Movement patterns, habitat utilization, and spawning habitat of Lake Sturgeon (*Acipenser fulvenscens*) in the Pic River, a northeastern Lake Superior tributary in Ontario, Canada

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ABSTRACT

Movement patterns, habitat utilization, and spawning habitat of Lake Sturgeon (*Acipenser fulvenscens*) in the Pic River, a northeastern Lake Superior tributary in Ontario, Canada

Andrew Ecclestone

Lake Sturgeon (*Acipenser fulvenscens*) have undergone significant declines in abundance and distribution throughout their native range in the Laurentian Great Lakes and are listed as threatened under the Endangered Species Act of Ontario and by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC). In response to this, there has been a push to identify for protection the critical Lake Sturgeon habitat within spawning tributaries in the Great Lakes, especially those tributaries where no data currently exists. The Pic River is one of twelve tributaries in Lake Superior that continues to support Lake Sturgeon spawning, but very little is known about the movements, habitat utilization, or spawning habitat of this population. To address these knowledge gaps, a radio telemetry and spawning assessment study was undertaken from 2007 to 2010 to monitor movement patterns as they related to abiotic conditions and to identify and assess critical habitat in the Pic River. Three unique migration patterns were observed, two of which related to foraging individuals and one relating to spawning individuals. Spawning individuals entered the river earlier and rapidly ascended the river to one of two uppermost barriers (Manitou and Kagiano Falls), whereas foraging individuals either remained at the mouth of the river or migrated 20 km to 30 km upriver to deep pools throughout the lower rapids. An unusually warm spring and early melt in 2010 resulted in Lake Sturgeon entering, reaching their uppermost point, and exiting the river roughly 55 days earlier compared to the previous two years. The onset of their migrations were highly correlated with ice conditions and when the river became ice free (R^2=0.88), although water temperature and discharge were not accurate predictors for migration timing. Critical habitat features were identified and potential spawning sites were evaluated using a Lake Sturgeon habitat suitability model (HSM). By comparing spawning assessment results with model predictions, this study found that the HSM could not accurately predict where spawning would occur between different spawning sites, but did reasonably well within a spawning site for predicting the timing and location of spawning. It is advocated that the HSM incorporate the presence or absence of a barrier to migration to increase the validity of its prediction. This study not only contributes to the expanding knowledge base and conservation efforts that exist for Lake Sturgeon in the Great Lakes, but will also contribute to the decision making and planning process for proposed local hydroelectric developments.

Keywords: movement patterns, habitat suitability, Lake Sturgeon, Pic River

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Chapter 1: General Introduction

Lake Sturgeon (*Acipenser fulvescens*) are one of the world's largest and longest lived freshwater fish species, and the only species of sturgeon species that is native to the Laurentian Great Lakes (Scott & Crossman, 1998). These potamodromous bottom-feeders have a primitive appearance and a downward facing snout that enables them to detect prey in soft bottom sediment using sensory pits and barbels (Harkness & Dymond, 1961; Peterson et al., 2007; Stelzer et al., 2008). Juveniles allocate a disproportionate amount of energy towards somatic growth (Beamish et al., 1996), and therefore sexual maturity is not reached until approximately 12-15 years for males and 18-27 years for females (Kempinger, 1988; Bruch & Binkowski, 2002; Peterson et al., 2007; Barth et al., 2009). These extreme life history characteristics of the Lake Sturgeon make it a difficult species to manage and research given the resource and time constraints of most fisheries projects.

Each spring, when water temperatures are between 11ºC to 21ºC, a proportion of each adult population migrate upriver to reproduce at their natal spawning grounds that contain cobble-boulder-gravel substrates and fast flowing water (Harkness & Dymond, 1961; McKinley et al., 1998; Bruch & Binkowski, 2002; Peterson et al., 2007). Bruch & Binkowski (2002) found that spawning sites in the Winnebago system were close to deep overwintering pools (<2 km), had an extensive amount of spawning substrate (>700 m^2) that was comprised of clean rock, limestone, or granite with clean interstitial spaces, and high flows for cleaning rocks and aerating eggs. Several other studies report Lake Sturgeon spawning at depths of 0.1 m to 2.0 m over gravel or cobble substrate, and at water velocities that range from 15 cm/s to 70 cm/s (Priegel and Wirth, 1974; LaHaye et al., 1992; McKinley et al., 1998; Auer & Baker, 2002). Spawning temperatures can also vary quite substantially. A long-term study in the Wolf River found evidence of spawning at temperatures between 8.3ºC and 23.3ºC (Kempinger, 1988) and up to 21.5ºC in the L'Assomption River (LaHaye et al., 1992). Most spawning, however, is observed between 13ºC to 18ºC (Scott & Crossman, 1973; Bruch & Binkowski, 2002; Peterson et al., 2007). Lake Sturgeon have a polyandrous mating system, whereby two to five males will fertilize eggs that are broadcasted by a spawning female while traversing the length of the spawning habitat (Harkness, 1988; Auer & Baker, 2002; Bruch & Binkowski, 2002; Hodgeson et al., 2006; Peterson et al., 2007). Since females only spawn every 3-5 years, and males every 1-3 years, inter and intra population variation in movement patterns and habitat utilization are often observed throughout the spring (Kempinger, 1988; Fortin et al., 1996; Rusak & Mosindy, 1997; Peterson et al., 2007). By late-summer, and throughout the fall and winter, populations typically reduce their home range size and show strong site fidelity for deep-water pools, which are typically located in the lower sections of rivers, or a connected lake (Hay-Chmielewski, 1987; Lyons & Kempinger, 1992; Fortin et al., 1993; Rusak & Mosindy, 1997; McKinley et al., 1998; Auer, 1999; Knight et al., 2002; Haxton, 2003b; Lallaman et al., 2008). Spawning females are highly fecund (Harkness & Dymond, 1961; Scott & Crossman, 1998; Peterson et al., 2007) and can potentially lay more than 10,000 eggs per kilogram of fish (Bruch et al., 2006), but natural mortality and a lack of parental care can result in less than 0.1% of those eggs reaching age-0 (Carofino et al., 2010, 2011).Lake Sturgeon was once considered one of the Great Lake's most abundant and widely distributed endemic fish species (Hay-Chmielewski & Whelan, 1997; Auer, 1999; Peterson, 2007). In the early-1800s Lake Sturgeon were so abundant and widely distributed that they were considered a nuisance species by most commercial fisheries (Stone & Vincent, 1900; Harkness, 1988; Hay-Chmielewski & Whelan, 1997). They were an essential bartering commodity during the fur trade era and have always been traditionally important to aboriginal peoples for subsistence and cultural purposes, especially in northern Ontario (Hannibal-Paci, 1998; Holzkamm & Waisberg, 2005; Ontario Ministry of Natural Resources, 2009; Kline et al., 2010). At the Rainy River, the 1868 spawning run attracted roughly 1,000 Ojibwa people from as far east as Winnipeg and as far west as Lake Superior (Holzkamm et al., 1988). While the purpose of these trips was to harvest the meat and medicinal benefits (Hopper & Power, 1991), the spawning runs also served as social gatherings where political discussions, religious ceremonies, or traditional teachings would occur (Holzkamm et al., 1988). Historical accounts report Lake Sturgeon being brought into the Detroit fish markets by the wagon load and piled like cord-wood where they would be sold for as low as 50 cents apiece and used for fertilizer or fuel (Stone & Vincent, 1900).

Beginning in the mid-1800s, a valuable and targeted commercial fishery for Lake Sturgeon developed, which was driven by the demand for fertilizer, isinglass, biofuel, and towards the start of the 20th century, caviar (Stone & Vincent, 1900; Harkness, 1988; Hay-Chmielewski & Whelan, 1997; Williamson, 2003). As catches exceeded the maximum sustainable yield in the late 1800s, Lake Sturgeon stocks rapidly collapsed throughout the Great Lakes Region (Baldwin et al., 1979; Hay-Chmielewski & Whelan, 1997; Auer, 1999; Baker & Borgeson, 1999). This led to heavy regulations in the 1920s followed by the closure of most American commercial fisheries by 1980 (Baldwin et al., 1979; Auer, 2003; Peterson et al., 2007) and the recent closure of the recreational fishery in Ontario and bordering states (Ontario Ministry of Natural Resources, 2009). Despite these mitigation measures, however, the majority of sturgeon populations have still not rebounded in the Great Lakes.

In more recent decades, the most prominent anthropogenic threat that is inhibiting the recovery of populations is habitat degradation and fragmentation (Hay-Chmielewski & Whelan, 1997; Auer, 1999; Peterson et al., 2007). Estimates suggest that Lake Sturgeon require 250 km to 300 km of unimpeded river-lake habitat as a minimum home range size to complete their life cycle (Auer, 1996). If Lake Sturgeon do not have access to this large river-lake habitat, then populations may become vulnerable to immediate extirpation when habitat is severely impacted or unreachable (Harkness & Dymond, 1961; Baker & Borgeson, 1999). Even if the effects of habitat fragmentation are not immediately felt, over time populations residing in unimpeded stretches of river have greater abundances and faster growth rates compared to populations occupying impounded sections of river (Haxton, 2002, 2003a; Haxton & Findlay, 2008). Natural barriers, such as fast flowing rapids or small waterfalls, may not fragment habitat or population connectivity (Welsh & McLeod, 2010). However artificial developments, such as hydroelectric developments or water diversions, have resulted in severely fragmented habitats, isolated populations, and altered spawning behaviour (Haxton, 2002; Daugherty et al., 2008a, 2008b; Paragamian et al., 2001). Furthermore, the altered flow regimes that often accompany such developments can also hinder the spawning ability and behavior of Lake Sturgeon, thus having an equally negative impact on the spawning success (Haxton, 2002; Paragamian et al., 2001). Beyond overfishing and habitat fragmentation, several other threats continue to inhibit the recovery of Lake Sturgeon, including invasive species and their control measures (Boogard et al., 2003), pollution and poaching (Auer, 1999), and the potential erosion of locally adapted genes (Welsh et al., 2008; Welsh et al., 2010).

Currently, the abundance of Lake Sturgeon in the Great Lakes is estimated to be less then 1 % of its historical level and 27 populations have become extirpated from historically active tributaries in the Great Lakes (Scott & Crossman, 1973; Hay-Chmielewski & Whelan, 1997; Auer, 1999; Ontario Ministry of Natural Resources, 2009). In response to this weakened state, Lake Sturgeon populations have been grouped into eight designatable conservation units throughout their native Canadian range by COSEWIC based on their genetic and biogeographical differences (Ferguson & Duckworth, 1997; COSEWIC, 2006; Welsh et al., 2008; Kjartanson, 2008; Hutchings & Festa-Bianchet, 2009). Designatable unit 8 (DU8) contains the Upper Great Lakes and the St. Lawrence River system, which has been further broken down into three designatable subunits (Lake Erie-Lake Huron (DU8a); Northern Lake Superior (DU8b); and St. Lawrence River (DU8c)) (Velez-Espino & Koops, 2009) and six genetically significant units (Welsh et al., 2010). These designatable subunits and genetically significant units have been developed in light of new evidence that focuses on population trends, biogeography, genetic differences, and life history characteristics within each area (Velez-Espino & Koops, 2009; Welsh et al., 2010). Furthermore, they have been listed as threatened or endangered by all states and provinces surrounding the Laurentian Great Lakes, which has led to an increasing amount of conservation and research efforts (Auer, 2003; Peterson et al., 2007; Ontario Ministry of Natural Resources, 2009).

Habitat restoration and stocking efforts to rehabilitate populations have been introduced with mixed success (Auer, 2003; Peterson et al., 2007; Ontario Ministry of Natural Resources, 2009). Habitat restoration projects have been largely spawning focused, including spawning habitat enhancement and improving accessibility to potential spawning grounds (Daugherty et al., 2008a, 2008b; Trested, 2010). At the Des Prairies River in Quebec, catch per unit of effort (CPUE) of eggs and larvae increased by three to five fold in years following the enhancement of a spawning shoal at the base of a hydroelectric facility (Dumont et al., 2011). Spawning was also documented in the St. Lawrence River following a spawning habitat enhancement project, although comparable baseline assessments were not performed to evaluate success (Johnson et al., 2006). Barriers to migration have also been removed to provide access to historical spawning sites in the Grasse River, New York (Trested, 2010), and potential spawning sites have been evaluated to prioritize future dam removals in the Green Bay basin of Lake Michigan (Daugherty et al., 2006). Reintroduction and supplemental stocking efforts have been ongoing for 20 years, with considerable effort occurring in Michigan and Wisconsin (Smith, 2009). Many of these programs continue with an unknown amount of success, and several issues remain, such as finding suitable donor populations (Drauch et al., 2008; Welsh et al., 2010) and assessing the survival and adaptability of stocked individuals (Drauch & Rhodes, 2007; Smith, 2009). As these rehabilitation projects are costly and unpredictable, research that aims to identify and protect significant Lake Sturgeon habitat before it becomes depleted is both proactive for conservation and more cost-effective.

To date, the movement patterns and habitat utilization of Lake Sturgeon have been identified in several rivers throughout North America (Table 1.1). Through a combination of netting, radio telemetry, and acoustic telemetry, these studies were able to successfully identify critical habitat, the timing of migration, and the environmental or seasonal cues that stimulate these movements. Habitat suitability modeling has also been performed on the Fox, Oconto, Menominee, and Peshtigo Rivers of Green Bay in Lake Michigan to assess critical habitat that could become accessible pending the removal of an artificial obstruction (Gunderman & Elliot, 2004; Daugherty, 2006). Results from these studies become even more powerful when movement patterns are associated with the quantitative assessment of physical habitat features, such as depth and substrate suitability; however few studies such as this exist. Despite the demand and usefulness of results that are generated from the analysis of movement patterns and habitat utilization, such analyses have only been performed in a fraction of Lake Sturgeon systems.

Table 1.1 – River systems and their associated watersheds where Lake Sturgeon movement or migration studies have already been or continue to be undertaken.

River System	**Watershed, Province/State, Country**	**Reference**
Rainy River	Lake of the Woods Watershed, Ontario/Minnesota, Canada/United States of America (respectively)	Rusak & Mosindy, 1997
Mattagami River	Hudson Bay Watershed, Ontario, Canada	McKinley et al., 1998
Ottawa River	Ottawa River Watershed, Ontario/Quebec, Canada	Haxton, 2003b
Menominee River	Lake Michigan Watershed, Michigan/Wisconsin, United States of America	Thuemler, 1985
Sturgeon River	Lake Superior Watershed, Michigan, United States of America	Auer, 1999
Black Sturgeon River	Lake Superior Watershed, Ontario, Canada	Friday, 2005a
Kaministiquia River	Lake Superior Watershed, Ontario, Canada	Friday, 2005b
St. Lawrence River	St. Lawrence Watershed, Ontario/Quebec, Canada	Fortin et al., 1993
Namakan River	Lake of the Woods Watershed, Ontario/Minnesota, Canada/United States of America (respectively)	Welsh & McLeod, 2010
Manistee River	Lake Michigan Watershed, Michigan, United States of America	Lallaman et al., 2008
Grasse River	St. Lawrence River Watershed, New York, United States of America	Trested, 2010
Kettle River	Mississippi River Watershed, Minnesota, United States of America	Borkholder et al., 2002
Mississippi River	Mississippi River Watershed, Minnesota/Wisconsin, United States of America	Knights et al., 2003
Peshtigo River	Lake Michigan Watershed, Michigan/Wisconsin, United States of America	Benson et al., 2005
Detroit River	Lake Erie Watershed, Ontario/Michigan, Canada/United States of America (respectively)	Caswell et al., 2004
Lake Winnebago	Lake Michigan Watershed, Wisconsin, United States of America	Lyons & Kempinger, 1992
Black Lake	Lake Huron Watershed, Michigan, United States of America	Smith & King, 2005
Portage Lake	Lake Superior Watershed, Michigan, United States of America	Holtgren & Auer, 2004

The Pic River in Ontario, a tributary that drains into north eastern Lake Superior, is a system where little is known about Lake Sturgeon population demographics, movement patterns, and/or habitat utilization. Studies of these subjects would inevitably help guide decision making and land use planning for the Pic River watershed for the enhancement and protection of critical Lake Sturgeon habitat. Furthermore, with no artificial obstructions and limited development within the watershed, the Pic River Lake Sturgeon population may be one of the least disturbed populations in the Great Lakes, thus making it a good reference population to collect baseline conditions. In response to this knowledge gap, the Anishinabek/Ontario Fisheries Resource Centre (A/OFRC), the Department of Fisheries and Oceans Canada (DFO), Pic River First Nation, the Ontario Ministry of Natural Resources (OMNR), and the United States Fish and Wildlife Service (USFWS) have been conducting research on Lake Sturgeon in the Pic River with various methodologies since 2002. The overall objective of this research has been to identify critical Lake Sturgeon habitat, monitor seasonal movement patterns, and assess baseline conditions of the population. This thesis is the culmination of these efforts and is broken into two main chapters that relate to Lake Sturgeon movement patterns and spawning habitat, respectively.

The second chapter of this thesis reports Lake Sturgeon movement patterns that were monitored for three years using radio telemetry to identify environmental cues for migration, to assess commonly used habitat and associated physical features, and to describe general movement patterns as they related to spawning and non-spawning individuals. First, it was hypothesized that inter-annual differences in the timing of Lake Sturgeon migration should coincide with abiotic conditions that deviate from average flow, thermal, or ice conditions in the Pic River. Second, it was hypothesized that Lake Sturgeon moving from lakes to rivers, or vice versa, should be stimulated to do so by a narrow range of thermal and flow conditions that vary seasonally and annually. Finally, since spawning and non-spawning Lake Sturgeon utilize the river for different purposes, it was hypothesized that their timing of migration and movement patterns should also vary.

The third chapter of this thesis reports on Lake Sturgeon spawning habitat that was mapped at three potential spawning sites to quantitatively assess the habitat suitability using a model that was developed for northern Ontario rivers (Threader et al., 1998). Spawning assessments were also performed to confirm the location and timing of spawning and to evaluate the predictive ability of the habitat suitability model (HSM) by comparing the modeled results with empirical observations of spawning activity. Since the HSM evaluates the overall spawning suitability based on depth and substrate, and the daily suitability by factoring in thermal and flow conditions, two hypotheses were formulated to test the overall and daily predictions that were generated by the HSM. The first hypothesis for this chapter was that Lake Sturgeon should reproduce at spawning sites, and locations within those sites, that have the greatest proportion and amount of highly suitable habitat relative to poorly suited habitat. The second hypothesis of this chapter is that Lake Sturgeon should spawn when optimal thermal conditions of 12˚C to 16˚C are reached at each respective spawning site (Threader et al., 1998). Identifying and protecting critical Lake Sturgeon habitat has been identified as a priority research objective for the recovery of Lake Sturgeon in Lake Superior and throughout the Great Lakes (Auer, 2003; Hay-Chmielewski & Whelan, 1997; OMNR, 2009). This study will contribute to these research efforts by monitoring movement patterns, identifying critical habitat, and quantitatively assessing spawning suitability at three potential spawning sites within a tributary where very little information previously existed.

Chapter 2: Patterns, Timing, and Environmental Cues to Lake Sturgeon Migration

2.1 INTRODUCTION

Throughout the world, fish species undertake long and perilous migrations with the intention that their overall fitness and well-being will be optimized in the habitat conditions of their destination. Scombridae (Tuna) undertake long migrations in search of highly suitable spawning and foraging habitat (Block et al., 2005), Gadidae (Cod) undertake migrations to reduce interspecific and intraspecific competition (Laurel et al., 2004), and Gasterosteidae (Sticklebacks) undertake migrations to avoid inbreeding with closely related individuals (Frommen & Bakker, 2006; Cano et al., 2008). Although it is important to understand why species and individuals migrate, it is equally important to determine the timing of these migrations and the environmental cues that are responsible for stimulating migration patterns.

Numerous studies have examined the timing and environmental cues of commercially valuable migrating fish stocks, particularly for salmonid fishes (Svendsen et al., 2004; Anderson & Beer, 2009; Mathes et al., 2010). Many salmonid species undertake these migrations in search of their natal spawning habitat, and fishing regulations within these spawning tributaries are often aligned with the timing and environmental cues of these migrations (Bardonnet & Bagliniere, 2000). In the Columbia River system, for example, harvest regulations for Chinook Salmon (*Onchorhynchus tshawytscha*) are related to the timing of their migrations, which are predicted by models based on oceanic environmental variables (Keefer et al., 2008; Jepson et al., 2010). In Norwegian rivers, Brown Trout (*Salmo trutta*) coordinate their migrations with peaks in water discharge in order to ascend barriers or obstacles on route to their natal spawning grounds (Rustadbakken et al., 2004). In regulated waterways in Europe, dam operators must establish minimum river flows to facilitate the up and downriver migration of Atlantic Salmon (*Salmo salar*) (Lundqvist et al., 2008). Although the timing and environmental cues to salmonid migrations, and other commercially valuable fish stocks, are well studied, less is known about the migrations of Lake Sturgeon.

Lake Sturgeon undertake annual migrations from lakes to rivers in search of quality foraging and spawning habitat (Bemis & Kynard, 1997; Peterson et al., 2007). Although not all Lake Sturgeon populations use both lake and river habitats (Borkholder et al., 2002; Friday, 2004), estimates suggest that most Lake Sturgeon require 250 km to 300 km of unimpeded river-lake habitat as a minimum home range size (Auer, 1996). If Lake Sturgeon do not have access to this large non-degraded riverine habitat, then populations are susceptible to extirpation, as they were throughout the 1900s in response to overfishing and impoundments (Harkness & Dymond, 1961; Baker & Borgeson, 1999). Furthermore, Lake Sturgeon populations residing in unimpeded stretches of river had greater relative abundances and faster growth rates compared to populations occupying impounded sections of the river (Haxton, 2002; Haxton & Findlay, 2008). Therefore, it is well understood amongst Lake Sturgeon biologists that long and unimpounded rivers, which facilitate long distance migrations, are essential in the recovery and long term conservation of this species (Hay-Chmielewski & Whelan, 1997; Auer, 2003). However, despite this acknowledgement, there has been relatively little research focused on the migration patterns of Lake Sturgeon in natural unimpeded river systems.

In the unimpeded Rainy River and Lake of the Woods system in northern Ontario, spawning Lake Sturgeon entered the river with increasing water temperatures and flows, but researchers could not identify an absolute temperature or flow value that induced this movement (Rusak & Mosindy, 1997). Inter-annual differences in the timing of migration were also observed in this system, where late movements coincided with delayed increases in water temperature (Rusak & Mosindy, 1997). In the Sturgeon River, a regulated tributary flowing into southern Lake Superior, spawning Lake Sturgeon left the spawning site in mid May, where they rapidly descended the river and returned to the lake by late June (Auer, 1999). In contrast, non-spawning Lake Sturgeon left the river later in the season and were highly congregated in localized distributions throughout the lower sections of the river where deep river habitat is available (Auer, 1999). In the Grasse River, a tributary connected to the St. Lawrence River system, a strong preference for pool mesohabitats was selected for by adult Lake Sturgeon in all seasons except for spring, where home range sizes expanded to include runs, riffles, and pool mesohabitats (Trested, 2010). Similar migration patterns have been observed in the St. Lawrence and Ottawa River systems in Quebec (Fortin et al., 1993), the Mattagami River system in northern Ontario (McKinley et al., 1998), and the Upper Mississippi River system (Knights et al., 2002). Unlike these aforementioned systems, where Lake Sturgeon migrate from lakes to rivers to facilitate spawning and other life cycles, in the Kaministiquia River sturgeon form a resident population within the river, despite it being connected to Lake Superior (Friday, 2004; 2005b). In the Black Sturgeon River, Lake Sturgeon leave the river, but remain in Black Bay, which is in Lake Superior, to overwinter (Friday, 2005a). In each of these systems, Lake Sturgeon movements coincided with increases in water temperature and flow, however, the timing of migration varied from system to system and from year to year depending on thermal and flow regimes. Cumulatively, these studies have revealed that there is sufficient ambiguity in the movements of Lake Sturgeon between different systems, between spawning and non-spawning individuals, and in the timing of migration, which coincides with environmental variables.

The objectives of this chapter are to investigate inter-annual differences in the timing of migration, to identify differences in the migration patterns between spawning and non-spawning individuals, and to identify environmental variables that can be used to accurately predict the timing of Lake Sturgeon migration. Furthermore, this study aimed to summarize the migration patterns of Lake Sturgeon and to identify commonly used habitat within the Pic River, a relatively pristine northern Ontario tributary that is connected to Lake Superior. First, it is hypothesized that inter-annual differences in the timing of Lake Sturgeon migration should coincide with abiotic conditions that deviate from average flow, thermal, or ice conditions in the Pic River. It is therefore hypothesized that delayed warming, spring freshets, or ice free conditions should coincide with later migrations, and conversely, early warming, spring freshets, or ice free conditions should coincide with earlier migrations. Secondly, it is hypothesized that Lake Sturgeon moving from lakes to rivers, or vice versa, should be stimulated to do so by abiotic conditions, commonly referred to as environmental cues to migration. It is predicted that Lake Sturgeon will enter the Pic River during the high flows of the spring freshet and leave once flows have decreased in the late summer. As well, individuals should enter the Pic River as temperatures warm and shortly after ice out, and return to the lake once higher temperatures are reached in the late summer. Finally, since spawning and non-spawning Lake Sturgeon utilize the river for different purposes; the timing of their migrations should likewise vary. It is predicted that spawning Lake Sturgeon should enter the river, reach their uppermost point (e.g. the spawning grounds), and descend to deep-water pools near the mouth of the river significantly earlier compared to their non-spawning counterparts.

2.2 METHODS

2.2.1 Study Area:

The Pic River drains into north-eastern Lake Superior at the community of Pic River First Nation and Pukaskwa National Park, Ontario, Canada (UTM: 551435W, 5393249N). The river begins at McKay Lake Dam (UTM: 550822W, 5497725N) near the community of Caramat, Ontario, and has a gross drainage area of 4270 km^2; making it a medium-sized river within Ontario (Water Survey of Canada, 2010). Within the Pic River watershed there are very few developments, and the rugged terrain surrounding the river makes it difficult to access large portions of it. Navigation can also be difficult due to high turbidity and large amounts of floating or sunken debris within the river (mainly logs).

This study was conducted in the lower 103 km of the Pic River from the mouth north eastwards to the uppermost navigable point of Manitou Falls (UTM: 566912W, 5450909N) near the community of Manitouwadge, Ontario (Figure 2.1). Within this segment, there are two major tributaries that flow into the Pic River, the Black River and the Kagiano River which confluence with the Pic River at 4 km and 98 km from Lake

Superior, respectively. The uppermost navigable point in the Black River is a hydroelectric facility located 10.2 km from Lake Superior (UTM: 556601W, 5389998N), whereas the uppermost navigable point in the Kagiano River is a natural barrier located 99.8 km from Lake Superior (UTM: 565457W, 5449256N).

Preliminary studies, both scientific and traditional ecological knowledge, indicated that the most heavily utilized Lake Sturgeon habitat within the Pic River was contained in the upper and lower 25 km of the river, in locations hereby referred to as; the mouth (foraging; 0 river km), the Lower Rapids (foraging; 25 river km), Henry's Honey Hole (staging and foraging; 97 river km), Kagiano Falls (spawning; 98 river km), and Manitou Falls (spawning; 103 river km) (Quinlan, 2002; Couchie, 2008; Deary, 2008; Bill Gardner, personal communication; Nikki Commanda, personal communication). Accordingly, crews of two to three people captured Lake Sturgeon and monitored their migration patterns in the lower (Figure 2.2A) and upper (Figure 2.2B) 25 km of the river. Fisheries and Oceans Canada, along with Pic River Hydro and Hatch Energy in 2010, focused their efforts in the upper 25 km of the river, while the Anishinabek/Ontario Fisheries Resource Centre, on behalf of Pic River First Nation, and Trent University focused their efforts in the lower 25 km of the river. Crews were present at each portion of the river in 2008, 2009, and 2010, from early spring to late summer. The spring arrival of crews varied from year-to-year and so did their availability, therefore sampling times were limited by the availability of crews and a compromised routine.

A

B

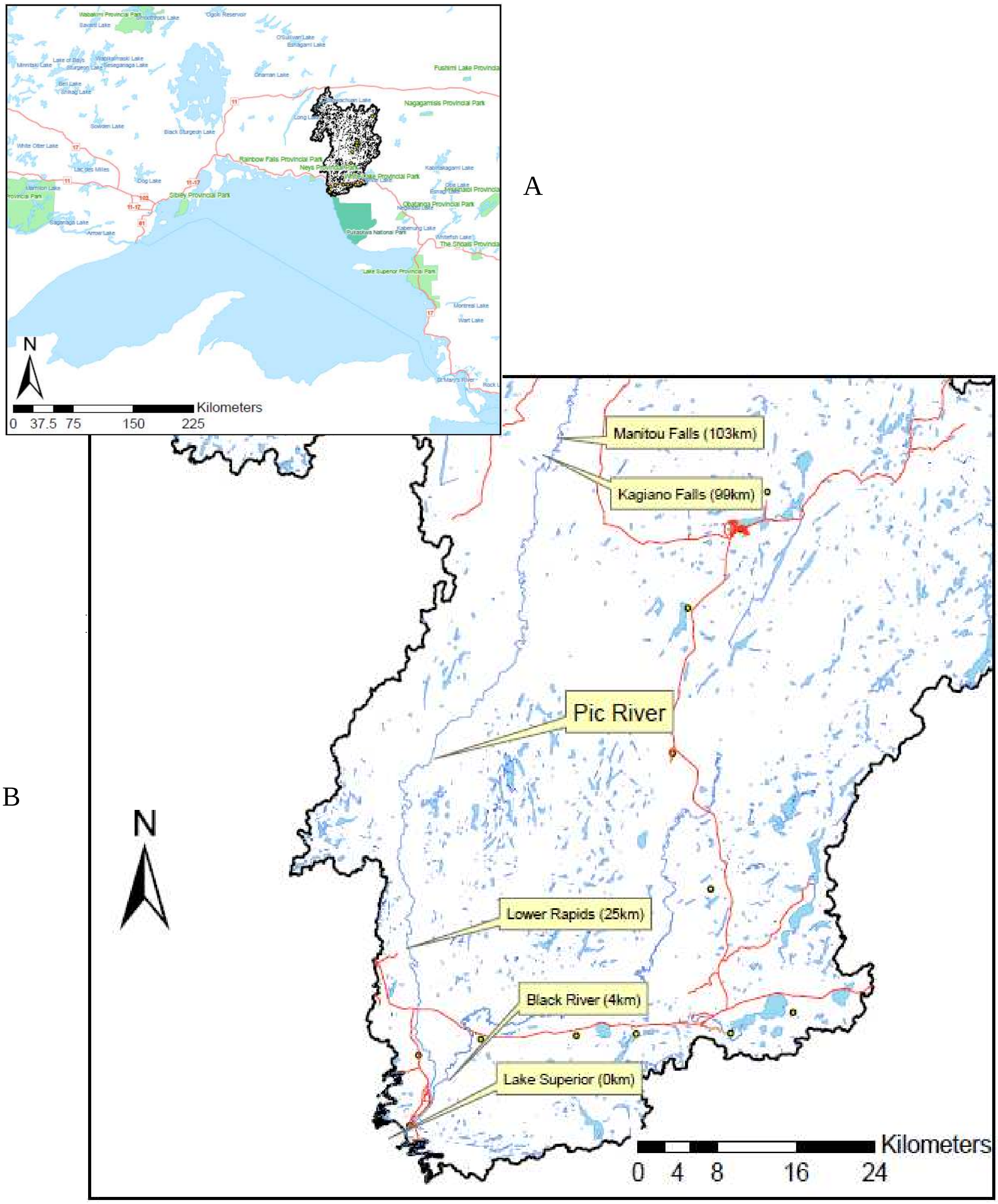


Figure 2.1 – The location of the Pic River watershed relative to the Lake Superior catchment (A) and an enlarged map of the Pic River watershed (B). The labeled points in part B of this figure indicate key locations for Lake Sturgeon research in the Pic River.

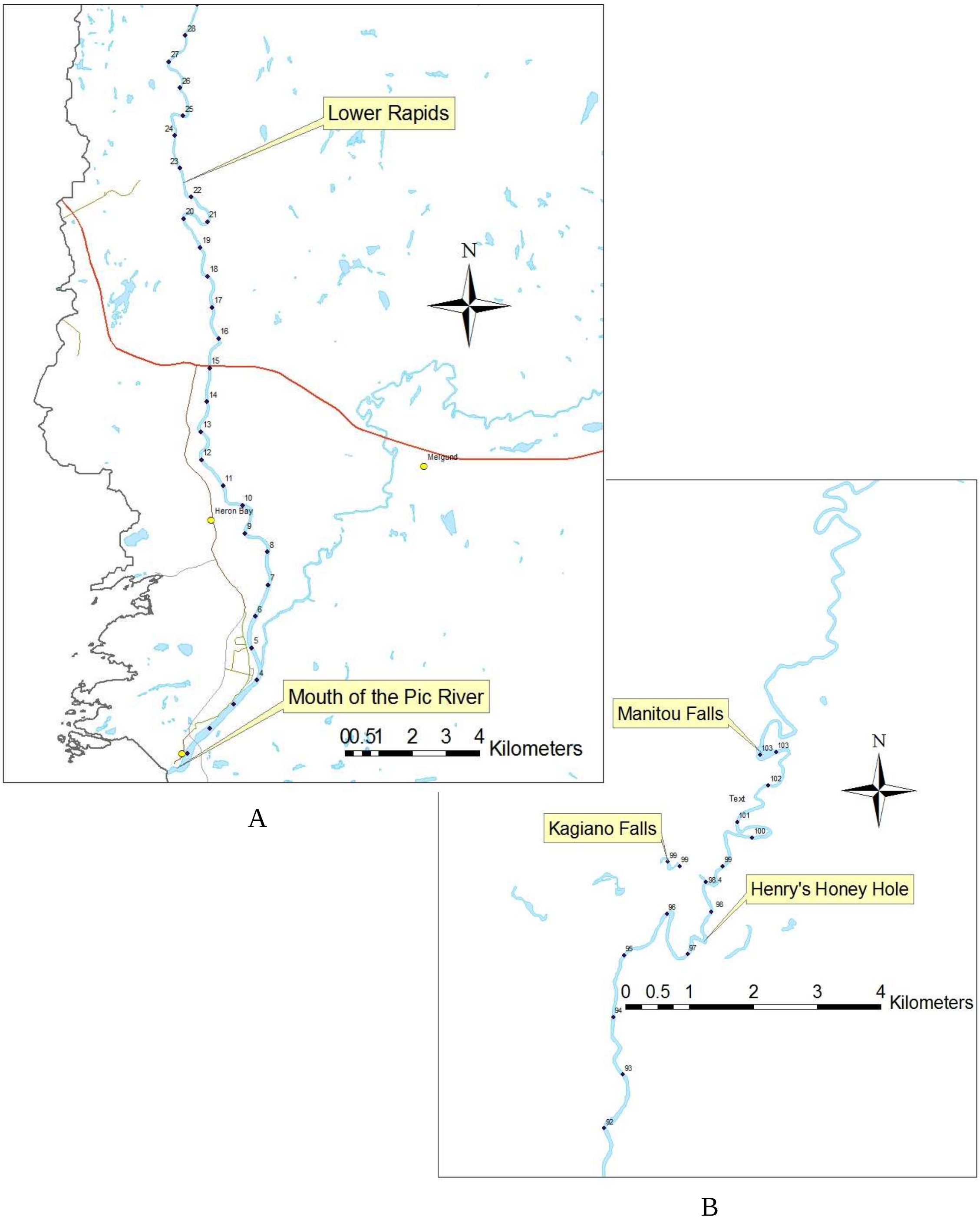


Figure 2.2 – The lower (A) and upper (B) portions of the Pic River, which were identified in previous studies as habitat that was frequently utilized by Lake Sturgeon. Numbers indicate the upstream distances in kilometers from Lake Superior.

2.2.2 Gill Netting:

Gill netting occurred in the Pic River from 2002 to 2003 and from 2007 to 2010 with varying amounts of effort. This study will primarily consider the catch data from 2008-2010, when Lake Sturgeon were radio-tagged and their migrations monitored. Netting occurred from May 28 to August 14 in 2008, from May 24 to August 14 in 2009, and from May 5 to June 29 in 2010. Nylon gill nets were set perpendicular to shore at an angle of roughly 90°. Stretch mesh size ranged from 16.51 cm (6.5") to 30.48 cm (12"), with the majority of nets being between 20.32 cm (8") to 25.4 cm (10"). Net lengths ranged from 30.5 m (100') to 91.5 m (300') depending on the width of the river where it was being set. Gill nets were set overnight and upon retrieval the location, duration, depth, water temperature, net length, mesh size, cloud cover, and precipitation type were recorded for each set. Nets were set throughout the river, with the majority nets being set in the lower 20 km and upper 10 km of the river. The distance of each net from Lake Superior, in kilometers, was calculated using ArcMap.

Physical attributes of all captured Lake Sturgeon were recorded, including; fork length (mm), total length (mm), round weight (g), and girth (mm). If distinguishable, the sex and stage of gonadal development were also recorded based on criteria provided by Bruch et al. (2001). As well, the first fin ray from the left pectoral fin was removed for ageing and a small tissue sample from this location was taken for genetic analysis. Lake Sturgeon were tagged with a passive integrated transponder (PIT) tag under their third dorsal scute and a Floy tag to the left of their dorsal fin to allow for the identification of recaptured individuals. Individuals exceeding 4500 g (4.5 kg) were given an internal or external radio tag, if one was available, to monitor their future movement patterns within the Pic River.

2.2.3 Radio Telemetry:

For this study, five external radio tags (model number: F2090) and forty five internal radio tags (model number: F1855B) were used(Advanced Telemetry Systems Inc., Isanti, Minnesota). Each radio tag had a pulse rate of 55 pulses per minute (ppm), a pulse width of 20 milliseconds, and a unique radio frequency ranging from 150.011 kHz to 151.485 kHz. The weight and battery life varied between the two types of radio tags, with internal radio tags weighing 87 g and having a battery life of 1185 days and external radio tags weighing 47 g and having a battery life of 1086 days. Fewer external radio tags were applied due to concerns that external tags would become detached and tag retention would be low, which the results verified to be a valid concern. External radio tags were attached to Lake Sturgeon exceeding 4500 g (4.5 kg) by embedding the posterior and anterior attachments of the radio tag through the base of the dorsal fin.

Surgical procedures were undertaken to implant internal radio tags into the body cavity of Lake Sturgeon exceeding 9000 g (9 kg). 9000 g Lake Sturgeon were selected in order to minimize any harm or unnatural behaviour that may result from the application of the tag and in accordance with the “two percent rule” (Adams et al., 1998; Brown et al., 1999; Jepsen et al., 2003). The surgical procedure used to implant radio tags into the body cavity of Lake Sturgeon was similar to that described by Friday (2005a; 2005b) and followed guidelines outlined by the Canadian Council on Animal Care (Ackerman et al., 2000). Lake Sturgeon were sampled and then put into a large tub (Rubbermaid Commercial 4244-Bla 70 Gallon Stock Tank Black) with 60 L of river water, to which 32 mL of a clove oil and ethanol solution (1.2 mL clove oil to 10.8 mL of ethanol) was added as an anesthetizing agent. Fish remained in the anesthetizing tub until they could no longer control their orientation in the water, lacked locomotory skills, and their stomachs appeared to have a concave indent. Once fish showed these symptoms of the anesthetic (Ackerman et al., 2000), they were removed from the tub and placed in a canvas surgery sling that provided adequate water circulation around the gills and drainage. All surgical tools were thoroughly cleaned and decontaminated before commencing the surgical procedure using isopropyl alcohol. A 4 cm to 6 cm incision was then made along the mid-ventral line of the fish, using a size 10 scalpel, to expose the Lake Sturgeon's body cavity. Another small incision, using a 14 gauge needle tip, was then made posterior to the initial incision to feed the antenna tail of the radio tag outside of the body cavity. The radio tag was then activated, the frequency recorded, and carefully inserted into the body cavity. The 4 cm to 6 cm incision was then sutured together with four to five stitches (Ethicon Monocryl Plus, CT-1 36 mm ½ Circle, Violet Monofilament) and strengthened using tissue adhesive (3M™ Vetbond™). The Lake Sturgeon were immediately immersed in fresh river water and constantly monitored until they showed symptoms of recovery from the anesthetizing agent (Ackerman et al., 2000). The entire procedure took roughly 30 minutes and upon completion the Lake Sturgeon was then released in the river, away from any nets or debris.

