rapids (~6 km downstream) (Figure 4.1). Sampling methodologies were the same as for lake sturgeon sampled upstream, except that a variety of mesh sizes (51 – 152 mm) and net lengths were used, Floy tags were not applied, and a fin clip was removed from the right pelvic fin (as opposed to the caudal fin) so that upstream and downstream sampled fish could be distinguished. Recaptured fish identified as having originated from upstream of Slave Falls based on Floy tags or fin clips were noted and included in downstream sampling.

Genetic samples were also collected from known full-sibling, half-sibling and unrelated hatchery raised lake sturgeon, generated from wild Slave Falls Reservoir parents. In 2009, larvae were generated by fertilizing the eggs from each of two females with the milt of a different male, in order to generate two full-sibling families (unrelated at the first generation). These fish were then raised in a University of Manitoba hatchery (C. Klassen unpublished data), and in fall 2010, finclips were collected from 15 fish from each of the two families, and preserved in ethyl alcohol. In spring 2010, additional lake sturgeon larvae were generated by fertilizing the eggs of two wild females with the milt of five wild males. Two larvae from each of the 10 parental combinations (i.e. full-sibling and half-sibling relationships were generated) were preserved in 95% ethyl alcohol prior to genetic analysis.

4.2.3 Laboratory processing

Dried lake sturgeon fin rays were mounted in epoxy and sectioned using a Struers Minitom low-speed saw (Struers Inc, Cleveland, Ohio, USA). Two 0.6 mm sections were cut, placed on an individually labelled glass slide and coated in cytoseal (Cytoseal 60, Thermo Scientific, Waltham, Massachusettes). Under 30 – 40x magnification, fin ray sections were aged (annuli counted) without knowledge of the length, weight, or tag identification of individual fish. Each fish was aged twice by the author (blind) and once by a technician with 7 years experience in ageing (Mark Blanchard, North/South Consultants). When differences in age estimates arose, assigned ages were determined by modal consensus of the three readings. Only downstream fish < 12 years old were assigned ages as older fish tended to lack the annuli separation needed to confidently assign ages. Downstream fish which had ageing structures indicative of faster rates of growth than the majority of the downstream population and more characteristic of the upstream population were noted (Figure 4.2).

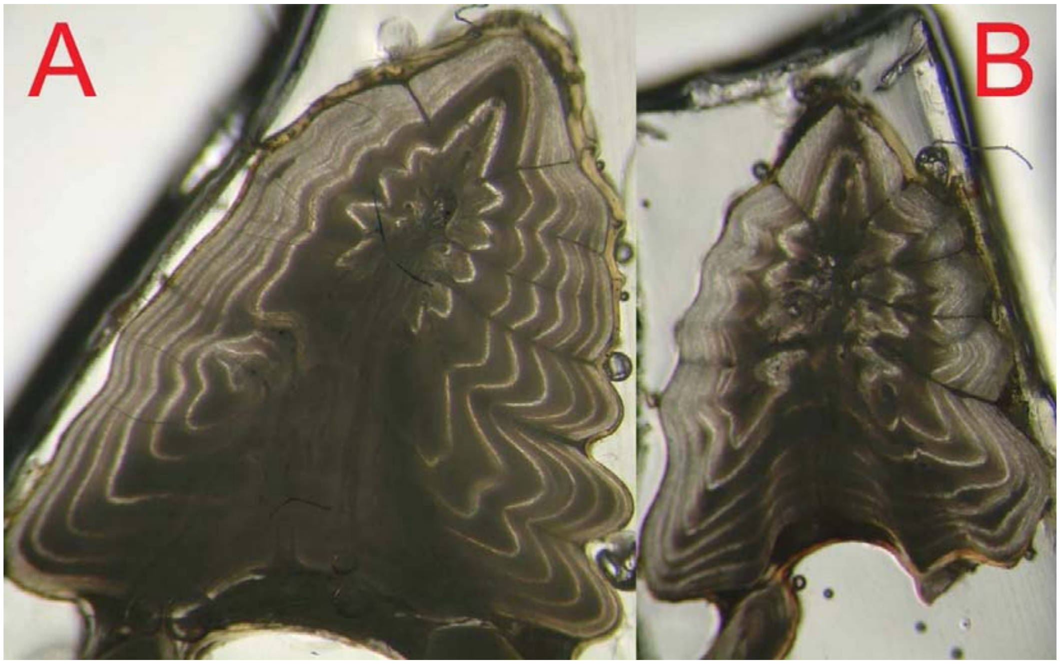

Figure 4.2. Sample lake sturgeon pectoral fin-ray sections from a typical upstream age 8 (A) and a typical downstream age 7 (B), indicative of markedly different rates of growth. Photos taken at 40x magnification.

Laboratory processing of genetic samples was conducted at the State University of New York (Dr. Amy Welsh). DNA was extracted from the collected samples using the Promega Wizard SV 96 Genomic DNA Purification System (Promega Corporation, Madison, Wisconsin) according to the manufacturer's protocol. Fin-clip samples were eluted in 500 µl and larval samples were eluted in 50 µl. Extracts were then quantified using a microplate reader. Twelve microsatellite loci were amplified in the first batch of 50 samples (*AfuG 9*, *AfuG 56*, *AfuG 63*, *AfuG 74*, *AfuG 112*, *AfuG 160*, *AfuG 195*, *AfuG 204*, *Afu 68*, *Afu 68b*, *Spl 120*, *Aox 27*; described in Welsh and May 2006). *Aox 27* and *AfuG 204* were monomorphic in all 50 samples, as observed previously in Winnipeg River and other Hudson Bay drainage basin localities (Kjartanson 2009; Welsh et al. 2008; Welsh and McLeod 2010), so these loci were not analyzed in the remaining samples. Polymerase chain reaction (PCR) conditions are described in Welsh and McLeod (2010). PCR products were pooled into four groups and visualized on a Beckman Coulter CEQ 8000 Genetic Analysis System (Beckman Coulter Incorporated, Brea, California). Alleles were scored according to standardized designations (Welsh and May 2006).

4.2.4 Data analysis

Biological data were compared between the three sampling zones: Zone B, Zone A, and Zone DS. Because body condition of lake sturgeon tends to be positively correlated with length (Craig et al. 2005), comparisons of Fulton`s Condition Factor were made across 50 mm fork length intervals (e.g. 551 – 600 mm, 651 – 700 mm). Trends in length-at-age were assessed by age class. Statistical analysis of biological data was conducted using ANOVA and Tukey’s Honestly Significant Differences (HSD). Gillnet catch-per-unit-effort (CPUE) was compared between upstream Zones A and B using a Wilcoxon signed rank test, due to non-normality. Zone DS was omitted from this comparison due to mesh-size inconsistencies.

To determine if lake sturgeon from the various sampling zones were genetically distinct, F_{ST} was calculated in Arlequin (Excoffier and Lischer 2010) and assessed for significance based on 10,000 permutations. In addition, Fisher’s exact tests for genotypic differentiation were calculated in GENEPOP version 4.1 (Rousset 2008), using settings of 1,000 dememorization steps, with 200 batches and 1,000 permutations per batch. F_{ST} and genotypic differentiation tests were also run to check for the presence of year-class based population structure. Allele frequencies were calculated in COANCESTRY (Wang 2011). Standardized allelic richness (A_S) and total allele counts were calculated using

HP-Rare (Kalinowski 2005). Loci were tested for linkage disequilibrium in GENEPOP version 4.1 and for Hardy-Weinberg equilibrium in Arelquin, and assessed for significance using a Bonferroni correction (Rice 1989). Inbreeding coefficient (F_{IS}) was calculated using GENEPOP version 4.1.

Maximum likelihood estimation routines were employed to infer sibship using the software COLONY (Jones and Wang 2010). Final runs were conducted assuming polygamy of both sexes (Bruch and Binkowski 2002), the out-breeding model, genotyping error rates (including mutations) of 0.0001, and using known allelic frequencies that were generated based on all samples analyzed (i.e. assuming panmixia). The ability to recover sibship was also assessed using hatchery reared control samples, but with allelic frequencies based only on the upstream population. Control samples from known full-sibling families (2 families each with 15 individuals), half-siblings (7 half-sibling groups), and unrelated individuals were used (total number of control fish = 50).

Based on known control samples, pairwise relatedness distributions (full-sibling, half-sibling, and unrelated) were generated using seven common relatedness estimators implemented in COANCESTRY (Wang 2011). The following estimators were used: 1) TrioML, a triadic maximum likelihood estimator (Wang 2007); 2) Wang's estimator, a moment estimator (Wang 2002); 3) Lynch's estimator, a moment estimator (Lynch 1988); 4) Lynch and Ritland's estimator, a moment estimator (Lynch and Ritland 1999); 5) Ritland's estimator, a moment estimator (Ritland 1996); 6) Queller and Goodnight's estimator, a moment estimator (Queller and Goodnight 1989); and 7) Milligan's estimator, a dyadic maximum likelihood estimator (Milligan 2003). Final COANCESTRY runs were conducted using 500 reference individuals, 500 bootstrapping samples, and the allelic frequency of the upstream population as determined from field samples. In total, 220 full-sibling, 100 half-sibling and 905 unrelated pairwise combinations were generated for each of the seven estimators. The relative ability of the estimators to resolve differences in *a priori* relatedness was assessed using the variance (r^2) and F Ratio scores, as well as the maximum probability value associated with Tukey's HSD following an ANOVA. The best estimator was then used to generate relatedness values for pairwise combinations of field samples in COANCESTRY. Parameters for the final field run were the same as used to generate control distributions, except that allelic frequency was calculated from all field samples analyzed (i.e. assuming panmixia). Except for where previously noted, statistical analyses were conducted using JMP 8.0 (SAS Software, Cary, North Carolina) to a significance level of 0.05.

4.3 Results

4.3.1 Biological data

A total of 535 lake sturgeon were sampled: 145 from Zone B, 80 from Zone A and 310 from Zone DS. Catch-per-unit-effort was much higher in Zone B (mean=33.4 fish/100 m/24 h, range: 21.0 – 51.4) than in Zone A (mean=3.0 fish/100 m/24 h, range: 0 – 13.4) (Wilcoxon signed rank test, $Z = 3.55$, $p = 0.0004$). Condition factor varied significantly by zone for size classes of 551 – 600 mm (ANOVA, $F_{2,112} = 21.4$, $p < 0.0001$), 601 – 650 mm (ANOVA, $F_{2,157} = 28.3$, $p < 0.0001$) and 651 – 700 mm (ANOVA, $F_{2,66} = 14.05$, $p < 0.0001$). For the 551 – 600 mm and 601 – 650 mm size classes, Tukey`s HSD indicated that condition factor in Zone A was greater than Zone B, which in turn was greater than Zone DS (Table 4.1). For the 651 – 700 mm size class, Tukey's HSD indicated no significant differences in condition factor between Zone A and Zone B, but that both upstream zones were significantly higher than Zone DS. No significant differences were found in the 701 – 750 mm size class (ANOVA, $F_{2,15} = 0.19$, $p = 0.83$), although this may have been a function of small sample sizes.

Table 4.1. Comparison of Fulton`s Condition Factor for lake sturgeon captured in the three sampling zones, by 50 mm fork length interval. Data is summarized by number of fish (n), mean condition factor (k), standard deviation of condition factor (StDev), and ranked order of significant differences as determined by Tukey`s HSD (Rank). Zones which share the same rank (i.e. 1, 2 or 3) are not significantly different.

Zone	551 - 600 mm				601 - 650 mm				651 - 700 mm				701 - 750 mm			
	n	k	StDev	Rank	n	k	StDev	Rank	n	k	StDev	Rank	n	k	StDev	Rank
B	65	0.72	0.06	2	60	0.68	0.05	2	16	0.67	0.04	1	3	0.64	0.05	-
A	27	0.75	0.06	1	31	0.74	0.07	1	15	0.70	0.07	1	7	0.66	0.05	-
DS	23	0.65	0.05	3	69	0.65	0.06	3	38	0.61	0.06	3	8	0.65	0.06	-

As fish from Zones A and B were between 7 and 10 years old, only fish from Zone DS that were 6 – 11 years old (n=183) were included in subsequent analysis, so as to maximize the potential for relatedness (i.e. siblings). Length-at-age analysis revealed that fish from Zones A and B were markedly larger for a given age compared to Zone DS (Table 4.2). Significant differences in growth rate were found for age 7 (ANOVA, $F_{2,46} = 33.7$, $p < 0.0001$), age 8 (ANOVA, $F_{2,232} = 282.0$, $p < 0.0001$), age 9 (ANOVA, $F_{2,92} = 182.4$, $p < 0.0001$) and age 10 lake sturgeon (ANOVA, $F_{1,11} = 31.8$, $p = 0.0002$). Also, Zone A fish tended to be larger for a given age than Zone B fish, although differences were only significant for age 8 fish. No lake sturgeon ≤ 5 years old were identified in the downstream catch.

Table 4.2. Comparison of length-at-age distribution for lake sturgeon captured in the three sampling zones, by age class. Data is summarized by number of fish (n), mean fork length (FL), standard deviation of fork length (StDev), and ranked order of significant differences as determined by Tukey`s HSD (Rank). Zones which share the same rank (i.e. 1, 2 or 3) are not significantly different.

Zone	Age 7				Age 8				Age 9				Age 10			
	n	FL	StDev	Rank	n	FL	StDev	Rank	n	FL	StDev	Rank	n	FL	StDev	Rank
B	16	583	26.1	1	95	603	33.2	2	30	637	36.2	1	-	-	-	-
A	2	610	8.5	1	64	621	42.4	1	10	655	45.0	1	2	697	5.7	1
DS	31	490	45.0	3	76	483	42.0	3	55	486	40.0	3	11	507	45.9	2

Length-at-age data also revealed the presence of fast-growing outliers (n=25) in the downstream population (Figure 4.3). During laboratory ageing, many of these fish were noted as having widely spaced annuli, highly similar to those observed in upstream fish and markedly different from the majority of the downstream fish. Three of these “fast growers” were identified as having descended over the Slave Falls GS between 2009 and 2010 based on mark-recapture (i.e. Floy tags or caudal fin-clips), and it was therefore suspected that the other fast-growing outliers had also descended from the upstream population. Including fish ≥ 12 years of age, 23 of the 151 lake sturgeon between 525 and 750 mm (fork length) captured in Zone DS, or 15.2% (95% confidence interval of 10.4 – 21.8%) were fast-growing outliers.

