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ASSESSMENT OF AMERICAN WHITE PELICAN PREDATION AND
REPRODUCTIVE SUCCESS OF WALLEYE IN THE TAMARAC RIVER, MN

by

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A Thesis Submitted to the Faculty of the
DEPARTMENT OF BIOLOGY

In Partial Fulfillment of the Requirements
For the Degree of

MASTER OF SCIENCE IN BIOLOGY

BEMIDJI STATE UNIVERSITY
Bemidji, Minnesota, USA

May 2016

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Jake Graham

The Tamarac River is a major tributary of the Red Lakes MN, which provides an economically important multispecies fishery. The river experiences spring spawning migrations of northern pike, walleye, and white suckers. However, limited data exists related to reproductive success of fishes in the river. Furthermore, in the previous decade large congregations of American white pelicans (AWPE) have been observed using the Tamarac River as a foraging ground each spring. Assessing reproductive success of fishes in the Tamarac River provides a more holistic understanding of fish ecology in the river and the importance of the Tamarac River to the Red Lakes walleye fishery. Additionally, quantifying AWPE consumption in the river allows for assessment of the possible impacts of AWPE predation on the Red Lakes walleye fishery. Aerial surveys, diet composition data, and a bioenergetics model were used to estimate AWPE consumption of fishes in 2014 and 2015. AWPE diet was primarily composed of walleye (99.5%) and AWPE consumption in 2014 and 2015 accounted for 1.46 and 0.09% of the mean walleye annual natural mortality in the Red Lakes, respectively. Walleye spawning habitat was assessed using side scan sonar mapping that provided 78.0% overall accuracy when used to predict suitable spawning substrate. Side scan sonar mapping yielded an estimate of 26,398 m2 of suitable walleye spawning substrate that was accessible in 2015. The estimated area of suitable substrate represented 8.4% of the total riverbed mapped. Drift nets were used to evaluate temporal and spatial variations of larval fishes and provided evidence to suggest horizontal position in the river influences larval densities in multiple species. Low walleye larvae catch provided evidence to suggest low dissolved oxygen concentrations associated with high water levels resulted in high walleye embryo and/or larvae mortality.

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Abstract. - Ephemeral populations of American white pelicans (AWPE) have been observed using the Tamarac River, a tributary of Upper Red Lake, as a foraging ground each spring. The Red Lakes support a productive recreational and commercial walleye fishery. The number of APWE on the river has been increasing and causing concern regarding the effect AWPE are having on walleye stocks in the Red Lakes. This study addressed that concern and quantified the effect of AWPE predation in the Tamarac River. Peak AWPE abundance and foraging bird days were estimated at 1,198 birds and 15,618 bird days in 2014, and 120 birds and 920 bird days in 2015. Walleye comprised 99.5% of AWPE diet and the vast majority of predation occurred between sunrise and sunset. Analysis of sex ratios in walleye available in the river and those consumed provided evidence to suggest AWPE were selecting for female walleye. A bioenergetics model estimated fish consumption at 1.57 kg day^{-1} bird^{-1}, which resulted in total walleye consumption estimates of 24,397 kg and 1,438 kg in 2014 and 2015, respectively. Consumption in 2014 and 2015 represented 1.46 and 0.09% of mean walleye natural mortality in the Red Lakes for the previous five years, respectively. These proportions were small and provided evidence to suggest AWPE predation of walleye in the Tamarac River was not having a concerning effect on walleye stocks in the Red Lakes.

INTRODUCTION

The intersection of piscivorous birds and fish stocks has been studied since the early twentieth century, but has become a topic of increasing interest and studied more intensely in the previous two decades. Two of the most studied piscivorous bird species in North America are the American white pelican (AWPE; *Pelecanus erythrorhynchos*)

and the double-crested cormorant (*Phalacrocorax auritus*). AWPE are large, white, highly visible birds. High visibility, combined with increased angler awareness of their fish eating potential, often leads to anglers voicing concern over AWPE's impact on fisheries. Such is the case on the Red Lakes, MN, a large popular walleye fishery.

The Red Lakes walleye (*Sander vitreus*) fishery collapsed in the 1990's as a result of overfishing, but has since recovered after a harvest moratorium and intensive short-term stocking program (RLFTC 2006). The walleye population has been maintained entirely by natural reproduction since 2006 and currently has record-high levels of abundance (Kennedy 2013) with standing stock in each of the last five years estimated to be greater than 4.5 million kg (Brown and Kennedy 2016). Recreational and commercial harvest was reopened in 2006 and the Red Lakes now support a highly valued walleye fishery. Recreational anglers on state waters of Upper Red Lake harvested over 160,000 walleye in 2015. The Red Lakes also provide an economically-important commercial fishery for the Red Lake Nation which harvested over 600,000 walleyes in 2015 (Brown and Kennedy 2016).

The fishery's history, combined with its high recreational and commercial value is the cause for annual creel and gill net surveys. Data from these surveys, as well as commercial harvest records, yield robust annual estimates of natural and fishing mortality. Since 2007 mean annual natural mortality is 31.5% (age $\geq$ 3), but has ranged from 15.5% to 50.2% in 2015 and 2013, respectively (Brown and Kennedy 2016). Rigorous sampling provides parameter estimates for walleye reproductive potential, including spawning stock biomass and potential fry production. Since 2005, spawning stock biomass has been over 3.36 kg/hectare, which is the upper limit of the optimal

range, and thus considered "surplus" (RLFTC 2006; Kennedy 2013; Brown and Kennedy 2016). Also since 2005, walleye fry production has been within or above the optimal range of 400-600 fry/littoral acre as identified in the Harvest Plan for Red Lakes' Walleye Stocks (RLFTC 2006; Kennedy 2013, Brown and Kennedy 2016). Spawning occurs naturally in both the lakes and in tributaries, though the proportion that comes from each component is unknown. Walleye undergo spawning migrations in several tributaries each spring and, although the magnitude of each has not been quantified, the Tamarac River is thought to have the largest walleye spawning migration of any of the tributaries of the Red Lakes.

Relative abundance of walleye during their spring spawning migration in the Tamarac River has been estimated for the last 15 years via spring electrofishing surveys. Northern pike (*Esox lucius*) and white suckers (*Catostomus commersonii*) also migrate the Tamarac River to spawn prior to and after walleye, respectively. While performing electrofishing surveys a substantial temporary population of AWPE has been observed by electrofishing crews on the river. These AWPE are assumed to be migrants coming from the Gulf of Mexico using this temporary feeding ground as they wait for ice to recede from nesting sites and feeding grounds farther north. AWPE populations are expanding in both abundance and geographic distribution. The two nesting colonies closest to the Red Lakes are no exception, with nest counts increasing from 11 in 2004 to 174 in 2011 on Leech Lake and 569 in 2004 to 1,028 in 2011 on Lake of the Woods (Wires et al. 2011).

AWPE are opportunistic piscivores that display annual and seasonal variation in prey selection relative to available forage (Findholt and Anderson 1995). AWPE are known to prey heavily on migrating fish during spring riverine spawning migrations

(Scoppettone et al. 2014; Teuscher et al. 2015), and are able to forage successfully in water less than 1.5 m deep during day or night (McMahon and Evans 1992). Walleye migrate into riverine spawning grounds at night, preferring riffles with water depths of 0.3 – 1.5 m (McMahon et al. 1984). Therefore, temporal and spatial overlap between walleye spawning and AWPE foraging suggests walleye may comprise a substantial portion of AWPE diets during this time. Further, AWPE predation on walleye has been confirmed by observations of disturbed AWPE regurgitating stomach contents before fleeing (Tony Kennedy MNDNR, personal communication). While previous studies have examined AWPE consumption of game and non-game species (Hall 1925; Major et al 2003; Idaho Fish and Game 2009; King et al. 2010; Frechette et al. 2012; Scoppettone et al. 2014; Teuscher et al. 2015) and the effect on fish stocks, none have focused on walleye as a prey species.

Establishing robust AWPE population and fish consumption estimates on the Tamarac River will quantify the effect of AWPE on walleye mortality and provide baseline AWPE-induced walleye mortality estimates during a time when the walleye population in the Red Lakes is thriving. Total fish consumption in combination with diet composition data also provides insight into potential effects AWPE could have on northern pike and white sucker populations. A better understanding of AWPE foraging during multispecies riverine spawning migrations will help managers anticipate potential effects on fish stocks if new AWPE nesting colonies and foraging waters are established.

In this study we assessed the extent of walleye predation by AWPE during the time the birds occupy the Tamarac River. In addition, aspects of AWPE foraging ecology on the Tamarac River were examined. The objectives of this study were to (1) determine

the number of AWPE that used the Tamarac River to forage during fish spawning migrations, (2) determine what proportion of AWPE diet walleye comprise, (3) determine the number and biomass of walleye that were consumed by AWPE, and (4) determine what portion of Red Lakes' walleye's natural mortality was attributed to AWPE predation.

METHODS

Study Site

The Red Lakes are the largest body of water by surface area contained within Minnesota borders at over 116,550 ha. The Tamarac River is the main tributary to the upper basin of the Red Lakes and flows 34.9 km into the northeast corner of the basin (Groshens 2000). The Tamarac River has a drainage of 815 km^2 including a portion of a 1,295 km^2 peat bog, the largest in the lower 48 states (Groshens 2000). The drainage is primarily wetlands but approximately 35% of the watershed is forested (Groshens 2000). The river has a low gradient with substrates ranging from silt to cobble but is dominated by silt and sand. Water depths typically measure around one meter but can reach depths over three meters near the mouth. This study focused on a 5.5-km reach starting 5.5 km upstream of the mouth (Figure 1.1). The riparian zone along the study section is comprised of rice paddies and peat bog, whereas reaches upstream and downstream are dominated by wooded shorelines and moderate development along wooded shorelines, respectively.

Aerial surveys were conducted to assess AWPE abundance on the Tamarac River in a fixed wing aircraft every 2-4 days depending on weather and pilot availability (2014 n=7, 2015 n=5). Surveys could not be conducted during the first 9 days of AWPE

presence on the river in 2014 (20-29 April) due to weather conditions that made flying unsafe. The first two days AWPE were observed on the river in 2014 (20 and 21 April), and the first day AWPE were observed in 2015 (13 April), ground counts were conducted just before dark when large numbers of AWPE were visible in flight at one time. These ground counts are not estimates of the true number of AWPE using the river on those days, but can be considered minimum numbers. In both years, aerial surveys were discontinued when AWPE and/or walleye numbers were low and it was concluded the walleye migration and AWPE foraging on the river had all but ceased.

Flights were conducted as close as possible to the end of nighttime foraging in an effort to obtain the most accurate estimate of the number of AWPE foraging on the river the previous night. Aerial surveys consisted of three passes when birds were present, and two when they were not, following the entire section of river where AWPE were present. Each pass was recorded using a digital camcorder. Recordings were later analyzed on a computer and AWPE were enumerated for the length of the river and area immediately surrounding the river mouth (approximately 500 m). The mean number of AWPE from aerial surveys and 95% confidence intervals were calculated for each sampling date.

Daily estimates of AWPE abundance were made assuming changes in abundance between surveys were linear. Using this approach, AWPE abundance was estimated for every day of the study period. Total bird foraging days on the Tamarac River was calculated by summing AWPE abundance from when AWPE were first seen until the day of the last aerial survey. In 2015 AWPE abundance was much lower than in 2014 and an AWPE abundance estimate from the aerial survey on 22 April 2015 was zero. On this

occasion, the abundance estimate was made from the maximum number of AWPE seen on camera traps at one time.

To assess when AWPE foraged on the Tamarac River, camera traps were set throughout the portion of the river where AWPE were observed. In 2014, a total of twelve camera traps (8mp Bushnell Trophy Cam) were placed along a river segment approximately 5 km long where birds had been seen foraging in previous years by Minnesota Department of Natural Resources personnel (Figure 1.1). Eleven camera traps (eight 8mp Bushnell Trophy Cam and three Moultrie GM-80xt) were placed along the same stretch of river in 2015. Both proximity to other camera traps and river morphology were considered when placing camera traps. Camera traps were placed in locations that covered the longest stretch of river and minimized "blind spots". Series of three photos, one second apart, were taken every five minutes, as well as whenever motion triggered the cameras.

All photos were subsequently examined for AWPE in the act of foraging. The time of day when the first and last AWPE was seen foraging on any camera was recorded each night. The time period between when the first and last AWPE was seen foraging was defined as the foraging period. The number of times AWPE were observed foraging outside the foraging period was recorded. AWPE were considered foraging when photos displayed actions and/or body language similar to that seen during direct observations of foraging AWPE in the field (e.g. bill dipping, head leaned forward scanning water, multiple birds alertly swimming along shorelines in unison, or large groups systematically working the river channel).

Camera traps experienced several technical issues while deployed including, but not limited to: time resetting after each photo, failing to take pictures at defined intervals, weather (e.g. snow) affecting camera traps ability to capture interpretable photos at night, and continuously taking photos every second. As a result, data from all camera traps were not available for each night. During a typical 24-hr period, reliable data were collected by a median of 6 camera traps in 2014 and 10 in 2015.

Fyke nets were set in the Tamarac River to assess the timing and relative magnitude (i.e. catch per unit effort) of spawning migrations while AWPE were present. Fyke nets (frame 0.9 x 1.5 m; bar mesh 2.5 cm) were set overnight at two standardized locations in 2014 and six standardized locations in 2015. Nets were fished every third day from the day after the river was ice free until low catches after peak numbers and high water temperatures indicated the walleye spawning migration was near completion (fyke netting events n=8 in 2014; n=6 in 2015). Half of the nets were set associated with an outside bend and half being set associated with an inside bend to capture fish in habitats containing both faster and slower moving water. Fyke nets were set faced downstream with the lead extending to shore at an angle such that fish moving upstream encountered the lead, followed it upstream and were captured. In 2014 two nets were set in each habitat type, but one fyke net in each habitat did not fish correctly due to rising water levels and increased water velocity during all fish sampling after 28 April 2014. As a result, relative fish abundance was described using two fyke nets, one from each habitat type in 2014. One of the two nets used to describe fish abundance did not fish correctly on 21 April 2014, and thus, data from that net were not included. However, this occurred

during the first sampling period while catch in the second net was low (n=2), indicating the walleye spawning migration was still in its initial stage.

Captured fish were identified to species, sexed, and measured for total length to the nearest millimeter, and a subset were weighed to the nearest gram. Total walleye catch from nets was averaged and examined over time to describe the duration of the spawning migration and also when peak walleye abundance in the river occurred. Biological data collected from a subset of walleye caught by these nets were used to establish independent length-weight relationships for male (n=163) and female (n=113) walleye. A wet-weight to total length relationship was produced with a linear regression of log-transformed lengths and weights similar to methods described by Anderson and Neumann (1996).

AWPE stomach contents were collected in 2014 by dip-netting fish that were voluntarily regurgitated by disturbed birds. Floating regurgitated fish were collected and identified to species. Fish that were not digested to a level that would affect the accuracy of measurements were measured for total length. Sex was recorded for all fish. In 2015 few AWPE were observed on the river, and as a result no voluntary regurgitations could be collected.

AWPE were captured two ways: night lighting using similar techniques to those used for waterfowl (Bishop and Barratt 1969), and modified, five-inch mesh gill nets. When night lighting during this study, many AWPE would begin to regurgitate upon approach. Thus, the person operating the net watched individual AWPE to ensure captured individuals had not regurgitated upon approach. Prior to deployment in the field, gill nets were fastened together to create two layers of netting. Nets were suspended

between two tamarack poles such that the bottom of the net was slightly above the water surface. AWPE were captured by gill nets when their bills became entangled after swimming into the net, which prevented regurgitation. Entangled AWPE were immediately removed from the net. In 2015 the intention was to collect 80 AWPE via shotgun just before sunrise to determine total consumption and diet composition at the end of the foraging period. However, efforts were terminated after sampling a single bird due to unusual circumstances including low walleye density in the Tamarac River, few birds foraging in the river, and rapid ice out across a broad geographic area which provided alternative foraging areas.

Prior to release, stomach contents were removed using forced regurgitation employing a stomach pump modified from methods described by Wilson (1984). A garden sprayer was used to pump water into the AWPE's stomach to illicit a regurgitation response. The bird was then inverted over a large tub and pressure was applied to the lower abdomen to force regurgitation. If the bird did not regurgitate, the process was repeated. After three attempts, a bird was considered to have an empty stomach. Stomach contents recovered using the stomach pump were examined and all food items were identified. Whenever possible, total length and sex were recorded for each fish. Fish recovered using stomach pumps were classified into two distinct categories based on the degree of digestion. One category included fish that had not been digested or showed only slight digestion of the head. These fish were measured for total length and sexed. The second category included fish that had been highly digested with only the posterior ≈1/3 of the fish remaining. These highly digested fish could not be measured or sexed.

Captured AWPE were weighed to the nearest tenth of a kilogram and a leg bands and

patagial tags were placed on AWPE prior to release.

In 2014 three AWPE were sacrificed after their stomachs had been pumped to

determine stomach pump efficacy. After euthanasia, visual inspection of AWPE

stomachs occurred on site to extract all stomach contents. Captured AWPE were

euthanized using cervical dislocation following methods in the US Geological Survey

Field Manual of Wildlife Diseases: General Field Procedures and Diseases of Birds

(Friend and Franson 1999).

Fish consumption estimates for AWPE were made using the bioenergetics model

for waterbirds from Madenjian and Gabrey (1995). This model uses bird mass to estimate

the daily caloric intake required to maintain the bird's mass and uses 0.80 for an

assimilation efficiency. AWPE masses (n=23) were taken after efforts were made to

remove digested fish from their stomachs, these masses were then averaged and used as

the bird mass input. An energy density for walleye of 6.14 kJ/kg was used from Liao et

al. (2004). This estimate is the mean energy density of walleye during spring, for

individuals exhibiting a total length larger than 305 mm, which are criteria walleye in this

study meet.

Total consumption of fishes was estimated by multiplying total bird foraging days

by the daily consumption estimate from the bioenergetics model. To estimate total

walleye consumed, total fish consumption was multiplied by the proportion of the AWPE

diet that was composed of walleye. Total walleye consumption was then divided by mean

annual natural mortality numbers from 2011 to 2015 provided by the Red Lakes Fishery

Technical Committee (Brown and Kennedy 2016) to estimate the proportion of mean

annual natural mortality that is attributed to AWPE predation on the Tamarac River.

Statistics

A Wilcoxon rank-sum test (Hollander and Wolfe 1999) was used to test if walleye

total lengths from fyke nets (available fish) were similar to walleye collected from the

stomach pump and voluntary regurgitations (consumed fish) and to compare walleye total

lengths between years. A contingency table following methods in Zar (1999) was used to

test if sex ratios between walleye from fyke nets and consumed fish were similar in

defined size classes. Sex ratios were compared within size classes because it was thought

sampling methods may have been biased for AWPE which had consumed larger fish.