Base stations (model number: R4500S) (Advanced Telemetry Inc., Insanti, Minnesota) were powered by a deep cycle marine battery that was charged by a solar panel and were comprised of two antennas, one pointing directly upriver and the other pointing directly downriver. Based on field tests at the base stations, it was estimated that each antenna could detect a radio signal approximately 500-1000 m away in the direction of the antenna (depending on the topography of the river). The base stations could collect and store up to 80,000 bytes of information before overwriting previously recorded data, therefore downloading times were coordinated to avoid losing any data (roughly every week during the spring/summer and twice during the fall/winter). Radio frequencies were inputted into the receivers once they were surgically implanted into Lake Sturgeon. Base stations were setup as close to the shoreline as possible and in locations that could be easily accessed by boat or vehicle (Figure 2.3). Some of the stations were moved throughout the year to coordinate with the migration patterns being observed. Upon setup, the location of each base station (UTM), the direction of each antenna (upriver or downriver), and the distance of the base station from Lake Superior were recorded (Table 2.1).

Table 2.1 – Date, location, and orientation of antennas for each base station that was operable over the course of this study. * = Julian calendar date was one day behind until it was corrected or on July 6th, 2008.

Year	Station #	Installation Date	Decommissioning Date	Distance from Lake (km)	Easting	Northing	Antenna 1	Antenna 2
2008*	1	June 17	November 3	0.085	551527	5383215	Upriver	Downriver
2008	2	June 18	October 26	24.750	551645	5402597	Downriver	Upriver
2008	3	July 25	November 3	4.432	554237	5386437	Downriver	Upriver
2008	3	November 3	November 18	1.441	552316	5384144	Upriver	Downriver
2009	1	May 21	December 31	0.085	551527	5383215	Upriver	Downriver
2009	3	June 3	October 26	24.750	551645	5402597	Upriver	Downriver
2010	1	January 1	December 31	0.085	551527	5383215	Upriver	Downriver
2010	2	April 7	July 10	24.750	551645	5402597	Upriver	Downriver
2010	3	April 25	May 21	90.456	564500	5443592	Upriver	Downriver
2010	3	May 21	July 12	103.000	567183	5450923	Upriver	Downriver

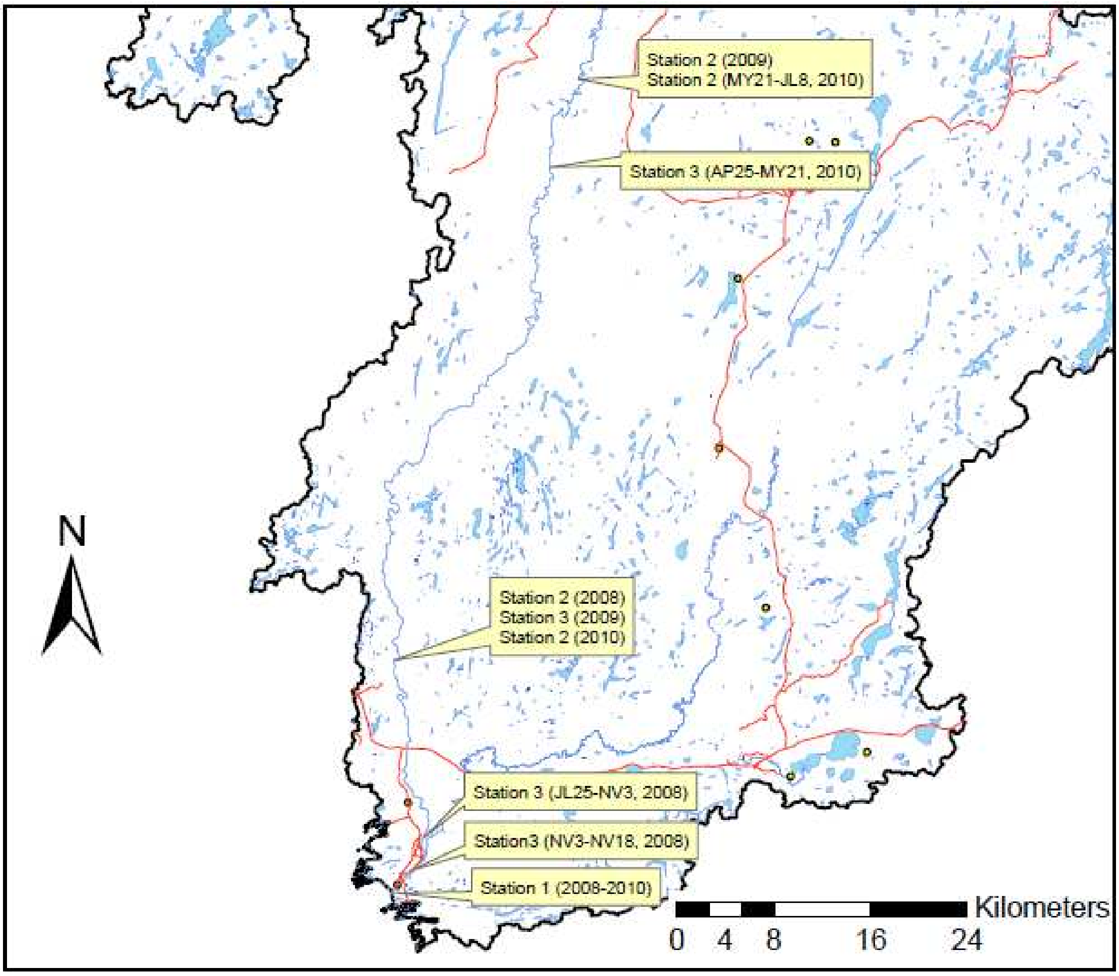


Figure 2.3 – Location of base stations throughout this study with details of the set up of each base station provided in Table 1.

The base stations often collected interference or ‘noise’ while operating on the Pic River (especially base station #3). Therefore, a method was developed to classify valid and invalid information that was collected from each base station. For a base station recording to be considered valid, the radio frequency in question had to first be picked up by antenna 0 (the default control antenna) and then by antenna 1 and/or 2. As well, the radio frequency had to be recorded at least twice per hour by either antenna 1 and/or 2. The classification method also factored in the ratio of pulses to matches, whereby the number of pulses should vary between 10 and 16 and the number of matches should be between 75% and 100% of this value. This classification variable is based on the setup of each base station, whereby each base station scans each radio frequency for 15 seconds per antenna at a pulse rate of 1 pulse per second and each radio tag has a pulse rate of 55 pulses per minute (Mike Friday, personal communication; Sound Metrics Inc., personal communication). Cumulatively, these three steps were able to accurately decipher and classify valid and invalid data that were collected by the base stations.

Where possible and as time permitted, manual telemetry sweeps of the river were performed throughout the study period. These were performed by travelling in the boat at a speed of approximately 10-15 km/h while scanning each radio frequency that had already been activated (2-3 s per frequency). Once detected from afar, the precise location of the individual (±1.5 m) would be found by reducing the boat speed and the amount of gain on the manual receiver (i.e. its search radius). In the lower section of the river an Advanced Telemetry System Inc. receiver was used (model number: R410) and at the upper section of the river a Lotek receiver was used (model number: SRX 600). When radio tagged Lake Sturgeon were found, the location (Garmin eTrex), date, time, depth, and temperature were recorded at that location. Whenever a Lake Sturgeon was recorded, either manually or by base station, the distance of that Lake Sturgeon from Lake Superior was determined using ArcMap.

2.2.4 Abiotic Conditions:

Part of this study aimed to identify the environmental cues that may be responsible for stimulating and terminating Lake Sturgeon migration. Therefore, monitoring of water temperature and discharge occurred at the mouth of the Pic River to represent the abiotic conditions that would be experienced by migrating Lake Sturgeon at that time. Water temperature was recorded once every half hour using a temperature data logger (model number: HOBO Water Temp Pro v2 Data Logger) which was located approximately 500 m from Lake Superior (UTM: 551578W, 5383243N). Mean daily temperature was based on the 48 daily readings from this temperature logger. Mean daily water discharge was provided by Environment Canada’s Water Surveying Station (station name: PIC RIVER NEAR MARATHON; station ID: 02BB003) (Water Survey of Canada, 2010). This autonomous surveying station records water level and calculates water discharge based on a rating curve that has been established between water level and discharge for the Pic River. This station also monitors ice conditions on the Pic River and records the day when the river becomes ice free. Issues with the instrumentation occurred from June 2 to June 7, 2009 and from June 18 to August 12, 2009, resulting in estimates of water discharge during these dates. These estimates were calculated by Environment Canada based on water discharge levels at other gauging stations within close proximity and weather conditions.

2.2.5 Data Analysis:

To determine inter-annual differences in the timing of Lake Sturgeon migration, the data collected by base station 1 (at the mouth of the river) was used to assess when individuals entered and exited the river. Individuals were considered to have entered the river once they were recorded by antenna 1 (i.e. directed into the Pic River) and had been recorded at some later point within the river. Also, if individuals were first captured or recorded more than 10 km upriver from Lake Superior, an entry date was not given to that individual for that particular year and they were excluded from the analysis. Conversely, individuals were considered to have exited the river once they were exclusively recorded by antenna 2 (i.e. directed into Lake Superior) and were not recorded at some later point within the river. The duration that Lake Sturgeon remained in the river (number of days) was determined by subtracting the exit date from the entry date. The date when Lake Sturgeon reached their uppermost distance was based on data that were collected by any of the three base stations, manual telemetry records, or catch records. Individuals were classified into either the spawning or non-spawning portion of the population based on their uppermost point of migration.

Julian dates for when Lake Sturgeon entered the river, reached their uppermost point, and exited the river were compiled for each year and analyzed using STATISTICA (Version 6.0; StatSoft Inc.; Tulsa, Oklahoma, USA). One-way ANOVAs were performed to identify interannual differences in the timing of migration and differences between spawning and non-spawning individuals. A 95% confidence interval was used to identify significant differences between years and spawning versus non-spawning individuals.

Year and spawning status were used as categorical variables for this analysis, while Julian date at entry, uppermost point, and exit served as dependent variables for this analysis. Tukey post-hoc tests were then performed to identify which years of study were significantly different.

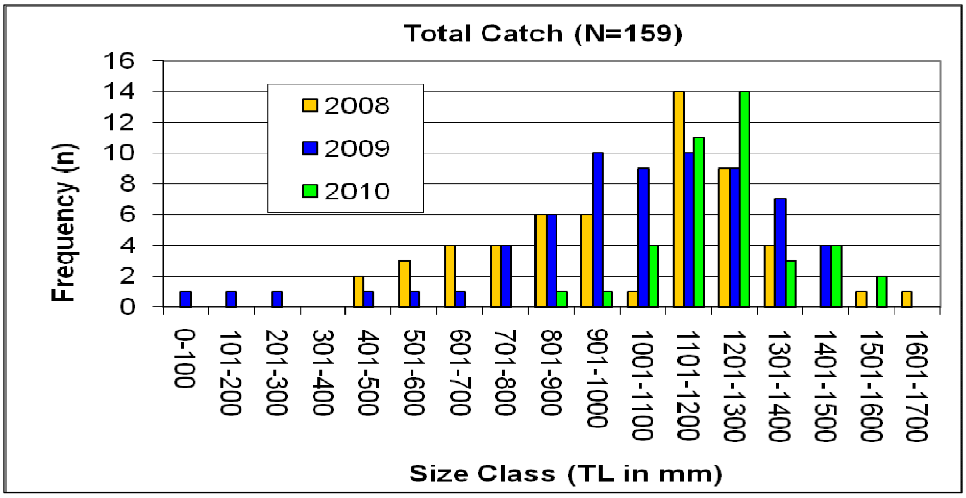
Once Lake Sturgeon entered the river (location = 0), reached their uppermost point (location = 0.5), and exited the river (location = 1), the mean daily water discharge and mean daily temperature for that day was recorded. Backward stepwise multiple regression analysis was then performed with the dependent variable of location (entry, uppermost, and exit) and the independent variables of mean daily water discharge and mean daily water temperature. This analysis determined whether temperature or water discharge was a better environmental cue for predicting the timing of Lake Sturgeon migration. Box plots, with 95% confidence intervals, were then created to show the nature of the relationship between environmental cues and the location of migrating Lake Sturgeon. Finally, to determine if Lake Sturgeon migration was stimulated by ice conditions, a bivariate correlation between the mean annual date of entry and the day of ice disappearance was performed.

2.3 RESULTS

Throughout the course of this study, a total of 159 Lake Sturgeon were captured and 30 individuals were recaptured. Of these 159 Lake Sturgeon, 47 of them were fitted with either an internal (N=43) or external (N=4) radio tag. The mean total length for radio tagged individuals was 1236.6 mm (1.2 m), while the mean round weight of these individuals was 13686.0 g (13.7 kg), size class frequency distributions are shown in

Figure 2.4. Tag retention was high for the internal radio tags (100%) and low for the external radio tags (50%). The loss of two external radio tags (frequencies: 150.571 kHz and 150.612 kHz), meant that only 45 Lake Sturgeon were radio tagged for the duration of this study.

A



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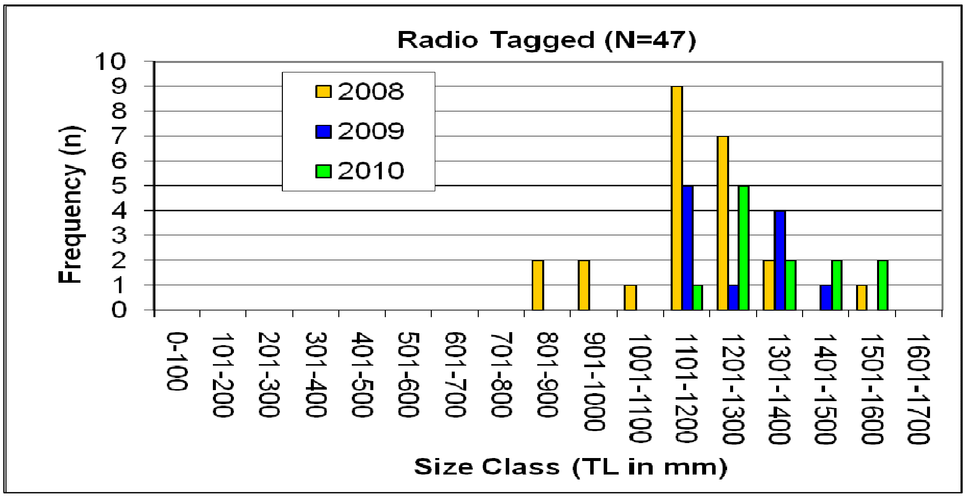


Figure 2.4 – Size class frequency distributions of all Lake Sturgeon that were captured during this study (A) and of Lake Sturgeon that were radio-tagged during this study (B).

2.3.1 Migration Patterns:

The migration patterns of Lake Sturgeon for each year of study, as well as their relationship with mean daily water discharge and mean daily water temperature are shown in Figures 2.5a and 2.5b. There were three distinct migration patterns that were observed during this study. The first was that Lake Sturgeon entered the river and remained within the lower 5km to 10km of the river for all or part of the spring-summer months. The second was that Lake Sturgeon entered the river and traveled upriver to the lower rapids, which were located roughly 25km upriver from Lake Superior. Given that no evidence of spawning was collected at either of these sites (see Section 3.3.3), combined with the fact that Lake Sturgeon were often found in deep water habitat with silt or clay substrate, it is thought that Lake Sturgeon exhibiting either of these migration patterns were most likely seeking higher quality foraging habitat. The third common migration pattern that was observed was exclusive to the spawning portion of the population. Spawning individuals tended to enter the river and ascend the river very quickly, usually reaching Henry’s Honey Hole (97km upriver from Lake Superior) within 10 days of entering the river. They would remain at Henry’s Honey Hole, Manitou Falls (103km), or Kagiano Falls (99km), for a period of 10 days to 15 days and would then rapidly descend the river, where they would spend a variable amount of time within the lower 10km of the river before returning to Lake Superior for the fall and winter. These three distinct migration patterns were observed in each year of study by a varying pool of individuals depending on their reproductive cycle.

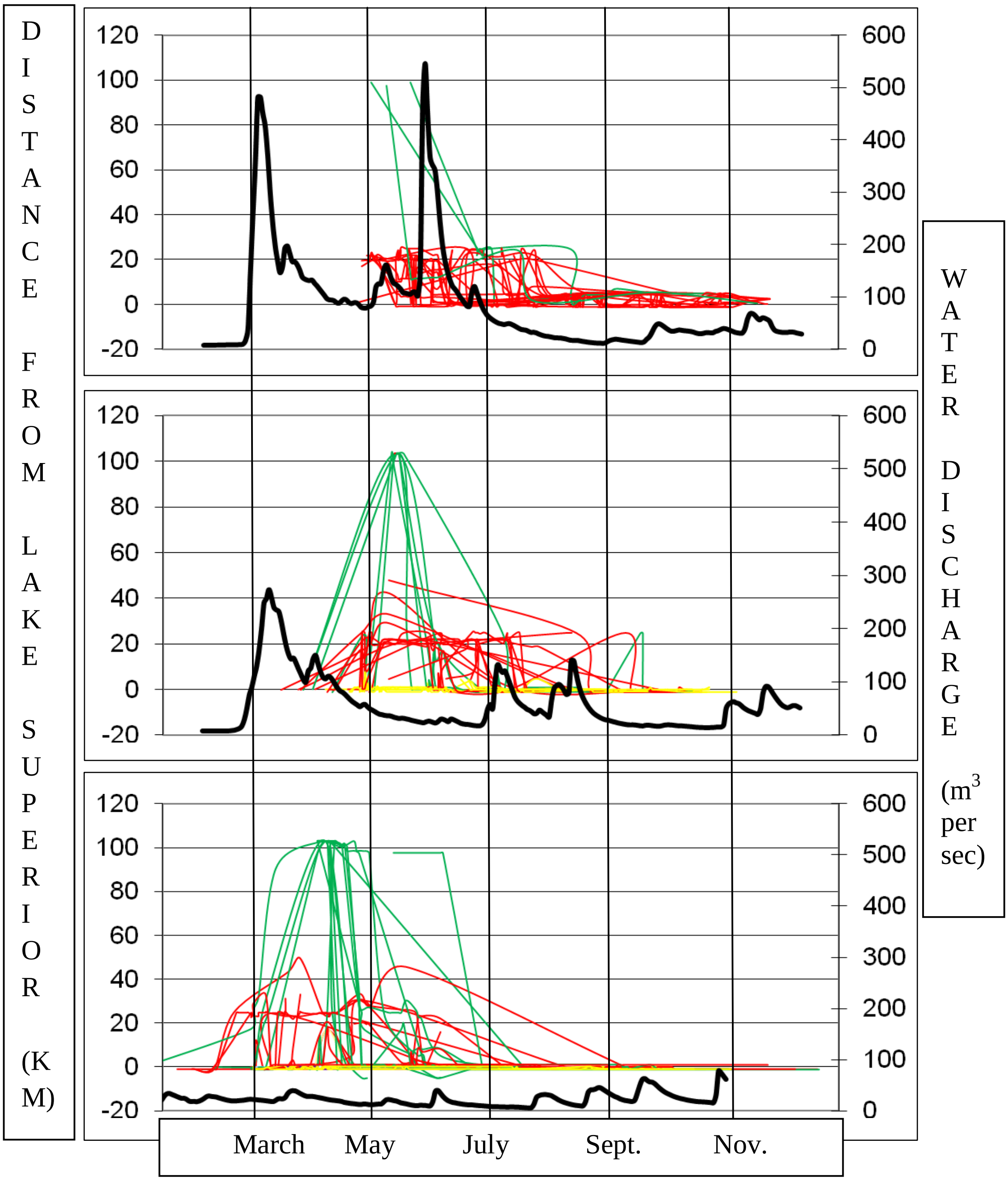


Figure 2.5a - Migration patterns for individual sturgeon in relation to mean daily water discharge (black line) in each year of the study (2008 top; 2009 middle; 2010 bottom). Yellow lines correspond to migration pattern one, red lines correspond with migration pattern two, and green lines correspond with migration pattern three (see text above for description of patterns).

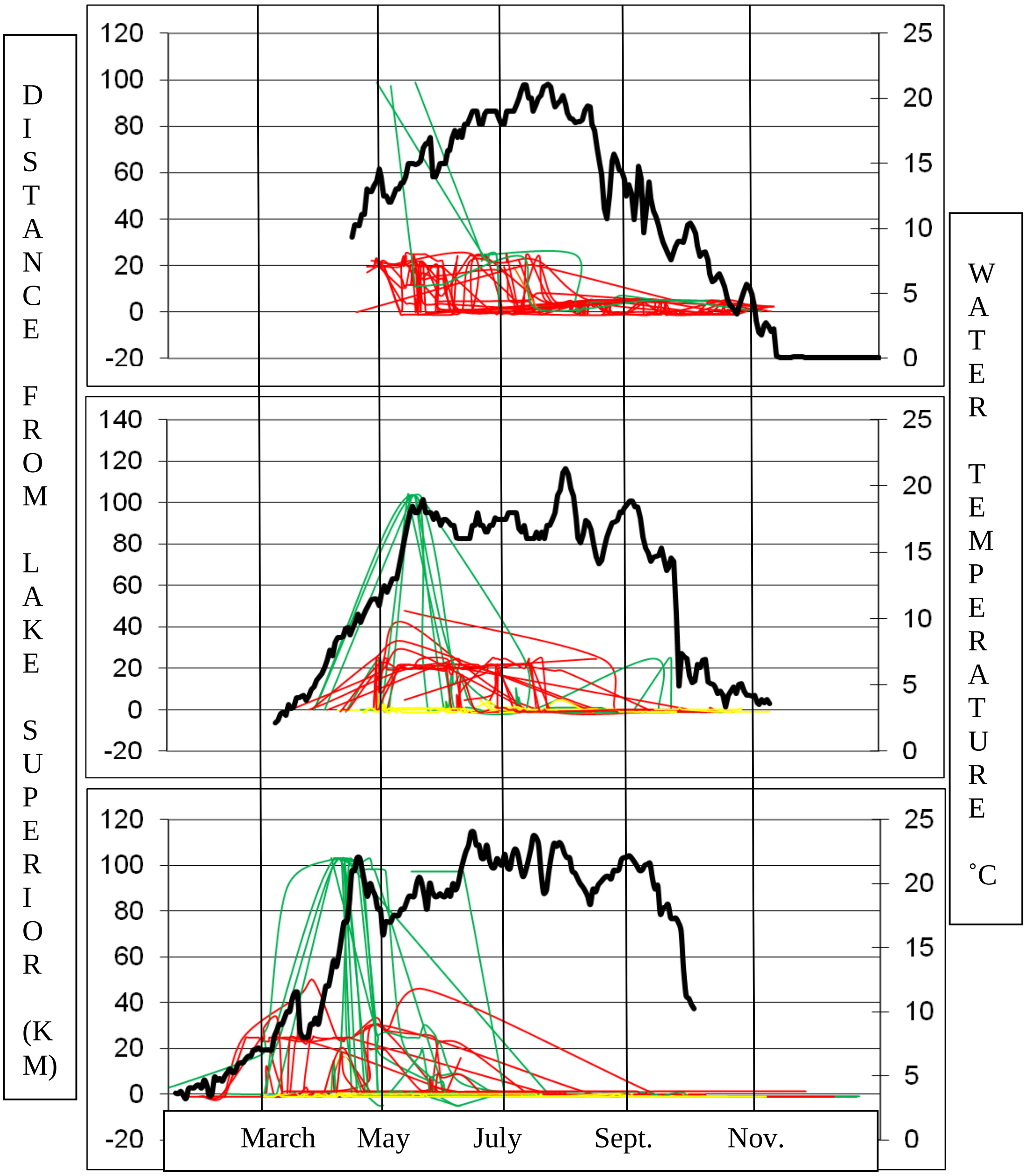


Figure 2.5b - Migration patterns for individual sturgeon in relation to mean daily water temperature (black line) in each year of the study (2008 top; 2009 middle; 2010 bottom). Yellow lines correspond to migration pattern one, red lines correspond with migration pattern two, and green lines correspond with migration pattern three (see text above for description of patterns).

Results from the manual tracking also indicated that Lake Sturgeon tended to congregate in distinct locations within the Pic River, most noticeably within the mouth of the Pic River (0 km to 5 km), the lower rapids (16 km to 25 km), and Henry's Honey Hole (96 km to 100 km) (Figure 2.6). Of all the detections from the manual telemetry sweeps in 2008, 2009, and 2010, a total of 75.8 %, 85.6 %, and 66.1 % were detected within these three locations, respectively (N_{2008}=149; N_{2009}=155; N_{2010}=165). Although it may appear from Figure 2.6 that there were few manual telemetry detections within Henry's Honey Hole, given the relatively low amount of effort at the upper Pic, it appears that this location is the most frequently utilized location within the upper portion of the Pic River and therefore was considered a frequently used location. Portions of the river outside of these three destinations tended to be used exclusively by transient individuals, whereby Lake Sturgeon would use it as a corridor or for spawning purposes. At the mouth of the river Lake Sturgeon distribution was relatively uniform, with a slightly aggregated distribution along the bedrock wall that makes up the southern shoreline of the river's mouth (i.e. 0 km to 0.5 km within the Pic River). At the lower rapids, Lake Sturgeon distribution was extremely aggregated within deep pools that were below the start of the rapids, immediately above the rapids, or in pools that occurred intermittently between sets of rapids (Figure 2.7). Maximum depth within these pools exceeded 6 m throughout the spring and summer months and Lake Sturgeon were often found within close proximity of the shoreline that had the greatest slope or that had a bedrock wall. At Henry's Honey Hole, the inner bend drops off very steeply and the river bottom gradually ascends towards the eastern shoreline. Like at the lower rapids, Lake Sturgeon at Henry's Honey Hole were most frequently found within close proximity of the inner bend, where a steep shoreline slope occurs. Although Lake Sturgeon will inevitably depend on transient corridors and fast-flowing spawning habitat at some point within their migrations and life cycles, these results indicate that deep slow-flowing pools are much more frequently utilized by Lake Sturgeon within rivers during the spring and summer months.

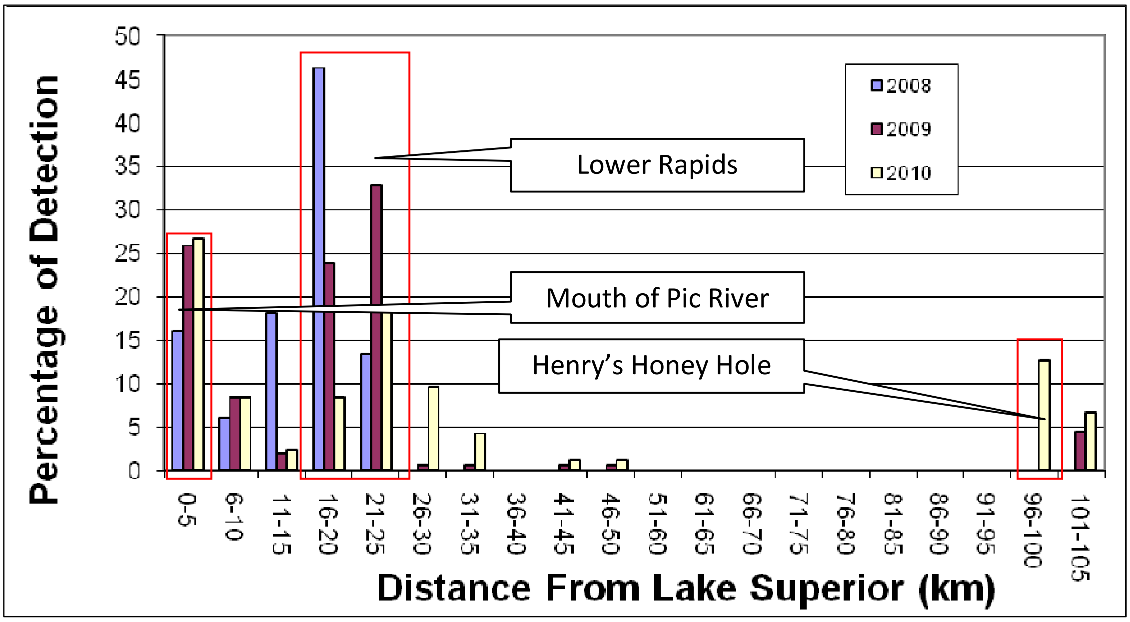


Figure 2.6 – Percentage of manual telemetry detections in each 5 km interval of the Pic River, starting from the mouth of the river (0 km) to Manitou Falls (103 km). Although there appears to be fewer detections at Henry's Honey Hole, there was an unequal amount of effort at this location (see preceding text).

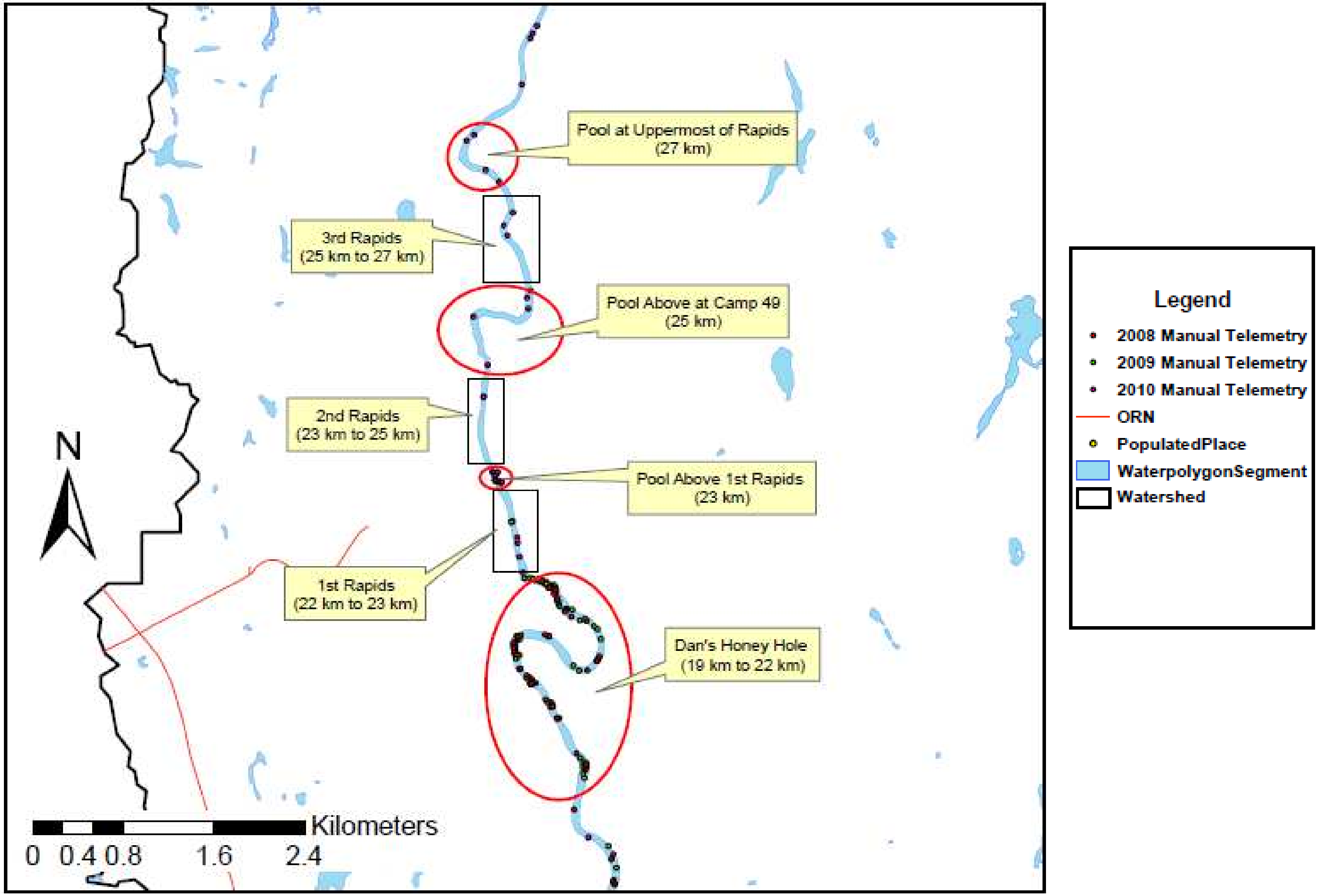


Figure 2.7 – Location of pools within the lower rapids that were most frequently used by migrating Lake Sturgeon in the Pic River based on telemetry data from 2008 to 2010.

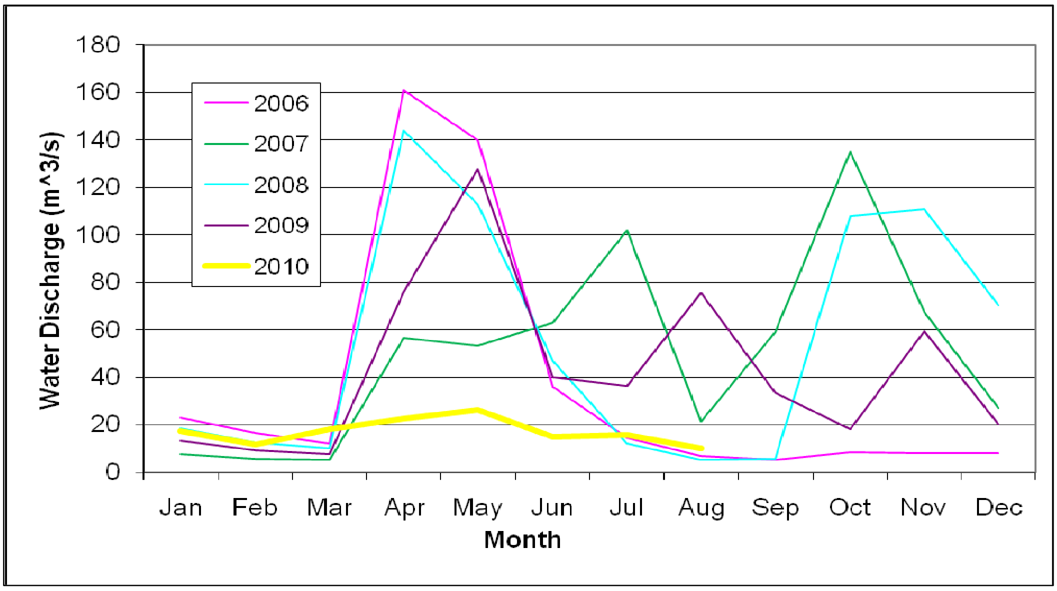
2.3.2 Abiotic Conditions:

Spring abiotic conditions were substantially different in 2010 compared to 2008 and 2009 (Table 2.2), whereby environmental conditions typically observed in August were experienced in May of 2010. Water temperatures reached 20°^{C} 47 days earlier and the river was ice free 39 days earlier in 2010 compared to 2008 and 2009 (Figure 2.8). Furthermore, the river was ice-covered for approximately 49 days longer in 2008 and 2009 compared to 2010, which coincided with the earlier timing of migration in 2010 by roughly 50 days (see Section 2.3.3). Not only was the temperature regime very different in 2010, the flow regime was also different, whereby the mean monthly discharge (m^3/s) in 2010 was roughly 22%, 21%, and 17% of the mean monthly discharge for April, May, and June in 2008 and 2009, respectively. Furthermore, due to a limited amount snow cover during the winter of 2009/2010, there was virtually no spring freshet in 2010. According to the Environment Canada water gauging station, mean monthly discharge in April, May, and June of 2010 were the lowest mean monthly discharge rates since the station's existence in 1970. These warm and dry abiotic conditions provided a unique opportunity to study potential changes in the movements of Lake Sturgeon in a natural setting.

Table 2.2 – Annual comparison of spring abiotic conditions within the Pic River.

	Date when 20°C was reached	Date when river was ice free	Number of days with ice cover	April mean monthly discharge (m^3/s)	May mean monthly discharge (m^3/s)	June mean monthly discharge (m^3/s)
2008	August 5	April 21	149 days (Nov 24 to Apr 21)	131.00	128.00	138.00
2009	August 16	April 25	157 days (Nov 19 to Apr 25)	76.20	128.00	39.90
2010	May 26	Mar 15	104 days (Dec 3 to Mar 15)	22.82	26.47	15.02

A



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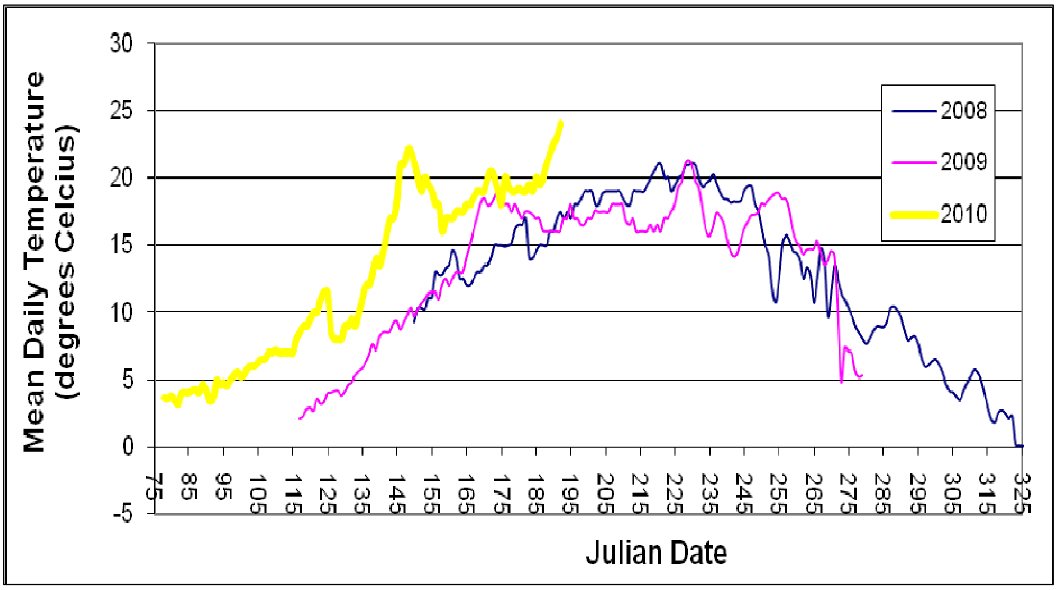
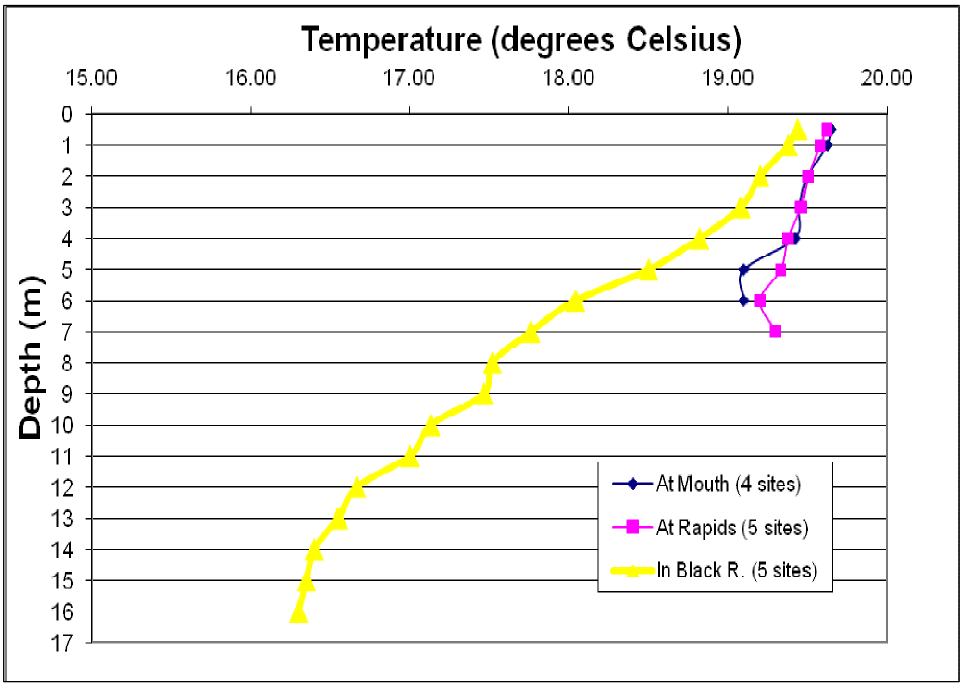


Figure 2.8 – Mean monthly water discharge (A) and mean daily water temperature (B) of the Pic River during the study period.

The unusually warm and dry abiotic conditions observed in the spring of 2010 resulted in some Lake Sturgeon modifying their regular movement patterns and habitat utilization within the Pic River. Manual telemetry within the Black River in 2008 and 2009 indicated that there was limited activity within this tributary, with all manual telemetry detections occurring exclusively within the first 500 m of the Black River. However in 2010, four Lake Sturgeon inhabited the Black River throughout late June and early July for a period of two to four weeks as water temperatures peaked within the Pic River. They occupied a deep hole that was roughly 750 m downriver from the mouth of the Little Black River and had maximum depth of 16.2 m – a depth that exceeds the maximum depth within the Pic River by two-fold. Four temperature and dissolved oxygen (DO) depth profiles were taken at this deep hole within the Black River and compared with the mean temperature and DO depth profiles taken from the four random locations at the mouth of the Pic River and at the pools within the lower rapids. Results from the lower rapids and the mouth of the Pic River indicated that there was no thermal stratification at either of these locations, whereas within the Black River, the deeper pool did establish thermal stratification (Figure 2.9).