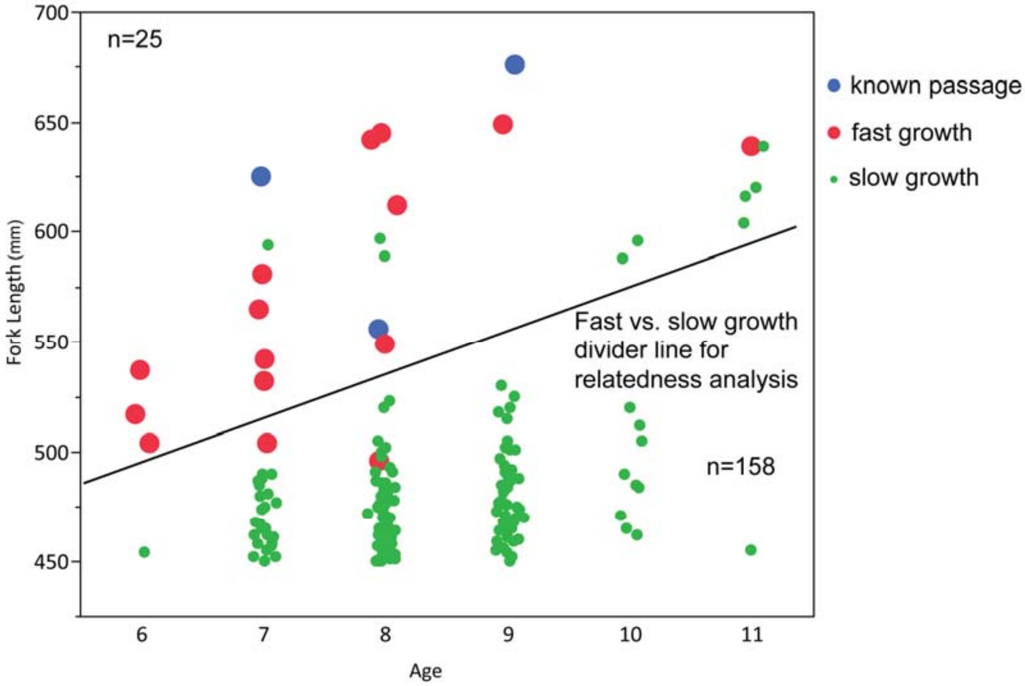

Figure 4.3. Length-at-age data for lake sturgeon ages 6 – 11, captured downstream of the Slave Falls GS. The line drawn represents the divider for defining fast-growing versus slow-growing fish for relatedness analyses. Ageing structures qualitatively identified in the laboratory as having growth chronologies similar to those for upstream (fast-growing) fish are indicated in red, while those identified as being slower growing are indicated in green. Three fish known to have passed downstream over the Slave Falls GS based on mark-recapture are indicated in blue.

4.3.2 Genetic diversity

Based on results presented thus far, microsatellite analysis was conducted on 131 fish from the upstream population and 124 from the downstream population. Of the upstream fish, all lake sturgeon of appropriate size captured in Zone A (n=80) were included, as well as a random sub-sample (n=51) of those captured in Zone B. Of the 183 fish from Zone DS that met the criterion of being 6 – 11 years old, all fish observed to be growing considerably faster than the majority of the population (n=25) were included, as were a random sub-sample (n=99) of the slow-growing downstream fish. Samples missing data at three or more microsatellite loci were excluded from subsequent analysis.

The total number of alleles per polymorphic locus ranged from 2 (*Afu195*) to 9 (*Afu68* and *Afu69*), for an average of 5.7 alleles per locus. F_{ST} did not vary significantly between Zone A and Zone B ($F_{ST} = 0.005$, $p = 0.064 \pm 0.009$), and similarly, no significant differences in genotypic differentiation were observed (Fisher's exact test, $p = 0.11$). As such, the two upstream zones were grouped together for subsequent analysis. No evidence for year-class based population structure was observed in either the upstream or downstream populations. Only *AfuG9* in the upstream population deviated from Hardy-Weinberg equilibrium ($p = 0.0033$). The only significant linkage disequilibrium occurred between *AfuG112* and *AfuG63* ($p = 0.00003$) in the upstream population.

Despite similar allelic frequencies observed upstream and downstream of the Slave Falls GS (Figure 4.4), significant differences in F_{ST} were found between upstream (i.e. Zone A + Zone B) and downstream locations ($F_{ST} = 0.011$, $p = 0.0000 \pm 0.0000$) when all downstream samples were included in the analysis. Differences in genotypic differentiation were also significant between upstream and downstream locations (Fisher’s exact test, $p < 0.0001$). Allelic richness and observed heterozygosity were higher downstream ($A_S = 4.31$, $H_O = 0.609$) than upstream ($A_S = 4.15$, $H_O = 0.556$), while the inbreeding coefficient was considerably higher upstream ($F_{IS} = 0.051$) than downstream ($F_{IS} = 0.002$) (Table 4.3).

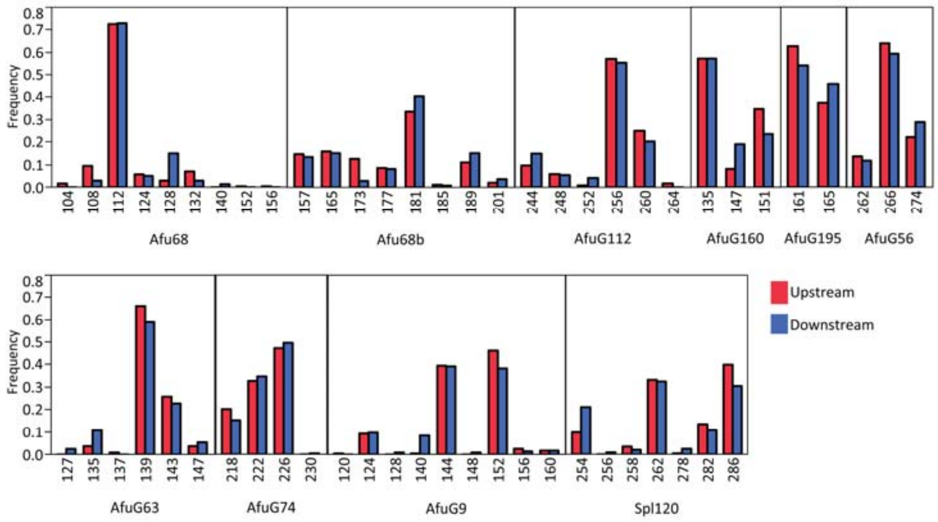

Figure 4.4. Comparison of allelic frequencies for lake sturgeon sampled upstream and downstream of the Slave Falls GS. The upstream population is indicated in red and the downstream population in blue.

Table 4.3. Summary of genetic data, with number of samples (n), mean number of alleles observed per locus (A_n), allelic richness standardized to 40 genes (A_s), expected heterozygosity (H_e), observed heterozygosity (H_o), and inbreeding coefficient (F_{IS}). Note that sample size deviates from total number of samples processed, since samples that did not amplify at 3 or more loci were excluded.

Location	n	A_n	A_s	H_e	H_o	F_{IS}
Upstream	124	5.1	4.15	0.586	0.556	0.051
Downstream	123	5.1	4.31	0.610	0.609	0.002
Fast-growing	25	4.2	4.11	0.576	0.578	-0.005
Slow-growing	98	5.1	4.33	0.619	0.617	0.003

When downstream samples were separated into fast-growing versus slow-growing fish, there was no significant genetic distinction between upstream and fast-growing downstream fish, as indicated by F_{ST} ($F_{ST} = 0.001$, $p = 0.36 \pm 0.01$) and genotypic differentiation (Fisher's exact test, $p = 0.39$). While probabilities were lower, there was no significant genetic distinction between fast-growing downstream and slow-growing downstream fish, again based on F_{ST} ($F_{ST} = 0.003$, $p = 0.15 \pm 0.01$) and genotypic differentiation (Fisher's exact test, $p = 0.18$). Conversely, the upstream and slow-growing downstream fish were genetically distinct, based on F_{ST} ($F_{ST} = 0.014$, $p = 0.0000 \pm 0.0000$) and genotypic differentiation (Fisher's exact test, $p < 0.0001$).

4.3.3 Maximum likelihood sibship assignment

Known control relationships (full-sibling, half-sibling, or unrelated) were often unable to be accurately recovered using the maximum likelihood routines employed in COLONY (Jones and Wang 2010) (Figure 4.5). True relationships were frequently missed and false relationships were frequently assumed, despite multiple runs varying all parameters. It was therefore concluded that results generated from field samples would be of questionable value, and are not presented.

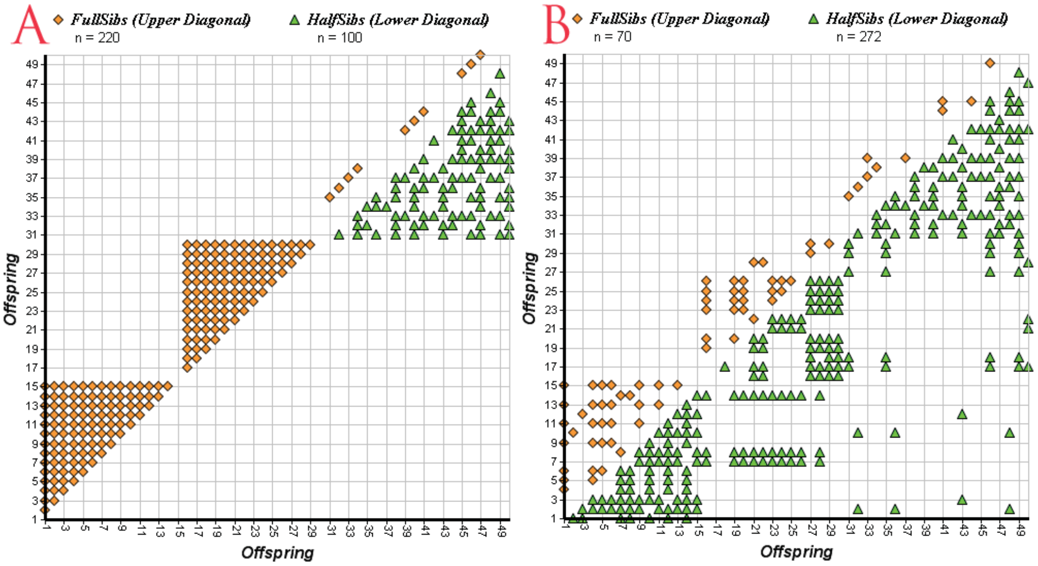

Figure 4.5. Differences in maximum likelihood sibship assignment plots for control samples, depicting results generated in COLONY with (A) and without (B) *a priori* knowledge of relatedness. Orange markers (above the diagonal) indicate full-sibling relationships, while green markers (below the diagonal) indicated half-sibling relationships.

4.3.4 Pairwise relatedness

Based on variance and F ratio estimates, pairwise relatedness distributions (full-sibling, half-sibling, or unrelated) of control fish were best described, in decreasing order, by the Lynch and Ritland estimator (Lynch and Ritland 1999), the TrioML estimator (Wang 2007), and the Milligan estimator (Milligan 2003) (Table 4.4). However, the Lynch and Ritland estimator had a comparatively larger maximum Tukey's HSD probability associated with it, indicative of this estimator's relative inability to resolve differences between full-siblings and half-siblings in the control data. As such, the TrioML estimator was used for subsequent analysis.

Table 4.4. Performance comparison of seven pairwise relatedness estimators, based on the ability of the estimators to resolve distributions of full-sibling, half-sibling, and unrelated fish, analyzed using an ANOVA on known pairwise combinations. High variance (R^2 and R^2_{adj}) and F Ratio values indicate better ability to resolve overall differences in relatedness, while low Tukey's HSD_{max} indicates a better ability to resolve differences between all variable pairs.

Statistic	TrioML	Wang	Lynch	Lynch and Ritland	Ritland	Queller	Milligan
R^2	0.440	0.310	0.310	0.477	0.370	0.336	0.430
R^2_{adj}	0.439	0.301	0.308	0.477	0.369	0.335	0.429
F Ratio	479.8	275.1	274.3	558.1	358.9	309.6	461.1
HSD_{max}	<0.0001	<0.0001	<0.0001	0.0013	0.0103	<0.0001	<0.0001

As expected, the TrioML relatedness distribution indicated that the probability of two fish being siblings increased with relatedness (Figure 4.6). For example, two fish with a pairwise relatedness score of 0.2 would have a 69% chance of being either full-siblings or half-siblings, while a score of 0.7 would equate to a 93% chance. However, because of the overlap in the distributions and the nature of comparing each of the 124 upstream fish to each of the 123 downstream fish included in the analysis, the probability of false positives (Type I errors) made sibling identification via this method impractical for all but the highest values of relatedness ($0.8 < r \leq 1.0$), which will be rare in natural populations. Only three pairs of field sampled fish had relatedness values exceeding 0.8. Two of these pairs were upstream-downstream with similarly assigned ages (7 and 8 years, and 8 and 8 years), while the remaining pair was downstream-downstream (7 and 10 years). As such, little can be inferred from this data.

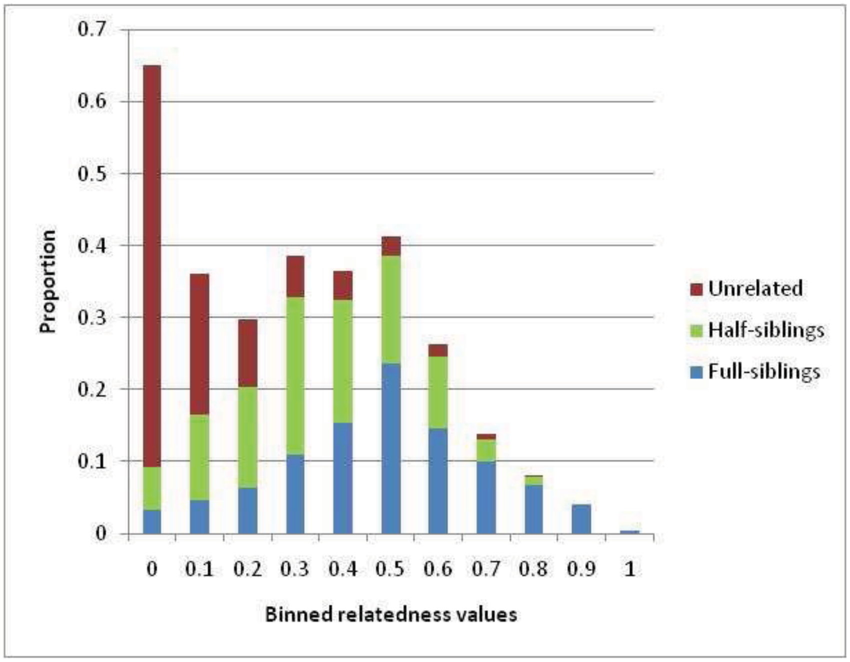

Figure 4.6. Probability distribution of relatedness values for full-sibling, half-sibling, and unrelated fish, based on the TrioML estimator. Relatedness is binned at 0.1 unit intervals.

Using the TrioML estimator, each individual fish's mean relatedness with all fish in the upstream population was calculated. The mean relatedness of upstream fish (n=124), fast-growing downstream fish (previously identified via length-at-age analysis, n=25), and slow-growing downstream fish (n=98) with the upstream population were found to be significantly different (ANOVA, $F_{2,244} = 26.2$, $p < 0.001$). Tukey's HSD indicated that the slow-growing downstream fish tended to be less related to the upstream fish than were either the fast-growing downstream fish or the upstream fish (Figure 4.7). Mean relatedness of upstream fish and fast-growing downstream fish to the upstream population were not significantly different. This pattern was consistent across five of the six other estimators (Table 4.5). Only the Wang estimator found no significant differences in mean relatedness to the upstream population among the three groups.