Mature female walleye are larger than mature male walleye, and thus a size bias could

have caused artificially high proportions of females in the distribution of consumed

walleye. Comparing fish within defined size classes alleviates this possible bias.

Quartiles from the distribution of consumed fish were used as size classes (330-413, 414-

447, 448-509, and 510-635 mm). Because only one bird was sampled to assess diet in

2015, all previously mentioned statistical analysis on diet were conducted using only diet

data collected in 2014.

RESULTS

AWPE were first detected on the Tamarac River on 20 April, the first day the

river was ice free in 2014. In 2015, AWPE were first seen on 13 April, when ice still

covered portions of the river. In 2014, AWPE abundance peaked on 4 May at 1,198 birds

(95% CI, 1,176-1,219 birds) and, in 2015 it peaked on 15 April at 120 (95% CI, 114-127

birds; Figure 1.2). An estimated total of 15,618 and 920 foraging bird days occurred on

the Tamarac River during the walleye spawning migration in 2014 and 2015, respectively.

Camera trap photos indicated that on average AWPE foraging began at 2028 hours (95% CI, 2021-2035 hours) and ended at 0621 (95% CI, 609-635 hours) during our study period in 2014 (Figure 1.3). In 2015 the mean time when AWPE were first observed foraging was 2048 hours (95% CI, 2035-2101 hours) and were last observed foraging was 0424 (95% CI, 0351-0457 hours; Figure 1.3). On average, AWPE started foraging within 32 minutes of sunset and stopped foraging within 71 minutes of sunrise. Photos indicated that in 2014 AWPE were frequently feeding during this time period, especially in the middle and downstream section of our study area (Figure 1.1). In 2015 the frequency of AWPE in camera trap photos during this time, and in general, was drastically lower. Between 21 April and 14 May a total of 122,217 photos were taken and examined in 2014, in which AWPE were only seen feeding 12 times total outside of the foraging period across all camera traps. In 2015 from 13 April to 24 April 29,608 photos were taken and examined in which AWPE were never observed foraging outside the foraging period.

In 2014, total walleye catches during the first three fyke netting events were low (CPUE = 1.0, 2.5, 1.0 on 21, 25 and 28 April, respectively; Figure 1.2). On 2 May, total walleye catch increased to 39.5 fish/net and continued to increase to 144.0 fish/net on 5 May and peaked on 9 May at 251.5 fish/net. Walleye catch in fyke nets then declined to 30.5 and 13.0 fish/net on 13 and 16 May, respectively. During 2015 walleye abundance throughout the study period was much lower, ranging from 3.7-10.8 fish/net, and did not have a distinct peak (Figure 1.2).

Fyke net catches in 2014 had a significantly smaller proportion of female walleye (χ^2 = 29.96, df = 1, P < 0.001) than 2015 at 11% and 24%, respectively. Mean lengths of female walleye were smaller (W = 2,061, p > 0.001) in 2014 at 467 mm (95% CI, 462-471 mm) than in 2015 at 509 (95% CI, 501-516 mm). Male walleye mean length was also smaller (W = 66,624, P < 0.001) at 417 mm (95% CI, 416-419 mm) in 2014 than 437 (95% CI, 434-440 mm) in 2015. Length-weight regressions for male and female walleye caught in fyke nets were logW= -5.25+3.07*logL and logW= -4.93+2.95*logL, respectively, where W= weight and L= length.

Northern pike and white sucker catches in fyke nets were lower than walleye catches in both years (Figure 1.4). In 2014, the maximum northern pike catch was 17.5 fish/net on 28 April, and maximum white sucker catch of 2.5 fish/net on 16 May. Northern pike catches were highest in the first four trapping events ranging from 11.5-17.5 fish/net. White suckers were first captured in 2014 on 5 May and only caught during three of the last four fyke netting events (range, 1-5 fish). Northern pike abundance in 2015 was lower than in 2014, ranging from 1.3-9.7 fish/net, with the two highest catches in the first two trapping events. White sucker abundance in 2015 followed the pattern of the other two species and was lower in 2015 than in 2014 with catches ranging from 0-1.2 fish/net, with half of the trapping events catching no white suckers.

Water levels in 2014 were much higher than 2015, and resulted in much higher discharges. Mean discharge in 2014 (n=8) was 13.88 m^3/s and -0.32 m^3/s in 2015 (n=3). Negative discharge should be interpreted as the river flowing backwards. Discharge was not used for any calculations, but rather used to demonstrate the vast differences in river conditions between years.

A total of 166 voluntarily-regurgitated fish were collected immediately after AWPE were disturbed during three collection events on 28 April (fish collected n=12), 2 May (fish collected n=44), and 6 May 2014 (fish collected n=110). Only walleye and one white sucker where found in voluntary regurgitations. Mean lengths of regurgitated male and female walleye were 429 mm (95% CI, 425-433 mm) and 507 (95% CI, 500-513 mm), respectively. All regurgitation samples were collected between 2300 and 0230 hours.

All fish recovered from the stomach pump were walleye. The mean number of walleye recovered from AWPE, regardless of digestion category, was 1.0 fish per bird (95% CI, 0.81-1.19 fish per bird; n=22). Total lengths of recovered walleye ranged from 388-601 mm. Mean length of recovered female walleye was 537 mm (95% CI, 525-550 mm) and recovered male walleye had a mean length of 443 mm (95% CI, 415-471 mm).

Nearly all (99.5%) consumed fish were walleye. Mean total length of consumed walleye (464 mm, 95% CI, 459-468) was significantly higher than those collected in fyke nets (423 mm, 95% CI, 422-424; $W = 119{,}243.5$, $P < 0.001$). The proportion of females was higher in consumed walleye (40%) than in fyke nets (11%). Further, when only compared within size classes, AWPE consumed a higher proportion of female walleye than what was observed in walleye captured in fyke nets ($\chi^2 = 47.88$, df = 4, $P < 0.001$; Figure 1.5).

A total of 23 AWPE were captured in 2014, 21 via night lighting and two via gill nets. Two AWPE were not tagged and one did not have its stomach pumped due to an injury and equipment failure. All captured AWPE were breeding-age birds. In 2015 a lack of birds on the river limited our ability to collect AWPE, and thus only one AWPE

was collected in 2015 via shotgun. The mean mass of captured AWPE from both years was 7.81 kg (95% CI, 7.68-7.94).

Two of three sacrificed AWPE yielded no additional fish upon visual inspection. However, one bird had three fish that were not recovered using the stomach pump. Two of these fish were intact and had been minimally digested; the third had been heavily digested. On another occasion, a bird that was not sacrificed had its stomach pumped which yielded no fish, though after it was released regurgitated an intact, slightly digested walleye.

The bioenergetics model yielded an estimated fish consumption of 1.57 kg day^{-1} bird^{-1}. This results in total walleye consumption estimates of 24,397 kg and 1,438 kg in 2014 and 2015, respectively. When these mass estimates are divided by the average weight of consumed fish derived from length-weight regressions (0.868 kg), resulting estimates of individual walleye consumed are 28,119 fish in 2014 and 1,656 fish in 2015. These estimates of walleye consumption account for 1.46% (2014) and 0.09% (2015) of mean walleye annual natural mortality (age $\geq$ 3) for the previous five years (Table 1.1).

DISCUSSION

When large numbers of piscivorous birds congregate they have the potential to impact fish stocks (Rudstam et al. 2004; Fielder 2008; Scoppettone et al. 2014; Teuscher et al. 2015). When this occurs, quantifying consumption by these birds is an important component of well managed fisheries. The ability of fisheries managers to make scientifically sound decisions regarding piscivorous birds and fish stocks will improve as scientific data on such consumption becomes available for multiple fisheries with a wide array of environmental conditions and fish assemblages. Data from this study provides

evidence to suggest AWPE are having little effect on the walleye population in the Red Lakes, MN. Although consumption was 17 times higher in 2014 than 2015, the proportion of mean walleye natural mortality in the previous five years attributed to AWPE predation for each year of the study was extremely low (1.46% and 0.09%, respectively). This level of predation is not likely to be a concern for the vast majority of healthy fisheries. AWPE's influence on walleye stocks in the Red Lakes seems even less concerning when considering how variable natural mortality is in the fishery. For example, year to year variation in walleye natural mortality in the last five years is high, exhibiting a standard deviation of 11.9% of the total (age $\geq$ 3) walleye population (Brown and Kennedy 2016). This means the high AWPE consumption estimate from 2014 would account for less than 3.5% of the typical yearly variation in walleye natural mortality from the mean.

Record high walleye abundance estimates and a mean natural mortality (age $\geq$ 3) of over 34% in the last five years (Brown and Kennedy 2016) would suggest walleye in the Red Lakes are near their carrying capacity. During this same time, mean walleye fishing mortality in the Red Lakes was 11.3% and spawning-stock biomass has exceeded surplus levels (Brown and Kennedy 2016). Therefore, mean total annual mortality for walleye age $\geq$ 3 is over 45%. Compensatory mortality hypothesis suggests mortality rates will stay unchanged at low to moderate exploitation rates by a means of density-dependent population regulation (Anderson and Burnham 1976). Previous studies suggest this hypothesis applies to harvest of both fish and wildlife populations (Anderson and Burnham 1976; Allen et al. 1998). Since the mechanism is presumed to be density dependent, it is suggested that as the population approaches the carrying capacity the

effect of compensatory mortality is greater, which has been supported by Bartman et al. (1992). Thus, given the Red Lakes walleye population is likely at or near carrying capacity, walleye mortality attributed to AWPE predation in this study may have been largely compensatory. If AWPE induced mortality was largely compensatory, it would provide further support that AWPE predation is not having a meaningful effect on the walleye population.

Bioenergetics models are a popular method used to estimate caloric needs of fish and wildlife, but these models are often reliant on assumptions, that when not met reduce the accuracy of the estimate. The bioenergetics model used in this study to estimate daily fish consumption assumes the bird maintains a constant body weight, an assumption that may have been violated. AWPE on the Tamarac River at this time have just completed a migration from the Gulf of Mexico and are also presumably preparing to reproduce, both of which are energetically demanding processes. The necessity for elevated caloric intake likely results in AWPE consuming fish at a level that would increase body weight instead of maintain their current body weight, when possible. Increasing body mass of AWPE violates the assumption of the model and would result in AWPE consuming more than the estimate from the bioenergetics model. An easily accessible, abundant food source during the time of this study likely allowed AWPE to consume large quantities of walleye. On multiple occasions the caudal fin of a walleye was readily observed in the throat of captured AWPE. These birds were likely sated, further supporting a caloric intake greater than the bioenergetics model estimated. Though daily fish consumption may have been underestimated by the bioenergetics model, the estimate was well within the range of consumption estimates from previous studies.

The daily fish consumption estimate of 1.57 kg day^{-1} bird^{-1} in this study was intermediate when compared to consumption estimates in previous studies. The estimate in this study was higher than the estimate from Werner (2004) of 1.0 kg day^{-1} bird^{-1}, which was estimated by observing how many fingerling catfish were consumed in an aquaculture pond. Werner's study was conducted in a 0.6-hectare aviary with aquaculture ponds contained within, and thus AWPE were not able to fly other than extremely short distance and did not have to search for food sources. This almost certainly resulted in lower activity levels and a lower energy requirement than what a free-range AWPE in the wild would experience. In contrast, this study yielded a lower estimate of fish consumption than the 1.98 kg day^{-1} bird^{-1} reported by Hall (1925), which is frequently cited when referring to AWPE fish consumption. However, Hall (1925) does not have a clear outline of how consumption was actually estimated, so a comparison of methods is not possible. Further, Hall (1925) focused on a different subpopulation (birds wintering along the west coast of the US) than Werner (2004) and this study (birds wintering along the Gulf of Mexico), which may account for part of the difference in consumption estimates.

Previous studies on AWPE predation found no size or sex selection (Coppettone et al. 2014; Teuscher et al. 2015), whereas this study provides evidence to suggest AWPE selected for female walleye while foraging in the Tamarac River. Coppettone et al. (2014) and Teuscher et al. (2015) examined AWPE foraging near the mouth of rivers where water levels are shallow and APWE could stand in the water to forage. Conversely, in this study AWPE were foraging several kilometers upstream of the mouth in water too deep to stand and forage. This increases the difficulty of capturing fish and

may make behavioral differences between sexes in fish more likely to result in a sex selection. The mechanism behind a sex selection is unclear, but may be related to female walleye being gravid. Reduced mobility, reduced endurance, and an increased chance of predation in gravid females has been found in other oviparous taxa (Shine 1980; Cooper et al. 1990) and may be present in fishes as well. Further, Ellis and Giles (1965) observed female walleye having lower activity levels than males while spawning. Female walleye being slower and less active than males at the time AWPE are utilizing spawning walleye as a food source appears to be a likely explanation for a sex selection by AWPE.

AWPE exhibit opportunistic foraging habits which allows them to modify foraging behavior spatially and temporally in accordance to the behavior of their prey species (Findholt and Anderson 1995). For example, when prey species are more available at night they are more likely to forage nocturnally. Nocturnal foraging in AWPE has been reported in previous studies (Low et al. 1950; McMahon and Evans 1992; Werner 2004), but observation of nearly exclusive nocturnal AWPE foraging appears to be undocumented prior to this study. AWPE began to congregate and prepare to forage just before sunset, and on most nights AWPE were actively foraging by sunset. AWPE would continue to forage throughout the night and early morning. Foraging was complete by daybreak on most days, though occasionally would continue until just after sunrise. McMahon and Evans (1992) observed both diunral and nocturnal foraging but suggest nighttime foraging is likely a response to increased energetic demands associated with breeding season. This study occurs at the beginning of the breeding season when energy demands are elevated, and focuses on a predominant prey species in which spawning occurs at night (Ryder 1977). Such intensive nocturnal foraging in this study is

likely a response to increased availability of walleye on AWPE foraging grounds at night, and provides evidence to suggest walleye are an important food source at this time.

In addition to data from camera traps suggesting the vast majority of foraging occurred during nocturnal and crepuscular periods, two distinct categories of digestion in fish collected from the stomach pump further support the absence of diurnal foraging. The two categories were interpreted as fish that had been eaten the night of collection and the night prior to collection. Had appreciable daytime foraging occurred, walleye retrieved with the stomach pump should have exhibited continuous degrees of digestion.

The collection of reliable diet data from piscivorous birds when assessing interactions between piscivorous birds and fish stocks is imperative. Ideally such methods would be non-lethal but the stomach pump was not effective at removing all stomach contents. Although the pump successfully removed an unknown portion of stomach contents on several occasions, it was unable to remove all stomach contents in one third of sacrificed AWPE. Often multiple applications of stomach pumps were needed to force regurgitations from AWPE and twice stomach pumping was unable to remove fish that could be seen or felt in AWPE's throat. Further, an AWPE regurgitated a walleye after being stomach pumped and released. As a result, all stomach contents were not removed from at least four of the 22 birds that were forced to regurgitate via stomach pumping. Therefore, the efficacy of the stomach pump to remove all stomach contents in this study is thought to be limited. Duffy et al. (1986) suggest a second application of similar stomach pumps should ensure clearance of stomach contents for species in which the ventriculus is not highly differentiated (which is true of AWPE); however these studies typically had food items that were smaller than in this study. For instance, Wilson (1984)

reported the largest food item being 310 mm, which was smaller than any food item recovered in this study. Food items in this study (mature walleye) were not only larger fish (range = 330-630 mm, interquartile range = 414-509 mm) but also had sharp, rigid dorsal spines. Had food items been smaller and/or lacked fin spines the pump would likely have worked more effectively. Future studies should not consider using stomach pumps to analyze piscivorous bird stomach contents if food items are large and/or have fin spines.

Predicting how predation rates relate to flow conditions is complex, largely because flow conditions which provide favorable foraging habitat for AWPE can result in reduced prey availability. Such is the case in this study, which had one year of high and low flow which correlated with high and low walleye abundance. Vast differences in AWPE abundance between years is likely a response to walleye abundance, with AWPE abundance positively correlated to walleye abundance. Consequently, AWPE predation on the Tamarac River was much lower during the low flow year in this study. This parallels findings by Scoppettone et al. (2014), who reported low flow years resulted in lower APWE predation because Cui-ui (*Chasmistes cujus*) did not attempt a spawning migration, and therefore were unavailable to AWPE. The lack of fish availability to AWPE reported by Scoppettone et al. (2014) was due to an absence of adequate passage to the river, whereas in this study adequate passage was present but lack of flow resulted in little or no warm, turbid water entering the lake to elicit a walleye spawning migration. In contrast to this study and Scoppettone et al. (2014), Teuscher et al. (2015) suggest AWPE predation on Cutthroat trout (*Oncorhynchus clarkii*) is higher in low flow years because trout are more easily captured by wading AWPE. This indicates low flow

conditions can result in increased or decreased predation rates by AWPE, depending on the system and the magnitude in reduction of flow. Further, it demonstrates AWPE ability to respond to, and capitalize on, increases in prey availability and/or vulnerability due to flow.

This study provides evidence to suggest the effect of AWPE predation on the walleye fishery of the Red Lakes during the time of this study was small and currently appears to not warrant management action or concern. High variability in walleye natural mortality and low AWPE-induced walleye mortality suggest factors other than AWPE predation currently regulate the abundance and natural mortality of the Red Lakes' walleye population. However, if a scenario arises in which walleye stocks decline to levels of concern while AWPE predation in the Tamarac River remains at or above its current level, managers should consider reevaluating the potential impact of AWPE on the mature walleye population.

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Table 1.1. Estimates of total kilograms and numbers of walleye consumed by American white pelicans on the Tamarac River, MN during the spawning migration, and percent of the mean walleye natural mortality for the previous five years in the Red Lakes.