A



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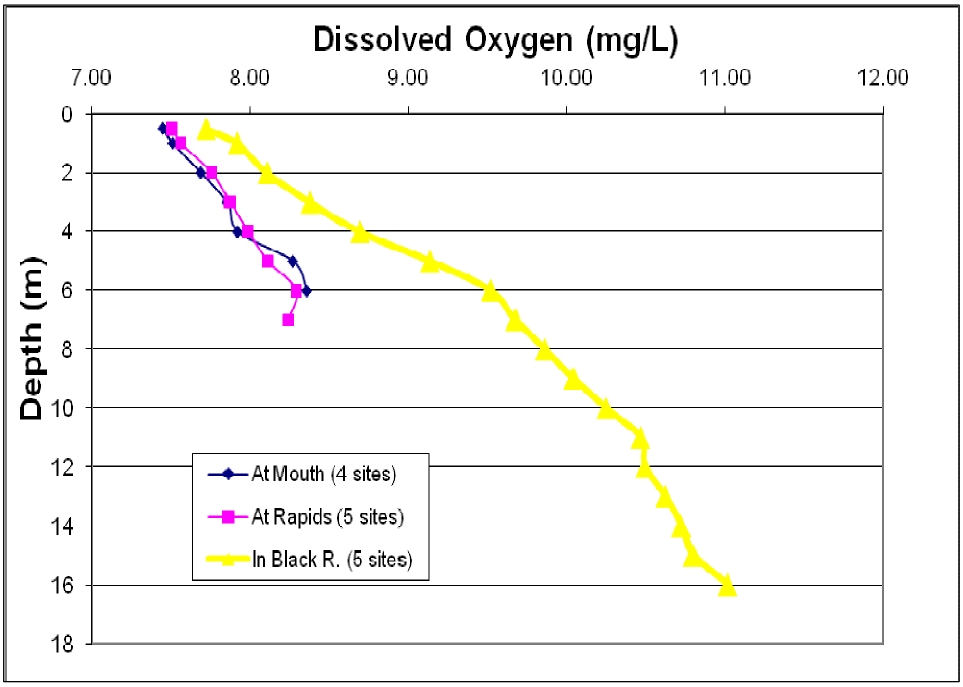

Figure 2.9 – Temperature (A) and dissolved oxygen (B) depth profiles within the Black River, at the mouth of the Pic River, and at the lower Pic River rapids based on the mean of four depth profile readings.

Not only did Lake Sturgeon alter their habitat utilization within the Pic River in 2010, their decision to enter or not to enter the river and their residency time within the river were also modified. The percentage of radio tagged Lake Sturgeon entering the river only moderately declined in 2010 (n=39) compared to 2009 (n=32) by just over 5%. However, the percentage of Lake Sturgeon that entered the river in 2010 (n=33) and remained within the river for more than two days decreased by over 18% from 2009 (n=32) (Figure 2.10). This substantial decrease in the residency times of Lake Sturgeon in 2010 suggests that individuals were entering the river, identifying the unfavourable or unusual abiotic conditions, and returning to Lake Superior to avoid such abiotic conditions.

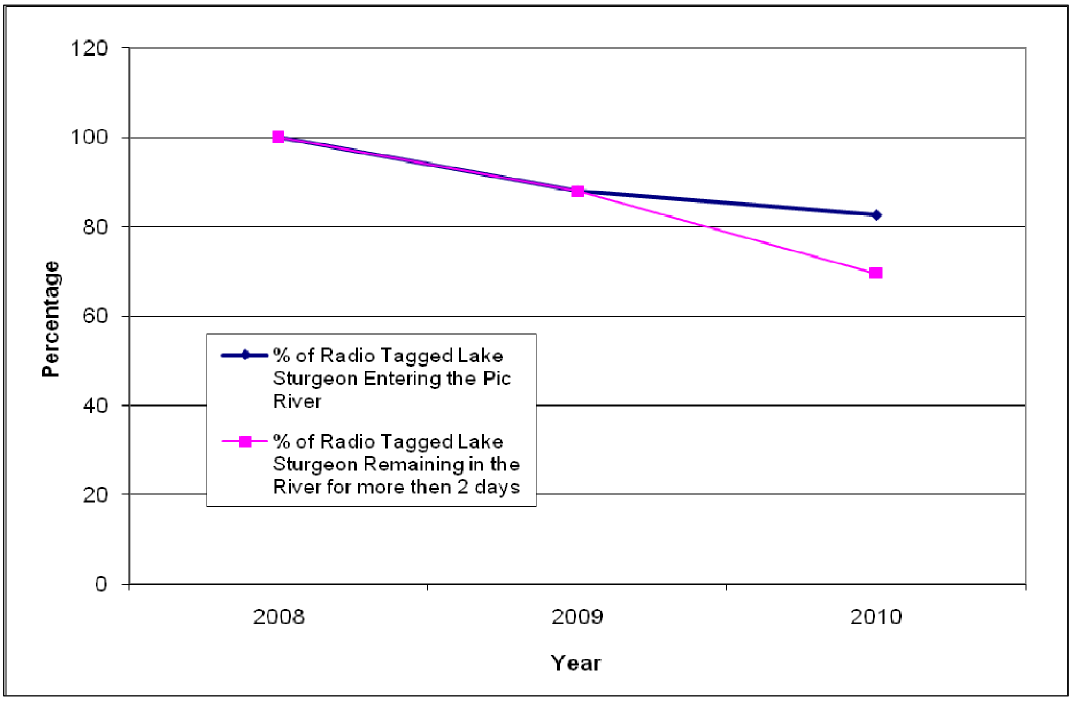

Figure 2.10 – The percentage of Lake Sturgeon that entered the Pic River in each year of study and the percentage of Lake Sturgeon that entered the Pic River and remained within the Pic River for a duration exceeding 2 days.

2.3.3 Timing of Migration:

Tagged Lake Sturgeon showed inter-annual differences in the timing of migration (Figure 2.11). A one-way ANOVA found significant differences between each year of study (2008, 2009, 2010) and the timing of Lake Sturgeon migration (entry, uppermost, exit) ($F_{(8, 148)}$=12.891, p<0.01). An earlier onset to spring in 2010 (see Section 2.3.2) resulted in a much earlier entry into the river (117.4 Julian days or April 27th ±4.6 days), an earlier uppermost distance (140.9 Julian days or May 20th ±5.09 days), and an earlier exit from the river (203.1 Julian days or July 22nd ±7.83 days). On average, Lake Sturgeon migration occurred roughly 50 days earlier in 2010 compared to the mean entry date (168.5 Julian days or June 17th ±4.9 days), uppermost date (187.5 Julian days or July 6th ±6.0 days), and the exit date (275.6 Julian days or Oct 2nd ±6.4 days) of 2008 and 2009. Tukey post-hoc tests indicated that the timing of exit was significantly different between each year of study, with the earliest times occurring in 2010 (Table 2.3C). As well, Tukey post-hoc tests found that Lake Sturgeon entered the river and reached their uppermost distance significantly earlier in 2010 compared to 2008 and 2009; however there was no significant difference between 2008 and 2009 (Table 2.3A and Table 2.3B). Finally, there was no significant inter-annual difference in the duration of time that Lake Sturgeon were in the river (Table 2.3D); indicating that Lake Sturgeon shifted their timing of migration, as opposed to their total amount of time spent within the river.

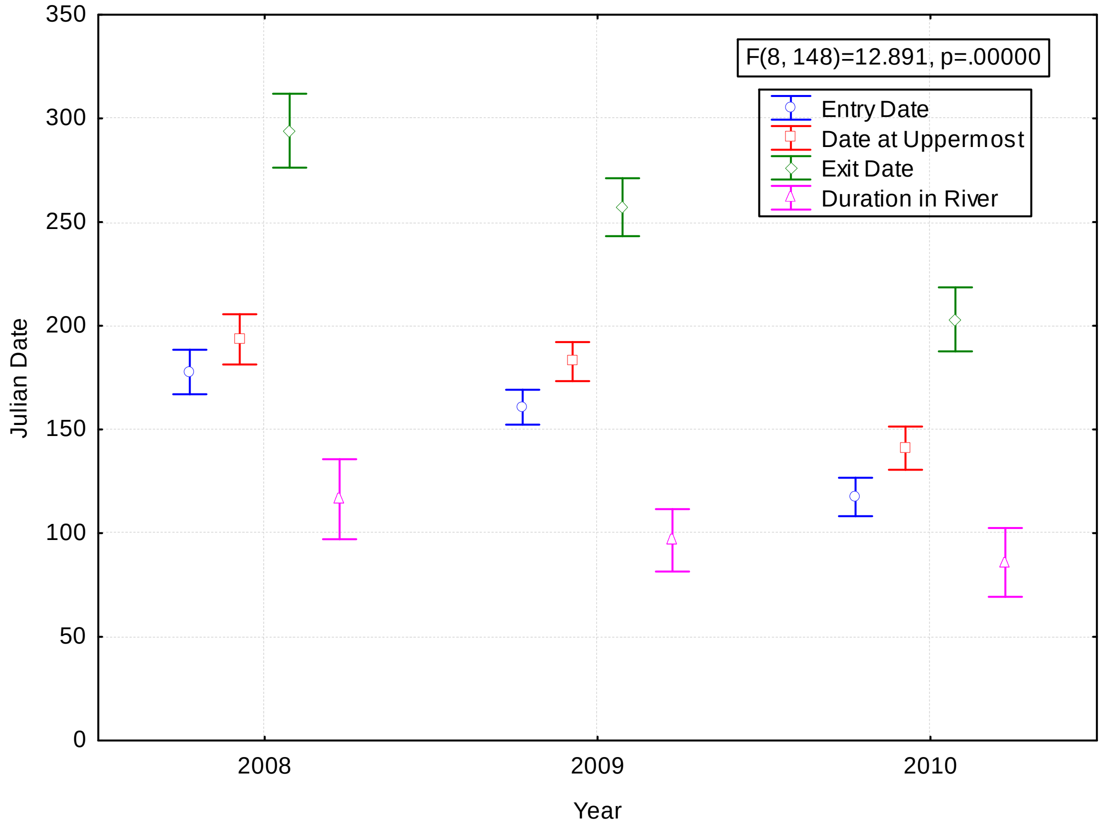

Figure 2.11 – Inter-annual annual differences in the timing of entry, exit, and uppermost point in Julian days and the duration spent in the river each year.

Table 2.3 – Tukey Post-hoc summaries to test for significant inter-annual differences in the timing of Lake Sturgeon entry (A), exit (B), and uppermost point (C), as well as the duration (D) that Lake Sturgeon spent within the Pic River, showing probability values for differences between years, with significant values ($p < 0.05$) shown in bold.

A (Entry)

	2008	2009	2010
2008		0.318	**<0.001**
2009	0.318		**<0.001**
2010	**<0.001**	**<0.001**	

B (Uppermost)

	2008	2009	2010
2008		0.776	**<0.001**
2009	0.776		**<0.001**
2010	**<0.001**	**<0.001**	

C (Exit)

	2008	2009	2010
2008		0.008	**<0.001**
2009	0.008		**<0.001**
2010	**<0.001**	**<0.001**	

D (Duration)

	2008	2009	2010
2008		0.244	0.051
2009	0.244		0.615
2010	0.051	0.615	

A one-way ANOVA found no significant differences in the timing of migration between spawning and non-spawning individuals ($F_{(4,75)}$=1.86, p=0.126) (Figure 2.12). However, these results were based on a low sample size of spawning individuals in each year of study (2008 N=3; 2009 N=8; 2010 N=15). Despite there being no overall differences in the movement patterns of spawning and non-spawning individuals, spawning Lake Sturgeon did enter the river (122.3 Julian days or May 1 ±7.0 days) significantly earlier compared to their non-spawning counterparts (154.8 Julian days or June 3 ±2.7 days) ($F_{(2, 77)}$ = 41.20, p<0.001). Therefore it appears that spawning Lake Sturgeon enter the river earlier, but otherwise, their movements are fairly similar to non-spawning individuals.

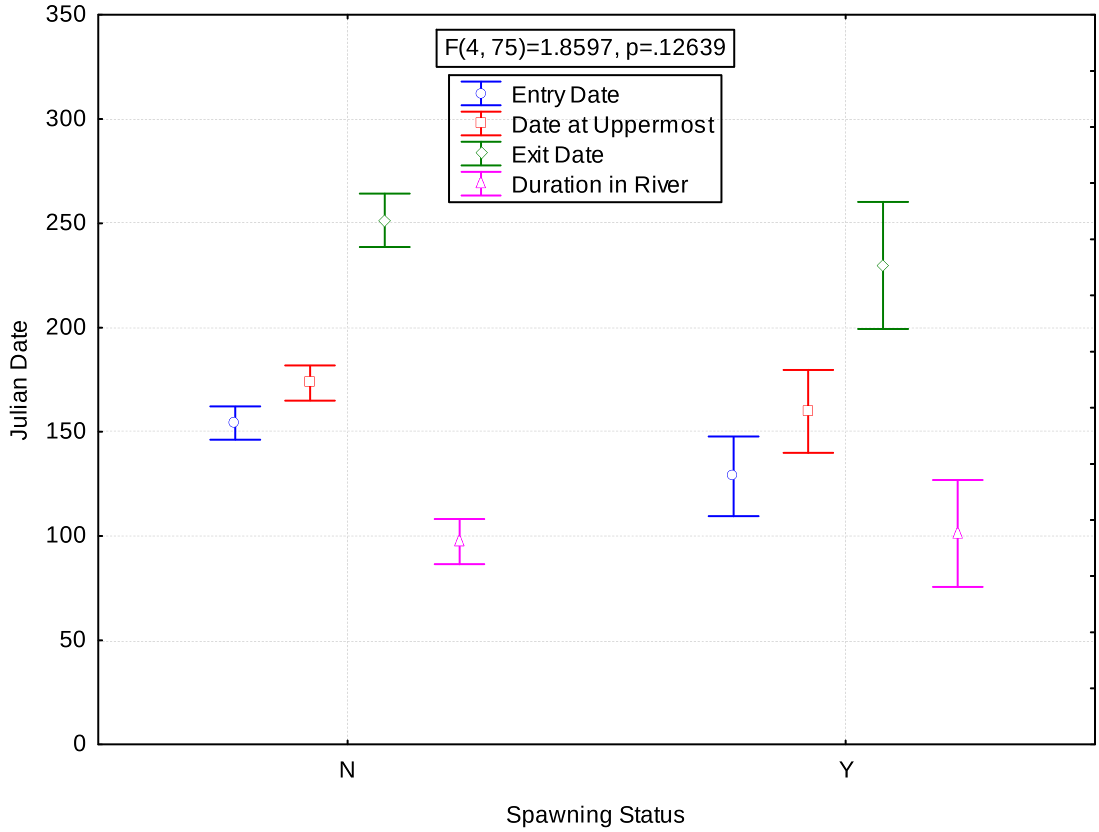

Figure 2.12 – Differences in the timing of migration between spawning (Y) and non-spawning (N) individuals indicated no significant differences between these two groups.

2.3.4 Environmental Cues:

Results from the multiple regression analysis indicated that mean daily water discharge was a better environmental cue then mean daily water temperature for predicting the timing of Lake Sturgeon migration ($F_{(1,268)}$=22.672, $p<0.01$, R^2=0.07455) (Figure 2.13). Although water discharge was a better environmental cue to predict the timing of Lake Sturgeon migration, there was a lot of variation within this relationship, therefore indicating that neither environmental cue could accurately predict the timing of migration. Lake Sturgeon entered the river at a mean daily water discharge of 60.53 m^3/s (±4.86 m^3/s), reached their uppermost distance at a mean daily discharge of 49.54 m^3/s (±4.54 m^3/s), and exited the river at a mean daily discharge of 32.62 m^3/s (±2.53 m^3/s), therefore suggesting that Lake Sturgeon entered the river at higher water discharges and exited the river once discharges subsided in the late-summer or early-fall. As for mean daily water temperature, Lake Sturgeon entered the river at temperatures of 11.55˚C (± 0.61˚C), reached their uppermost point at temperatures of 15.03˚C (± 0.56˚C), and exited the river at temperatures of 13.12˚ (± 0.57˚C).

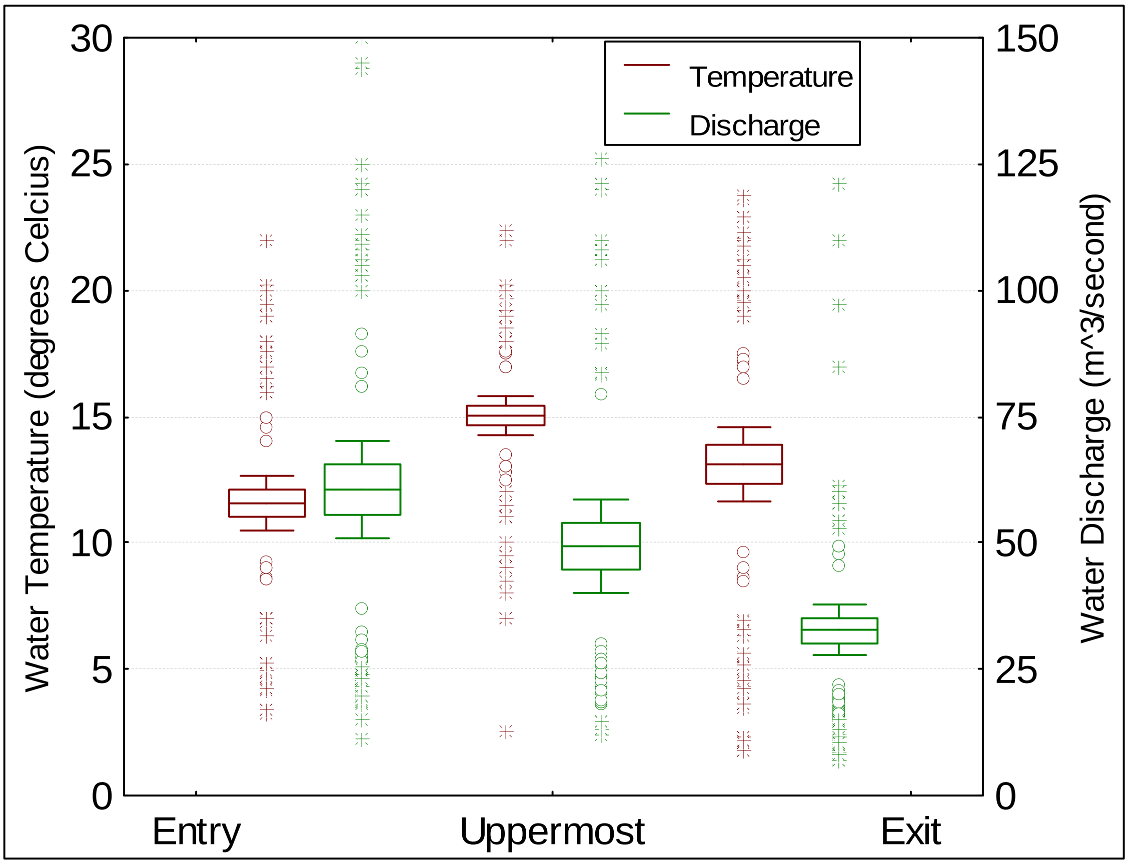

Figure 2.13 – Mean water temperature and discharge when Lake Sturgeon entered, reached their uppermost point of migration, and exited the river. Boxes are equal to the mean, plus or minus one standard error unit, while the whiskers represent the 95% C.I.

Although results from the multiple regression yielded no definitive environmental cues to migration, it is still possible to ascertain environmental cues to migration by plotting temperature and discharge with the immigration and emigration of Lake Sturgeon (Figure 2.14a and Figure 2.14b). For water discharge, results indicated that Lake Sturgeon entered the river shortly after flows peaked during the spring freshet. This was even the case in 2010, when individuals entered following a peak in water discharge, albeit a relatively small peak due to the dry conditions. Lake Sturgeon emigration from the Pic River occurred later in the fall once basal flows were reached. Therefore, in general, Lake Sturgeon entered and began their upriver migration shortly after peak flows and began their downriver migration and exited the river once basal flows were reached (Figure 2.14a). For water temperature, results indicated that Lake Sturgeon entered the river when temperatures were less then 7ºC and began their upriver migration once temperatures reached 9ºC, therefore suggesting that these temperatures induced upriver migrations. This was also confirmed by manual telemetry in 2010, when three individuals promptly retreated downriver when water temperatures decreased from 9.3ºC to 7.8ºC overnight. In general, Lake Sturgeon entered the river and began their upriver migration prior to peak thermal condition and began their downriver migration and exited the river shortly after peak thermal conditions (Figure 2.14b). Therefore, it appears that Lake Sturgeon are responding to trends in environmental conditions, as opposed to distinct and narrow ranges of environmental conditions.

A

B

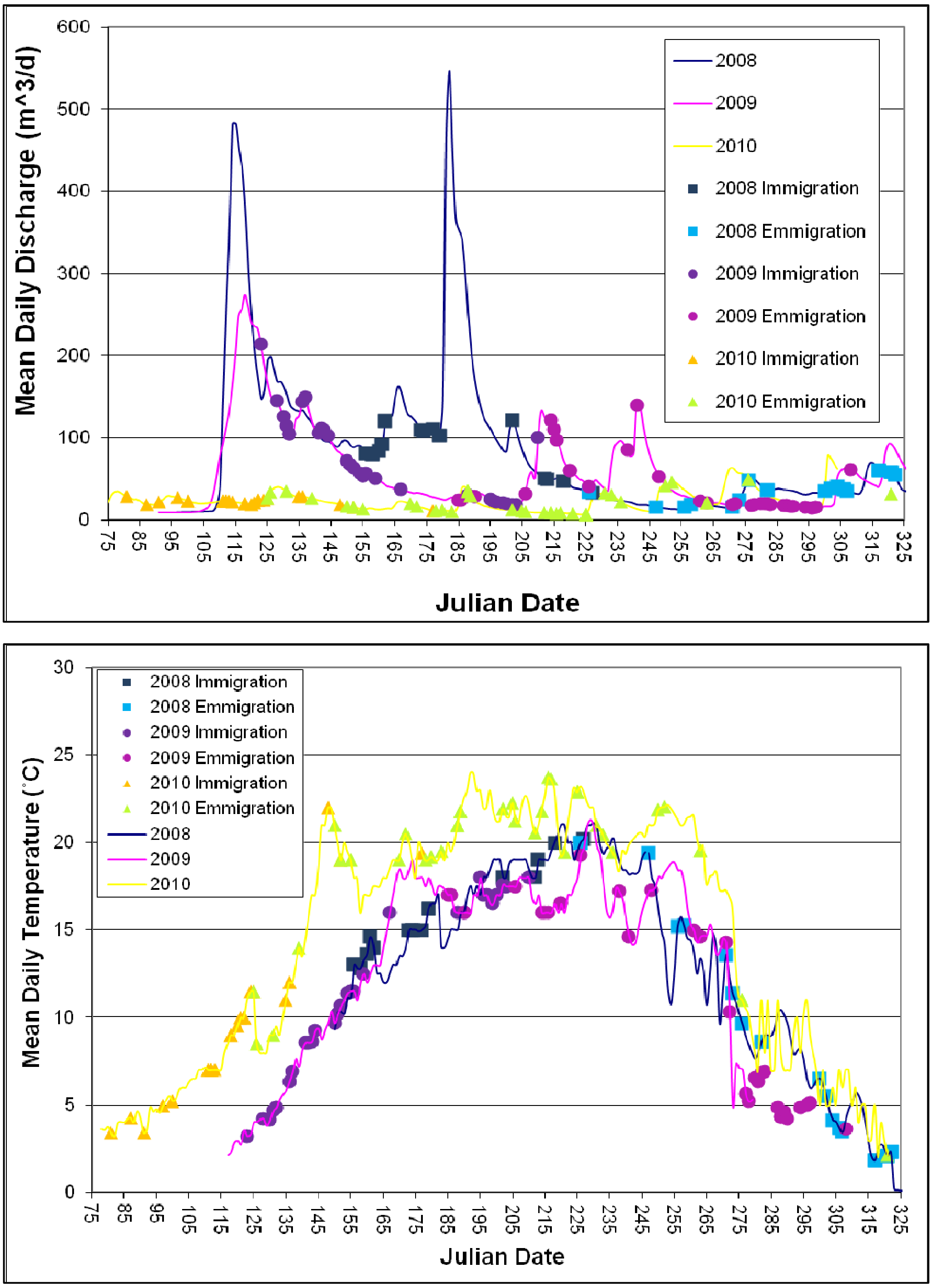

Figure 2.14 – Trends in mean daily discharge (m3/second) (A) and mean daily water temperature (˚C) (B) as they related to the immigration and emigration of Lake Sturgeon in 2008, 2009, and 2010.

Ice cover was the only environmental variable that correlated with the timing of migration, whereby the ice free date of the river correlated with the mean entry date of Lake Sturgeon in each year of study (R^2=0.8879) (Figure 2.15). According to these results, Lake Sturgeon entered the river 47 days, 43 days, and 36 days after it became ice free in 2008, 2009, and 2010, respectively, for a mean entry of 42 days post ice-free conditions. This relationship is only based on three data points; however the strong relationship suggests that ice cover, and the disappearance of ice, may be the best environmental cue to predicting the timing of Lake Sturgeon movements into the Pic River.

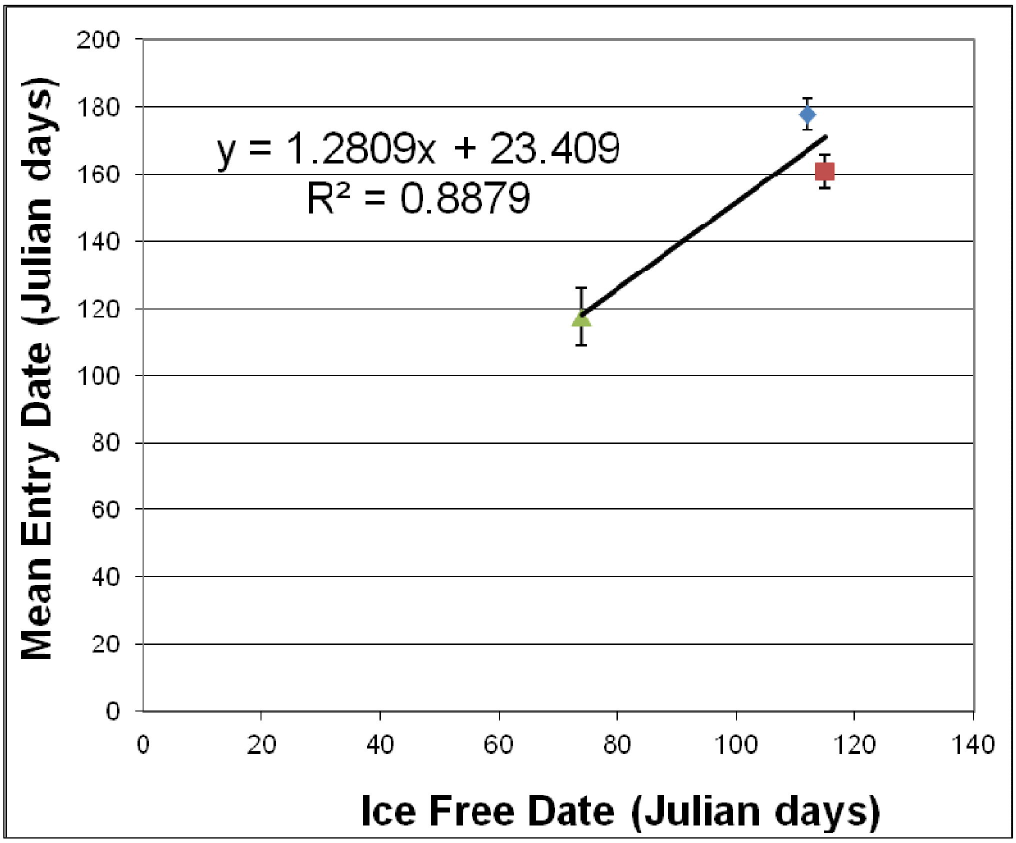

Figure 2.15 – Bivariate correlation between the mean entry date of Lake Sturgeon in each year and the ice free date of that respective year. The blue diamond represents the year 2008, the red square represents the year 2009, and the green triangle represents the year 2010.

2.4 DISCUSSION

The objectives of this study were three fold. The first objective was to determine if inter-annual differences in the patterns or timing of Lake Sturgeon migration existed when unusual abiotic conditions occurred. These predicted differences were indeed observed, with individuals entering, reaching their uppermost point, and exiting the river significantly earlier in 2010 compared to the previous two years (2008 and 2009). The earlier timing of migration in 2010 coincided with unusually warm and dry abiotic conditions, which resulted in virtually no spring freshet, earlier disappearance of ice, fewer ice covered days, and higher rates of temperature increase. To offset these conditions, Lake Sturgeon utilized novel deep-pool habitat within the Black River and fewer foraging individuals remained within the river system for an extended period of time (> 2 days). Therefore it appears that Lake Sturgeon modified their habitat utilization in 2010 by occupying habitats that would provide them with a cool water refuge from the elevated water temperatures in the Pic River.

The second objective of this study was to determine if there were differences in the patterns or timing of migration between spawning and non-spawning individuals. Consistent with hypothesis two of this study, spawning individuals did enter the river significantly earlier compare to non-spawning individuals. Furthermore, analysis of the manual radio telemetry results indicated that spawning individuals migrated further upriver, had greater daily movement rates during their upriver and downriver migration, and remained at the mouth of the river for a shorter period of time throughout the spring/summer before returning to Lake Superior.

The third objective of this study was to determine whether environmental cues such as water temperature, water flow, and ice cover were responsible for stimulating Lake Sturgeon migration between Lake Superior and the Pic River. Ice cover, and the disappearance of ice, was the best indicator to determine when Lake Sturgeon would enter the Pic River from Lake Superior in the spring. This environmental cue to migration was also identified by elders of Pic River First Nation, who suggested that Lake Sturgeon entered the river shortly after the disappearance of ice (Couchie, 2009). Water discharge, and not temperature, was a better environmental variable for predicting the timing of migration. However less than 10% of the variation was explained in this relationship, indicating that neither variable accurately predicted the timing of migration. Therefore Lake Sturgeon movements did not appear to be stimulated by specific abiotic conditions, but rather by trends in abiotic conditions. Lake Sturgeon were stimulated to enter the river shortly after the peak of the spring freshet and as temperatures increased to approximately 9ºC. While their exit from the river occurred once water flows subside to base levels and temperatures exceeded 20ºC.

2.4.1: Migration Patterns

The migration patterns of Lake Sturgeon varied quite substantially from one system to another and especially between natural and modified systems. One consistent finding, regardless of the system, is that Lake Sturgeon express strong site fidelity for specific pool mesohabitats within riverine systems. In the Grasse River, 60% of all manual telemetry detections occurred within three areas over a 22-month period (Trested, 2010). In the Mississippi River, 50% of all manual telemetry detections occurred within one area over an 18-month period (Knight et al., 2002). In a natural reach of the Ottawa

River, Lake Sturgeon had a tendency to remain within one basin, and although they may have left periodically, they always returned to the same basin (Haxton, 2003b). Finally, in the Kettle River, 80% of all manual telemetry detections occurred within a 1 km portion of the lower river over a 23-month study period (Borkholder et al., 2002). These locations have been identified as core areas (Knights et al., 2002) or activity centers (Borkholder et al., 2002) that Lake Sturgeon depend upon for foraging and/or spawning purposes. In this study, 46% of all manual telemetry recordings occurred within the 16.1 km to 25 km portion of the river, and more specifically, within four slow flowing pools in the lower rapids.

This study also found strong site fidelity for the mouth of the Pic River, with 22% of manual telemetry detections occurring within the lower 5 km of the river and over 350,000 detections from the respective base station. This finding is consistent with other findings in unfragmented lake-river systems, including the Rainy River, the Jackfish River, and the Grasse River systems (Rusak & Mosindy, 1997; Kim Tremblay, personal communication; Trested, 2010; respectively). In the Grasse River, three Lake Sturgeon were radio tagged in the lower portion of the river and 72% of all their manual telemetry detections thereafter came within the same lower section of the river, indicating that Lake Sturgeon at the mouth of the Grasse River undertook few movements throughout the summer and fall seasons of the year (Trested, 2010). Within a Lake Superior river system, Auer et al. (1999) found that post-spawning Lake Sturgeon remained at the mouth of the Sturgeon River for a period of 3 to 53 days before dispersing into Portage Lake or Lake Superior in late August.

Beyond the mouth of the river and the pools throughout the lower rapids, Lake Sturgeon also showed fidelity for Henry's Honey Hole, which is located 98 km upriver from Lake Superior (King, 2010; Bill Gardner, personal communication). Pre- and post-spawning Lake Sturgeon would congregate in large numbers within this staging pool, presumably to synchronize spawning times amongst individuals and to descend the river post-spawning (Auer, 1996; Bruch & Binkowski, 2002; Daugherty, 2006; Daugherty et al., 2008a). Unlike some systems, where non-spawning individuals mimic spawning individuals at these staging locations (Friday, 2004; 2005b; Lallaman et al., 2008; Tim Haxton, personal communication), this did not seem to be the case in the Pic River. Beyond the 50 km mark of the river, captured Lake Sturgeon tended to be ripe unless they were caught prior to the estimated spawning time (see Section 3.3.3). This may be the case in the Pic River since it is a relatively long tributary with suitable foraging habitat that is close to Lake Superior. Under such conditions, it appears that non-spawning Lake Sturgeon tended to exploit near-lake foraging locations that were energetically profitable (i.e. Lower Rapids instead of Henry's Honey Hole).

Although not statistically tested, differences in the movement rates also existed between spawning and non-spawning Lake Sturgeon, with spawning individuals ascending the entire river within 10 days of entering (~10 km/day) and foraging individuals meandering with minimal displacement distances. This is quite common amongst other populations of Lake Sturgeon. In the Grasse River, upriver migration rates of spawning individuals moved between 4.3 km/day and 16.1 km/day, while their non-spawning counterparts were between 0.82 km/day and 1.22 km/day (Trested, 2010). In the Rainy River, foraging and spawning individuals had a two-fold increase in movement rates during the spring and summer compared to the fall and winter (Rusak and Mosindy, 1997). Similar observations can be seen in other sturgeon species, including the Gulf Sturgeon, whereby spawning individuals entered tributaries earlier and travelled greater distances in shorter time periods compared to non-spawning Gulf Sturgeon (Fox et al., 2002). The current study was not able to accurately detect small changes in the daily movements of Lake Sturgeon given the size and relative inaccessibility of the river. However, despite these limitations, it was quite apparent that spawning individuals migrated further and had greater migration rates compared to their non-spawning counterparts. This finding was particularly true during the late-spring for the Pic River.

This study also found that Pic River Lake Sturgeon are not a resident population, meaning that they return to Lake Superior in the fall to overwinter. There are examples of similar and alternate residency strategies in the literature. In the Sturgeon River, Lake Sturgeon dispersed into Lake Superior in late August and were found up to 280 km away (Auer et al., 1999). In the Grasse River, non-spawning Lake Sturgeon returned to either Lake St. Francis or the St. Lawrence River for the spring and summer, whereas spawning individuals remained within the river for the spring and the previous winter to increase energy reserves and to reach the spawning site as early as possible (Trested, 2010). This finding was also reported in the Rainy River system, where spawning Lake Sturgeon overwintered and spent the spring in the river and non-spawning individuals left the river during the spring but returned in the fall to overwinter (Rusak & Mosindy, 1997). Friday (2004) found a non-resident population of Lake Sturgeon within the Black River, but within a relatively close tributary (i.e. Kaministiquai River), Lake Sturgeon formed a resident population (Friday 2005b). Resident populations are also very common in fragmented systems, where populations have become isolated due to anthropogenic obstructions or developments and have few other options (Haxton, 2002, 2003b; Haxton & Findlay, 2008). In the Kettle River, Lake Sturgeon continue to form a resident population, despite all obstructions being moved over a decade ago (Borkholder et al., 2008). Even within a system, the population could be divided into resident and non-resident groups; such is the case in the Fox River, Wolf River, and Embarrass River (Lyons & Kempinger, 1992). Lake Sturgeon may leave the river to over winter for various reasons, but regardless of their reasoning, it is assumed that they must encounter more suitable habitat within the lake ecosystem for this migration pattern to be maintained. Although this study did not look at potential habitat within Lake Superior, it has been identified as a future direction for this study and more broadly as an emerging field of interest in Lake Sturgeon ecology (Tom Pratt, personal communication).

2.4.2: Environmental Cues & Timing of Migration

This study found a significant inter-annual difference in the timing of migration, particularly in 2010 when an earlier spring onset. These results are consistent with those found on the Rainy River, Ontario, where unusual abiotic conditions observed in 1988, characterized by warm temperatures, low flows, and the early disappearance of ice, resulted in an earlier spawning time by individuals who entered the river (Rusak & Mosindy, 1997). Using Rusak & Mosindy's (1997) migration data for mean entry times from 1988 to 1990 and the same hydrometric data that was used for this study to determine the disappearance of ice (i.e. Water Survey of Canada), a bivariate correlation between mean entry date and the date of ice disappearance was performed for the Rainy River (Figure 2.16). Although the correlation was not as strong for the Rainy River as it was for the Pic River (R^2_{RAINY} = 0.57 versus R^2_{PIC} = 0.89), there is still strong evidence within both systems to support the hypothesis that spring movements are strongly influenced by ice conditions. Bruch & Binkowski (2002), reiterated this finding through angling records and electrofishing surveys in the Winnebago system. Annual angling records show in increase in the accidental by-catch of Lake Sturgeon and a large number of gravid males and females at the spawning site shortly after ice-out in late-March (Bruch & Binkowski, 2002). Although the current study did not look at ice out as it relates to spawning times, it did find strong evidence relating ice-out to entry times, which could then be used to estimate spawning times given the movement rates of spawning Lake Sturgeon.

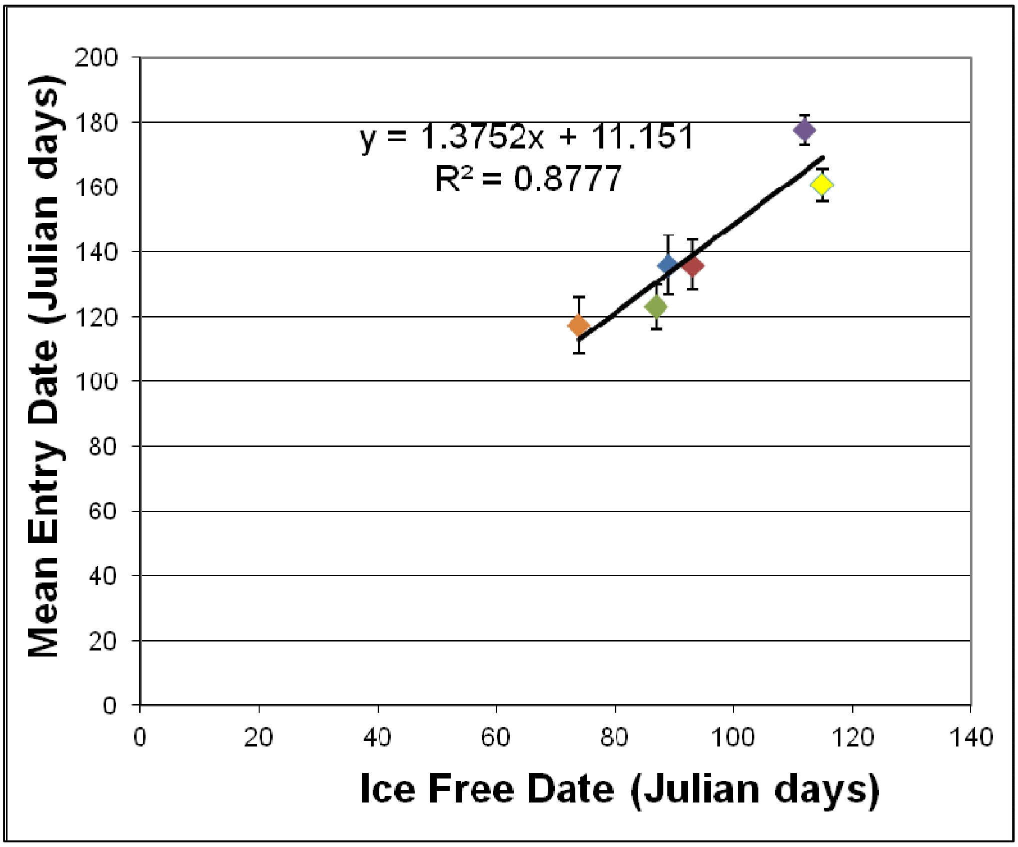

Figure 2.16 – Correlation between mean entry date and ice-out date for the Rainy River (Rusak & Mosindy, 1997), Ontario, combined with the Pic River data. The purple, yellow and orange points represent the Pic River data from 2008, 2009, and 2010, respectively. The blue, red and green points represent the Rainy River data from 1988, 1989, and 1990, respectively.

