LAKE STURGEON (*ACIPENSER FULVESCENS*) POPULATION ATTRIBUTES, REPRODUCTIVE STRUCTURE AND DISTRIBUTION IN NAMAKAN RESERVOIR, MINNESOTA AND ONTARIO

BY

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A thesis submitted in partial fulfillment of the requirements for the

Master of Science

Major in Wildlife and Fisheries Sciences

South Dakota State University

2010

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This thesis is approved as a creditable and independent investigation by a candidate for the Master of Science degree and is acceptable for meeting the thesis requirements for this degree. Acceptance of this thesis does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

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AKNOWLEDGMENTS

I would like to take this opportunity to thank Dr. Steven R. Chipps for allowing me the opportunity to pursue a Master's degree at South Dakota State University. I would also like to thank Dr. David W. Willis for his involvement in this research and scientific and professional guidance throughout my time at SDSU. Thank you to Steve Windels for his expertise and support throughout this project. Thank you to all of the people who put forth the time and effort to complete field sampling throughout the duration of this project; from the National Park Service Cam Trembath, from the Ontario Ministry of Natural Resources Darryl McLeod, Jeff Eibler of the Minnesota DNR, Larry Kallemeyn formerly of the USGS, the U.S. Forest Service, Brian McLaren and his students from Lakehead State University and all the technicians and graduate students from SDSU, Travis Brezden, Mark Fincel, Dan James, Hilary Meyer, Luke Schultz, Chris Sundtmark, and Megan Thul. I would like to acknowledge Geno Adams, South Dakota Game Fish and Parks and Susan Mann, Ontario Regional Aging Specialist for their help in validation of lake sturgeon ages. I would also like to extend a sincere thank you to Molly Webb and Eli Cureton for their expertise in the analysis of lake sturgeon sex steroid concentrations. I would like to acknowledge the use of the imaging equipment provided by the SDSU-Functional Genomic Core Facility supported in part by NSF/EPSCoR Grant No. 0091948 and by the State of South Dakota. Funding for this study was provided by the National Park Service, CESU task number J6820081161.

Lastly, I would like to extend a special thanks to my parents for their steadfast support and encouragement throughout my life.

ABSTRACT

LAKE STURGEON (*ACIPENSER FULVESCENS*) POPULATION ATTRIBUTES, REPRODUCTIVE STRUCTURE AND DISTRIBUTION IN NAMAKAN RESERVOIR, MINNESOTA AND ONTARIO

Stephanie L. Shaw

August 2010

Population declines of lake sturgeon (*Acipenser fulvescens*) have resulted in their protected status as a species of special concern in the state of Minnesota and threatened in the province of Ontario. Water bodies that lie along the Minnesota-Ontario border are home to historic populations of lake sturgeon. Research has been conducted on the neighboring lake sturgeon populations (i.e., Rainy Lake, the lower Seine River in Ontario, and Rainy River/Lake of the Woods). However, little research has been conducted on the lake sturgeon population of the Namakan Reservoir. The objectives of this project were to 1) assess the lake sturgeon in Namakan Reservoir by quantifying age, growth, mortality, and reproductive structure, and 2) to examine the influence of gender and reproductive condition on seasonal distribution and movement patterns of lake sturgeon in the Namakan Reservoir.

I evaluated year class strength and reproductive structure of lake sturgeon collected in the U.S. and Canadian waters of Namakan Reservoir. Reproductive structure of lake sturgeon was assessed during spring 2008 and 2009 using plasma testosterone and estradiol-17β concentrations. Age of lake sturgeon > 75 cm ranged from 9 to 86 years of age (n=533, mean=36 years). Using logistic regression analysis, I found that total annual precipitation was positively associated with lake sturgeon year class strength in Namakan Reservoir. Plasma steroid analysis revealed a sex ratio of 2.4 females:1 male and, on average, 10% of female and 30% of male lake sturgeon were reproductively mature each year (i.e., potential spawners). Moreover, I found evidence based on re-captured male fish of both periodic and annual spawning, as well as the ability of males to rapidly undergo gonadal maturation prior to spawning. Knowledge of lake sturgeon reproductive structure and factors influencing recruitment success contribute to the widespread conservation efforts for this threatened species.

I evaluated the influence of gender and reproductive condition on seasonal distribution and movement patterns of lake sturgeon in Namakan Reservoir. Sixty adult lake sturgeon were implanted with acoustic transmitters prior to spawning in spring 2007 and 2008. Fish movement was monitored using an array of 15 stationary receivers covering both U.S. and Canadian waters of Namakan Reservoir and its major tributaries. Blood samples were collected from 133 lake sturgeon prior to spawning and plasma concentrations of testosterone and estradiol-17ß were analyzed using radioimmunoassay. The greatest recorded distance traveled by a lake sturgeon was 130 km. In general, females traveled greater distances (mean=38.8 km) than males (mean=29.9 km). Lake sturgeon of both sexes traveled greater distances during the spawning and post-spawning periods compared to all other seasons. Distance traveled was lowest (mean=5.3 km) and site fidelity was highest (mean=17.8 days) during winter months. Five females were characterized as potentially reproductive and 14 as non-reproductive based on plasma steroid concentrations. Potentially reproductive females had lower site fidelity and traveled greater distances across all seasons than non-reproductive females. Distance traveled by reproductive females was highest in the fall (mean=38.8 km) compared to other seasons (means ranged from 3.2 to 24.0 km) and may be linked to gonadogenesis (e.g., increased energy acquisition) prior to spring spawning. A link between migration distance and female reproductive condition may have implications for lake sturgeon conservation particularly in water bodies that have experienced loss of preferred lake sturgeon habitat, are heavily impounded or facing future impoundment.

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CHAPTER 1

INTRODUCTION

Lake sturgeon (*Acipenser fulvescens*) are a member of the Acipenseridae family of fishes. The family is most closely related to elasmobranchs having no scales and a jaw that is detached from the skull (Peterson et al. 2007). Lake sturgeon, like other acipenserids, are a long lived species that exhibit late age-at-maturation with males first spawning around 8 to 12 years of age and females around 20 to 25 years of age (Peterson et al. 2007). Male and female lake sturgeon spawn periodically. Males spawn every 1 to 7 years and females every 4 to 9 years (Craig et al. 2005; Peterson et al. 2007). Spawning occurs in the spring at water temperatures between 13 and 18˚C (Harness and Dymond 1961). Spawning habitat is generally located in tributaries in water depths of 1 to 5 m with cobble or gravel substrate and water velocities of 0.35 to 1.5 m/sec (Manny and Kennedy 2002; Peterson et al. 2007; Chiotti et al. 2008). Males and females congregate shortly after ice-out in pools, 2 to 10 m deep, and move upstream to spawn when induced by favorable conditions (Bruch et al. 2002). Eggs incubate 6-10 d depending on water temperature (Chiotti et al. 2008) and after hatching, larvae settle into the substrate until the yolk sac is absorbed then begin to drift downstream to nursery areas characterized as having sand substrate (Auer 1996b). Juveniles and adults feed on benthic invertebrates and commonly reported diet items include amphipods and gastropods, and to a lesser degree trichopterans, chironomids, isopods, hirudineans, oligochaetes, and age-0 fishes (Jackson et al. 2002).

Lake sturgeon are distributed among three major drainages in North America that include the Mississippi River, Great Lakes and Hudson Bay drainages. Historically, lake sturgeon were relatively abundant throughout their range, but have declined in many areas due to pollution, overharvest, and barriers to migration (Auer 1996a). Because of their slow growth, late maturation, and intermittent spawning, lake sturgeon populations are slow to recover. In the Great Lakes region, commercial catches decreased by over 90% from 1885 to the early 1920's (Auer 1996a). Since 1977, all commercial fishing in the U.S. waters of the Great Lakes has been closed with little to no evidence of lake sturgeon abundance increasing (Hay-Chmielewski and Whelan 1997). Moreover, populations that experienced high commercial harvest in the past generally lack females greater than 50 years of age (Bruch 1999).

Lake sturgeon are known to migrate long distances to access foraging and spawning habitat, avoid seasonally unfavorable conditions, and to allow time for gonadal maturation prior to spawning. However, construction of dams in North America from the 1800's to mid 1900's created barriers limiting access to foraging and spawning habitat, fragmenting populations and in some cases resulting in extirpation of lake sturgeon from their native ranges (e.g., Cuyahoga River, Ohio; Auer 1996b). Lake sturgeon populations that have access to large heterogeneous environments tend to be more abundant, with larger and more fecund individuals (Auer 1996a). In addition, hydroelectric development has altered the flow regimes of many large river systems that were important to lake sturgeon. Run-of-river flows lead to gradual changes in water levels and consistent flows allowing easier access to spawning habitat, especially for large females. Dams utilizing peak operating flows during the spring cause dramatic fluctuations in water levels and flow regimes (Auer 1996b). Research by Auer (1996b) on the Sturgeon River, Michigan found that return to run-of-river flows resulted in an increase in the total number of individuals, particularly females, reaching the spawning grounds, an increase in the number of larger fish, and the number of gravid fish reaching the spawning grounds. Natural flow regimes that maintain suitable water depths allowed more females and larger fish access to spawning sites (Auer 1996b).

Lake sturgeon populations have been listed as threatened or endangered throughout much of their range owing to decreased abundance. A ban on lake sturgeon products was implemented through the Convention on International Trade of Endangered Species (CITES) in 1975. Globally, lake sturgeon are listed as G3-Vulnerable, which indicates that a species is at moderate risk of extinction due to a restricted range, relatively few populations, recent and widespread declines, or other factors (NatureServe 2005). The American Fisheries Society listed lake sturgeon as “Vulnerable” in 2008 (Jelks et al. 2008). Current management efforts for lake sturgeon focus on protection, improvement and/or restoration of habitat (Wallace 1991; Moreau and Parrish 1994).

The lake sturgeon is one of the most significant biological and cultural resources within Voyageurs National Park (VNP), Minnesota. The major water bodies within VNP include those lakes and tributaries that make up Rainy Lake and Namakan Reservoir. Rainy Lake and Namakan Reservoir are separated by the Kettle and Squirrel Falls dams constructed at the outlet of Namakan Lake in the early 1900s. The construction of the dams prevents the upstream movement of lake sturgeon and fragmented the original population into Namakan Reservoir and Rainy Lake populations (Mosindy and Rusak 1991). Adams et al. (2006) completed an assessment of the lake sturgeon population in Rainy Lake, downstream of Namakan Reservoir. However, little research has been conducted to assess the Namakan Reservoir population of lake sturgeon.

Namakan Reservoir has a surface area of approximately 26,700 ha. It encompasses Kabetogama, Namakan, Sand Point, Crane and Little Vermilion lakes. Kabetogama is the only lake that lies completely within the boundary of the park. Crane and Little Vermilion lakes lie just south of the Voyageurs National Park boundary. The Minnesota-Ontario border runs through Namakan, Sand Point and Little Vermillion lakes. In Minnesota lake sturgeon are listed as a species of special concern while in north west Ontario they are listed as threatened (McLeod 2008; McLeod and Martin 2010).

The lake sturgeon population within VNP mimics the decline of other populations throughout North America. Commercial fishing existed in the Canadian waters of Namakan Lake from 1916 to 2001. Recreational harvest in Canadian waters was reduced from one to zero fish in July, 2008 (McLeod 2008). In the Minnesota-Canada border waters and the St. Croix River, Minnesota recreational angling and possession of one sturgeon is allowed with the purchase of a sturgeon tag. All sturgeon harvested must be registered with the Minnesota Department of Natural Resources (MN DNR) within 48 hours. Catch and release angling for lake sturgeon is allowed during open seasons (May 8 -15 and October 1 - April 23) in the Minnesota-Canada border waters only (MN DNR 2008). Concerns about the effects of regulated lake levels on the aquatic biota of Namakan Reservoir and Rainy Lake have been expressed since the construction of the two dams. However, it was not until the creation of VNP in 1975 that more emphasis was placed on restoring and preserving the natural environment of the area (Kallemeyn et al. 2003). Currently, water levels in Namakan Reservoir are regulated by the International Joint Commission (IJC) through the International Rainy Lake Board of Control (IRLBC) (McLeod 2008). In 2000, the IJC instituted a hydrologic regime more closely approximating natural flows (Kallemeyn et al. 2003).

In Ontario a private company in collaboration with the Lac La Croix First Nation is proposing to build two hydroelectric generation sites on the Namakan River, the major spawning tributary for lake sturgeon in Namakan Reservoir. The Namakan River is located entirely within Ontario. Preliminary data from the Ontario Ministry of Natural Resources (OMNR) suggest that movements of spawning lake sturgeon would be affected by construction of the dams. Preliminary data also suggest that lake sturgeon that spawn in the Namakan River move freely throughout the reservoir and are therefore an internationally shared stock. To understand the potential impacts of the hydropower development on the lake sturgeon population in Namakan Reservoir, more information is needed about spawning locations and movement patterns of lake sturgeon within the reservoir. The objectives of this project were 1) to quantify age, growth, mortality and reproductive structure of lake sturgeon, and 2) to identify potential spawning sites of the lake sturgeon that inhabit Namakan Reservoir, as well as the effects of gender and maturity on seasonal distribution and movement patterns.

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CHAPTER 2

LAKE STURGEON POPULATION ATTRIBUTES AND REPRODUCTIVE STRUCTURE IN NAMAKAN RESERVOIR, VOYAGEURS NATIONAL PARK, MINNESOTA, USA[1]

Abstract

I evaluated year-class strength and reproductive structure of lake sturgeon (*Acipenser fulvescens*) collected in the U.S. and Canadian waters of Namakan Reservoir. Reproductive structure of lake sturgeon was assessed during spring 2008 and 2009 using plasma testosterone and estradiol-17β concentrations. Ages of lake sturgeon >75 cm ranged from 9 to 86 years of age (n = 533, mean = 36 years). Using logistic regression analysis, I found that total annual precipitation was positively associated with lake sturgeon year-class strength in Namakan Reservoir. Plasma steroid analysis revealed a sex ratio of 2.4 females:1 male and, on average, 10% of female and 30% of male lake sturgeon were reproductively mature each year (i.e., potential spawners). Moreover, I found evidence based on re-captured male fish of both periodic and annual spawning, as well as the ability of males to rapidly undergo gonadal maturation prior to spawning. Knowledge of lake sturgeon reproductive structure and factors influencing recruitment success contribute to the widespread conservation efforts for this threatened species.

Introduction

The lake sturgeon (*Acipenser fulvescens*) is a large, long-lived freshwater fish considered threatened throughout most of its range in North America (Harkness and

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[1] This chapter to be submitted as a peer-reviewed journal article to the Journal of Applied Ichthyology.

Dymond 1961; Bruch et al. 2009). Overharvest and habitat loss (spawning and migration) have been implicated as factors influencing population declines in lake sturgeon (Priegel and Wirth 1978; Auer 1999). Because lake sturgeon mature at a late age and exhibit periodic spawning, information on age, growth and abundance is important for developing effective recovery and conservation plans (Brousseau 1987; Scott and Crossman 1998).

Construction of dams can have an important influence on lake sturgeon by blocking migration routes, altering spawning and nursery habitat, and changing natural flow regimes (Auer 1996a; Auer 1996b). Namakan Reservoir is a large system (approximately 26,700 ha) located along the Minnesota-Ontario border. Water in this system flows northwest from the Namakan Reservoir into Rainy Lake, Rainy River and then Lake of the Woods. Since the early 1900s, dams at the outlets of Rainy and Namakan lakes have prevented the upstream movement of lake sturgeon thus isolating these fish into three populations: Namakan Reservoir, Rainy Lake, and Rainy River/Lake of the Woods (Mosindy and Rusak 1991; Adams et al. 2006). Previous lake sturgeon research in northern Minnesota and Ontario has been conducted in Rainy Lake (Adams et al. 2006), the Rainy River (Mosindy and Rusak 1991; Stewig 2005), and the lower Seine River, Ontario (McLeod 1999). However, little is known about the lake sturgeon population of Namakan Reservoir -- a large, complex system where future hydropower development is being proposed (McLeod 2008).

In this study, I quantified age, growth, mortality and reproductive structure of lake sturgeon in Namakan Reservoir. I compared age and growth of Namakan Reservoir lake sturgeon to that from other North American populations and discuss factors associated with year-class strength.

Study Area

The Namakan Reservoir is a complex system located along the Minnesota-Ontario border (Figure 2-1). It lies downstream of the Boundary Waters Canoe Area Wilderness and Quetico Provincial Park and upstream of Rainy Lake. It includes five water bodies: Kabetogama, Namakan, Sand Point, Crane and Little Vermilion lakes, and their associated tributaries. The Minnesota-Ontario border traverses Namakan, Sand Point and Little Vermilion lakes. Voyageurs National Park, established in 1975, encompasses Kabetogama Lake and the U.S. waters of Namakan and Sand Point lakes. The Superior National Forest borders Crane and Little Vermilion lakes on the U.S. side of the border. Water levels are regulated by the International Joint Commission (IJC) through the International Rainy Lake Board of Control (IRLBC) (McLeod and Debruyne 2008). In 2000, the IJC implemented a hydrologic management regime that more closely resembles natural flows for the Namakan Reservoir (Kallemeyn et al. 2003).

Methods

Lake sturgeon collection

I used existing data from a multi-agency database to quantify age, growth and mortality of lake sturgeon. The database contained information on all lake sturgeon sampled in the Minnesota and Ontario waters of the reservoir since 2004 (J. Eibler, Minnesota Department of Natural Resources; D. McLeod, Ontario Ministry of Natural

Resources). In short, lake sturgeon were collected in spring or early summer by biologists from Voyageurs National Park, the Ontario Ministry of Natural Resources (OMNR), Minnesota Department of Natural Resources, the U.S. Forest Service and the U.S. Geological Survey. The Ontario Ministry of Natural Resources conducted additional sampling in autumn of 2005 to 2008, concentrating efforts in the Namakan River. Lake sturgeon were collected with multifilament gillnets (178, 203, 230, 254, 305 and 356-mm stretch meshes) that measured 1.8 m high and varied in length from 30 to 100 m. Gillnets were bottom set for approximately 24 h in tributaries, embayments, or main lake locations. All lake sturgeon were measured for total length, fork length, and girth (mm), and then weighed on a hand scale (kg). A 2-3 cm section of the pectoral fin spine was obtained for age determination. Each lake sturgeon was tagged with a uniquely numbered Carlin disc tag.

Age and growth

I used sections of the pectoral fin spine to determine age of lake sturgeon. Fin spine sections were air dried for at least four weeks and two 0.5 mm sections were cut from the proximal end using an Isomet saw (model 11-1280-160, Buehler). Age was estimated by imaging the fin spine cross-sections using an Olympus Model SZX16 stereo microscope. Spine cross-sections were aged independently by two viewers from South Dakota State University. Ages were cross-validated by sending a subset of cross-section images to two fisheries biologists experienced in lake sturgeon aging (W. E. Adams, Jr., South Dakota Department of Game, Fish and Parks, Pierre, South Dakota and S. Mann, OMNR, Dryden, Ontario).

The growth increments on pectoral fin spines of lake sturgeon are difficult to differentiate during periods of slowed growth, which increase in frequency with age. Bruch et al. (2009) found that pectoral fin spines underestimate the age of lake sturgeon older than 14 years. As a result, I adjusted ages of fish using the formula of Bruch et al. (2009):

$$\text{adjusted age} = [\text{estimated age}]^{1.055} .$$

I applied this correction to all lake sturgeon 15 years of age and greater.

I used length-at-age data (total length) for Namakan Reservoir lake sturgeon to develop a von Bertalanffy growth function. The relationship between weight and length was derived using log-log linear regression analysis (Pope and Kruse 2007), where body weight (W) was predicted as a function of total length (TL) as $\log_{10}W=a+b(\log_{10} TL)$. The von Bertalanffy growth functions were fit to the Namakan Reservoir lake sturgeon data using the Fishery Analyses and Simulation Tools software (FAST; Slipke and Maceina 2000). I compared growth of lake sturgeon in Namakan Reservoir to published data from 33 other lake sturgeon populations from the United States and Canada (Fortin et al. 1996). For this comparison, I used the mean total length from all lake sturgeon (sexes pooled) calculated for ages 23 to 27 (unadjusted) and the predicted weight of a 1 m individual as described by Fortin et al. (1996), Adams et al. (2006), and Stewig (2005).

Year-class strength

I quantified year-class strength of lake sturgeon using the residual method described by Maceina (2003). Year-class strength was indexed by calculating the residuals from a catch-curve analysis. I used a weighted regression in the catch-curve analysis to deflate the influence of older and (or) rarer year-classes (Maceina and Pereira 2007). Stronger year-classes were associated with positive residual values whereas weaker year-classes were associated with negative residuals. Fishery analyses and simulation tools (FAST; Slipke and Maceina 2000) software was used to calculate both the catch-curve residuals and the total annual mortality rate using the weighted (by number) regression option.

Climate data on mean monthly air temperature (1885-2006) were obtained from the National Oceanic and Atmospheric Administration, International Falls Station. Air temperature has been found to be correlated with surface water temperature (McCombie 1959; Magnuson et al. 1990). Historic water temperature data were unavailable therefore, we used mean air temperature as a indicator of mean water temperature. Mean air temperature was calculated for each season. Seasons were defined based on the dates of yearly solstices and equinoxes (March 20, June 21, September 22, December 21). Hydrologic data (1941-2009) were obtained from the Lake of the Woods Control Board and included total annual precipitation (cm; 1885-2006), mean spring (March 20 to June 20) water elevation (m), and weekly inflow and daily outflow discharge data (m^3/s). Mean inflow and outflow data were calculated for each season. Ice-out dates prior to 1980 from the Namakan Reservoir were unavailable, so ice-out dates (1930-2009) from

Rainy Lake, the reservoir immediately downstream of the Namakan Reservoir, were obtained from the Ontario Ministry of Natural Resources (D. Mcleod, unpublished data). Annual ice-out dates were defined ordinally, where January 1 was equal to date 001 and December 31 was equal to date 365.

I evaluated the influence of climatologic and hydrologic variation on year-class strength using logistic regression analysis (PROC LOGISTIC; SAS© Institute Inc., 1999). The frequency distribution of residual values was strongly skewed to the right, with most 'strong' year-classes occurring in the upper 33% of the frequency distribution. Because of [unknown] error associated with using pectoral fin spines to determine exact ages of adult lake sturgeon, I grouped 'strong' year-classes as those that had residual values in the upper 33% of the distribution. Average (or weak) year-classes were characterized by low (positive) or negative residual values in the lower 67% of the distribution. For modeling purposes, I assigned a value of '1' to strong year-classes and a value of '0' to others.

I tested the odds of occurrence of a strong lake sturgeon year-class against all climatologic and hydrologic variables. The Hosmer-Lemeshow goodness-of-fit test ($P > 0.05$) was used to assess how well the global logistic model met the assumptions underlying logistic regression (Hosmer and Lemeshow 1989; Rich et al. 2003). I used odds ratios, calculated as *e* raised to the ith logistic regression coefficient (e.g., $e^{\hat{\beta} i}$), to evaluate the importance of each variable in the model. Because odds ratios are based on a single unit change, I calculated a scaling factor (*C*) for each variable to establish a unit of change that would be biologically relevant (Rich et al. 2003). The scaling factor was determined by taking the difference in the median value (of climate and hydrologic variables) between strong (value = 1) and weak (value = 0) year-classes and rounding to the nearest unit of 5. The scaled odds ratio was then calculated as $e^{C \cdot \hat{\beta}i}$ to reflect a more meaningful change in the magnitude of the variable (Rich et al. 2003). I used the 95% confidence interval of each significant variable to evaluate the biological significance of the value at the lower (positive coefficient) and upper (negative coefficient) bounds. Confidence intervals were calculated for the scaled odds ratio as $e^{(\mathrm{C} \cdot \hat{\beta}i \pm \mathrm{z}0.975 \cdot \mathrm{C} \cdot \mathrm{SE}(\hat{\beta}i)}$, where $z_{0.975}$ = 1.96l (Rich et al. 2003).

Reproductive attributes

In spring 2008 and 2009, blood (~2 mL) was collected from the caudal vasculature of pre-spawning lake sturgeon (N = 136) using heparinized syringes (3 cc, 23 gauge, 38 mm needle). Samples were stored on wet ice and processed within 1 h of collection by centrifuging at 2000 g for 10 minutes at room temperature. The steroids, testosterone (T) and estradiol-17ß (E2), were extracted from plasma and analyzed by radioimmunoassay (RIA; Fitzpatrick et al. 1987; Webb et al. 2002). Briefly, 100 µL of plasma was extracted twice with 2 mL of diethyl ether. Tubes were vortexed vigorously with ether, and the aqueous phase was removed by snap-freezing in liquid nitrogen. Combined extracts were dried in a Speed Vac centrifuge, resuspended in 1 mL of phosphate-buffered saline with gelatin (PBSG), and 10 or 50 µL were assayed for each steroid. Recovery efficiencies for all steroids were determined by adding tritiated steroids to tubes containing plasma (n = 4), which were extracted as described above. The average recovery efficiencies for T and E2 were 94 and 75%, respectively. All steroid assay results were corrected for recovery. All samples were analyzed in duplicate. The lowest quantifiable concentration for both T and E2 was 0.20 ng/mL. The intra- and inter-assay coefficients of variation for all assays were less than 5 and 10%, respectively.

I assigned gender and stage of maturity to each lake sturgeon based on plasma T and E2 concentrations using methods outlined in Webb et al. (2002). Mean total length (TL), weight, and age were compared between male and female fish using analysis of variance (ANOVA). Female lake sturgeon were classified into three reproductive groups: pre-vitellogenic, vitellogenic and post-vitellogenic (Webb et al. 2002; Webb and Erickson 2007; Allen et al. 2009). The post-vitellogenic stage corresponds to gravid females that would be capable of reproducing in the season they were sampled. I compared mean total length, weight and girth among pre-vitellogenic, vitellogenic, and post-vitellogenic females using ANOVA (Webb and Erickson 2007). Similarly, male lake sturgeon were classified into three reproductive groups based on plasma T levels: mitotic, meiotic and spermiating. Males with the elevated T levels (>30 ng/mL) were considered spermiating fish and capable of reproduction in the year sampled (Webb and Erickson 2007). I used ANOVA to compare size characteristics among mitotic, meiotic, and spermiating male lake sturgeon (Webb and Erickson 2007). Multiple comparison tests were performed using a Tukey's Studentized range test.

Results

Age and growth

A total of 663 lake sturgeon were collected from 2004 to 2009 in U.S. and Canadian waters of the Namakan Reservoir (including the Namakan River). The total length of lake sturgeon ranged from 774 to 1746 mm (mean = 1245 mm; Figure 2-2). Lake sturgeon weight (W) was positively related to total length (TL) as,

$$\log_{10}W = -9.593 + 3.448(\log_{10}TL)$$

(log-log linear regression, $n = 506$, $P < 0.0001$, $r^2 = 0.92$; Figure 2-3).

Of the lake sturgeon collected, 533 were successfully aged using pectoral fin spines. Ages of lake sturgeon ranged from 9 to 86 years, with a mean age of 36. The age distribution was represented by the 1923 to 1999 year classes with 75% of lake sturgeon from the 1953 to 1981 year classes (Figure 2-2). The von Bertalanffy growth model provided a good fit to growth data for Namakan Reservoir lake sturgeon ($P < 0.001$, $r^2 = 0.57$) and was used to estimate length at age using the equation,

$$l_t = 1857 * (1 - e^{-0.019 * (t - (-10.0))}).$$

I used catch data for 28 to 56 year old lake sturgeon (1981 to 1953 year classes) to conduct the catch-curve analysis (Figure 2-4). The 1981 year-class was the first year-class considered fully recruited to the gear. When using a catch-curve approach to estimate mortality rate, including the oldest (e.g., rarest) individuals can complicate the analysis. Therefore, I followed the approach outlined by Miranda and Bettoli (2007), and truncated the age distribution by considering only the oldest age group with at least five individuals—in this case, the 1953 year-class. Using this approach, total annual mortality was estimated at 4.8%, and total annual survival was 95.2%. The most abundant (strongest) year-classes occurred between 1963 and 1972 (ages 46-37). Weak year-classes were particularly evident in 1974 (age 35), 1959 (age 50) and 1957 (age 52; Figure 2-4).

I compared the weight and length of Namakan Reservoir lake sturgeon to values of other North American lake sturgeon populations reported by Fortin (1996). The estimated weight of a 1 m lake sturgeon in Namakan Reservoir (5.65 kg) was similar to the North American average (5.68 kg; Table 2-1). Similarly, mean total length of age 23 to 27 year old fish ($TL_{23\text{-}27}$ = 1185 mm) was similar to the North American average ($TL_{23\text{-}27}$ = 1143 mm; Table 1; Fortin 1996).

Year-class strength

A total of 15 variables were included in the logistic regression analysis; total annual precipitation, spring water elevation, ordinal ice-out date, and seasonal means (n = 4 seasons) for air temperature, mean inflow and mean outflow. Using a stepwise forward regression model, if a variable did not meet the entry-level significance value of 0.05 it was excluded from the final model. Total annual precipitation and mean fall air temperature were the only significant variables included in the final model (Table 2-2). The Hosmer and Lemeshow Goodness of fit results (P > Chisq = 0.58, df = 8, chisq = 6.65) showed that the model provided a reasonable fit for the data.

Total annual precipitation was positively associated with year-class strength (Table 2-2). A 10 cm increase in total annual precipitation was associated with at least a

39% (1.39/1) increase in the odds of occurrence of a strong year-class of lake sturgeon. In contrast, mean fall air temperature was negatively associated with year-class abundance (Table 2-2). A 3˚C increase in mean fall air temperature was associated with about an 8% (1/0.93) decrease in the odds of occurrence of a strong lake sturgeon year-class.

Reproductive attributes

Plasma T and E2 concentrations were analyzed from 133 pre-spawning lake sturgeon collected in 2008 and 2009. Classification of fish using steroid concentrations revealed 94 females and 39 males. Females were significantly longer, heavier and older than males (Table 2-3).