Year	Bird Days	Walleye Consumption		5 Year Mean % Natural Mortality
		Kilograms	Numbers	
2014	15,618	24,397	28,119	1.46
2015	920	1,438	1,657	0.09

Figure 1.1. An aerial photo of the Tamarac River with a gray box defining the 5.5-km river reach where the highest American white pelican activity occurred.
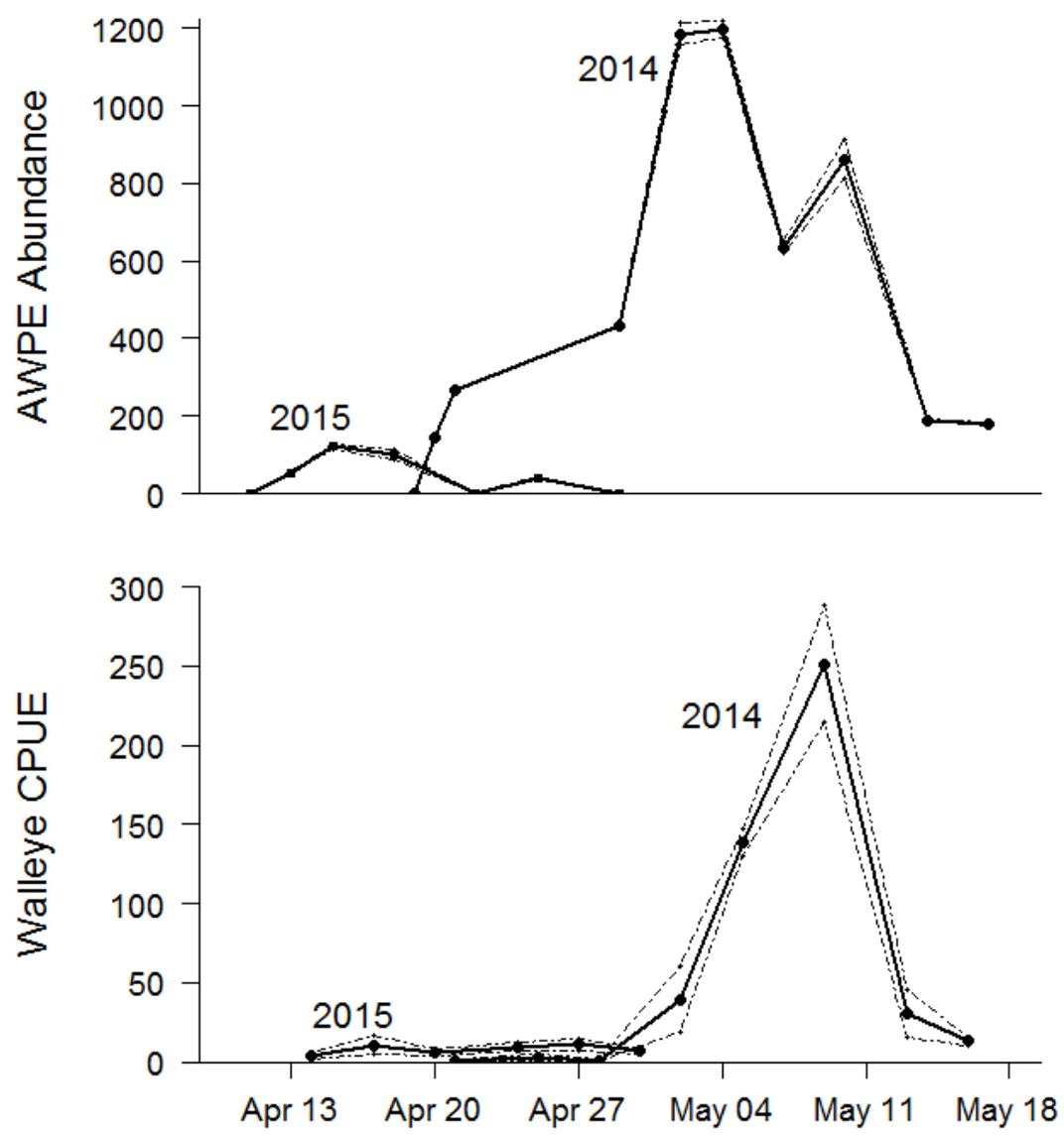
Figure 1.2. American white pelican abundance (AWPE) and walleye catch per unit effort (CPUE) for 2014 and 2015 demonstrating the timeline and abundance of both species in both years, mean abundances are represented by black lines and 95% confidence intervals are represented by gray hashed lines.
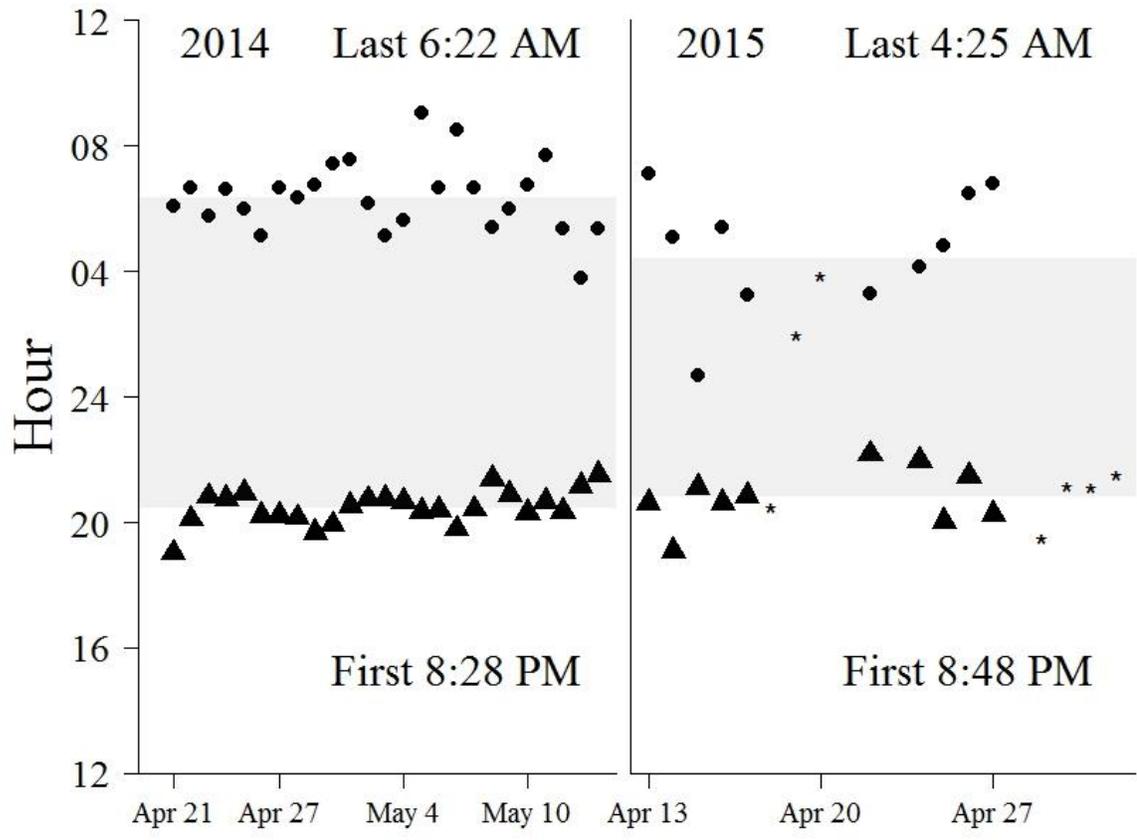
Figure 1.3. Foraging times for American white pelicans in both years of the study with grey shaded regions representing the mean foraging period. The mean time of first and last seen foraging American white pelican are labeled. Triangles, circles, and asterisks represent observed first bird seen foraging, last bird seen foraging and only bird seen foraging, respectively.
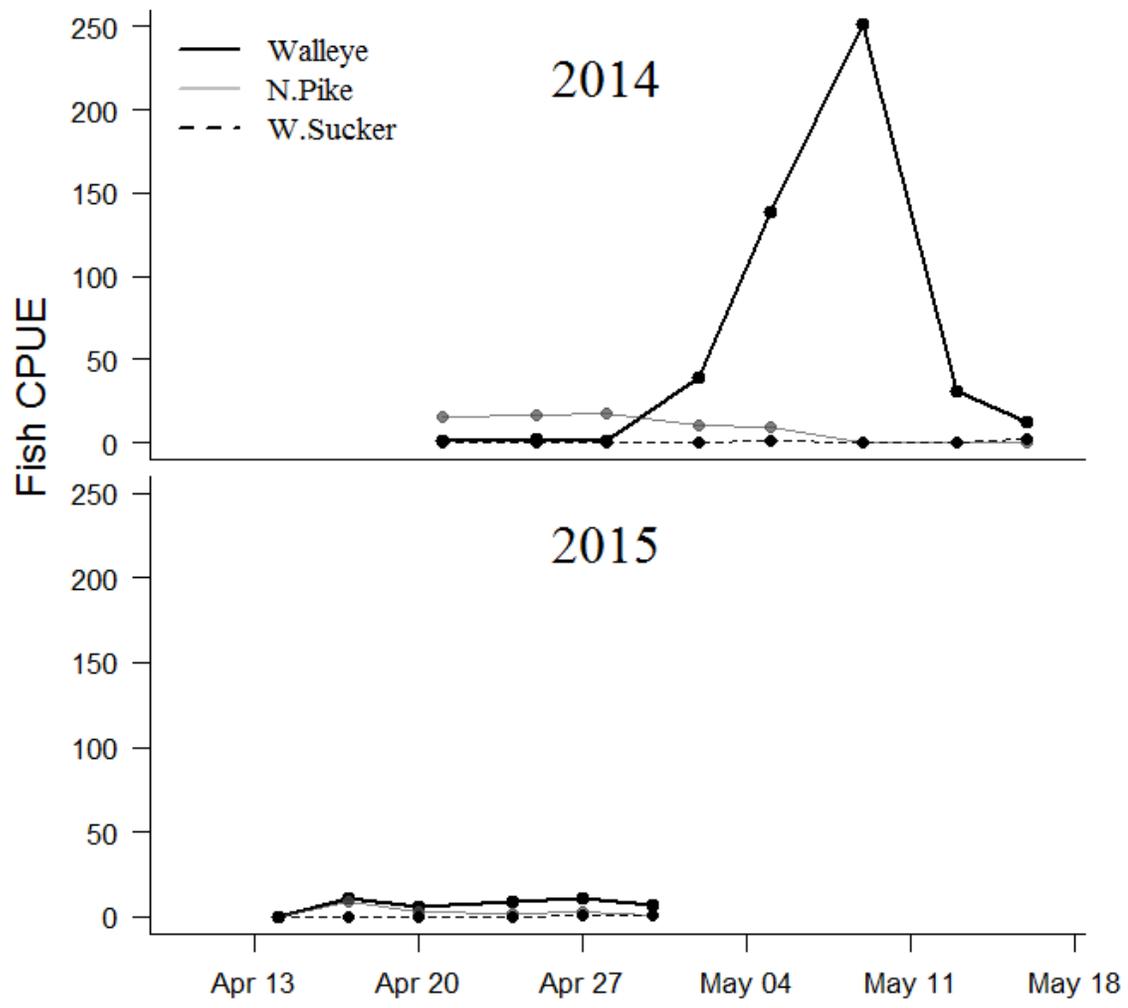
Figure 1.4. Fyke net catch per unit effort (CPUE) for all three species of fishes with spawning migrations in the Tamarac River during the spring 2014 and 2015. Black solid lines represent walleye, grey lines represent northern pike, and black dashed lines represent white suckers.
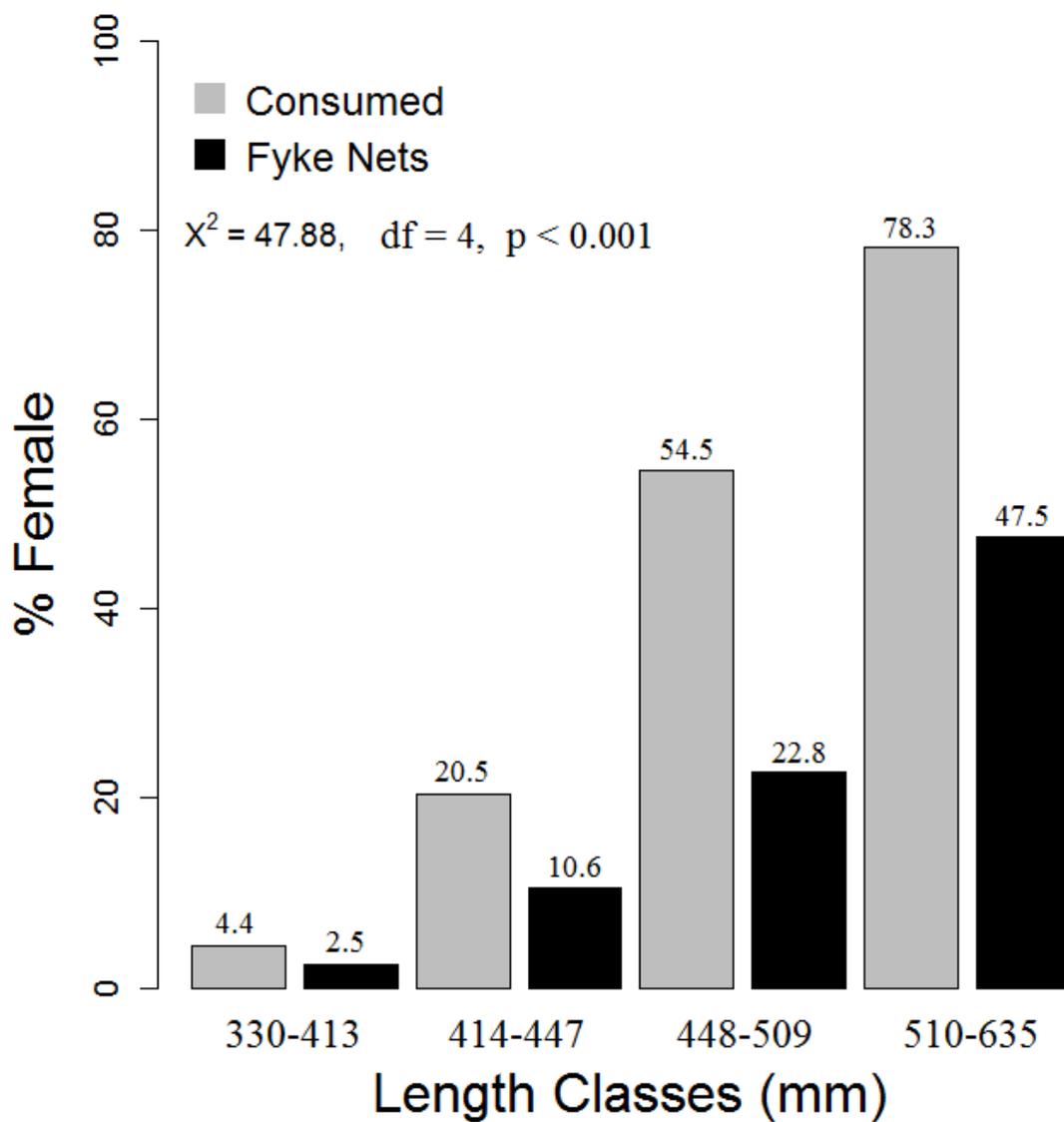
Figure 1.5. Percent female of walleye consumed by American white pelicans and available walleye (those captured in fyke nets) within defined size classes.

Chapter 2: Assessment of Side Scan Sonar Habitat Mapping and Quantity of Accessible Walleye Spawning Substrate in a Northern MN River

Abstract.- Evaluating aquatic habitats is an important component of many ecological studies and natural resource assessments. Traditional habitat evaluations are time and labor intensive, and do not provide continuous data. Recently, techniques using side scan sonar (SSS) have been developed to provide a low cost method which collects continuous aquatic habitat data. This study employed SSS mapping to quantify suitable spawning substrate available to walleye (*Sander vitreus*) during spring spawning migrations in the Tamarac River, MN. The Tamarac River is a major tributary of the Red Lakes, MN an economically important walleye fishery. Evaluation of possible limitation was performed by calculating the number of females required to produce enough eggs to saturate suitable substrate. Sonar images were taken of the Tamarac River and used to create a sonar map which was delineated by substrate type. An evaluation of SSS thematic accuracy was conducted using reference points classified in the field. Overall thematic accuracy of the SSS map was 78.0%, and the proportion of reference points predicted as suitable using the SSS map was not significantly different than the proportion of observed suitable reference points. The total area of suitable substrate accessible to walleye was 26,398 m^2 and could theoretically support 106,291 females. This study demonstrates that SSS habitat mapping is an efficient and cost-effective method to acquire quantitative and qualitative freshwater habitat assessment data.

INTRODUCTION

Assessment of aquatic habitats provides useful information for a variety of ecological applications. Assessing components of abiotic habitat present in a system, and where specific conditions occur, yields insight into what biotic communities may be

present and where certain taxa will likely be found (Knapp et al. 1998; Jackson et al. 2001; Bornette and Puijalon 2011). Further, determining where certain habitat occurs aids in estimating the ability of certain taxa to grow, develop, survive, and reproduce (Knapp et al. 1998; Jackson et al. 2001; Hafs et al. 2014). An important component of reproduction in fishes is the availability of suitable spawning habitat, with reduced quantity and quality of spawning habitat having been linked to reduced egg deposition, egg survival, age-0 abundance, and recruitment to the adult population (Johnson 1961; Dombeck et al. 1984; Knapp et al. 1998). Thus, estimating the quantity and location of suitable spawning habitat is an important component when assessing reproductive success of fishes.

River habitat has typically long been evaluated and mapped using techniques which traditionally consist of taking measurements visually or physically at points, transects, or grids throughout the river (Fitzpatrick et al. 1998; Maddock 1999; Hafs and Gagen 2010). These techniques require extensive time and effort in the field and result in a tradeoff between level of detail and size of area being mapped (Maddock 1999). In addition to this trade off, traditional techniques typically do not produce continuous data, thus areas not evaluated must be inferred from areas which have been evaluated. Traditional techniques can also be limited by both water depth and turbidity. Recently, techniques have been developed using relatively inexpensive recreational side scan sonar (SSS) units and GIS software, which are not limited by deep or turbid water, to effectively map and evaluate freshwater habitats (Edsall et al. 1989; Kaeser and Litts 2008; Kaeser and Litts 2010; Kaeser et al. 2012).

Previous freshwater SSS studies have evaluated and/or quantified variables including sedimentation, large woody debris, substrate type, fish abundance, and fish spawning substrate (Edsall et al. 1989; Barton 2000; Kaeser and Litts 2008; Manly and Singer 2008; Kaeser and Litts 2010; Kaeser et al. 2012). Kaeser et al. (2010) reported time in the field for data collection when river mapping using SSS to be 11 min/km, and total map making time to be ≈3hr/km, which was ≈1/10 of the time required when using transect based techniques. Reported overall thematic accuracy when using SSS to evaluate substrate type in freshwater habitats ranges from 53 – 84% (Kaeser and Litts 2010; Kaeser et al. 2012, Koeller 2014). However, the number of studies in the literature which provide accuracy assessments of the technique in freshwater systems is fairly small. Furthermore, the diversity of freshwater systems which have had accuracy assessments is relatively low. Therefore, studies evaluating SSS habitat mapping in freshwater systems with varying morphologies and hydrology will supplement the expanse of current scientific knowledge regarding the technique and increase potential robustness of future analyses using the technique.