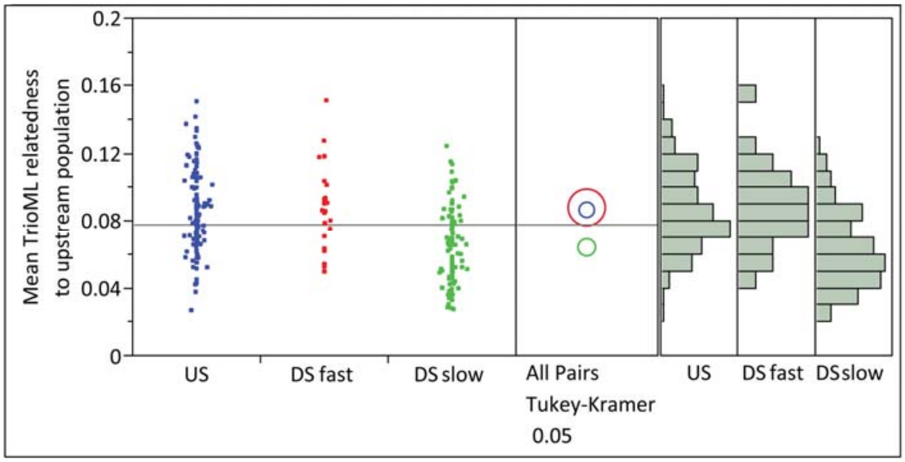

Figure 4.7. Mean TrioML relatedness of upstream (US, n=124), fast-growing downstream (DS fast, n=25) and slow-growing downstream (DS slow, n=98) lake sturgeon with the upstream population. As indicated by Tukey's HSD, the slow-growing downstream fish are significantly less related to the upstream population than are the upstream and downstream fast-growing fish. A histogram showing the distribution of relatedness values by group is also shown.

Table 4.5. Comparison of mean relatedness of upstream (US), fast-growing downstream (DS fast) and slow-growing downstream (DS slow) fish with the upstream population, based on the seven relatedness estimators used. Data is summarized by mean relatedness (r), standard deviation of relatedness (StDev), and ranked order of significant differences as determined by Tukey`s HSD (Rank).

Location	TrioML			Wang			Lynch			Lynch & Ritland		
	Mean	StDev	Rank	Mean	StDev	Rank	Mean	StDev	Rank	Mean	StDev	Rank
US	0.087	0.025	1	-0.007	0.118	1	0.010	0.128	1	0.011	0.025	1
DS fast	0.087	0.025	1	0.019	0.100	1	0.031	0.107	1	0.002	0.026	1
DS slow	0.064	0.023	2	-0.040	0.115	1	-0.044	0.126	2	-0.021	0.025	2

Location	Ritland			Queller			Milligan		
	Mean	StDev	Rank	Mean	StDev	Rank	Mean	StDev	Rank
US	0.010	0.029	1	0.026	0.075	1	0.110	0.027	1
DS fast	-0.003	0.031	1	0.030	0.077	1	0.110	0.027	1
DS slow	-0.023	0.033	2	-0.025	0.076	2	0.084	0.027	2

4.4 Discussion

In this study, analysis of basic biological data revealed small differences in growth rate and condition factor, as well as an order of magnitude difference in CPUE between two adjacent upstream sampling Zones (A and B). However, growth rates of fish in both upstream zones were far greater than the majority of fish located between Slave Falls and Scot Rapids (Zone DS). Based on the assumption that mean pairwise relatedness to the upstream population would be higher in former upstream fish than in fish spawned downstream of the station, analysis supported the notion that the majority of fast-growing outliers originated upstream of the Slave Falls GS. This sort of observation is as yet unreported for lake sturgeon, and highlights the utility of combining genetic analysis with traditional biological metrics such as length-at-age when examining lake sturgeon populations within a given river system.

Lake sturgeon that were entrained through the Slave Falls GS after residing upstream for at least several years were considerably larger for a given age than fish that have resided downstream of the dam for most of their life. Given the proximity of the two locations and the genetic similarity between upstream and downstream populations, it is extremely unlikely that differences in growth rate are related to genetics, and more likely that they are related to factors such as food availability, water velocity influenced energetics, or population density. As such, it is expected that the growth rate of sub-adults which pass downstream over the Slave Falls GS will decline in their new environment. Still, fecundity in lake sturgeon is strongly correlated with body size (Bruch et al. 2006), and it can be reasoned that fast-growing former upstream fish will probably also reach maturity quicker than the slow-growing fish. Therefore, these fast-growing outliers may well have an advantage in regards to making a meaningful genetic contribution to the downstream population (i.e. spawning) relative to the slow-growing residents of similar age.

The lack of fast-growing outliers ≤ 5 years of age in the downstream sampled fish is consistent with the observation that the degree of juvenile entrainment immediately prior to and during the study period was considerably less than the degree of sub-adult and adult entrainment (see Chapters 2 and 3). This may in part be related to behavioural differences making juveniles less susceptible to entrainment than are sub-adults (and adults), but it may also be related to the relatively small stock of juvenile fish located in Zone A during the past few years.

Based on previous literature on early life stage mortality at hydroelectric facilities, it is likely that downstream passage survival of larval lake sturgeon through the Slave Falls GS would be high (Coutant and Whitney 2000; Federal Energy Regulatory Commission 1995). Following downstream passage, it is assumed that lake sturgeon would grow at rates characteristic of the downstream population, so identification of origin based on biological data alone would not be possible. Maximum likelihood sibship inference may be the best way to evaluate the early life stage contribution of the Slave Falls Reservoir to the downstream population. Sibling to sibling relationships are probabilistically difficult to identify (Jones and Wang 2010), and so a considerable number of genetic markers are required to resolve sibship in species with low levels of polymorphism, such as lake sturgeon. In the present study, analysis of control samples of known relatedness demonstrated that as many as 10 polymorphic microsatellite loci were insufficient to accurately resolve sibship in Winnipeg River populations. In order to assess the early life stage contribution, development and incorporation of additional makers, microsatellite or single nucleotide, may be required to accurately resolve these relationships. Incorporation of potential parents into the analysis may also hold some merit, since parent-offspring relationships are probabilistically easier to identify via maximum likelihood routines (Jones and Wang 2010).

The finding that 15.2% of the downstream fish between 525 and 750 mm (fork length) were fast-growing outliers is somewhat surprising, given the large number of juvenile/sub-adult lake sturgeon captured (n=2473) in this area between 2006 and 2008 (Barth 2011). However, only 326 of these fish were between 530 and 879 mm, indicative of a severe population bottleneck in the Slave Falls to Scot Rapids population (Barth 2011). Therefore, it is suspected that the slow-growing, poor condition downstream fish may be succumbing to mortality prior to reaching this size class. Indeed, in the current study, slow-growing age 10 – 11 (n=10) fish represented only a small proportion of the catch compared to the number of slow-growing age 7 – 9 fish (n=148), which is consistent with this hypothesis. Whether or not the influx of fast-growing outliers from the upstream population has an influence on growth and mortality rates of fish resident downstream of the station for most of their lives is unclear. However, there is strong evidence to suggest that the influx of sub-adults from upstream of the Slave Falls GS into the downstream population is influential demographically. Furthermore, considering that the early life stage (larval) contribution could not be accurately measured in this study, the total upstream contribution to the downstream population may well be an underestimate.

It is notable that traditional population genetic analyses (i.e. F_{ST} and genotypic differentiation) were unable to verify the hypothesis that fast-growing downstream fish were former upstream individuals. Using these methods, fast-growing downstream lake sturgeon were not significantly distinct from either upstream or slow-growing downstream fish, although the probabilities associated with the tests suggested these fish were more similar to the upstream fish than to the slow-growing downstream fish. Bergek (2010) noted that due to the influence of family relationships, population structure can be present in a genetically homogenous population. As such, pairwise relatedness measures can be highly revealing, which was certainly the case in the current study.

As previously mentioned, it is known that hydroelectric generating stations fragment rivers (Jager et al. 2001; Nilsson et al. 2005; Rosenberg et al. 2000). In the case of sturgeon species, this has resulted in formerly panmictic populations being segregated into distinct sections of unconnected habitat, with even downstream gene flow being uncertain (Jager et al. 2001; Thuemler 1997; Wozney et al. 2011). However, the concern that Winnipeg River generating stations have restricted upstream movements (and thus upstream gene flow) of lake sturgeon may be unfounded, as many stations were built at river narrows near the sites of historic falls/rapids, which may have acted as natural barriers to upstream movement. Based on contemporary bathymetry of the Slave Falls area and historical elevations of the Winnipeg River (Appendix 1), it seems likely that a natural barrier to upstream movement existed in the Slave Falls area prior to dam construction. If so, one would expect that prior to hydroelectric development, genetic diversity of the population located downstream of the Slave Falls GS would theoretically have been higher than that of the upstream population, as a result of asymmetric gene flow. Other studies have documented relatively higher genetic diversity in populations of white spotted-char, *Salvelinus leucomaenis* (Yamamoto et al. 2004) and river sculpin, *Cottus gobio* (Hanfling and Weetman 2006), located downstream of barriers relative to those isolated upstream. If the lake sturgeon populations upstream and downstream of Slave Falls were historically panmictic, no population differentiation would be expected prior to dam construction. Furthermore, it has been suggested that genetic differentiation due to fragmentation in long-lived species such as lake sturgeon will not be apparent for many years, as genetic differences can only accumulate over many generations (O'Grady et al. 2008; Reid et al. 2008; Wozney et al. 2011). This delayed genetic response was attributed to the lack of genetic differentiation between Ottawa River lake sturgeon populations fragmented by dams constructed between 1880 and 1964 (Wozney et al. 2011).

Construction of the Slave Falls GS was underway over 83 years ago (1928), but equivalent to 3.3 generations of lake sturgeon, assuming a generation time of 25 years. Kjartanson (2009), based on eight polymorphic microsatellite markers, found no significant genetic differentiation and nearly identical allelic richness between adult lake sturgeon from the Slave Falls Reservoir (n=21) and those from downstream of the Slave Falls GS (n=61), findings which are consistent with the pre-hydroelectric development panmixia hypothesis. Conversely, data from the current study show that the Slave Falls Reservoir and the Slave Falls to Scot Rapids population are genetically differentiated, albeit moderately ($F_{ST} = 0.011$), and that allelic richness and heterozygosity are higher in the downstream ($A_S = 4.31$, $H_O = 0.609$) versus the upstream ($A_S = 4.15$, $H_O = 0.556$) population. Considering the temporal scale of hydroelectric development relative to lake sturgeon generation time, these observations are consistent with the notion that a barrier to upstream gene flow existed prior to generating station construction. It seems that additional markers and larger sample sizes employed in the current study better facilitated detection of the genetic subtleties between locations. Heterozygosity observed in the current study was found to be comparable to 27 lake sturgeon populations from across North America (range: 0.46 – 0.63, Welsh et al. 2008) and to populations occurring in nine Ottawa River impoundments (range: 0.53 – 0.56, Wozney et al. 2010), but considerably higher than Namakan River populations (range: 0.31 – 0.35, Welsh and McLeod 2010), which is located further upstream in the Winnipeg River watershed. Comparisons of allelic richness with other studies are not entirely appropriate as the methods of standardisation in previous published reports are not disclosed and therefore direct comparisons can only be inferred.

The degree of contemporary downstream gene flow relative to historical levels also warrants discussion. In the Winnipeg River, it has recently come to light that downstream movements of juveniles and sub-adults through natural river narrows are rare (Chapter 2, Barth 2011). Prior to hydroelectric development, it is speculated that the historical downstream movement frequency of juveniles and sub-adults through Slave Falls would have been comparable to that observed contemporarily at other Winnipeg River narrows. As noted in Chapter 3, entrainment rates of sub-adult lake sturgeon at the Slave Falls GS appear to exceed the rate of downstream movement through natural river narrows. As such, it is suspected that the contemporary frequency of sub-adult movement through Slave Falls is considerably higher than it was historically, and therefore the relative genetic contribution made by the upstream population via the sub-adult life stage is also higher than it was historically. It is perhaps notable that in the current study, allelic richness and heterozygosity values in the downstream population were higher when only slow-growing downstream fish were included in the analysis (i.e. omitting fast-growing outliers reasoned to have descended from the upstream population). Furthermore, genetic differentiation between the upstream and downstream population is slightly higher (F_{ST} = 0.014) when the fast-growing outliers were excluded. Since the genetic diversity of the upstream population is currently lower than the downstream population, it may be that genetic differentiation between these populations is actually diminishing due to the contemporary influx of upstream sub-adults into the downstream population.

5.0 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

The results of this thesis indicate that survivable downstream passage of lake sturgeon through the Slave Falls GS is a frequent occurrence, with a mean estimate of 3.1% (range: 0 – 4.5) of tagged adults and 17.9% (range: 13.3 – 20%) of Zone A tagged sub-adults being entrained annually. Furthermore, results indicate that patterns of movement and therefore downstream passage susceptibility vary considerably by lake sturgeon size class. Coarse-scale movements of juveniles and sub-adults in the Slave Falls Reservoir are generally restricted to areas of interconnected deep-water habitat, with movement ranges typically approaching the distance between the shallow river narrows that sub-divide the reservoir. This means that juveniles and sub-adults located in the upper zones would rarely (if ever) be susceptible to entrainment at the Slave Falls GS. Adult movements tended to be more wide ranging and diverse than the other life history stages examined in this study, but also appeared to be restricted at natural river narrows, albeit to a lesser degree. While individuality was certainly apparent in the data, coarse-scale movements of adults tended to be correlated with abiotic variables. However, data collected did not support the hypothesis that high flows during the summer/fall period would result in increased concentrations of adults and sub-adults immediately upstream of the Slave Falls GS. Since lake sturgeon that spend time in the lowermost section of the reservoir often utilize the area immediately upstream of the station as part of their open-water home range, with entrainment frequently resulting, the multi-basin nature of the Slave Falls Reservoir effectively limits the number of lake sturgeon susceptible to entrainment.

This and other recent lake sturgeon research conducted on the Winnipeg River have demonstrated how differently these fish behave in comparison to Great Lakes populations, from which the vast majority of the lake sturgeon literature is derived. As such, caution is suggested prior to extrapolating patterns observed in the Winnipeg River to other river systems. However, because there appears to be a high degree of consistency in the juvenile/sub-adult movement restriction pattern in the Slave Falls Reservoir (Chapter 2) in addition to the 41 rkm Slave Falls GS to Seven Sisters Falls GS stretch of river (Barth 2011), it seems likely that at least for Winnipeg River populations, downstream passage susceptibility of sub-adults (and perhaps juveniles) will effectively be dictated by patterns of larval drift. If larvae drift downstream far enough to settle out in deep-water forebays immediately upstream of generating stations, several years later these fish may well become susceptible to downstream passage. Given that lake sturgeon tend to spawn near the upstream ends of Winnipeg River impoundments, it can be reasoned that entrainment of sub-adults (and likely juveniles) is probably less of a concern in the larger impoundments (i.e. Slave Falls to Seven Sisters Falls – 41 rkm, Seven Sisters Falls – MacArthur Falls – 35 rkm, and Great Falls to Pine Falls – 21 rkm). However, in addition to the Slave Falls Reservoir (9.8 rkm), downstream passage may also be a frequent occurrence in the Great Falls Reservoir (i.e. MacArthur Falls to Great Falls – 8.6 rkm).