A total of 8 females were classified as post-vitellogenic (gravid) which corresponded to an average of 9.5% of the females sampled each year. Moreover, mean size of females differed among reproductive stages. Gravid females were significantly larger than pre-vitellogenic females in mean total length, mean weight, and mean girth (Table 2-4). Mean weight of gravid females was also significantly higher than for vitellogenic females but other size characteristics were similar. Vitellogenic females were larger than pre-vitellogenic females in mean weight and mean girth (Table 2-4).

In 2008 and 2009, a total of 11 males were classified as spermiating (ripe) fish, corresponding to an average of 30% of the males sampled each year. There was no difference in mean total length, mean weight or mean girth among reproductive stages in males (Table 2-4).

Discussion

Low annual mortality (4.8%) of adult lake sturgeon in the Namakan Reservoir indicates that year-class strength is likely determined at the larval or juvenile stage of development, congruent with other studies (Richmond and Kynard 1995; Nilo et al 1997). I found no missing year-classes from 1953 to 1981 indicating relatively consistent recruitment patterns for lake sturgeon. Moreover, the size and age distribution of lake sturgeon in Namakan Reservoir was similar to those reported for other North American lake sturgeon populations (Fortin et al. 1996).

Annual variation in environmental conditions is known to influence growth and survival of sturgeon during their first year of life (Lebreton and Beamish 2004). I found a positive relationship between lake sturgeon year-class strength and total annual precipitation in Namakan reservoir. Lake water levels generally increase in years with higher precipitation (Goldman and Amazaga 1984) and could provide increased spawning and nursery habitat for lake sturgeon that enhance year-class strength. In a study of Siberian sturgeon, *Acipenser baeri,* year-class strength was directly related to water levels in the Ob River, USSR (Votinov and Kas'yanov 1978). Similarly, increased water flow in the St. Lawrence system was positively related to year-class strength for lake sturgeon (Nilo et al. 1997). Mechanisms associated with enhanced year-class strength of sturgeon have not been well documented but may be related to better spawning and (or) rearing conditions during periods of high water levels (Kohlhorst et al. 1991). Long-term studies in Lake Tahoe, California indicated that percent change in primary productivity was positively correlated to annual precipitation (Goldman and

Amazaga 1984; Goldman 1988). Thus, in years with more precipitation, increased productivity may enhance growth and survival of lake sturgeon larvae (Cech and Doroshov 2004).

Seasonal water temperature can be an important factor affecting growth, survival and year-class strength in sturgeon (Khoroshko 1972; Nikol'skaya and Sytina 1978; Nilo et al. 1997). In a study of 32 lake sturgeon populations, Fortin et al. (1996) found that fish growth was positively correlated to mean annual air temperature. Similarly, Power and McKinley (1997) showed that length-at-age for adult lake sturgeon was positively related to length of the growing season (i.e., degree days >5°C). I found that mean fall air temperature was negatively related to year-class strength of lake sturgeon. The reason for this is not clear. One explanation may be related to reduced activity and (or) increased energetic efficiency at cooler water temperatures. Telemetry studies indicate that lower fall water temperatures are associated with decreased movement rates of adult lake sturgeon (Hay-Chmielewski 1987; Mosindy and Rusak 1991; McLeod and Debruyne 2009). Decreased activity combined with lower energetic costs may result in a growth advantage for juvenile lake sturgeon during autumn. Other factors, such as food quality and availability, also vary with seasonal changes in water temperature and lake productivity, and may influence growth and overwinter survival for juvenile fishes (Shuter and Post 1990).

Female lake sturgeon classified by circulating plasma steroid concentrations from Namakan Reservoir represented 71% of the total catch, which was within the range (68-95%) reported for other populations (Threader and Brousseau 1986; Auer 1999). Female lake sturgeon are known to reach larger sizes than males (Probst and Cooper 1954; Mosindy and Rusak 1991). Thus, females may be more vulnerable to the sampling gear than males and make up a larger proportion of the lake sturgeon sampled. Female lake sturgeon also live longer than males, which coupled with the low annual mortality of adult fish (4.8%) would lead to a larger proportion of females present in the population (Probst and Cooper 1954; Mosindy and Rusak 1991). A larger proportion of reproductive male lake sturgeon rather than reproductive female lake sturgeon in the reservoir during each spawning season indicates that although more females may be present in the Namakan Reservoir population as a whole the availability of sexually mature ripe males is not likely a limiting factor in reproductive success.

Adult male lake sturgeon generally exhibit a 2-4 year reproductive cycle and evidence of annual spawning has not been well documented (Auer 2004). Plasma T concentrations from male lake sturgeon in Namakan Reservoir indicated that the majority of fish sampled in both years were characterized by a non-reproductive stage of gonadal development, while 30% of the males had elevated concentrations of T suggesting late gametogenesis and a 3-year reproductive cycle. However, one male fish captured in both years of our study was classified as ripe in 2008 and 2009. Although reportedly not common (Auer 1999), annual reproduction by male lake sturgeon is physiologically possible, although likely exhibited by a small fraction of adult males.

The annual proportion of ripe males (30%) found in our study may be a conservative estimate. In 2009, a male captured twice in a three day span exhibited the ability to rapidly mature from a non-reproductive to a reproductive stage of development prior to the spawn. The first collection occurred on May 5, 2009 at which time the fish was determined to be in a non-reproductive, meiotic, stage of gonadal development (T = 23.84 ng/mL). The same sturgeon was sampled again on May 7, 2009 in the same location and plasma T concentration indicated the fish had matured to a spermiating or ripe gonadal stage (T = 35.21 ng/mL). The ability of male lake sturgeon to undergo a rapid gonadal maturation prior to the spawn means that my estimate of the proportion of males that are capable of spawning in any given year is likely low and also suggests a faster gametogenic cycle.

Currently, the Namakan Reservoir supports a viable population of lake sturgeon characterized by low total annual mortality, consistent recruitment and an age and size distribution similar to other North American populations. A sex ratio skewed toward females is countered by a shorter spawning periodicity of males. Thus, a larger proportion of the male population is capable of reproduction during the spawning season. The use of plasma steroid concentrations to determine the reproductive stage of development as well as the proportions of both males and females capable of reproducing each spawning season has important implications for evaluating reproductive structure and conservation strategies for this protected species.

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Table 2-1. Condition measurements (weight [W] of 1000 mm individual; mean total length [TL] of ages 23 to 27) of lake sturgeon from Namakan Reservoir and other North American populations (Fortin et al. 1996; Adams et al. 2006).

Population	W_{1000mm} (kg)	Mean $TL_{23\text{-}27}$ (mm)
North American minimum	4.13	659
North American mean	5.68	1143
Namakan Reservoir	5.65	1185
Rainy Lake	5.97	1289
Rainy River/Lake of the Woods	6.12	1361

Table 2-2. Parameters included in a logistic regression model for predicting occurrence of a strong lake sturgeon year-class.

Variable	DF	Parameter Estimate	Standard Error	Scaling Factor	Scaled Odds Ratio	95% CI for Scaled Odds Ratio	P > Chisq
Intercept	1	-16.75	5.49				0.0099
Total Annual Precipitation (cm)	1	0.19	0.079	10	6.69	(1.39, 32.07)	0.046
Mean Fall Air Temperature (˚C)	1	-0.75	0.37	3	0.11	(0.012, 0.93)	0.016

Table 2-3. Mean total length, mean weight and mean age (years) of female and male lake sturgeon sampled in Namakan Reservoir in 2008 and 2009. For female and male lake sturgeon, values with the same letter are not significantly different (P>0.05). Fish gender was determined using plasma steroid concentrations.

Gender	n	Mean total length (mm)	Mean weight (kg)	Mean Age
Female	94	1335 (832 - 1715)a	16.23 (5.0 - 35.0)a	47 (9 - 86)a
Male	39	1257 (1005 - 1650)b	13.83 (6.0 - 36.0)b	40 (19 - 66)b

Table 2-4. Mean total length (TL), mean weight (WT) and mean girth by reproductive stage for female and male lake sturgeon collected in Namakan Reservoir in 2008 and 2009. For reproductive stages, values with the same letter are not significantly different (P>0.05). Gender was predicted using plasma steroid concentrations.

Gender	Reproductive Stage	n	Mean Total Length (mm)	Mean Weight (kg)	Mean Girth (mm)
Female	Pre-vitellogenic	60	1298 (832-1639)a	14.0 (5.4-28.5)a	482 (327-598)a
	Vitellogenic	26	1371 (1145-1715)ab	18.8 (12.0-35.0)b	538 (415-699)a
	Post-vitellogenic	8	1490 (1410-1534)b	24.3 (17.0-31.1)c	591 (525-658)b
Male	Mitotic	21	1232 (1100-1442)a	12.5 (6.0-22.0)a	469 (397-595)a
	Meiotic	7	1258 (1166-1344)a	12.8 (10.2-15.5)a	467 (417-530)a
	Spermiating	11	1308 (1005-1650)a	17.2 (8.5-36.0)a	510 (364-728)a

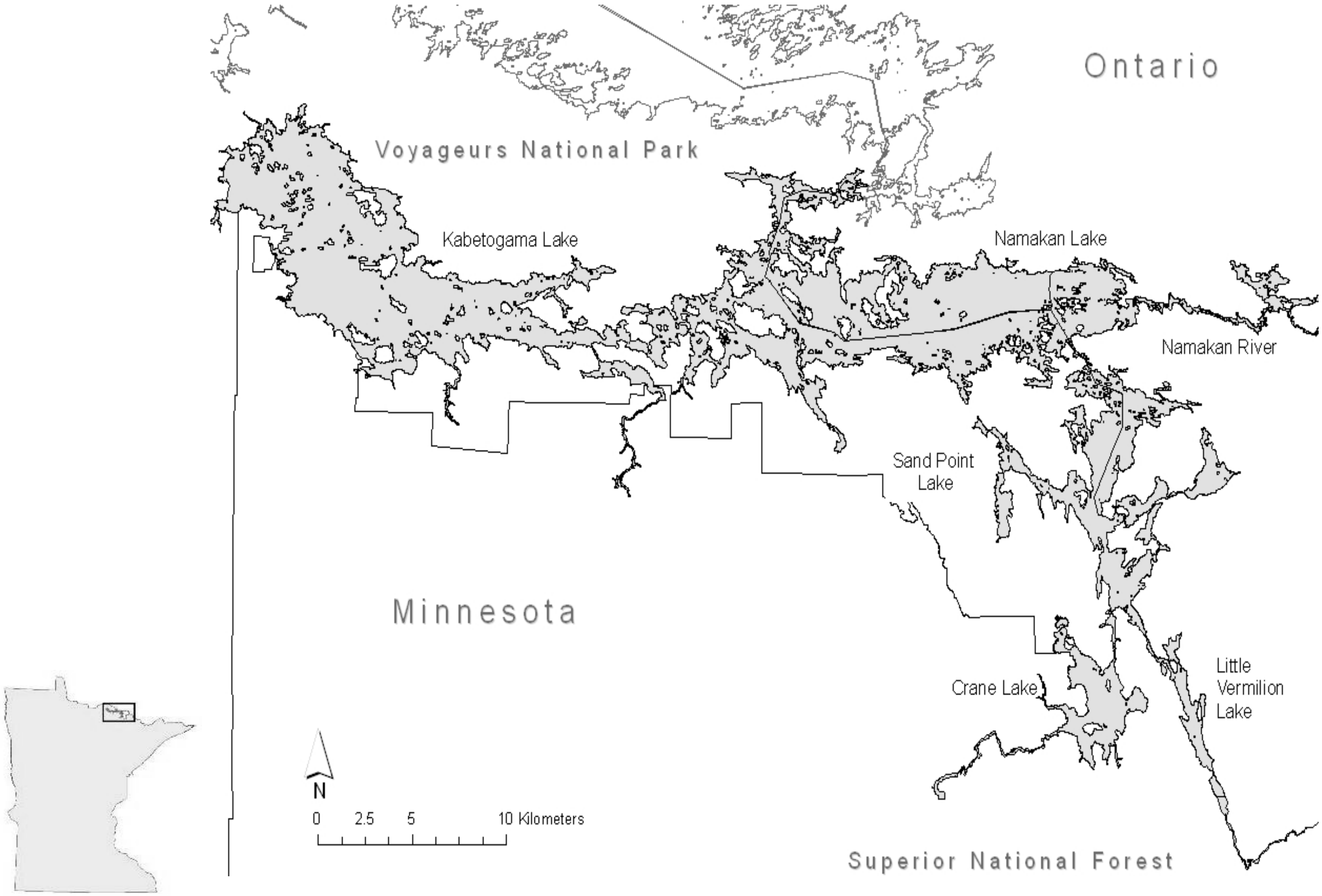

Figure 2-1. Map of the study area, Namakan Reservoir, located on the Minnesota-Ontario border.

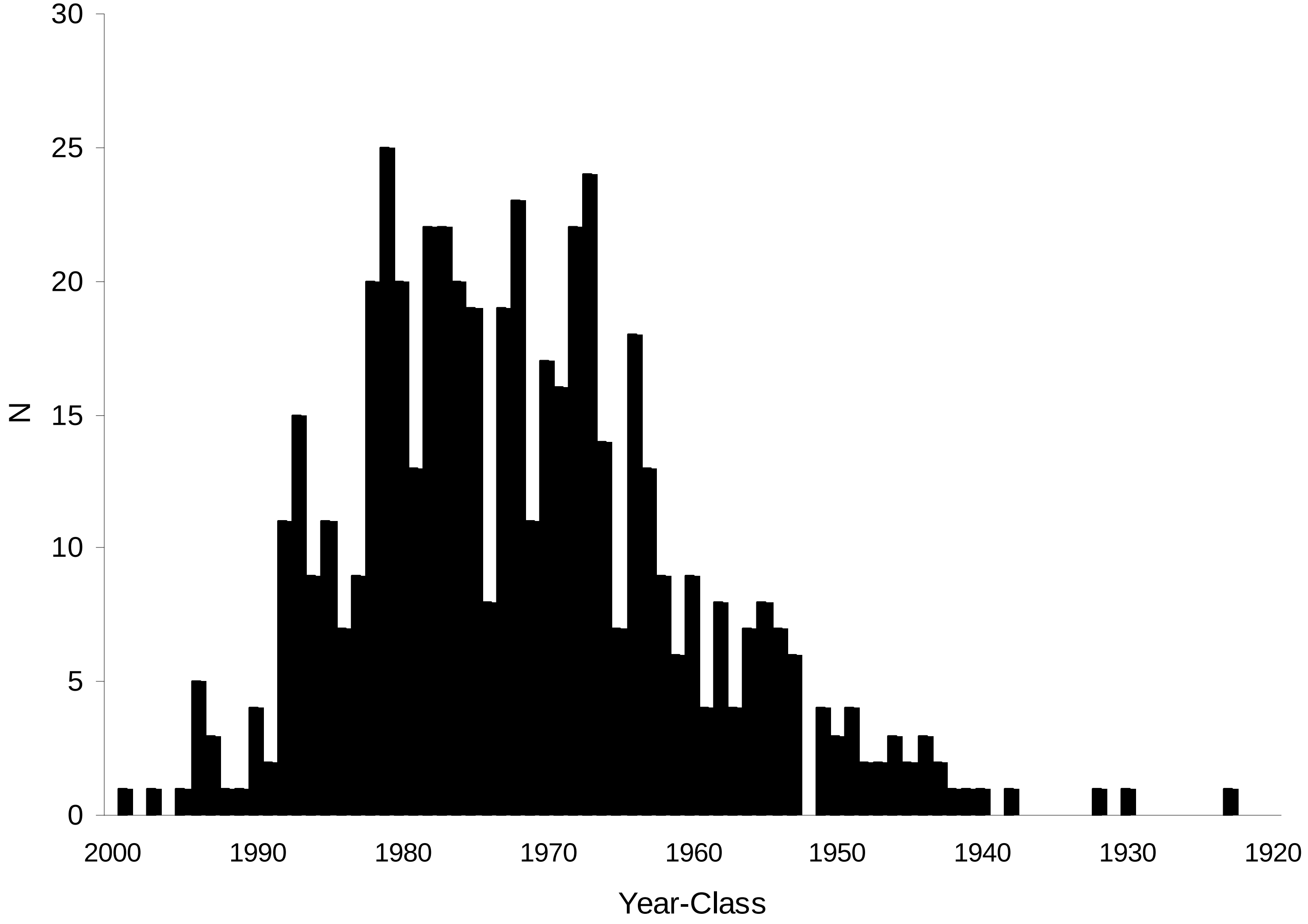

Figure 2-2. Frequency distribution of lake sturgeon year-classes (sexes combined) collected from Namakan Reservoir, 2006-2009.

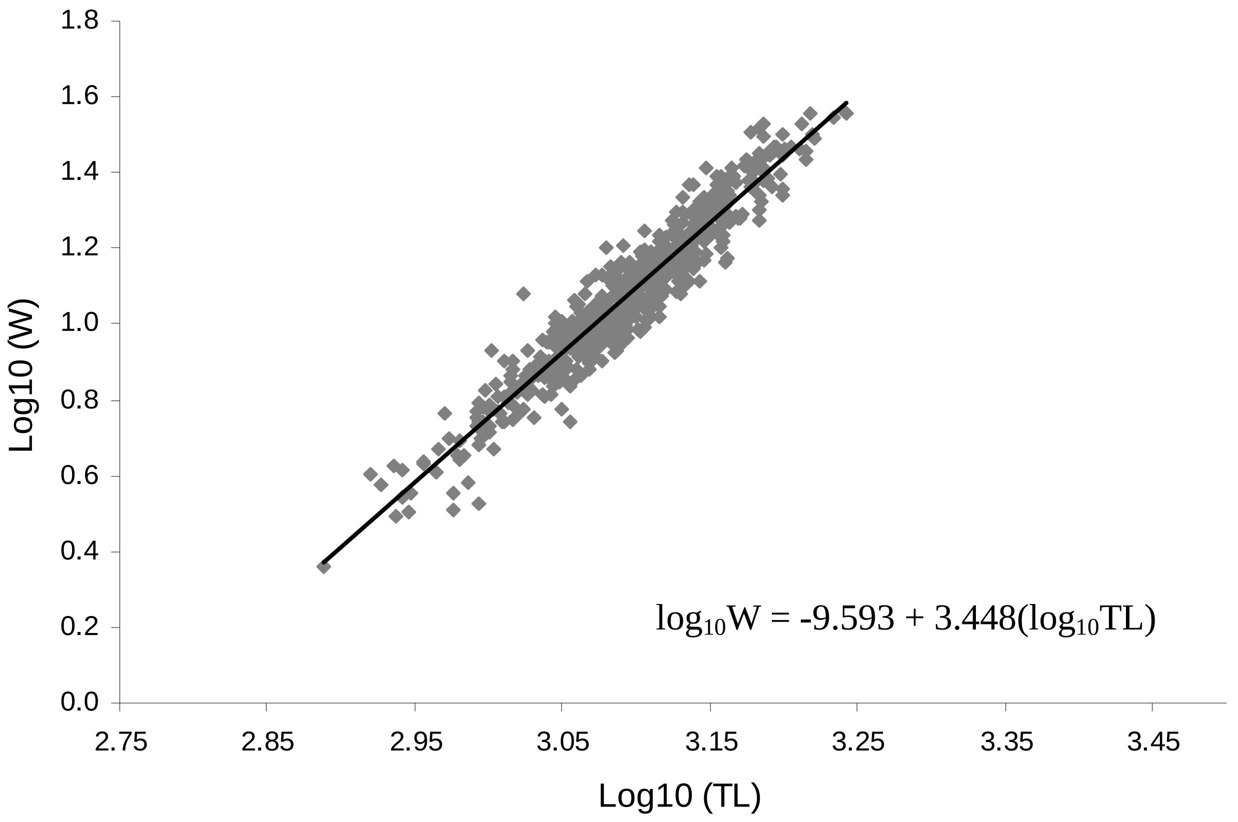

Figure 2-3. Log transformed (base 10) total length (mm; TL) and weight (kg; W) relationship of lake sturgeon collected in the Namakan Reservoir from 2004 to 2009 (log-log linear regression, $n = 506$, $P < 0.0001$, $r^2 = 0.92$). The total length to weight regression was used to estimate the weight of a 1 m individual for population comparison (Table 2-1; Fortin 1996, Stewig 2005, Adams et al. 2006).

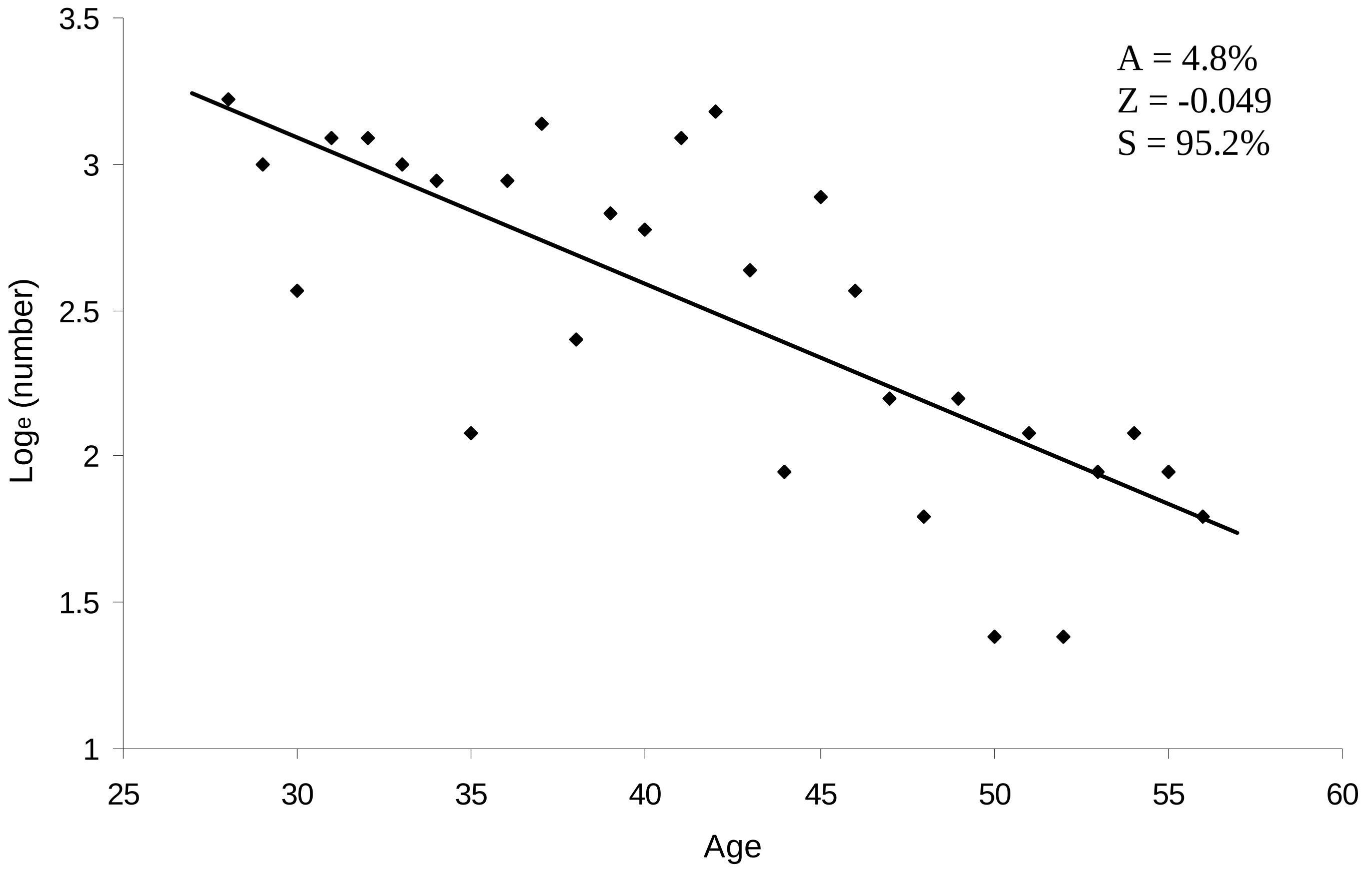

Figure 2-4. Abundance ($\log_e$ total catch) of lake sturgeon (ages 28-56) collected from Namakan Reservoir, 2006-2009 (regression analysis, n = 30, $r^2 = 0.57$; $P < 0.0001$). Catch curve analysis (FAST software) was used to estimate annual mortality (A), instantaneous mortality (Z), and annual survival (S).

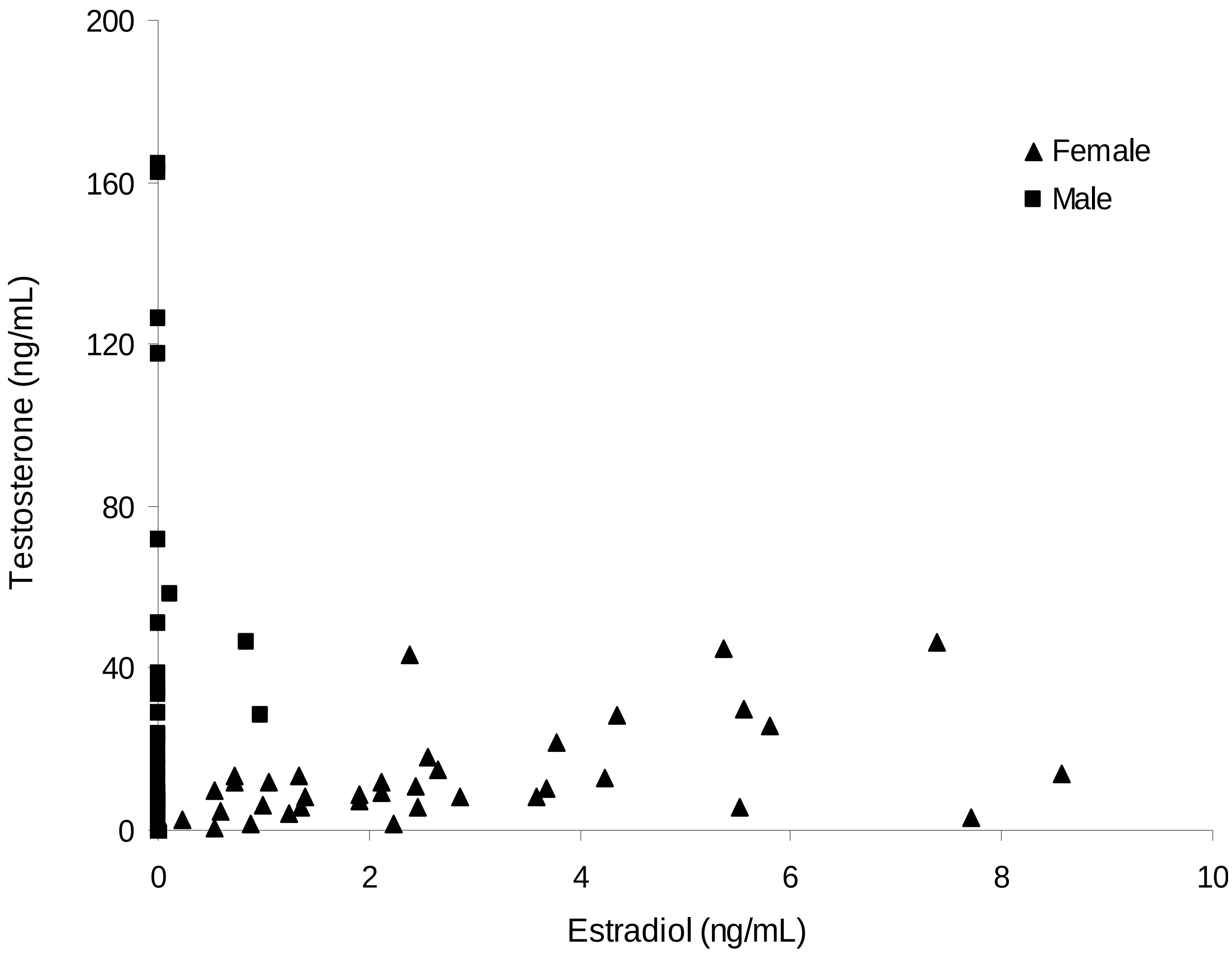

Figure 2-5. Plasma steroid concentrations (testosterone and estradiol-17ß) of male (n = 39) and female (n = 94) lake sturgeon collected from Namakan Reservoir in spring 2008 and 2009.