Unlike most studies that have found a significant relationship between either water temperature or flow and Lake Sturgeon movements, this study did not. In the Kettle River movements were strongly correlated with water discharge and mildly correlated with temperature; however, this is a resident Lake Sturgeon population that does not experience two environmental mediums (i.e. river and lake conditions) (Borkholder et al., 2002). In the Rainy River, Lake Sturgeon that overwintered in the river were stimulated to migrate from the river into Lake of the Woods by increases in both temperature and flow, whereas their return movements from the lake to the river always coincided with thermal maximas in the Rainy River (Rusak & Mosindy, 1997). In Lake Winnebago, long-term movement records are correlated with temperature, whereby Lake Sturgeon moved onto and off of the spawning site at temperatures between 6ºC and 16ºC and at 15ºC to 21.1ºC, respectively (Bruch & Binkowski, 2002). The results of this study indicated no overall relationship between Lake Sturgeon movements into or out of the river and temperature or flow. It is possible that no relationship was found because this study focused on both the spawning and non-spawning portion of the population. Given that these two groups are utilizing the river for different purposes, it is likely that these groups are responding to different abiotic cues and therefore no statistical relationship can be established (Bruch & Binkowski, 2002; Auer, 2003; Peterson et al., 2007). Despite not being able to find statistical relationships between the movements of Lake Sturgeon and environmental variables, it was possible to decipher environmental cues from trends in water temperature and flow relative to the distance of Lake Sturgeon from Lake Superior. A similar approach and result was found by Friday (2005 and 2006), whereby movement onto the spawning site and spawning itself occurred eight days prior to peaks in water flow.

Perhaps even more interesting than determining the specific environmental cues that induce movements, and certainly more conclusive, are the results related to Lake Sturgeon modifying their habitat utilization and timing of migration in the face of unusually warm abiotic conditions. Shifts in the timing and patterns of migration have become an important field of research for migrating species of ichthyo and avian fauna, especially given the threats of climate change (Quinn & Adams, 1996; Sims et al., 2004; Hodgson et al., 2006; Ydenberg et al., 2005). In this study, Lake Sturgeon shifted their migrations by roughly 50 days earlier and utilized novel habitats within the system to mitigate the extremely warm conditions within the Pic River throughout the summer of 2010. These results are most likely related to the finding by McKinley (1998), which found that Lake Sturgeon significantly reduce their movements during the thermal maxima to reduce metabolic stress on the body. The initial perception of these results may be viewed as positive, since Lake Sturgeon seem to be able to offset drastic increases in temperature that may be foreseeable under some climate change predictions. However it is important to understand the implications of this modified behaviour to truly understand what the long term impacts of these changes may be (Nilo et al., 1997). Adams (2004) and Adams et al. (2006) found that Lake Sturgeon year class strength and water levels were positively correlated for Rainy Lake in Minnesota and Ontario. Also, unlike warm water fish species, Lake Sturgeon body condition and size is negatively correlated with air temperature (Fortin et al., 1996) and a latitudinal counter gradient in the thermal opportunity for growth exists, meaning that the potential for growth decreases once temperatures exceed a thermal threshold (Power & McKinley, 1997). Furthermore, with reduced water levels, parts of the river may become unnavigable or portions of the spawning habitat may rise above the water level, making them completely unusable for spawning – such may have been the case at Kagiano Falls in 2010. Therefore, the results presented here should not be considered as evidence that Lake Sturgeon are resilient to climate change, but rather that they can offset exceedingly high thermal conditions for short periods of time, potentially at the cost of their long term fitness.

2.4.3: General Conclusions

Consistent with the findings of other studies on Lake Sturgeon movement patterns (Lyons & Kempinger, 1992; Auer 1996; Rusak & Mosindy, 1997; Borkholder et al., 2002; Fox et al., 2002; Knight et al., 2002; Haxton, 2003b; Friday, 2005a, 2005b; Trested, 2010), adult Lake Sturgeon showed strong site fidelity on an annual basis for three deep-pool habitats in the Pic River. Lake Sturgeon movements were stimulated by ice cover and the disappearance of ice in the Pic River, especially movements by non-spawning individuals. Although the relationship between ice-out and the onset of migration has not been as defined as the relationship between water temperature or flow and migration, there is some primary and anecdotal evidence of this relationship suggesting that it should be investigated further (Stone &Vincent, 1900; Rusak & Mosindy, 1997; Bruch & Binkowski, 2002; Couchie, 2009).

The identification and protection of critical Lake Sturgeon habitat is, at least contemporarily, the highest priority for conservation efforts and for the long-term sustainability of this endemic species (Harkness & Dymond, 1961; Hay-Chmielewski & Whelan, 1997; Holey et al., 2000; Auer, 2003). This chapter of the study was able to identify critical habitat that was used on a seasonal and annual basis, assess the environmental cues that stimulated the onset of migration, and monitored the changes in movement patterns that were induced by drought-like abiotic conditions. Daily movement rates, home range sizes, and diurnal variations in movement patterns were not able to be assessed in this study because of the river's size and relative inaccessibility. More base stations (1 base station per 10 km of river) and a greater amount of manual telemetry effort (2 sweeps of the river per day) would have to be considered to accurately measure the aforementioned variables. Nevertheless, this study should aid fisheries biologists within this region, and more broadly within Ontario, to develop and implement policies that not only protect Lake Sturgeon spawning habitat, but also the deep pool habitats that are frequently utilized on a seasonal and annual basis.

Chapter 3: Validation of a Lake Sturgeon Habitat Suitability Model for Spawning

3.1 INTRODUCTION

Habitat suitability models (HSMs) are an important tool in fisheries management that enable the quantitative assessment of geographical data and have been used for a wide range of applications (Fisher & Toepfer, 1998; Fisher & Rahel, 2004; Zorn et al., 2011). HSMs typically incorporate spatially referenced habitat information about physical features with temporal changes in abiotic or chemical conditions to predict what habitat will be most suitable for a given species (O'Neil et al., 1988; Rubec et al., 1999; Valavanis et al., 2008). On the St. Marys River, HSMs have been used to retroactively assess the impacts of developments on fish stocks over time (Bray, 1996). In contrast, on the Yangtze River, they have been used to forecast the potential impacts of the Three Gorges and Gezhouba Dams on Chinese Sturgeon (*Acipenser sinensis*) and Common Carp (*Cyprinus carpio*) (Chen & Wu, 2011; Yi et al., 2010; respectively). Their applications are not limited to only predicting habitat suitability, as they have also been used to estimate fish abundance (Toepfer et al., 2000) and to assess the recovery potential of a species within a river (Daugherty et al., 2006). Although HSMs are widely used and critical decisions are based upon them, few of these models have ever been validated (Ortigosa et al., 2000; Morris & Ball, 2006; Vinagre et al., 2006) and therefore their predictive ability or transferability may be weak and/or unreliable (Burgman et al., 2001; Olden et al., 2002).

In theory, these models should be able to accurately predict habitat suitability since they are based on pre-existing studies, but these predictions are frequently contested. A long-standing deficiency of HSMs is their inability to incorporate biological features such as stream ecology, population dynamics, energetics, predation, and competition, which influence both population abundance and distribution (Orth, 1987). Cianfrani et al. (2010) advocated for the use of an iterative HSM for non-equilibrium species such as species at risk or invasive species, after finding that over 50% of HSMs for the threatened Eurasian otter (*Lutra lutra*) provided unreliable recolonization predictions. Other common criticisms of HSMs are that they lack variability in the input variables, they use inappropriate spatial scales, and do not sample over long enough temporal periods (Brooks, 1997; Roloff & Kernohan, 1999). Despite these limitations, the temptation to use them remains high because they can be easily applied and produce seemingly powerful results that are spatially referenced and relative to a target species.

For Lake Sturgeon (*Acipenser fulvescens*), Threader et al. (1998) developed a HSM to predict the suitability of foraging and spawning habitat based on substrate, depth, temperature, and flow. The foraging component of this HSM has been independently validated on the Ottawa River by comparing CPUE of adult and juveniles at locations with high and low foraging suitability (Haxton et al., 2008). Although the variation in CPUE was significant between high and low foraging suitability areas, the predictions of the model was low (Haxton et al., 2008). The spawning component of the HSM has not been independently validated, despite it being used to influence management decisions and restoration efforts (Daugherty, 2006; Daugherty, 2007; 2008a; 2008b). This component of the HSM evaluates the overall suitability of a potential spawning site based on substrate and depth, and the daily suitability of a potential spawning site by incorporating temperature and flow into its predictions (Threader et al., 1998). In this study, the spawning component of the HSM will be independently validated by comparing the model's predictions with empirical observations of spawning behaviour.

Lake Sturgeon typically spawn at the uppermost impassable barrier immediately below a water chute or within the rapids of a natural or artificial waterfall (Auer, 1996; Seylor, 1997a; Threader et al., 1998; Bruch & Binkowski, 2002; Peterson et al., 2007; Ontario Ministry of Natural Resources, 2009), although spawning can also occur within the lower portions of rivers or on lake shorelines (Harkness & Dymond, 1961; Carlson, 1995). Bruch & Binkowski (2002) found that spawning sites in the Winnebago system were close to deep overwintering pools (<2 km), had an extensive amount of spawning substrate (>700 m^2) that was comprised of clean rock, limestone, or granite with clean interstitial spaces, and high flows for cleaning of rocks and aerating eggs. Several other studies report Lake Sturgeon spawning at depths of 0.1 m to 2.0 m over gravel or cobble substrate, and at water velocities that range from 15 cm/s to 70 cm/s (Priegel and Wirth, 1974; LaHaye et al., 1992; McKinley et al., 1998; Auer & Baker, 2002). Spawning temperatures can also vary quite substantially. A long-term study in the Wolf River found evidence of spawning at temperatures between 8.3ºC and 23.3ºC (Kempinger, 1988) and up to 21.5ºC in the L'Assomption River (LaHaye et al., 1992). Most spawning, however, is observed between 13ºC to 18ºC (Scott & Crossman, 1973; Bruch & Binkowski, 2002; Peterson et al., 2007). Spawning typically occurs over a very short period, lasting only a matter of a few hours (Auer & Baker, 2002), and is associated with a polyandrous mating system, whereby two to five males will swim beside a female and fertilize her eggs as they are being expelled (Bruch & Binkowski, 2002, Peterson et al., 2007; Ontario Ministry of Natural Resources, 2009). These characteristics of Lake Sturgeon spawning habitat and behaviour were used to develop the habitat suitability index values for substrate, depth, temperature, and flow, which are applied to calculate the overall and daily suitability of potential spawning sites (Threader et al., 1998).

There are three objectives for this chapter and two hypotheses that are derived from postulates of the HSM (Threader et al., 1998). The first objective is to model the overall suitability of spawning habitat based on substrate composition and depth at three potential spawning sites (i.e. the Lower Rapids, Manitou Falls, and Kagiano Falls). The second objective will build onto this model by predicting the spawning times of Lake Sturgeon based on mean daily water temperature. Finally the model's predictions will be compared with empirical observations of spawning to ground truth its results and evaluate its predictive ability. The first hypothesis of the HSM is that Lake Sturgeon should spawn at locations that increase their likelihood of success and therefore have higher suitability indices (Threader et al., 1998). If this is the case, then there should be a higher CPUE of ripe adults, eggs, and larvae at locations with greater proportions of highly suited habitat relative to poorly suited habitat. The HSM also hypothesizes that peak spawning times should occur when water temperatures are optimal, between 12ºC and 16ºC because this is when temperature suitability is at its highest level (Threader et al., 1998). If the HSM's daily predictions for optimal spawning times are valid, then empirical evidence of spawning, such as eggs, larvae, and the movement of ripe adults onto the spawning habitat, should coincide with peaks in the spawning suitability of that respective site.

3.2 METHODS

3.2.1 Habitat Variables:

Substrate Composition

Substrate composition analysis was performed between the days of May 26th, 2010 and May 30th, 2010 using a Dual-frequency Identification Sonar (DIDSON) (DIDSON 300m, Sound Metrics, Chesapeake, VA., USA). The DIDSON was operated from an anchored boat at a known UTM coordinate and was held over the side of the boat at a downward angle of 1° to 7° depending on water depth. Once in the water, the DIDSON began recording as it was slowly rotated 360° to digitally record the substrate in the 30 m diameter circle surrounding the boat. The DIDSON's built in compass simultaneously recorded the direction of the DIDSON footage in degrees.

Using the DIDSON™ Software (V.5) (Sound Metrics, Chesapeake, VA., USA), a grid with 1 m intervals was overlaid onto the footage to determine the distance of the substrate relative to the boat. Substrate type, by proportion, was classified at the intersect of every 8° interval (starting at 4°) (i.e. 4°, 12°, 20° … 340°, 348°, 356°) and every 2.5 m away from the boat (starting at 5m) (i.e. 5 m, 7.5 m, 10 m, 12.5 m, 15 m). Therefore, for each site that the boat was anchored at, a total of 225 habitat points were classified and a total area of 706 m^2 was observed. At each point, the proportion of clay, silt, sand, gravel, cobble, boulder, bedrock, or other (i.e. woody debris) was estimated. Clay, silt, and sand substrates were classified based on their coloration, reflectivity, and amount of backscatter (bright white and no shadows = clay; darker shades and grainy shadows = sand). Whereas gravel, cobble, boulder, bedrock, and other materials were classified using the measuring tool within the DIDSON software and by criteria in Threader et al. (1998) (Table 3.1).

Table 3.1 – Substrate particle size statistics as measured by Threader et al. (1998).

Substrate Type	Particle size range (mm)	Median Particle Size (mm)
Other (i.e. logs, woody debris, etc.)	Highly variable	Highly variable
Clay	---	0
Silt	<1	0.5
Sand	1 to 2	1.5
Gravel	2.1 to 80	41.1
Cobble	81 to 250	166.5
Boulder	>250	250
Bedrock	---	500

The UTM coordinates of each habitat point were calculated using the cosine (Easting) and sine (Northing) of the footage direction (º), multiplied by the distance (m) of the habitat point from the boat. This value was then added to the known UTM coordinate of the boat to produce new coordinates that georeferenced each habitat point. A total of 55 boat sites, 12,375 habitat points, and 38830 m^2 was observed along the three potential spawning sites, including; the Lower Rapids (n= 23 boat sites; n= 5,175 habitat points, A= 16,238 m^2), Manitou Falls (n= 22 boat sites; n= 4,950 habitat points, A= 15,532 m^2), and the lower Kagiano River (n= 10 boat sites; n= 2,250 habitat points, A= 7,060 m^2).

Georeferenced substrate point data were then downloaded to ArcMap 9.1 (ESRI (Environmental Systems Research Institute), Redlands, California) to create a point shape file for each substrate type, whereby each point represented the proportion of that particular substrate. Point data were then interpolated using inverse distance weighting (Bolstad, 2002) with a variable search radius to the nearest four points, a power of 0.5, and a cell size of 25 m^2. The rasters were then masked to remove portions of the raster that existed outside of the river polygon boundary (Tools; Spatial Analyst; Extraction; Extract by Mask). Therefore at each potential spawning site, there was a substrate raster for each substrate type with a value ranging from 0 to 1.

Depth

Bathymetry maps were created for the Lower Rapids, Manitou Falls, and the lower Kagiano River using a bathymetric automated surveying system (BASS) and a Garmin 421s sonar unit. Data from each location were collected from July to August 2009 and in June of 2010. Georeferenced depth data were added to ArcMap 9.1 [(ESRI

(Environmental Systems Research Institute), Redlands, California)] to generate a point shape file. Depth data were then interpolated using Topogrid to generate a bathymetry raster for Manitou Falls, Kagiano Falls, and the Lower Rapids. The bathymetry raster was then masked to remove portions of the raster that existed outside of the river polygon boundary.

Temperature

At Manitou Falls, temperature was recorded every 2 hours from April 29th, 2010 to July 30th, 2010 using a temperature data logger (TidbiT v2) located directly above Manitou Falls (Easting: 566904, Northing: 5450977). Mean daily temperature at this location was based on 12 readings per day over the course of this period (Appendix 2). At Kagiano Falls, temperature was recorded every 2 hours from April 29th, 2010 to July 30th, 2010 using a temperature data logger (TidbiT v2) located immediately below the rapids of Kagiano Falls (Easting: 565486, Northing: 5449117). Mean daily temperature at this location was based on 6 readings per day over the course of this period (Appendix 2). At the Lower Rapids, temperature was recorded four times daily from April 29th, 2010 to July 30th, 2010 using a temperature data logger (TidbiT v2) located immediately below the rapids (Easting: 552000, Northing: 5400155). Mean daily temperature at this location was based on 4 readings per day over the course of this period (Appendix 2).

3.2.2 Habitat Suitability Model:

According to Threader et al. (1998), the suitability of Lake Sturgeon spawning habitat is dependent on substrate, depth, temperature, and flow. For this study, detailed measurements and monitoring of flow were not available and therefore only substrate, depth, and temperature were considered for suitability analysis. The HSM was developed based on habitat preferences of spawning Lake Sturgeon in northern Ontario rivers (Groundhog River & Moose River; Seylor et al. 1997a & Seylor, 1997b; respectively). The model provides suitability index values for each substrate type, depth interval, and temperature interval (Table 3.2, Table 3.3, and Table 3.4, respectively). Two modifications to Threader et al.'s (1998) original suitability indices were made. First, sand was given a suitability index of 0.0 instead of 0.1 because of evidence that Lake Sturgeon spawn near sand bars or beaches, but not on sandy substrates (Daugherty et al., 2008a; Daugherty et al., 2008b). Secondly, this study further refined the depth and temperature intervals so that small scale changes in the overall suitability of spawning habitat could be observed, these revised values are presented below.

Table 3.2 – Suitability index values for each substrate type based on Threader et al. (1998).

Substrate Type	**Suitability Index Value**
Other (i.e. logs, woody debris, etc)	0.0
Clay	0.0
Silt	0.0
Sand	0.0
Bedrock	0.3
Gravel	0.5
Cobble	1.0
Boulder	1.0

Table 3.3 – Suitability index values for each depth interval based on Threader et al (1998).

Depth Interval (m)	**Suitability Index Value**
<0.3	0.0
3 to <5	1.0
5 to<8	0.75
8 to <11	0.5
11 to <14	0.2
14 to <18	0.1
≥18	0.0

Table 3.4 – Suitability index values for each temperature interval based on Threader et al (1998).

Temperature Interval(°C)	**Suitability Index Value**
<8.3	0.0
8.3 to <10	0.25
10 to <12	0.75
12 to <16	1.0
16 to <20	0.75
20 to <23.3	0.25
≥23.3	0.0

To determine the suitability of substrate at each potential spawning site, the raster calculator was used in ArcMap 9.1 (Tools; Spatial Analyst). The overall substrate suitability was equal to the sum of the proportion of each substrate type (i.e. the substrate rasters) multiplied by its respective suitability index value. Therefore, the substrate rasters representing the proportion of “other”, “clay, “silt”, “sand”, “bedrock”, “gravel”, “cobble”, and “boulder” were multiplied by 0.0, 0.0., 0.0, 0.0, 0.3, 0.5, 1.0, and 1.0, respectively, to determine the substrate suitability for spawning. The new raster layer produced from this calculation had 25 m^2 cells with a value ranging from 0 to 1; 0 being very unsuitable substrate for spawning and 1 being highly suitable substrate for spawning. The depth rasters were then reclassified (Tool; Spatial Analyst; Reclass; Reclassify) to convert negative depth values into positive depth suitability index values based on Table 3.3. The reclassification resulted in a depth raster with each 25 m^2 cell having a value ranging from 0 to 1; 0 being a highly unsuitable depth for spawning and 1 being a highly suitable depth for spawning.

Upon generating depth and substrate suitability rasters, the raster calculator was once again used to calculate the geometric mean of each cell within the depth and substrate suitability rasters. The raster that was produced from this calculation represented the overall suitability of each potential spawning site based solely on depth and substrate type. The final variable for the HSM is mean daily water temperature. Since this variable changes daily, so do the model’s predictions of daily suitability. To accommodate this, a suitability map representing the overall suitability of each potential spawning location had to be created for each day from April 29th, 2010 to July 30th, 2010. To do this, mean daily water temperature was converted into a suitability value based on

Table 2.4 (Appendix 2). Upon converting the mean daily temperature to a suitability index value, the raster calculator was once again used to calculate the geometric mean of the water temperature suitability index and the suitability index in each cell within the depth and substrate suitability rasters. The raster layer that was produced from this calculation represented the daily suitability of each potential spawning site based on water temperature, substrate composition, and depth.

Upon generating the overall and daily suitability outputs, the proportion of cells with a spawning suitability value of very poor (0.0), poor (>0.0 to 0.2), fair (>0.2 to 0.5), good (>0.5 to 0.8), and excellent (>0.8 to 1.0) was determined. To rank each of the potential spawning sites based on their overall suitability, the proportion of cells within each suitability class were compared. Spawning sites were ranked higher if they had a higher proportion of highly suitable spawning habitat relative to poorly suitable spawning habitat and vice-versa. Once spawning sites were ranked from first to third, the spawning assessments were considered to determine if there was a higher presence of spawning adults and a greater contribution to natural recruitment at higher ranked spawning sites versus poorly ranked spawning sites.

Cells within the daily habitat suitability outputs were also classified into each of the five suitability classes (i.e. very poor, poor, fair, good, and excellent) and were used to estimate the theoretical timing of Lake Sturgeon spawning at each of the potential spawning sites. The proportion of cells within each class was plotted against time for each spawning site and results from the spawning assessments were used to determine the accuracy of the HSM's predictions. According to the HSM's daily outputs for spawning suitability, Lake Sturgeon spawning should occur on days where there is the greatest proportion of highly suitable spawning habitat relative to poorly suited spawning habitat. Therefore the HSM's prediction for the timing of spawning was compared with empirical evidence for the timing of spawning to test the accuracy of the model's predictions.

3.3.3 Spawning Assessments:

To determine the validity of the HSM's predictions for spawning suitability (described in Section 3.3.2), spring spawning assessments were performed at all three potential spawning sites within the Pic River. A range of methodological approaches was applied throughout the study to determine if spawning was occurring at particular locations, and if so, the relative importance of the spawning site to natural recruitment. To address these questions, the methodological approaches to assess spawning included; visual observations, gill netting, larval drift netting, and deploying egg mats in prime spawning locations.

Visual Observations

Visual observations of spawning were extremely limited within the Pic River due to high levels of turbidity. In 2010, lower flows and fewer heavy rain events enabled some visual observations to be made at Manitou Falls. Apart from these observations, no other evidence of spawning was collected through this method.

Gill Netting

For this portion of the study, only gill netting data collected in 2008 and 2009 were considered, as these were the only two years when gill netting was performed at all three potential spawning sites. Netting occurred from May 28 to August 14 in 2008 and from May 24 to August 14 in 2009. Nylon gill nets were set perpendicular to shore at an angle of roughly 90° with stretch mesh sizes ranging from 20.32 cm (8”) to 25.4 cm

(10”). Gill nets were set overnight and upon retrieval the location, duration, depth, water temperature, net length, mesh size, cloud cover, and precipitation type were recorded for each set. Since this portion of the study was focused on spawning individuals at each of the potential spawning sites, only data that were collected from ripe individuals within 500m of a potential spawning site were used to determine catch per unit of effort (CPUE) (# ripe adults/day). CPUE of ripe adults at each spawning site was used as a surrogate measure of abundance to rank the relative importance of each potential spawning site within the Pic River.

Larval Drift Netting

Larval drift netting occurred in 2010 at the lower rapids, Manitou Falls, and Kagiano Falls, from May 22nd to June 20th, from May 24th to July 5th, and from May 28th to June 16th, respectively. Larval drift nets with a mesh size of 1600 µm were anchored in the river channel overnight at various depths and locations within 1 km of potential spawning sites. Larval drift nets that were set below the confluence of the Pic and Kagiano Rivers were not included in this analysis since it could not be determined whether their natal site was Manitou or Kagiano Falls. All contents collected in the larval drift nets were preserved in 95% Ethanol Alcohol (ETOH) and identified through a dissecting microscope. In cases where larvae could not be identified through a microscope, DNA sequencing was used to identify the species. Using methods outlined in the NRDPFC Laboratory Manual, the mitochondrial cytochrome b gene was amplified and sequenced, and the nucleotide sequence was inputted into BLAST (Basic Local Alignment Search Tool) to determine the species. The total number of Lake Sturgeon larvae captured at each spawning site was divided by the total amount of effort at that respective site to assess the relative recruitment rate based on CPUE of larvae.

Egg Mats

Egg mats were deployed in 2010 at the lower rapids, Manitou Falls, and Kagiano Falls, from May 25th to June 2nd, from May 18th to June 5th, and from May 22nd to June 7th, respectively. Egg mats were deployed overnight within 50 m of Manitou and Kagiano Falls and in fast flowing waters that were along the lower rapids. Egg mats were thoroughly checked each day and all eggs were collected from the mats, regardless of their appearance. All eggs that were collected were preserved in 95% ETOH and identified as Lake Sturgeon, if they were a dark olive-brown colouration. To confirm that visual observations were sufficient, a subsample of 100 transparent eggs that were collected at the lower rapids and Manitou Falls were genetically sequenced for the mitochondrial cytochrome b gene. This confirmed that they were not sturgeon. All olive-black coloured eggs were then identified as Lake Sturgeon based solely on visual observation. The total number of Lake Sturgeon eggs collected per spawning site was divided by the total amount of effort at that respective site to assess the relative recruitment based on CPUE of eggs.

3.3 RESULTS

3.3.1 Overall Spawning Habitat Suitability:

At each potential spawning location, a substrate raster was generated that represented the proportion of that particular substrate type at that location (8 substrate types total x 3 potential spawning sites) (Figure 3.1 to Figure 3.21 in Appendix 1). The resultant suitability index values were then used to convert the proportion of substrate type to a composite substrate suitability index value for the Lower Rapids, Manitou Falls, and Kagiano Falls (Figure 3.22; Figure 3.23; Figure 3.24; respectively). Cells with an area of 25 m^2 were then classified into 5 different groups depending on their substrate suitability index value, defined as: 0.0 (very poor), >0.0 to <0.2 (poor), 0.2 to <0.5 (fair), 0.5 to < 0.8 (good), and 0.8 to 1.0 (excellent). Results indicated that the lower rapids had the largest proportion of highly suitable substrate, with nearly a threefold higher proportion of highly suitable substrate relative to Manitou and Kagiano Falls (Figure 3.25). Furthermore, the lower rapids were nearly a fourfold lower in the proportion of very poor, poor, and fair substrate suitability for spawning. According to these results, the substrate suitability for spawning Lake Sturgeon is predicted to be substantially better at the lower rapids compared to Manitou and Kagiano Falls, whereas the proportions of high and low substrate suitability were roughly equal at these two latter locations.

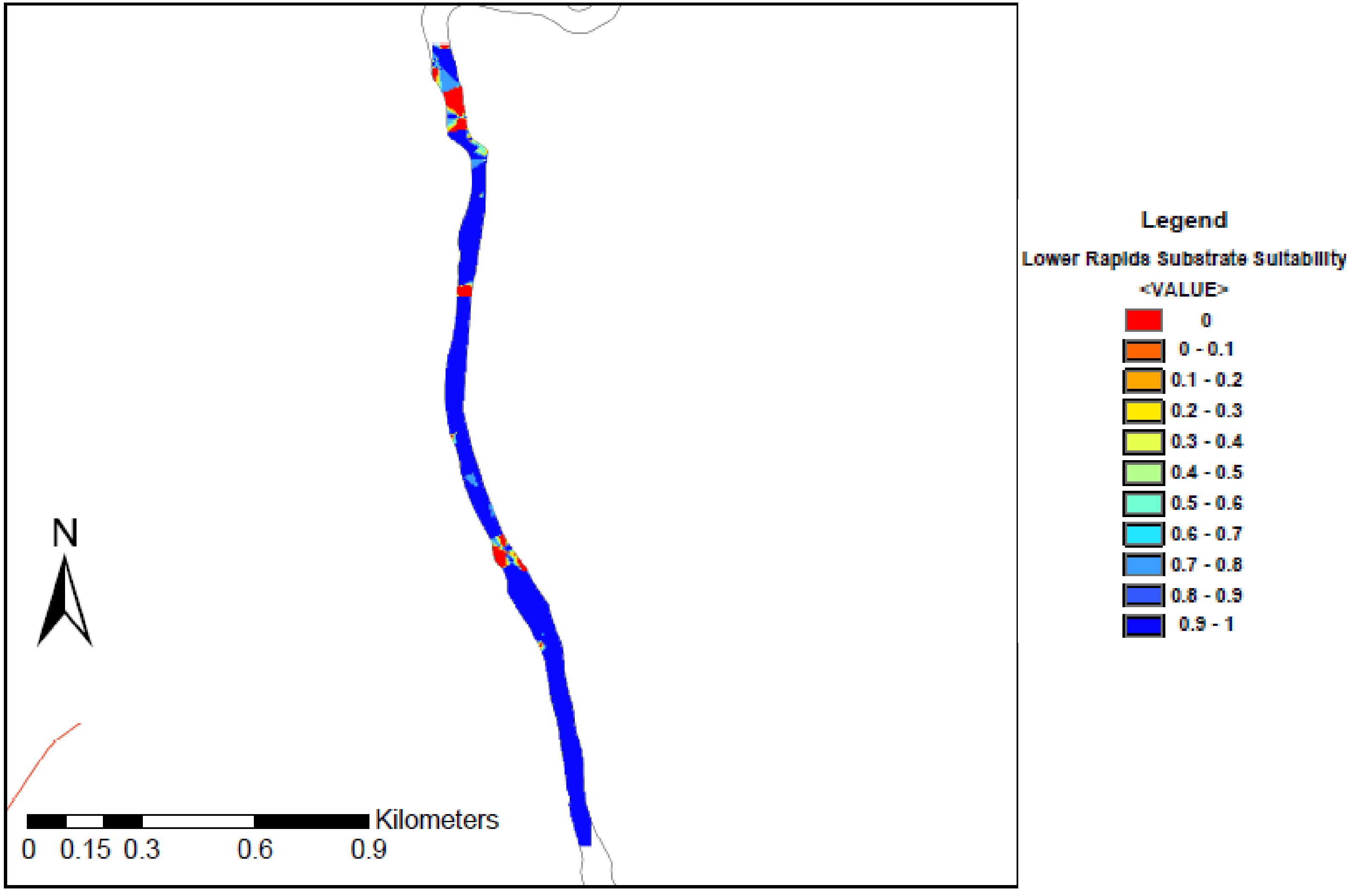

Figure 3.22 – Substrate suitability of the Lower Rapids based on the suitability index values (Table 3.2).

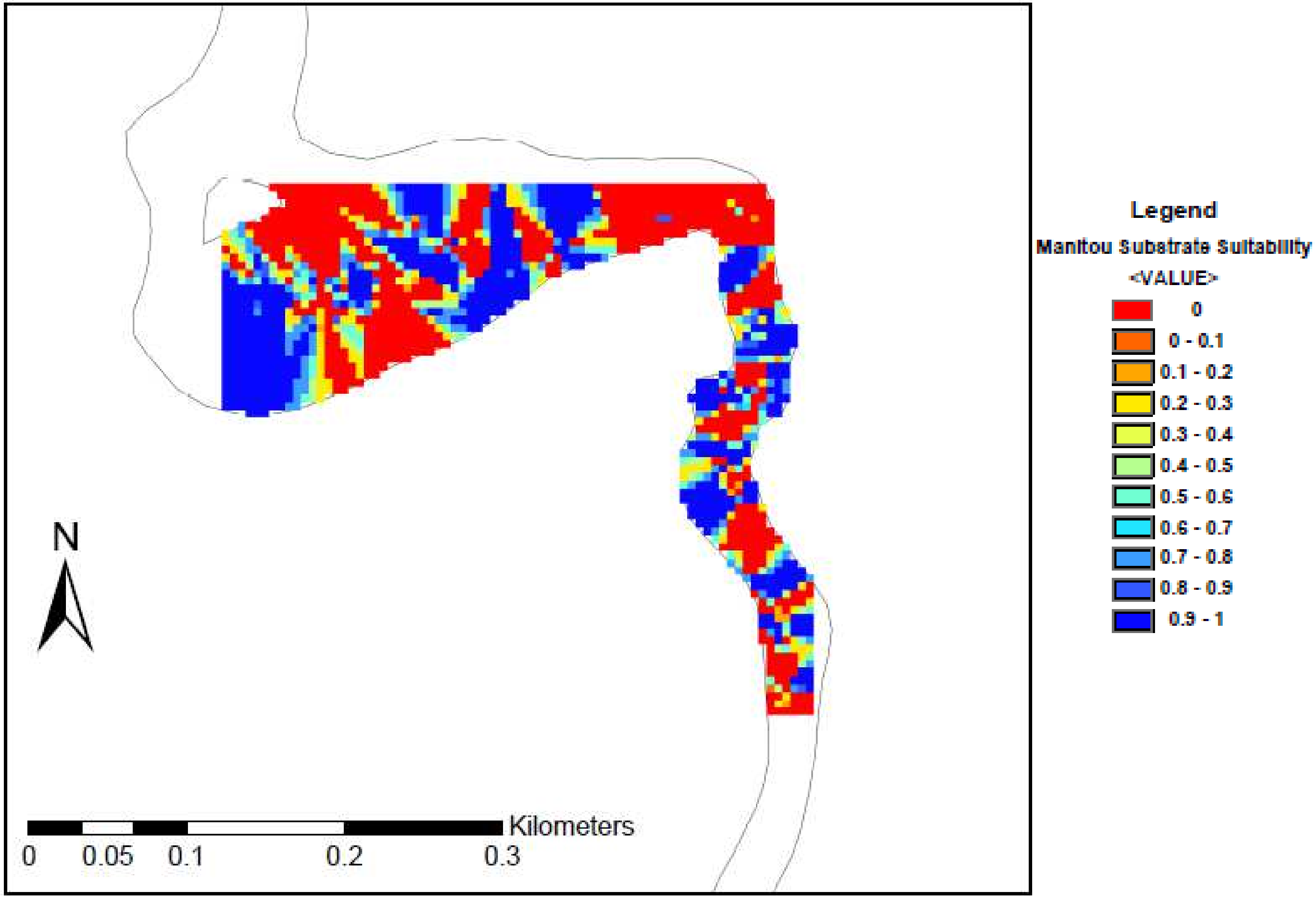

Figure 3.23 – Substrate suitability of Manitou Falls based on the suitability index values (Table 3.2).

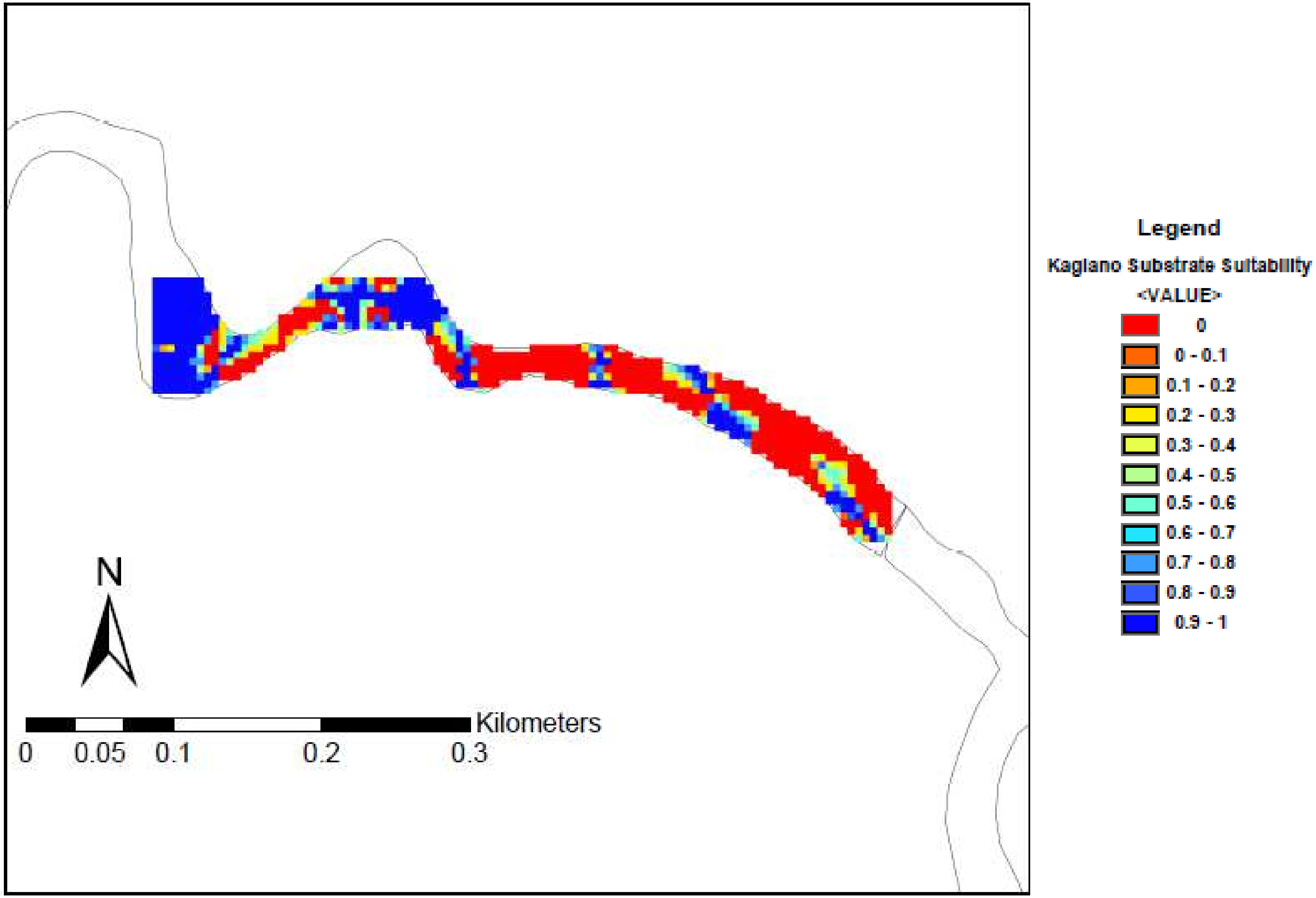

Figure 3.24 – Substrate suitability of Kagiano Falls based on the suitability index values (Table 3.2).

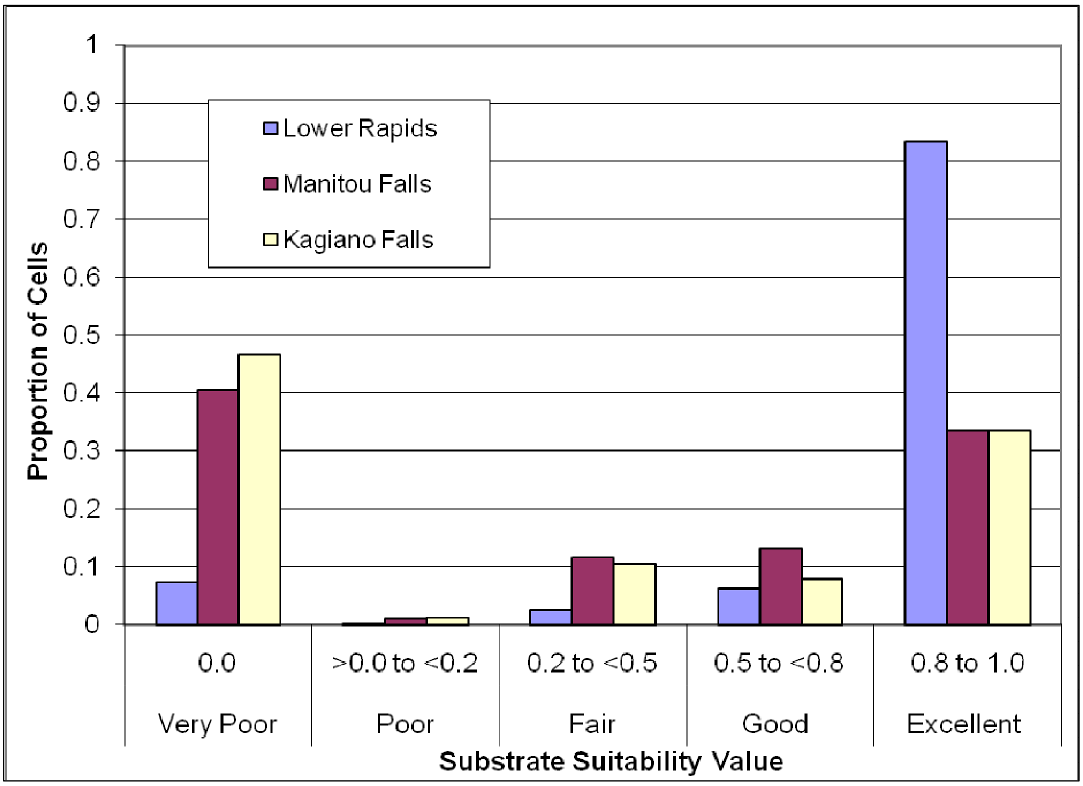

Figure 3.25 – The proportion of cells with a substrate suitability index value that is representative of very poor (0.0), poor (>0.0 to <0.2), fair (0.2 to < 0.5), good (0.5 to <0.8), and excellent (0.8 to <1.0) spawning substrate.