Coarse-scale spawning site selection in relation to flow conditions (which vary considerably from year-to-year) warrants further investigation, since this should influence where drifting larvae settle out, and therefore subsequent juvenile/sub-adult distribution patterns. Furthermore, it is suspected that the distance larvae drift in the Winnipeg River is positively correlated with flow, another hypothesis that warrants future investigation.

With this in mind, it is important to note that while Winnipeg River generating stations operate as run-of-the-river, Winnipeg River flow patterns are far from natural. In addition to backwatering and velocity reduction caused by generating station construction, outflow from Lake of the Woods (and the English River tributary) is regulated (Lake of the Woods Control Board 2002). Most notably, the spring freshet on the Winnipeg River is delayed relative to smaller unregulated systems (St. George 2007) and is very likely reduced in magnitude compared to historic levels. This alteration of flow pattern during a critical period for lake sturgeon may be having a significant impact on both spawning site selection and the extent of larval drift, and therefore the distribution pattern of juvenile/sub-adults in the Winnipeg River.

Fine-scale movement investigations have shed much light on the downstream passage phenomenon. Most notably, movement tracks of several lake sturgeon culminated near the entrance of regulating gates, while it was reasoned that several others must have also passed via this route. It seems likely that passage occurred via this route in part because unlike turbine and spillway gate intakes, these regulating gates draw water directly from the river bottom. However, it is speculated that the location of these gates along a pronounced current edge may also influence the downstream passage phenomenon at the Slave Falls GS. While further research is certainly required to confirm the pattern at other generating stations, if the aim is to encourage downstream passage via a low-risk route, it seems logical that the lake sturgeon’s tendency to be bottom oriented be exploited. This might be in the form of specifically tailored fish by-passes, or via periodic operation of spillway gates that draw from the river bottom. Of course, such gates may not exist at all stations lake sturgeon interact with. How to facilitate safe downstream passage may become even more critical if upstream fish passage technology for lake sturgeon is successfully developed, or trap-and-transport employed, for systems on which it is required to restore historical connectivity. It is expected that on many systems (e.g., Great Lakes tributaries), the vast majority of adult lake sturgeon which would move or are transported upstream past a dam to spawn would later need to descend past the same dam to return to foraging habitats. Downstream passage related mortality of either adult or early life stages could severely reduce the overall benefit associated with providing upstream passage.

Results of this study also indicate a diel pattern to lake sturgeon movements, with movements into shallower depths near the spillway only occurring during the night. Since fish that approached via shallow depths tended to move closer to spillway infrastructure, there may be some merit to examining the use of underwater lights as a deterrent, should managers wish to prevent downstream passage, particularly via high risk routes such as turbines. However, it can be reasoned that such a technology would only be effective in waters with high clarity (if at all), and for example, is unlikely to be effective on the Nelson River, Manitoba where water clarity is very low. Furthermore, no data collected in this thesis suggested that turbine related mortality at Slave Falls is a concern. While these results are encouraging, caution is urged prior to extrapolating these results to generating stations with markedly different configurations.

From the perspective of the population downstream of Slave Falls, downstream passage of sub-adults appears to be significant both genetically and demographically, with ~15.2% of the lake sturgeon between 525 and 750 mm captured being fast-growing outliers, reasoned to have descended over Slave Falls after residing upstream for several years. Fast-growing outliers likely have an advantage in regards to making a contribution to the gene pool, since they are larger at age and in better condition than downstream fish which have resided in this area for most (or all) of their lives. Furthermore, the effective contribution of the upstream population may well be underestimated, since the methods employed were not able to detect fish which may have descended during early life stages. The inability of maximum likelihood methods to identify sibship in known control samples highlight the need for additional genetic markers in lake sturgeon, either microsatellite or single nucleotide, to attain the genetic resolution needed to answer these sorts of directed questions.

Because it is impossible to separate the impact of commercial harvest from that of hydroelectric development, it is difficult to speculate what effects hydroelectric development alone would have had on Winnipeg River lake sturgeon populations. However, as previously alluded to, several of the most often cited negative impacts of hydroelectric operations on lake sturgeon populations, including long and short-term flow manipulation, habitat alteration/loss, and restriction of access to spawning grounds are most pronounced in relation to spawning and early life stages. Based on recent research, spawning and juvenile recruitment is occurring within all the impoundments on the Manitoba portion of the Winnipeg River, suggesting that the net negative effect of hydroelectric development on lake sturgeon spawning and recruitment is not as severe here as it is on other systems. In some areas of the Winnipeg River, lake sturgeon have been living with hydroelectric development (and river regulation) for over 100 years, but considering the biology of the species, this likely equates to only 2 – 4 generations. As such, it is possible that less obvious impacts have yet to be fully realized. While the high rate of downstream passage survival observed in this study is encouraging from a fish protection standpoint, genetic results raise many questions with regards to contemporary versus historic rates of gene flow. While some degree of downstream gene flow almost certainly occurred prior to hydroelectric development, the rate of sub-adult passage at the Slave Falls GS appears to exceed the rate of downstream movement through natural river narrows. As such, it is conceivable that genetic differentiation between the populations upstream and downstream of Slave Falls is diminishing. Alternatively, the high rate of sub-adult passage may actually balance the speculated reduced extent of downstream gene flow via larval drift. Based on population genetics data collected in this study, historical upstream gene flow over Slave Falls seems unlikely. Indeed, the paradox is that hydroelectric development may have actually increased habitat and population connectivity on the Winnipeg River, by inundating what may well have been historic barriers to upstream movements, which is a stark contrast to the patterns observed on many river systems which lack the extreme gradient of the Winnipeg River. For example, prior to construction of the Slave Falls GS and the subsequent inundation of Eight Foot Falls, this narrows may well have been impassable in the upstream direction, as historical photos seem to indicate (Appendix 8).

Recently, methodologies have been developed that allow for the assessment of historical versus contemporary gene flow (Chiucchi and Gibbs 2010). Given that restoration of historical population connectivity is believed to be a critical factor in the long-term viability of sturgeon populations (Auer 1996a; Haxton and Findlay 2008; Jager 2006; Jager et al. 2001; Peterson et al. 2007), it seems prudent that the methodologies used by Chiuchhi and Gibbs (2010) be pursued to determine if they can address the data gaps relating to historical connectivity and rates of gene flow (both upstream and downstream) in Winnipeg River lake sturgeon populations. The results of such studies could provide considerable insight into whether or not mitigation is required to restore historical patterns of gene flow in the Winnipeg River, perhaps the next major data gap in our understanding of these populations.

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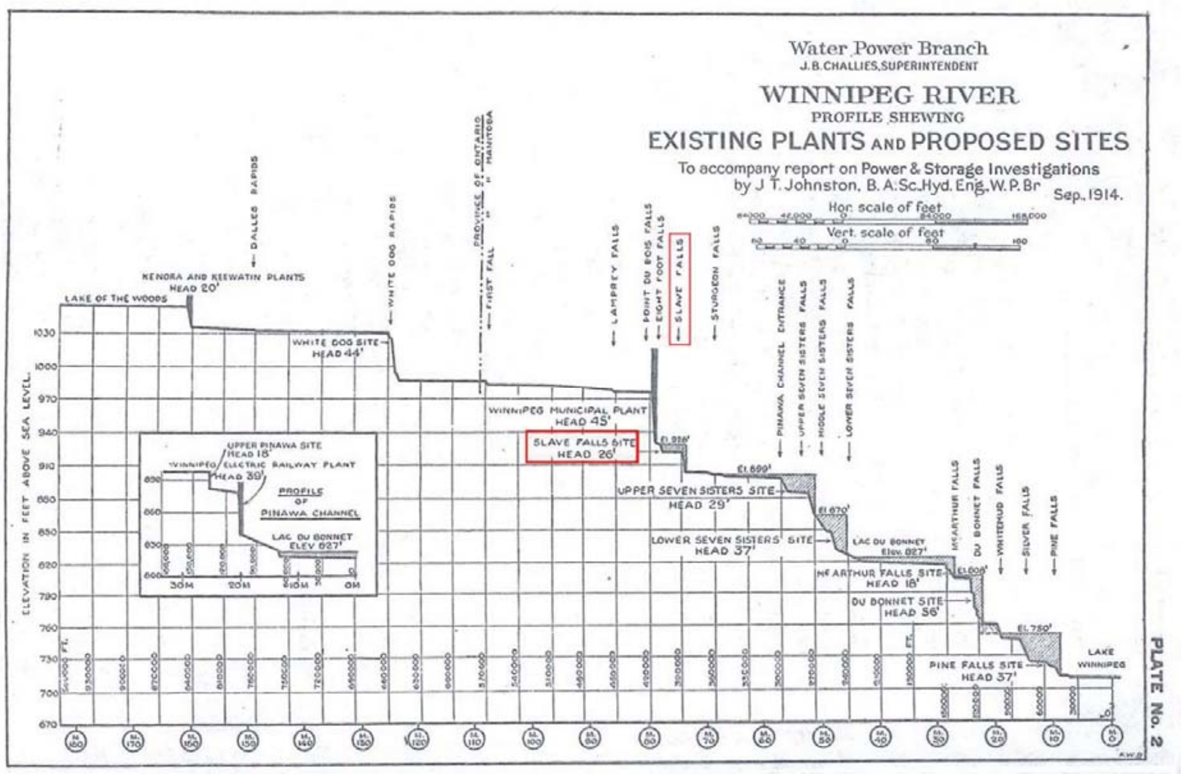
APPENDICIES

Appendix 1. Winnipeg River elevation profile showing existing plants and proposed sites, circa 1914, excerpt from “Report on the Winnipeg River Power and Storage Investigations” by J.T. Johnston, Department of the Interior Canada, Dominion Water Power Branch, Water Resources, Paper No. 3 Volume I, Ottawa 1915. The Slave Falls GS location is highlighted in red. This profile indicates a sharp hydraulic drop of ~ 6 m in the immediate vicinity of Slave Falls.



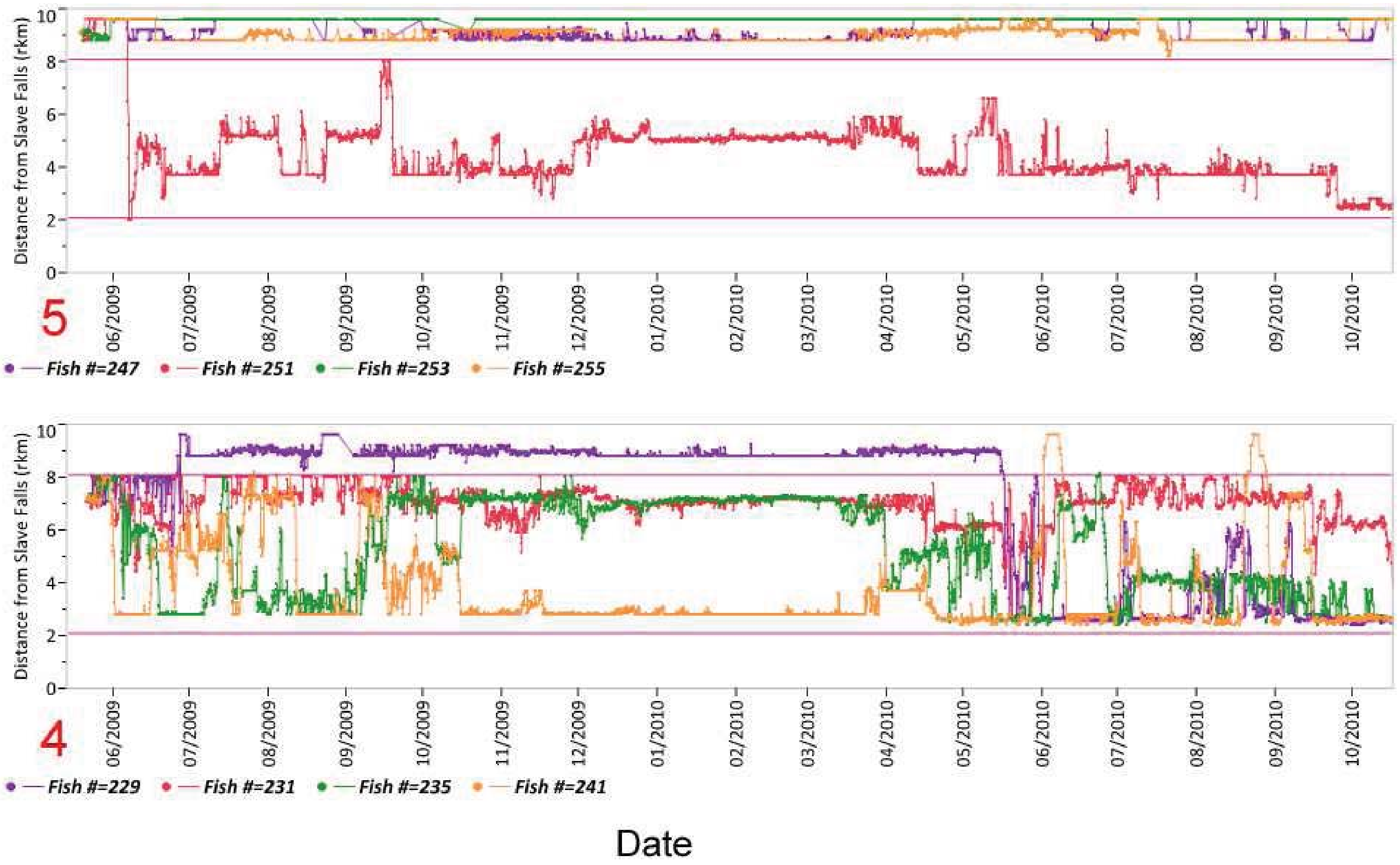
Appendix 2. Tagging information and first/last detection summary for lake sturgeon implanted with Vemco acoustic transmitters in spring 2009. A * denotes the single sub-adult which was last detected several months prior to scheduled tag deactivation, but was able to be confirmed alive based on a subsequent recapture.