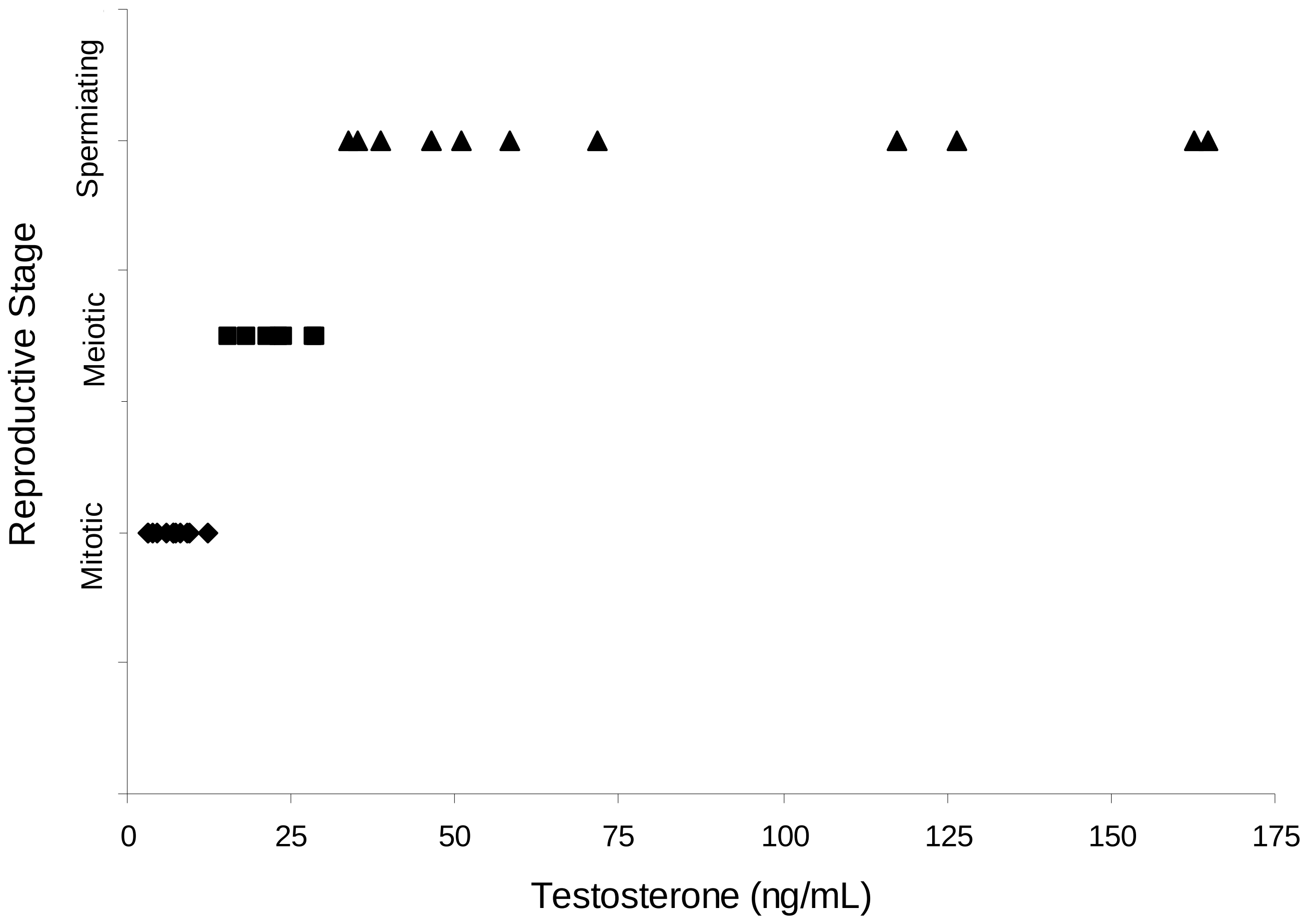

Figure 2-6. Plasma testosterone concentration of male lake sturgeon (n = 39) classified into three reproductive stages collected from Namakan Reservoir in spring 2008 and 2009.

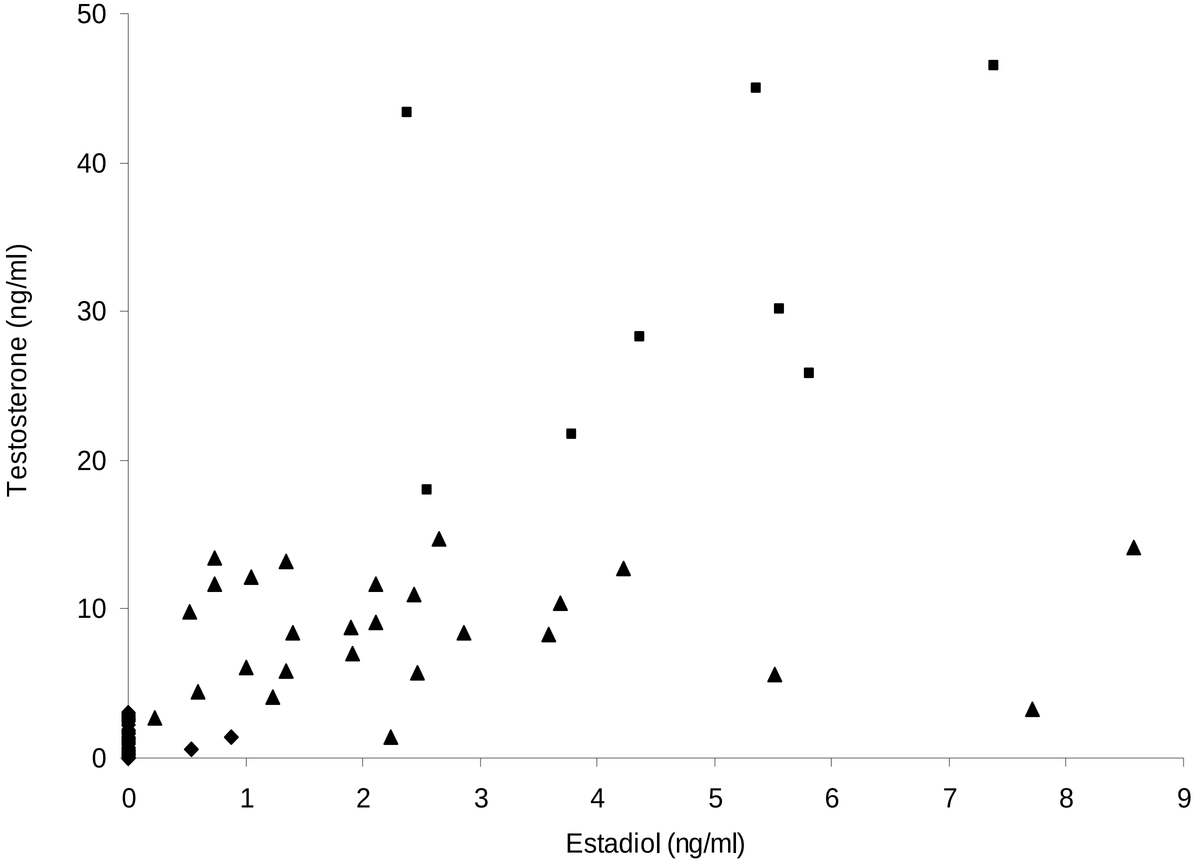

Figure 2-7. Plasma estradiol-17ß and testosterone concentration of female lake sturgeon (n = 94) collected from Namakan Reservoir in spring 2008 and 2009. Females were classified into one of three reproductive stages following methods outlined in Webb et al. (2002). Symbols represent: ◆ pre-vitellogenic, ▲ vitellogenic, and ■ post-vitellogenic fish.

CHAPTER 3

INFLUENCE OF REPRODUCTIVE STATUS ON SEASONAL MOVEMENT OF LAKE STURGEON IN NAMAKAN RESERVOIR[1]

Abstract

I evaluated the influence of gender and reproductive condition on seasonal distribution and movement patterns of lake sturgeon in Namakan Reservoir. Sixty adult lake sturgeon were implanted with acoustic transmitters prior to spawning in spring 2007 and 2008. Fish movement was monitored using an array of 15 stationary receivers covering both US and Canadian waters of Namakan Reservoir and its major tributaries. Blood samples were collected from 133 lake sturgeon prior to spawning and plasma concentrations of testosterone and estradiol-17ß were analyzed using radioimmunoassay. The greatest recorded distance traveled by a lake sturgeon was 130 km. In general, females traveled greater distances (mean = 38.8 km) than males (mean = 29.9 km). Lake sturgeon of both sexes traveled greater distances during the spawning and post-spawning periods. Distance traveled was lowest (mean = 5.3 km) and site fidelity was highest (mean = 17.8 days) during winter months. Five females were characterized as potentially reproductive and 14 as non-reproductive based on plasma steroid concentrations. Potentially reproductive females had lower site fidelity and traveled greater distances across all seasons than non-reproductive females. Distance traveled by reproductive females was highest in the fall (mean = 38.8 km) compared to other seasons (mean 3.2 to

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[1] This chapter to be submitted as a peer-reviewed journal article to the Canadian Journal of Fisheries and Aquatic Sciences.

24.0 km) and may be linked to gonadogenesis (e.g., increased energy acquisition) prior to spring spawning.

Introduction

Lake sturgeon populations have declined across much of their range in North America owing to factors that include overharvest, impoundment of rivers, and water pollution (Harkness and Dymond 1961; Auer 1996; Auer 2004). Commercial fishing harvest in the late 1800s and early 1900s depleted lake sturgeon stocks across North America (Auer 2004). The boom of riverside industry during the same time frame hindered population recovery by altering spawning and nursery habitat (Auer 1999, 2004). Moreover, the life-history characteristics of the species, (e.g., age at maturation) make lake sturgeon vulnerable to overharvest and slow to recruit to the spawning population (Auer 2004).

Conservation of lake sturgeon populations requires effective management and long-term monitoring. Female lake sturgeon do not mature until they are 20 to 25 years of age and spawn only once every 4 to 9 years while males mature around 8 to 12 years of age and spawn once every 1 to 5 years (Craig et al. 2005; Peterson et al. 2007). Thus, information about the abundance, spawning behavior (e.g., seasonal movement), and reproductive structure of lake sturgeon is important for species recovery.

Previous studies have used telemetry to identify habitat use and migration patterns of lake sturgeon (Rusak and Mosindy 1997; McKinley et al. 1998; Auer 1999; Adams et al. 2006; Friday 2006). Research in Ontario, Minnesota, and Michigan used telemetry data to identify seasonal movement, habitat use, potential spawning sites, spawning intervals, and movement rates of lake sturgeon (Rusak and Mosindy 1997; McKinley et al. 1998; Auer 1999; Adams et al. 2006). All previous studies documented differences in habitat use, movement patterns and movement rates, generally attributed to seasonal changes in water temperature and behavior related to spawning, foraging or overwintering. No studies are known to combine telemetry data with reproductive status to examine differences in movement patterns related to age, gender, and reproductive maturity.

The reproductive structure of lake sturgeon populations can provide important information to fishery managers (McLeod et al. 1999; Craig et al. 2009). However, lake sturgeon gender is difficult to identify externally because they are not dimorphic (Vescei et al. 2003). The use of plasma steroid concentrations offers a minimally invasive alternative to determine the reproductive structure (i.e., sex ratio, proportions of immature and mature fish, proportions of reproductive and non-reproductive fish in a spawning season) of North American sturgeon species (Webb et al. 2002; Webb and Erickson 2007; Craig et al. 2009; Stahl et al. 2009). I examined the influence of gender and reproductive condition on seasonal distribution and movement patterns of lake sturgeon in the Namakan Reservoir -- a large complex system on the Minnesota-Ontario border where little information on the lake sturgeon population currently exists.

Study Area

The Namakan Reservoir is a complex system located along the Minnesota-Ontario border (Figure 3-1). It lies downstream of the Boundary Waters Canoe Area

Wilderness and Quetico Provincial Park and upstream of Rainy Lake. It includes five water bodies: Kabetogama, Namakan, Sand Point, Crane and Little Vermilion lakes, and their associated tributaries. The Minnesota-Ontario border traverses Namakan, Sand Point and Little Vermilion lakes. Voyageurs National Park, established in 1975, encompasses Kabetogama Lake and the U.S. waters of Namakan and Sand Point lakes. The Superior National Forest borders Crane and Little Vermilion lakes on the U.S. side of the border. Water levels are regulated by the International Joint Commission (IJC) through the International Rainy Lake Board of Control (IRLBC) (McLeod and Debruyne 2009). In 2000, the IJC implemented a hydrologic management regime that more closely resembles natural flows for the Namakan Reservoir (Kallemeyn et al. 2003).

Methods

Lake sturgeon collection

Lake sturgeon were collected shortly after ice-out during May of 2007 through 2009 by biologists from Voyageurs National Park, the Ontario Ministry of Natural Resources, Minnesota Department of Natural Resources, the U.S. Forest Service and the U.S. Geological Survey. Lake sturgeon were collected using multifilament gillnets (178, 203, 230, 254, 305 and 356-mm stretch meshes) that measured 1.8 m high and varied in length from 30 to 100 m. Gillnets were bottom set for approximately 24 h in tributaries, embayments, or main lake locations. All lake sturgeon were measured for total length, fork length, and girth (mm), and then weighed to the nearest g on a hand scale. A 2-3 cm section of the pectoral fin spine was obtained for age determination.

A total of 60 adult lake sturgeon (> 860 mm total length) were implanted with Vemco V16 acoustic transmitters (Vemco – Amirix Systems Inc., Halifax, Nova Scotia) in May 2007 (n = 30) and 2008 (n = 30). Of the 60 sturgeon implanted with acoustic transmitters, 26 (43%) were collected in the Voyageurs National Park waters of the reservoir and 34 (57%) were collected in the Namakan River by the Ontario Ministry of Natural Resources (Table 3-1). The transmitters were single frequency (69 kHz) coded tags, 68 x 16 mm and weighed 10 g in water (McLeod and Debruyne 2009).

All surgeries performed on fish to implant the V16 transmitters were conducted by an experienced biologist (D. McLeod, Fort Frances District, Fort Frances, Ontario) and followed protocols similar to Hart and Summerfelt (1975) and Adams et al. (2006). Prior to surgery, lake sturgeon were held in a 350 L tank filled with approximately 300 L of water and 1.5 kg of salt (NaCl). Surgical instruments and transmitters were disinfected in a solution of Germiphene germicidal concentrate (50 mL) and distilled water (4 L). To implant an acoustic tag, the lake sturgeon was placed ventral side up in a canvas cradle suspended in the holding tank while water was flushed over the gills using a small pump and hose. A sterile, fenestrated polylined towel (Convertors) covered the ventral surface of the sturgeon. Using a surgical scalpel, a 3 – 5 cm incision was made on the ventral surface approximately 1 cm off the midline and 3 – 4 cm anterior to the pelvic girdle. Prior to transmitter insertion if gonads were readily visible the gender and stage of maturity were noted then the transmitter was inserted into the peritoneal cavity. The peritoneum and muscle tissue were closed with a continuous modified Cushings suture technique (3-0 Ethicon PDS II, 12.7 mm CT-2 needle). To close the skin 5 simple interrupted sutures were used (2-0 Ethicon Prolene, 12.7 mm SH needle). Lake sturgeon were monitored after surgery to assess recovery. They were placed in a 12 m^3 holding net suspended by a floating plastic frame. The sturgeon was released after approximately 1 h of observation near the site of capture (McLeod and Debruyne 2009). Fish handling and care protocols followed guidelines established by the American Fisheries Society (Nickum et al. 2004).

Reproductive condition

Blood samples were obtained from the caudal vasculature of 133 pre-spawned lake sturgeon collected in the Namakan Reservoir in early May of 2008 (n = 46) and 2009 (n = 87; see Chapter 2). Plasma extracted from the blood samples was analyzed for concentrations of estradiol-17β (E2) and testosterone (T) as described in Chapter 2. Concentrations of T and E2 were used to differentiate gender and classify lake sturgeon into reproductive stages (Webb et al. 2002). Male lake sturgeon have lower E2 concentrations not exceeding 1.0 ng/mL and T levels greater than 3.0 ng/mL. Males were differentiated into three reproductive stages; mitotic, meiotic, and spermiating. The spermiating stage (T > 30.0 ng/mL, E2 < 1.0 ng/mL) included reproductive or ripe males capable of reproducing in the season sampled. Testosterone in the female reproductive cycle is a precursor to E2, and as a result, levels of both steroids vary depending on reproductive stage. The lower reproductive stages of females do not exceed T levels of 3.0 ng/mL and increasing T levels are accompanied by increasing E2 levels. Females were classified into three reproductive stages; pre-vitellogenic, vitellogenic and post-vitellogenic. The post-vitellogenic stage (T > 17.0 ng/mL, E2 > 2.0 ng/mL) was the only reproductive stage that included gravid females that would be capable of spawning in the season sampled (Shaw et al., unpublished manuscript).

Acoustic telemetry

I used a passive telemetry array consisting of 15 stationary Vemco VR2W receivers positioned throughout the main reservoir (Figure 3-1). VR2W receivers have a factory recommended maximum range of 0.5 km so locations were chosen that would maximize detection efficiency (i.e., interlake narrows, bays, and tributaries). The receivers were attached to a line with a float to keep the receiver suspended approximately 1 m off the bottom. Receiver lines were anchored to the bottom using cement blocks and anchor lines were attached to a point on the nearest shoreline. Float lines were shortened depending on the depth of the water so that floats would remain suspended approximately one meter below the water line and the anchor lines were camouflaged on the shore to discourage tampering. HOBO temperature loggers (HOBO U22-0001 Water Temperature Logger © Onset Computer Corporation) were attached to the float line of each receiver in the summer of 2008 to record temperature once every 4 hours. Receivers were range tested in the summer of 2008 to determine the detection range using protocols established by the manufacturer.

Data from the receivers were used to analyze seasonal distribution, site fidelity and migration patterns. I summarized the total number of lake sturgeon detected at each receiver. Individual fish detections were exported from the Vemco VUE software into a

Microsoft Excel file and summarized by season for each lake sturgeon. I used water temperature data from Namakan Reservoir to characterize fish movement during spring (pre-spawning and spawning), summer (post-spawn), fall and winter (Figure 3-2; Rusak and Mosindy 1997). The spring pre-spawning period (April 16 - June 4) started as water temperatures increased above 2˚C and prior to the onset of optimum lake sturgeon spawning temperatures (13˚C; Harkness and Dymond 1961). The spring spawning season (June 5 - June 22) was defined as the time during which water temperatures were within the range of reported lake sturgeon spawning temperatures (i.e., 13 - 18˚C; Harkness and Dymond 1961). The summer post-spawn period began as temperatures exceeded 18°C and continued until water temperatures declined (fall period; September 3 - December 12). Winter was characterized as the period corresponding to low, stable water temperatures (0 - 2°C; December 12 - April 15).

The degree of site fidelity, defined as the amount of time spent within a receiver's range, was summarized for individual sturgeon (Lowe et al. 2006). Upon entering the detection range of a receiver, events are logged every 1 to 3 min. A lake sturgeon was considered to be within the receiver area until the time between detection events exceeded 10 minutes. Once the time between detections exceeded 10 minutes the sturgeon was considered to have left the area of the receiver and the event was ended. For each fish, total time (days) spent within a receiver's detection range was summarized by season and for the entire census period (2008 - 2009).

Individual lake sturgeon movements were used to estimate minimum distance traveled (MDT; Chateau and Wantiez 2007) and identify migration patterns (Peterson

2007) using ArcMap 9.3 (© ArcGIS ESRI, Redlands, CA). A least-cost distance map of the Namakan Reservoir was created in ArcMap with any water being considered no cost to travel and all land considered a barrier to lake sturgeon movement. The shortest water route between receiver locations was calculated using the shortest path tool in the Spatial Analyst toolbar. For each sturgeon, the paths it traversed between receivers were summarized by season and for the entire time period (2008 - 2009). Due to the distance between receiver locations I was unable to characterize localized movement patterns. Thus, MDT was used to determine the minimum distance traveled around the reservoir (i.e., seasonally or for the entire time series) and not an attempt to summarize a continuous movement pattern. If during the time period being summarized a lake sturgeon made repeated trips between two of the same receivers that path was only counted once.

I used analysis of variance to examine the effect of gender (i.e., male, female and unknown) and season (i.e., spring pre-spawn, spring spawn, summer post-spawn, fall and winter) on MDT and site fidelity (PROC MIXED; SAS$^{©}$ Institute Inc., 2007). To conduct this analysis, I used detections that occurred from the fall of 2008 to summer 2009. During this time period, all lake sturgeon had been acoustically tagged for at least 4 months, which I assumed was a reasonable time for fish to resume normal behavior (e.g., movement).

Gonad maturation and spawning success is influenced by lake sturgeon spawning migration (McKeown 1984; Auer 1996). I used a two-way analysis of variance to determine the effect of maturity level (i.e., potentially reproductive or non-reproductive) and season on MDT and site fidelity (PROC MIXED; SAS$^{©}$ Institute Inc., 2007). Because reproductive status of female lake sturgeon was positively related to body size, and girth of post-vitellogenic females was significantly higher than that of non-reproductive stages (i.e., vitellogenic and pre-vitellogenic; see Chapter 2), I used weight and girth as a metric of maturity (i.e., potentially reproductive or non-reproductive) for all female lake sturgeon implanted with transmitters. Potentially reproductive females (n = 5) were defined as those females where weight (kg) was equal to or exceeded 2% of fork length (mm) and girth (mm) was equal to or exceeded 40% of fork length (mm). Non-reproductive females (n = 14) included all those with proportionally lower weight and girth in comparison to fork length. There was no significant difference in size characteristics of male lake sturgeon of differing stages, so males were not included in the analysis (see Chapter 2). To compare movement data between potentially reproductive and non-reproductive females, I used telemetry data from the fall 2008 - summer 2009, as previously described.

Habitat suitability for spawning adult lake sturgeon was characterized for the six main tributaries in the reservoir using the habitat suitability index (HSI) developed by Daugherty (2005). Water velocity and depth were recorded in each tributary in the summer of 2008 and the spring of 2009. Transects perpendicular to the current were recorded approximately every 150 - 200 m using a 1.5 MHz SonTek RiverCat Acoustic Doppler Profiler (ADP). Substrate samples were collected along every other transect using a petite ponar grab and characterized according to particle size. Gradient was determined using elevation data from Google Earth (Google © 2010). The habitat characteristics within each receiver’s range were summarized using water velocity and substrate data from habitat sampling conducted in the summer of 2008.

Results

Acoustic telemetry

Two hundred and forty-three lake sturgeon were collected in the spring of 2007-2009. Fish implanted with acoustic transmitters ranged from 780 to 1527 mm fork length (mean = 1149 mm), 329 to 659 mm girth (mean = 455 mm) and weighed 4.3 to 31.1 kg (mean = 13.5 kg; Table 3-1). Range testing confirmed that all receivers had a maximum detection range of at least 0.5 km. Complete detection efficiency (100%) covered an area from bank to bank in all but two receiver locations: Smuggler's Point, Larkin Island (Figure 3-1; Table 3-2). Forty-seven of the 60 (78%) lake sturgeon implanted with transmitters were detected by receivers in the reservoir. All 26 of the sturgeon collected and tagged in the main waters of the Namakan Reservoir were relocated by reservoir receivers. Twenty-one of the 34 lake sturgeon (62%) collected from the Namakan River were relocated on the reservoir receivers. The mean number of lake sturgeon detected at each receiver was 14.7 (range 0 - 35). The greatest numbers of lake sturgeon (n = 35) were detected at the mouth of the Namakan River (Figure 3-1; Table 3-2). Other receivers with a relatively high number of lake sturgeon detections included Namakan Narrows (n = 25), Smuggler's Point (n = 25), Blackstone Island (n = 20) and the Redhorse River (n = 20; Figure 3-1; Table 3-2). No lake sturgeon were detected at the Moose River receiver (Figure 3-1; Table 3-2).

Lake sturgeon moved throughout the entire reservoir using all five lakes and four of the six main tributaries, supporting earlier conclusions that lake sturgeon in the Namakan Reservoir complex constitute an internationally shared stock (D. McLeod personal communication, Fort Frances District, Fort Frances, ON). The highest MDT for the entire time series (May 2008 - October 2009) was 129.91 km. Females generally had a higher, mean MDT than males at 38.84 km versus 29.92 km respectively. The majority of lake sturgeon (83%, sexes combined) had a total MDT exceeding 20 km. There were only 8 fish that exhibited an MDT for the entire time series of less than 20 km or were only detected at one receiver.

The mean MDT of lake sturgeon (fall 2008 - summer 2009) did not differ significantly by gender (ANOVA; df = 2; F = 0.80; P = 0.45) or season (ANOVA; df = 4; F = 1.08; P = 0.37). All lake sturgeon generally traveled longer distances during the spring spawning period (mean = 10.7 km) and summer, post-spawning period (mean = 13.3 km) compared to other seasons (Table 3-3). The lowest MDT (sexes combined) occurred in the winter season with a mean of 5.3 km traveled (Table 3-3).

I used an ANOVA to determine the effect of season and gender on site fidelity of lake sturgeon (fall 2008 - summer 2009). Mean site fidelity varied significantly by season (ANOVA; df = 4, F = 5.52, P = 0.0004). Mean site fidelity was significantly higher during the winter season (mean = 17.8 d) compared to other seasons (range 1.0 to 7.3 days; Table 3-4). Mean site fidelity differed significantly by gender, and males generally had a higher site fidelity at 8.6 d than females at 6.9 d (ANOVA; df = 2, F =

3.18, P = 0.045; Table 3-4). Lake sturgeon of unknown gender had the lowest mean site fidelity at 2.5 d (Table 3-4).

I used a two-way ANOVA to examine the effects of female maturity (i.e., potentially reproductive versus non-reproductive) and season on MDT and site fidelity. Of the 19 females implanted with transmitters, five were classified as potentially reproductive and 14 were classified as non-reproductive (Table 3-5). The mean MDT of potentially reproductive females (21.0 km) was significantly higher than that of non-reproductive females at 8.7 km (Two-way ANOVA; df = 1, F = 13.11, P = 0.0007; Table 3-6). Potentially reproductive females had the highest mean MDT in the fall (38.8 km; Table 3-6). Mean MDT for potentially reproductive females was similar for spring pre-spawning and spawning periods at 21.0 km and 24.0 km respectively (Table 3-6). Difference in mean site fidelity between non-reproductive and potentially reproductive females were marginally significant (Two-way ANOVA; df = 1, F = 3.40, P = 0.071; Table 3-7). Non-reproductive females had a higher site fidelity during all seasons than potentially reproductive females, and site fidelity was highest during the winter for both classifications (Table 3-7).

Discussion

Migratory patterns of lake sturgeon have been well documented and are often linked to seasonal foraging and spawning requirements (McKeown 1984; Auer 1996; Bemis and Kynard 1997). The highest MDT observed in the Namakan Reservoir (130 km) was similar to what has been observed for other lake sturgeon populations, 180-280 km (Sandilands 1987; Auer 1999; Knights et al. 2002). The highest spawning migrations that have been recorded for lake sturgeon occur in areas that contain both lake and river habitat (Auer 1996). The tributaries of the Namakan Reservoir are currently unimpounded allowing lake sturgeon access to historic spawning grounds.

Increased movement (i.e., MDT) for lake sturgeon during the spawning and post-spawning seasons is consistent with findings from other studies and indicates a movement pattern to and from spawning grounds in the spring and summer (Rusak and Mosindy 1997; Auer 2004; McLeod and Debruyne 2009). Increased movement by female lake sturgeon in the fall (18.6 km), especially for potentially reproductive females (38.8 km) contrasts with information reported in other studies that lake sturgeon migrated only short distances to overwintering sites and that movements other than spawning migrations were not extensive (Scott and Crossman 1973; Threader and Brousseau 1986; Rusak and Mosindy 1997). The higher MDT of potentially reproductive females versus non-reproductive females in the Namakan Reservoir indicates the importance of migration to reproductive strategy as a way to optimize forage and spawning success (Auer 2004). Potentially reproductive females may travel greater distances in the fall to acquire enough energy during the final stages of gonad maturation and to find higher-quality overwintering habitat prior to the spawn. High fall MDTs may also be associated with a two-step migration pattern, where lake sturgeon initiate upstream movement in the fall and overwinter near the spawning site before resuming a spawning migration in spring (McLeod and Debruyne 2009). The two-step migration pattern is often seen in larger river systems and may enable lake sturgeon to use energy reserves for long migrations prior to the overwinter season when they will be depleted (Bemis and Kynard 1997; Bruch and Binkowski 2002).

Water temperature is the abiotic factor most associated with signaling spawning migrations (Rusak and Mosindy 1997; Bruch and Binkowski 2002; Auer 2004). Lake sturgeon typically begin upstream migrations at water temperature ranging from 5˚C to 10˚C (Rusak and Mosindy 1997; McKinley et al. 1998; Friday 2006). In Namakan Reservoir, lake sturgeon were detected moving upstream to potential spawning sites at water temperatures ranging from 5 to 8˚C, similar to findings on the Rainy River where lake sturgeon began upstream migrations at temperatures between 5 and 6˚C (Rusak and Mosindy 1997).

A wide range of spawning temperatures, 8.8 - 21.5˚C, has been reported for lake sturgeon populations (LaHaye et al. 1992; Bruch and Binkowski 2002). Differences in spawning temperatures may be related to the rate of warming and cooling of yearly water temperature (Bruch and Binkowski 2002). Most scientists also believe that female lake sturgeon are pre-disposed to spawn at certain temperatures (i.e., lower or mid-range and higher; Bruch and Binkowski 2002; Webb et al. 2001). Potentially reproductive females in Namakan Reservoir initiated migrations in either the spring pre-spawning or spawning seasons supporting the belief that female lake sturgeon are pre-disposed to spawn at certain temperatures. Those that initiated migrations during spring pre-spawning may be low range temperature spawners and those that initiated migrations within the optimum temperature range may be mid-range and higher temperature spawners. In a 16 year study of lake sturgeon spawning behavior on the Wolf River system, WI, Bruch and

Binkowski (2002) noted that fewer females initiated spawning at low and high temperature ranges and the majority spawned in the mid-range. In the Namakan Reservoir, lake sturgeon remained near potential spawning sites as temperatures ranged from 8 to 20˚C before dispersing back downstream into the reservoir. This temperature range is consistent with other studies and may reflect the optimum spawning temperature range for lake sturgeon in the reservoir.

Optimum lake sturgeon spawning habitat includes areas with a combination of fast-flowing water, medium grain substrate, and depths of 0.5 - 5 m (Auer 1996, 2004). In Namakan Reservoir, lake sturgeon were detected moving into four tributaries in the spring of 2008 and 2009: Loon River, Vermilion Gorge, Namakan River, Redhorse River (Figure 3-1, Table 3-2). However, reproductive lake sturgeon were only collected in three of these tributaries during the spring pre-spawning period of 2008 and 2009: Loon River, Vermilion Gorge, and Namakan River (Figure 3-3). Only non-reproductive lake sturgeon were collected near the mouth of the Redhorse River (Figure 3-4). No lake sturgeon were collected in the Ash or Moose rivers (Figure 3-3, Figure 3-4). The three rivers where reproductive lake sturgeon were collected generally have higher HSI values (Table 3-2). Each of these rivers has a natural barrier with a combination of relatively high bottom water velocity (1.7 m/s to > 5.5 m/s), depths between 1 and 5 m, and fine (silt, sand) to medium grain (gravel, cobble) substrates known to be characteristic of preferred lake sturgeon spawning habitat (Scott and Crossman 1973; LaHaye 1992; Chaisson et al. 1997; Rusak and Mosindy 1997; Auer 2004; Daugherty 2005). The Loon River generally had high HSI values; however, substrate suitability was determined to be zero. Thus, the total HSI for the Loon River was zero (Table 3-2). Due to limitations in our ability to sample substrate near potential spawning areas in the Loon River it is likely that the substrate HSI for the Loon River is higher than we estimated. The Namakan River contains several areas with the combination of preferred adult spawning habitat characteristics and may therefore have multiple spawning locations (McLeod and Debruyne 2009). Tributaries where no reproductive lake sturgeon were collected were dominated by fine grain substrates (clay, silt and sand), shallow water depths (1 to 3 m), and relatively low water velocities (< 1.6 m/s). Each of these rivers had an HSI of zero (Table 3-2).