Using SSS to identify and quantify areas containing suitable spawning habitat requires an understanding of what environmental variables constitute suitable spawning habitat. The U.S. Fish and Wildlife Service synthesizes habitat suitability indices for many game and non-game species based on compiled research literature and expert reviews (Schamberger et al. 1982). One such habitat suitability index has been constructed for walleye (*Sander vitreus*), which suggests two major factors affecting reproductive success of walleye are water temperature regime and the quality and quantity of suitable substrate (McMahon et al. 1984). The substrates most suitable for

walleye spawning have been determined to be those with diameters between 2.0 – 250.0 mm, which can be categorized as gravel, pebble, and cobble using the sediment classification scheme from Wentworth (1922). In systems where walleye naturally reproduce, mapping and quantifying areas of suitable spawning substrate can aid in quality management of walleye stocks. The benefit of such assessments is magnified when the system is completely sustained by natural reproduction.

The walleye fishery of the Red Lakes, MN is economically important and supports popular recreational and commercial fisheries. During the 2014 harvest year recreational and commercial harvest of walleye exceeded 700,000 walleye (Brown and Kennedy 2015). The fishery is currently at record high levels of walleye abundance, and is completely supported by natural reproduction (Brown and Kennedy 2015). Although comparative quantification of migrations in other Red Lakes tributaries has not been conducted, the Tamarac River is presumed to support the largest walleye spawning migrations. The mean walleye catch at the Tamarac River egg station between 1927 and 1979 was 203,066 individuals, and reached as many as 646,161 (Groshens 2000). Furthermore, mean spring electrofishing survey catch rates over the last ten years were 638 fish/h during the spawning migration (Brown and Kennedy 2016). The size of historic migrations in the Tamarac River and current electrofishing catch rates provide evidence to suggest reproduction in the river may be an important component of Red Lakes walleye reproduction. However, assessments of quantity and quality of spawning habitat and reproductive success in the river is lacking.

Previously, two evaluations by the Minnesota Department of Natural Resources have been conducted to assess walleye reproduction in the Tamarac River (Fraune and

Scidmore 1963; Groshens 2000). Fraune and Scidmore (1963) reported egg deposition in all locations where walleye were observed in the Tamarac River, with heavier deposition on areas containing gravel or cobble and few or no eggs deposited on pure sand or areas in which gravel was thinly scattered. This demonstrates that coarse substrate is one of the most significant variables defining suitable walleye spawning habitat, which is consistent with previous studies of walleye spawning (Colby et al. 1973; Scott and Crossman 1973; McMahon et al. 1984). A coarse-scale substrate map was produced for the Tamarac River by Fraune and Scidmore (1963) with the majority of areas containing suitable substrate being in the upstream portions of the river and its tributaries. The map was very generalized and classified reaches of river several kilometers long, including the entire reach mapped in this study, as being a combination of two or three substrates. This map provides no insight into the quantity or location of coarse substrates in each reach. This is likely an artifact of traditional river habitat evaluation techniques requiring extensive time and effort in the field to produce detailed maps. The vagueness of substrate classification may also be the result of an inability to sample due to unwadable water depths in certain areas and low water clarity. River bottom could not be visually assessed because of low water clarity at most locations, except in the sections far upstream of where beaver (*Castor canadensis*) dams inhibited walleye passage (Fraune and Scidmore 1963).

Both previous assessments of walleye reproduction in the river stated that walleye movement upriver was eventually inhibited by the presence of beaver dams. The dams preventing walleye passage in both studies were in different locations and, during the time of this study a beaver dam further downstream than in either of the previous reports

was a barrier to walleye migration. The presence of beaver dams that inhibit walleye migration in different locations during different years suggests the quantity of suitable spawning habitat accessible to walleye varies temporally based on the size and location of beaver dams in combination with flow conditions.

The acquisition of accurate continuous substrate data, low time and effort in the field, and an ability to sample in un-wadable water with poor clarity make SSS mapping an ideal technique to provide data which greatly improves current knowledge of walleye spawning substrate in the Tamarac River. In addition, SSS mapping provides more sophisticated and detailed digital maps than those produced using traditional techniques. Substrate mapping using SSS in the Tamarac River also provides an opportunity for evaluation of the use of SSS to accurately map habitat in a river system with different hydrology and morphology than those in previous studies. Assessing the use of SSS in an application with a specific management oriented goal will provide insight regarding the validity of SSS habitat assessment in freshwater resource management. Therefore, the objectives of this study were to (1) assess the thematic accuracy of the SSS map, (2) quantify suitable walleye spawning substrate in the 10.8 km reach accessible to walleye in the Tamarac River during the spring of 2015, and (3) compare map production techniques to those used in previous studies.

METHODS

Study Site

The Red Lakes are the largest body of water by surface area contained within Minnesota borders at over 116,550 hectares (Figure 2.1). The Tamarac River is the main tributary to the upper basin of the Red Lakes and flows 34.9 km into the northeast corner

of the basin (Groshens 2000). The river's drainage encompasses 815 km^2 including a

portion of a 1,295 km^2 peat bog, the largest in the lower 48 states (Groshens 2000). The

drainage is primarily wetlands but approximately 35% of the watershed is forested

(Groshens 2000). The river has a low gradient with substrates ranging from silt to cobble

but is dominated by silt and sand (Fraune and Scidmore 1963; Groshens 2000). Water

depths typically measure around one meter but can reach depths over three meters near

the mouth. This study focused on the 10.8 km of river upstream of the mouth (Figure

2.1).

A recreational-grade Humminbird 1199ci HD sonar unit (cost ≈$2,000) was used

to collect sonar images, with the transducer mounted on the bow of the boat to eliminate

the effect of prop-wash. All sonar images of the Tamarac River riverbed were collected

in the same day during the fall of 2015. A frequency of 455 kHz was used following

setting recommendations in Kaeser et al. (2012). The range setting used in this study was

lower than that recommended by Kaeser et al. (2012) because it provided more than

adequate bank to bank coverage, and Kaeser et al. (2012) reported a strong linear

relationship ($r^2 = 0.89$) between range and the proportion of areas classified as unsure due

to poor resolution in areas approaching the maximum range. Therefore, so long as bank

to bank coverage is achieved, a lower range setting should increase accuracy by

increasing image resolution.

Sonar images were taken moving downstream from the upstream-most portion of

the study area, where boat passage was inhibited by a large beaver dam, to a boat access

approximately 200 m from the mouth of the river (Figure 2.1). Sonar "snapshots" and

associated GPS waypoints were taken such that each image contained overlap of the

previous to ensure complete coverage of the river and a continuous sonar image of the riverbed similar to methods described by Kaeser and Litts (2010). The boat was positioned as close to stream center as possible and speed was kept between five and eight km/h (3-5 mph) following methods described by Kaeser and Litts (2010) and Kaeser et al. (2012).

Reference data points were collected during late spring of 2015 using a rough grid pattern, where substrate was classified every ten paces at approximately 25, 50, and 75% of the stream's width in the upstream most 1.6 km of the study area. This section of the river was chosen because the water depth allowed for the collection of the highest number of reference points. During the spring and summer of 2015 the Tamarac River and its watershed experienced very low precipitation, thus discharge was low so shifts in substrate composition during the summer were unlikely. At each point, substrate was identified as being suitable or unsuitable and a GPS waypoint was taken using a Garmin eTrex 20 GPS unit. Substrate class was determined by tactile sensation and rotation of a wooden rod to determine substrate type. If there was uncertainty in which category the substrate should be classified as following previously described methods, a small sample was retrieved with a shovel, placed on a piece of wood with a 2 mm measurement marked and visually assessed to determine if the mean diameter was greater than 2 mm.

Suitable habitat was defined as having a predominant substrate with diameters > 2 mm, and unsuitable habitat being defined as having a predominant substrate with diameters < 2 mm. McMahon et al. (1984) suggest substrates with diameters between 2 and 250 mm were the most suitable substrates for walleye spawning, but considering the Tamarac River is located in a large peat bog and has a low gradient it is highly unlikely to

contain substrates with diameters > 250.0 mm. This was supported both by observations from the investigators for this study and previous assessments of the river (Fraune and Scidmore 1963; Groshens 2000). Therefore, a maximum threshold for suitable substrate diameter was not applicable or necessary.

Each raw sonar snapshot was processed manually to remove all metadata and areas of no-data (Figure 2.2). After images were processed, ArcGIS 10.3 (Environmental Systems Research Institute; ESRI), was used to georeference sonar images using control point matrices. All georeferencing, digitization, and delineations in this study were conducted using Universal Transverse Mercator (UTM) Zone 15 and the 1984 World Geodetic System datum (WGS 1984). An iterative process was used to select the number of control points to use per image, where the number of control points was increased until the addition of control points appeared to provide minimal benefit to accuracy. Fourteen control points per image were used for georeferencing, with control point matrices consisting of six control points along each bank and one at both the upstream and downstream edge of the sonar image (Figure 2.3). Control points for sonar images were generated from GPS points recorded by the SSS at the time each snapshot was taken and by then generating control points at equal intervals along both the edges of the sonar image and the river edges on the world imagery layer provided by ESRI in ArcGIS, which provides imagery with a resolution of < 0.3 m at our study site (ESRI 2016).

Sonar images typically represented 36.9 m (mean) of river, at this scale river curvature was generally uniform and spline transformation was chosen based on its appropriateness for the method with which control points were generated (Figure 2.3), and its low root mean squared error. All sonar images occurring in the reference site were

georeferenced for thematic accuracy assessment. The remaining sonar images were

assessed in their raw form and only images containing areas of suitable substrate were

georeferenced. Images not containing suitable substrate were not georeferenced to reduce

processing time which would yield no benefit to the habitat map. River boundaries were

digitized using the world imagery layer provided by ESRI (2016). Field survey, image

processing, and georeferencing times per km mapped were calculated to provide an

estimate of mean time required for each process. Image processing and georeferencing

time were calculated by timing a subset of each process and multiplying it by the mean

number of images/km mapped.

The habitat classification scheme used to classify substrates from sonar images

consisted of the two simple classifications used for reference data, either suitable or

unsuitable. The ability to interpret sonar signatures and accurately classify substrates into

their respective categories was attained by examining the signatures of substrates that

were confirmed visually or physically in water bodies with a variety of substrate types.

Sonar signatures from previous studies were also examined. Substrate type was assessed

for sonar images following methods similar to those described by Kaeser and Litts

(2010), which used intensity of return (tone), texture, and pattern to differentiate between

substrate classes (Figure 2.4). Using these characteristics, areas containing suitable

habitat were delineated and saved as an ESRI shapefile. This shapefile was merged with

the digitized river boundary to produce a layer with two polygons, one representing

suitable substrate and one representing unsuitable substrate. From this layer the total area

(m^2) and percent area of the river containing suitable substrate were calculated using the

"calculate geometry" tool in ArcGIS. The quantity and proportion that was suitable and unsuitable in each half km reach of the study site were calculated.

To assess the ability to predict the correct substrate class at any given point using the SSS map, reference points representing suitable substrate were "clipped" from the shapefile of delineated suitable substrate from the SSS map. The number of reference points representing suitable substrate that were predicted correctly and incorrectly was calculated. The same procedures were followed for reference points representing unsuitable substrate. These data were entered in an error matrix (Table 2.1). The error matrix was used for statistical analysis, which included calculations of overall, user's, and producer's accuracies. Producer's accuracy (omission errors) was calculated as the proportion of reference points in a category which were classified correctly by the SSS map (Congalton 2005). User's accuracy (commission errors) was calculated as the proportion of points from the SSS map in a category which were classified correctly (Congalton 2005). Overall accuracy was the proportion of all reference points which were classified correctly. Misclassified reference points were assessed to evaluate if spatial inaccuracy of the GPS unit and/or SSS map were likely sources of misclassification. This was performed using the "spatial join" and "buffer" tools in ArcGIS to calculate the distance from misclassified points to polygons that would have classified them correctly, and the area of a 3.0-meter buffer (manufacturer reported accuracy of GPS unit) which overlapped a polygon that would have resulted in a correct classification.

The estimate of total area of suitable substrate from the SSS map was used to calculate the quantity of spawning stock biomass (SSB) required to saturate all accessible

suitable substrate in the river. Egg production in female walleye is proportional to body mass with a typical production of 60,000 eggs/kg (Nickum 1986), with a mean egg diameter of 2.0 mm (Smith 1941; Colby et al. 1979). Stacking of eggs has been shown to reduce fertilization rates in laboratory settings (Moore 2003), and would likely increase the chance of transport and ensuing siltation, abrasion, and predation which are the presumed causes for reduced egg survival on finer substrates (Bozek et al. 2011). Assuming homogeneous egg distribution, it would take 250,000 eggs to cover each square meter of suitable substrate without stacking. Thus, every square meter of suitable substrate could support egg production from 4.17 kg of SBB, which was multiplied by the total area of suitable substrate from the SSS map to estimate the quantity of SSB required to saturate all suitable substrate. This estimate was compared to mean kg of SSB in the Red Lakes over the last ten years (Brown and Kennedy 2015) to estimate the proportion of total SSB in the system required to saturate suitable substrate in the river.

Mean mass of female walleye migrating the river was calculated and used to estimate mean egg production of females in the Tamarac River, and ultimately the number of females that would be required to saturate suitable substrate with eggs. To determine mean body weight of female walleye migrating the Tamarac River, overnight fyke net sets were made every third day during the 2014 and 2015 spawning migrations. All female walleye (n=168) were measured for total lengths and a subsample (n=113) were weighed to establish a weight-length relationship following methods described by Anderson and Neumann (1996). Overall abundance of walleye migrating the Tamarac River has not been quantified since 1979. Therefore, mean abundance between 1927 and 1979 from Groshens (2000) and mean proportion of walleye migrating the Tamarac River

comprised of females during the previous ten years from Brown and Kennedy (2016) was used to provide insight regarding how large current migrations would need to be compared to historically to saturate suitable substrate.

Statistics

Overall accuracy and a 95% confidence interval, user's accuracies, and producer's accuracies were calculated from an error matrix for the SSS map (Congalton 1991; Congalton and Green 1999). The ability to predict substrate type using SSS better than random was determined by performing a Kappa analysis (Congalton 1991; Congalton and Green 2009). Pearson's chi-squared tests were performed using program R (R Core Team 2014) to assess non-site specific thematic accuracy, and producer's and user's accuracies between substrate types. Assessment of possible bias towards either class when delineating transitions from suitable to unsuitable substrates was performed using Wilcoxon Rank-Sum tests in program R (Hollander and Wolfe 1999, R Core Team 2014).

RESULTS

A total of 10.8 river km were mapped in this study, over which 293 sonar snapshots were taken containing 315,275 m^2 of riverbed (Appendix A). The estimate of substrate classified as suitable for walleye spawning using the SSS map was 26,398 m^2, which was 8.4% of total riverbed area (Appendix A). The reach with the largest quantity of suitable substrate was between river km 3.5 and 4.0 with 3,386 m^2 of suitable substrate, which was 16.5% of the total area of that reach (Figure 2.5). The reach between river km 10.0 and 10.5 contained the highest percentage of its area which was suitable substrate at 34.1% (Figure 2.5). Georeferencing was the most time intensive processes of

sonar map production (3.82 h/km, n=39) followed by image processing (16.87 min/km, n=50). SSS field survey time was the least time intensive process in map production (9.41 min/km). A total of 598 reference points were collected with 218 representing suitable substrate. Eight polygons representing suitable substrate were delineated in the reference site using the SSS map ranging in size from 98.6-3,047.8 m^2.

Within the reference site, only one polygon delineated as suitable substrate did not contain reference points representing suitable substrate. This was the smallest polygon (98.6 m^2) and had two reference points representing suitable substrate 0.09 and 0.26 m from its border, well within the 3.0 m error level of the GPS unit used. The majority of misclassifications (67.4%) occurred in close proximity (< 3.0 m) to polygons that would have classified them correctly (Figure 2.6). Median distance to correct classification polygons for suitable points misclassified by the SSS map was 2.6 m (interquartile range, i.e. IQR $= 0.7 – 6.9$ m), and 1.6m (IQR $= 0.8 – 2.9$ m) for misclassified unsuitable points (Figure 2.6). The median distance of correctly classified points (6.6 m) was significantly higher than the median distance for all misclassified reference points (1.8 m) to a SSS delineated substrate transition, indicating misclassifications were frequently associated with substrate transitions ($W = 48,085$, $P < 0.001$). Median area of the 3.0 m buffer overlapping polygons with the correct classification for misclassified referenced points for suitable and unsuitable points were 8.7 m^2 (IQR $= 4.9 – 11.6$ m^2) and 7.4 m^2 (IQR $= 3.8 -11.3$ m^2), respectively. Neither distance to, nor area of buffer overlapping the correct classification polygon was significantly different between substrate classes ($W = 2,453$, $P = 0.07$; $W = 907$, $P = 0.53$, respectively).

The ability to predict substrate type at reference points using the SSS map was significantly better than random and had moderate agreement with reference points ($K =$ 0.54, 95% CI = 0.47 – 0.61, $P > 0.001$). The percent of reference points classified as suitable using the SSS map (41.8%) was higher than observed in reference data (36.8%). Though, the percent of points classified as suitable using the SSS map was not significantly higher than reference data ($\chi^2 = 3.37$, df = 1, $P = 0.066$), which suggests non-site specific thematic accuracy was high. Producer's accuracy was similar for both substrate types at 76.8% and 78.6% for suitable and unsuitable substrate respectively, and were not significantly different ($\chi^2 = 0.16$, df = 1, $P = 0.692$). Conversely, user's accuracy was significantly lower for suitable substrate (67.6%) than unsuitable (85.3%; $\chi^2 = 25.61$, $df = 1$, $P < 0.001$). Overall site-specific thematic accuracy for the SSS map was 78.0% (95% CI = 72.4 – 85.4; Table 2.1).

Using theoretical egg distribution of a single layer of eggs deposited over all suitable substrate, the estimate of total area containing suitable substrate could support 109,992 kg of SSB. This quantity of SSB would represent 15.4% of mean SSB present in the system over the previous 10 years. Mean mass of female walleye that migrated the Tamarac River was 1.03 kg, and thus 106,291 females would be required to achieve egg saturation. If the size of current migrations is equal to the historical mean, 52.3% of the migration would have to be composed of females, or if current proportion of females (9.7%) is used a total run of 1,095,780 walleye would be required to saturate suitable substrate.

DISCUSSION

The acquisition of remotely-sensed continuous data in freshwater habitats using SSS provides a cost-effective means of habitat mapping. This technique has potential to collect numerous types of data (e.g. substrate, depth, fish counts, large woody debris etc.), though published literature using this technique remains sparse. The SSS map produced in this study provided accuracy likely acceptable for most habitat assessments. Further, the use of SSS enabled the acquisition of an immense quantity of data, which was considerably more than what would have been obtained using traditional habitat assessment techniques in a fraction of the time in the field. Equipment and software used to produce the SSS map are typically readily available to, or well within budgets of, the majority of government agencies, academic institutions, and groups interested in performing aquatic habitat surveys.