Size class	Tag #	Tag type	Section	Fork length (mm)	Date tagged	1st valid detection	Last detection	Comments
Adult	247	V16	5	1105	6-May-09	20-May-09	15-Oct-10	Eggs present
Adult	249	V16	5	1172	6-May-09	20-May-09	18-Jul-10	Eggs present, mortality in January 2010
Adult	251	V16	5	1208	6-May-09	20-May-09	16-Oct-10	Eggs present
Adult	253	V16	5	1357	6-May-09	20-May-09	16-Oct-10	
Adult	255	V16	5	985	5-May-09	19-May-09	16-Oct-10	
Adult	229	V16	4	926	8-May-09	22-May-09	16-Oct-10	
Adult	231	V16	4	1109	8-May-09	22-May-09	16-Oct-10	
Adult	235	V16	4	985	8-May-09	22-May-09	16-Oct-10	
Adult	239	V16	4	930	8-May-09	22-May-09	16-Oct-10	Mortality in July 2009
Adult	241	V16	4	943	8-May-09	22-May-09	16-Oct-10	
Adult	70	V16	3	968	9-May-09	23-May-09	16-Oct-10	
Adult	213	V16	3	1174	9-May-09	23-May-09	16-Oct-10	
Adult	215	V16	3	1197	9-May-09	23-May-09	16-Oct-10	
Adult	233	V16	3	963	7-May-09	21-May-09	16-Oct-10	
Adult	237	V16	3	1065	9-May-09	23-May-09	26-Aug-09	Passed downstream over Slave Falls
Adult	209	V16	2	1222	11-May-09	25-May-09	16-Oct-10	
Adult	211	V16	2	1278	10-May-09	24-May-09	16-Oct-10	
Adult	217	V16	2	865	11-May-09	25-May-09	16-Oct-10	
Adult	221	V16	2	978	11-May-09	25-May-09	16-Oct-10	
Adult	223	V16	2	1287	11-May-09	25-May-09	28-Jul-10	Passed downstream over Slave Falls
Adult	219	V16	1	1130	12-May-09	26-May-09	16-Oct-10	
Adult	225	V16	1	1160	13-May-09	27-May-09	16-Oct-10	
Adult	227	V16	1	1067	14-May-09	28-May-09	16-Oct-10	
Adult	243	V16	1	853	14-May-09	28-May-09	16-Oct-10	
Adult	245	V16	1	896	14-May-09	28-May-09	16-Oct-10	
Sub-adult	159	V13	5	553	5-May-09	19-May-09	16-Oct-10	
Sub-adult	161	V13	5	627	5-May-09	19-May-09	16-Oct-10	
Sub-adult	163	V13	5	709	6-May-09	21-May-09	12-Oct-10	
Sub-adult	165	V13	5	606	6-May-09	20-May-09	16-Oct-10	
Sub-adult	167	V13	5	584	6-May-09	20-May-09	16-Oct-10	
Sub-adult	199	V13	4	516	8-May-09	22-May-09	16-Oct-10	
Sub-adult	201	V13	4	564	8-May-09	22-May-09	16-Oct-10	
Sub-adult	203	V13	4	589	7-May-09	21-May-09	16-Oct-10	
Sub-adult	205	V13	4	565	8-May-09	22-May-09	16-Oct-10	
Sub-adult	207	V13	4	659	7-May-09	21-May-09	16-Oct-10	
Sub-adult	169	V13	3	640	10-May-09	24-May-09	16-Oct-10	
Sub-adult	173	V13	3	660	10-May-09	24-May-09	16-Oct-10	
Sub-adult	175	V13	3	631	10-May-09	24-May-09	16-Oct-10	
Sub-adult	197	V13	3	652	9-May-09	23-May-09	16-Oct-10	
Sub-adult	171	V13	2	585	10-May-09	24-May-09	16-Oct-10	
Sub-adult	179	V13	2	554	12-May-09	26-May-09	16-Oct-10	
Sub-adult	181	V13	2	572	12-May-09	26-May-09	16-Oct-10	
Sub-adult	193	V13	2	632	11-May-09	25-May-09	16-Oct-10	
Sub-adult	195	V13	2	552	11-May-09	25-May-09	16-Oct-10	
Sub-adult	91	V9 On	1	711	20-Jun-09	13-Jul-09	18-Aug-09	*
Sub-adult	95	V9 On	1	530	20-Jun-09	4-Jul-09	16-Oct-09	
Sub-adult	113	V9 Del.	1	702	22-Jun-09	26-Apr-10	13-Oct-10	
Sub-adult	115	V9 Del.	1	548	22-Jun-09	28-Feb-10	4-Oct-10	
Sub-adult	129	V9 Del.	1	635	18-Jun-09	19-Apr-10	13-Oct-10	
Sub-adult	141	V9 Del.	1	554	20-Jun-09	-	-	Never detected, passed downstream
Sub-adult	177	V13	1	608	13-May-09	28-May-09	6-Jul-09	Passed downstream over Slave Falls
Sub-adult	183	V13	1	620	13-May-09	28-May-09	16-Oct-10	
Sub-adult	187	V13	1	609	13-May-09	27-May-09	24-May-10	Passed downstream over Slave Falls
Sub-adult	189	V13	1	634	21-May-09	4-Jun-09	16-Oct-10	
Sub-adult	191	V13	1	570	12-May-09	26-May-09	16-Oct-10	

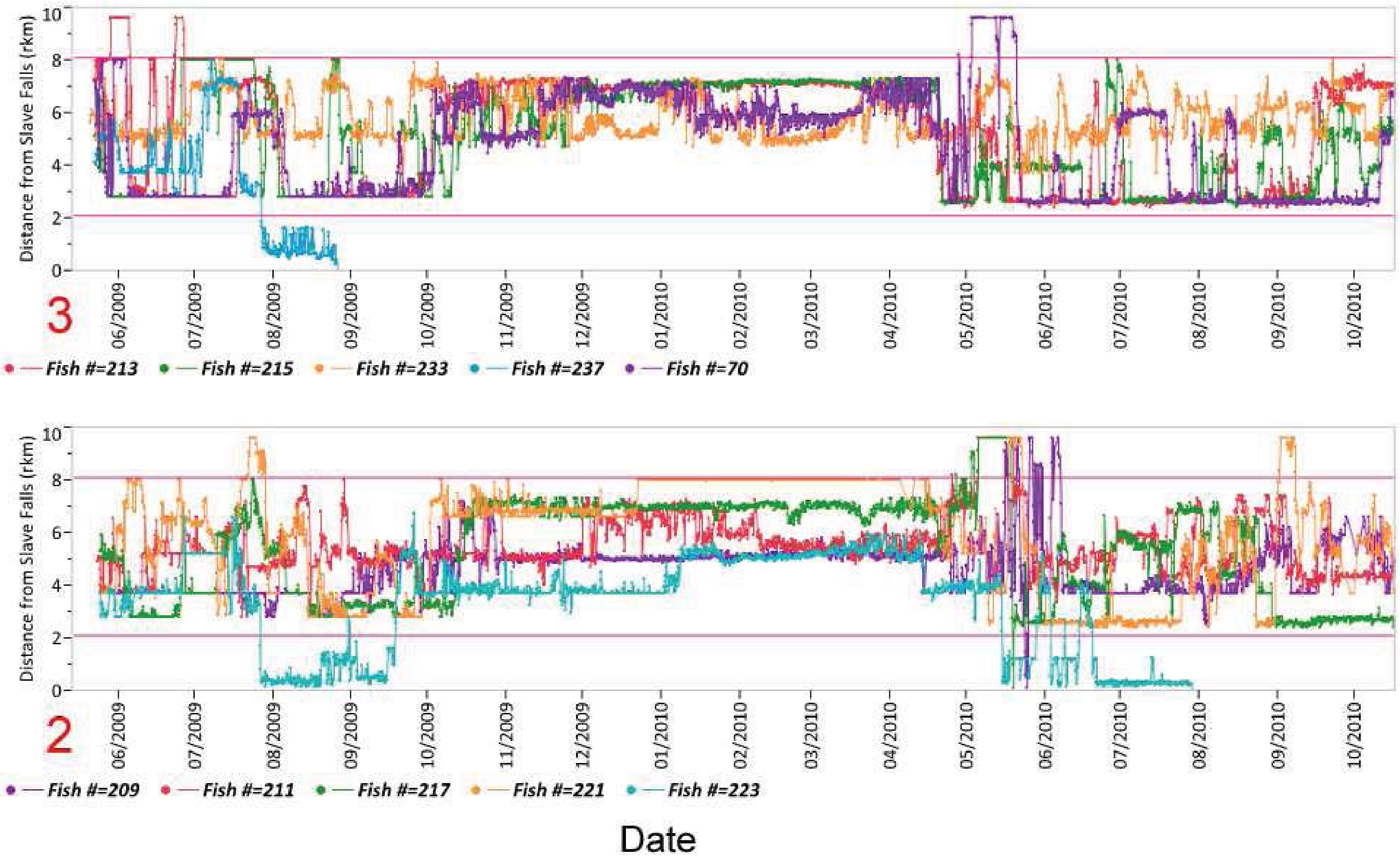
Appendix 2. Continued. A ** denotes juveniles last detected several months prior to scheduled tag deactivation. It is unclear if these fish were mortalities, if they simply remained out of receiver detection range for the remainder of the tag's life, or if these tags became inactive prematurely.

Size class	Tag #	Tag type	Section	Fork length (mm)	Tagged	1st valid detection	Last detection	Comments
Juvenile	40	V9 On	5	420	6-May-09	20-May-09	27-Dec-09	
Juvenile	42	V9 On	5	371	6-May-09	21-May-09	27-Dec-09	
Juvenile	62	V9 On	5	466	13-May-09	27-May-09	31-Dec-09	
Juvenile	103	V9 On	5	392	16-Jun-09	30-Jun-09	17-Jan-10	
Juvenile	111	V9 Del.	5	406	22-Jun-09	3-Mar-10	16-Oct-10	
Juvenile	119	V9 Del.	5	470	21-Jun-09	29-Mar-10	15-Aug-10	**
Juvenile	135	V9 Del.	5	442	17-Jun-09	21-Mar-10	28-Jul-10	**
Juvenile	137	V9 Del.	5	419	17-Jun-09	8-Mar-10	3-Sep-10	**
Juvenile	153	V9 Del.	5	407	6-May-09	23-Jan-10	2-Jun-10	**
Juvenile	155	V9 Del.	5	472	6-May-09	2-Jun-10	23-Jun-10	**
Juvenile	44	V9 On	4	358	7-May-09	21-May-09	14-Jan-10	
Juvenile	46	V9 On	4	422	8-May-09	22-May-09	14-Jan-10	
Juvenile	48	V9 On	4	393	8-May-09	22-May-09	15-Jan-10	
Juvenile	50	V9 On	4	393	8-May-09	22-May-09	15-Jan-10	
Juvenile	52	V9 On	4	470	8-May-09	22-May-09	15-Jan-10	
Juvenile	143	V9 Del.	4	339	21-May-09	4-Feb-10	22-Apr-10	**
Juvenile	145	V9 Del.	4	361	21-May-09	27-Jan-10	4-Jun-10	**
Juvenile	147	V9 Del.	4	376	21-May-09	8-Feb-10	24-Aug-10	**
Juvenile	151	V9 Del.	4	360	8-May-09	15-Jan-10	20-Sep-10	
Juvenile	157	V9 Del.	4	348	8-May-09	14-Jan-10	21-Jun-10	**
Juvenile	54	V9 On	3	372	9-May-09	23-May-09	16-Jan-10	
Juvenile	56	V9 On	3	376	20-May-09	3-Jun-09	27-Jan-10	
Juvenile	60	V9 On	3	346	20-May-09	3-Jun-09	24-Dec-09	
Juvenile	99	V9 On	3	372	21-May-09	4-Jun-09	25-Jan-10	
Juvenile	107	V9 On	3	341	21-May-09	4-Jun-09	24-Jan-10	
Juvenile	109	V9 Del.	3	354	21-Jun-09	25-Apr-10	15-Oct-10	
Juvenile	117	V9 Del.	3	378	21-Jun-09	31-Mar-10	16-Oct-10	
Juvenile	125	V9 Del.	3	434	21-Jun-09	27-Feb-10	16-Oct-10	
Juvenile	131	V9 Del.	3	431	19-Jun-09	25-Feb-10	16-Oct-10	
Juvenile	139	V9 Del.	3	498	22-May-09	28-Jan-10	4-Oct-10	
Juvenile	58	V9 On	2	380	20-May-09	3-Jun-09	27-Jan-10	
Juvenile	66	V9 On	2	351	13-May-09	27-May-09	17-Jan-10	
Juvenile	68	V9 On	2	500	20-May-09	3-Jun-09	3-Oct-09	
Juvenile	89	V9 On	2	371	21-May-09	4-Jun-09	25-Jan-10	
Juvenile	97	V9 On	2	401	21-May-09	4-Jun-09	25-Jan-10	
Juvenile	105	V9 On	2	379	21-May-09	4-Jun-09	25-Jan-10	
Juvenile	121	V9 Del.	2	378	20-Jun-09	26-Feb-10	16-Oct-10	
Juvenile	123	V9 Del.	2	411	20-Jun-09	18-Mar-10	16-Oct-10	
Juvenile	127	V9 Del.	2	387	20-Jun-09	26-Feb-10	16-Oct-10	
Juvenile	149	V9 Del.	2	509	20-Jun-09	2-Mar-10	16-Oct-10	
Juvenile	64	V9 On	1	437	21-May-09	9-Jun-09	28-Jan-10	
Juvenile	93	V9 On	1	396	22-Jun-09	9-Jul-09	12-Aug-09	**
Juvenile	101	V9 On	1	366	20-Jun-09	4-Jul-09	23-Jan-10	
Juvenile	133	V9 Del.	1	419	20-Jun-09	22-Apr-10	30-Jul-10	**

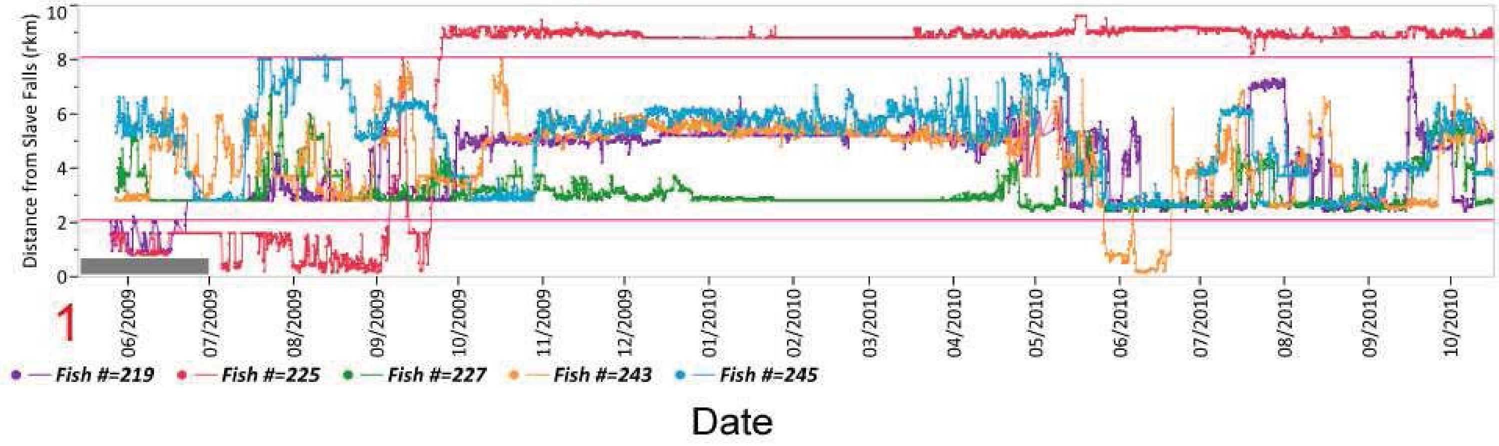
Appendix 3. Algorithm output (4 hour interval) for adult lake sturgeon, with fish grouped by Section (red number). Pink lines indicate Old Slave Falls and Eight Foot Falls.