Lake sturgeon use overwintering sites following spawning and foraging movement patterns (Auer 2004; Rusak and Mosindy 1997). Rusak and Mosindy (1997) found that lake sturgeon in the Rainy River and Lake of the Woods moved into overwintering sites in the fall as water temperatures ranged between 4 and 9˚C. Overwintering sites on Lake of the Woods were characterized by fine grain substrate and depths > 7 m (Rusak and Mosindy 1997). Mean, overwinter movement (November 1 - April 4) of lake sturgeon on Lake of the Woods was 5 - 6 km (Rusak and Mosindy 1997). Overwinter movement and habitat use by lake sturgeon in the Namakan Reservoir (5.3 km) was similar to that of the Lake of the Woods lake sturgeon. Fish moved into overwintering sites in the fall as water temperatures reached 8 - 9˚C. Overwintering sites were dominated by fine grain substrates and had depths ranging from 1 - 40 m. The low mean MDT (5.3 km) and high mean site fidelity (17.8 d) of both genders during the winter season reflect a significant decrease in movement similar to that seen on Lake of the Woods and the Rainy River (Rusak and Mosindy 1997).

Acoustic telemetry allowed me to determine areas important for seasonal use throughout the reservoir and to observe temperature related cues to movement patterns. By linking movement data with information on lake sturgeon gender and reproductive status, I was able to identify three tributaries as potential spawning areas. Using both movement data and reproductive status, I identified potentially reproductive females as having relatively extensive fall migrations which may be important for optimizing energy acquisition prior to spawning the following spring. Lake sturgeon reproductive structure and seasonal movement patterns provide important information to managers and can be useful for lake sturgeon conservation and restoration efforts.

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Table 3-1. Summary of lake sturgeon collected and implanted with acoustic transmitters in Namakan Reservoir and the Namakan River in the spring of 2007 and 2008. Also included are the mean and range of fork length and weight of tagged individuals.

Capture Location	2007 (n)	2008 (n)	Total (n)	Mean fork length (mm)	Mean weight (kg)
Namakan Reservoir	0	26	26	1203 (962 - 1428)	16.1 (8.3 - 31.1)
Namakan River	30	4	34	1095 (780 - 1527)	11.5 (4.3 - 30.8)

Table 3-2. The total number of lake sturgeon detected at each receiver location in the Namakan Reservoir from May 15, 2008 to Oct. 23, 2009. Also included are the habitat characteristics within the receiver range (~ 0.5 km radius around each receiver). Values in parentheses represent adult spawning habitat suitability index (HSI) values based on scoring criteria provided in Daugherty (2005). The combined HSI for the six main tributaries in Namakan Reservoir are given in the last column.

Receiver	Location number (see Figure 3-1)	Total lake sturgeon detected	Dominant substrate	Depth range (m)	Summer water velocity range (m/s)	Total HSI
Loon River	1	3	sand (0)	1-2 (0.93)	0.50 - 1.0 (1)	0
Little Vermilion Narrows	2	12	silt	1 - 7	0.5 - 1.5	
Vermilion Gorge	3	8	sand (0.43)	1-4 (0.69)	0.75 - 1.5 (1)	0.29
King William's Narrows	4	16	sand	1 - 5	1.0 - 1.5	
Grassy Bay	5	16	silt	1 - 5	1.0 - 1.75	
Redhorse River bay	6	20	silt (0)	1-5 (1)	1.0 - 1.75 (1)	0
Namakan Narrows	7	25	sand	1 - 10	1.0 - 2.0	
Namakan River mouth	8	35	silt (0.33)	1-8 (0.27)	0.5 - 2.0 (1)	0.087
Smuggler's Point	9	25	--	1 - 35	1.0 - 2.0	
Blackstone Island	10	20	bedrock/ boulder	1 - 3	1.0 - 1.75	
Squaw Narrows	11	11	--	1 - 25	1.0 - 2.0	
Squirrel Narrows	12	3	bedrock/ boulder	1 - 10		
Moose River	13	0	silt (0)	1-2 (1)	0.75 - 1.5 (1)	0
Kabetogama Narrows	14	16	silt	1 - 15	1.0 - 2.0	
Larkin Island	15	11	--	1 - 15	--	
Ash River [a]	--	--	silt (0.09)	1-4 (0.93)	0.5 – 1.5 (1)	0

[a] No receiver was placed in the Ash River. Lake sturgeon spawning habitat suitability was estimated to be zero due to low gradient conditions (Daugherty 2005).

Table 3-3. The mean and range of MDT (km) for lake sturgeon in the Namakan Reservoir from the fall 2008 - summer 2009 summarized by gender and season. For ANOVA comparing mean MDT by gender (last column) and season (bottom row) values with the same letter are not significantly different (P > 0.05).

	Mean MDT (km)			
Season	Female (n = 19)	Male (n = 9)	Unknown (n = 17)	Sexes combined (n = 45)
Spring pre-spawn	10.5 (0.0-34.3)	5.6 (0.0-24.17)	7.9 (0.0-14.24)	8.0 (0.0-34.3)a
Spring spawn	11.1 (0.0-44.51)	12.4 (0.0-31.64)	8.5 (0.0-30.85)	10.7 (0.0-44.51)a
Summer post-spawn	13.4 (0.0-34.3)	5.6 (0.0-24.23)	20.6 (0.0-56.03)	13.3 (0.0-56.03)a
Fall	18.6 (0.0-52.9)	7.8 (0.0-17.79)	2.73 (0.0-10.65)	9.7 (0.0-52.93)a
Winter	3.6 (0.0-16.71)	6.38 (NA)	5.8 (0.0-9.25)	5.3 (0.0-16.71)a
Seasons combined	11.4 (0.0-44.51)a	7.6 (0.0-31.64)a	9.1 (0.0-56.03)a	

Table 3-4. The mean and range of site fidelity (days) for lake sturgeon in the Namakan Reservoir from the fall 2008 - summer 2009 summarized by gender and season. For ANOVA comparing mean site fidelity by gender (last column) and season (bottom row) values with the same letter are not significantly different (P > 0.05).

	Mean site fidelity (days)			
Season	Female (n = 19)	Male (n = 9)	Unknown (n = 17)	Sexes combined (n = 45)
Spring pre-spawn	2.2 (0.02-11.1)	0.35 (0.02-0.8)	2.0 (0.06-5.3)	1.5 (0.02-11.1)a
Spring spawn	1.6 (0.002-9.3)	0.9 (0.04-3.9)	0.6 (0.002-2.8)	1.0 (0.002-9.3)a
Summer post-spawn	3.8 (0.08-20.4)	13.0 (0.04-45.8)	5.0 (0.002-42.6)	7.3 (0.002-45.8)b
Fall	3.5 (0.4-18.3)	0.7 (0.06-1.8)	2.8 (0.02-16.9)	2.3 (0.02-18.3)a
Winter	23.4 (0.02-74.4)	28.2 (NA)	1.9 (0.01-5.4)	17.8 (0.01-74.4)c
Seasons combined	6.9 (0.002-74.4)a	8.6 (0.02-45.8)b	2.5 (0.002-42.6)c	

Table 3-5. Mean fork length (mm), weight (kg) girth (mm) and age (years) of potentially reproductive and non-reproductive female lake sturgeon implanted with acoustic transmitters from the Namakan Reservoir. Values in parentheses represent the range.

	n	Mean fork length (mm)	Mean weight (kg)	Mean girth (mm)	Mean age (years)
Non-reproductive	14	1189 (1022-1,378)	14.6 (8.3-19.4)	479 (388-606)	45 (32-59)
Potentially reproductive	5	1416 (1308-1,494)	26.5 (21.8-31.1)	604 (573-658)	47 (32-67)

Table 3-6. Mean, minimum distance traveled (MDT) for female lake sturgeon summarized by stage of gonadal maturity and season. For two-way ANOVA values with the same letter are not significantly different (P > 0.05). Values in parentheses represent the range.

	Mean MDT (km)	
	Non-reproductive (n = 14)	Potentially reproductive (n = 5)
Spring pre-spawn	6.3 (0.0 - 20.3)	21.0 (0.0 - 34.3)
Spring spawn	7.3 (0.0 - 20.3)	24.0 (6.4 - 44.5)
Summer post-spawn	12.3 (0.0 - 32.7)	18.2 (6.4 - 34.3)
Fall	13.6 (0.0 - 34.3)	38.8 (24.7 - 52.93)
Winter	3.8 (0.0 - 16.71)	3.2 (0.0 - 6.38)
Seasons combined	8.7 (0.0 - 34.3) a	21.0 (0.0 - 52.93) b

Table 3-7. Mean site fidelity of female lake sturgeon summarized by stage of gonadal maturity and season. For two-way ANOVA values with the same letter are not significantly different (P > 0.05). Range is given in parentheses.

	Mean Site Fidelity (days)	
	Non-reproductive (n = 14)	Potentially reproductive (n = 5)
Spring pre-spawn	2.9 (0.02 - 11.1)	0.6 (0.05 - 2.2)
Spring spawn	1.7 0.002 - 9.3)	1.1 (0.9 - 1.5)
Summer post-spawn	4.0 (0.08 - 20.4)	2.6 (0.2 - 4.4)
Fall	4.1 (0.4 - 18.3)	1.4 (NA)
Winter	30.1 (0.01 - 74.4)	6.7 (0.02 - 13.4)
Seasons combined	8.6 (0.002 - 74.4)a	2.5 (0.05 - 13.4)a

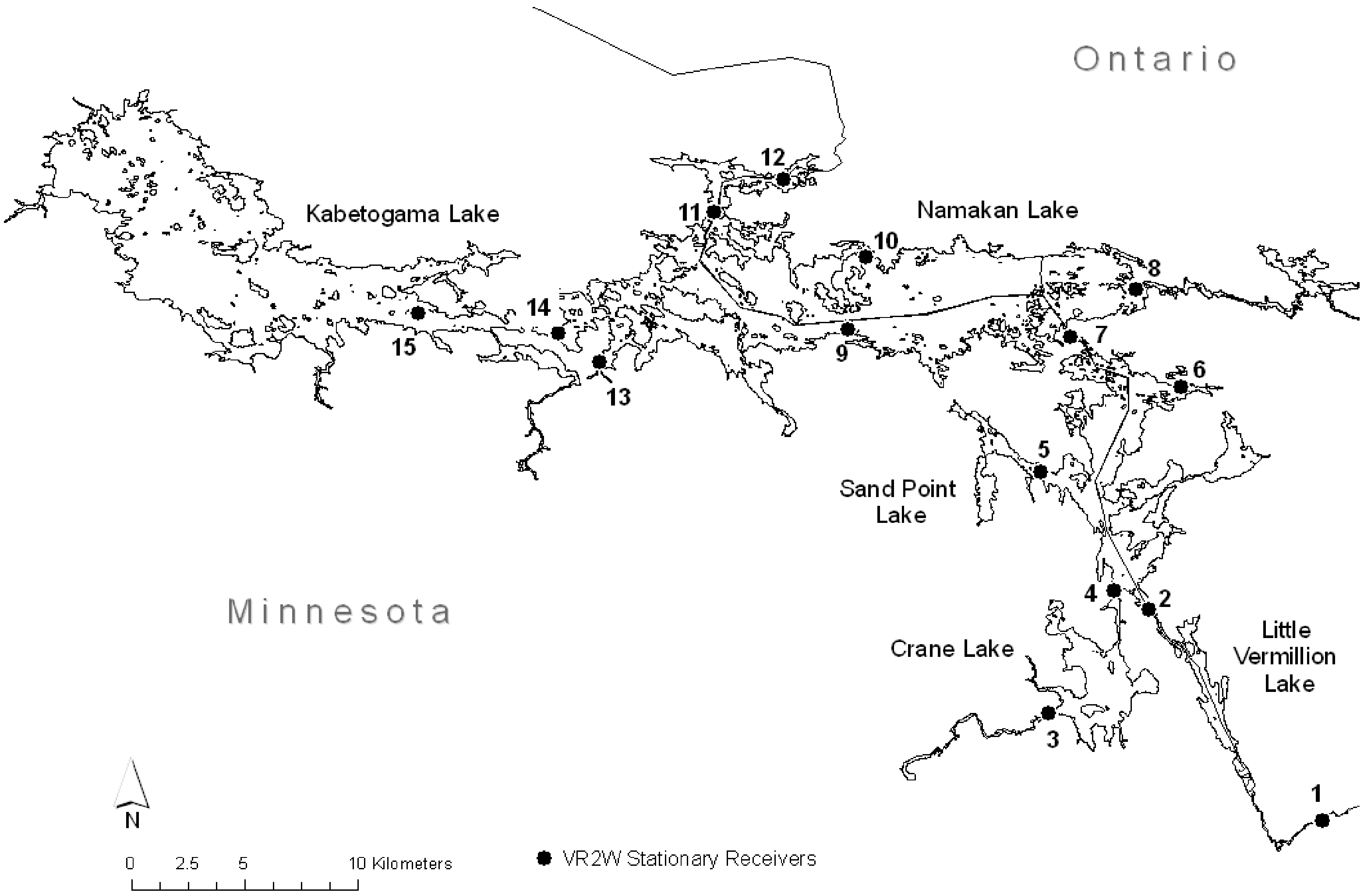

Figure 3-1. Map of the Namakan Reservoir including the 15 stationary locations of Vemco VR2W receivers.

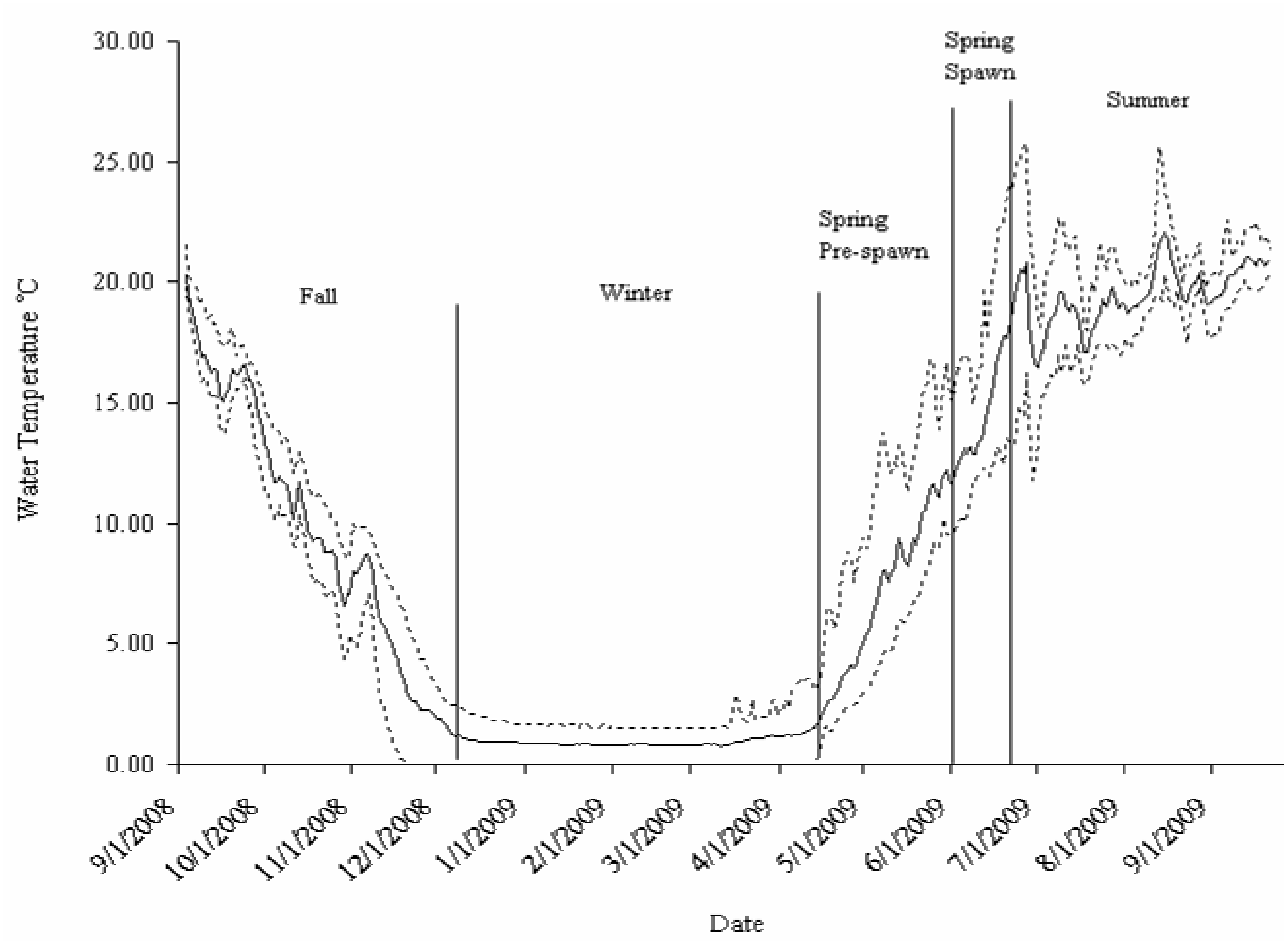

Figure 3-2. Mean, minimum and maximum reservoir water temperature in degrees Celsius recorded from HOBO temperature loggers attached to VR2W receivers 2008 - 2009.

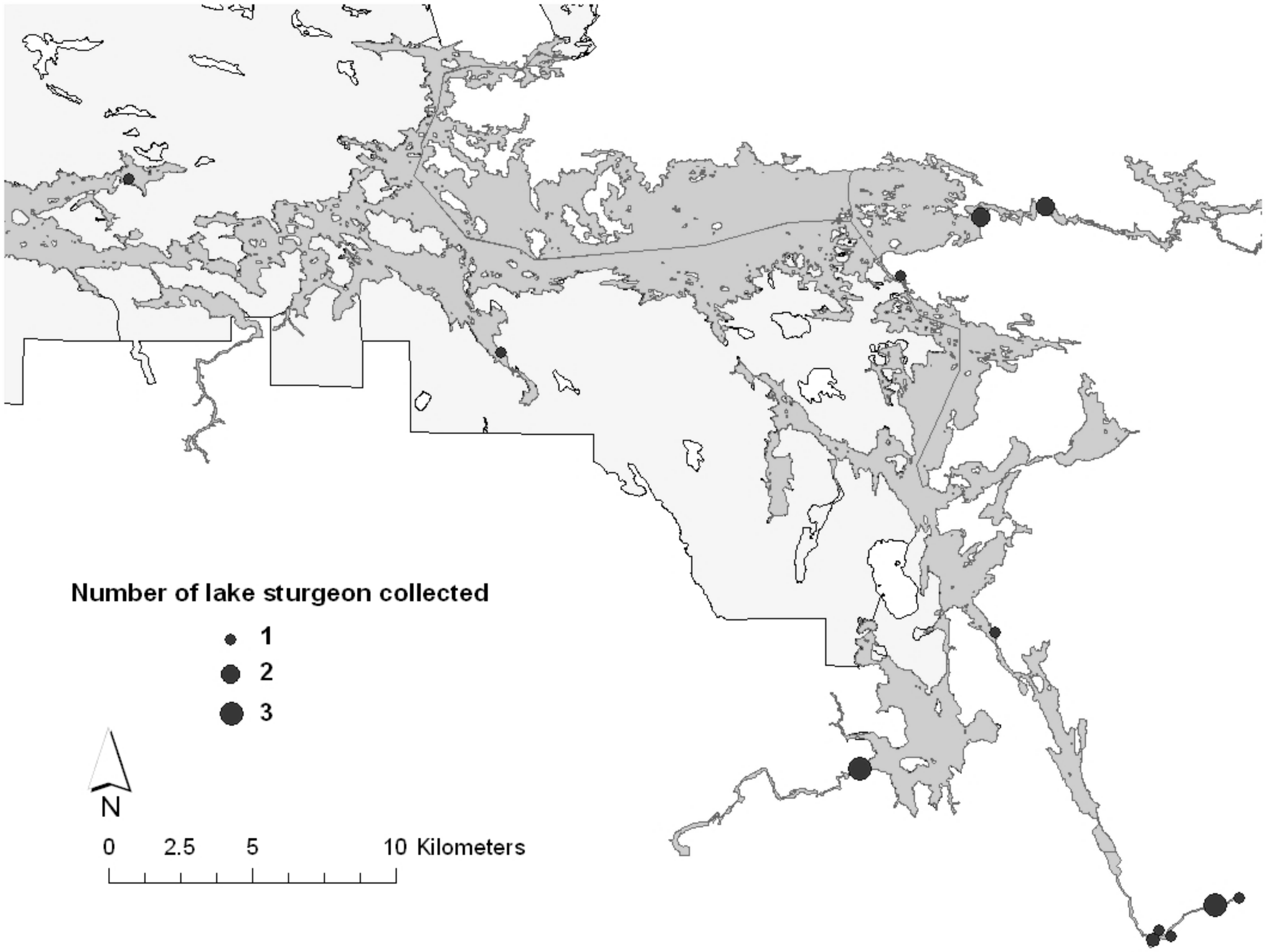

Figure 3-3. Map of the gillnet capture locations of reproductive lake sturgeon collected in the spring pre-spawn season of 2008 and 2009.

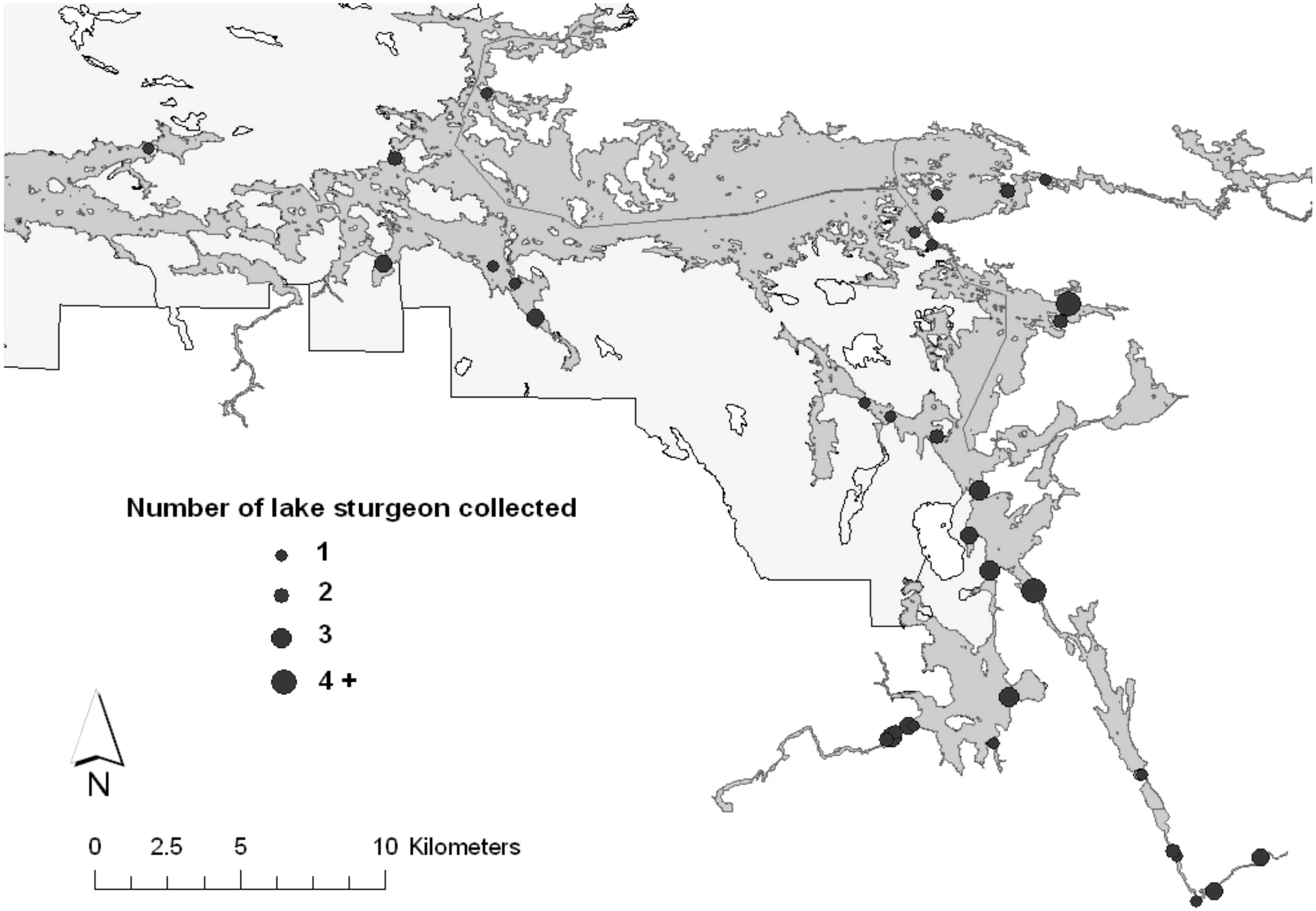

Figure 3-4. Map of the gillnet capture locations of non-reproductive lake sturgeon collected in the spring pre-spawn season of 2008 and 2009.

CHAPTER 4

MANAGEMENT IMPLICATIONS

Population declines of lake sturgeon have resulted in their protected status as a species of special concern in the state of Minnesota and threatened in the province of Ontario (McLeod 2008; McLeod and Martin 2010). Water bodies that lie along the Minnesota-Ontario border are home to historic populations of lake sturgeon. Research has been conducted on the lake sturgeon populations of Rainy Lake, the lower Seine River in Ontario, and Rainy River / Lake of the Woods (Mosindy and Rusak 1991; McLeod 1999; Adams et al. 2006). However, little research has been conducted on the lake sturgeon population of the Namakan Reservoir, which has experienced declines in abundance similar to those seen across North America. The assessment of the lake sturgeon in Namakan Reservoir, including quantification of age, growth, mortality, and reproductive structure, will provide managers with the information necessary to gauge the recovery of the population. In addition, seasonal distribution information will help identify habitat important for spawning and other life stages of lake sturgeon in the reservoir.

The population assessment of lake sturgeon in the Namakan Reservoir revealed low total annual mortality of adults (4.8%), relatively consistent recruitment, a wide range of year-classes, and a size distribution similar to that observed in other North American populations. The Namakan Reservoir population meets several guidelines for a restored lake sturgeon population as described by the Great Lakes Fishery Trust (Holey et al. 2000). According to the guidelines, a restored population should occupy 50% of its historic spawning grounds, have at least 70 year-classes in the population, a high percentage of older fish, females up to age 70, and males up to age 40. To date the tributaries in the Namakan Reservoir are unimpounded allowing lake sturgeon access to historic spawning grounds and potentially 100% of historic spawning habitat, although the definition of historic habitat varies depending on the time frame in question. The lake sturgeon sampled and aged from the Namakan Reservoir represented 61 year-classes with 76% older than 30 years of age. The oldest female determined by plasma sex steroid concentrations was 86 years and 2 other females were older than 70. Of the 39 males determined by plasma sex steroid concentrations 16 were older than 40 years of age (range 40 - 66 years of age).

Several restoration guidelines exist to assess younger life stages of lake sturgeon as well as spawning success. These include, determination of whether or not a population is self-reproducing or self-sustaining, and determining if recruitment is successful and occurring on an annual basis. Particular attention is often placed on whether lake sturgeon between zero to five years of age are recruiting to the population. It is unclear whether the lake sturgeon population in Namakan Reservoir would meet these guidelines without further sampling including an evaluation of egg, larvae and juvenile lake sturgeon. Sampling of younger life stages would enable managers to determine whether spawning and recruitment in recent years have been successful. It would also provide a means of determining whether or not the lake sturgeon in the Namakan Reservoir constitute a self-sustaining population.

The use of plasma sex steroid concentrations (testosterone and estradiol-17β) allowed us to differentiate both sex and stage of sampled lake sturgeon in a relatively non-invasive manner. Using this method, I identified three tributaries as containing potential spawning sites (i.e., Namakan River, Loon River, Vermilion Gorge) as well as other areas of the reservoir where non-reproductive lake sturgeon congregate (i.e., Redhorse bay area).

The use of habitat suitability index values does not appear to be the best way to characterize potential spawning tributaries. Total HSI is calculated as the product of all suitability values. Therefore any zero value in any category will result in a total HSI of zero. Due to our inability to efficiently sample substrate especially in fast moving water near potential spawning sites it is likely that all our estimates of substrate HSI are low. To obtain a more accurate index of substrate suitability more substrate samples needed to be taken. In particular, more samples should have been taken near areas of suitable depth and water velocity for lake sturgeon spawning, but due to the nature of the water flow in these areas sampling was difficult. Substrate samples collected along every transect and in at least three locations (i.e., mid-channel, left bank and right bank) along every transect may have provided a closer estimate of substrate suitability.

There was evidence of annual and periodic spawning strategies being utilized by male lake sturgeon. However, I was unable to determine the spawning periodicity of female lake sturgeon due to a longer periodic spawning cycle. If lake sturgeon sampling continues the use of plasma sex steroid concentrations would help to further differentiate potential spawning areas and assess the spawning periodicity of female lake sturgeon in the reservoir. It may also help to determine if there is a difference in the relative importance of spawning tributaries based on the ratio of reproductive males and females and the total number of reproductive fish at each site. Differences in the choice of overwintering habitat by female lake sturgeon may reflect differences in lake sturgeon reproductive strategies. Long fall migrations may indicate the initiation of a two-step spawning migration pattern. Data from the Ontario Ministry of Natural Resources indicate that a number of lake sturgeon overwinter in the Namakan River (i.e., Little Eva Lake, Bill Lake, and Three Mile Lake; McLeod and Debruyne 2009). A comparison of the reproductive status of lake sturgeon that overwinter in the Namakan River with those that overwinter in the reservoir may reveal important information to managers about lake sturgeon spawning strategies and the importance of the Namakan River to lake sturgeon reproduction.

