11-2015

POPULATION DYNAMICS AND MOVEMENT OF CHANNEL CATFISH IN THE RED RIVER OF THE NORTH

Stephen F. Siddons
University of Nebraska-Lincoln, ssiddons2@unl.edu

POPULATION DYNAMICS AND MOVEMENT OF

CHANNEL CATFISH

IN THE RED RIVER OF THE NORTH

By

Stephen F. Siddons

A THESIS

Presented to the Faculty of

The Graduate College at the University of Nebraska

In Partial Fulfillment of Requirements

For the Degree of Master of Science

Major: Natural Resource Sciences

Under the Supervision of Professor Mark A. Pegg

Lincoln, Nebraska

November, 2015

POPULATION DYNAMICS AND MOVEMENT OF CHANNEL CATFISH IN THE RED RIVER OF THE NORTH

Stephen F. Siddons, M.S.

University of Nebraska, 2015

Advisor: Mark A. Pegg

Channel Catfish are widely distributed across North America and highly valued as a sport fish and for food. While most Channel Catfish fisheries are managed under liberal harvest regulations, the Red River of the North (Red River) in Manitoba, Canada is managed with restrictive harvest regulations to promote a trophy fishery. Two barriers (dams) are present on the main stem of the Red River and may fragment the population to some degree. My objectives were to: 1) analyze population dynamics of the trophy Channel Catfish population on the lower Red River, 2) compare population characteristics of Channel Catfish in selected reaches throughout the Red River in Manitoba, and 3) determine movement characteristics of Channel Catfish and the permeability of a dam on the lower Red River. We compared our results to the most recent studies on Channel Catfish in the Red River, and also to range-wide age, growth, and mortality statistics. Channel Catfish in the lower Red River commonly reached ages > 20, grew slowly, and had a low mortality rate. Trophy Channel Catfish were most abundant below the dam on the lower river. The size structure within the most upstream reaches we studied were predominantly comprised of small- and intermediate-sized Channel Catfish. We determined the dam is passable by large Channel Catfish (>600 mm), but may be an impediment to small Channel Catfish.

My mark-recapture data indicated Channel Catfish can move long distances, where upstream movements > 500 kilometers were common for large Channel Catfish. This research provides insight into the age, growth, and mortality of a trophy fishery for Channel Catfish. We believe restrictive harvest regulations are adequately maintaining the desired age structure and size structure of Channel Catfish in the lower Red River and by consequence, sustaining one of the premier fisheries in North America.

ACKNOWLEDGEMENTS

First, I thank Samantha, my sweetheart, for putting up with this passion of mine. She has not only supported me, but encouraged me to chase my dreams and do whatever it takes to be successful in my endeavors. I would not be where I am today if not for her understanding, patience, and acceptance of this wild ride. She is also a pretty good fisheries technician, and can out-fish any of the boys!

I thank my advisor, Dr. Mark Pegg. I know this project was not an easy one to pull off, and I offer a sincere thank you for giving me the opportunity to run with it. All I can say is that I hope I can make you and the University of Nebraska proud. To the others on my committee, Dr. Kevin Pope and Dr. Larkin Powell, thank you for your willingness to field my endless stream of questions, helping with field work in the middle of the night (especially during the hot August frog bite), and mentoring me through this process.

I also thank all of those that have helped me get to this point in my life, particularly my parents. They encouraged me to follow a career in the natural resources even though they knew it would not be easy. I cannot repay you for teaching me to work hard, chase my dreams, and always making sure I made it home from my adventures. Also, Dr. Wilson and Billy Minser, thank you for providing me with opportunities to succeed, and always pushing me in the right direction.

The list of people who have assisted with the Red River project is too long to list here. This project is the culmination of a chance meeting at a conference, a determined professor, and many, many caring individuals who sacrificed time, fingers (Dr. Hamel), and other opportunities to make it all happen. Here is a big shout out to the folks at Manitoba Conservation and Water Stewardship (Geoff Klein, Derek Kroeker, Kevin Casper), the Fisheries Enhancement Fund (Doug Watkinson, the Carrick family), each and every technician who has helped out (especially Michael Schilz), Keith Hurley, the helpful anglers of the Red River, the towns of Selkirk and Emerson, Manitoba, and everybody else who has lent a helping hand!!! I wish I had the space to mention you all here, you were instrumental in carrying this project forward by providing logistical support, knowledge, and assistance in the field. I sincerely appreciate your help!

Last, but not least, thank you to the crew at the University of Nebraska who has been there for me every step of the way! Jon Spurgeon, Dylan Turner, Nick Hogberg, Kelly Turek, and Caleb Uerling have all provided more than a few hours of their time and a helping hand when needed. Dr. Marty Hamel, kudos, thank you for the open door when I needed it! It has been a pleasure working, hunting, fishing, and partaking in Risky's trips with each and every one of you.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

CHAPTER 1

GENERAL INTRODUCTION AND STUDY OBJECTIVES

Channel Catfish *Ictalurus punctatus* are widely distributed across North America and across all types of freshwater systems (Pflieger 1997, Hubert 1999). Channel Catfish are a popular sport fish and are often harvested by anglers (Hubert 1999, Michaletz and Dillard 1999). In a survey of Mississippi River basin catfish anglers and biologists, Arterburn et al. (2002) documented that 61% of anglers commonly targeted Channel Catfish and 63% of these anglers harvested Channel Catfish annually. However, trophy catfish fisheries with more restrictive regulations on harvest are becoming popular throughout North America (Michaletz and Dillard 1999).