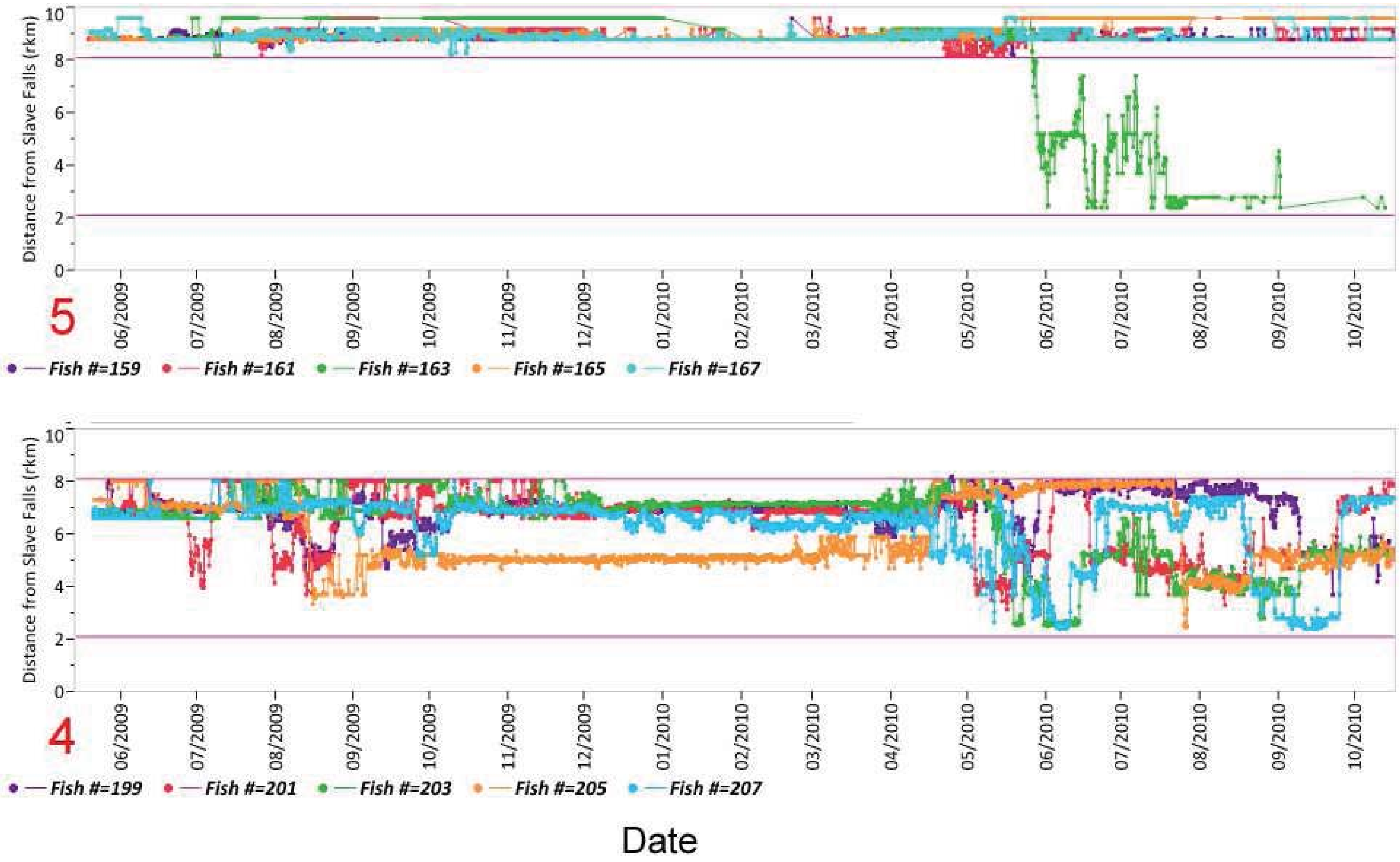
Appendix 3. Continued.



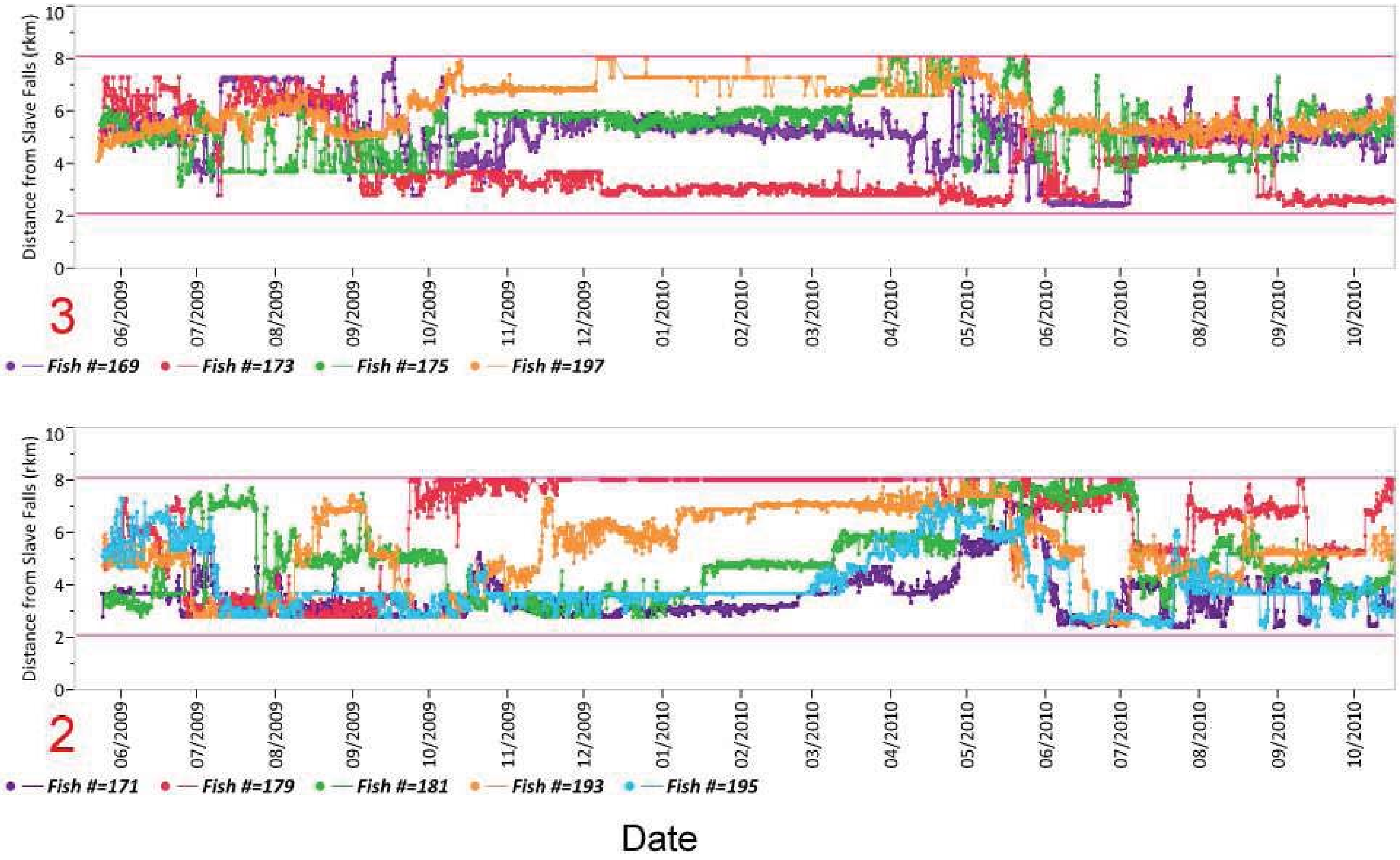
Appendix 3. Continued. Grey shaded area indicates the lack of VR2W coverage between rkm 0 and 0.8 prior to 30 June 2009. Supplemental coverage in this area during this time period was provided by the Vemco VRAP system, but this data is not reflected in algorithm output.



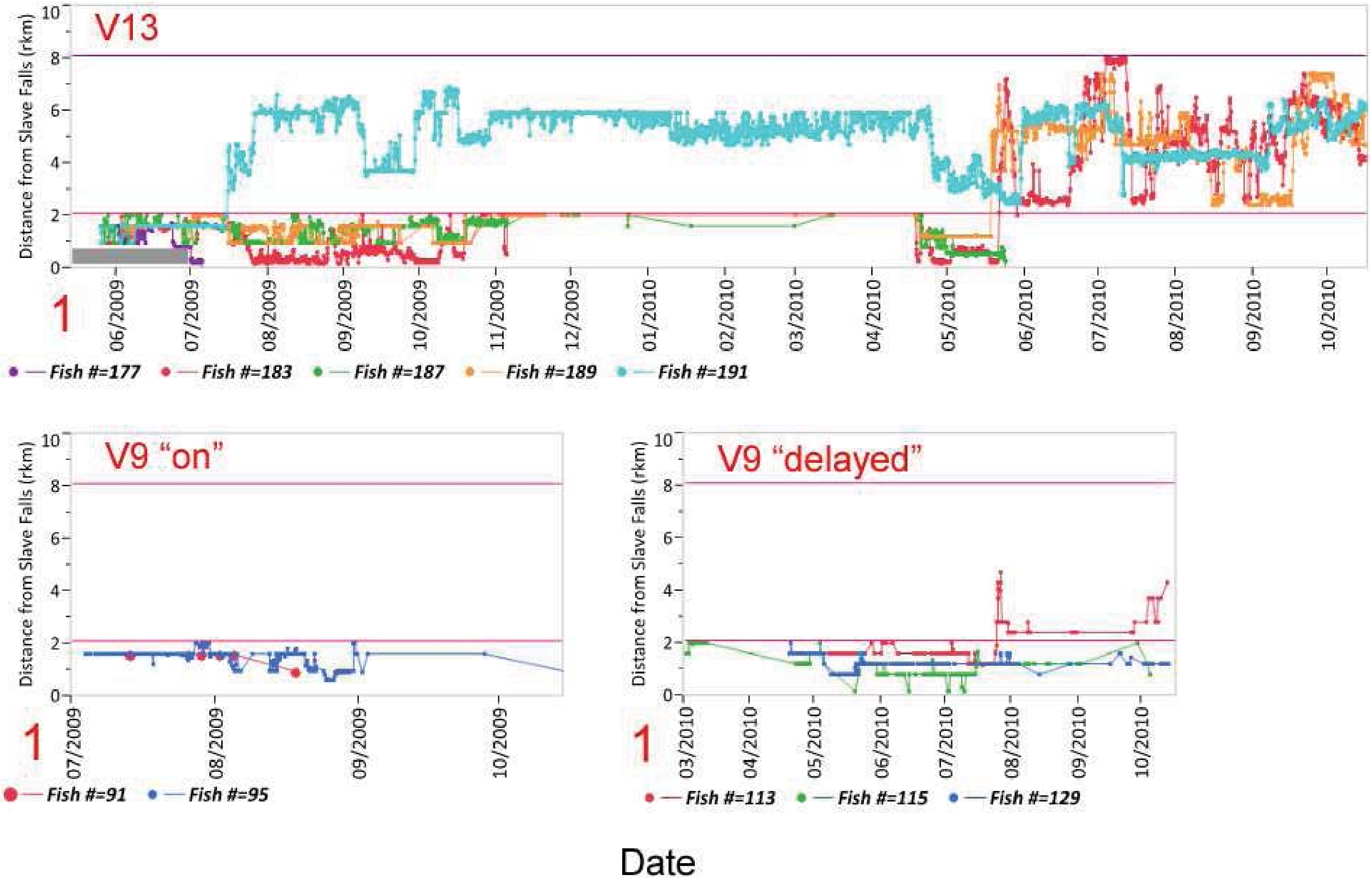
Appendix 4. Algorithm output (4 hour interval) for sub-adult lake sturgeon, with fish grouped by Section (red number). Pink lines indicate Old Slave Falls and Eight Foot Falls.



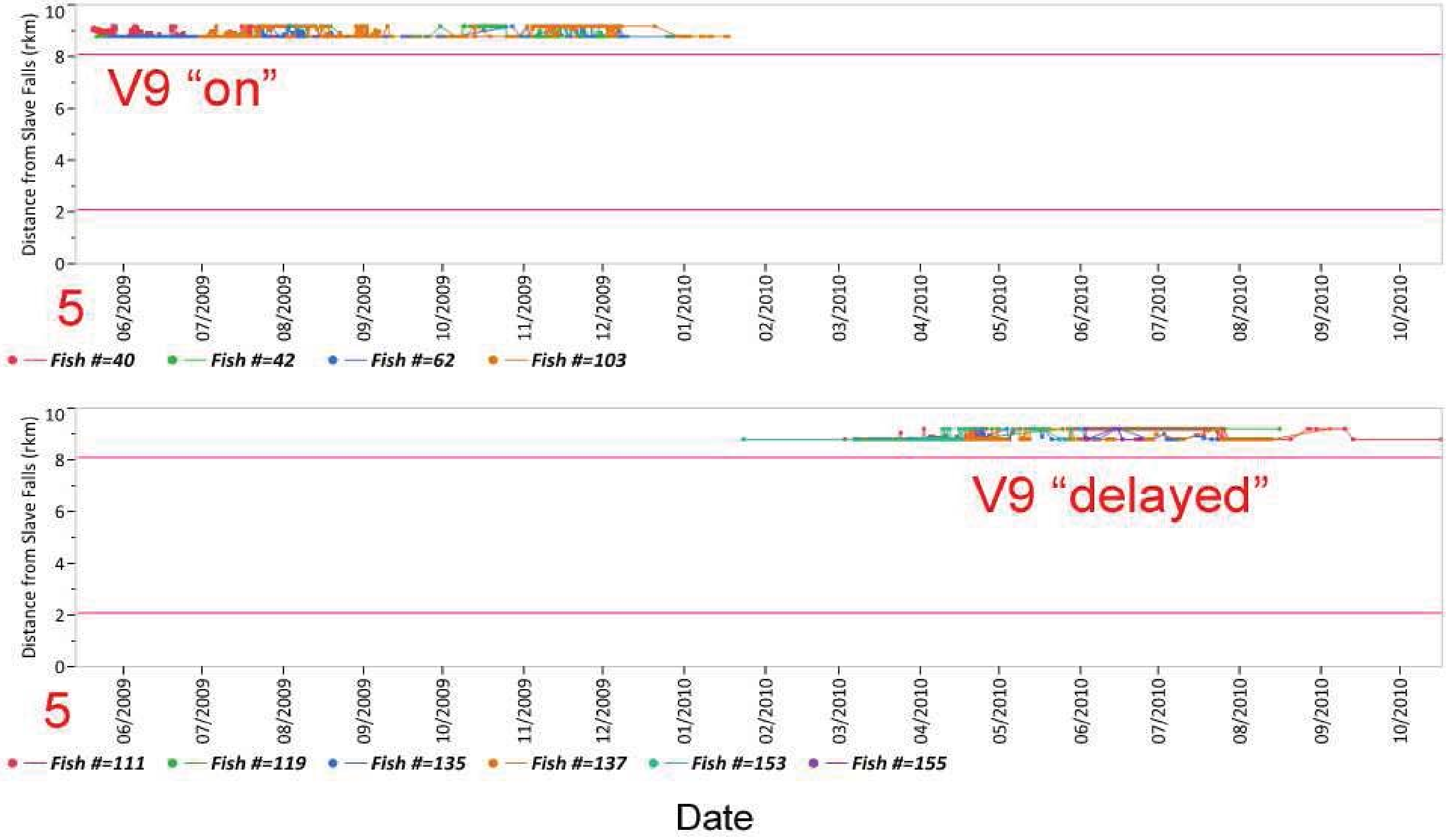
Appendix 4. Continued.