At each potential spawning site, a bathymetry raster was generated and each 25 m^2 cell was converted from a depth value to a depth suitability index value based on Table 3.3. Since Lake Sturgeon have a broad depth tolerance for spawning, 90% and 97% of the habitat at the lower rapids and at both Kagiano and Manitou Falls (respectively) was classified as excellent depth for spawning (i.e. depth suitability index value greater than or equal to 0.8). The depth suitability results factored out the deep foraging and/or staging habitat at the lower rapids, Kagiano Falls, and Manitou Falls, including plunge pools immediately below both falls and deep pools that occur intermittently throughout the lower rapids.

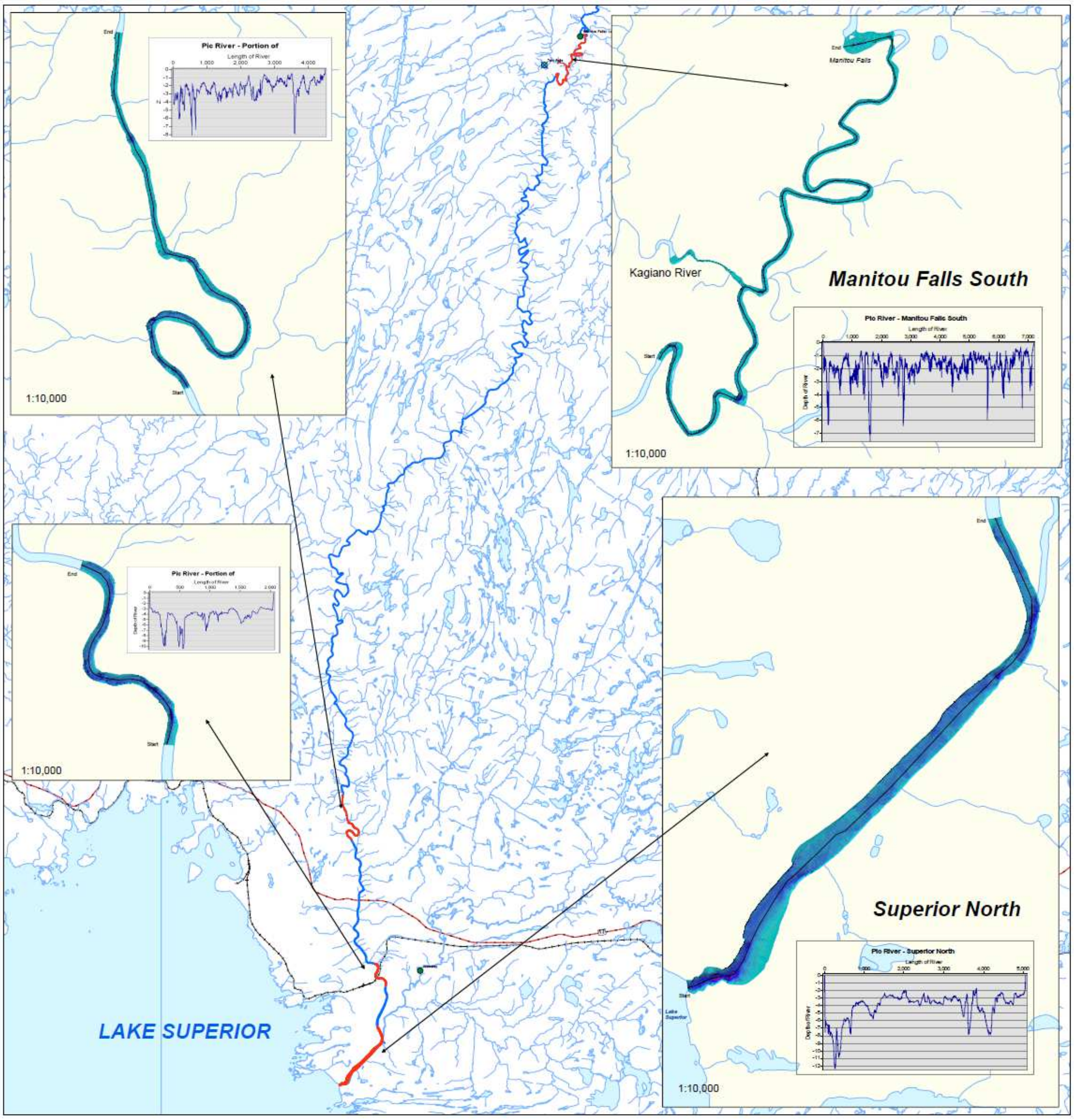

Figure 3.26 – Bathymetric maps of potential spawning sites in the Pic River. Data were collected from July to August in 2009 and in June 2010. The inset at the top left is of the lower rapids, whereas the inset at the top right is of Manitou and Kagiano Falls.

Upon generating substrate and depth suitability rasters, the geometric means of these two layers were calculated to generate a compound model estimate of the overall spawning suitability of the Lower Rapids, Manitou Falls, and Kagiano Falls (Figure 3.27; Figure 3.28; Figure 3.29; respectively). As was the case when only substrate was considered, the lower rapids had nearly a threefold increase in the proportion of highly suitable habitat when both substrate and depth were considered (Figure 3.30). With the exception of a 1700m^2 patch at the top of the site and a 5500m^2 patch in the middle of the site, all of the habitat at the lower rapids ranged from fairly to highly suitable for Lake Sturgeon spawning (Figure 3.27). Additionally, Manitou and Kagiano Falls had a greater proportion of spawning habitat that was very poorly suited compared to excellently suited habitat for Lake Sturgeon spawning. Of the entire area that was modeled at the lower rapids (78,475 m^2), Manitou Falls (23,775 m^2), and Kagiano Falls (13,100 m^2), a total area of 69,575 m^2, 8,925 m^2, 4,200 m^2 (respectively) was considered excellently suited for Lake Sturgeon spawning based on the compound model for overall suitability.

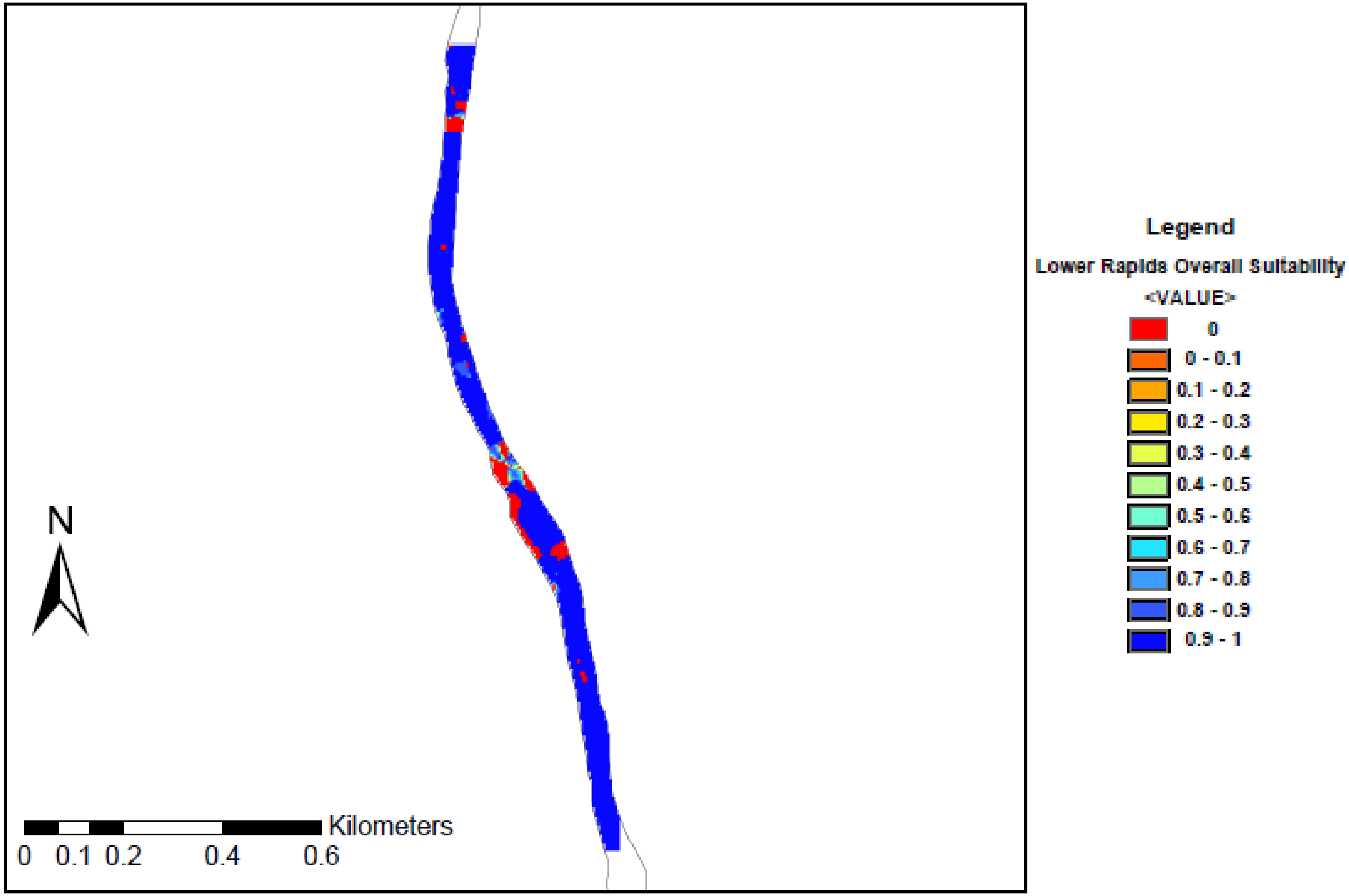

Figure 3.27 – Overall suitability of the lower rapids based on the depth and substrate suitability index values (Table 3.2 & 3.3).

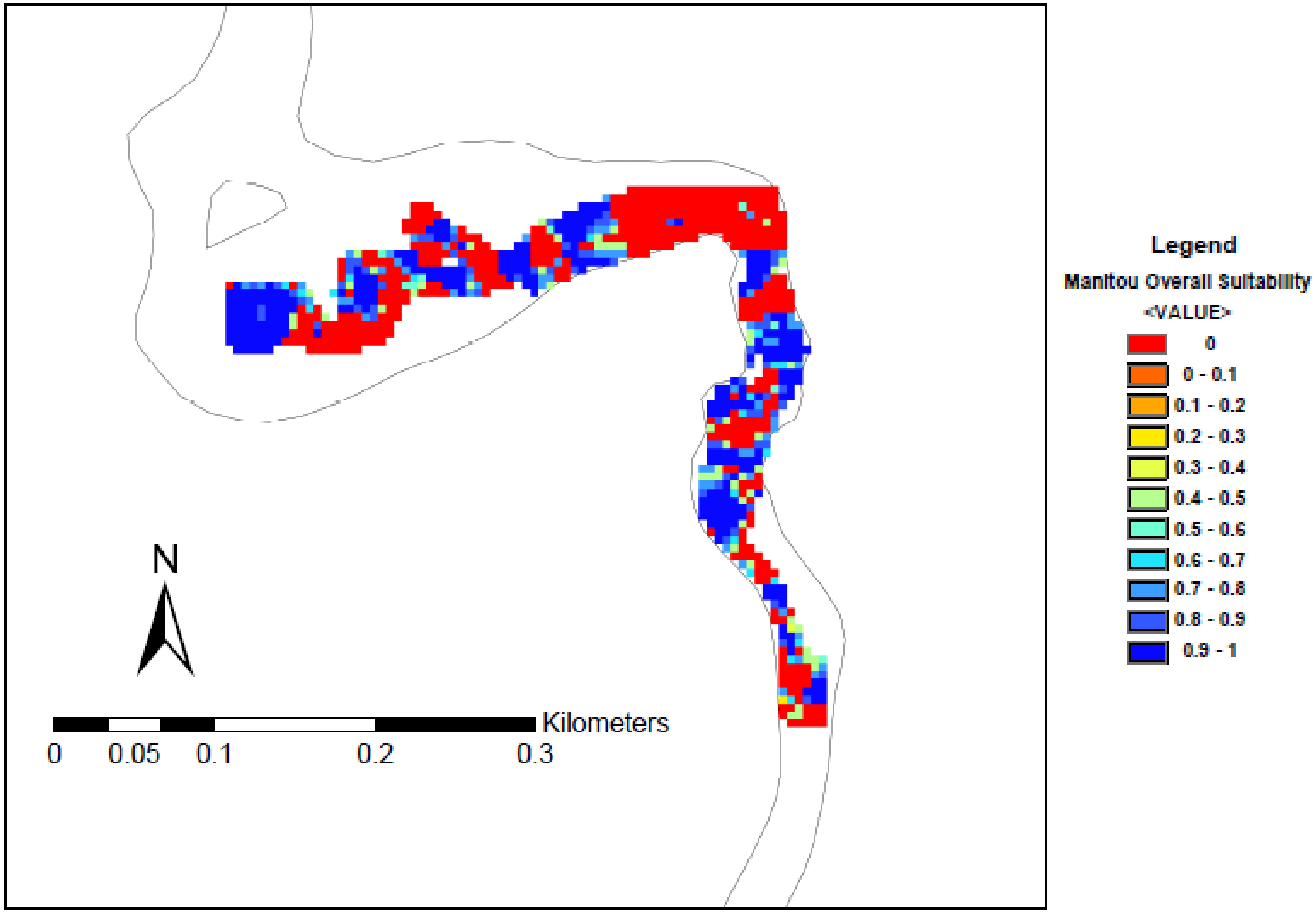

Figure 3.28 – Overall suitability of Manitou Falls based on the depth and substrate suitability index values (Table 3.2 & 3.3).

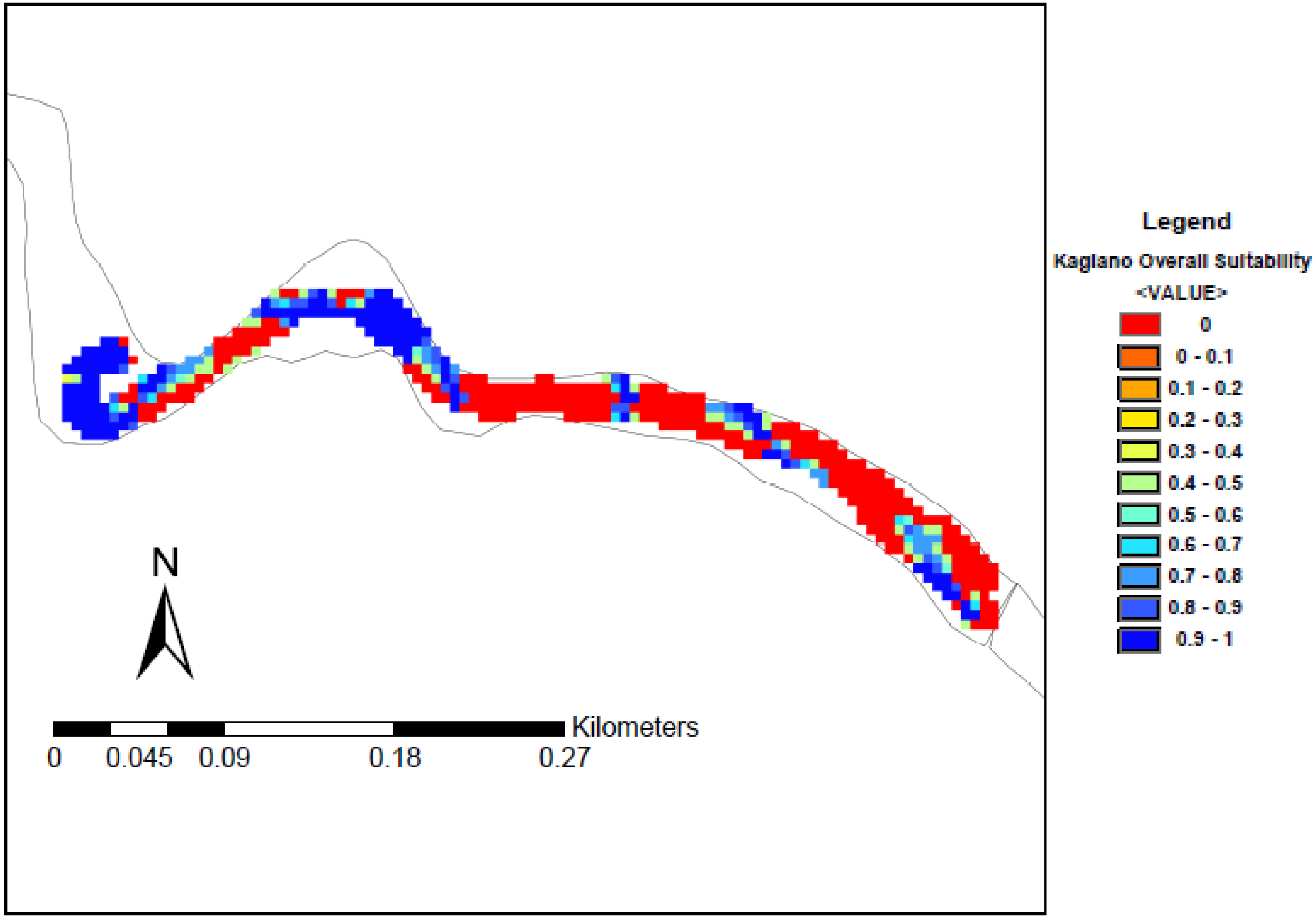

Figure 3.29 – Overall suitability of Kagiano Falls based on the depth and substrate suitability index values (Table 3.2 & 3.3).

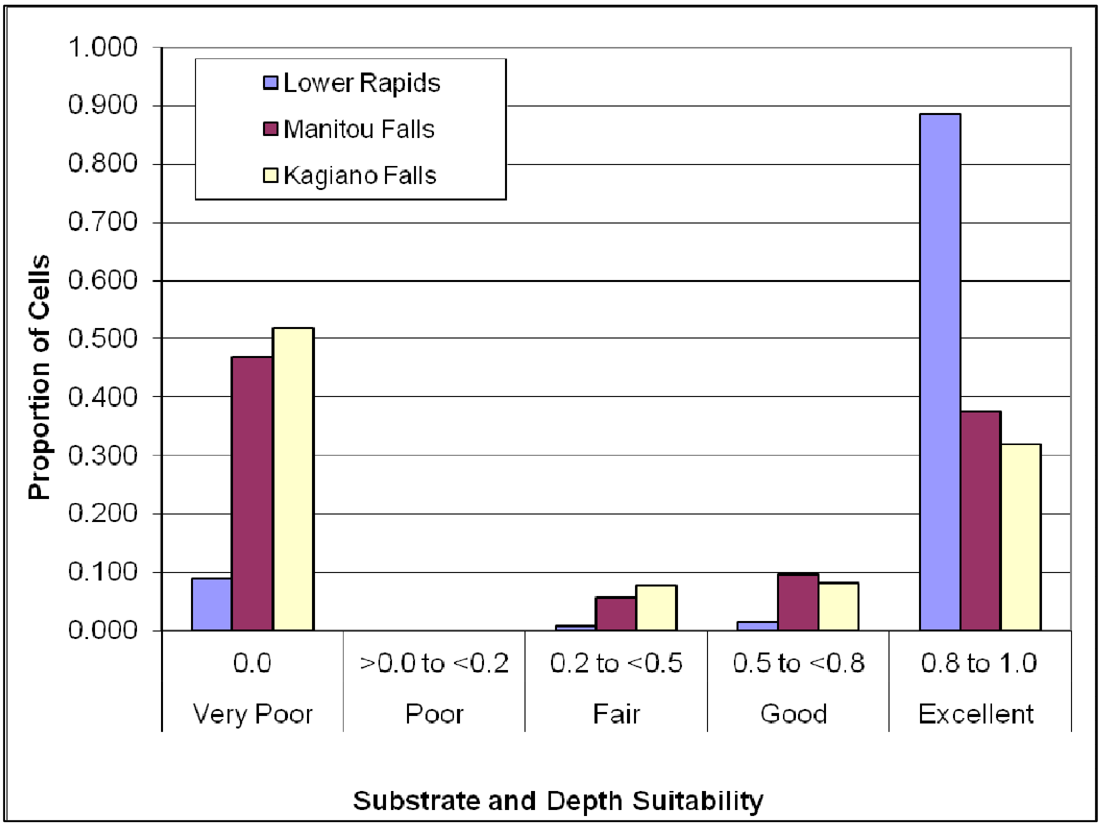

Figure 3.30 – The proportion of cells at each potential spawning site with a suitability index value that is representative of very poor (0.0), poor (>0.0 to <0.2), fair (0.2 to < 0.5), good (0.5 to <0.8), and excellent (0.8 to <1.0) spawning suitability based on substrate and depth.

Although Manitou and Kagiano Falls had less highly suitable spawning habitat, there was nonetheless some highly suitable spawning habitat that warrants attention. At Manitou Falls there was a large patch (1,700 m^2) of highly suitable spawning habitat that is immediately to the left of the base of the falls (Figure 3.28 and Figure 3.31). As well, there are four large patches (600 m^2 to 900 m^2) of highly suitable spawning habitat located where the river first begins to narrow below Manitou Falls. There was an additional six smaller habitat patches (300 m^2 to 700 m^2) that were located immediately below the first bend that is located below Manitou Falls. At Kagiano Falls, there were two large patches (roughly 1,300 m^2) of highly suitable Lake Sturgeon spawning habitat, one occurring immediately below the uppermost navigable point and another occurring at the second bend below the uppermost navigable point (Figure 3.29 and Figure 3.32). There were a few more intermittent patches of suitable spawning habitat near the mouth of the Kagiano River; however, given the low patch size and moderate suitability, these are unlikely spawning locations. It is also important to note that for both of these locations, sampling methods were not feasible immediately below the water chute of the falls because of boat accessibility and water flow issues (Figure 3.33). Although not navigable by boat or feasible to assess using the DIDSON camera, fish could still navigate these areas with relative ease. Therefore, is it is possible that both Manitou and Kagiano Falls had a greater proportion of highly suitable spawning habitat within these unsampled portions, especially given that these areas were mostly comprised of boulder and cobble substrate. The limiting factor to the suitability of both of these locations is depth, since ephemeral conditions exist within these portions. It is likely that these two unsampled locations could add up to 6,000 m^2 and 9,000 m^2 of highly suitable spawning habitat to both Kagiano and Manitou Falls, respectively.

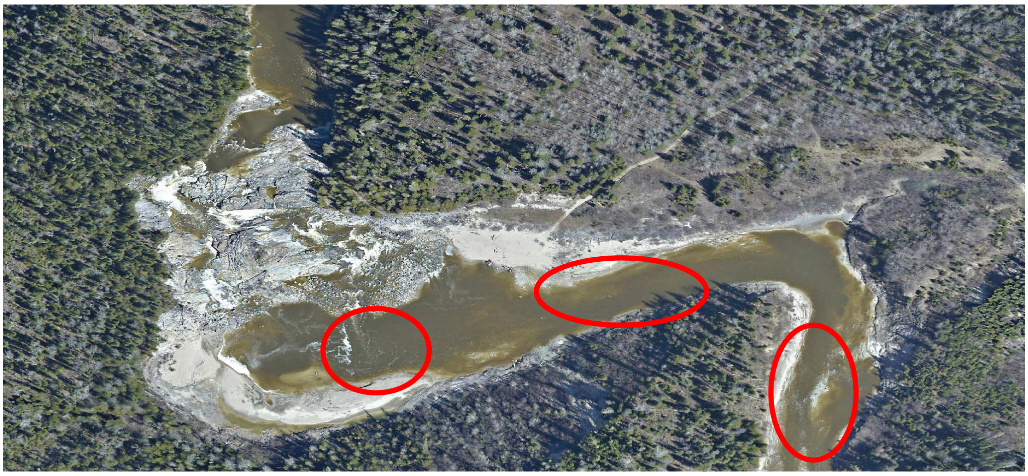

Figure 3.31 – Aerial photograph of Manitou Falls on the Pic River with circles indicating the locations of highly suitable Lake Sturgeon spawning habitat patches.

Figure 3.32 – Aerial photograph of Kagiano Falls on the Kagiano River with circles indicating the locations of highly suitable Lake Sturgeon spawning habitat patches.

Figure 3.33 – Areas of Kagiano (left) and Manitou Falls (right) that could not be sampled because of accessibility and/or water flow issues. Both areas are immediately above the uppermost navigable points of the river, but sturgeon were observed in these areas.

3.3.2 Daily Spawning Habitat Suitability:

To produce daily habitat suitability values for Lake Sturgeon spawning habitat, the geometric mean of each cell was calculated based on the substrate, depth, and temperature suitability index value. The proportions of very poor (0), poor (>0.0-0.2), fair (>0.2-0.5), good (>0.5-0.8), and excellent (>0.8-1.0) habitat were plotted against time (days) to determine when optimal spawning times at each spawning site occurred. According to the HSM, spawning should occur when a spawning site reaches its optimal spawning temperature or when there is a very high proportion of highly suitable spawning habitat. Results indicated that optimal spawning conditions were reached at roughly the same time at each of the potential spawning sites. According to the modeled results, optimal spawning conditions were reached at the lower rapids on May 18th, 2010 to May 22nd, 2010, and again on June 7th, 2010 (Figure 3.34). Modeled results were very similar at both Manitou and Kagiano Falls, whereby the HSM predicted that spawning was most likely to occur between May 2nd, 2010 and May 4th, 2010, between May 17th, 2010 and May 18th, 2010, or on June 10th, 2010 (Figure 3.35 and Figure 3.36, respectively). It is also important to note that in the 2 to 3 days preceding and proceeding the aforementioned optimal spawning windows, the overall suitability was at its second highest level at all three potential spawning sites (i.e. overall suitability < 0.8). The model therefore suggests, albeit with less confidence, that Lake Sturgeon could spawn in the 2 to 3 days before and after these windows as well.

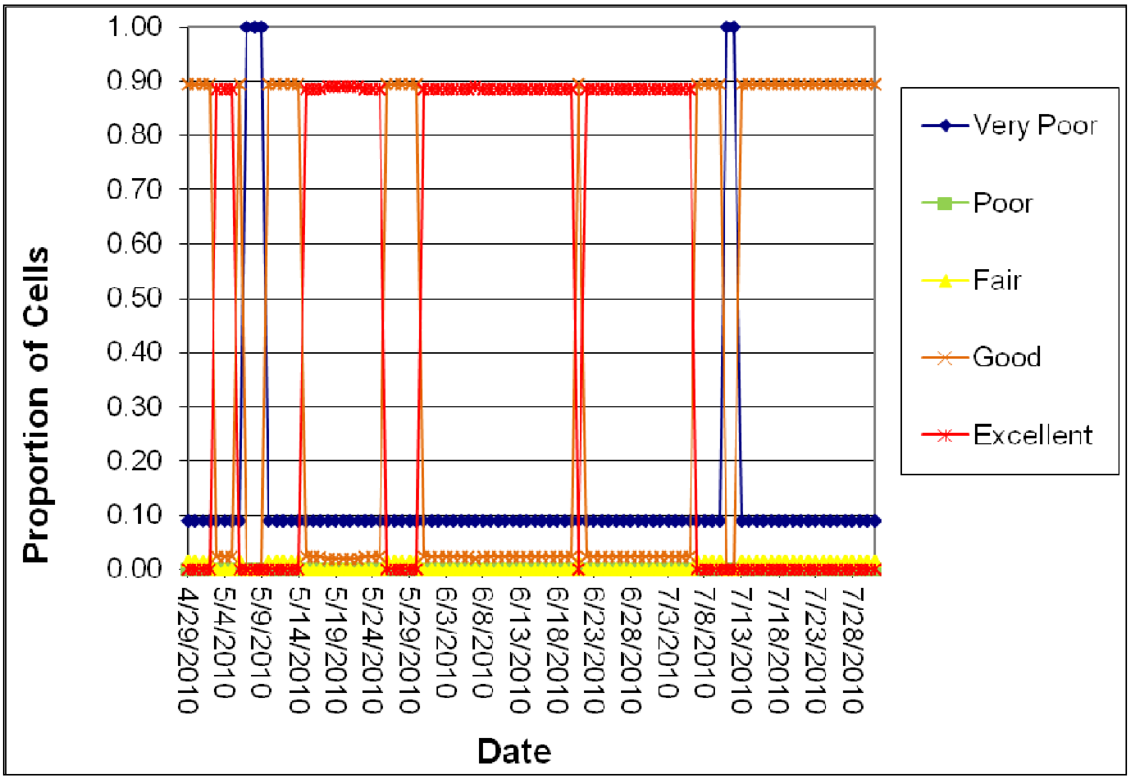

Figure 3.34 – Daily suitability of Lake Sturgeon spawning habitat at the lower rapids based on substrate, depth, and temperature.

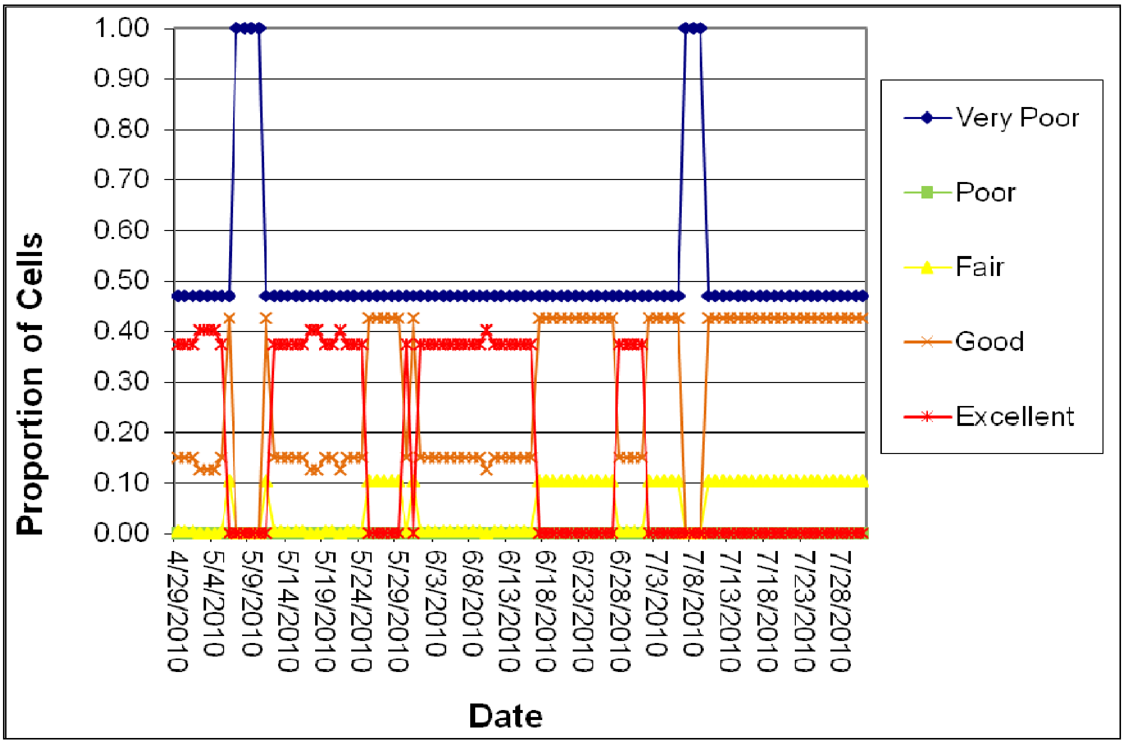

Figure 3.35 – Daily suitability of Lake Sturgeon spawning habitat at Manitou Falls based on substrate, depth, and temperature.

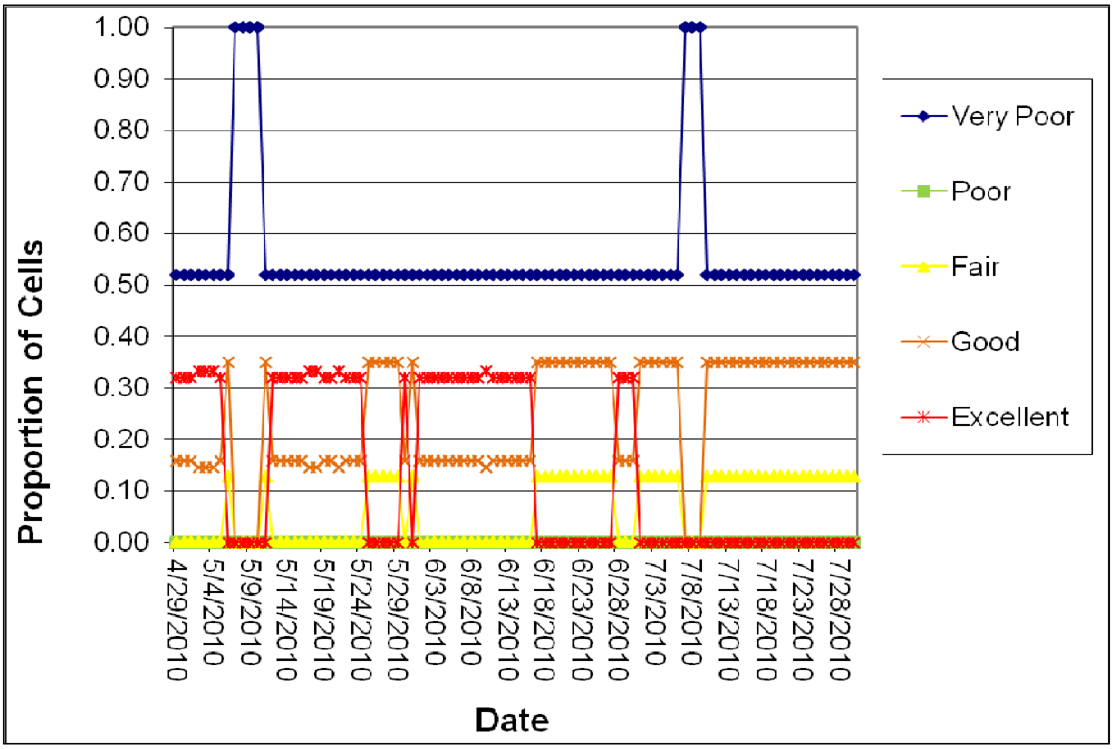

Figure 3.36 – Daily suitability of Lake Sturgeon spawning habitat at Kagiano Falls based on substrate, depth, and temperature.

3.3.3 Spawning Assessments:

To compare habitat utilization by spawning adult Lake Sturgeon at each of the potential spawning sites, three different methods were used to estimate the relative importance and rate of recruitment at each site. The first such measure was CPUE of ripe adults in 2008 and 2009 that were caught within 500 m of each potential spawning site (Figure 3.37). Results indicated that Manitou Falls had the greatest CPUE of ripe adults in 2009 compared to any other site in any given year (0.67 ripe adults captured per day). In 2008, no ripe adult Lake Sturgeon were captured at Manitou Falls, however, this is likely because the sampling period was inconsistent with the timing of migration at this location. In 2008 and 2009, CPUE of ripe adults at Kagiano Falls was relatively constant, with 0.37 ripe adults captured per day and 0.41 ripe adults captured per day, respectively. At the lower rapids, only two ripe adults were captured in 2008, resulting in a CPUE of 0.04 ripe adults captured per day in 2008 and 0.0 ripe adults captured per day in 2009. Given the date that these two individuals were captured (i.e. pre-spawning), it is likely that these two individuals were not spawning at the lower rapids, but instead migrating through the lower rapids to either Manitou or Kagiano Falls. These results suggest that based on CPUE of ripe adults, spawning Lake Sturgeon most frequently utilized Manitou Falls followed closely by Kagiano Falls. Furthermore these results show very limited evidence of spawning activity or habitat utilization by ripe spawning adults at the lower rapids.

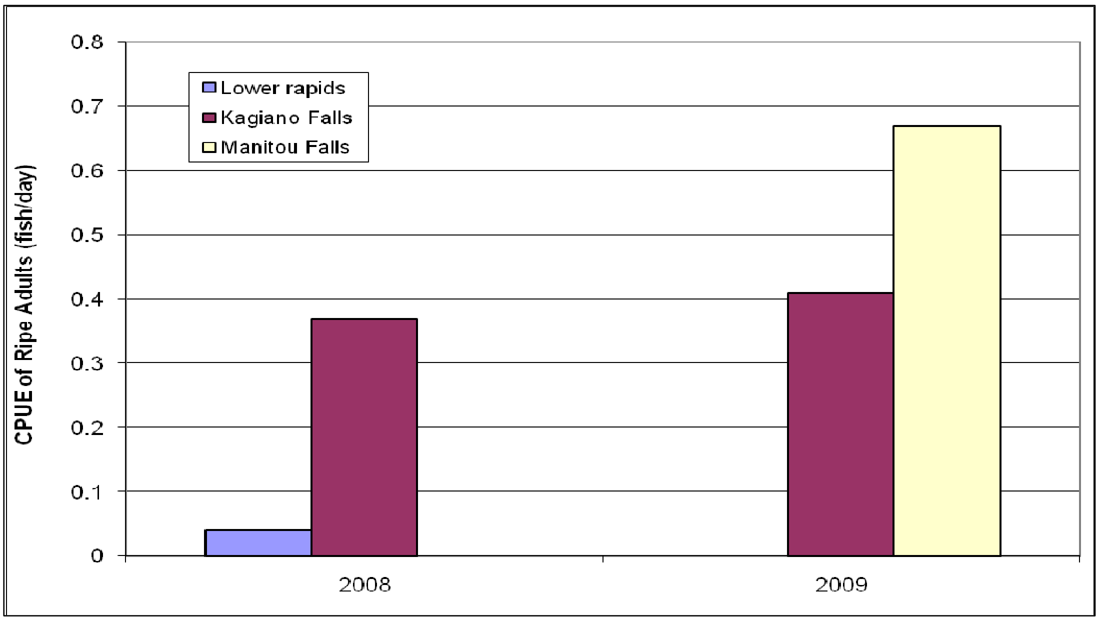

Figure 3.37 – CPUE (fish per day) of ripe adults captured within 500m of the Lower Rapids, Kagiano Falls, or Manitou Falls in 2008 and 2009. In 2008, no ripe adults were captured at Manitou Falls because of a late start to sampling.

The second and third measures that were used to estimate the importance of each site were egg and larvae collections (Figure 3.38). No eggs or larvae were captured at the lower rapids in 2010, despite logging over 4,300 hours of egg mat sampling and over 8,600 hours of larval drift net sampling. No eggs were captured at Kagiano Falls in 2010, possibly because of reduced effort (just over 1600 hours) or because sampling times did not coordinate with spawning times. Of the three potential spawning sites, Manitou Falls was the only location where Lake Sturgeon eggs were captured in 2010. A total of 9 Lake Sturgeon eggs were captured on May 24th, 2010 at Manitou Falls, for a CPUE of 0.02 eggs per day. All of these eggs were captured at the same location, which was immediately above the waterfall break, in the rapids that are located to the left of the waterfall fan (Easting: 566936, Northing: 5450850) (Figure 3.39). A total of 2 and 5 Lake Sturgeon larvae were captured a Kagiano and Manitou Falls in 2010, respectively, resulting in a CPUE 0.03 larvae per day at Kagiano Falls and 0.06 larvae per day at Manitou Falls. As was the case for CPUE of ripe adults at each spawning site, these results indicate that Manitou Falls is the most frequently utilized and most important spawning site to natural recruitment within the Pic River. Evidence of spawning also suggests that Kagiano Falls is an important spawning site for recruitment within the Pic River, while the lack of spawning evidence collected at the lower rapids suggests that Lake Sturgeon may not spawn at this location.

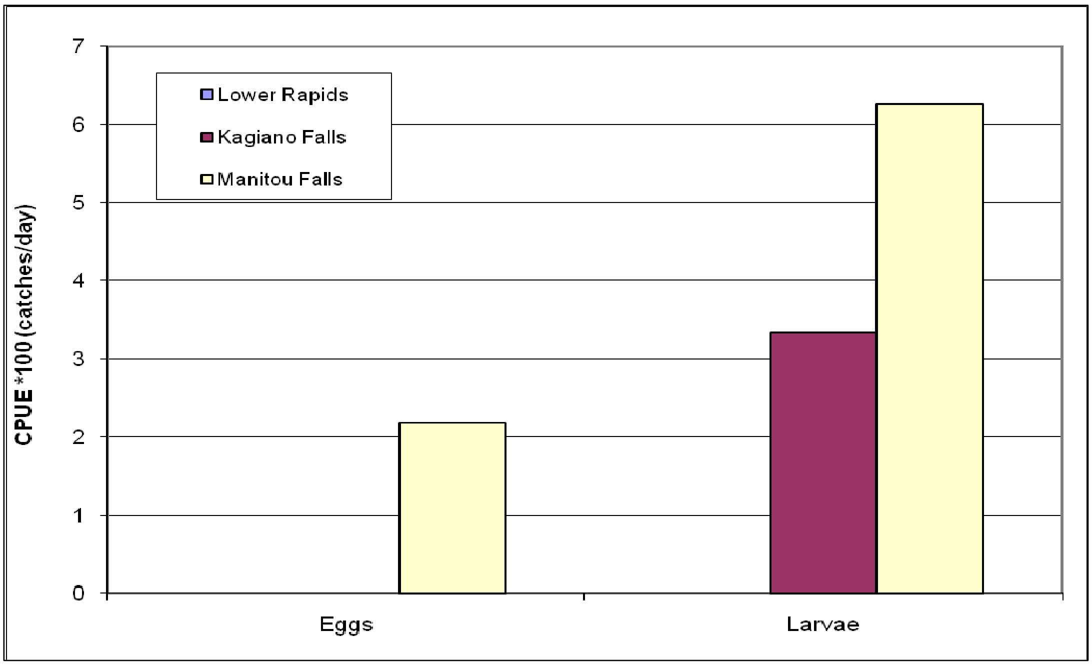

Figure 3.38 – CPUE *100 (catches per day) of Lake Sturgeon eggs and larvae at the Lower Rapids, Kagiano Falls, and Manitou Falls in 2010.