The passive acoustic telemetry array used to monitor lake sturgeon movements was useful for determining migration patterns and seasonal habitat use. I found that lake sturgeon in the reservoir used seasonal habitat and temperature cues similar to what has been reported in other studies. I observed increased distances traveled during the spring spawning and summer post-spawning periods. However, while the passive telemetry array was useful for observing long range movement patterns it was not adequate for monitoring localized movement or movement rates. Continued monitoring of the movement patterns of lake sturgeon implanted with acoustic transmitters would be beneficial, but if the goal is to monitor localized movement (i.e., within potential spawning tributaries), diel movement patterns, or determine movement rates it would be helpful for managers to consider concentrating receivers in the areas of interest and potentially in a tighter overlapping array.

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APPENDIX A

Habitat data collection

Habitat variables in the Namakan Reservoir were measured in the summer of 2008 and spring of 2009. Information on water depth and vertical water velocity profiles were collected using a boat mounted 1.5 MHz SonTek RiverCat Acoustic Doppler Profiler. Water velocity profiles were recorded approximately every 150 m from bank to bank, perpendicular to the current. Water velocity profiles were extracted from the RiverSurveyor Software (© SonTek/YSI Inc., San Diego, CA). Substrate samples were collected along every other transect using a petite ponar grab and characterized according to particle size (Wentworth 1922). Spatially explicit maps of substrate and water depth were generated in ArcMap 9.3 (© ArcGIS ESRI Inc., Redlands, CA) using the ordinary kriging method in the Geostatistical Analysis Wizard. Bathymetry contour shapefiles were obtained from The DNR Data Deli website of the Minnesota Department of Natural Resources (http://deli.dnr.state.mn.us).

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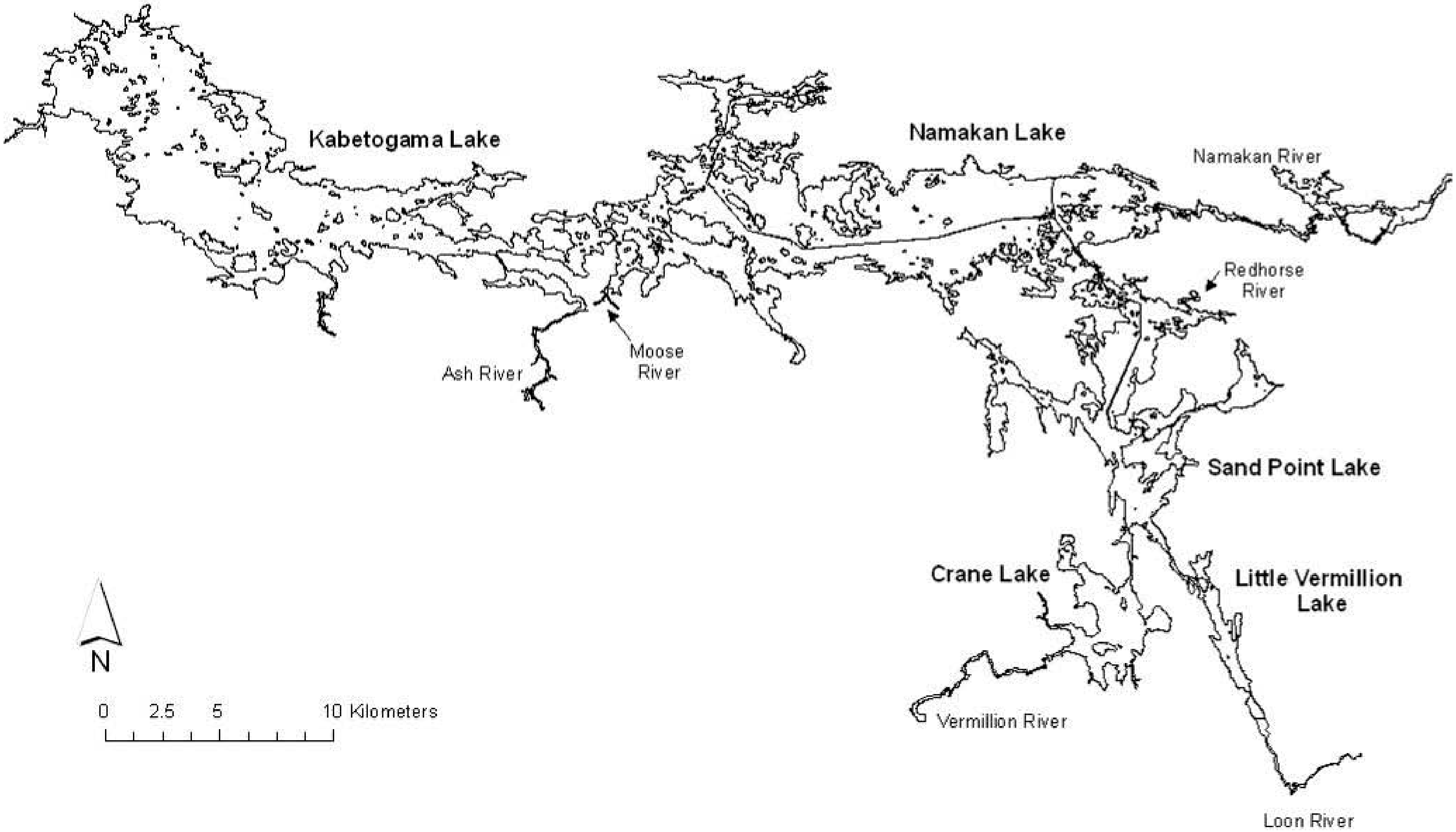
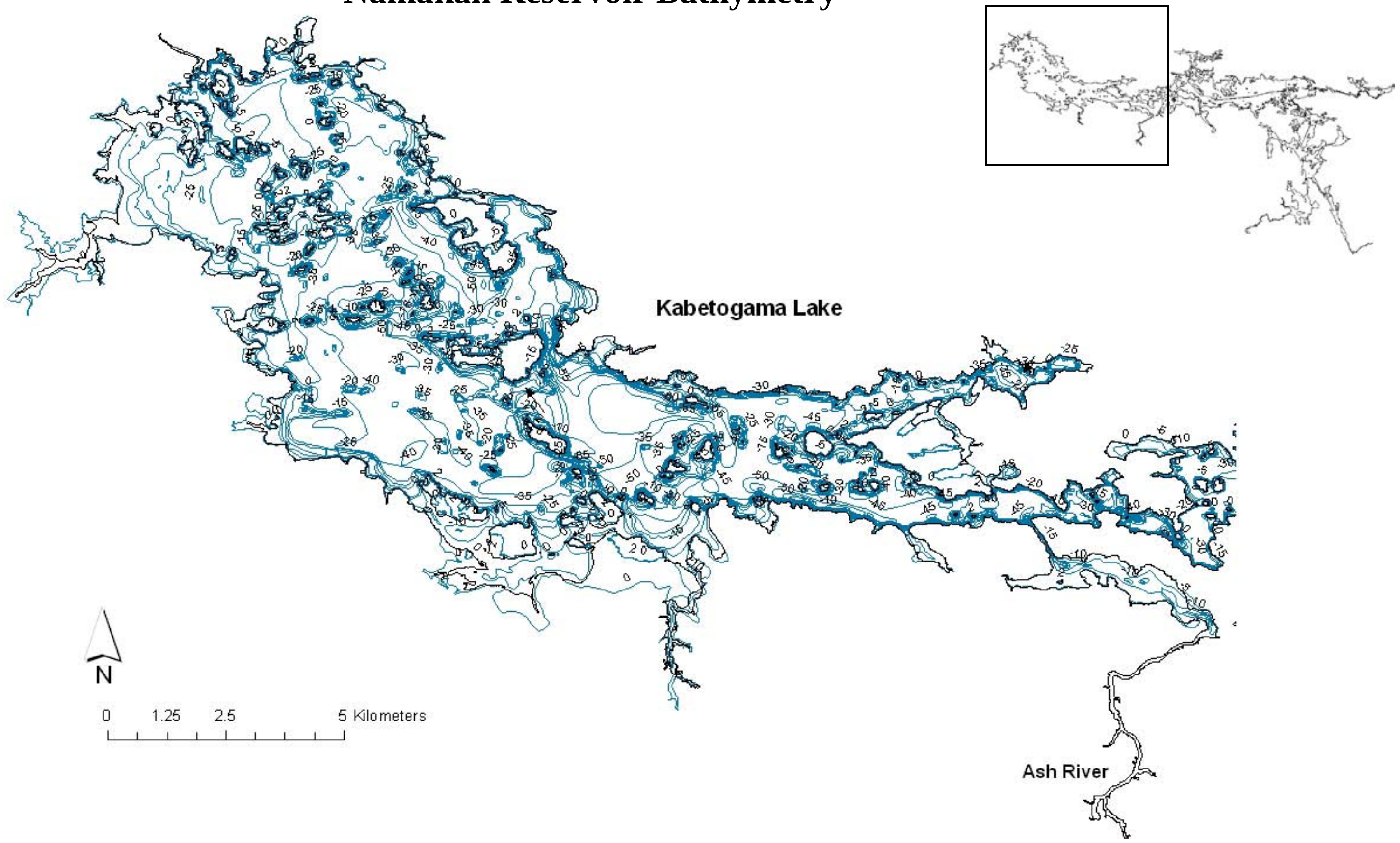
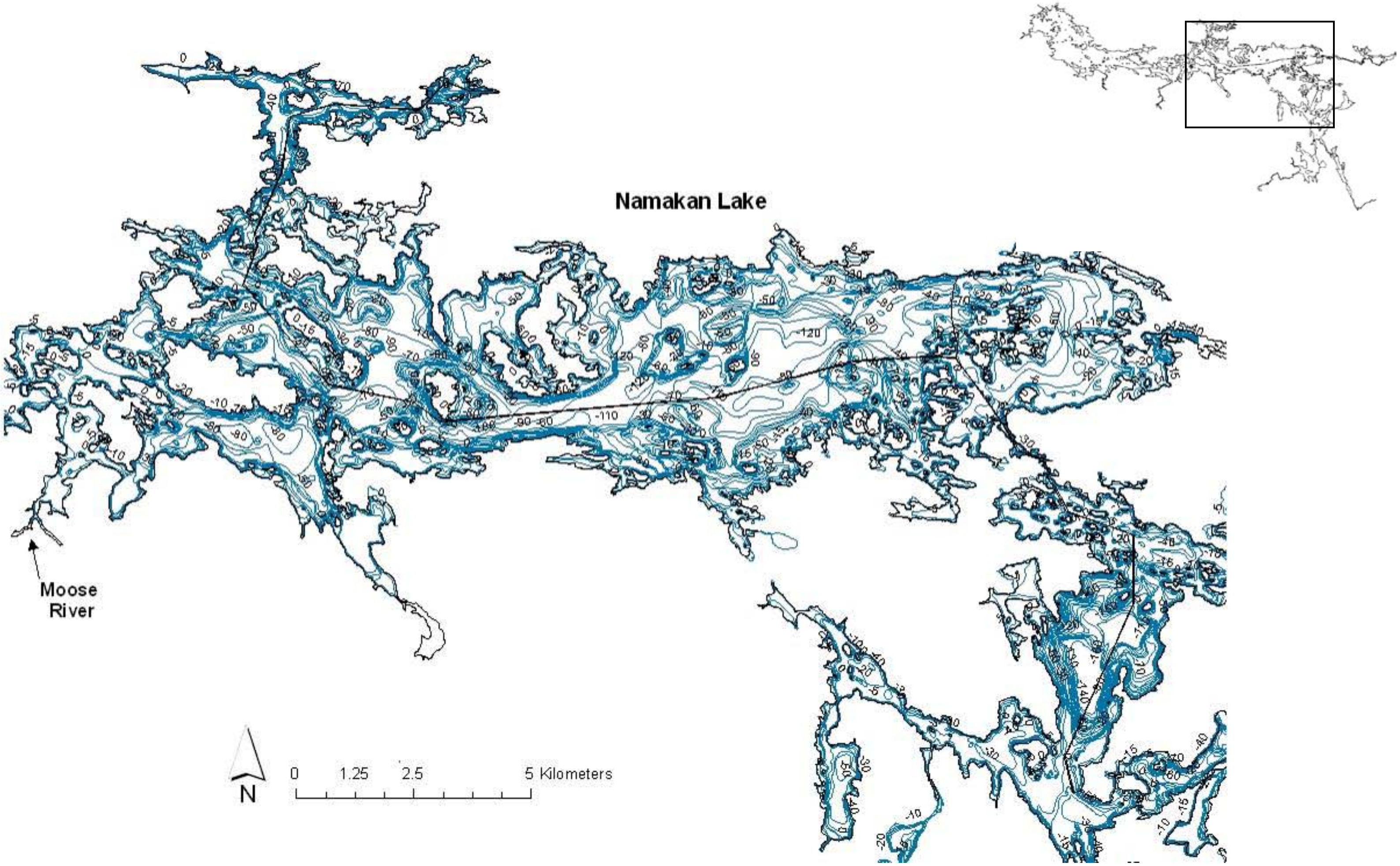


Appendix A-1. Map of the Namakan Reservoir including U.S. and Canadian waters.

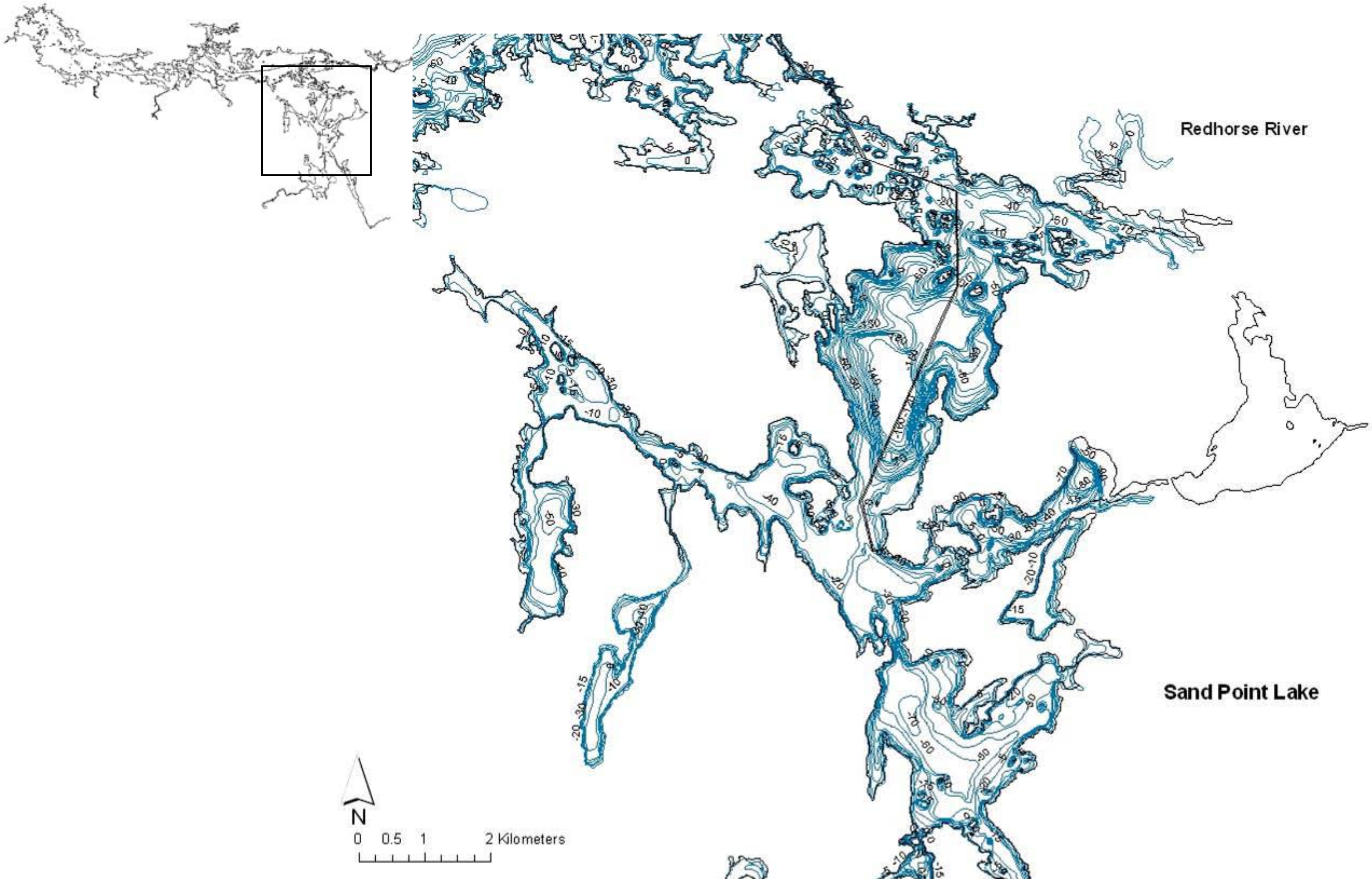
Namakan Reservoir Bathymetry



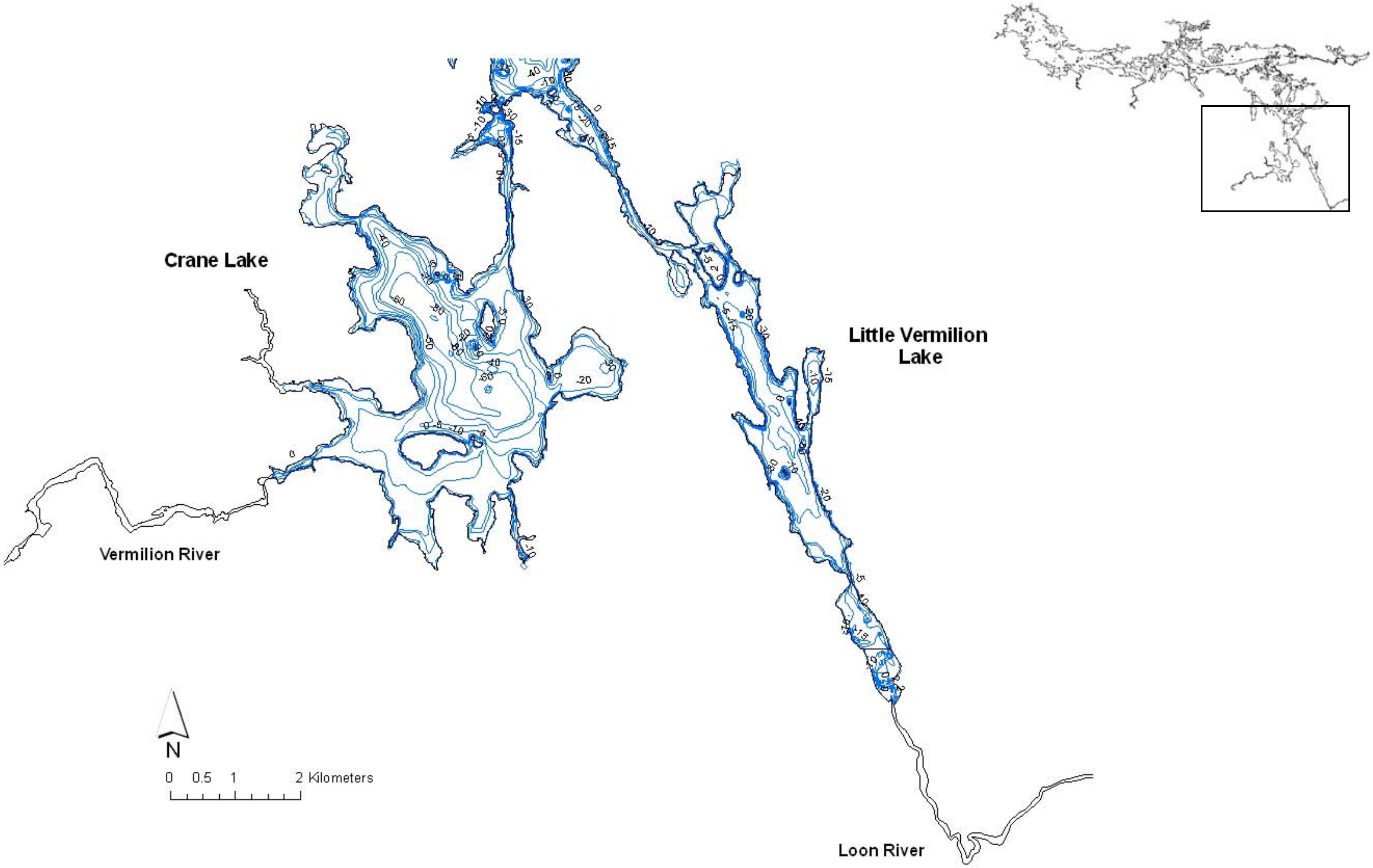
Appendix A-2. Kabetogama Lake bathymetry (shapefile Minnesota Department of Natural Resources (http://deli.dnr.state.mn.us).



Appendix A-3. Namakan Lake bathymetry (shapefile Minnesota Department of Natural Resources (http://deli.dnr.state.mn.us).

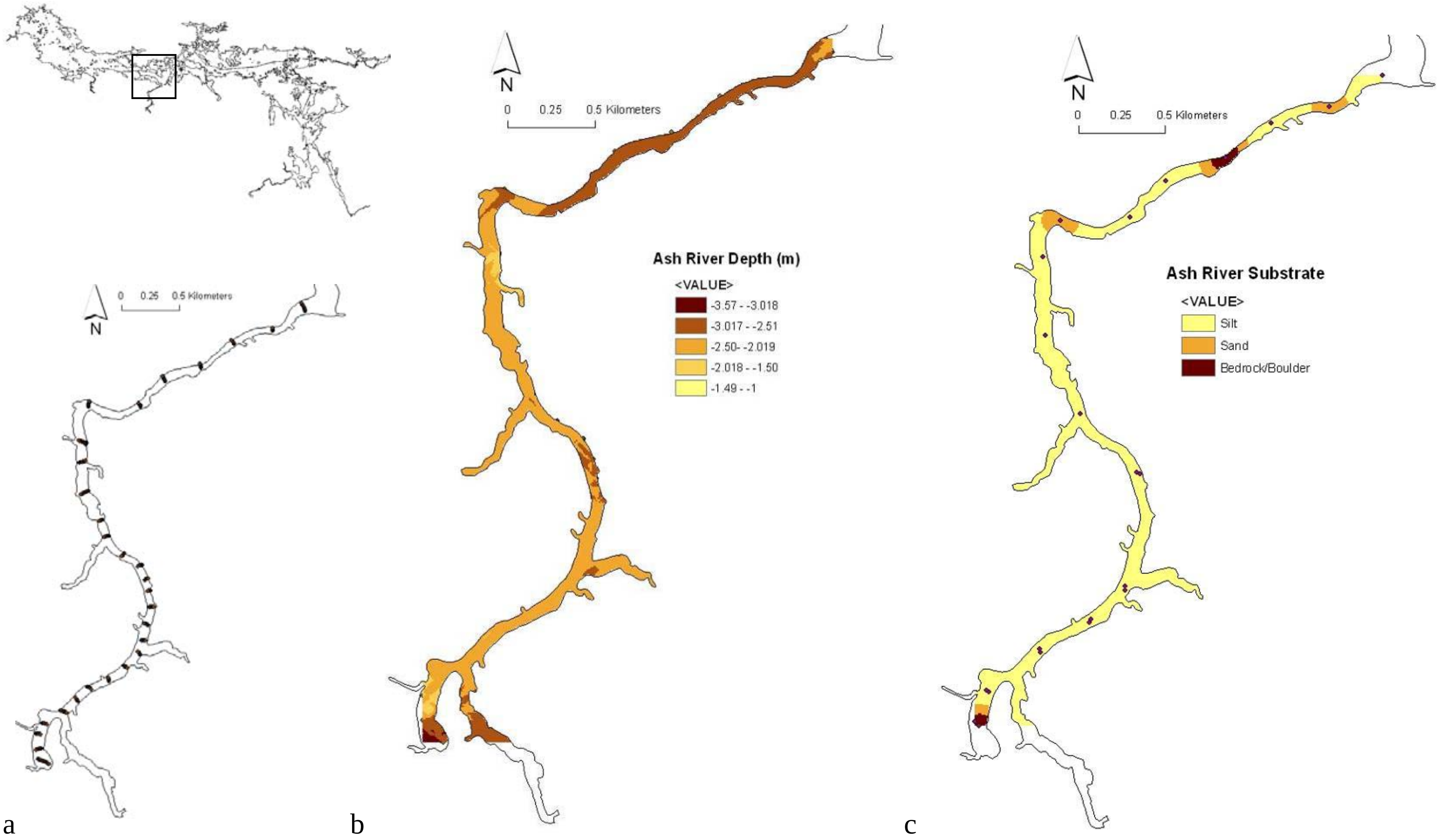


Appendix A-4. Sand Point Lake bathymetry (shapefile Minnesota Department of Natural Resources (http://deli.dnr.state.mn.us).



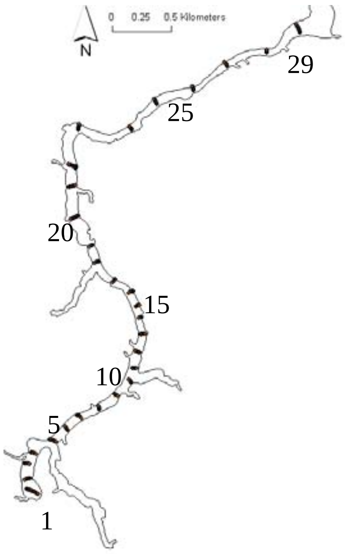
Appendix A-5. Crane Lake and Little Vermilion Lake bathymetry (shapefile Minnesota Department of Natural Resources (http://deli.dnr.state.mn.us).

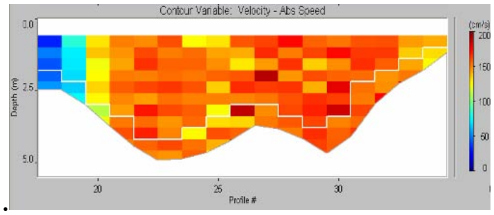
Ash River



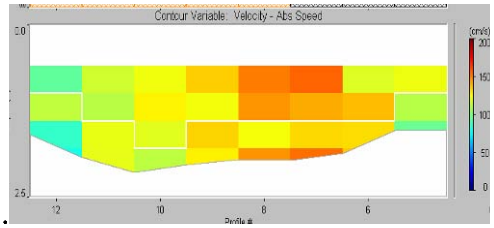
Appendix A-6. a) Spring 2009 ADP transects; b) depth (m) map interpolated from spring 2009 ADP transect points; c) interpolated substrate map including ponar grab collection points in the Ash River, Namakan Reservoir.

Ash River Water Velocity Spring 2009





1.



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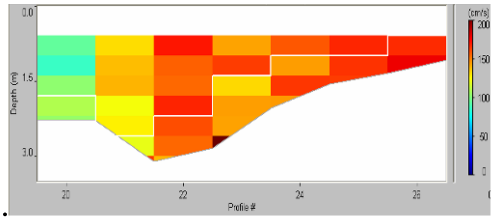

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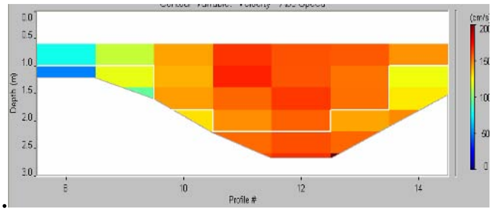
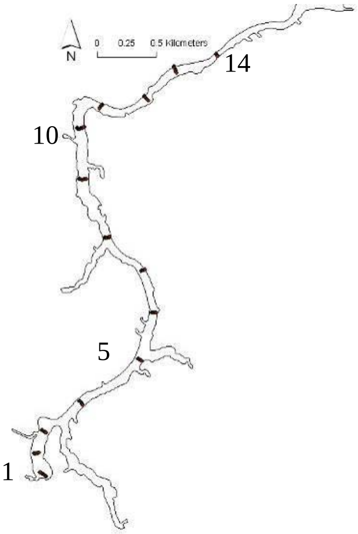
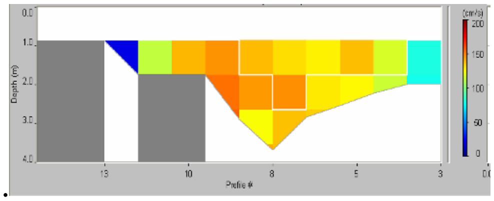


4.

Ash River Water Velocity Summer 2008





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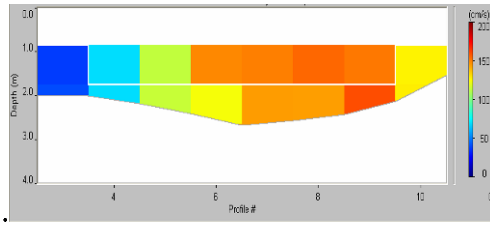

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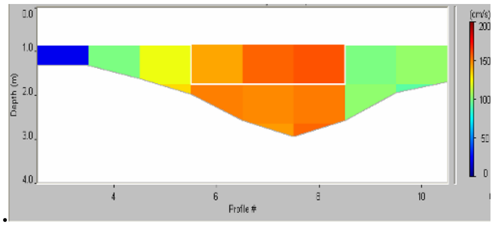

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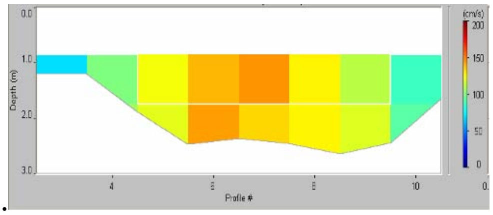

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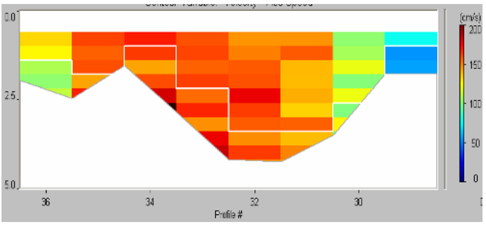
Ash River Water Velocity
Spring 2009 (cont.)