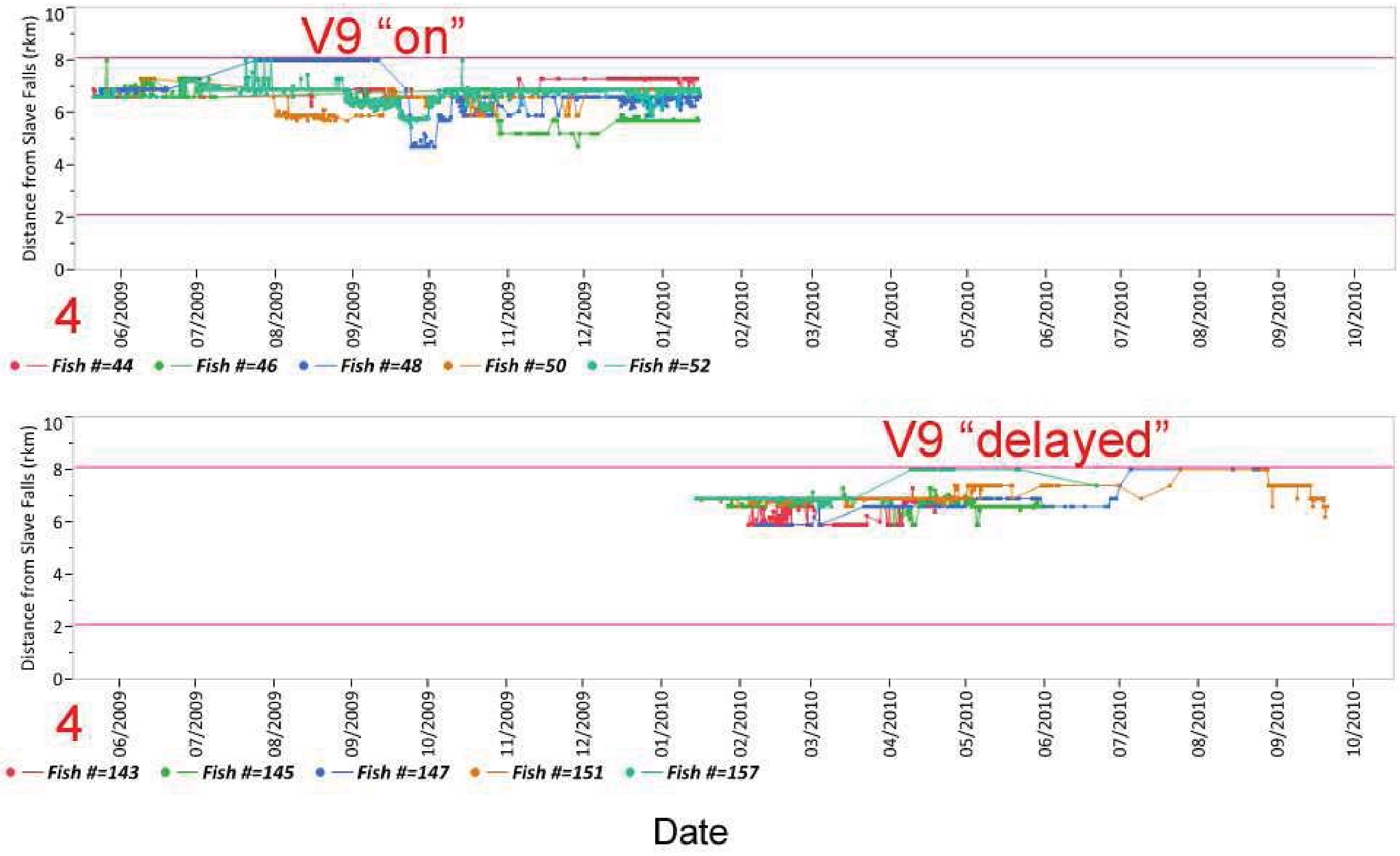
Appendix 4. Continued. Section 1 tagged sub-adults are separated by tag type. Grey shaded area indicates the lack of VR2W coverage between rkm 0 and 0.8 prior to 30 June 2009. Supplemental coverage in this area during this time period was provided by the Vemco VRAP system, but this data is not reflected in algorithm output.



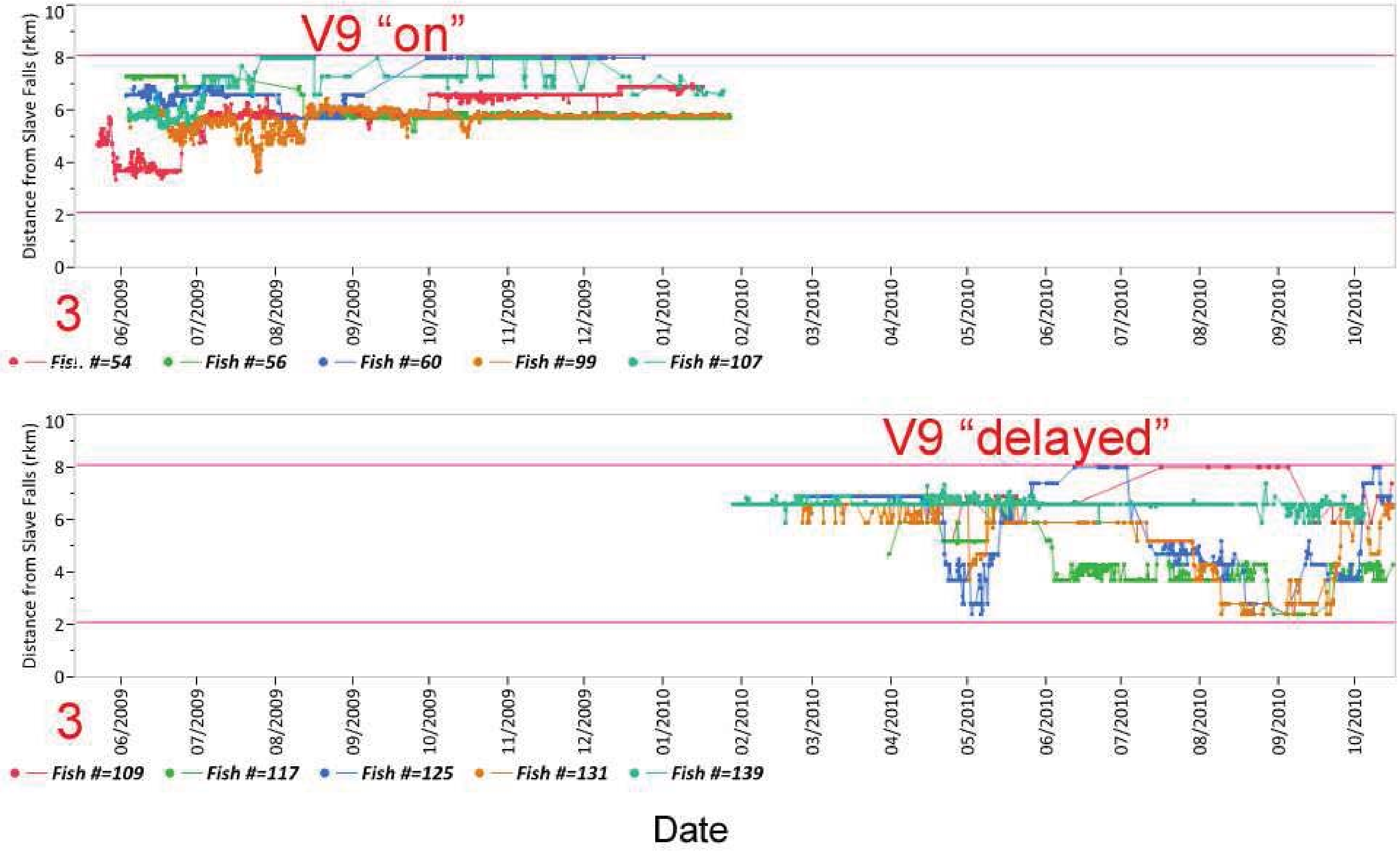
Appendix 5. Algorithm output (4 hour interval) for juvenile lake sturgeon, with fish grouped by Section (red number). Pink lines indicate Old Slave Falls and Eight Foot Falls. Fish from each Section are separated by tag type.



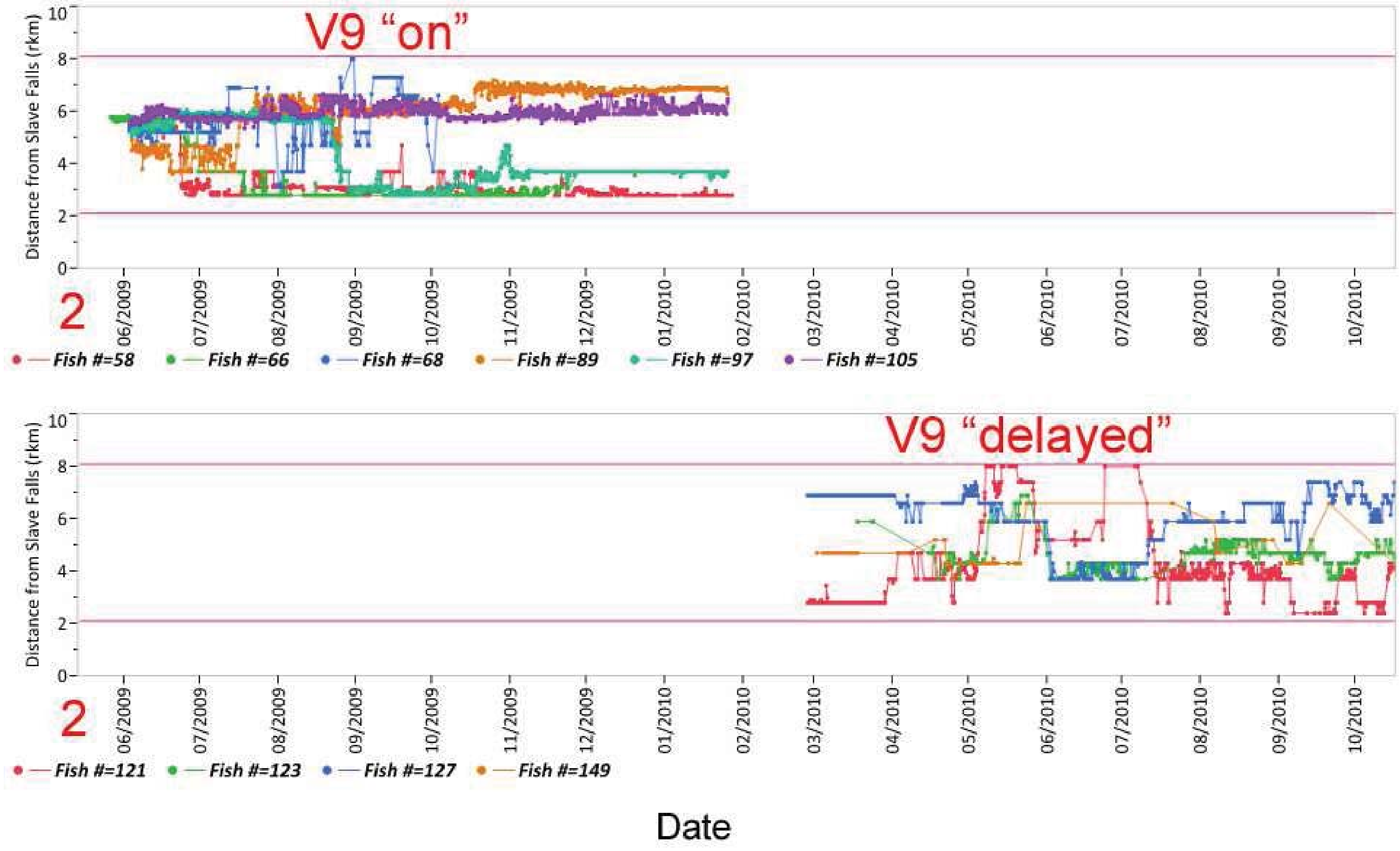
Appendix 5. Continued.



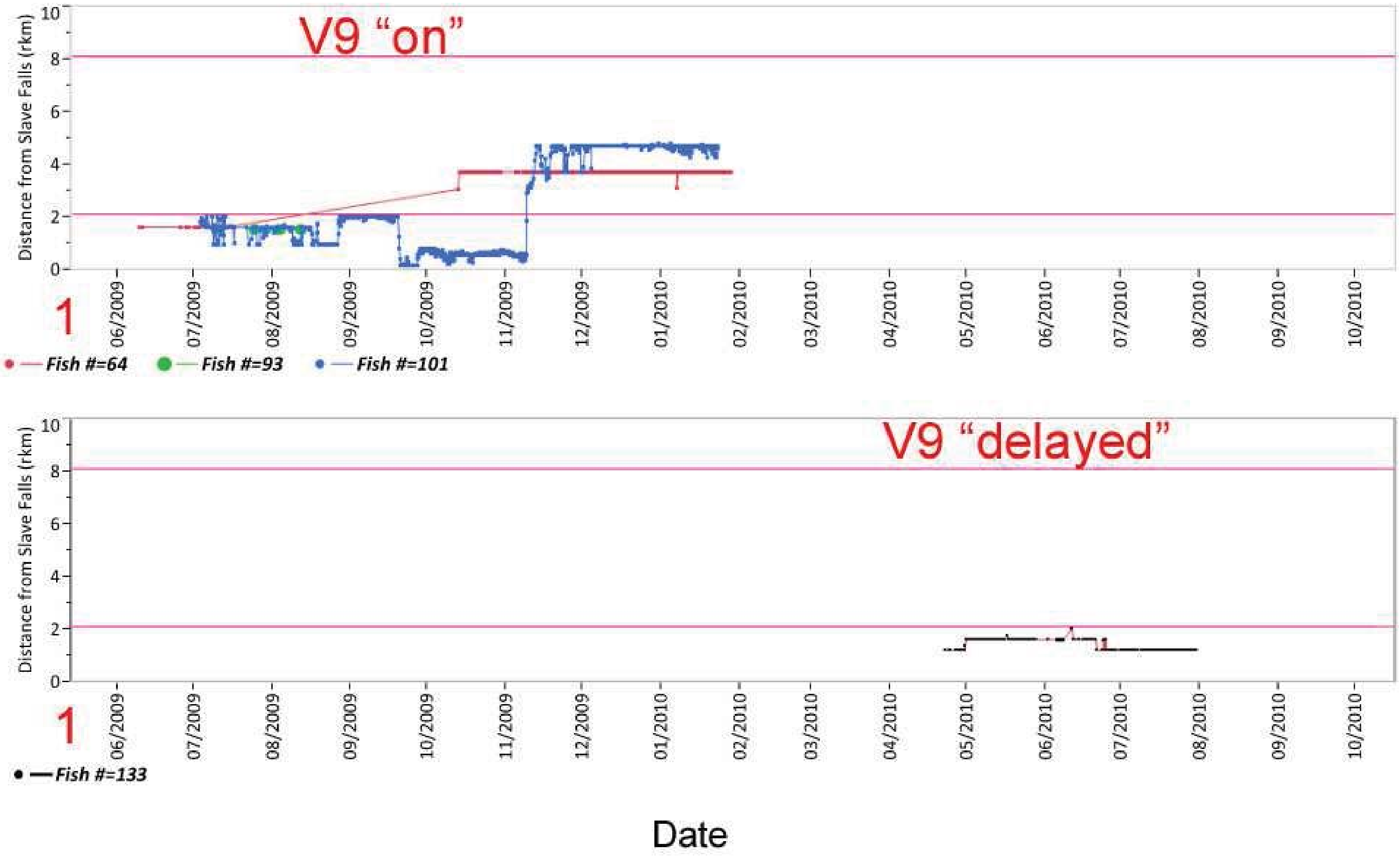
Appendix 5. Continued.