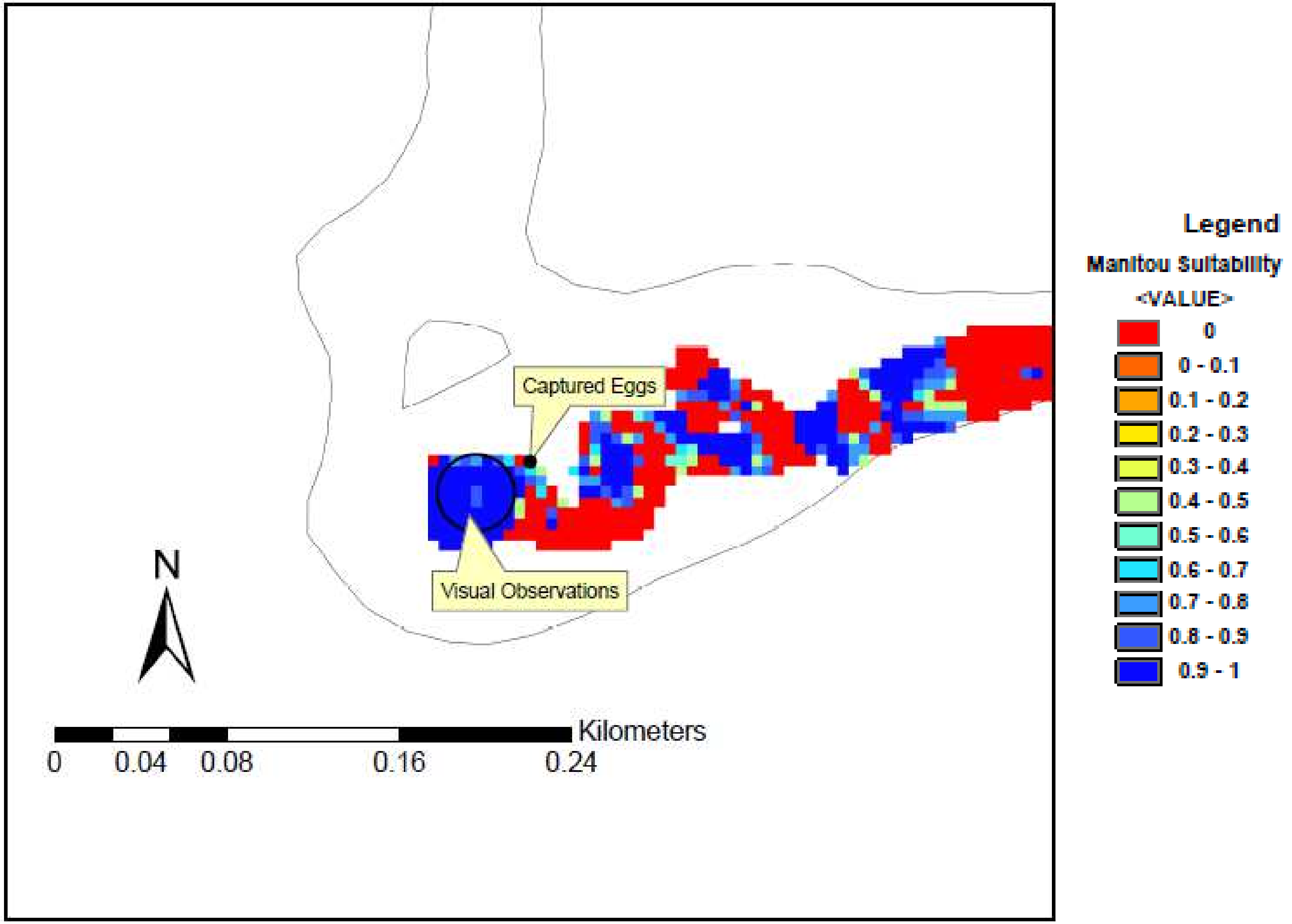

Figure 3.39 – Daily suitability at Manitou Falls on May 24th, 2011, when Lake Sturgeon eggs were collected.

3.4 DISCUSSION

The objective of this chapter was to model the overall and daily suitability of three potential spawning sites in the Pic River and to compare these modeled predictions with empirical evidence of Lake Sturgeon spawning activity at each respective spawning site. First, it was hypothesized that Lake Sturgeon should spawn at sites that maximize their chances of successfully reproducing. According to the HSM (Threader et al., 1998), this would be the site with a greatest proportion and amount of highly suitable habitat relative to poorly suitable habitat. Using this criteria, the HSM predicted that spawning would most likely occur at the lower rapids, followed by Manitou and Kagiano Falls respectively. However no empirical evidence of spawning was collected at the lower rapids, therefore rejecting the predictions of the HSM and the first hypothesis of this chapter. Secondly, it was hypothesized that Lake Sturgeon should spawn at the most highly suitable locations within each spawning site and at temperatures between 12ºC and 16ºC (i.e. the temperature range with a suitability index of 1.0) (Threader et al., 1998). Lake Sturgeon eggs were collected on May 24th at Manitou Falls, which coincided with the HSM's predictions of when spawning would occur at this location. Furthermore, the eggs were captured near a large patch of spawning habitat, indicating that the model accurately predicted the spawning times and locations of Lake Sturgeon at Manitou Falls. This evidence supports the second hypothesis of this chapter since empirical evidence of spawning was collected during and at the location that was predicted by the HSM. Discussion surrounding the first hypothesis (i.e. the predictive ability of the HSM *between* different spawning sites) and the second hypothesis (i.e. the predictive ability of the HSM *within* a spawning site) is respectively outlined in the following two subsections.

3.4.1 Predictive Ability *Between* Sites:

According to the results of the spawning assessments, it appears that the lower rapids is the least utilized and contributes the least to natural recruitment within the Pic River. However, results from the habitat suitability modeling indicated that this site had the greatest proportion and the greatest quantity of highly suitable spawning habitat. This inconsistency between the modeled and empirical data suggests that the HSM may not accurately reflect the likelihood of Lake Sturgeon spawning at a potential spawning sites (i.e. between different sites). If the HSM for spawning Lake Sturgeon were accurate, then the lower rapids would have contributed more to Lake Sturgeon recruitment within the Pic River and would have been more frequently utilized by spawning Lake Sturgeon relative to Manitou and Kagiano Falls. The HSM was able to accurately discriminate between Manitou and Kagiano Falls, whereby it predicted that there was a greater proportion and quantity of highly suitable spawning habitat at Manitou Falls and this location was more frequently used by and spawned at by adult Lake Sturgeon. Conversely, Kagiano Falls was ranked below Manitou Falls and appeared to have slightly less spawning adults per season and contributed slightly less to natural recruitment. Therefore between Manitou and Kagiano Falls, the HSM was able to accurately predict which site would be more significant to natural recruitment. Despite this, the lower rapids, where no evidence of spawning was collected, ranked higher than both Manitou and Kagiano Falls, suggesting that the overall predictive value of the HSM between spawning sites is relatively poor.

When assessing differences between the three potential spawning sites, the biggest fault of the Lake Sturgeon HSM was that it predicted the lower rapids to be the most highly suitable spawning site despite no evidence of spawning at this location (Threader et al., 1998). This may be because the substrate and interstitial spaces at the lower rapids were covered by a fine layer of clay and silt (Figure 3.2 and Figure 3.3, respectively). In the Wolf River, Wisconsin, Lake Sturgeon were less likely to spawn on substrates that were covered by a thin layer of clay, silt, detritus, or heavy algal growth (Floz & Myers, 1985; Kempinger, 1988). Spawning assessments in the St. Lawrence, St. Clair, and Detroit River systems also found that eggs were deposited on substrates that were dominated by cobble or boulders and contained a small mixture of medium to coarse gravel (LeHaye et al., 1992; Manny & Kennedy, 2002; Nichols et al., 2003; Caswell et al., 2004). In the lower rapids there was a very limited amount of medium to coarse gravel substrate (Figure 3.6), whereas at Manitou and Kagiano Falls there was a large proportion of substrate that had a mixture of cobble and/or boulders with coarse sand or gravel (see Section 3.3.1). When clay or silt covers suitable spawning substrate, Lake Sturgeon eggs lose their adhesive ability and therefore cannot develop properly (LeHaye et al., 1992). As well, eggs may become covered with silt or clay, preventing them from being oxygenated and developing (Threader et al., 1998; Peterson et al., 2007). The covering of suitable spawning substrate and eggs by fine particulate sediment may prevent or discourage Lake Sturgeon from spawning at the lower rapids. At both Manitou and Kagiano Falls, this is currently not an issue; however with a proposed dam at Manitou Falls, sedimentation at this spawning site could become an issue in the future (Ligon et al., 1995; Hay-Chmielewski & Whelan, 1997; Auer, 2003).

It is also possible that Lake Sturgeon do not spawn at the lower rapids because of its topography. Although the lower rapids have fast, boiling, white water like Manitou and Kagiano Falls, it does not present any barrier to migration and it does not have a waterfall. A waterfall and fan, that presents either a complete or partial barrier to migration, is a key topographical feature that is present at nearly all Lake Sturgeon spawning sites (Priegel and Wirth, 1974; LaHaye et al., 1992; Nilo et al., 1997; Rusak & Mosindy, 1997; Seylor 1997a; Seylor 1997b; McKinley et al., 1998; Auer & Baker, 2002; Peterson et al., 2007; Chiotti et al., 2008). In rare cases, Lake Sturgeon will spawn along bedrock formations at the mouth of a tributary or along lake shorelines (Harkness & Dymond, 1961; Carlson, 1995). However there is no evidence of Lake Sturgeon spawning in the middle portions of any tributary that is connected to a lake, such as the lower rapids are in the Pic River. Sturgeon spawning areas may be associated with waterfalls because they offer hydraulic complexity and a diversity of substrate and flow conditions (Le Haye et al., 1992; Perrin et al., 2003; Sulak & Clugston, 1998). In the Big Manistee River, Lake Sturgeon spawning occurred at the base of barchans that were produced by waterfalls, as they provided turbulent and irregular water flows (Chiotti et al., 2008).

Finally, the relatively short distance between the lower rapids and Lake Superior may also influence Lake Sturgeon to not spawn there, given the necessary development time for eggs and larvae. The relationship between migration distance and egg development has been well studied and most literature indicates that there is a positive correlation between these two variables (Kinnison et al., 2001). This positive correlation between gonadal somatic index (GSI) and migration distance was observed in White

Sturgeon in the Lower Columbia River and Atlantic Sturgeon in the Hudson River (Devore et al., 1995; Van Eenennaam et al., 1996). This relationship has not been well established for Lake Sturgeon, although Auer (1996) suggests that gonad development occurs during the migration of all Sturgeon species. Not only do eggs require development time during their upriver migrations, but Lake Sturgeon larvae also require development time during their downriver migrations before being swept into the connected lake environment. Lake Sturgeon larval dispersion occurs 5 to 11 days after spawning and at temperatures of approximately 16ºC (Smith & King, 2005b). Upon hatching, the larvae depend exclusively on their yolk sacs for nutrition and lack the most basic anatomical features for survival and locomotion (Peterson et al., 2007). Their phototactic lifestyle consists of rising to the surface during the night and drifting for a period of several hours downstream until finding a new hiding spot or refuge (Peterson et al., 2007). This process continues until Lake Sturgeon reach roughly 400 mm (Peterson et al., 2007), at which point they become juveniles and spend upwards of a year at their nursery habitat, which is typically at the mouth of the river (Auer & Baker, 2002; Nichols et al., 2003; Smith & King, 2005). In the Sturgeon River, after 61 km of drift in the river, larvae were still only 24.4 mm, just barely capable of swimming and controlling locomotion (Auer & Baker, 2002). The small size and slow development time for larval Lake Sturgeon may require them to be within a river habitat for a period of one year before entering a lake habitat. Therefore Lake Sturgeon may not spawn at the lower rapids because it does not give larvae adequate development time prior to entering the lake environment.

Despite not finding any physical evidence of spawning at the lower rapids (i.e. eggs or larvae), Lake Sturgeon movements near the lower rapids were consistent with spawning movements reported in the literature and observed at Manitou and Kagiano Falls, whereby individuals would reside in deep pools for long periods of time (2-3 days) and partake on short range movements through the rapids during optimal spawning conditions (Rusak & Mosindy, 1992; Auer & Baker, 2002; Peterson et al., 2007; Lallaman et al., 2008). It is probable that Lake Sturgeon exhibiting this movement pattern were foraging at the lower rapids and their distributions were congruent with the density of foraging biomass (Harkness & Dymond, 1961; Hay-Chmielewski, 1987; Peterson et al., 2007). Stelzer et al. (2008) performed gut and stable isotope analysis and found that Lake Sturgeon were not only feeding on benthic invertebrates (primarily chironomous larvae), but also dead age-0 Gizzard Shad (*Dorosoma cepedianum*) in the soft sediments of the profundal zone in Lake Winnebago, Wisconsin. At the lower rapids, macroinvertebrates could have higher abundances in the soft bottomed pools that are adjacent to riffles (Brown & Brusak, 1991). Furthermore, with the spawning of several fish species at the lower rapids (Walleye, *Sander vitreus*; Trout-Perch, *Percopsis omiscomaycus*; and Emerald Shiner, *Notropis atherinoides*), it is suggested that foraging Lake Sturgeon were utilizing the lower rapids to take advantage of high food availability. Therefore movement patterns at the lower rapids should not be confused with spawning behaviour since no physical evidence of spawning was collected; rather, these individuals may have been seeking optimal foraging habitat at the lower rapids. Future work should try and relate the distribution of Lake Sturgeon at the lower rapids with the available foraging biomass at that respective location to determine if this explains the movements surrounding the lower rapids.

To improve the predictive ability of the HSM for assessing differences between spawning sites, three modifications are suggested based on this research. The first suggestion is that the model factors in the relative distance of the potential spawning site from the mouth of the river. Given the development times for both eggs and larvae, it is suggested that Lake Sturgeon will always spawn at the uppermost navigable barrier to increase the chances of larvae survival. Secondly, it is suggested that the HSM for Lake Sturgeon spawning habitat should factor in waterfalls or contour gradients within its predictions. At Manitou and Kagiano Falls, topographic maps show a contour gradient that transects the water polygon layer (i.e. a waterfall). At the lower rapids this feature does not exist, therefore the lower rapids could be easily factored out if the HSM considered contour gradients as well. These two modifications to the HSM would have factored out the lower rapids as a potential spawning site, therefore leaving Manitou and Kagiano Falls as the highest-suited spawning habitats in the Pic River, respectively. Had this been the prediction of the HSM, then the modeled results would have been consistent with empirical observations, therefore validating the predictive ability of the HSM.

3.4.2 Predictive Ability *Within* Sites:

Although the model could not accurately determine which spawning site would be most frequently utilized by spawning adult Lake Sturgeon, it did provide relatively good estimates for spawning timing and locations within sites. A total of 9 Lake Sturgeon eggs were captured on May 24th, 2010 at the base of Manitou Falls (Easting: 566936, Northing: 5450850), indicating that Lake Sturgeon spawned on the night of May 23rd,

2010. These eggs were collected at a location that was characterized by a 4:1 boulder to bedrock ratio, a depth of 1.2 m, and a mean daily water temperature of 17ºC (King, 2010). Given these values, the daily suitability value at that specific location was 0.74. Although these eggs were not collected at a location with a daily suitability index value of 1.0, they were located within 20 m of location that had an abundance of excellent spawning habitat (1600 m^2 with a spawning suitability index of 1.0). Lake Sturgeon have a polyandrous mating system, whereby the broadcast spawning females will fertilize their eggs by two to five males while she traverses the length of the spawning habitat (Harkness, 1988; Auer & Baker, 2002; Bruch & Binkowski, 2002; Hodgeson et al., 2006; Peterson et al., 2007). Given this spawning behaviour, it is not surprising that eggs were not collected at a location that was in close proximity to a large upstream patch of highly suitable spawning habitat. Visual observations also spotted two spawning females on May 18, 2010, and a third spawning female on the following day (King, 2010). An additional 20 Lake Sturgeon were observed immediately below Manitou Falls between May 18th and May 21st, 2011 (King, 2011). All of these visual observations were made within spawning habitat that had an overall suitability index value that ranged from 0.69 to 1.00.

Chapter 4: General Discussion

Significant Lake Sturgeon habitat includes portions of the river or lake that are suitable for spawning, nursing, rearing, foraging, and migration (Auer, 2003). In Ontario, the most prevalent threats to these habitats are dams and hydroelectric facilities, pollution and contamination, siltation and sedimentation, and dredging and channelization (Kerr et al., 2011). Ultimately, the successful recovery and conservation of Lake Sturgeon will depend on our collective ability to identify, evaluate, and protect significant habitat in spawning tributaries throughout the Great Lakes (Hay-Chmielewsky & Whelan, 1997; Auer, 2003; Daugherty et al., 2008a; Kerr et al., 2011).

4.1 Significant Habitat, Movement Patterns, and Environmental Cues:

Lake Sturgeon movement patterns in the Pic River were consistent with observations in other Great Lakes tributaries, whereby spawning and non-spawning individuals exhibited different patterns throughout the spring, but aggregated in distinct locations throughout the summer and fall before overwintering in Lake Superior. Despite long spawning migrations that are undertaken by Lake Sturgeon (Auer, 1996), research from the Rainy River (Rusak & Mosindy, 1997), Grasse River (Trested, 2010), Mississippi River (Knight et al., 2002), Ottawa River (Haxton, 2003b), Manistee River (Lallaman et al., 2008), Sturgeon River (Auer, 1999), and Kettle River (Borkholder et al., 2002) have all indicated that Lake Sturgeon show a strong annual and seasonal site fidelity for deep water habitat that exists within spawning tributaries. Strong site fidelity is not only expressed by Lake Sturgeon, but is a common behaviour amongst all living sturgeon species (Bemis & Kynard, 1997). It is believed that the strong homing abilities are responsible for this site fidelity, whereby population-specific adaptations have evolved that reinforce the selection of such habitats within specific tributaries (Legget, 1977; Lyons & Kempinger, 1992; Auer, 1996). In the past, it has been difficult to assess the site fidelity and homing capacities of Lake Sturgeon, but with the advancement of novel molecular techniques, research in this field of study has become much more feasible (Welsh et al., 2008; 2010; Welsh & McLeod, 2010).

Environmental cues to Lake Sturgeon migration were partially identified through this study, but further research and revised methods are required to accurately distinguish abiotic conditions that stimulate migration. In the Kettle River, movements were strongly correlated with water discharge and mildly correlated with temperature (Borkholder et al., 2002). In Lake Winnebago, long-term movement records were correlated with temperature, whereby Lake Sturgeon moved onto and off of the spawning site at temperatures between 6ºC and 16ºC and at 15ºC to 21.1ºC, respectively (Bruch & Binkowski, 2002). These same movements were more strongly related to water flow in the Kaministiquai River, where movements onto the spawning grounds were strongly correlated with water discharges that ranged from 14 m^3/s to 23 m^3/s (Friday 2004; Friday 2005b). For foraging Lake Sturgeon, optimal water temperatures and flows are estimated to range from $11^{°C}$ to $18^{°C}$ and from 3 cm/s to 25 cm/s; however, both of these ranges can experience substantial spatial and temporal variation (Scott and Crossman, 1973; Peterson et al., 2007; Ontario Ministry of Natural Resources, 2009; Kerr et al., 2011). Several studies have also related the distribution of juvenile Lake Sturgeon to prey availability (Chiasson et al., 1997; Nilo et al., 2006).

In Lake Winnebago, adult Lake Sturgeon distributions and movements have been compared with detailed substrate and benthic invertebrate mapping to determine that Lake Sturgeon distributions were influenced by prey availability (Probst & Cooper, 1955; Stelzer et al., 2009). Furthermore, several studies have suggested that locations associated with high site fidelity are also associated with higher benthic invertebrates, but this has not been substantiated through the collection of scientific evidence (Rusak & Mosindy, 1997; McKinley et al., 1998; Auer, 1999; Peterson et al., 2007). This study found no significant relationship between environmental cues and the timing of Lake Sturgeon entering, reaching their uppermost point, and exiting the Pic River. It is possible that no significant relationship was found because the majority of Lake Sturgeon that entered the Pic River in each year of study were there to partake in foraging and not spawning activities. Therefore, it appears that environmental cues to migration are only applicable to spawning individuals within a population, whereas the distribution and movements of foraging individuals are much more strongly influenced by substrate type, depth, and prey availability. Not only does this rationale provide an explanation for why no significant environmental cues to migration were identified, but it also explains the distribution of Lake Sturgeon at the lower rapids of the Pic River.

This study also determined that Lake Sturgeon left the Pic River to overwinter out of the river, presumably in Lake Superior. Although it is not entirely clear where Lake Sturgeon went upon leaving the Pic River, four radio tagged Lake Sturgeon were tracked in the White River on July 12th, 2010, and one other individual was found at Oisseau Bay, approximately 40 km south of the Pic River. As well, two Lake Sturgeon were captured in the Pic River in 2008 that had originally been tagged in the Black Sturgeon River, approximately 200 km west of the Pic River near the city of Thunder Bay, Ontario (Dreary, 2008). Although it has been acknowledged both here and within the literature that site fidelity and homing capabilities appear to be strong for Lake Sturgeon, these results suggest that straying is somewhat common amongst Lake Sturgeon populations. In light of this evidence, it is advocated that the concept of a metapopulation be given greater consideration for Lake Sturgeon. Metapopulation dynamics have been suggested for Lake Sturgeon in the St. Marys River (Bauman et al., 2011), for populations in the Lower Niagara and Detroit/St. Clair Rivers (Welsh & McClain, 2001), and for White Sturgeon in the highly fragmented Columbia River system (Jager et al., 2001; Coutant, 2004). This possibility will be investigated further in 2011 by studying Lake Sturgeon in the White River and assessing rates of immigration and emigration. Also, a proposed study by Fisheries and Oceans Canada and the U.S. Fish and Wildlife Service could apply novel molecular techniques to identify to possibility of metapopulation dynamics throughout each basin in the Laurentian Great Lakes (Tom Pratt, personal communication).

4.2 Suitability Modeling of Lake Sturgeon Spawning Habitat:

Lake Sturgeon spawning habitat is typically associated with gravel-cobble-boulder substrate and depths of 0.3 m to 10 m (Threader et al., 1998; Bruch & Binkowsky, 2002; Peterson et al., 2007; Kerr et al., 2011). Using these variables, the overall suitability of three potential spawning sites in the Pic River was assessed using a HSM that was developed for Lake Sturgeon spawning habitat (Threader et al., 1998). Temperature was also included in the suitability model to estimate the spawning times of Lake Sturgeon in 2010. Empirical evidence of spawning (i.e. CPUE of eggs, larvae, and ripe adults) was then compared with modeled results to determine if the HSM could accurately predict the amount of spawning activity between each site and where spawning activity would occur within a site. The HSM could not accurately predict which spawning site would be most frequently used by spawning individuals, since it predicted that the lower rapids had the greatest proportion and amount of high quality habitat, but no evidence of spawning was collected there. Conversely, spawning evidence was collected and both Manitou and Kagiano Falls, but the proportion and amount of high quality habitat was far outweighed by low quality habitat at both of these sites. Despite the HSM's ability to predict which spawning site would be most frequently utilized by spawning individuals, its ability to predict the timing and location of spawning within a site was reasonably good. Lake Sturgeon eggs from Manitou Falls were collected within close proximity of the largest patch of highly suitable spawning habitat and during the optimal spawning times as predicted by temperature. Therefore, although the HSM for Lake Sturgeon spawning habitat did relatively well at predicting spawning locations and times within a site, clearly some modifications need to be made for the model to accurately predict the relative amount of spawning activity between different spawning sites.

To improve the predictive ability of the HSM between spawning sites, is it recommended that the model include the relative distance of the potential spawning site from the uppermost barrier and the presence and absence of a waterfall or comparative hydrological feature. Topographical features, such as waterfalls that generate hydrological complexities or underwater barchans, can be a good indicator of a potential Lake sturgeon spawning site (Le Haye et al., 1992; Bruch & Binkowski, 2002; Perrin et al., 2003; Chiotti et al., 2008). Given that most of these features pose a barrier to further migration, the relative distance of a spawning site from the uppermost barrier should also be considered, especially in lake-river systems such as the Pic River. Lake Sturgeon may also spawn at the uppermost barrier to maximize gonadal and larval development times, to increase the oxygen supply eggs for eggs, or to minimize egg predation (Auer, 1996; Kinnison et al., 2001; Auer & Baker, 2002; Smith & King, 2005; Peterson et al., 2007; Kerr et al., 2011). On rare occasions, spawning may occur at a location that does not represent the uppermost barrier to migration (Harkness & Dymond, 1961; Carlson, 1995), however the likelihood of this occurring is minimal and therefore the HSM should also consider this variable. The embeddedness of gravel, cobble, and boulder substrates at the lower rapids could have also reduced the likelihood of spawning occurring here; however this is also not reflected in the HSM's predictions. Lake Sturgeon spawning has not only been associated with gravel-cobble-boulder substrates, but it has also been negatively associated with habitat that lacks clean interstitial spaces or contains a thin layer of silt (Floz & Myers, 1985; Kempinger, 1988; LeHaye et al., 1992; Manny & Kennedy, 2002; Nichols et al., 2003; Caswell et al., 2004). New methods of measuring embeddedness should be applied and integrated into the HSM to further improve its predictive ability between potential spawning sites (McHugh & Budy, 2005; Senatt et al., 2007).

Daugherty et al. (2006, 2008a, 2008b) used the Lake Sturgeon HSM with depth, substrate, and flow potential as habitat parameters, to prioritize and evaluate the cost-benefit ratio of removing or modifying artificial impediments to migration in five tributaries that drain into Green Bay, Lake Michigan. In this study, Daugherty et al. (2006; 2008a; 2008b) suggest that new Lake Sturgeon habitat can be generated by removing barriers and assume that individuals will automatically spawn and/or stage at the existing habitat and at the newly accessible habitat. Using this assumption, Daugherty et al. (2006; 2008a; 2008b) propose that dam removals on Green Bay tributaries will result in an increase of highly suitable spawning and staging habitat 94% to 99% and 59% to 83% (respectively). I would argue against these claims of habitat generation by barrier removal, however, since spawning Lake Sturgeon in the Pic River bypassed suitable spawning habitat at the lower rapids in exchange for spawning habitat that was at the uppermost barrier to migration. I believe that Lake Sturgeon in these Green Bay tributaries would do the same and bypass the existing habitat in exchange for the habitat at the new uppermost barrier to migration. Therefore it is plausible that Daugherty et al. (2006; 2008a; 2008b) vastly overestimated the potential spawning and staging habitat that could be generated by the removal of artificial impediments because they assumed that spawning and staging would occur at both the existing and newly accessible habitat. My argument is also supported by evidence from the Kettle River, whereby Lake Sturgeon movements and habitat utilization did not change despite the removal Sandstone Dam (Borkholder et al., 2002). While dam removal has increasingly been advocated as a tool for habitat rehabilitation (Shuman, 1995; Hay-Chmielewski & Whelan, 1997; Furlong et al., 2006; Daugherty et al, 2006), and in some cases for good reasons, these projects should take a more holistic approach to river ecology and consider how the entire river ecosystem will respond to the removal of artificial barriers (Roni et al., 2008).

The obvious habitat parameter that was missing from the HSM in this study was measurements of water flow and spatial variation in flow that exists from topographical and bathymetric features. Inclusion of these data would have refined and improved the accuracy of the HSM predictions for daily spawning suitability and estimates of the spawning time. Although spawning has been observed at flows that range from 50 cm/s to 200 cm/s (Threader et al., 1998; Bruch & Binkowski, 2002; Peterson et al., 2007), however spawning has been observed at flows as low as 10 cm/s in the Lake Winnebago system (Kempinger, 1988) and as high as 550 cm/sec in the Namakan Reservoir system (Shaw, 2010). The collection of spatially explicit and time lapsing hydrological flow data requires a fair amount of resources and expertise, which were unfortunately not available to this study. Given difficulties involved in accurately measure water flow, an alternative method has been developed that measures the flow potential of a location based on a single point measurement (Chaudhry, 1993). This technique was used by Daugherty et al. (2006; 2008a; 2008b) and therefore already has suitability index values associated with respective intervals of stream flow potential. Aside from this limitation, this study did provide a novel method for assessing substrate composition using the DIDSON camera in turbid, remote, and difficult to access river. To date, the DIDSON camera has been used to estimate fish abundance and sizes in various river systems (Boswell et al., 2008; Maxwell & Gove, 2007), identify Chinook Salmon redds in the Columbia River (Tiffen et al., 2004), and to assess underwater fish structure (Moursaud et al., 2003). However this is the first Lake Sturgeon study to use the DIDSON camera and the first study to apply the hand-held overboard approach to capturing footage of substrate composition.

4.3 Implications and Future Directions:

Amongst the threats that continue to impact Lake Sturgeon, hydroelectric developments have been identified as the number one issue that continues to inhibit their recovery and compromise their long-term sustainability (Auer, 1996; Rosenberg et al., 1997; Auer, 1999; Peterson et al., 2007; Ontario Ministry of Natural Resources, 2009; Kerr et al., 2011). More specifically, hydroelectric developments have been associated with harming Lake Sturgeon by reducing or altering spring freshets (Zhong & Power, 1996; Haxton, 2002), reducing spawning success and recruitment through altered water flows (Carrofino et al., 2010; Ferguson and Duckworth, 1997), altering thermal regimes (Zhong & Power, 1996; Horne, 2004; Paragamian et al., 2001; Kappenman et al., 2009), entrainment (Seylor, 1997a; Seylor, 1997b), reduced water quality (Zhong & Power, 1999), and impediments or barriers to access upstream spawning or foraging sites (Ferguson & Duckworth, 1997; McLeod et al., 1999; Haxton, 2002; Knights et al., 2002; Friday, 2005b; Daugherty et al., 2008b). These factors, or a combination of them, may have occurred with the development of the Black River hydroelectric facility, since several elders from Pic River First Nation reported historical spawning at this location prior to the construction of this facility (Couchie, 2009). Hydroelectric facilities can also influence the movements and behaviours of spawning individuals. In the Mattagami River for example, manipulated water flows resulted in spawning at subprime locations and compromised the likelihood of successfully reproducing (McKinley et al., 1998). Some of these impacts can be mitigated; run-of-river facilities can reduce their impact by establishing minimum water flows and mimicking natural hydrological cycles (Auer, 1996b and Poff et al., 1997; respectively).

Despite the concerns and impacts that are associated with hydroelectric developments, especially when considering Lake Sturgeon, recently passed legislation in Ontario has created socio-economic incentives for producers of renewable energy, which has led to the proposal and development of many new hydroelectric facilities (Green Energy Act, 2009) (Figure 4.2). On April 28th, 2009, Pic River First Nation procured the hydroelectric rights to Manitou Falls and has proposed to construct a 2.8MW run-of-river generating station at this location (Figure 4.1). The results of this study have indicated that Manitou Falls is the most likely spawning site that contributes to the natural recruitment of Lake Sturgeon on an annual basis (Chapter 3). As well, the location of the proposed dam will inevitably influence water flow and thermal regimes at the location where definitive evidence of spawning (eggs and visual observations) was collected (King, 2010).

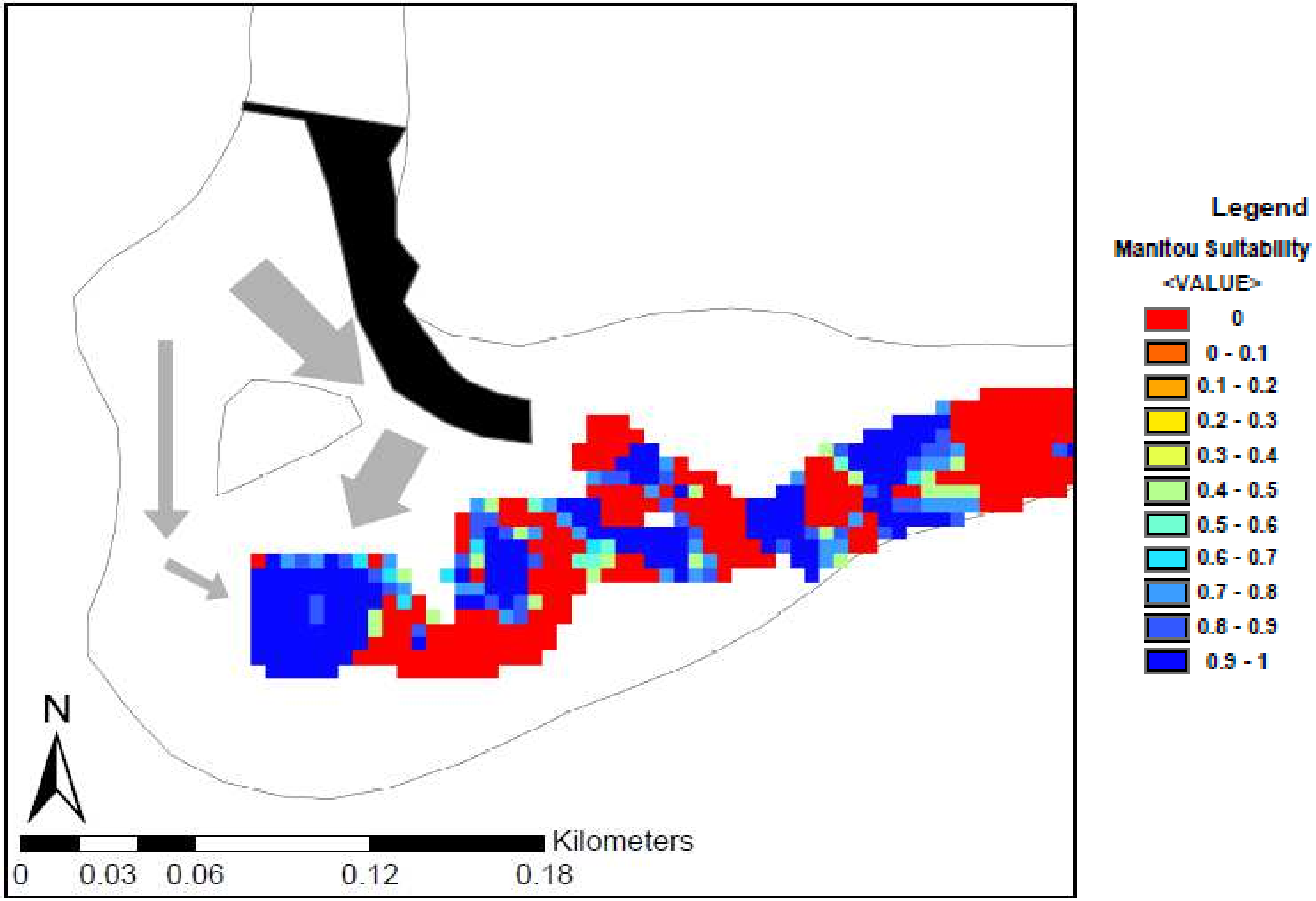

Figure 4.1 – The proposed hydroelectric development at Manitou Falls (black polygon) and flow patterns (gray arrows) relative to the spawning habitat suitability for Lake Sturgeon at Manitou Falls.

Despite the relatively minimal amount of impact that run-of-river generating stations have, they do still alter Lake Sturgeon spawning behaviour and can negatively impact recruitment (Auer, 1999). The Endangered Species Act of Ontario, makes it illegal to kill, harm, harass, or capture a threatened species, a classification that Lake Sturgeon were given in September of 2009 (Endangered Species Act, 2007; Ontario Ministry of Natural Resources, 2009). Based on results from the spawning assessments, habitat suitability modeling, and movement patterns, it seems likely that Lake Sturgeon will be harassed and/or harmed during the construction and subsequent operation of the Manitou Falls generating station. It is strongly recommended that the evidence provided within this report be considered in the approvals and planning of the Manitou Falls generating station and more broadly throughout all proposed hydroelectric developments in Ontario (Figure 4.2).

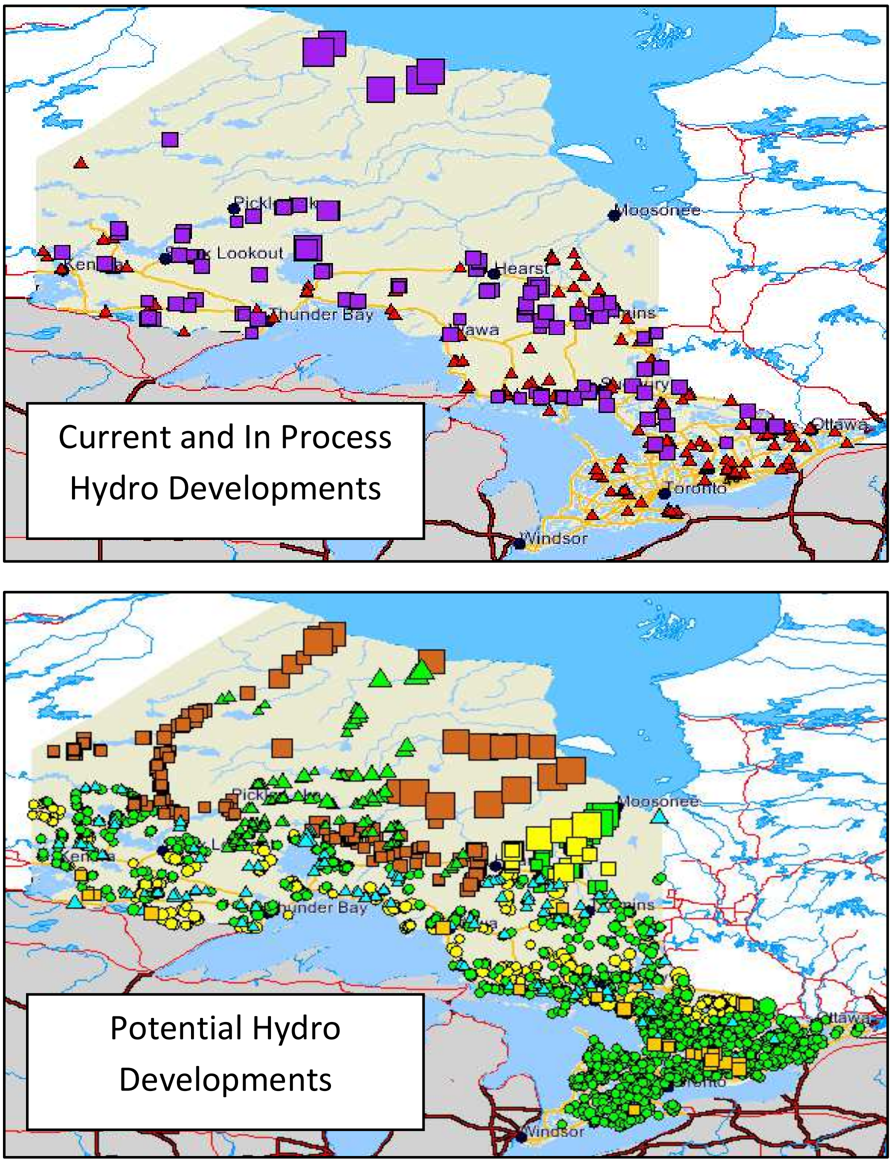

Figure 4.2 – Current and potential or proposed hydroelectric generating stations in Ontario. Source: Ontario Water Power Atlas.

This thesis successfully identified critical habitat and movement patterns in the Pic River, related the timing of movements to abiotic conditions, and evaluated the predictive ability for a Lake Sturgeon HSM that enables the quantitative assessment of spawning habitat suitability. Beyond the tributary specific implications of this research that were discussed above, this research provides a significant contribution towards identified research needs for Lake Sturgeon in Lake Superior and throughout the Great Lakes basin, especially because it is the first academic report that focuses specifically on the Pic River tributary. A spatially explicit HSM for spawning habitat was also evaluated, which could be used as a management tool for Lake Sturgeon biologists to predict and prioritize spawning locations based on habitat parameters alone (Daugherty et al., 2008a; Daugherty et al., 2008b). Based on the results and discussion from this research, it is suggested that future studies should further investigate the relationship between Lake Sturgeon and their prey biomass, the possibility of metapopulation dynamics between populations, the predictive ability of the HSM with spatially variable flow data and a greater collection of eggs, and most importantly, continue to monitor Lake Sturgeon movements upon the construction of Manitou Falls generating station to determine if movements are negatively influenced by its operation.