The statistical similarity in the proportions of observed and predicted suitable reference points and relatively high overall thematic accuracy indicate the estimated area of suitable substrate was fairly accurate. Furthermore, quantification of suitable substrate in the study site using the SSS map is likely more accurate than what would have been produced using traditional transect or grid based techniques. Overall thematic map accuracy in this study (78%) was near the upper end of the range reported from previous studies (53-84%; Kaeser and Litts 2010; Kaeser et al. 2012, Koeller 2014). Relatively high overall accuracy was presumably due to a simple two category classification scheme. The majority (67.4%) of misclassified points occurred less than 3.0 m from the correct polygon class, which provides evidence to suggest major sources of misclassification were the spatial accuracy associated with the SSS map and GPS unit.

Also, an inability to accurately define transitions between suitable and unsuitable substrates, particularly transitions from sand to gravel, was likely a major contributor to classification errors. This is similar to findings from Kaeser and Litts (2010), which reported sand and gravel having similar sonar signatures and suggested distinction between fine rocky substrate and sand as "a noteworthy source of misclassification". This is consistent with what was observed in this study where areas of sand and gravel often appeared similar and were the most difficult distinctions in assessment of sonar signatures. When this occurred, the presence of ripples or "dunes" (Figure 2.4) was interpreted as an indication of sand (Kaeser and Litts 2012). The simple classification scheme used in this study likely mitigated inaccuracy due to misclassification of substrates near the classification threshold (2 mm diameter) because larger substrates, like cobble, are unlikely to be mistaken for silt or sand.

Sonar images in this study were individually processed, providing the benefit of all areas of no-data outside the river channel and in the water column having been removed. This results in the sonar image fitting in the river channel with the riverbanks visible, and making the method of georeferencing much easier. This methodology also provides a more accurate estimate of area assigned to substrates than those used in previous studies (Kaeser and Litts 2012; Kaeser et al. 2015), because the water column is not classified as types of substrate. The area displayed as the water column is proportional to the current water depth, thus classification of the water column as a substrate type results in overestimating the area of substrate assigned to the water column in proportion to water depth. Further, an increase in spatial accuracy proportional to water depth occurs when the water column is removed because the GPS on the SSS unit

records the location of the boat directly in the middle of the water column. Therefore, any point is displayed increasingly further laterally from its true geospatial location as water depth increases. Image processing in this study contrasts methods used in previous studies (Kaeser and Litts 2012; Kaeser et al. 2015) largely because sonar images were individually processed to remove no-data.

One significant drawback to individually processing images is an increased processing time. Removal of meta/no-data in individual images comprised a significant portion of the processing time associated with map production in this study, and is not logistically feasible for large scale assessments like the one conducted in Kaeser et al. (2012), which required image processing and georeferencing of sonar images for over 20 times the river km performed in this assessment. Further, depending on the intended application of sonar maps, removal of no-data may not be necessary. For example, if the goal is simply to provide a general idea of what substrate or large woody debris is present but quantification and spatial accuracy is not imperative.

Similar to image processing, georeferencing of sonar images was done for individual sonar images. Though time consuming, this method was used because of its relative simplicity which did not require the use of algorithms or require any script writing. Although customized algorithms used in previous studies (Kaeser and Litts 2010; Kaeser et al. 2012) provide a systematic semi-automated process for generating control point matrices with possibly higher precision than those produced in this study, they require a fairly intimate knowledge of the programming language. These skills are not common to natural resource managers and researchers. The georeferencing method used in this study used point and click tools readily available in ArcGIS, a method which

likely has a much lower entry skill and knowledge requirement with a less-steep learning curve. Therefore, depending on the purpose of the study, future investigators using SSS to map freshwater habitat may prefer the method used for georeferencing in this study for its ease of use and simplicity. Ultimately, the nature of the ecological application for which a map is being produced, size of area to be mapped, and the programming skill level of the map producer will all factor into the decision of which image processing and georeferencing methodology will be most appropriate to produce the desired map.

Considering the majority of spawning substrate has been reported to occur upstream of what was accessible to walleye during the time of this study, the possibility of a low quantity of accessible spawning substrate limiting reproductive success became a point of management interest. If current migrations are equal in size to historic records, the number of females needed to saturate substrate would require walleye that migrated the river to be comprised of 52.3% female, which is over five times higher than the previous ten-years' mean of 9.7% (Brown and Kennedy 2016). Migrations being comprised of over 50% female appears more unlikely considering age at 50% maturity for male and female walleye in the system over the previous ten years are 2.9 and 4.7 years, respectively (Minnesota Department of Natural Resources, unpublished data). This difference in age to maturity should result in a considerably higher proportion of males being reproductively mature, which is supported by sex ratios observed in the river. Alternatively using current sex ratios, current migrations would need be composed of 1,095,780 walleye to reach egg saturation, which is 1.7 times larger than the largest historic migration and over five times larger than the historic mean.

Since no quantification of the migration has been done recently and there are not historic estimates of population size in the system, evaluating if it is reasonable that current migrations are over five times larger than historic mean is not possible. However, the previously mentioned estimates of the size of migrations and sex proportions required to saturate suitable substrate provide data useful when evaluating if substrate is a possible limiting factor of reproductive success. It is also necessary to consider walleye likely select for the best substrate and would violate the assumption of homogeneous distribution of eggs. Therefore, these estimates of number of females and quantity of SSB required to saturate suitable substrate are intended to provide reference points rather than direct reflections of reproductive success.

Beaver dams limiting fish passage in previous Tamarac River studies were observed further upstream where larger quantities of suitable substrate were suggested to exist (Fraune and Scidmore 1963; Groshens 2000), and thus more suitable substrate would have been accessible. The beaver damn location during the time of this study is less than 0.5 km from the site for annual electrofishing surveys, so it is unlikely a beaver dam would occur and remain intact further downstream. This provides evidence to suggest the quantity of suitable substrate quantified in this study is likely in the low range of what is accessible to walleye in the Tamarac River in a given year. When all relevant data and information is considered, it is possible access to suitable spawning substrate could limit reproductive success if migrations were much larger than historical migrations and accessible substrate was near its minimum.

Substrate mapping using SSS provided acquisition of a much higher quantity of data than what would have been feasible using point or transect based techniques.

Further, thematic accuracy of the SSS map was sufficient to conduct the intended habitat evaluation. Access to suitable spawning substrate limiting reproductive success in the Tamarac River would require large portions of the systems current total SSB and migrations much larger than what had been observed historically. This study demonstrates the successful application of SSS to effectively answer a specific fisheries management question and provides a methodology to be considered by future researchers and managers when conducting aquatic habitat assessments.

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Table 2.1. Error matrix for the side scan sonar map produced for the Tamarac River displaying overall, user's, and producer's accuracies, with grey shaded boxes representing correct classifications.

Classified Data	Reference Data		Total	User's Accuracy
	Suitable	Unsuitable		
Suitable	169	81	250	67.6%
Unsuitable	51	297	348	85.3%
Total	220	378	598	
Producer's Accuracy	76.8%	78.6%		Overall Accuracy = 78.0%

Figure 2.1. Aerial imagery of the Red Lakes (A) and the Tamarac River (B) with the study site outlined in black.
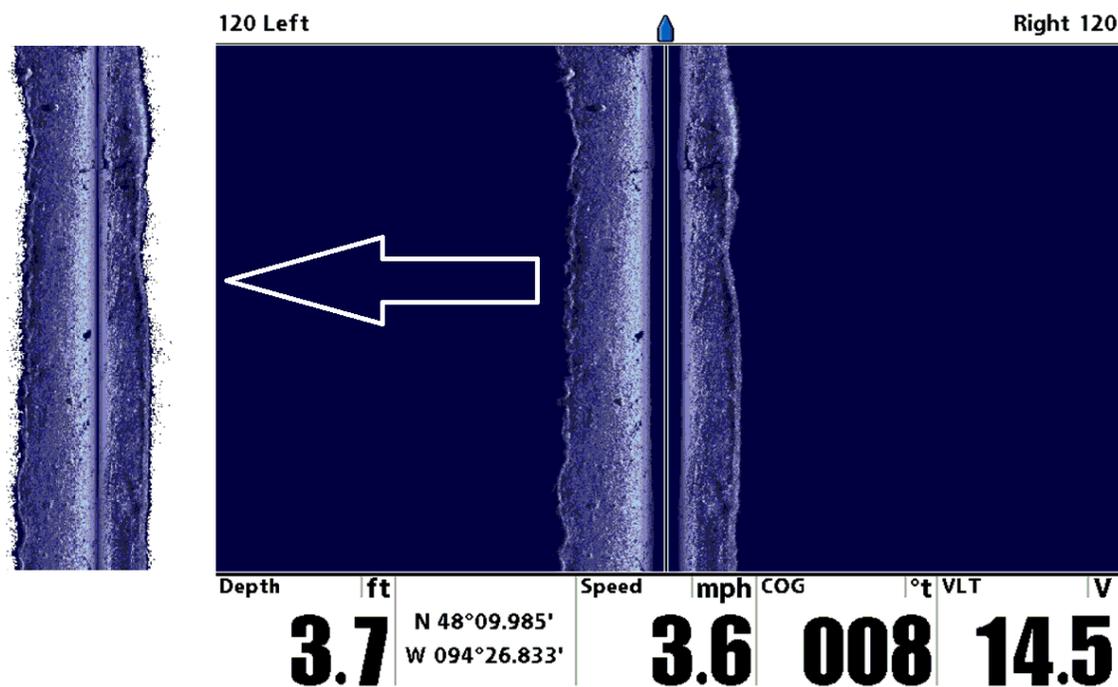
Figure 2.2. Demonstration of removal of metadata and no-data from the raw sonar image (right) to produce a sonar image ready for georeferencing (left).
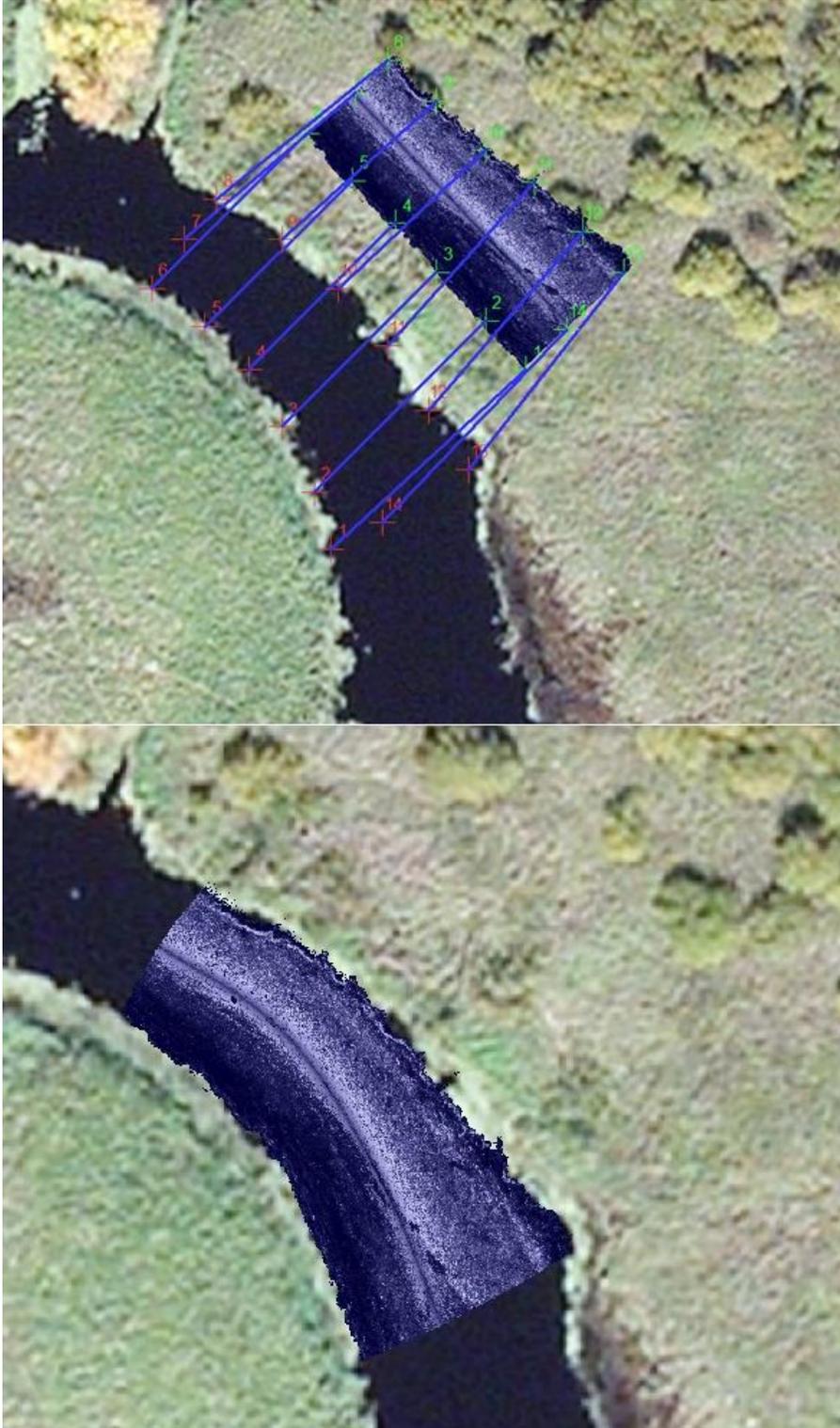
Figure 2.3. Sonar image with control point matrix being spline transformed and georeferenced into its geospatial location.
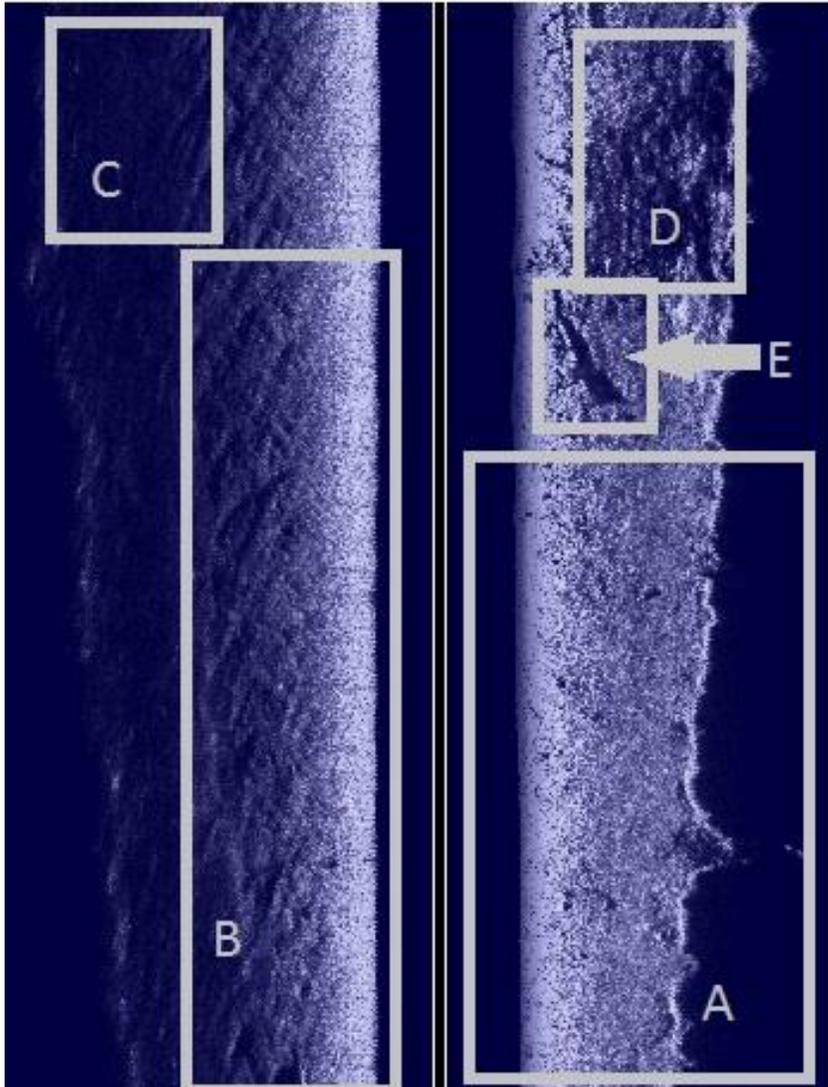
Figure 2.4. Image displaying sonar signatures of coarse suitable substrate (A), unsuitable substrate exhibiting ripples indicative of sand (B), unsuitable very fine silt substrate (C), a beaver cache identified in the field while conducting the sonar survey (D), and a single large deadhead log (E).
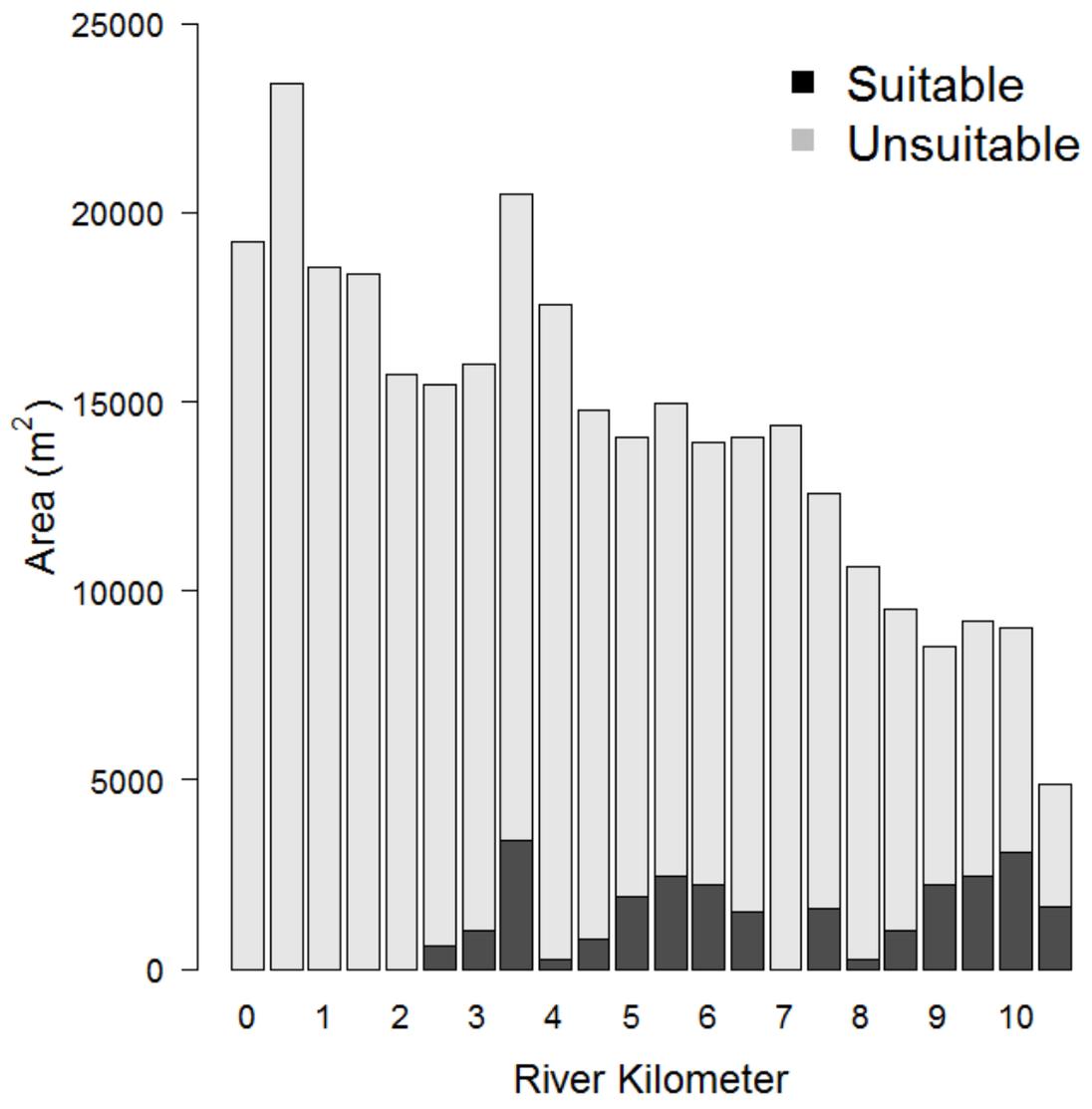
Figure 2.5. Area (m^2) of suitable and unsuitable substrates in each half kilometer reach in the downstream-most 10.8 km of the Tamarac River (last bar represents 0.3 km instead of 0.5).