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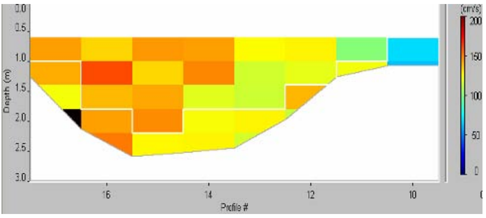

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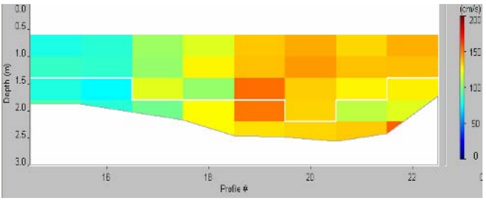

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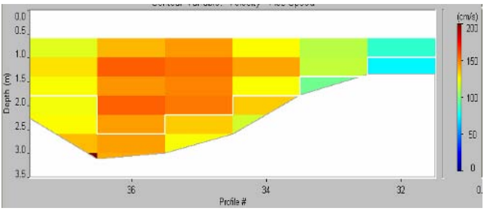

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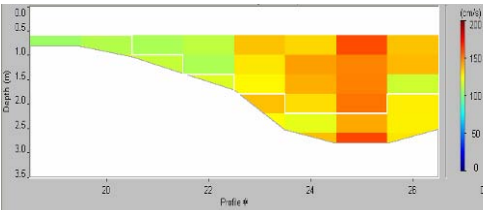

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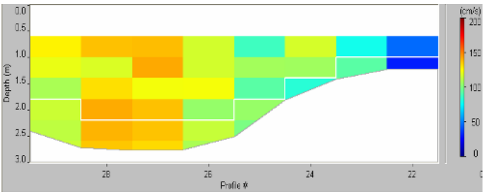

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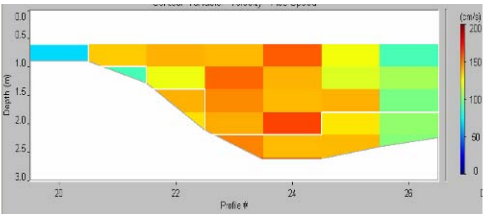

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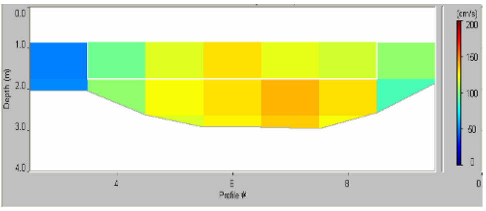
Ash River Water Velocity
Summer 2008 (cont.)



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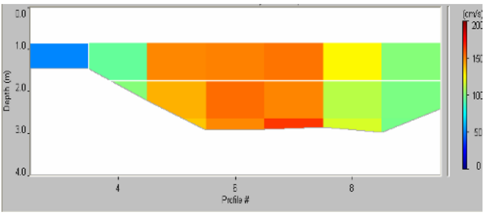

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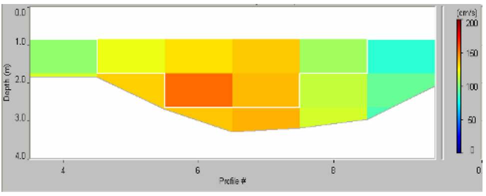

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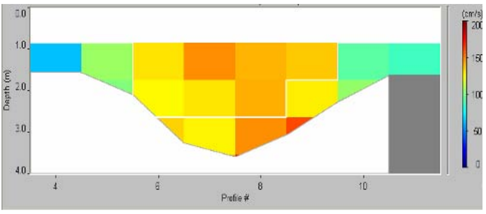

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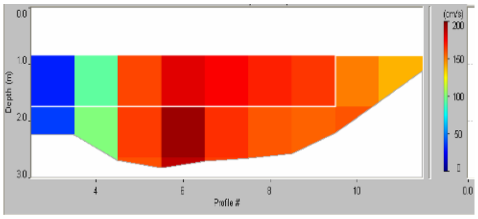

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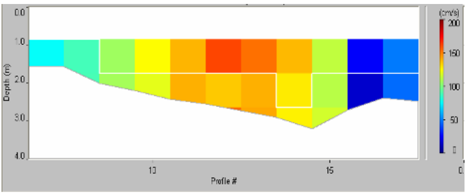

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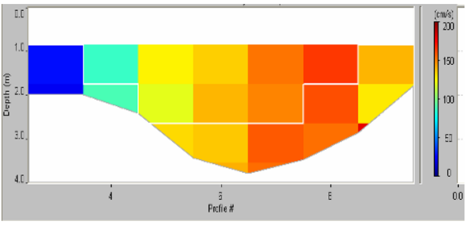

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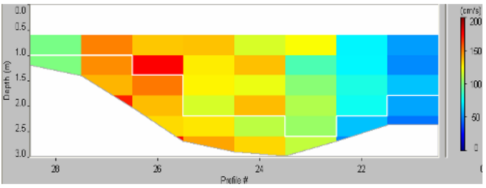
Ash River Water Velocity Spring 2009 (cont.)



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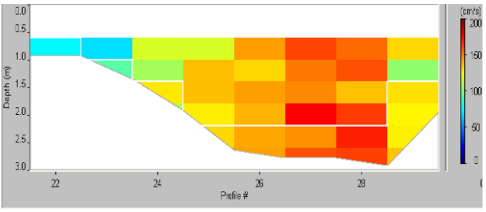

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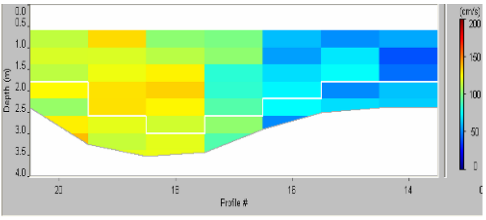

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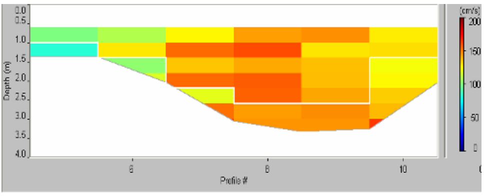

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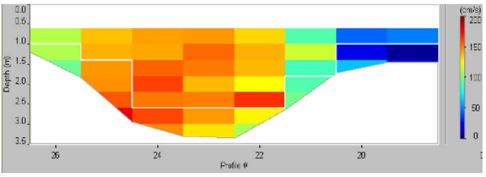

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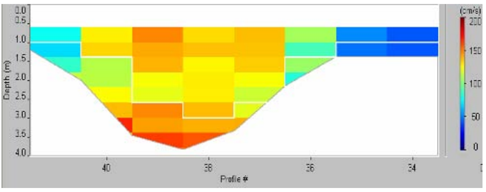

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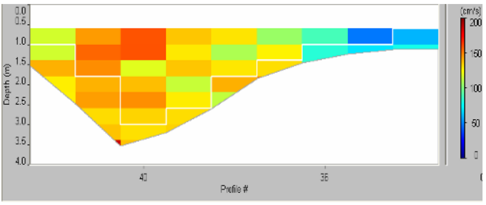

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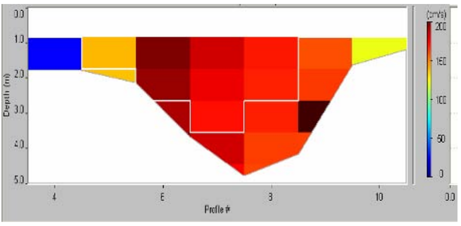
Ash River Water Velocity Summer 2008 (cont.)



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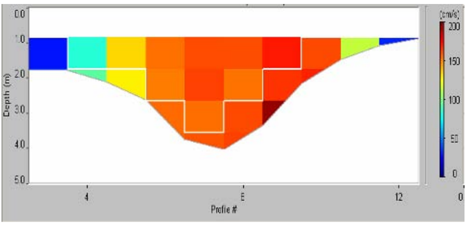

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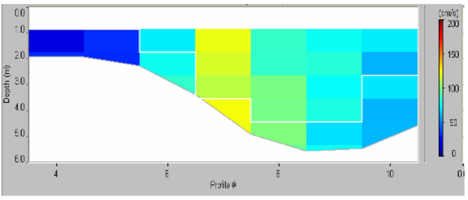

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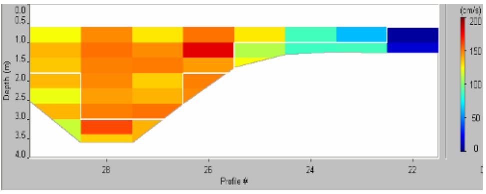
Ash River Water Velocity
Spring 2009 (cont.)



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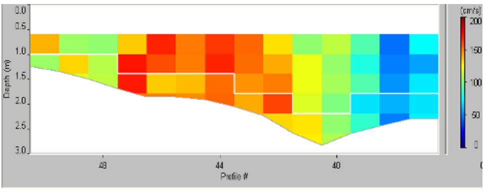

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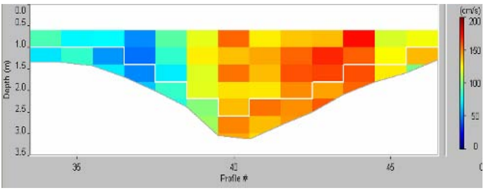

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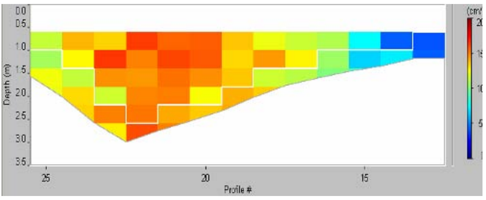

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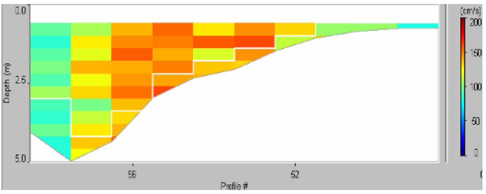

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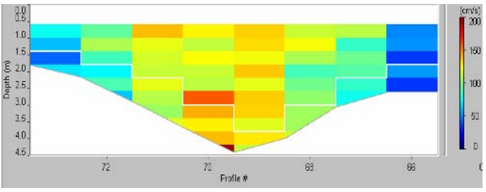

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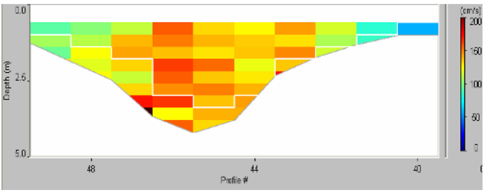
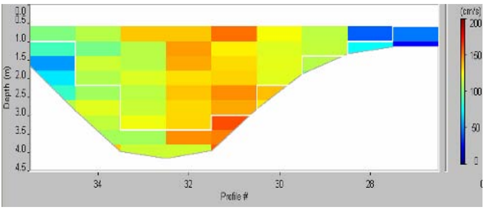


25.

Ash River Water Velocity
Spring 2009 (cont.)

26.



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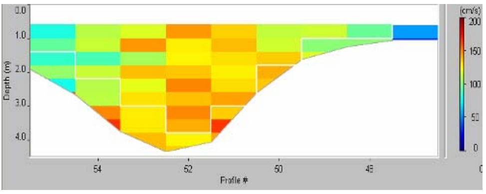

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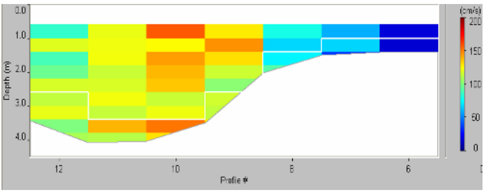

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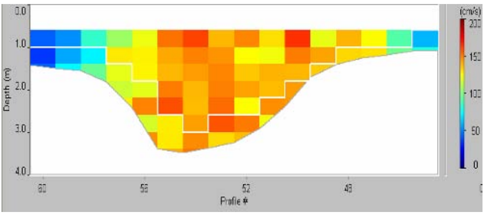
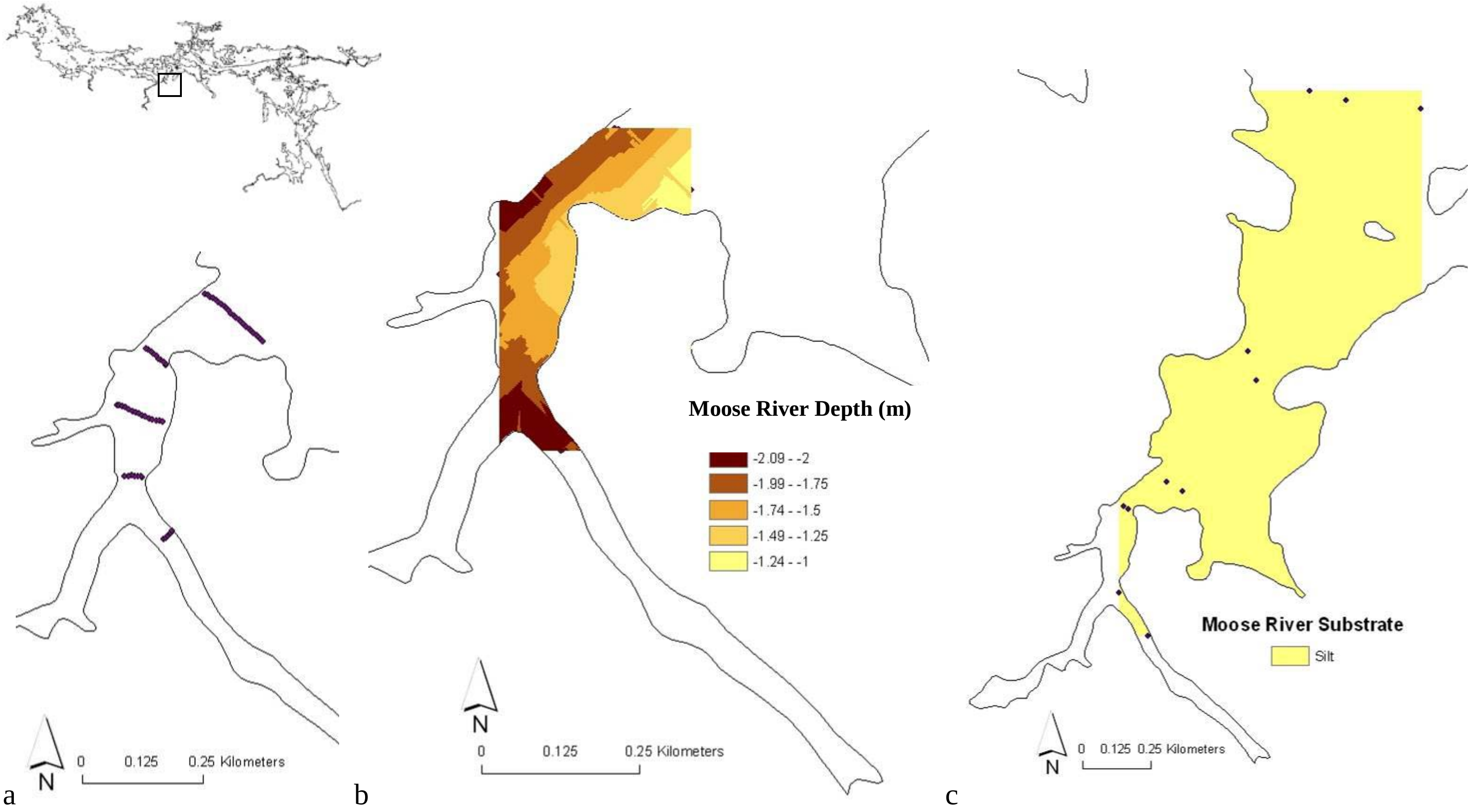


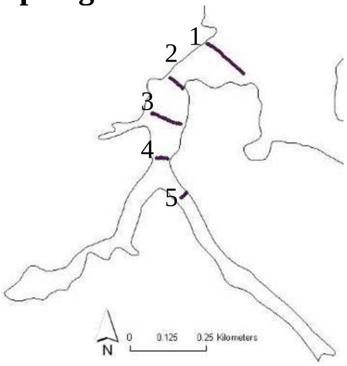
Appendix A-7. ADP transects and water velocity measurements (cm/s) on the Ash River in the spring 2009 and summer 2008.

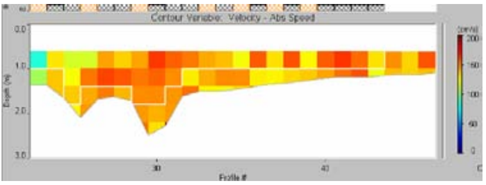
Moose River



Appendix A-8. a) Spring 2009 ADP transects; b) depth (m) map interpolated from spring 2009 ADP transect points; c) interpolated substrate map including ponar grab collection points in the Moose River, Namakan Reservoir.

Moose River Water Velocity Spring 2009 *





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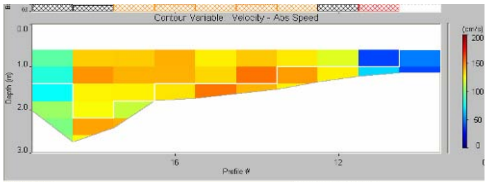

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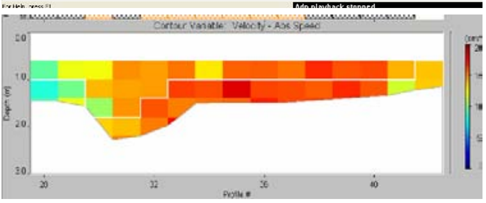

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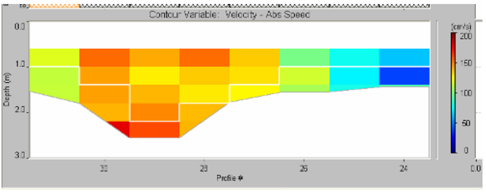

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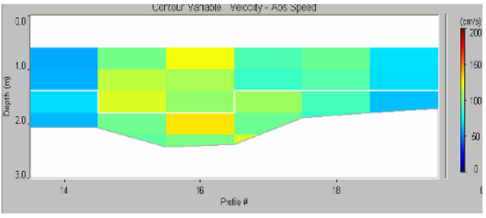
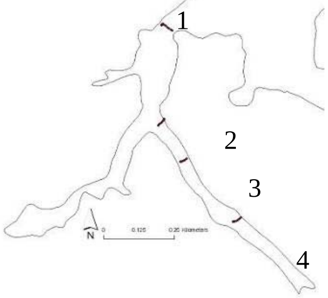
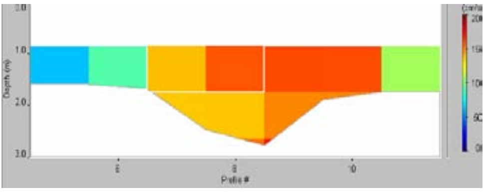


5.

Appendix A-9. ADP transects and water velocity measurements (cm/s) on the Moose River in the spring 2009 and summer 2008.

Moose River Water Velocity Summer 2008





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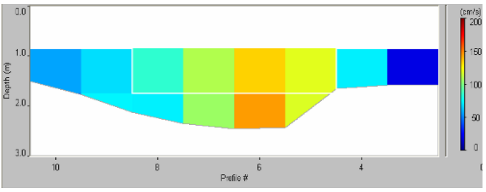

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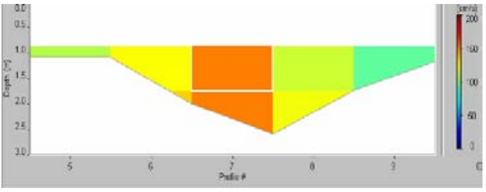

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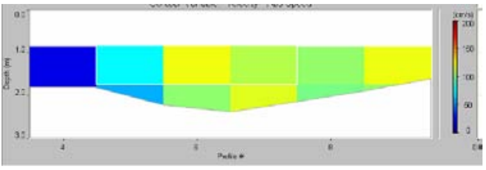
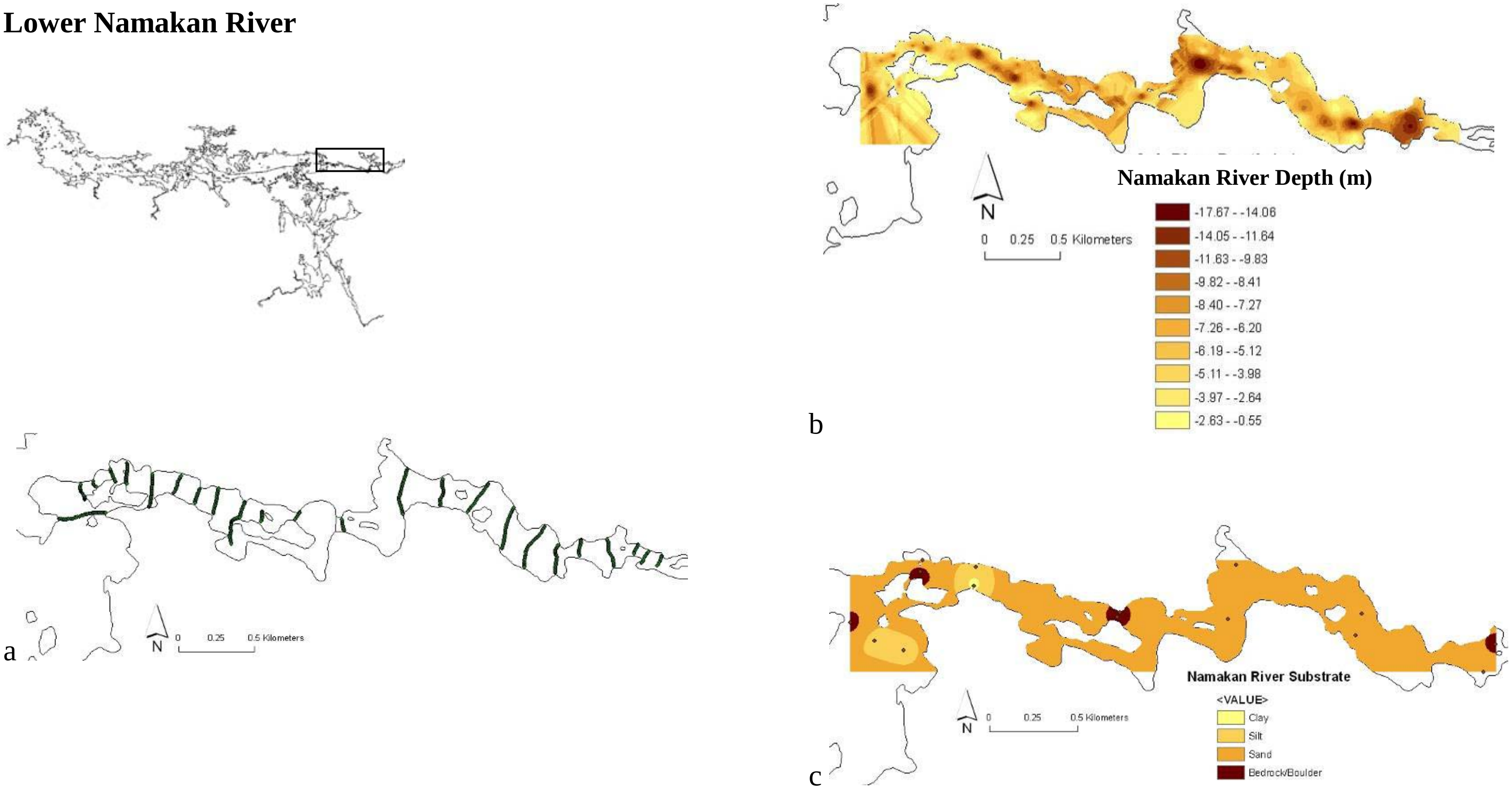


4.

*NOTE: A boat with a deeper draft was used in the spring of 2009 and we were unable to complete transects further up stream in the Moose River due to shallow water depths (i.e., upstream of old rail road girders).

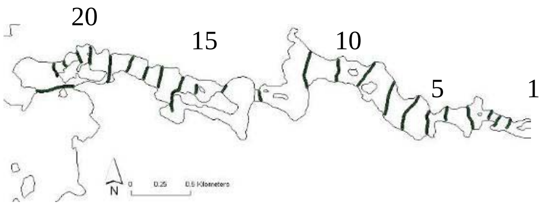
Lower Namakan River

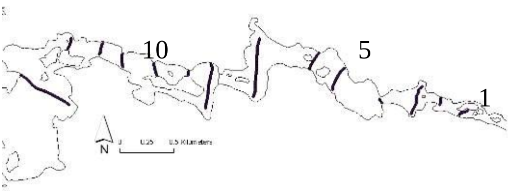


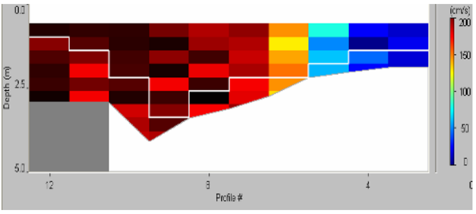
Appendix A-10. a) Spring 2009 ADP transects; b) depth (m) map interpolated from spring 2009 ADP transect points; c) interpolated substrate map including ponar grab collection points in the lower Namakan River, Namakan Reservoir.

Lower Namakan River Water Velocity Spring 2009

Lower Namakan River Water Velocity Summer 2008







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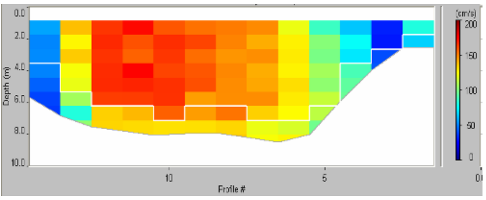

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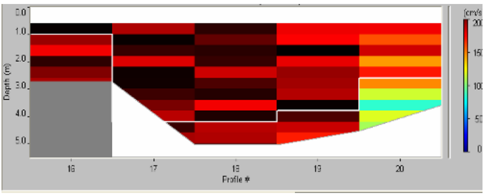

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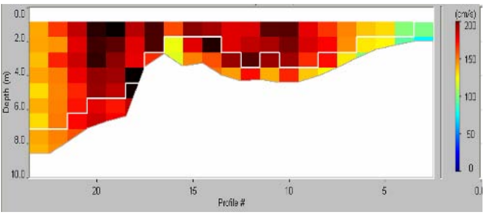

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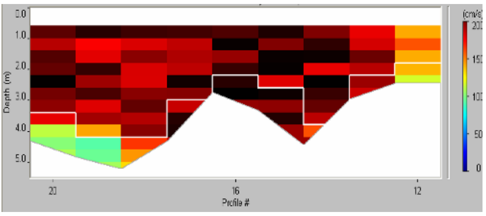

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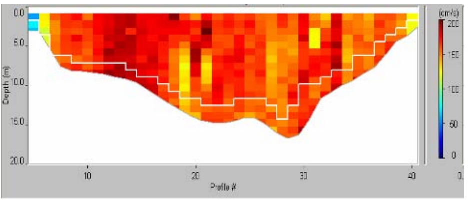

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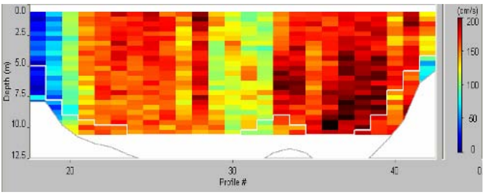

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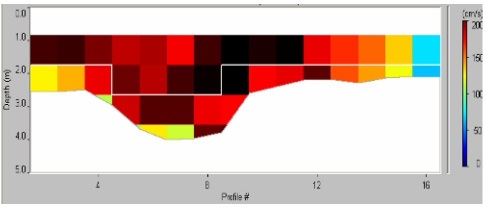

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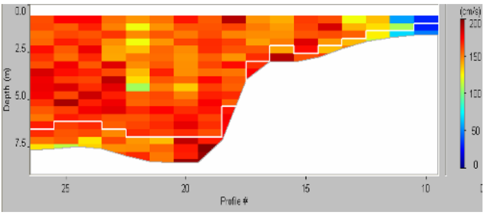

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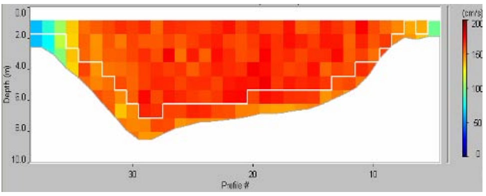

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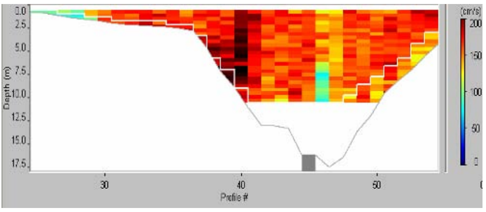

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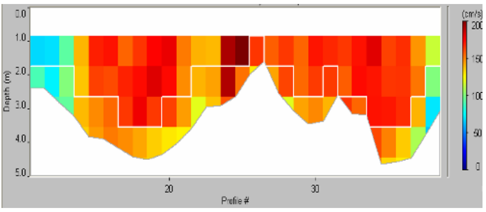
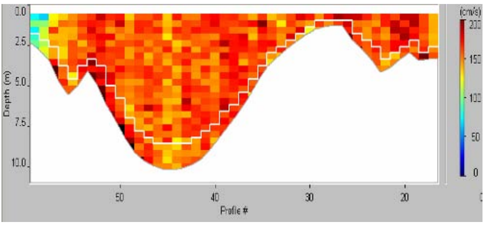


6.

Lower Namakan River Water Velocity Spring 2009 (cont.)