APPENDIX

Appendix 1: Proportion of each substrate type at the lower rapids, Manitou Falls, and Kagiano Falls. Appendix includes Figure 3.1 to Figure 3.21 and relates to Section 3.3.1.

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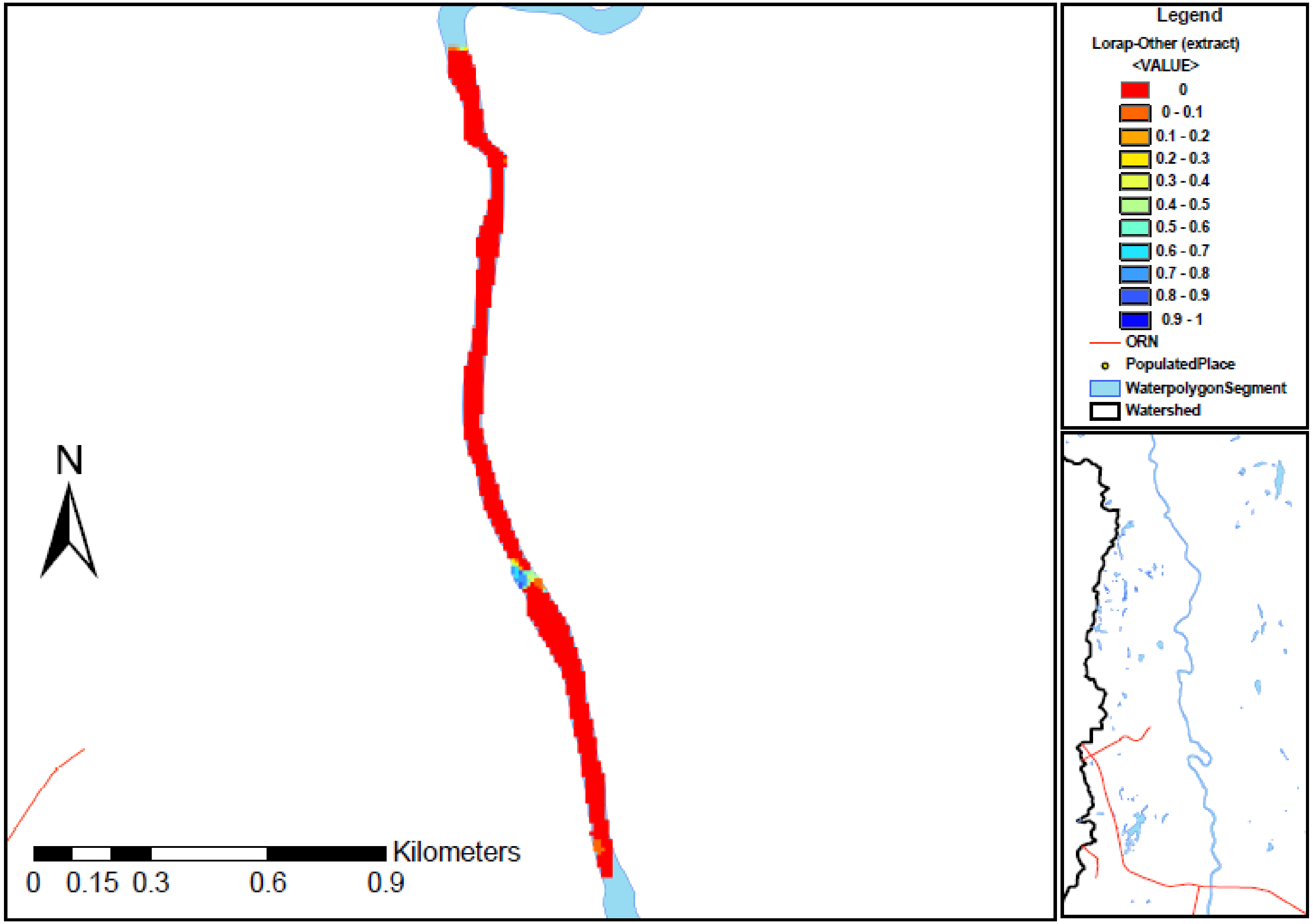

Figure 3.1 - Proportion of other as substrate type at the Lower Rapids.

Figure 3.2 - Proportion of clay as substrate type at the Lower Rapids.

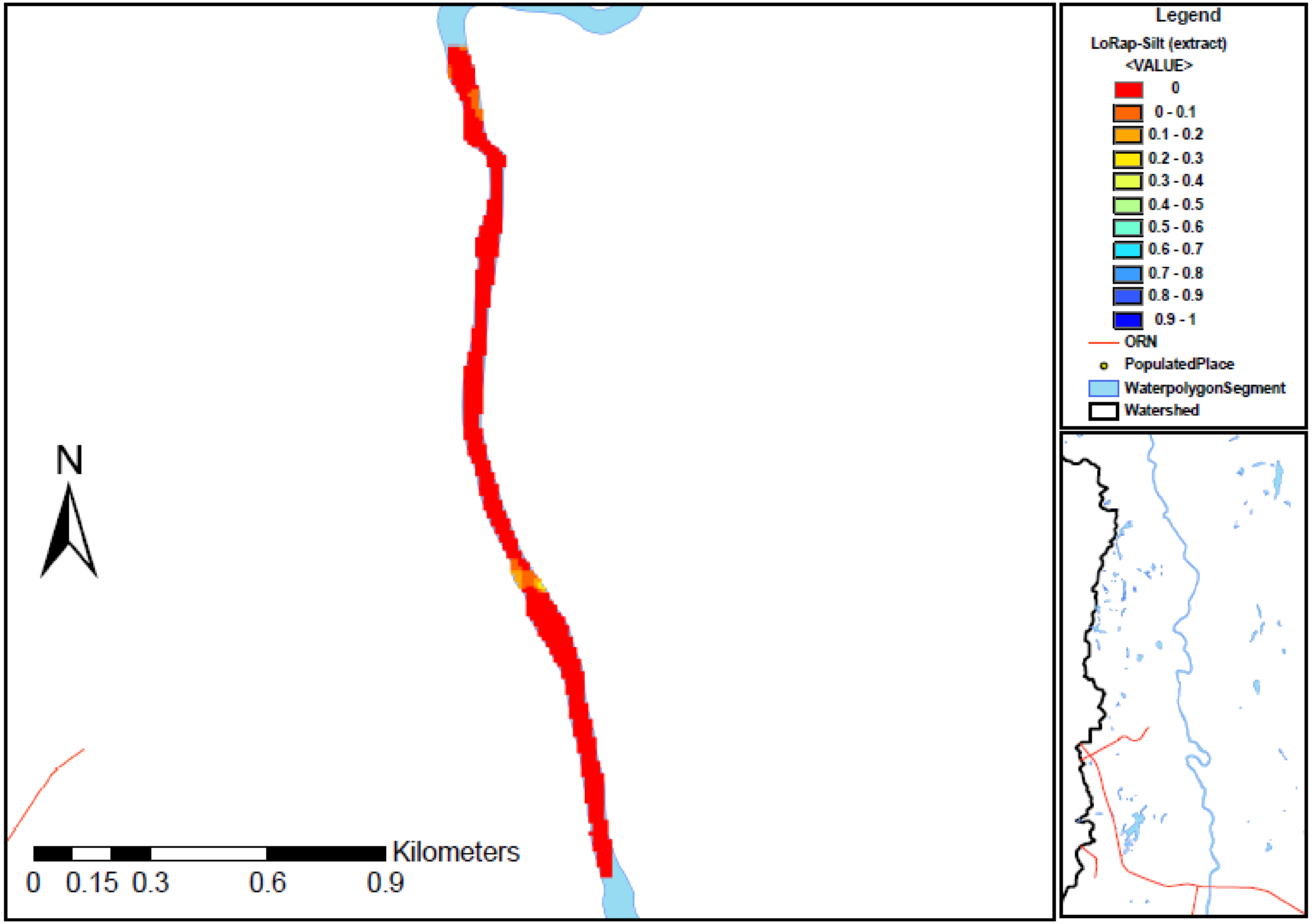

Figure 3.3 - Proportion of silt as substrate type at the Lower Rapids.

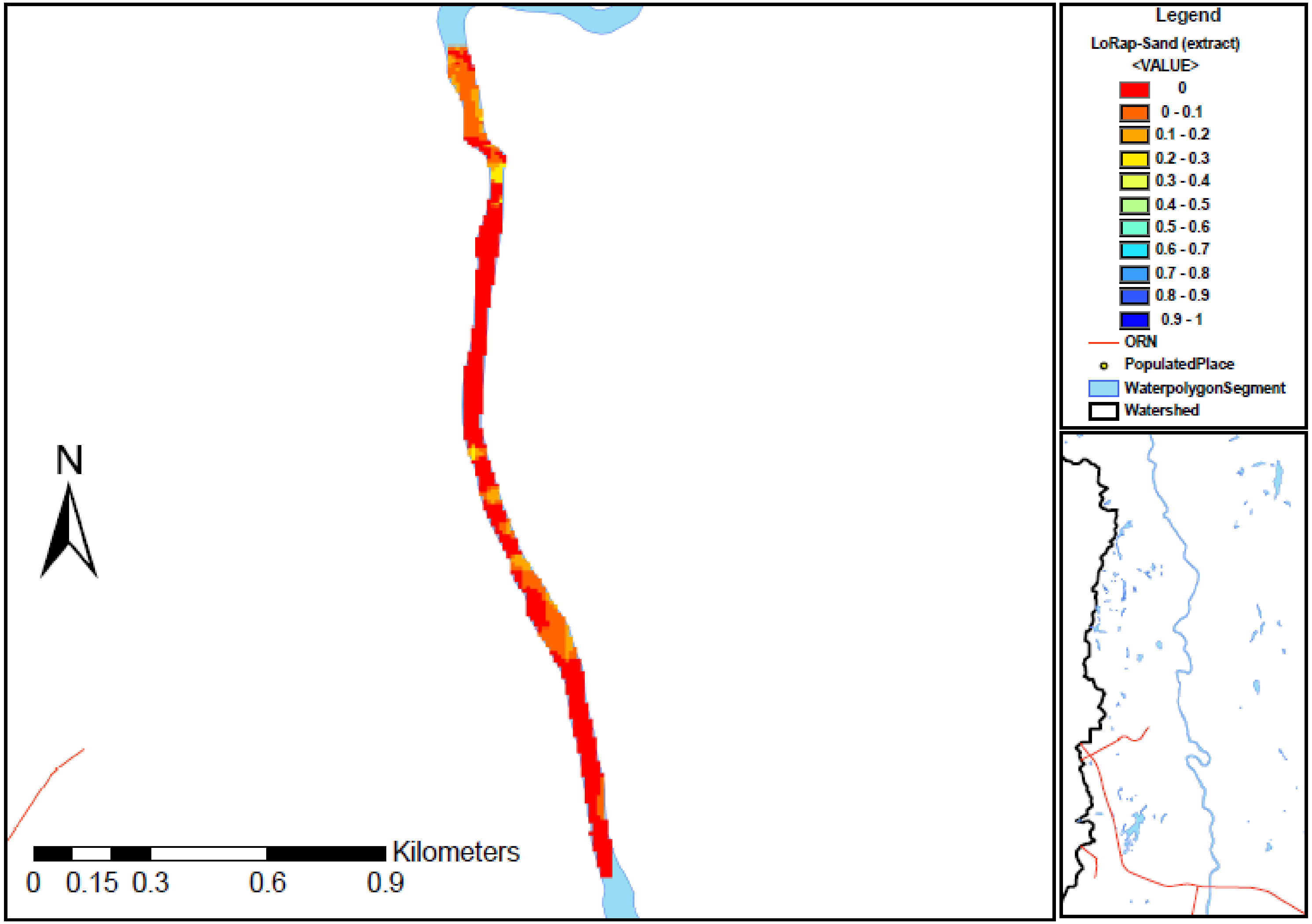

Figure 3.4 - Proportion of sand as substrate type at the Lower Rapids.

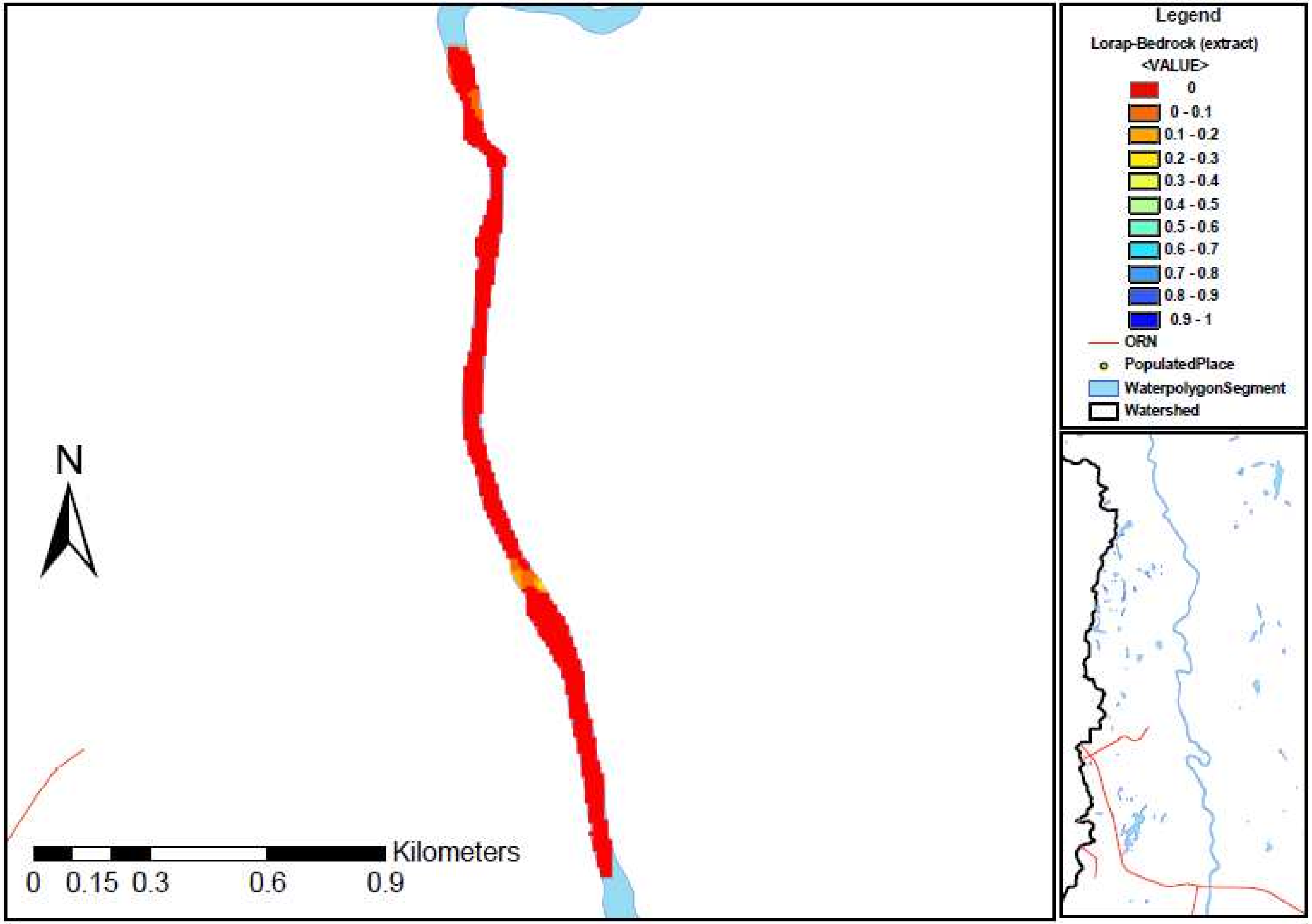

Figure 3.5 - Proportion of bedrock as substrate type at the Lower Rapids.

Figure 3.6 - Proportion of gravel as substrate type at the Lower Rapids.

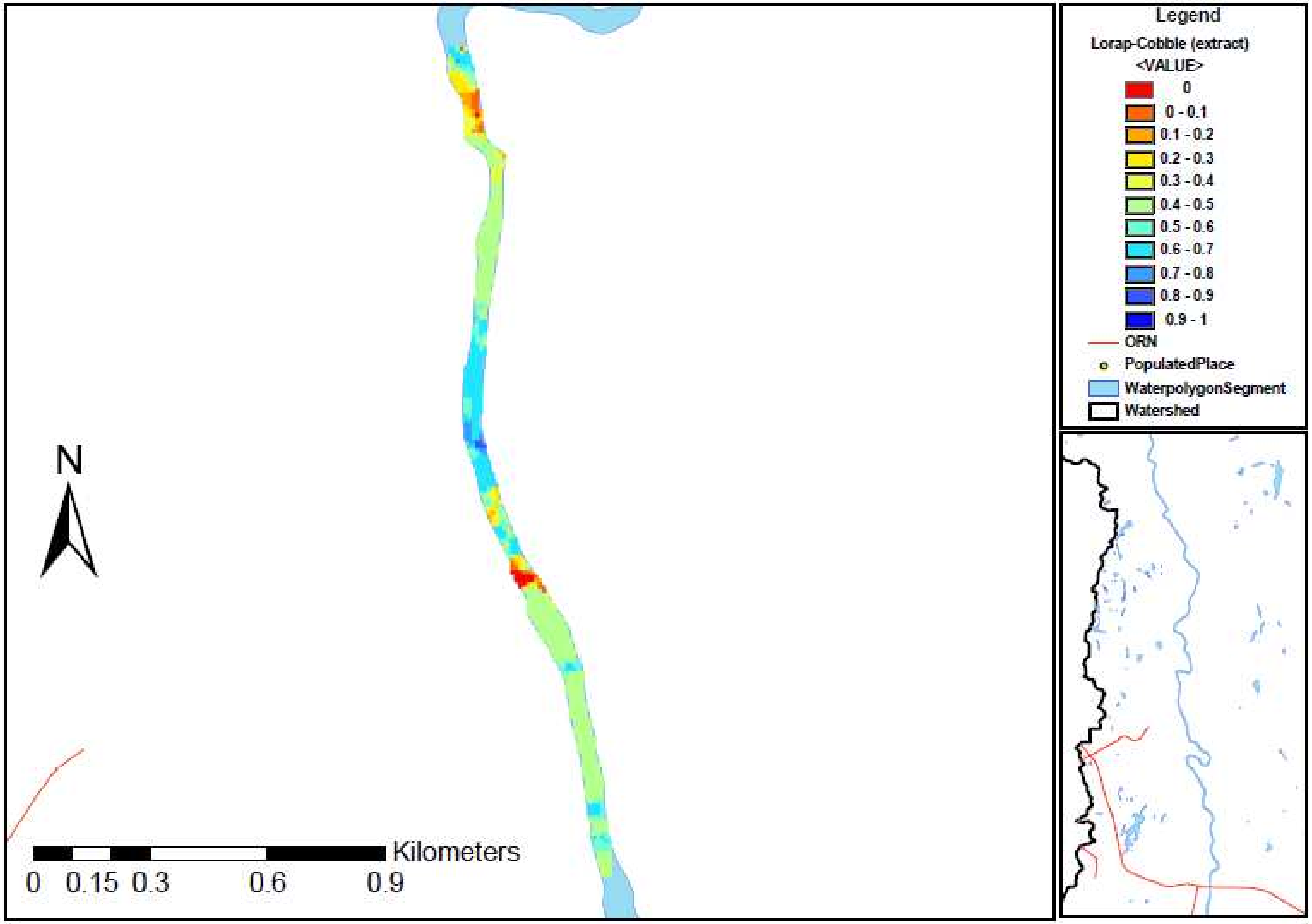

Figure 3.7 - Proportion of cobble as substrate type at the Lower Rapids.

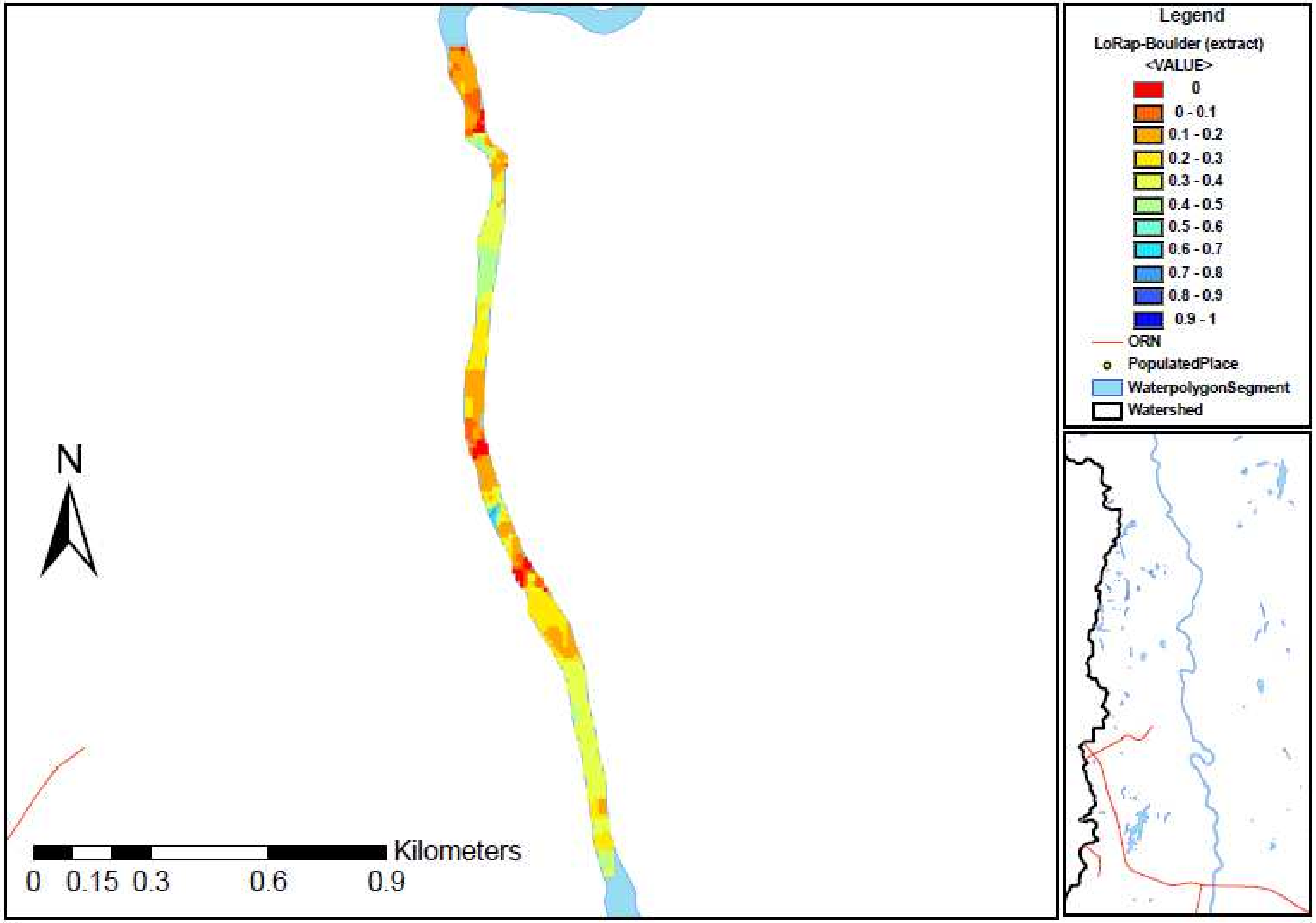

Figure 3.8 - Proportion of boulder as substrate type at the Lower Rapids.

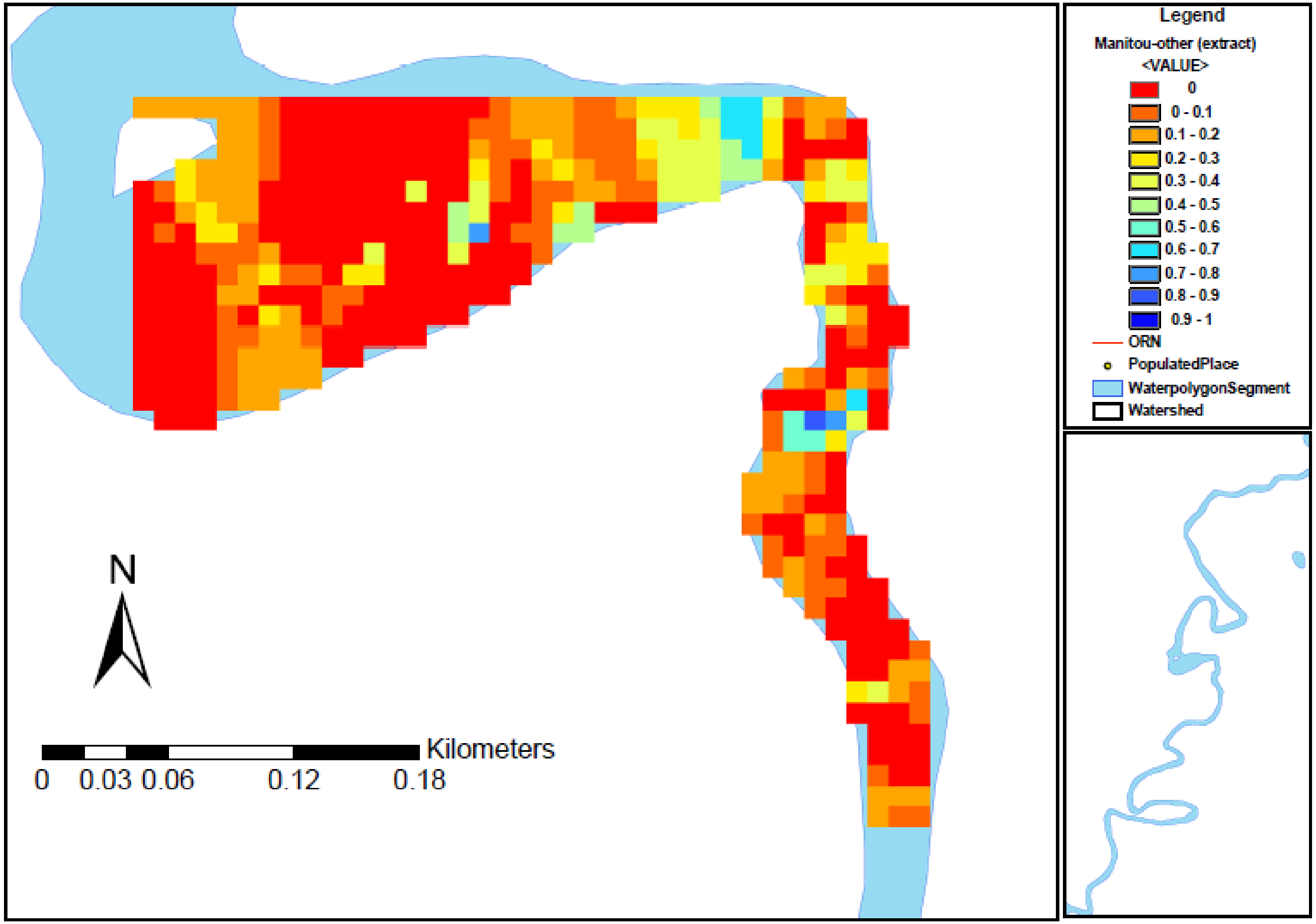

Figure 3.9 - Proportion of other as substrate type at Manitou Falls.

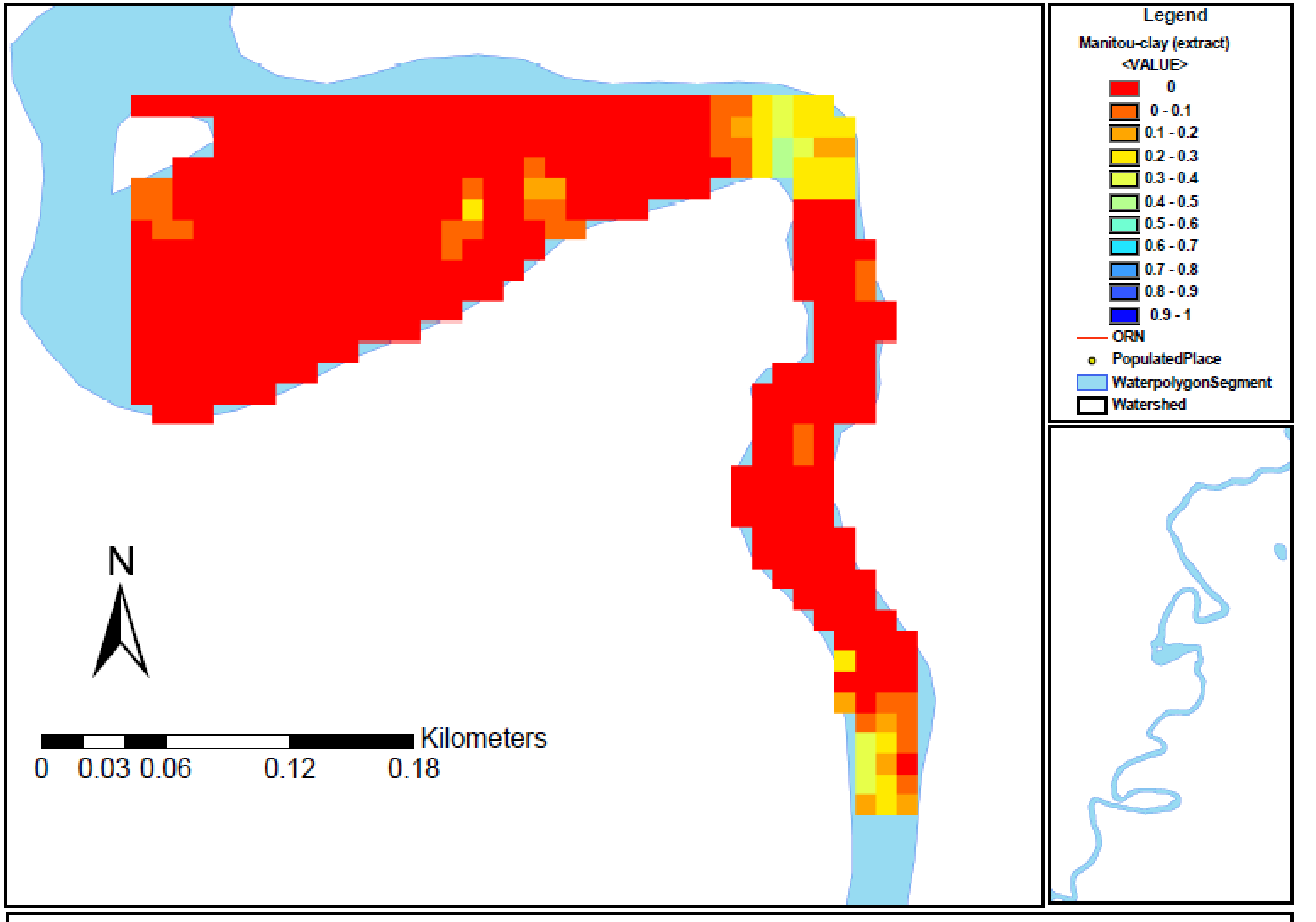

Figure 3.10 - Proportion of clay as substrate type at Manitou Falls.

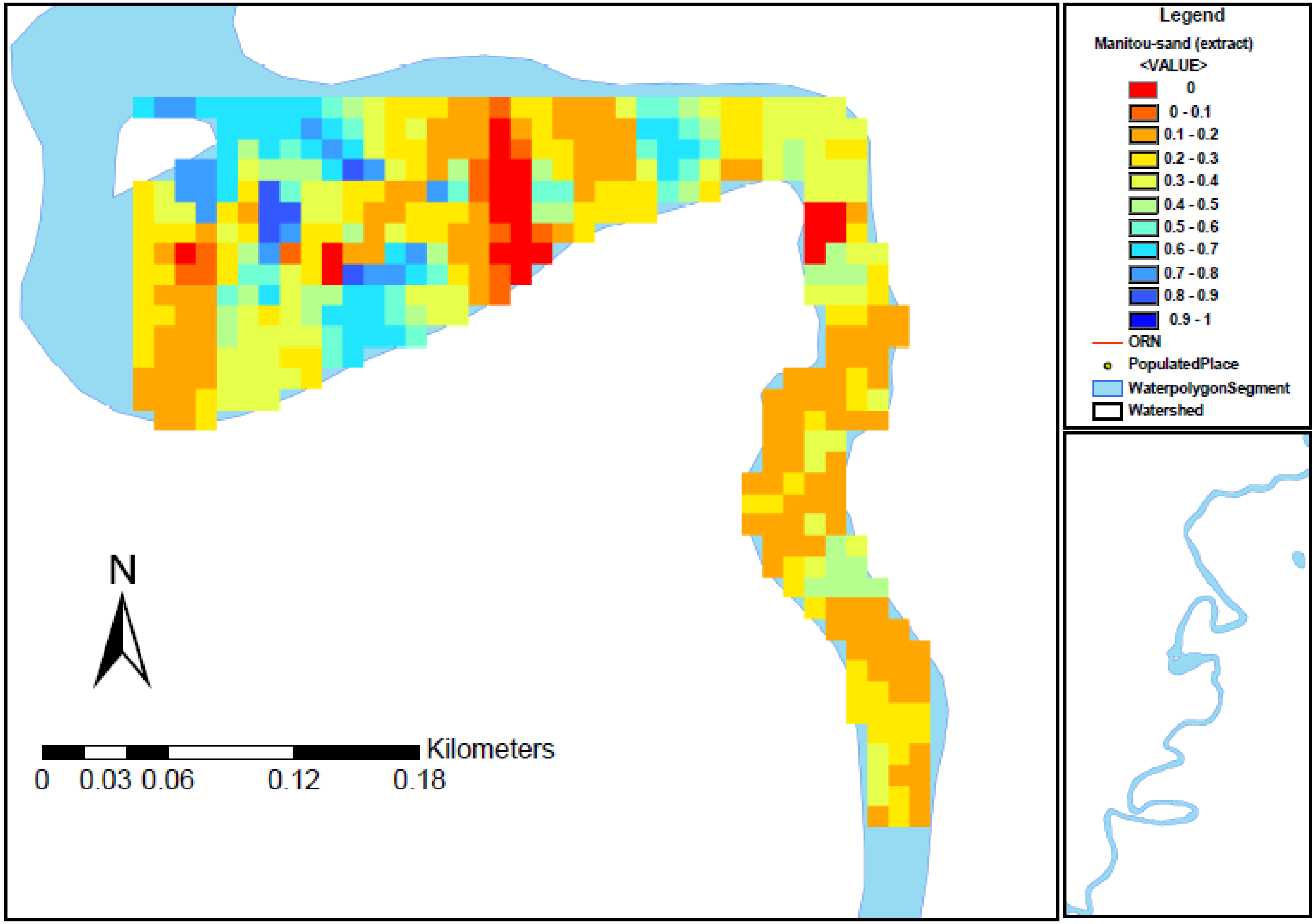

Figure 3.11 - Proportion of sand as substrate type at Manitou Falls.

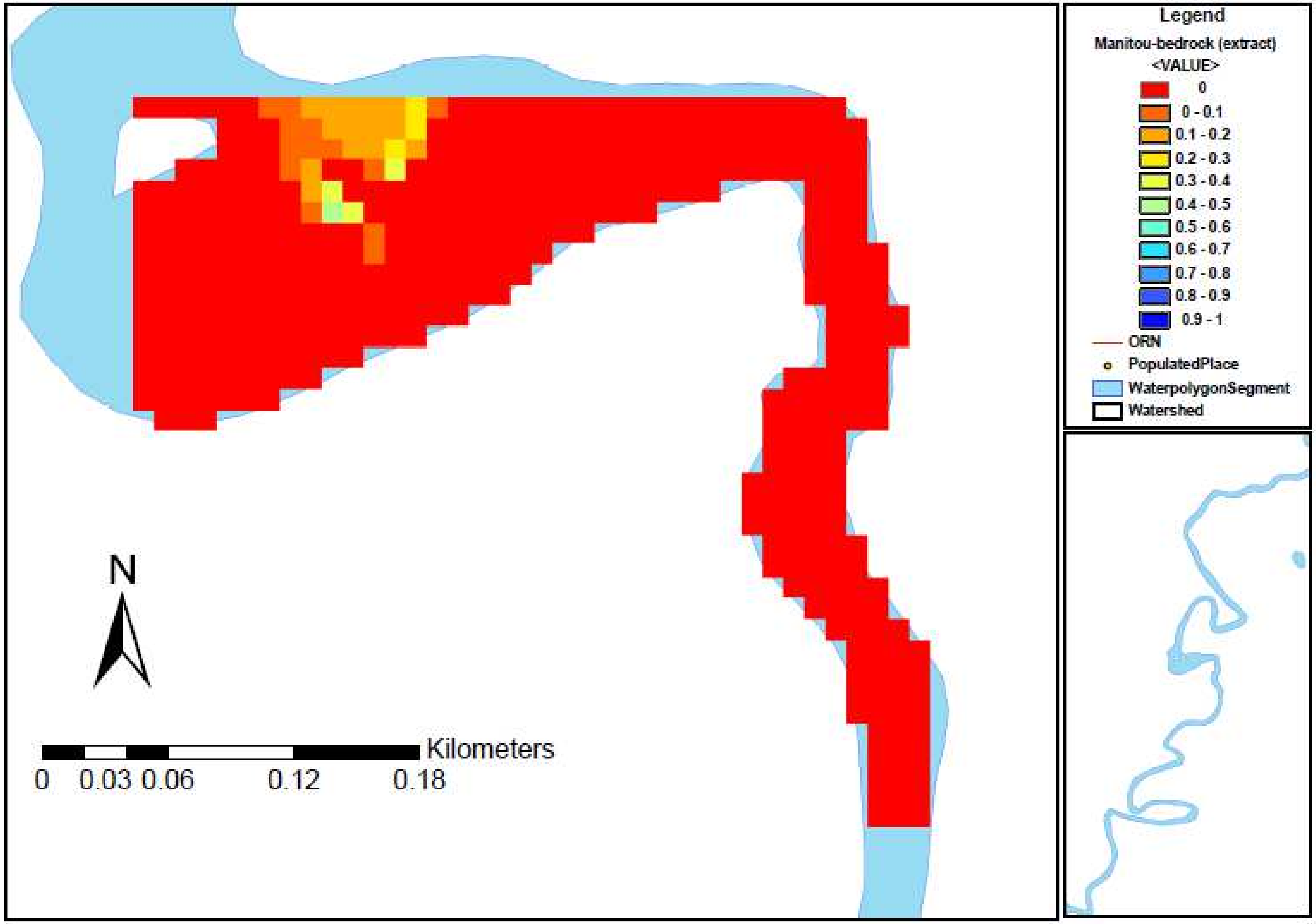

Figure 3.12 - Proportion of bedrock as substrate type at Manitou Falls.