Figure 2.6. Thematic substrate map with suitable and unsuitable reference points and delineated polygons, three meter buffers are shown to demonstrate misclassifications proximity to a polygon with the correct classification.

Chapter 3: Assessment of Drift Densities of Out-Migrating Larval Fishes, and Water Chemistry in the Tamarac River, MN

Abstract.- The Tamarac River is a major tributary of the Red Lakes MN, which provides an economically important multispecies fishery. The Tamarac River experiences spring spawning migrations of northern pike, walleye, and white suckers, but their reproductive success in the river is largely unknown. This study used drift nets and regression modeling to evaluate spatial and temporal factors that influenced larval densities for each species during outmigration. Evaluated variables were date, time of day, horizontal location, and vertical location. In addition, this study compiled data related to water chemistry and reproductive success in the river. Few larval walleye were caught and thus data were insufficient for regression modeling. Regression modeling indicated date and horizontal location influenced larval densities in northern pike and white suckers, and time of day influenced larval northern pike densities. Dissolved oxygen concentrations during the study were below concentrations that have been found to incur significant mortality in walleye larvae and embryos, however were near or above concentrations reported to incur mortality in northern pike and white suckers embryos and larvae. Unusually high stream flows from heavy precipitation during the study may have flushed water from the presumably anoxic bog surrounding the Tamarac River and be the origin of water containing low dissolved oxygen. This study provided data on larval ecology useful to future studies and provided preliminary data related to reproductive success and water chemistry in the Tamarac River.

INTRODUCTION

The Red Lakes are a highly valued commercial and recreational walleye (*Sander vitreus*) fishery which had over 730,000 walleye harvested in both the 2014 and 2015

harvest years (Brown and Kennedy 2016). Additionally, populations of northern pike (*Esox lucius*), and a white suckers (*Catostomus commersonii*) in the Red Lakes provide opportunities for recreational angling and spearing. The Tamarac River is a major tributary of the Red Lakes located in the northeastern corner of the upper basin. Each spring northern pike, walleye, and white suckers migrate the river to spawn. However, reproductive success of the three species in the river is largely unknown.

Evaluating reproductive success of fishes is an essential component of a well-managed fishery. Knowledge of reproductive success yields insight into parameters of population dynamics including year class strength (Johnston et al. 1995). One method used to evaluate reproductive success is the collection of larval fishes shortly after hatching. Drift nets are commonly used to sample larval fishes in flowing waters and can be used to evaluate success of habitat improvements, time of spawning and egg hatching, egg hatch success, and abundance of river spawning fish larvae (Corbett and Powles 1986; Franzin and Harbicht 1992; Dustin and Jacobson 2003; Smith and King 2005).

Temporal and spatial factors affecting the distribution of drifting larval fishes varies by species and system (Preigel 1970; Corbett and Powles 1986; Franzin and Harbicht 1992; Oesmann 2003; Smith and King 2005). Assessment of factors that influence larval fish distribution in the Tamarac River will provide useful data related to reproductive success in this system and insight into which factors are likely to affect larval densities for future studies in similar systems. Previous studies have found distance from shore, time of day, depth, and water velocity to influence the distribution of drifting larval fishes (Preigel 1970; Corbett and Powles 1986; Franzin and Harbicht 1992; Oesmann 2003). While there have been several previous studies examining larval drift of

walleye (Preigel 1970; Franzin and Harbicht 1992; Mion et al. 1998; Corbett and Powles 1986; Dustin and Jacobson 2003), there are relatively few studies in the literature related to northern pike and white sucker drift during outmigration from riverine spawning sites.

The three species examined in this study migrate up the Tamarac River each spring to spawn, and can be present in the river simultaneously. Timing of spawning migrations is dependent on water temperature with pike, walleye, and white suckers spawning migrations typically occurring when water temperatures reach 8-12°C, 6-12°C, and 10-18°C, respectively (Inskip 1982; McMahon et al. 1984; Twomey et al. 1984). White suckers and walleye use similar spawning habitat and select locations with coarse substrates and water less than 1.5 m deep (McMahon et al. 1984; Twomey et al. 1984). Alternatively, northern pike prefer dense matted vegetation in shallow water, with the majority of spawning occurring in water depths < 0.5 m (Williamson 1942; Clark 1950; Fabricius 1950; Inskip 1982).

The three species migrating the Tamarac River exhibit varying dissolved oxygen requirements, with white suckers and northern pike exhibiting a higher tolerance for low dissolved oxygen concentrations than walleye. White sucker embryos are able to survive at dissolved oxygen concentrations as low as 1.3 mg/L, with reduced fry growth when dissolved oxygen concentrations are less than 2.5 mg/L (Siefert and Spoor 1974). Siefert et al. (1973) reported dissolved oxygen concentrations of 4.5 mg/L were adequate for northern pike embryo survival and development in very low flow conditions (0.00027 m/sec), but concentrations of 3.2 mg/L appeared to be unsuitable for embryos and larvae. However, Fago (1977) did not observe significant mortality in northern pike reared in water with dissolved oxygen concentrations < 3 mg/L. Walleye eggs incubated in water

with dissolved oxygen concentrations < 5 mg/L result in reduced hatching success, and dissolved oxygen concentrations less than 3 mg/L negatively impacted size at hatch and severely reduced hatching success (Oseid and Smith 1971). Furthermore, Siefert and Spoor (1974) reported walleye embryos and larvae experienced over 25% mortality when exposed to dissolved oxygen concentration < 3 mg/L for one hour periods, and 100% mortality at dissolved oxygen concentrations less than 2.5 mg/L.

Dissolved oxygen tolerance of these species is relevant to the Tamarac River because its drainage is located in a portion of a 1,295 km^2 peat bog, the largest in the lower 48 states (Groshens 2000). Peat bogs are notorious for having anoxic conditions (Clymo 1992; Van Breemen 1995, Frolking et al. 2001). Therefore the potential exists for low dissolved oxygen concentrations in the river to affect embryo and larvae survival in the river.

A more complete understanding of drift distributions of larval northern pike, walleye, and white suckers will be useful to design future assessments of reproductive success of these species in riverine environments. Understanding spatial and temporal factors that influence larval densities provides knowledge that enhances the current understanding of larval ecology and behavior. Further, data related to dissolved oxygen concentrations in the Tamarac River during larval outmigration are useful to managers of the Red Lakes and similar fisheries associated with bog ecosystems because they provide insight regarding the possible negative effects of hypoxic conditions associated with bog drainages on larval fishes. Therefore, the objectives of this study were 1) to identify spatial and temporal factors influencing drift distribution of larval fishes in the Tamarac

River through regression modeling and 2) evaluate dissolved oxygen concentrations in the Tamarac River during larval outmigration.

METHODS

Drift nets were set at a location (15U 389683 5334513 UTM) downstream of where the majority of spawning was presumed to occur. Drift net sampling occurred between 28 May and 4 June 2014. Drift netting efforts were initiated when walleye eggs taken from a nearby river began to hatch in a hatchery operating at ambient water temperature. This indicator of when to begin sampling ensured drift netting efforts were initiated before significant larval walleye drift occurred in the Tamarac River because the walleye eggs in the hatchery were taken from a walleye spawning migration that began several days earlier than the Tamarac River. Because larval walleye hatch after northern pike and before white suckers, the sampling dates in this study captured a portion of each species drift period. Drift netting concluded when no larval fish were visually observed in collection jars upon retrieval. Measurements of water temperature, dissolved oxygen, and pH were taken at least once at each time interval, throughout the study, when larval collection occurred.

Drift nets were set in stream center, 25% stream width, and as near to shore as possible where the net could still be completely submerged. One net was set at the shore and 25% stream width location while the stream center had three nets set in a stacked orientation. This net configuration allowed for analysis of both horizontal and vertical variations in larval densities. Nets were set such that the top of the nets were ≈2 cm under the surface so floating debris would pass over the net, and therefore minimize the collection of debris that would increase the potential for back-flushing. Nets were set

every day at noon and midnight, and twice every three days a 12-hour evaluation was

conducted. During 12-hour evaluations, nets were set every 4 hours (0000-1200 hours

and 1200-0000 hours) alternating which 12-hour period was sampled such that a

continuous 24-hour evaluation did not occur. In each sampling period drift nets were set

for approximately one hour, though the duration nets were fished was adjusted based on

water velocities and the amount of debris collected in nets (i.e. when water velocities

were high nets were fished for a shorter duration). Contents in drift nets were preserved

in 95% ethanol and stored for later identification in the laboratory.

Number of larval fishes collected per m^3 sampled was calculated for each net set.

Water velocity measurements were taken directly in front of the net at the time of

deployment and retrieval. Average water velocity, length of time the net was deployed,

and area of drift net frame were used to calculate volume of water filtered. Drift nets

consisted of a 30x40 cm frame opening with a 150 cm long net (750 µm mesh) and

collection jar attached to the cod end.

To estimate the relative abundance of adults of each species migrating the

Tamarac River, two 1-inch bar-mesh fyke nets were fished overnight in the river. Fyke

nets were fished every third day between 21 April 2014 and 9 May 2014. Fyke net

sampling occurred from when the river was ice free until catches diminished and

migrations were presumed near completion. One fyke net was set associated with the

inside and one with the outside of a bend in an attempt to sample different water

velocities which may influence fish movement upriver. Fyke nets were set faced

downstream with the lead extending to shore at an angle such that fish moving upstream

encountered the lead, followed it upstream and were captured. Total catches of spawning

adults were subsequently used for comparison to total catches of larvae of each species.

Statistics

Multiple regression analysis using program R (R Core Team 2014) was used to

describe which variables influenced larval drift distributions of each species. Akaike's

information criterion (AIC) was used to select the best supported model for each species

(Akaike 1973). The model with the lowest AIC was selected as the best supported model,

though models with Δ AIC < 2 were also considered (Anderson et al. 2000; Burnham and

Anderson 2001). In the event two models had a Δ AIC < 2 but were nested, the simpler of

the two was selected as the best supported model.

Variables included in regression analysis were vertical position, horizontal

position, time of day, and date. Horizontal and vertical location were taken at three fixed

locations each, and were therefore treated as factors rather than continuous variables.

These variables were chosen based on those found to influence larval drift distribution in

previous studies (e.g., Preigel 1970; Corbett and Powles 1986; Franzin and Harbicht

1992; Oesmann 2003). Date was included in every candidate model because out-

migrating larvae should theoretically exhibit a peak in drift density and a following

decline, therefore some level of variation in density should be attributed to what point in

the outmigration sampling occurred. Including date as a variable in all candidate models

should alleviate variation associated with sampling date. For simplicity, the date the first

nets were set was considered one. No transformation was applied to date in the northern

pike regression models because sampling started near its presumed peak, therefore the

back slope of the peak is similar to a linear relationship. Date in white sucker candidate

models was transformed using a reciprocal transformation. This transformation was chosen because sampling started prior to its presumed peak, thus a linear relationship was not appropriate. Models for northern pike and white suckers containing all combinations of variables which included date without interactions were tested, and root mean squared error (RMSE) were calculated for all candidate models. The number of larval walleye collected was extremely low and regression modeling were not conducted on larval walleye.

RESULTS

During the study period and egg incubation, the Tamarac River experienced extremely high water levels. High water levels resulted in flooding, with several feet of water over the surrounding bog (Figure 3.1). Median water temperature during the drift netting period was 17.6 °C (range = 16.5-20.0°C, n=14), median dissolved oxygen concentration was 2.95 mg/L (range = 2.13-3.84 mg/L, n=12), and median pH was 7.27 (range = 7.07-7.45, n=12).

A total of 110 drift net samples were collected over an eight-day period at water velocities ranging from 0.09 – 0.97 m/sec. Nets set at the nearshore location had the lowest velocities, and the bottom net at stream center had the highest (Figure 3.2). Three drift net samples could not be analyzed because contents were compromised in collection or preservation. Total catches for all drift nets were 6,755 northern pike, 1,096 white suckers, and 17 walleye larvae (Figure 3.3). Adult walleye were the most abundant species collected in fyke nets, with a total of 955 walleyes captured in eight fyke netting events. Total northern pike catch was 140 fish and the least abundant species collected in fyke nets was white suckers with a total catch of 8 (Figure 3.3).

Densities of northern pike larvae ranged from 0.000-4.671 fish/m^3 and had a median of 0.768 (interquartile range, i.e. IQR = 0.000-0.610 fish/m^3). Northern pike densities were highest at the 25% stream width horizontal location (median = 0.290 fish/m^3) followed by the shore location (median = 0.190 fish/m^3) with the center location having much lower densities (median = 0.016 fish/m3; Figure 3.4). Northern pike larval densities where the highest in the top vertical position (median = 0.106 fish/m^3) and lowest at the bottom vertical position (median = 0.041 fish/m^3), with the middle position having intermediate densities (median = 0.066 fish/m^3; Figure 3.5). Northern pike densities peaked at midnight (median = 0.986 fish/m^3) and decreased as the day progressed until reaching the lowest densities at 2000 hours (median = 0.000; Figure 3.6).

White sucker larval densities ranged from 0.000-0.920 fish/m^3 with a median of 0.015 (IQR = 0.000-0.095 fish/m^3). The 25% stream width and center locations had higher larval white sucker densities (medians = 0.022 and 0.016 fish/m^3, respectively) than the shore location (median = 0.000 fish/m^3). There was little variation in larval white sucker densities between vertical locations with top, middle, and bottom positions having densities of 0.013, 0.018, and 0.012 fish/m^3, respectively. There was not a clear diel pattern in white sucker densities, though the highest densities occurred at 1600 hours (median = 0.028) and the lowest densities occurred at midnight (median = 0.006).

The best supported candidate model of northern pike larval densities contained date, time, and horizontal position. (AIC = 240.97, RMSE = 0.705). The Δ AIC for the next best model was > 3, and all other candidate models had Δ AIC > 8 (Table 3.1). The best supported candidate model for white sucker larval density contained date and horizontal location as variables (AIC = -117.03, RMSE = 0.134). The next best candidate

model's Δ AIC was 1.65, and contained time of day in addition to the variables in the selected model. Since these models were nested, the simpler model with a lower AIC score was chosen as the best supported model. All other white sucker larvae candidate models had Δ AIC > 3. Vertical position was not identified as a factor that influenced larval densities in either species.

DISCUSSION

Identifying spatial and temporal variables that affect the distribution of larval fishes enhances the understanding of their ecology and behavior. This study provides data related to factors influencing distributions of northern pike and white sucker larvae during out-migration from riverine spawning sites, a topic for which scientific data in the literature are sparse. Further, understanding factors that influence densities of drifting larval fishes will facilitate more effective sampling regimens in future studies that evaluate relative reproductive success of these species. This study also provides an analysis of fish reproduction and larval ecology relative to water chemistry in peatland ecosystems, a subject that has largely been unexplored.

Regression modeling of larval northern pike and white sucker densities provides evidence to suggest date and horizontal location in the river are factors which influenced larval densities of both species in the Tamarac River. Northern pike exhibited higher densities at the shore and 25% stream width location, and where captured less frequently in the center of the river (Figure 3.4). This behavior may occur because newly hatched northern pike can begin feeding 10 days after hatching and feed on invertebrates associated with vegetation, which is plentiful along the shoreline in the Tamarac River (Franklin and Smith 1963; Inskip 1982). In addition, vegetation offers cover and

protection from potential predators (Inskip 1982), which may further explain a preference for areas near shore which provide cover.

In contrast, white sucker larvae had the highest densities in the center and 25% width locations with the lowest densities at the shore location (Figure 3.4). During emigration northern pike are 7-13 days older than white suckers (Franklin and Smith 1963, Twomey et al. 1984). Therefore, emigrating northern pike are likely able to control their position in the river more effectively than white suckers. This is supported by collected northern pike exhibiting initial development of pectoral, whereas collected white suckers were largely undeveloped. Further, Corbett and Powles (1986) reported white sucker larvae drift passively and their position is dictated predominately by the current of the river, which was strongest in the center of the river.

It was not uncommon for larval northern pike to have eaten larval white suckers and have the posterior half of the larval white sucker extending out of the mouth. Therefore, high white sucker densities in the location where the lowest northern pike densities occurred could possibly be a behavioral response of white suckers avoiding areas with high northern pike densities. However, this assumes white suckers were able to effectively control their position in the river. Of these two possibilities, it seems more likely white sucker larvae drifted passively rather than a behavioral response to predation.