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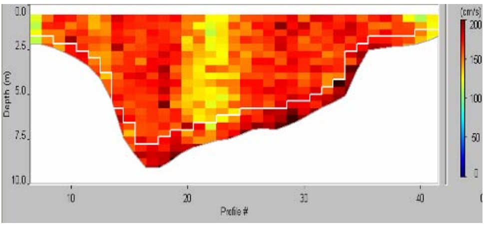

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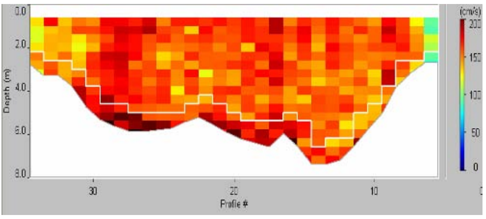

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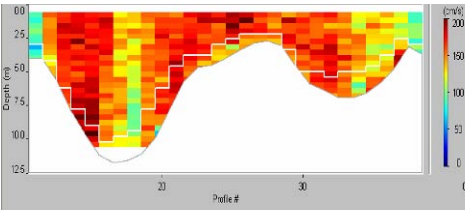

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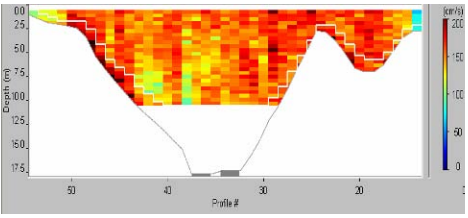

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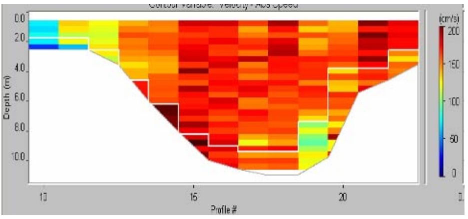
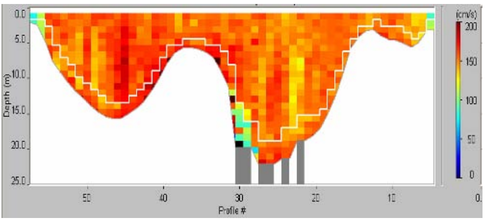


12.

Lower Namakan River Water Velocity Summer 2008 (cont.)



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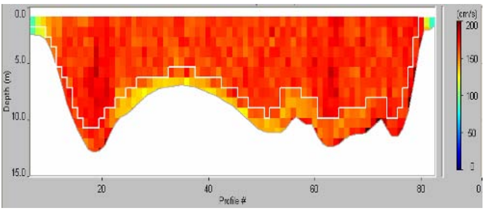

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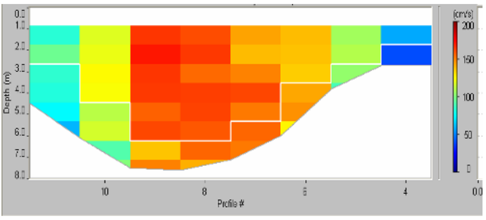

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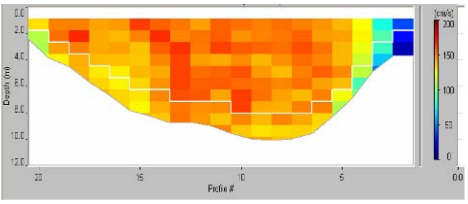

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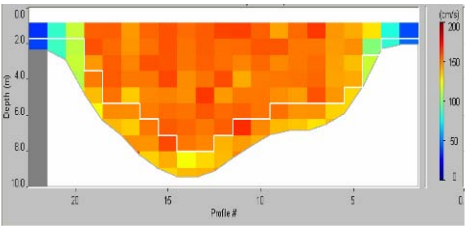

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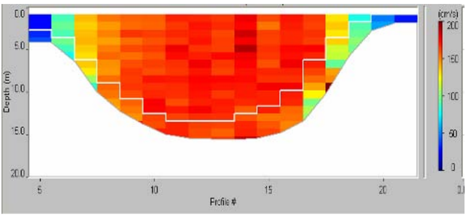
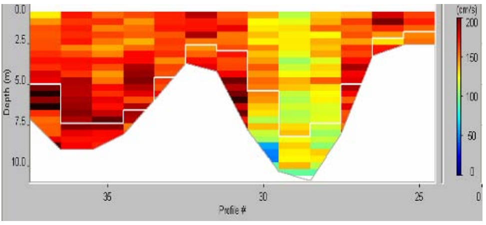


12.

Lower Namakan River
Water Velocity Spring 2009 (cont.)



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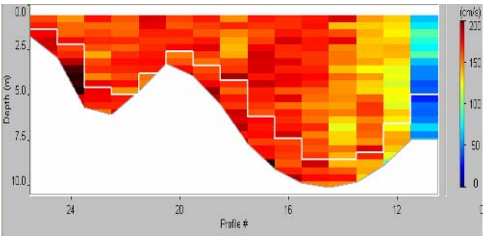

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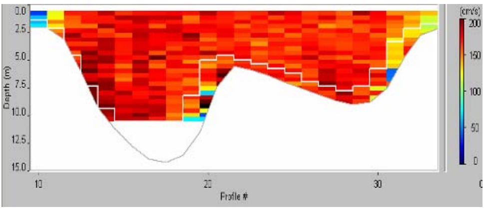

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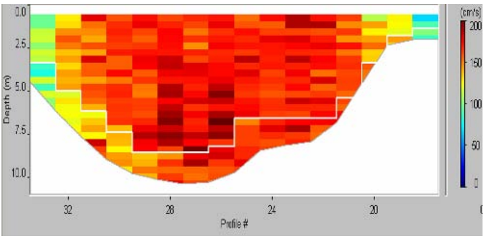

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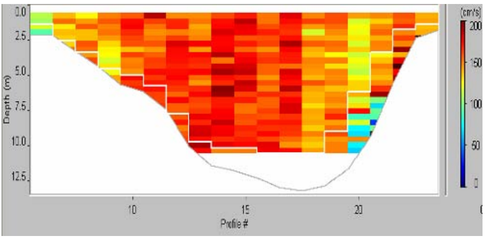

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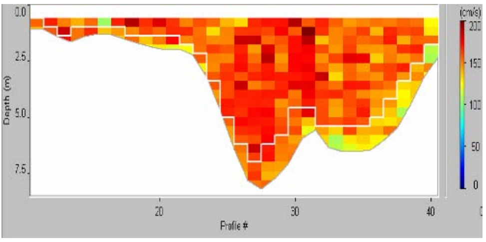

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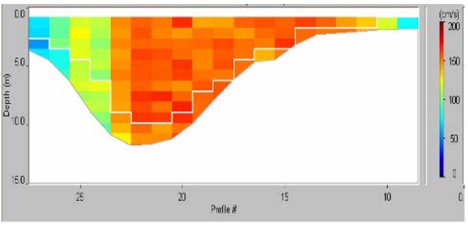
Lower Namakan River
Water Velocity Summer 2008 (cont.)



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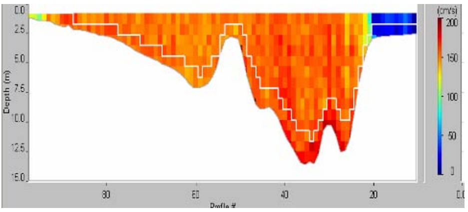
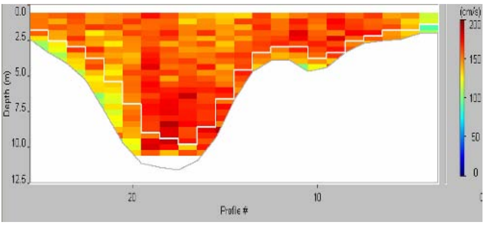


14.

* NOTE: Transects 1, 2, and 3 were not continually perpendicular to the flow due to high flow rates at the base of Lady Rapids. The flow measurements of these transects should be considered low, especially for transect 1. Transect 1 should potentially be discarded.

Lower Namakan River
Water Velocity Spring 2009 (cont.)

20.



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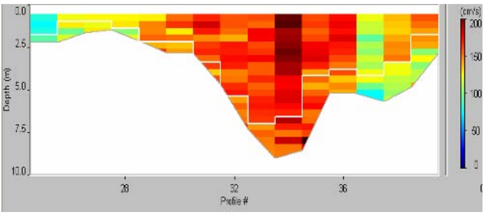

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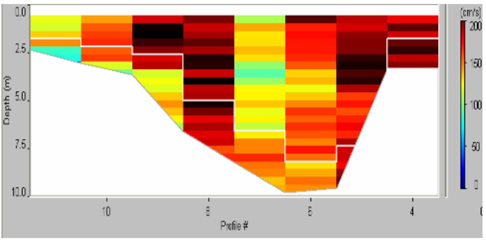

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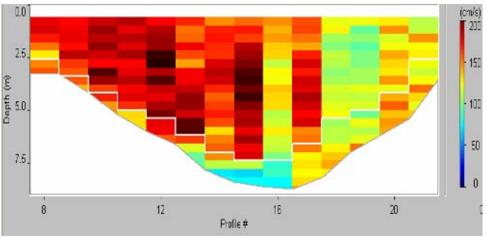

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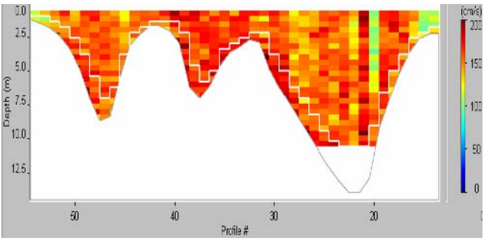
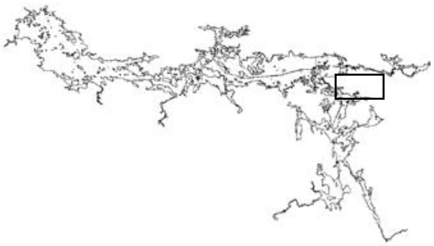
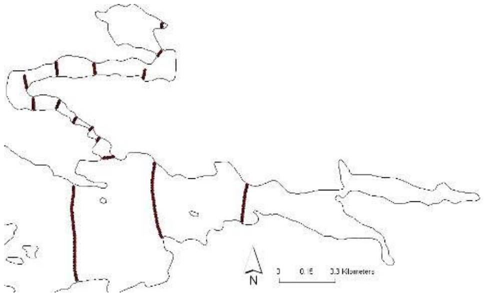
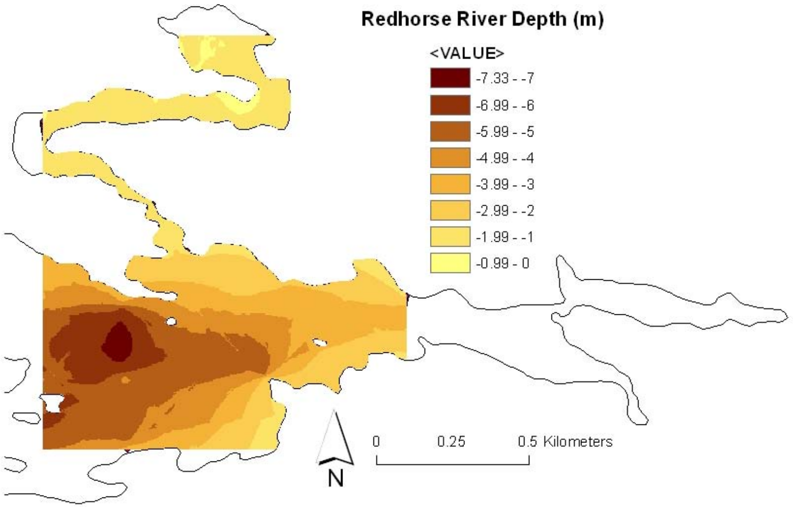


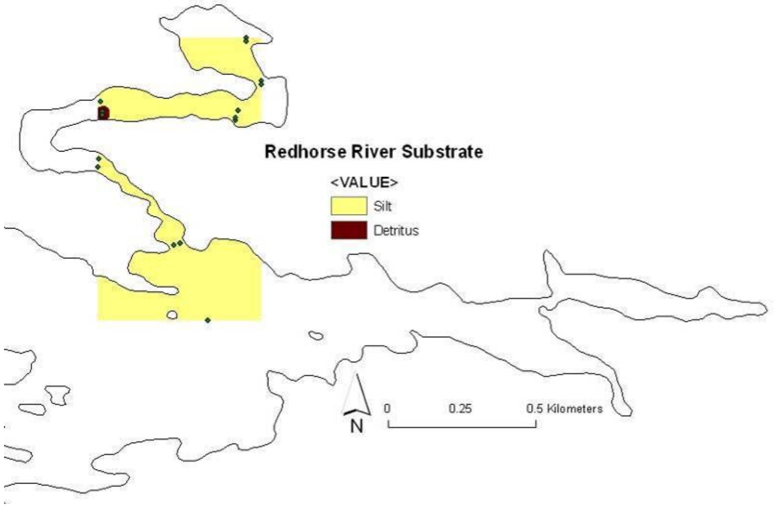
Appendix A-11. ADP transects and water velocity measurements (cm/s) on the lower Namakan River in the spring 2009 and summer 2008.

Redhorse River



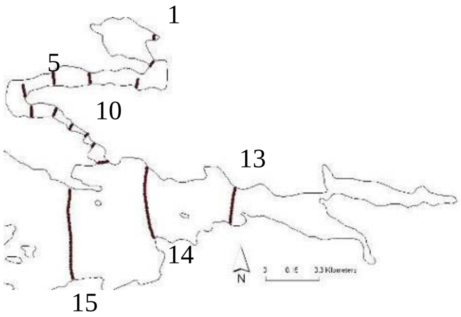


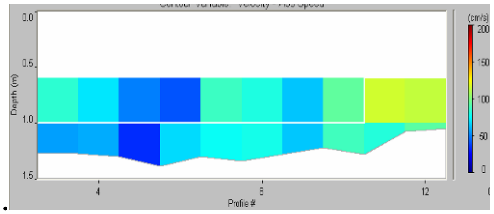




Appendix A-12. a) Spring 2009 ADP transects; b) depth (m) map interpolated from spring 2009 ADP transect points; c) interpolated substrate map including ponar grab collection points in the Redhorse River, Namakan Reservoir.

Redhorse River Water Velocity Spring 2009





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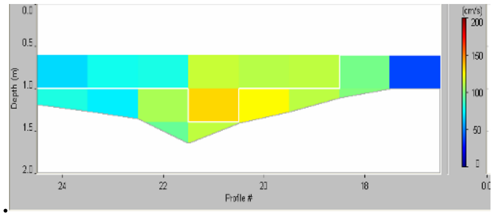

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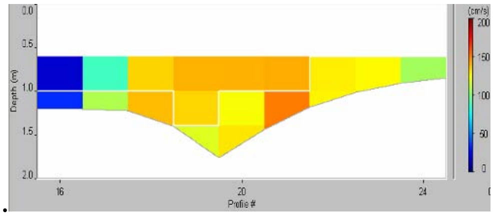

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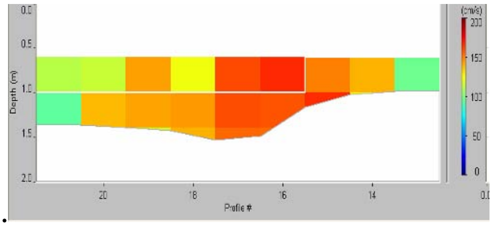

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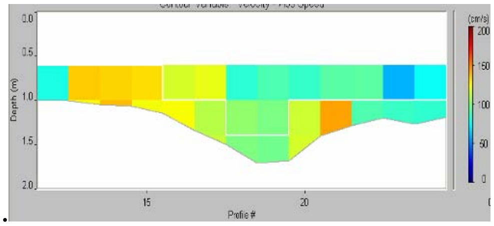
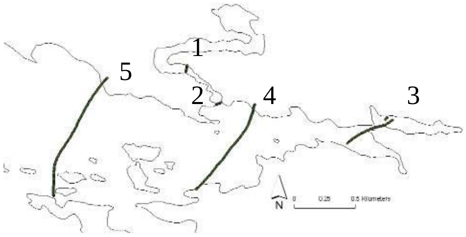
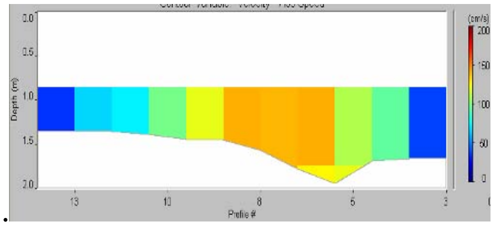


5.

Redhorse River Water Velocity Summer 2008 *





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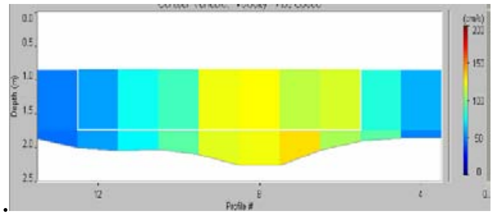

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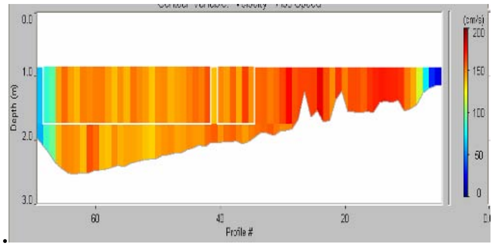

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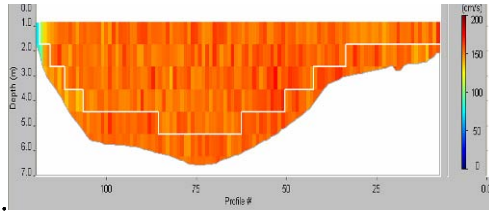

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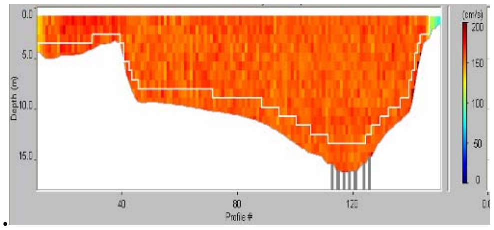
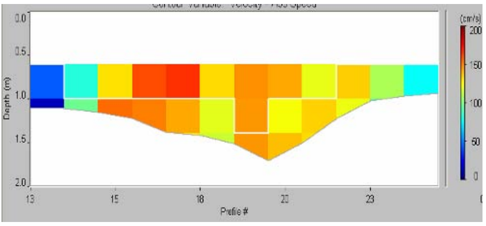


5.

Redhorse River Water Velocity Spring 2009 (cont.)



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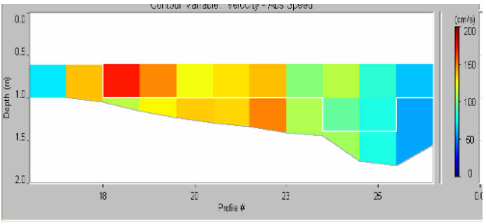

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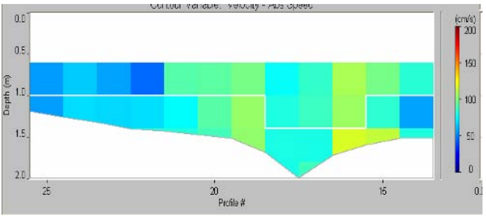

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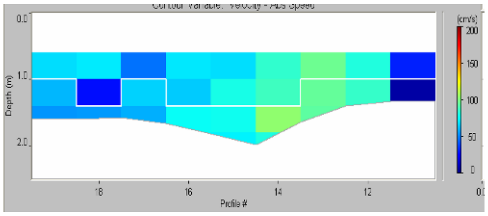

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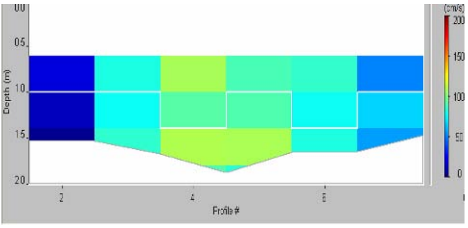

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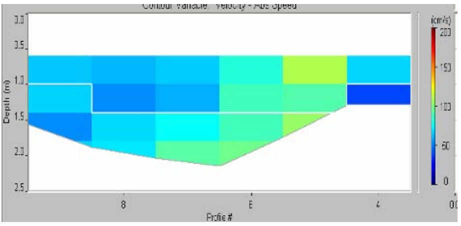


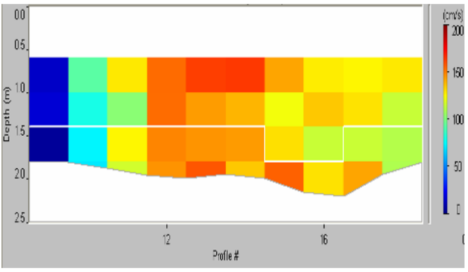
11.

Redhorse River Water Velocity Summer 2008 (cont.)

** NOTE: We were unable to continue transects upstream in the Redhorse River in 2008 due to low water levels.

Redhorse River Water Velocity
Spring 2009 (cont.)

12.



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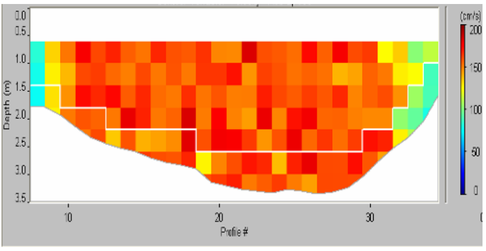

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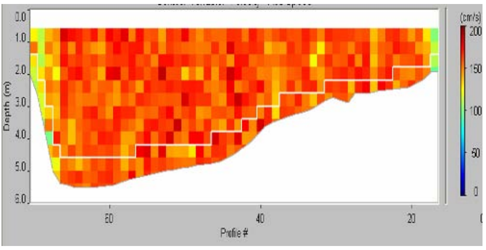

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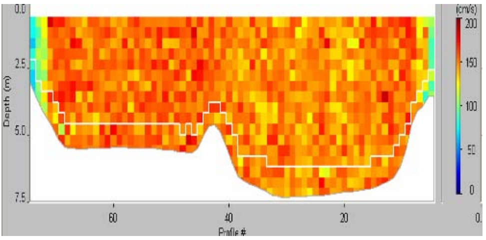
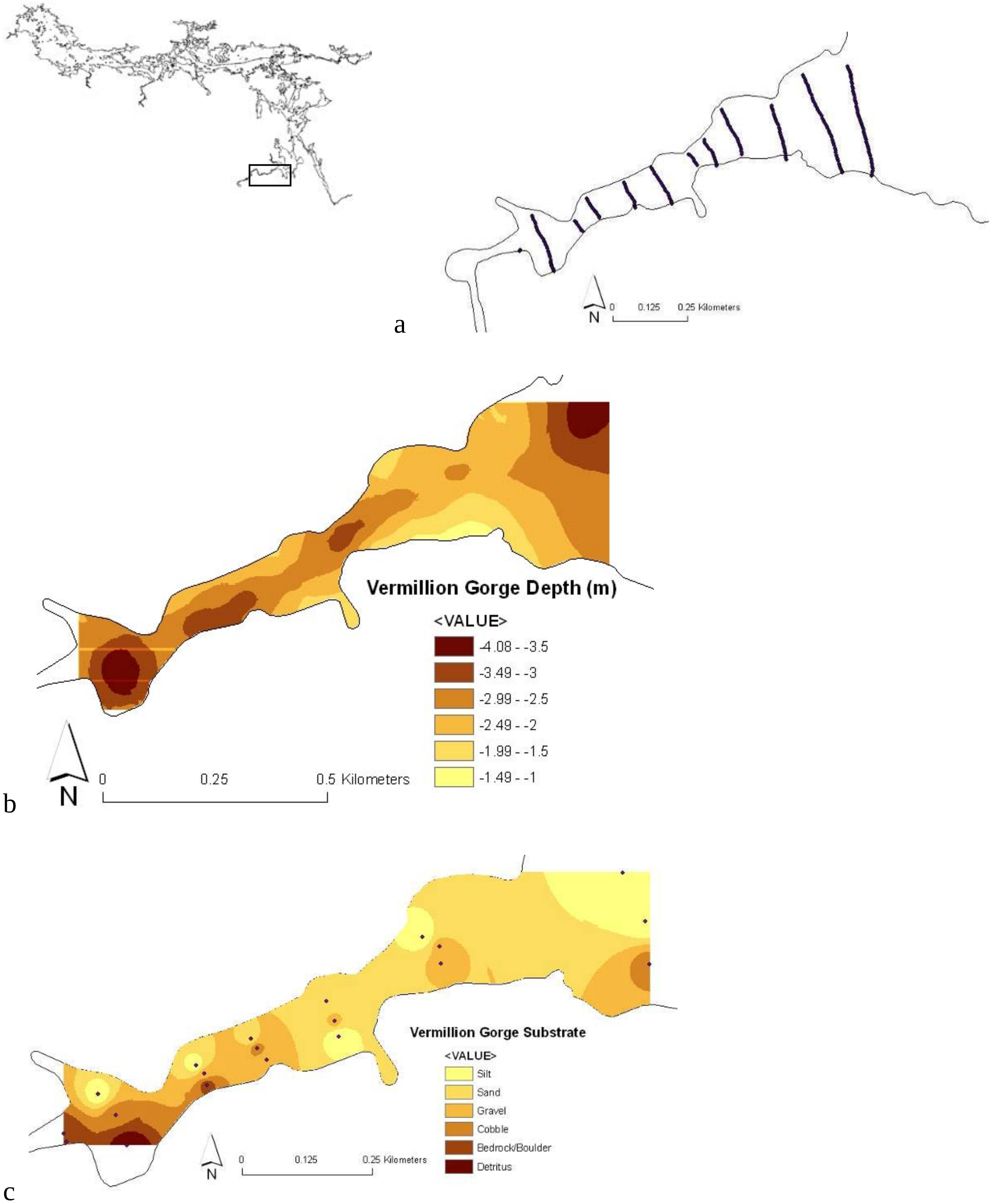


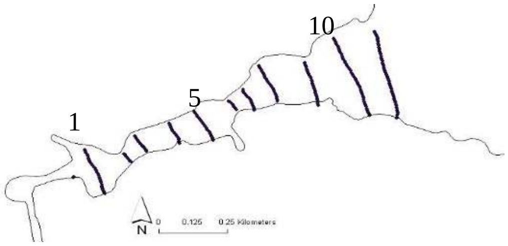
Appendix A-13. ADP transects and water velocity measurements (cm/s) on the RedhorseRiver in the spring 2009 and summer 2008.

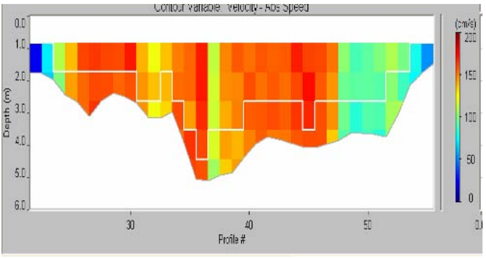
Vermilion Gorge



Appendix A-14. a) Spring 2009 ADP transects; b) depth (m) map interpolated from spring 2009 ADP transect points; c) interpolated substrate map including ponar grab collection points in the Vermilion Gorge, Namakan Reservoir.

Vermilion Gorge
Spring 2009 Water Velocity





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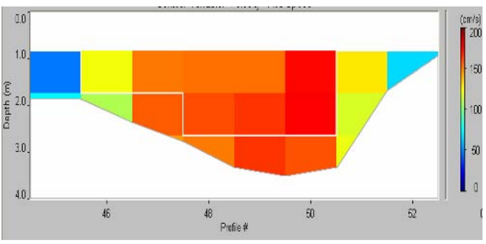

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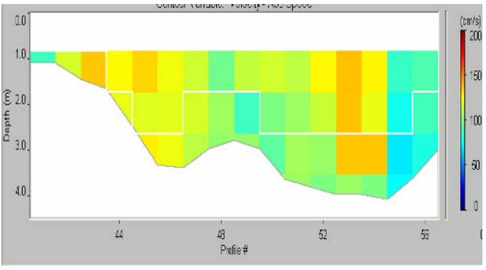

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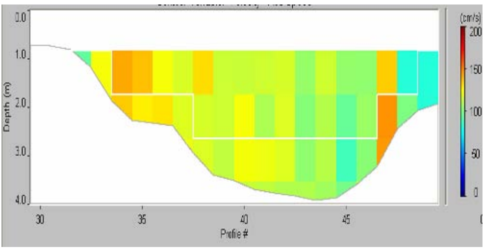
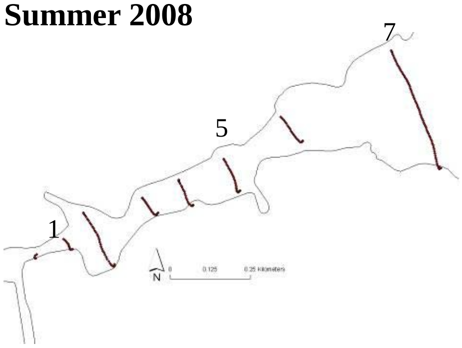
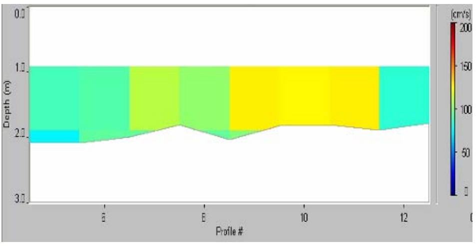


4.

Vermilion Gorge Water Velocity
Summer 2008





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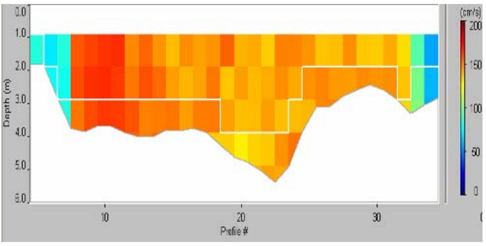

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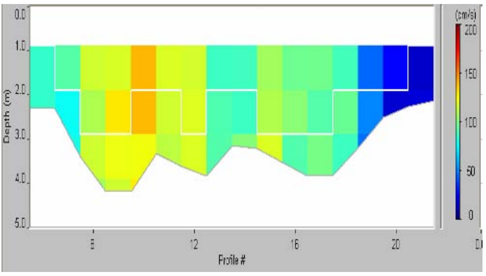

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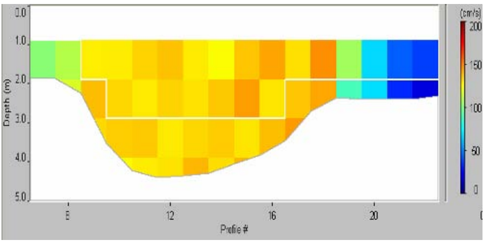
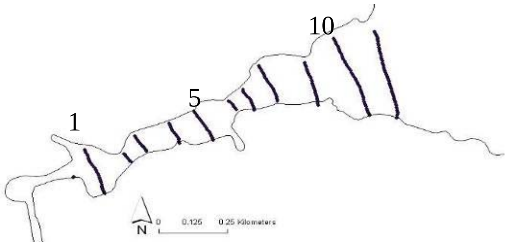
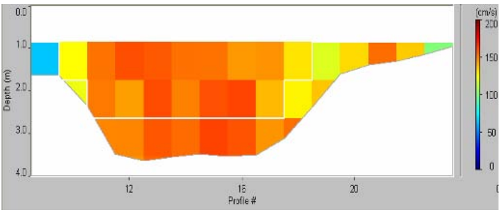


4.