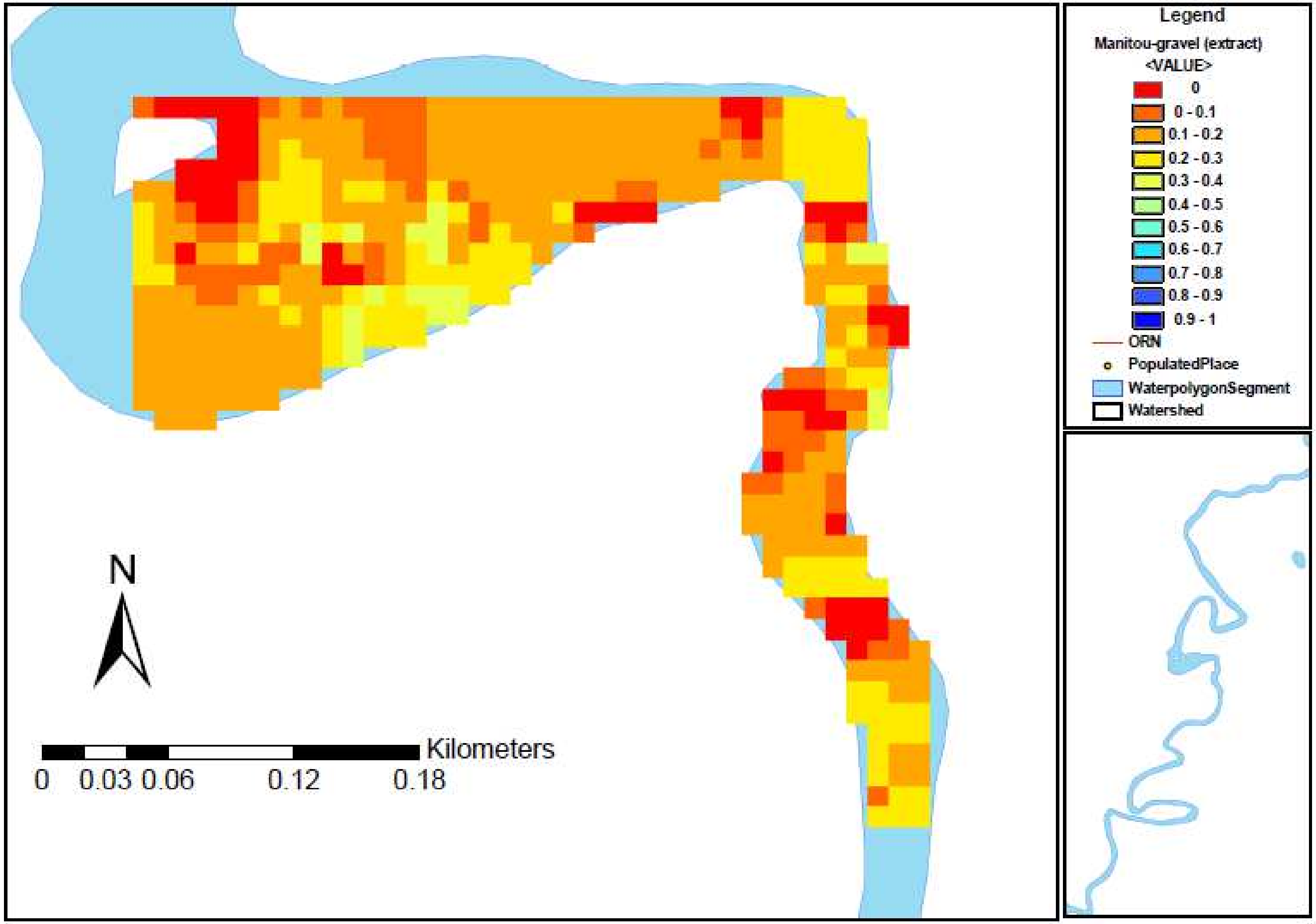

Figure 3.13 - Proportion of gravel as substrate type at Manitou Falls.

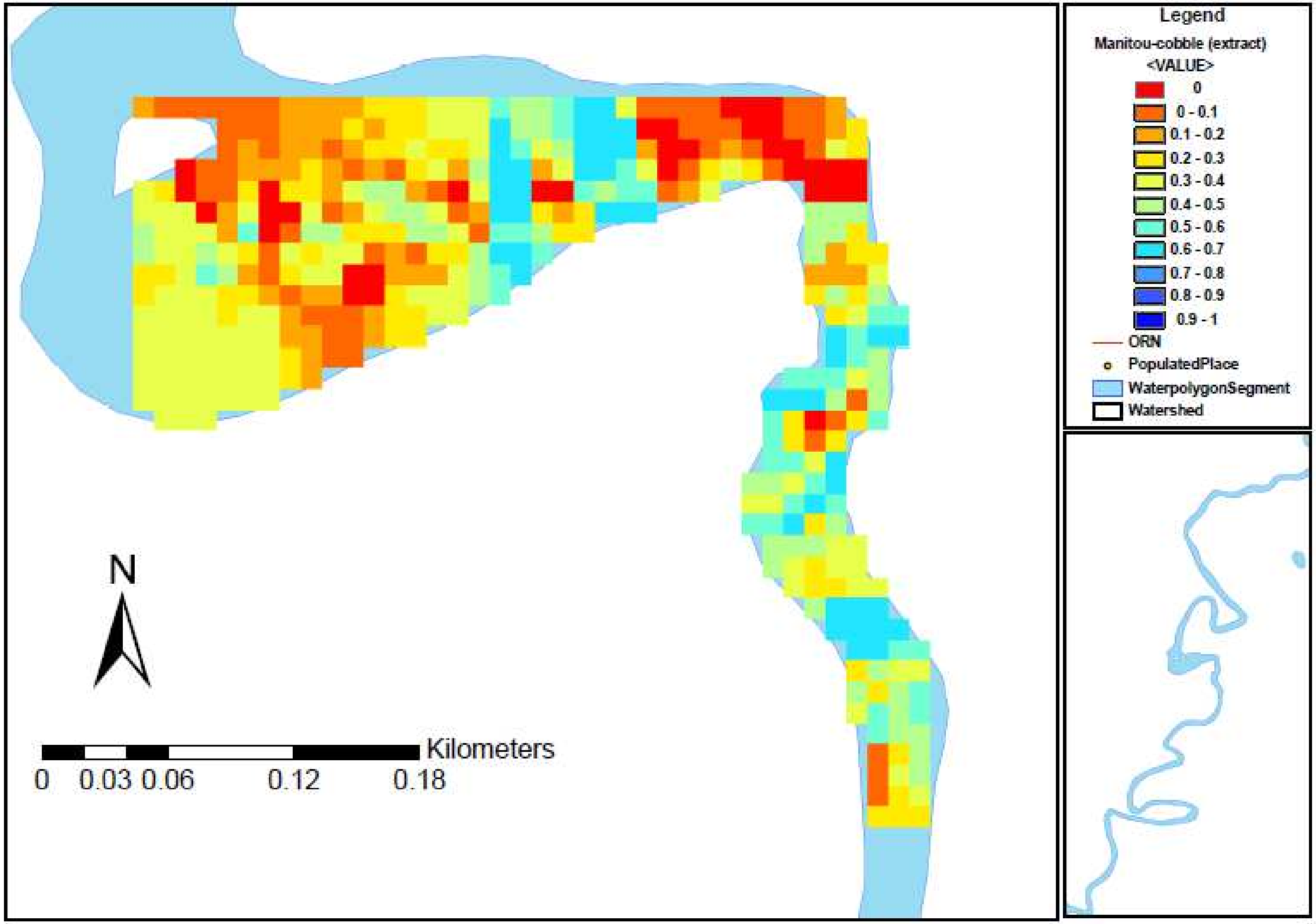

Figure 3.14 - Proportion of cobble as substrate type at Manitou Falls.

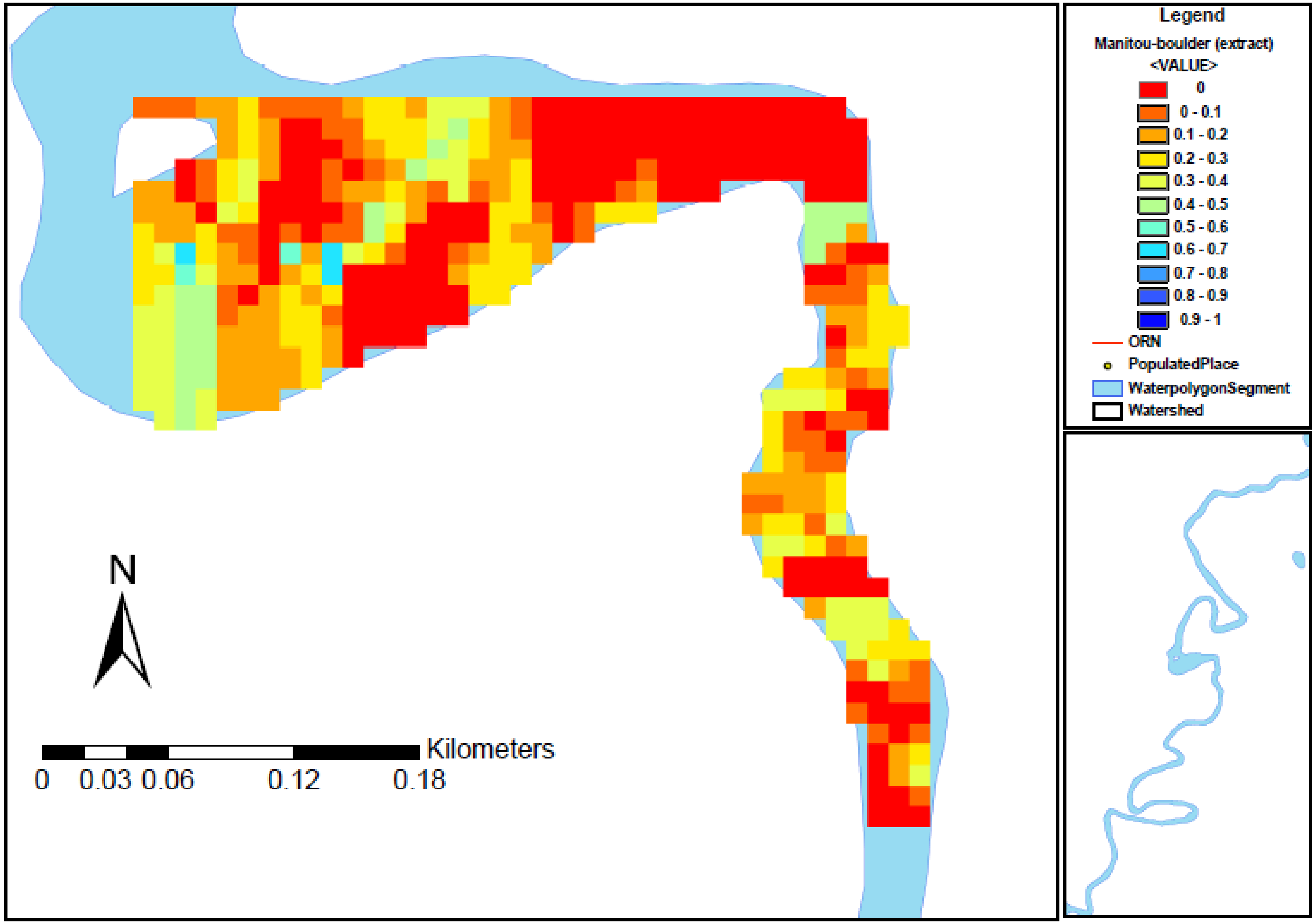

Figure 3.15 - Proportion of boulder as substrate type at Manitou Falls.

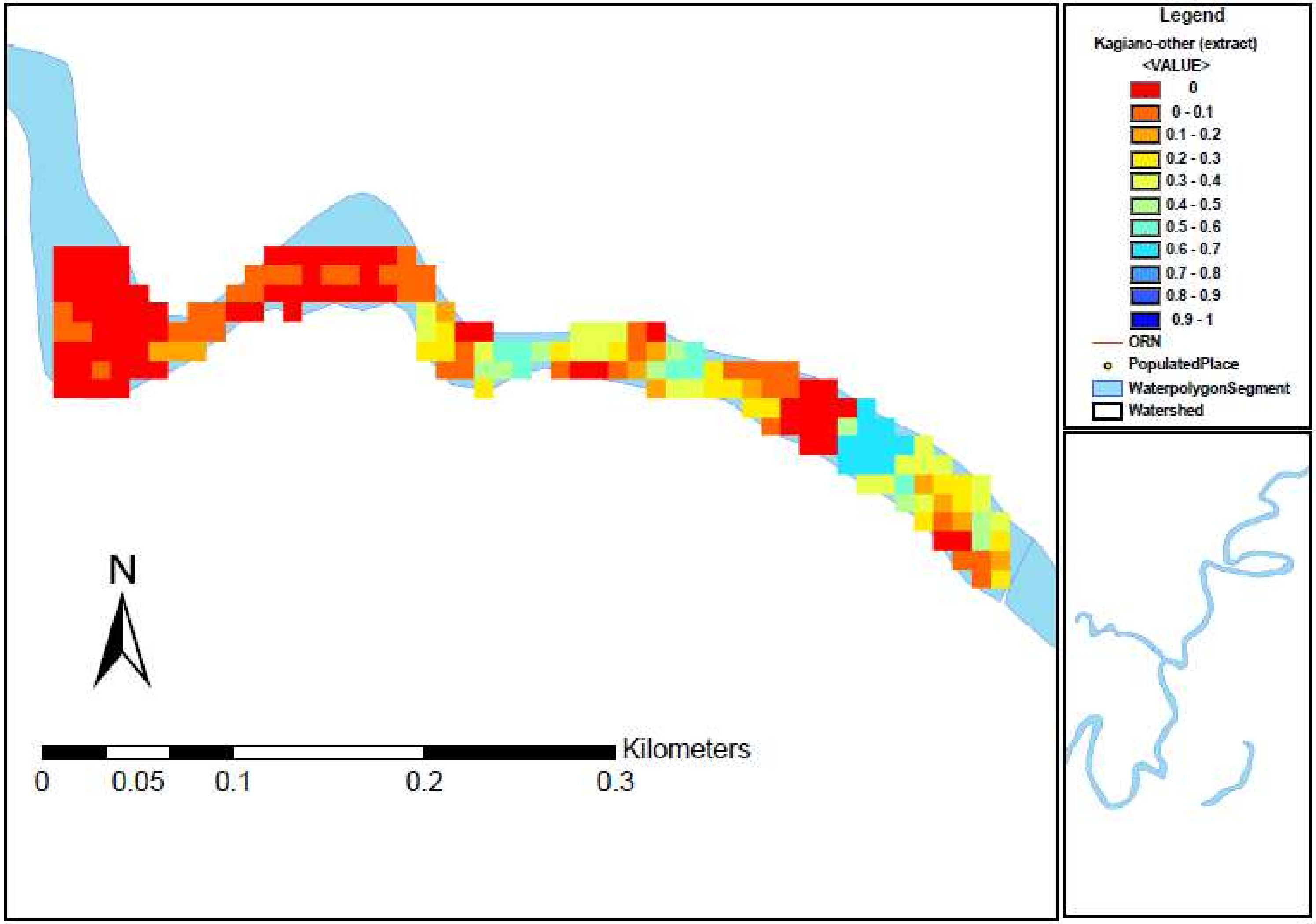

Figure 3.16 - Proportion of other as substrate type at Kagiano Falls.

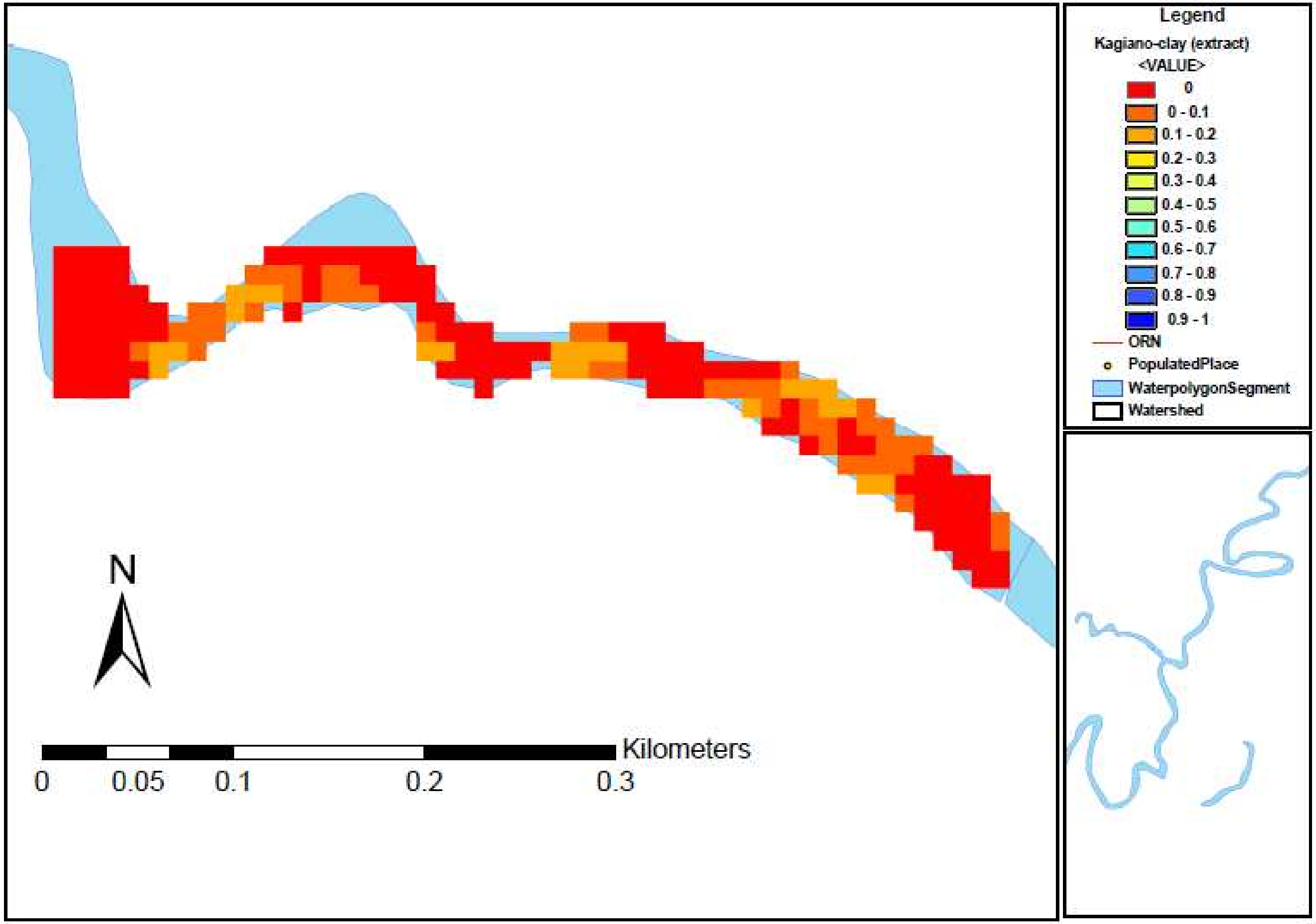

Figure 3.17 - Proportion of clay as substrate type at Kagiano Falls.

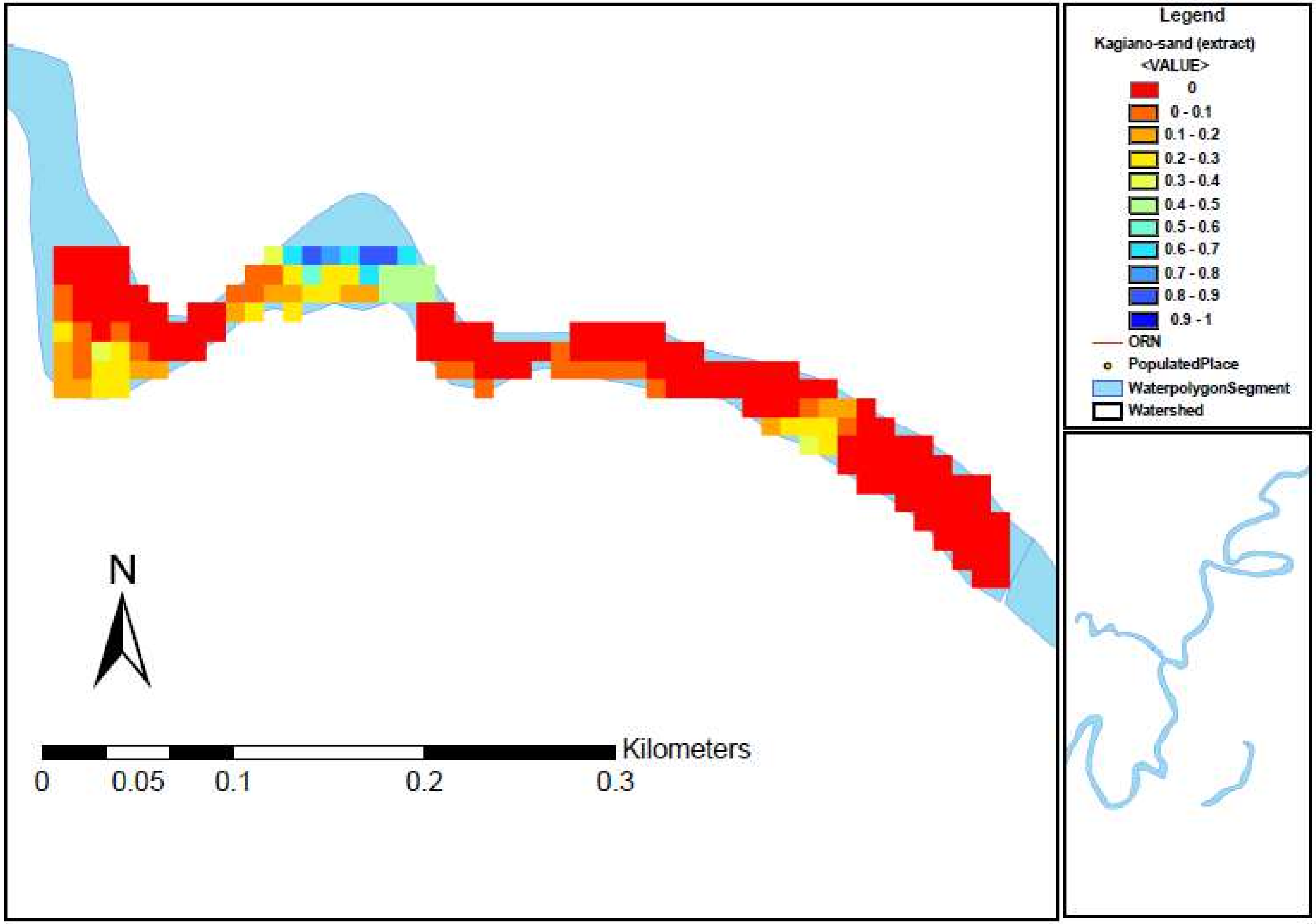

Figure 3.18 - Proportion of sand as substrate type at Kagiano Falls.

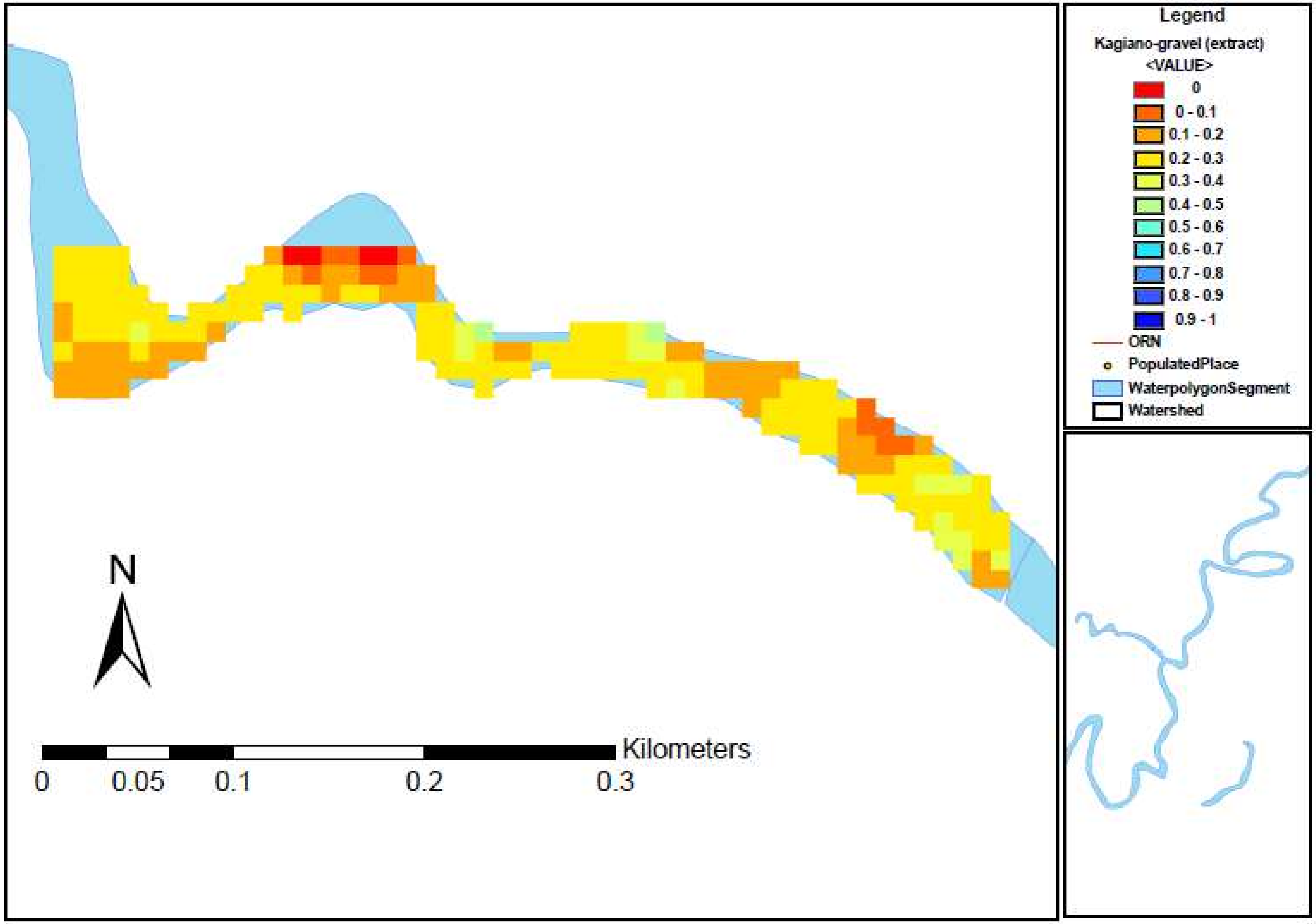

Figure 3.19 - Proportion of gravel as substrate type at Kagiano Falls.

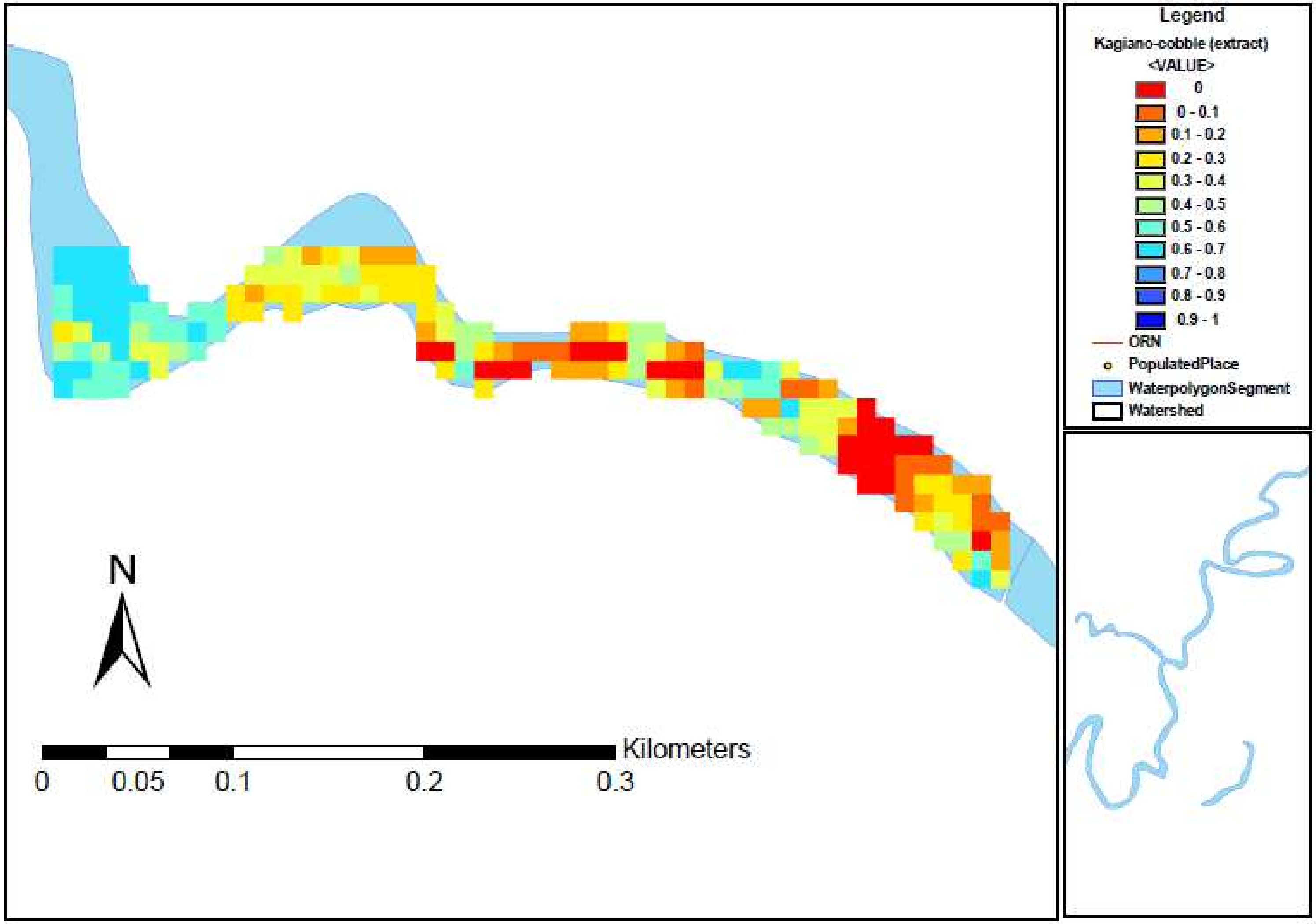

Figure 3.20 - Proportion of cobble as substrate type at Kagiano Falls.

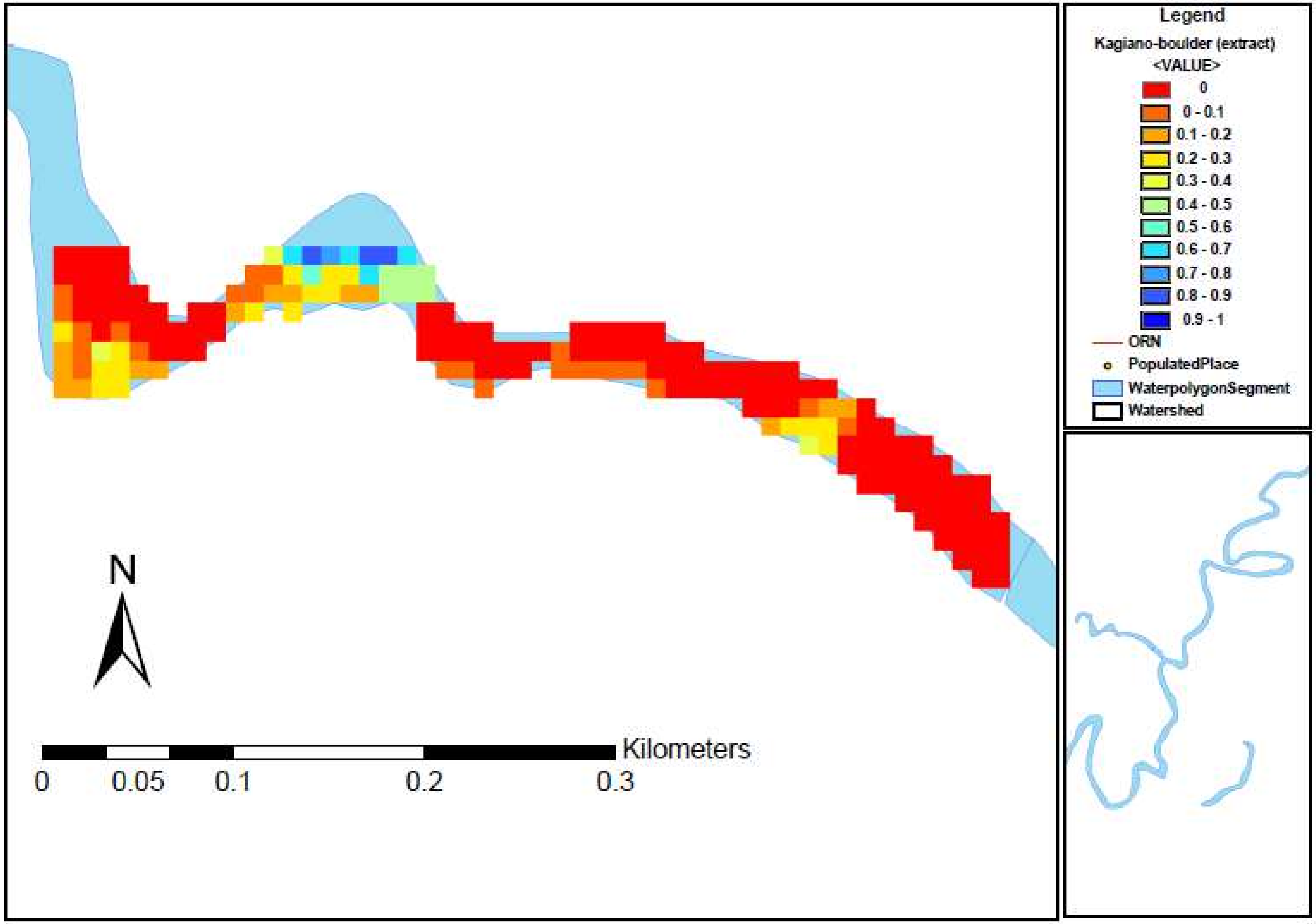

Figure 3.21 - Proportion of boulder as substrate type at Kagiano Falls.

Appendix 2: Mean daily temperature (˚C) and temperature suitability index values above Manitou Falls (Easting: 566904, Northing: 5450977), Kagiano Falls (Easting: 565486, Northing: 5449117), and below the Lower Rapids (Easting: 552000, Northing: 5400155).

Date	Manitou Falls Temp. (°C)	Temp. Suitability at Manitou Falls	Kagiano Falls Temp. (°C)	Temp. Suitability at Kagiano Falls	Lower Rapids Temp. (°C)	Temp. Suitability at Lower Rapids
4/29/2010	10.50	0.75	10.32	0.75	9.00	0.25
4/30/2010	11.46	0.75	11.28	0.75	9.50	0.25
05/01/2010	11.81	0.75	11.63	0.75	10.00	0.25
05/02/2010	12.98	1.00	12.80	1.00	10.00	0.25
05/03/2010	13.23	1.00	13.05	1.00	11.00	0.75
05/04/2010	13.06	1.00	12.88	1.00	11.50	0.75
05/05/2010	11.97	0.75	11.79	0.75	11.50	0.75
05/06/2010	9.48	0.25	9.30	0.25	8.50	0.25
05/07/2010	8.23	0.00	8.05	0.00	8.00	0.00
05/08/2010	8.08	0.00	7.90	0.00	8.00	0.00
05/09/2010	7.86	0.00	7.68	0.00	8.00	0.00
05/10/2010	8.03	0.00	7.85	0.00	9.00	0.25
05/11/2010	9.08	0.25	8.90	0.25	9.00	0.25
05/12/2010	10.69	0.75	10.51	0.75	9.50	0.25
5/13/2010	11.05	0.75	10.87	0.75	9.00	0.25
5/14/2010	10.56	0.75	10.38	0.75	10.00	0.25
5/15/2010	10.81	0.75	10.63	0.75	11.00	0.75
5/16/2010	11.96	0.75	11.78	0.75	12.00	0.75
5/17/2010	13.44	1.00	13.26	1.00	12.00	0.75
5/18/2010	14.63	1.00	14.45	1.00	13.00	1.00
5/19/2010	16.14	0.75	16.32	0.75	14.00	1.00
5/20/2010	16.27	0.75	16.45	0.75	13.50	1.00
5/21/2010	15.76	1.00	15.94	1.00	14.50	1.00
5/22/2010	16.36	0.75	16.54	0.75	15.80	1.00
5/23/2010	17.09	0.75	17.27	0.75	17.00	0.75
5/24/2010	18.50	0.75	18.68	0.75	17.00	0.75
5/25/2010	21.35	0.25	21.53	0.25	18.50	0.75
5/26/2010	22.63	0.25	22.81	0.25	21.00	0.25
5/27/2010	22.26	0.25	22.44	0.25	21.00	0.25
5/28/2010	21.70	0.25	21.88	0.25	22.00	0.25
5/29/2010	20.62	0.25	20.80	0.25	22.00	0.25
5/30/2010	19.36	0.75	19.54	0.75	21.00	0.25

5/31/2010	20.01	0.25	20.19	0.25	20.00	0.75
06/01/2010	19.39	0.75	19.57	0.75	19.00	0.75
06/02/2010	17.61	0.75	17.79	0.75	20.00	0.75
06/03/2010	17.61	0.75	17.79	0.75	19.50	0.75
06/04/2010	17.65	0.75	17.83	0.75	19.00	0.75
06/05/2010	17.10	0.75	17.28	0.75	18.00	0.75
06/06/2010	16.40	0.75	16.22	0.75	18.00	0.75
06/07/2010	16.34	0.75	16.16	0.75	16.00	1.00
06/08/2010	16.96	0.75	16.70	0.75	17.00	0.75
06/09/2010	17.19	0.75	16.93	0.75	17.00	0.75
06/10/2010	15.98	1.00	15.72	1.00	17.00	0.75
06/11/2010	16.51	0.75	16.25	0.75	17.50	0.75
06/12/2010	16.44	0.75	16.18	0.75	17.50	0.75
6/13/2010	17.16	0.75	16.90	0.75	17.50	0.75
6/14/2010	17.34	0.75	17.08	0.75	18.00	0.75
6/15/2010	18.47	0.75	18.21	0.75	18.00	0.75
6/16/2010	19.09	0.75	18.83	0.75	18.50	0.75
6/17/2010	20.29	0.25	20.03	0.25	19.00	0.75
6/18/2010	21.50	0.25	21.24	0.25	19.00	0.75
6/19/2010	21.56	0.25	21.01	0.25	19.00	0.75
6/20/2010	20.14	0.25	19.59	0.25	20.00	0.75
6/21/2010	20.36	0.25	19.81	0.25	20.50	0.25
6/22/2010	20.56	0.25	20.01	0.25	20.00	0.75
6/23/2010	20.09	0.25	19.54	0.25	19.00	0.75
6/24/2010	20.29	0.25	19.74	0.25	18.00	0.75
6/25/2010	20.08	0.25	19.53	0.25	20.00	0.75
6/26/2010	20.18	0.25	19.63	0.25	19.40	0.75
6/27/2010	20.28	0.25	19.73	0.25	19.00	0.75
6/28/2010	18.34	0.75	17.79	0.75	19.00	0.75
6/29/2010	17.23	0.75	16.68	0.75	19.20	0.75
6/30/2010	17.48	0.75	16.93	0.75	19.00	0.75
07/01/2010	18.56	0.75	18.01	0.75	19.00	0.75
07/02/2010	20.28	0.25	19.73	0.25	19.50	0.75
07/03/2010	21.31	0.25	20.76	0.25	19.00	0.75
07/04/2010	20.18	0.25	19.63	0.25	20.00	0.75
07/05/2010	20.93	0.25	20.38	0.25	19.50	0.75
07/06/2010	22.81	0.25	22.93	0.25	20.00	0.75
07/07/2010	23.83	0.00	23.95	0.00	21.00	0.25
07/08/2010	24.30	0.00	24.42	0.00	21.80	0.25
07/09/2010	23.67	0.00	23.79	0.00	22.50	0.25
07/10/2010	23.28	0.25	23.40	0.25	23.00	0.25
07/11/2010	22.86	0.25	22.98	0.25	24.00	0.00
07/12/2010	21.63	0.25	21.75	0.25	24.00	0.00
7/13/2010	22.18	0.25	22.30	0.25	23.00	0.25
7/14/2010	22.59	0.25	22.71	0.25	23.00	0.25

7/15/2010	22.99	0.25	23.11	0.25	22.00	0.25
7/16/2010	23.00	0.25	23.12	0.25	22.00	0.25
7/17/2010	21.89	0.25	22.01	0.25	23.00	0.25
7/18/2010	21.28	0.25	21.40	0.25	21.89	0.25
7/19/2010	21.25	0.25	21.37	0.25	21.28	0.25
7/20/2010	21.95	0.25	22.07	0.25	21.25	0.25
7/21/2010	21.58	0.25	21.70	0.25	21.95	0.25
7/22/2010	21.45	0.25	21.42	0.25	21.58	0.25
7/23/2010	22.28	0.25	22.25	0.25	21.45	0.25
7/24/2010	21.25	0.25	21.22	0.25	22.28	0.25
7/25/2010	21.16	0.25	21.13	0.25	21.25	0.25
7/26/2010	22.23	0.25	22.20	0.25	21.16	0.25
7/27/2010	22.71	0.25	22.68	0.25	22.23	0.25
7/28/2010	22.33	0.25	22.30	0.25	22.71	0.25
7/29/2010	21.31	0.25	21.28	0.25	22.33	0.25
7/30/2010	20.54	0.25	20.51	0.25	21.31	0.25

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Personal Communication:

Kim Tremblay	Address: Anishinabek/Ontario Fisheries Resource Centre 755 Wallace Rd, Unit 5 North Bay, Ontario P1B 8G4 Phone: (705) 472-7888
Nikki Commanda	Address: Anishinabek/Ontario Fisheries Resource Centre 755 Wallace Rd, Unit 5 North Bay, Ontario P1B 8G4

	Phone: (705) 472-7888
Bill Gardner	Address: Fisheries and Oceans Canada 1219 Queen St. E. Sault Ste. Marie, Ontario P6A 2E5 Phone: (705) 941-2664
Tim Haxton	Address: 300 Water St., 4th Floor S. Peterborough, Ontario K9L 8M5 Phone: (705) 755-3258
Thomas Pratt	Address: Fisheries and Oceans Canada 1219 Queen St. E. Sault Ste. Marie, Ontario P6A 2E5 Phone: (705) 941-2664