Larval densities of both species were not influenced by vertical location in this study. Although there is little available information related to vertical distribution in larval northern pike, Corbettt and Powles (1986) reported highest larval white sucker densities in the middle vertical position of a $\approx$ 1 m deep stream. Corbett and Powles (1986) also reported white sucker drift was passive and higher densities in the middle

position having been a result of larvae passing through a riffle with velocities high

enough to maintain suspension of larvae and an ensuing "settling out" when velocity

slowed near the sampling location. This likely was not possible in this study because

water velocities were homogeneous and differences in water velocity between the top,

middle, and bottom nets were similar, thus "settling" would not occur in this study

(Figure 3.2). Northern pike had the lowest densities in the center of the river where

vertical assessment occurred. Therefore, there was likely not a selection for a vertical

position because larval northern pike avoided the center of the river altogether. Also, the

lowest densities in the center of the river likely mitigated any differences in vertical

densities that may have existed because other variables, like horizontal position, had a

much higher influence on larval northern pike density in regression models.

Time of day was identified by regression modeling as a variable that influenced

larval densities of northern pike, with densities peaking at midnight and decreasing until

1600 hours. This pattern indicates the highest densities occur during night and decline to

the lowest densities during the middle of the day and afternoon (Figure 3.6). This diel

pattern is contrary to what may be expected for northern pike emigration considering they

are visual predators which primarily exhibit daytime activity (Carlander and Cleary 1949;

Polyak 1957; Braekevelt 1975; Diana 1980). In addition, low light intensities and

prolonged overcast weather have been reported to inhibit or extend the emigration period

of northern pike after hatching (Franklin and Smith 1963; Forney 1968). An explanation

for nighttime emigration in this study is not clear, though darkness may provide

protection from diurnal predators present in the Tamarac River including belted

kingfishers (*Megaceryle alcyon)*, Hooded mergansers (*Lophodytes cucullatus*), and

members of the Ardeidae (i.e., heron) family. Also, increased nighttime activity may be a response to increased food availability via invertebrate drift. While not quantified in this study, higher densities of invertebrates at night was readily observed by visual inspection of contents in drift net collection jars, and supported by previous studies on invertebrate drift (Tanaka 1960; Elliott 1969; Flecker 1992).

Larval white sucker densities where not influenced by time of day. This contrasts results from previous studies which suggest larval white suckers drift at higher densities during night (Twomey et al. 1984; Corbett and Powles 1986; Johnston et al. 1995). Corbett and Powles (1986) reported white sucker larvae oriented themselves upstream against the current along the shore during the day, but did not report water velocities in which larval white suckers exhibited this behavior. It is possible water velocities in this study were too high for white suckers perform this behavior, and therefore did not exhibit diel variations in drift densities because they could not maintain their position during the day.

Multiple studies report mixed effect of time of day on larval densities for other species. For example, the diel peak in larval walleye drift is not uniform across studies. Corbett and Powles (1986) found peak collection times of larval walleye at 2100-0100 hours, whereas Priegel (1970) found peak collection at 1300-1400 hours. One possible mechanism that may account for these differences is the distance of collection site from the spawning location and water velocity. This would be possible if the time drift is initiated is consistent but once initiated larvae drift passively until reaching their terminal destination. Therefore, the peak time of collection would be a result of both how long it takes larvae to drift to the collection site and the time drift was initiated.

Data in this study provides preliminary evidence to suggest low dissolved oxygen concentrations in the Tamarac River could be the cause of low walleye embryo and/or larvae survival. Data to relate water level and dissolved oxygen concentrations in the river are not available. Though Minnesota Department of Natural Resources personnel, who conduct yearly spring electrofishing surveys in the river, reported water levels during the time of this study being one of the highest they had observed in the previous ten years (T. Kennedy, Minnesota Department of Natural Resources, personal communication). During the incubation and drift netting period the river overtopped the banks and the bog in the surrounding area was covered with over one meter of water (Figure 3.1). Water draining from the surrounding bog is presumably void of oxygen and provides a likely explanation for dissolved oxygen concentrations in the river below lethal levels for walleye embryos and larvae.

Mean dissolved oxygen concentration during the time of this study (2.9 mg/L) was below concentrations which resulted in severely reduced walleye hatching success and reduced size at hatch (< 3 mg/L), and two dissolved oxygen measurements were below the concentration reported to incur 100% mortality (2.5 mg/L) in previous studies (Oseid and Smith 1971; Siefert and Spoor 1974). Considering walleye were the species with the highest adult abundance and the lowest larval abundance (Figure 3.3), low dissolved oxygen concentration appears to be a likely explanation for much lower larval walleye catch compared to the other two species.

Concentrations of dissolved oxygen during sampling were above the lethal range, and concentrations shown to reduce growth, for white sucker embryos (Siefert and Spoor 1974). However, dissolved oxygen concentrations were below those which appeared

unsuitable for northern pike embryo and larvae survival and growth in Siefert et al. (1973). Although Siefert et al. (1973) had extremely low flow conditions (0.00027 m/sec) which were orders of magnitude lower than any water velocity measured in this study (0.09 – 0.97 m/sec). Higher water velocities could result in more oxygen being available to larvae and embryos because higher volumes of water are passing over them. Furthermore, Fago (1977) observed no significant mortality in larval northern pike in rearing ponds when dissolved oxygen concentrations were below 3 mg/L. Dissolved oxygen concentrations in the Tamarac River did not appear to cause significant mortality in northern pike larvae based on the number of larvae collected. While there are discrepancies in dissolved oxygen requirements of larval northern pike in the literature, results from this study align more closely with those from Fago (1977).

Results from this study support findings in previous studies which suggest horizontal location across river is a common factor that influences densities of larval fishes (Priegel 1970; Corbett and Powles 1986; Oesmann 2003). However, inconsistencies between studies regarding how time of day and vertical location affect larvae densities in certain species indicates the relationship may be highly variable between systems, or variables which are currently unidentified influence these variations in drift densities. This highlights the need for robust spatial and temporal study designs when conducting larval drift assessments in unstudied systems.

The interaction of water level, dissolved oxygen concentrations, and survival of fishes in riverine habitats in bog ecosystems is largely unexplored. Further investigations should be conducted to identify such an interaction. This study provides preliminary evidence to suggest elevated water levels in rivers with bog associated drainages can

result in hypoxic conditions due to water stored in anoxic bog entering rivers and tributaries. These hypoxic conditions appear to have the potential to influence survival and growth of certain fish species

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Table 3.1. Results from regression analysis for the seven candidate models for white suckers and northern pike, parentheses represent variables treated as factors. Models are ordered top to bottom from the lowest to highest Akaike's information criterion (AIC), thus the first candidate model listed was the best supported model for each species. Tested variables were date, time of day, horizontal location (H. Location), and vertical location (V. Location).

Northern Pike

Model	AIC	Δ AIC	RMSE
Density ~ Date + Time + (H. Location)	241.0	0.0	0.705
Density ~ Date + Time + (V. Location) + (H. Location)	244.6	3.6	0.704
Density ~ Date + Time + (V. Location)	249.6	8.6	0.734
Density ~ Date + Time	254.6	13.6	0.766
Density ~ Date + (H. Location)	258.6	17.6	0.773
Density ~ Date + (H. Location) + (V. Location)	262.3	21.3	0.772
Density ~ Date + (V. Location)	266.0	25.0	0.800
Density ~ Date	269.9	28.9	0.830

White Suckers

| Model	AIC	Δ AIC	RMSE
Density ~ Date + (H. Location)	-117.3	0.0	0.134
Density ~ Date + Time + (H. Location)	-115.6	1.7	0.133
Density ~ Date + (H. Location) + (V. Location)	-114.0	3.3	0.133
Density ~ Date + Time + (V. Location) + (H. Location)	-112.3	5.0	0.133
Density ~ Date	-111.3	6.0	0.140
Density ~ Date + Time	-109.4	7.9	0.140
Density ~ Date + (V. Location)	-107.5	9.8	0.140
Density ~ Date + Time + (V. Location)	-105.7	11.6	0.140