Vermilion Gorge Water Velocity Spring 2009 (cont.)





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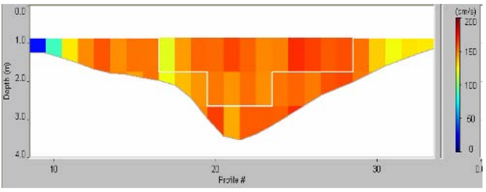

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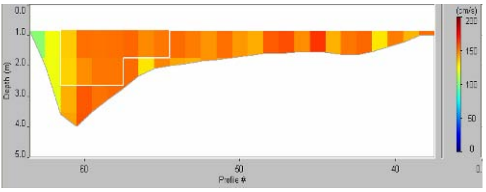

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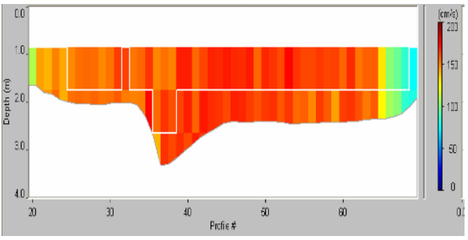

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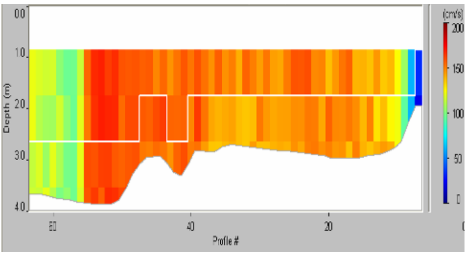
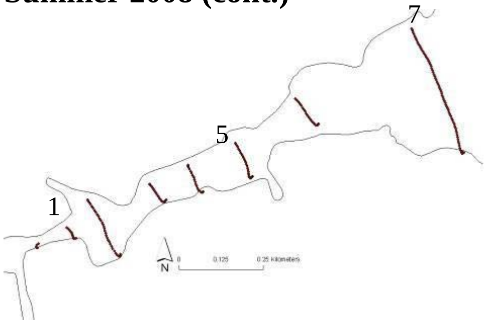
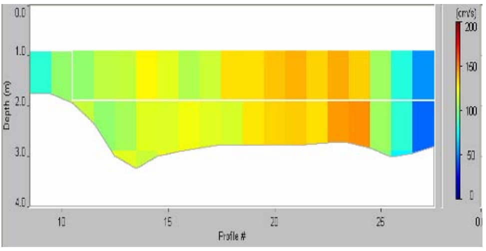


11.

Vermilion Gorge Water Velocity Summer 2008 (cont.)





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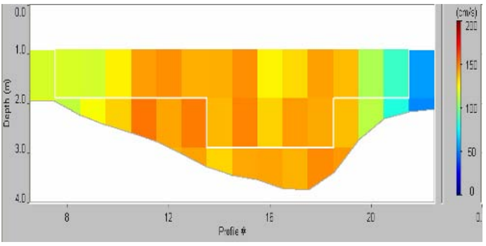

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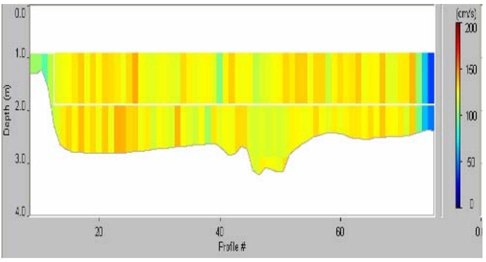

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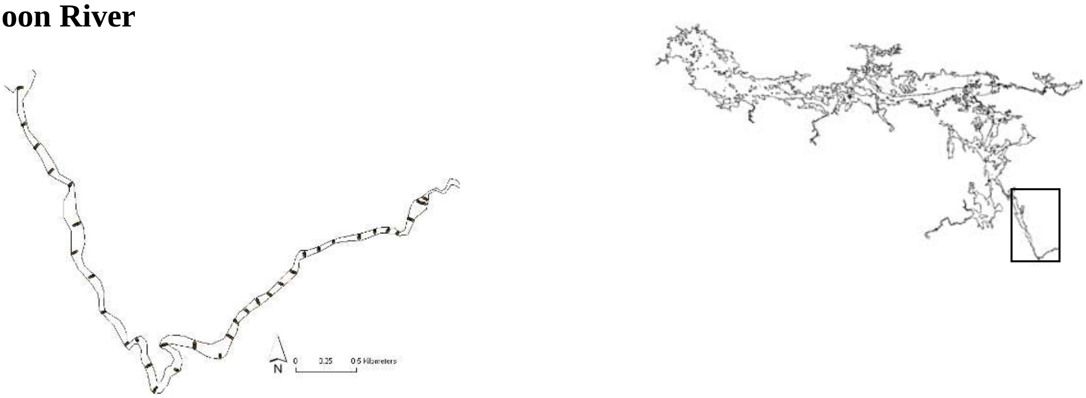
Appendix A-15. ADP transects and water velocity measurements (cm/s) on the Vermilion Gorge in the spring 2009 and summer 2008.

Loon River



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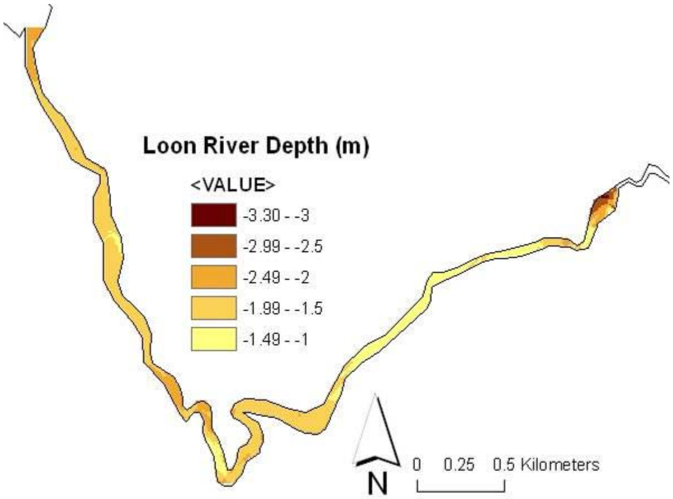

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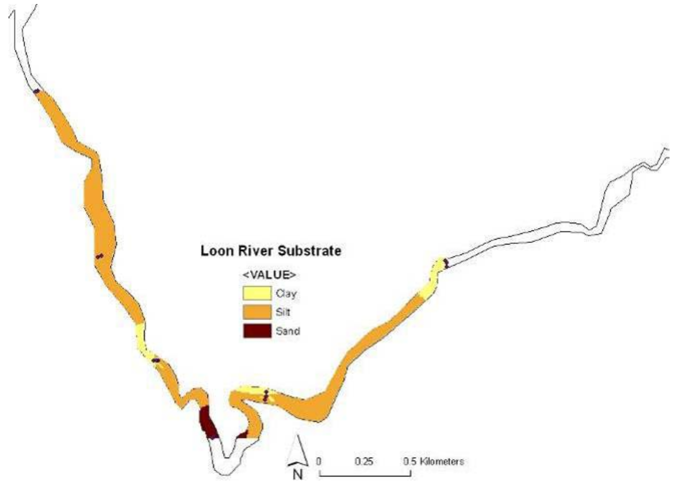
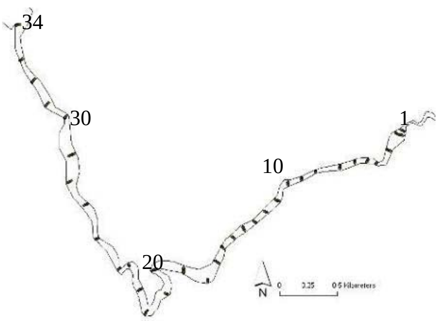
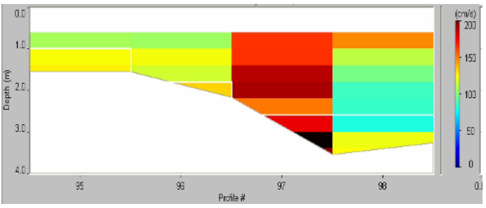


c

Appendix A-16. a) Spring 2009 ADP transects; b) depth (m) map interpolated from spring 2009 ADP transect points; c) interpolated substrate map including ponar grab collection points in the Loon River, Namakan Reservoir.

Loon River
Spring 2009 Water Velocity





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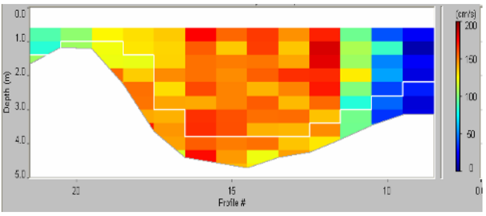

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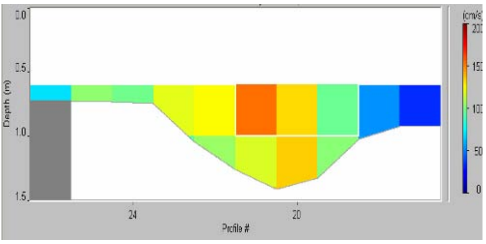

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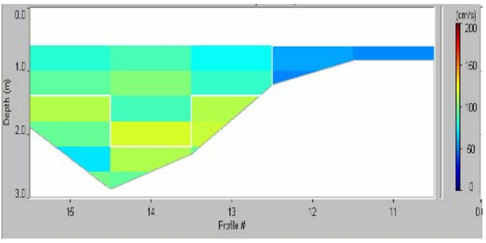

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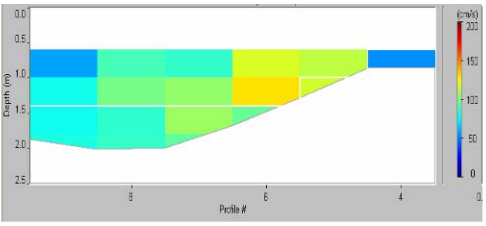
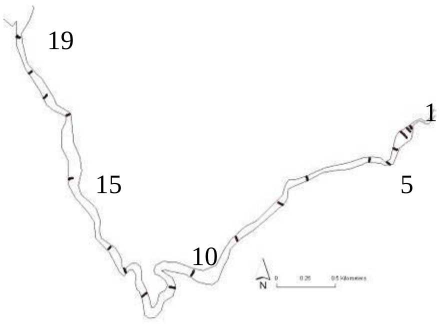
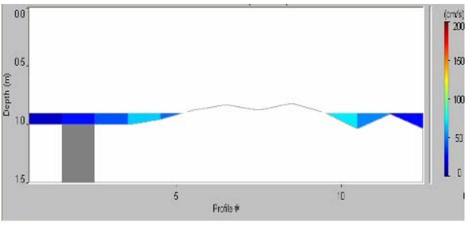


5.

Loon River Water Velocity
Summer 2008





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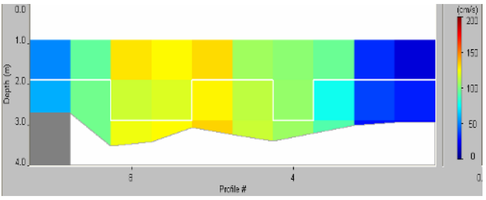

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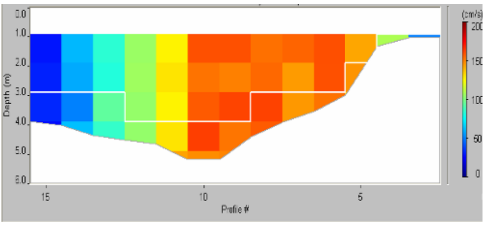

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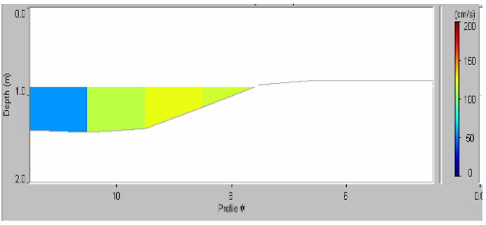

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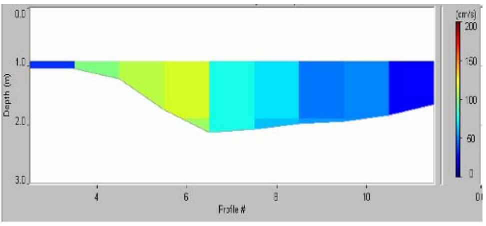

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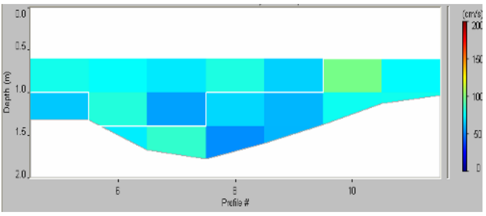
Loon River Water Velocity Spring 2009 (cont.)



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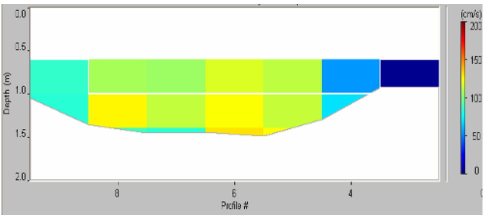

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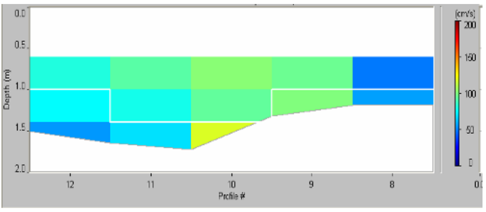

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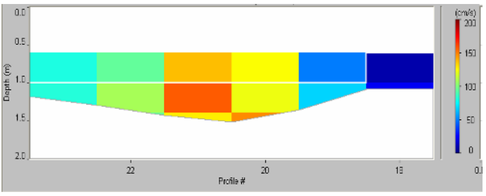

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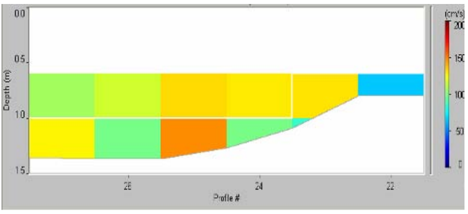

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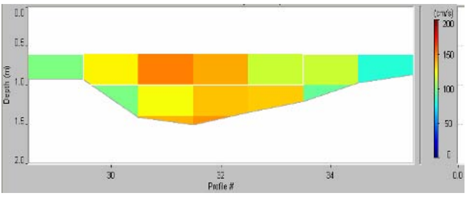

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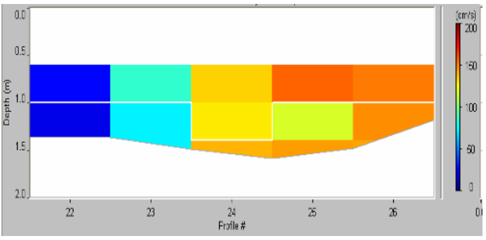

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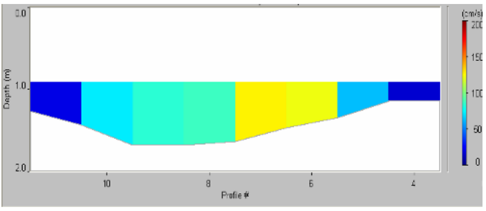
Loon River Water Velocity Summer 2008 (cont.)



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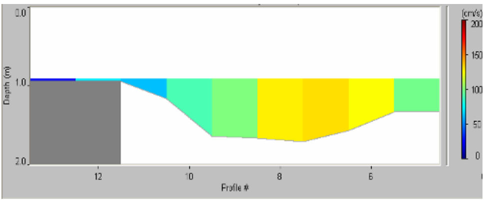

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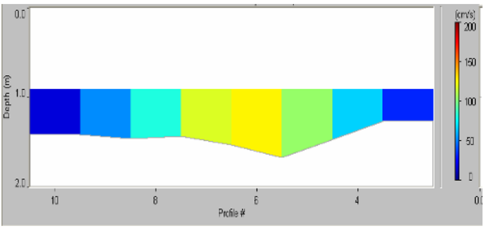

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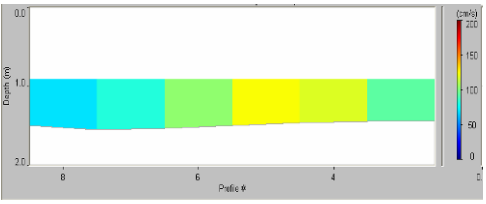

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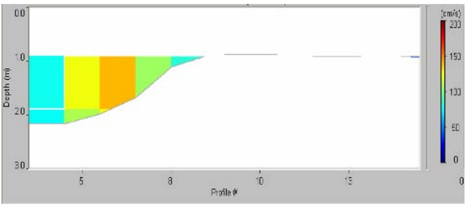

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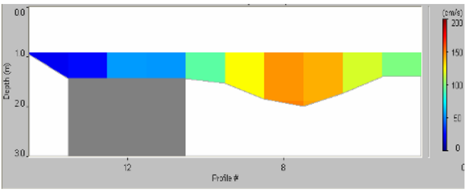

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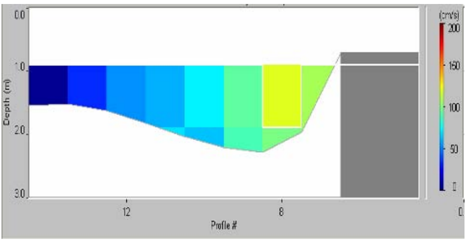

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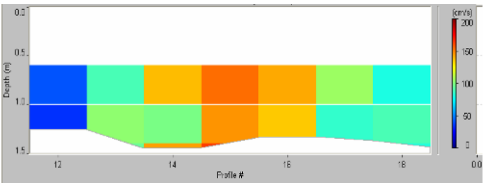
Loon River Water Velocity
Spring 2009 (cont.)



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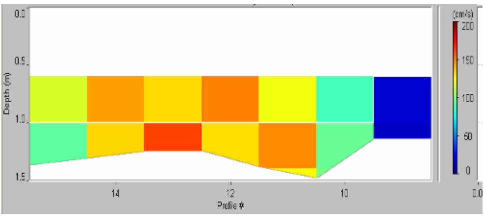

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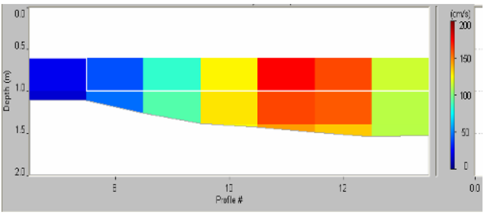

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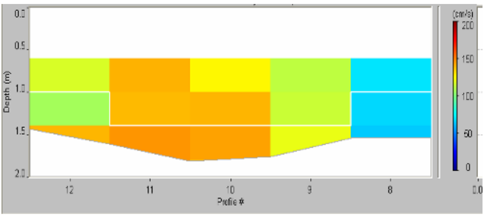

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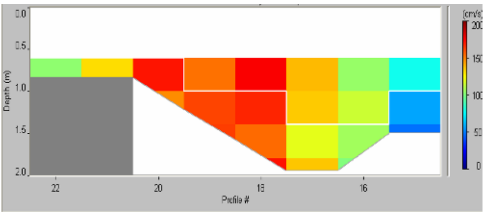

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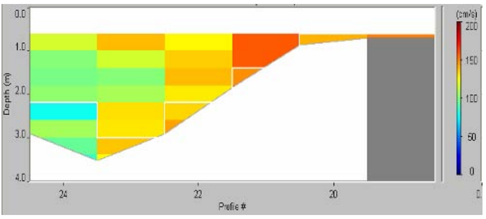

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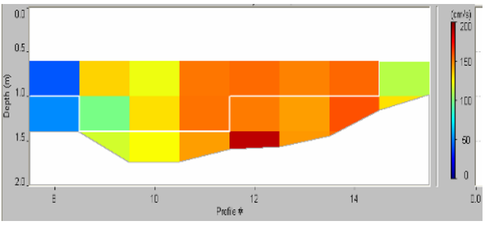

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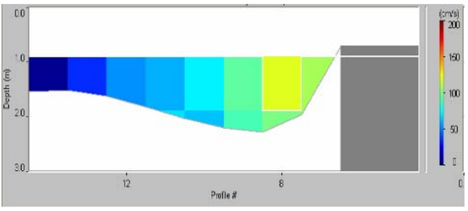
Loon River Water Velocity
Summer 2008 (cont.)



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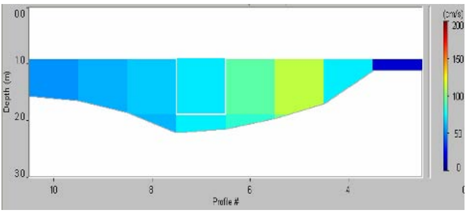

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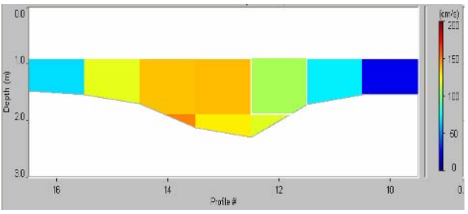

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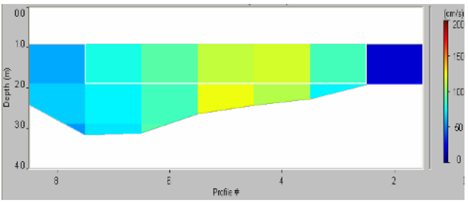

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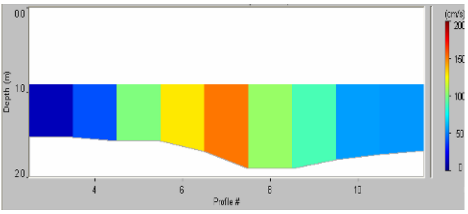

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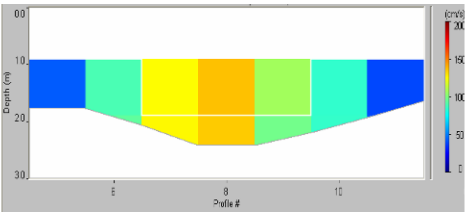

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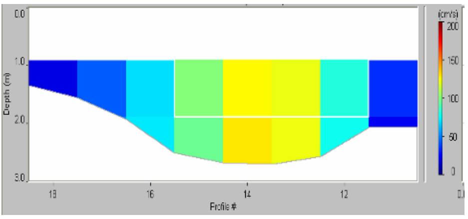

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Loon River Water Velocity
Spring 2009 (cont.)

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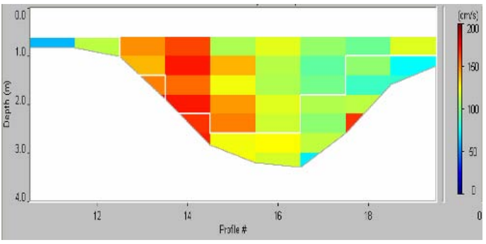

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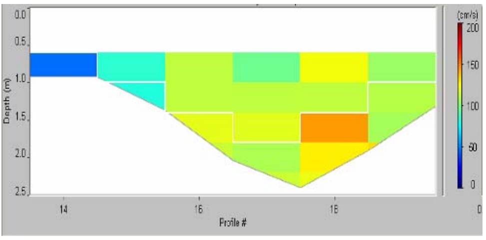

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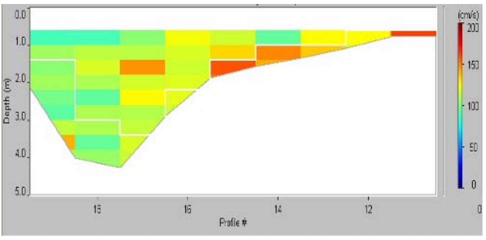

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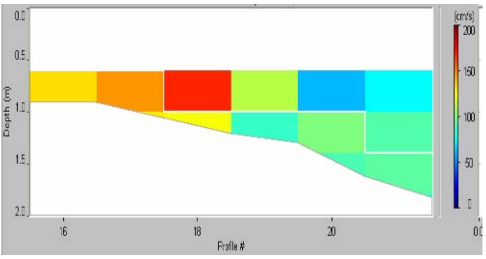

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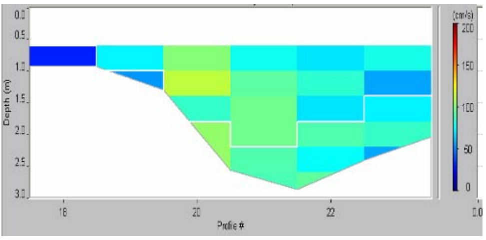

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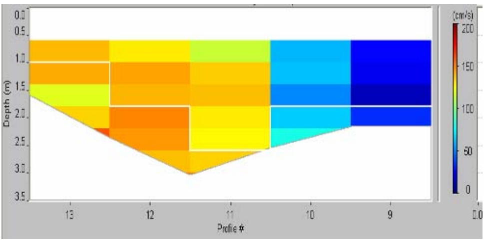
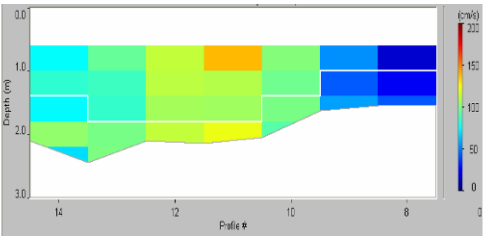


Loon River Water Velocity
Summer 2008 (cont.)

* NOTE: Transect number 1 at 56 Rapids should potentially be discarded due to the fact that it was not continually perpendicular to the current. Transect number 1 is likely an underestimate of true flows.

Loon River Water Velocity Spring 2009 (cont.)



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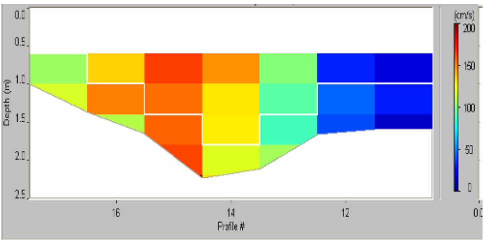

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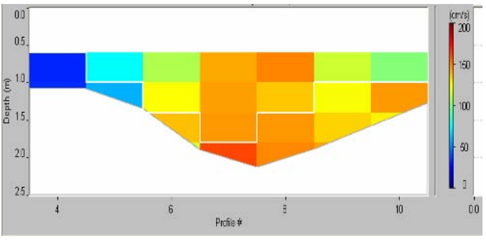

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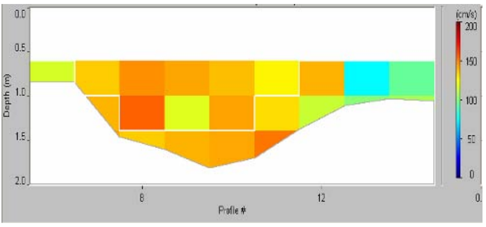

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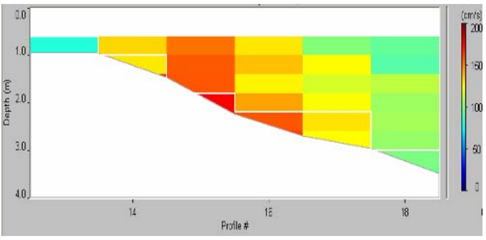

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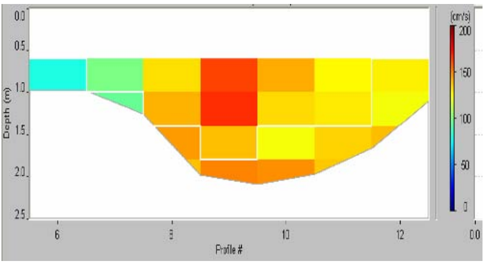
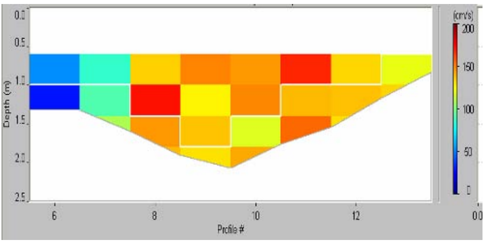


31.

Loon River Water Velocity Spring 2009 (cont.)

32.



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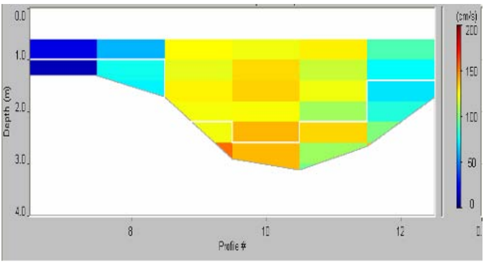

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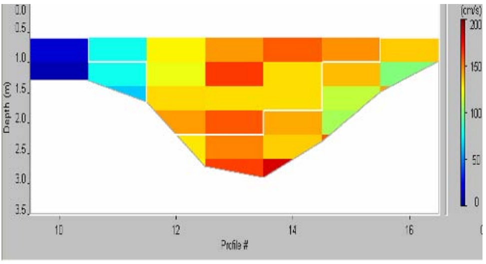

Appendix A-17. ADP transects and water velocity measurements (cm/s) on the Vermilion Gorge in the spring 2009 and summer 2008.