Appendix 5. Continued.



Appendix 5. Continued.



Appendix 6. Tagging information for lake sturgeon implanted with HTI acoustic transmitters in 2010, as well as which fish were detected by Slave Falls acoustic arrays.

Size class	Tag #	Tag type	Fork length (mm)	Tagging distance (rkm)	Tagging date	Estimated expiry date	Detected 48+ hours after tagging	Comments
Adult	1993	Z	1148	2.8	5-May-10	26-Mar-12	Yes	
Adult	2000	Z	1025	2.5	4-May-10	26-Mar-12		
Adult	2007	Z	1140	2.8	4-May-10	26-Mar-12		
Adult	2014	Z	1090	2.6	4-May-10	26-Mar-12		
Adult	2021	Z	1262	2.6	4-May-10	26-Mar-12		
Adult	2028	Z	1052	2.8	4-May-10	26-Mar-12		
Adult	2035	Z	1170	2.8	4-May-10	26-Mar-12		
Adult	2042	Z	1138	2.8	4-May-10	26-Mar-12		
Adult	2049	Z	962	2.8	4-May-10	26-Mar-12		
Adult	2056	Z	1335	2.8	4-May-10	26-Mar-12		
Adult	2063	Z	970	2.6	4-May-10	26-Mar-12		
Adult	2077	Z	1058	2.8	5-May-10	26-Mar-12		
Adult	2084	Z	1066	2.6	4-May-10	26-Mar-12		
Adult	2091	Z	1098	2.6	4-May-10	26-Mar-12		
Adult	2098	Z	1150	2.6	4-May-10	26-Mar-12		Vemco tagged: V16, # 213
Adult	3005	Z	995	2.7	4-May-10	26-Mar-12		
Adult	3012	Z	1001	2.6	4-May-10	26-Mar-12		
Adult	3019	Z	987	2.6	4-May-10	26-Mar-12		
Adult	3026	Z	1500	2.5	4-May-10	26-Mar-12		
Adult	3033	Z	990	2.6	4-May-10	26-Mar-12		
Adult	3040	Z	920	2.6	4-May-10	26-Mar-12		
Adult	3047	Z	1108	2.5	4-May-10	26-Mar-12		
Adult	3054	Z	1080	2.8	4-May-10	26-Mar-12		
Adult	3061	Z	1168	2.8	4-May-10	26-Mar-12		
Adult	3068	Z	1150	2.5	4-May-10	26-Mar-12	Yes	
Adult	3075	Z	855	2.8	4-May-10	26-Mar-12		
Adult	3082	Z	991	2.8	5-May-10	26-Mar-12		
Adult	3089	Z	1043	2.8	5-May-10	26-Mar-12		
Adult	3096	Z	1195	1.2	14-May-10	26-Mar-12	Yes	
Adult	4003	X	1009	5.5	23-Apr-10	13-Oct-10	Yes	
Adult	4010	X	1041	5.5	23-Apr-10	13-Oct-10		
Adult	4017	X	1184	5.5	23-Apr-10	13-Oct-10	Yes	
Adult	4024	X	1010	1.8	28-Apr-10	13-Oct-10	Yes	
Adult	4031	X	1310	1.8	28-Apr-10	13-Oct-10		
Adult	4045	X	1004	5.5	23-Apr-10	13-Oct-10		
Adult	4073	X	1255	2.4	29-Apr-10	13-Oct-10		
Adult	4087	X	1020	2.4	29-Apr-10	13-Oct-10		
Adult	4094	X	1042	5.5	23-Apr-10	13-Oct-10		
Adult	5001	X	878	5.5	23-Apr-10	13-Oct-10	Yes	
Adult	5008	X	1229	5.5	23-Apr-10	13-Oct-10		Eggs present
Adult	5015	X	1186	5.5	23-Apr-10	13-Oct-10		
Adult	5022	X	1060	2.4	30-Apr-10	13-Oct-10		
Adult	5029	X	1103	1.1	29-Apr-10	13-Oct-10	Yes	
Adult	5036	X	1020	2.4	29-Apr-10	13-Oct-10	Yes	
Adult	5043	X	916	2.4	30-Apr-10	13-Oct-10		
Adult	5050	X	1226	2.4	29-Apr-10	13-Oct-10		
Adult	5064	X	1040	5.5	23-Apr-10	13-Oct-10		
Adult	1937[a]	Z	1161	2.8	5-May-10	26-Mar-12		
Adult	1944[a]	Z	1174	2.8	4-May-10	26-Mar-12	Possibly[c]	
Adult	1951[a]	Z	1225	2.8	4-May-10	26-Mar-12		
Adult	1958[a]	Z	1265	2.8	4-May-10	26-Mar-12	Possibly[c]	
Adult	1965[a]	Z	1165	2.8	5-May-10	26-Mar-12	Possibly[d]	
Adult	1965[b]	X	1045	0.3	21-May-10	7-Nov-10	Possibly[d]	
Adult	1972[a]	Z	841	2.8	5-May-10	26-Mar-12		
Adult	1979[a]	Z	945	2.5	4-May-10	26-Mar-12		
Adult	1986[a]	Z	1128	2.7	4-May-10	26-Mar-12		

a, b - Duplicated tag ID.

c - Due to tag ID duplication, impossible to determine which of two fish (either sub-adult or adult) was detected in certain instances.

d - Due to tag ID duplication, unclear which of two fish assinged PRI #1965 (both adults) was detected.

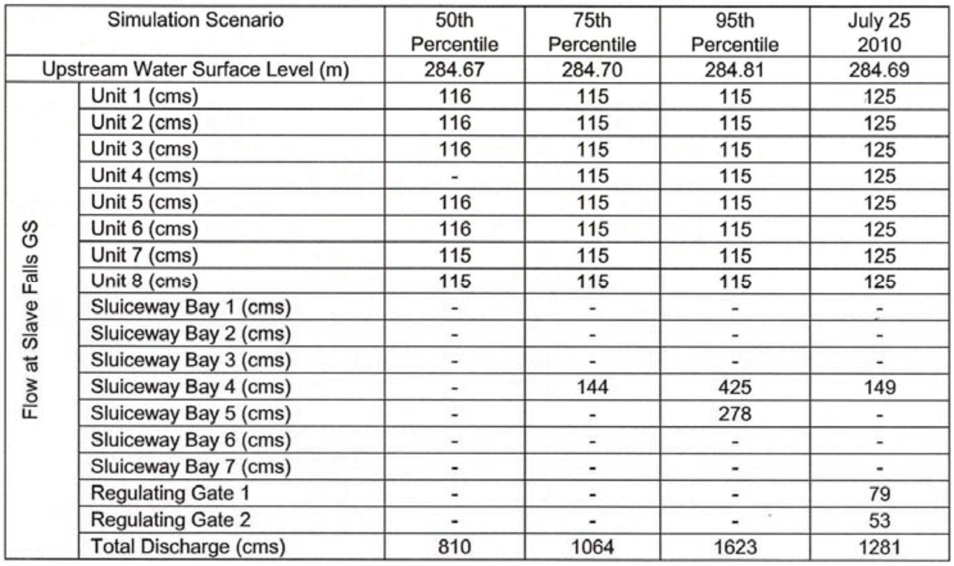
Appendix 6. Continued.

Size class	Tag #	Tag type	Fork length (mm)	Tagging distance (rkm)	Tagging date	Estimated expiry date	Detected 48+ hours after tagging	Comments
Sub-adult	1895	X	704	0.3	21-May-10	7-Nov-10	Yes	
Sub-adult	1902	X	600	0.3	21-May-10	7-Nov-10	Yes	
Sub-adult	1909	X	586	0.3	21-May-10	7-Nov-10		
Sub-adult	1916	X	651	0.3	21-May-10	7-Nov-10	Yes	
Sub-adult	1923	X	652	0.3	21-May-10	7-Nov-10	Yes	
Sub-adult	1930	X	623	0.3	21-May-10	7-Nov-10		
Sub-adult	4038	X	636	0.3	20-May-10	13-Oct-10	Yes	
Sub-adult	4052	X	587	0.3	20-May-10	13-Oct-10		
Sub-adult	4059	X	706	1.1	13-May-10	13-Oct-10	Yes	Vemco tagged: V9o, #91
Sub-adult	4066	X	665	1.2	14-May-10	13-Oct-10	Yes	
Sub-adult	4080	X	634	1.2	14-May-10	13-Oct-10		
Sub-adult	5057	X	660	1.1	13-May-10	13-Oct-10	Yes	
Sub-adult	5071	X	669	1.1	13-May-10	13-Oct-10	Yes	
Sub-adult	5078	X	732	1.1	12-May-10	13-Oct-10	Yes	
Sub-adult	5085	G	573	0.3	21-May-10	24-Aug-10	Yes	Vemco tagged: V9d, #115
Sub-adult	5099	G	596	1.0	24-Aug-10	16-Oct-10	Yes	
Sub-adult	5134	G	581	1.0	24-Aug-10	26-Nov-10		
Sub-adult	5148	G	530	1.8	21-Jul-10	16-Oct-10	Yes	
Sub-adult	5169	G	560	1.1	25-Aug-10	16-Oct-10		
Sub-adult	5176	G	620	1.0	24-Aug-10	26-Nov-10	Yes	
Sub-adult	5183	G	621	1.1	25-Aug-10	26-Nov-10		
Sub-adult	5190	G	565	1.0	24-Aug-10	26-Nov-10	Yes	
Sub-adult	5197	G	587	1.0	24-Aug-10	26-Nov-10		
Sub-adult	5204	G	584	1.0	24-Aug-10	26-Nov-10		
Sub-adult	5211	G	588	1.0	24-Aug-10	26-Nov-10		
Sub-adult	5239	G	603	1.0	24-Aug-10	26-Nov-10		
Sub-adult	5246	G	580	1.0	24-Aug-10	26-Nov-10		
Sub-adult	1937[b]	X	653	0.3	21-May-10	7-Nov-10		
Sub-adult	1944[b]	X	649	0.3	21-May-10	7-Nov-10	Yes	
Sub-adult	1951[b]	X	595	0.3	21-May-10	7-Nov-10	Yes	
Sub-adult	1958[b]	X	620	0.3	21-May-10	7-Nov-10	Yes	
Sub-adult	1972[b]	X	673	0.3	21-May-10	7-Nov-10	Yes	
Sub-adult	1979[b]	X	628	0.3	21-May-10	7-Nov-10		Vemco tagged[e]
Sub-adult	1986[b]	X	545	0.3	21-May-10	7-Nov-10		
Juvenile	5092	G	472	0.3	21-May-10	23-Aug-10	Yes	
Juvenile	5106	G	463	1.8	23-Jul-10	16-Oct-10		
Juvenile	5113	G	451	1.8	16-Jul-10	3-Oct-10	Yes	
Juvenile	5120	G	432	1.8	14-Jul-10	16-Oct-10	Yes	
Juvenile	5127	G	426	1.8	15-Jul-10	16-Oct-10		
Juvenile	5141	G	455	1.8	14-Jul-10	16-Oct-10		
Juvenile	5155	G	488	1.8	16-Jul-10	16-Oct-10		Vemco tagged: V9d, # 133
Juvenile	5162	G	435	1.8	22-Jul-10	16-Oct-10		
Juvenile	5218	G	470	1.0	24-Aug-10	26-Nov-10	Yes	
Juvenile	5225	G	474	1.0	24-Aug-10	26-Nov-10		
Juvenile	5232	G	501	1.0	24-Aug-10	26-Nov-10		
Juvenile	5253	G	436	1.0	24-Aug-10	26-Nov-10		

a, b - Duplicated tag ID.

e - Vemco tagged fish based on accoustic tagging scar, but unclear which fish since Floy tag was missing upon recapture

Appendix 7. Flow3D boundary conditions for velocity modelling upstream of the Slave Falls GS, detailing amount of flow directed through the various turbines, spillway gates and regulating gates. Flows are presented in cubic meters per second (cms), equivilant to m^3/s.



Simulation Scenario		50th Percentile	75th Percentile	95th Percentile	July 25 2010
Upstream Water Surface Level (m)		284.67	284.70	284.81	284.69
Flow at Slave Falls GS	Unit 1 (cms)	116	115	115	125
	Unit 2 (cms)	116	115	115	125
	Unit 3 (cms)	116	115	115	125
	Unit 4 (cms)	-	115	115	125
	Unit 5 (cms)	116	115	115	125
	Unit 6 (cms)	116	115	115	125
	Unit 7 (cms)	115	115	115	125
	Unit 8 (cms)	115	115	115	125
	Sluiceway Bay 1 (cms)	-	-	-	-
	Sluiceway Bay 2 (cms)	-	-	-	-
	Sluiceway Bay 3 (cms)	-	-	-	-
	Sluiceway Bay 4 (cms)	-	144	425	149
	Sluiceway Bay 5 (cms)	-	-	278	-
	Sluiceway Bay 6 (cms)	-	-	-	-
	Sluiceway Bay 7 (cms)	-	-	-	-
	Regulating Gate 1	-	-	-	79
	Regulating Gate 2	-	-	-	53
	Total Discharge (cms)	810	1064	1623	1281

Appendix 8. Historical photo (circa 1914) of Eight Foot Falls, with the Pointe du Bois GS shown in the background. This photo is an excerpt from “Report on the Winnipeg River Power and Storage Investigations” by J.T. Johnston, Department of the Interior Canada, Dominion Water Power Branch, Water Resources, Paper No. 3 Volume I, Ottawa 1915.