Figure 3.1. Aerial image of the Tamarac River during spring 2014 demonstrating high water levels that resulted in flooding of the surrounding bog, and may have contributed to low dissolved oxygen levels in the river.
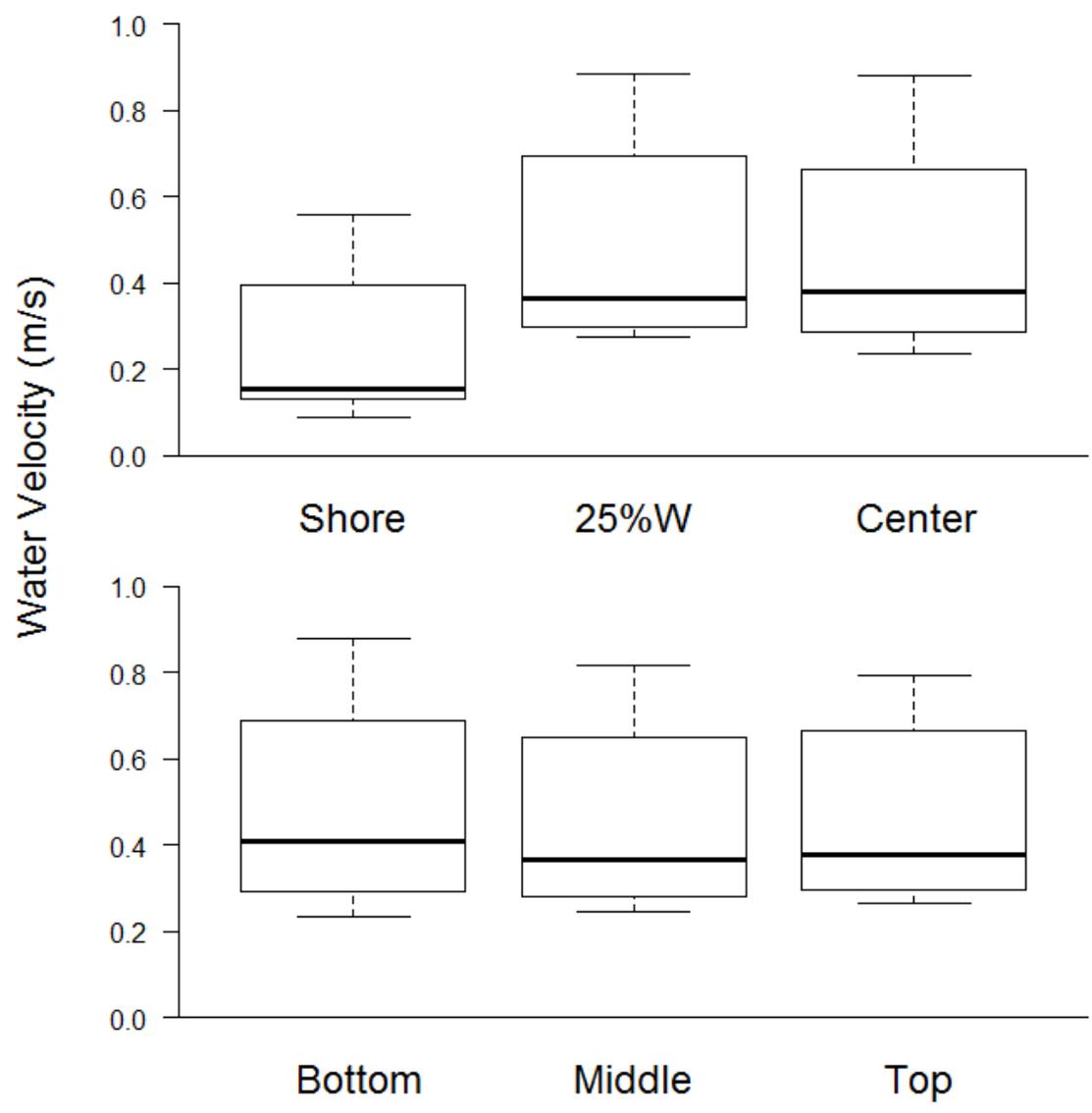
Figure 3.2. Water velocities for horizontal locations (top) and vertical locations (bottom) for all possible net locations set in the Tamarac River. Thick black lines represent medians, boxes represent interquartile ranges, and whiskers represent range.
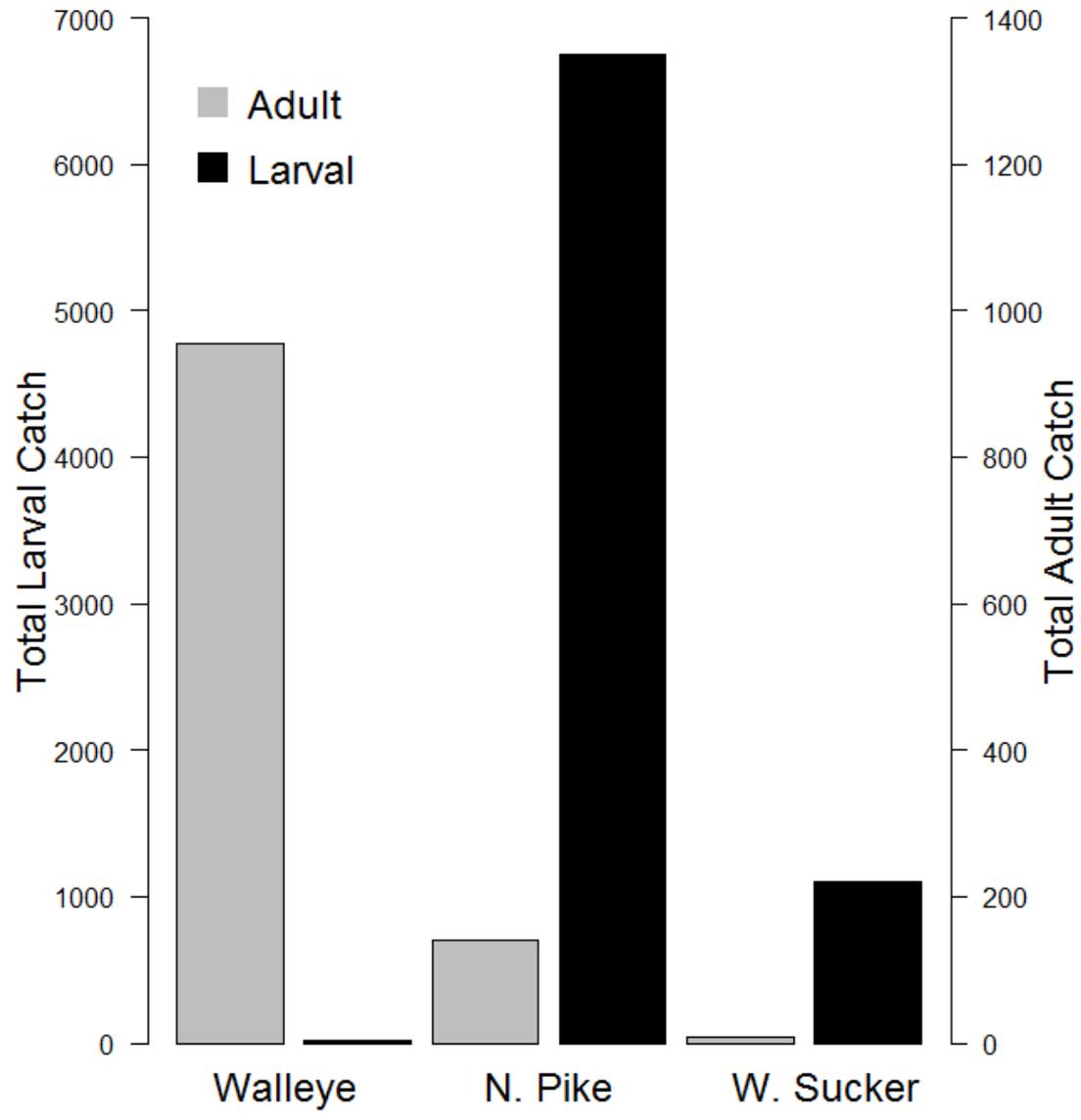
Figure 3.3. Total catches of adults in fyke nets and larvae in drift nets for northern pike, walleye, and white sucker collected in the Tamarac River, demonstrating the vast difference in adult to larvae ratio of walleye compared to the other two species.
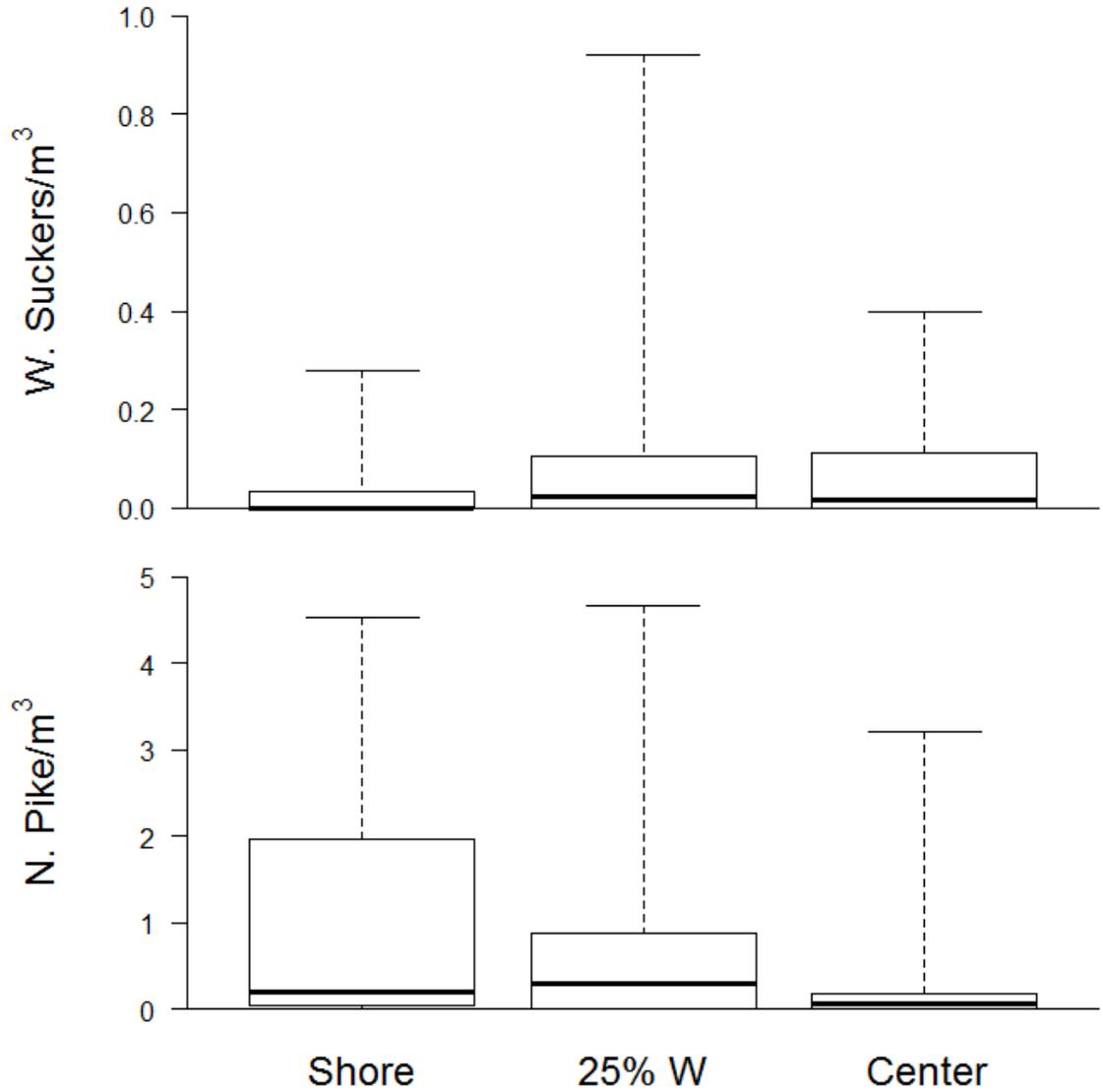
Figure 3.4. Larval densities of northern pike and white sucker by horizontal location across the Tamarac River, with thick black lines representing the median, boxes representing the interquartile range, and whiskers representing the range. Horizontal position was identified as a factor influencing larval densities for both species by regression modeling.
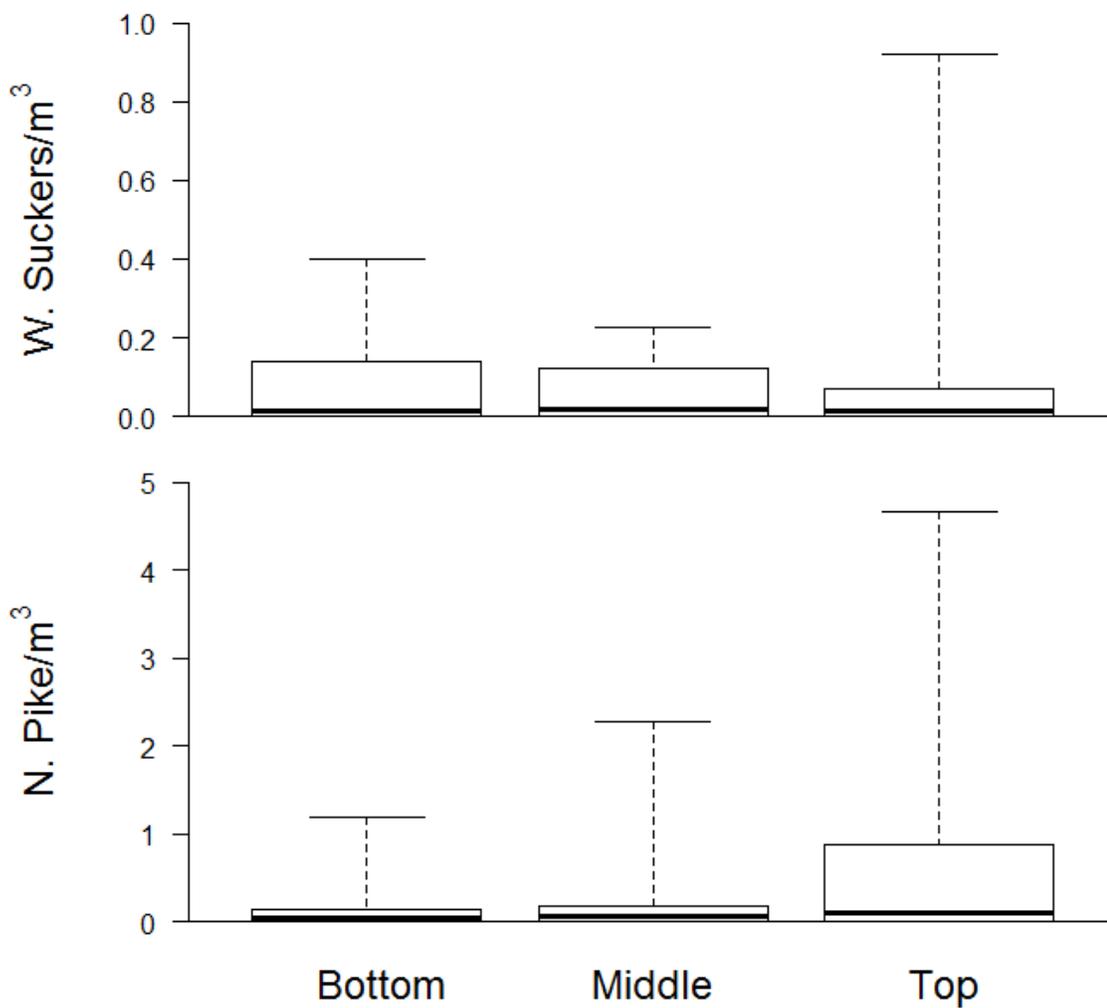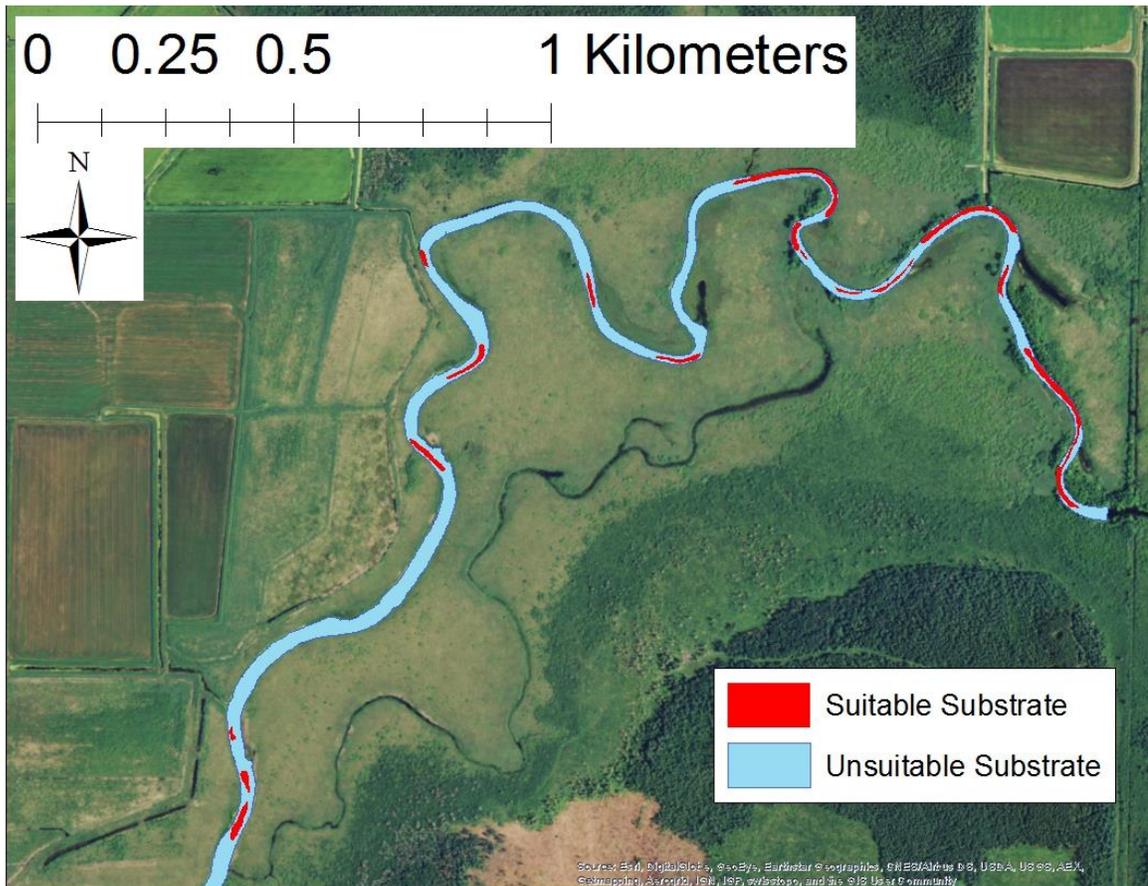
Figure 3.5. Northern pike and white sucker larval densities plotted by vertical location in the Tamarac River. Boxes represent interquartile range and whiskers represent range, vertical location was not identified by regression modeling as a factor which influenced larval densities in either species.
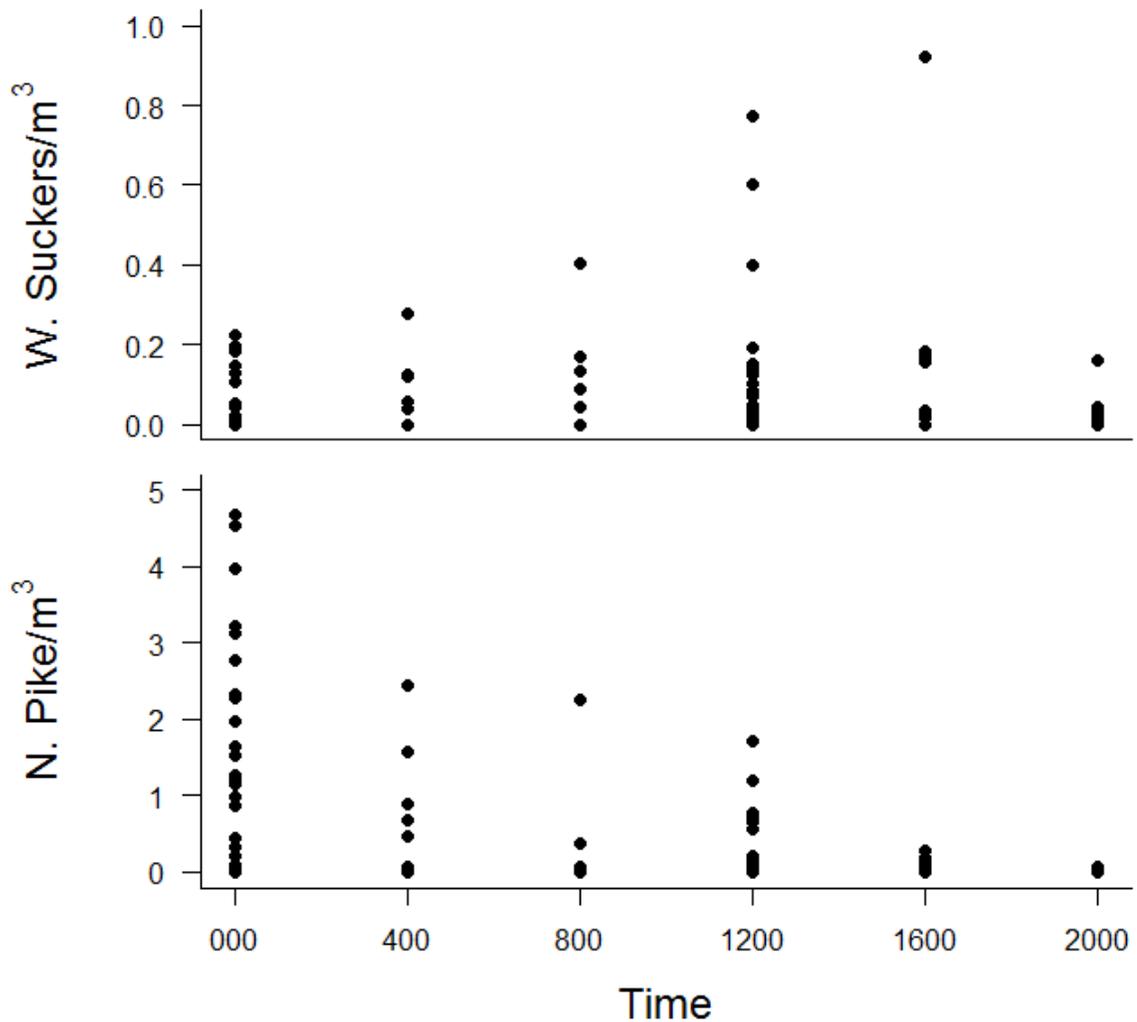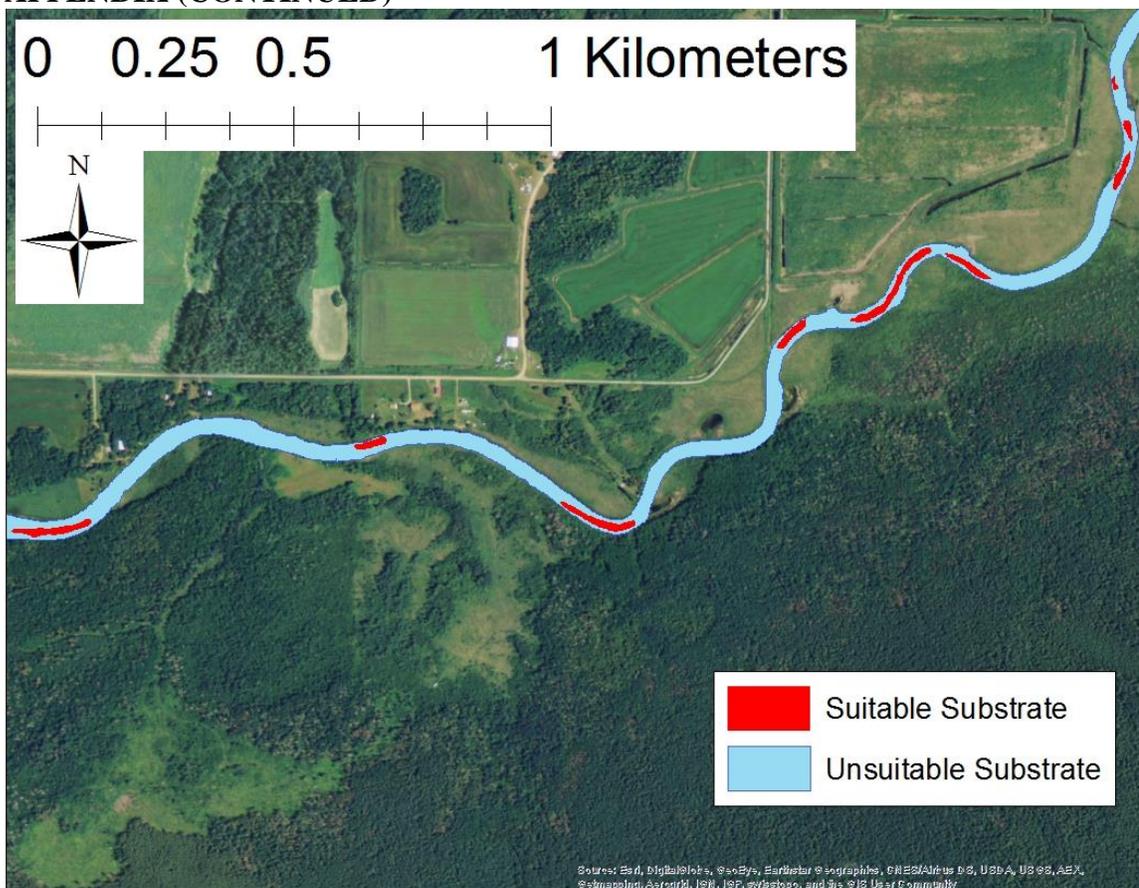
Figure 3.6. Larval densities of northern pike and white suckers in the Tamarac River plotted by time of day in four hour increments, with time 0 representing midnight. Regression modeling provided evidence to suggest time was a factor influencing larval densities for northern pike but did not influence white sucker larval densities.
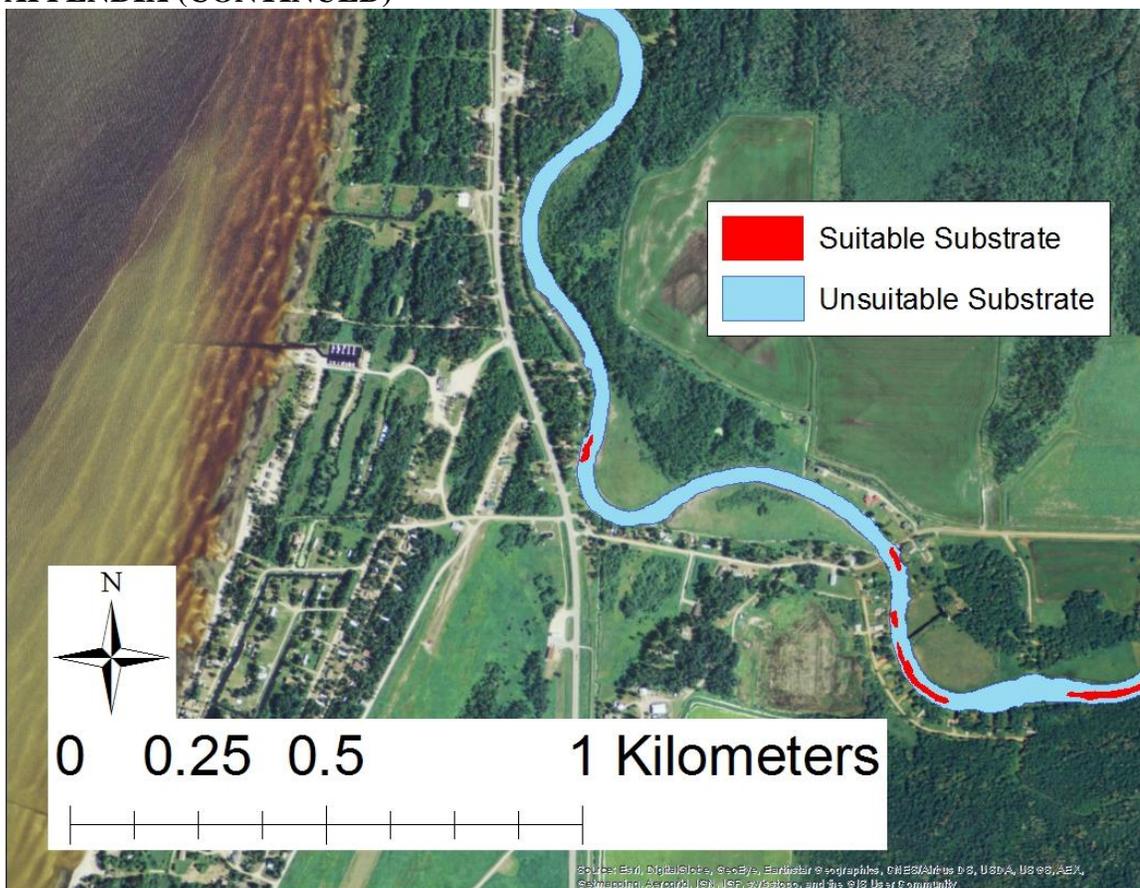
APPENDIX

Full substrate delineation using the side scan sonar map of the Tamarac River starting at the upstream mapping terminus and progressing to the downstream terminus. Blue portions represent unsuitable substrate and red portions represent suitable substrate.

APPENDIX (CONTINUED)

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