The Red River of the North (Red River) in Manitoba, Canada is one such fishery that supports an abundance of trophy Channel Catfish. This fishery gained popularity in the 1980s and large Channel Catfish were harvested regularly (Lysack 1986, Macdonald 1990). A creel study in 1986 reported almost 4,000 kg of Channel Catfish were harvested in just 16 km of the lower river that year, and most of the catfish harvested were greater than 750 mm (Lysack 1986). As such, the Province of Manitoba sought to protect the size structure of Channel Catfish on the Red River by enacting increasingly restrictive regulations. Manitoba enacted the first harvest regulations in 1981, by instituting a creel limit of eight individuals. In 1986, Manitoba further reduced the creel limit to four Channel

Catfish, only one of which could exceed 750 mm. The lower Red River is now managed primarily for catch and release, and since 1992, Manitoba regulations allow the harvest of four Channel Catfish less than 600 mm per day. The lower Red River remains a popular destination for many North American anglers and is worth several million dollars to the local economy. Other than Macdonald (1990), there has been little research on Channel Catfish in the lower Red River. Knowledge of basic population parameters (e.g., growth, mortality, and abundance) are needed to properly manage this fishery.

Channel Catfish in the Red River are older and larger than in other populations across their range (Macdonald 1990; Hegrenes 1992). Channel Catfish up to age 27 have been reported, and ages greater than 20 are common in the Red River (Stewart and Watkinson 2004, Macdonald 1990), whereas Channel Catfish from many other populations rarely live past age 8 (Pflieger 1997; Hubert 1999). Hubert's (1999) review of Channel Catfish age and growth studies documented that only eight of 102 studies reported Channel Catfish 15 years old and none were as large as Red River catfish. The largest specimen from the Red River, angled in 1992, was 1180 mm long (total length) and had a mass of 20 kg (Stewart and Watkinson 2004). Channel Catfish greater than 800 mm are currently common in the Red River (> 68% of angling catches; Chapter 2, this thesis).

Channel Catfish are known to move long distances (Pellett et al. 1998; Fago 1999; Butler and Wahl 2011). Movements within the Red River may be

limited only by physical obstructions, such as dams, and the northern limit of their range (Macdonald 1990). Macdonald (1990) reported three Channel Catfish tagged near Selkirk, Manitoba recaptured in Minnesota and North Dakota, over 450 km upstream. Murray and MacDonnell (2009) used telemetry and reported Channel Catfish moved more than Northern Pike *Esox lucius*, Walleye *Sander vitreus*, and Sauger *Sander canadensis* in the Red River, with one catfish travelling an average of 150 km per year. Another catfish was tagged at St. Jean Baptiste on the Red River and recaptured on the east side of Lake Winnipeg 13 days later, a distance of 350 km (Robert 1992). Low-head dams are present at several locations along the main stem of the river and are common on tributaries, yet this river still experiences a somewhat natural flow regime with overbank floods occurring in high-water years (Aadland et al. 2005; USGS). Dams likely prevent fish passage at low flows but we know passage is sometimes possible (either during high flows, through fish ladders, or through locks) from tag returns (Macdonald 1990; Robert 1992; Wendel and Kelsch 1999; Chapter 4, this thesis). Determining the proportion of catfish that are crossing a dam or moving into the upper Red River in the USA will help managers determine the best management actions for this fishery because regulations in Minnesota and North Dakota are more liberal than in Manitoba, allowing a daily harvest of 5 Channel Catfish, one of which may be greater than 610 mm (24 inches).

Longevity and maximum size may influence several interactions within a Channel Catfish population, such as spawning behavior, feeding, movements,

age-at-maturity, fecundity, and growth. For example, most Channel Catfish reach sexual maturity around age 5 (Hubert 1999), however, most Channel Catfish in the Red River do not reach sexual maturity until age 10 or older (Stewart and Watkinson 2004). Whether differences in age-at-maturity across populations is a function of density-dependent spawning behavior, life-history plasticity, or some other mechanism is unknown. Studying this unique population will broaden our understanding of the influence of longevity on Channel Catfish population ecology. Particularly, my objectives for this project were to: 1) determine the dynamic rate functions (growth and mortality) as well as the age structure and size structure of Channel Catfish in the lower Red River and compare them to previous studies (Macdonald 1990, Hegrenes 1992, Hubert 1999; Chapter 2); 2) determine if there were differences in population characteristics (size structure, abundance, and condition) among four different reaches along the length of the Red River in Manitoba (Chapter 3); and 3) quantify movement rates, especially pertaining to movement through a dam and across geopolitical boundaries (Chapter 4).

LITERATURE CITED

Aadland, L.P., T.M. Koel, W.G. Franzin, K.W. Stewart, and P. Nelson. 2005. Changes in fish assemblage structure of the Red River of the North. Pages 293-321 *in* J.N. Rinne, R.M. Hughes, and B. Calamusso, editors. Historical changes in large river fish assemblages. American Fisheries Society Symposium 45, Bethesda, Maryland.

Arterburn, J.E., D.J. Kirby, C.R. Berry Jr. 2002. A survey of angler attitudes and biologist opinions regarding trophy catfish and their management. Fisheries 27:10-21.

Butler, S.E., and D.H. Wahl. 2011. Distribution, movements and habitat use of channel catfish in a river with multiple low-head dams. River Research and Applications 27:1182-1191.

Fago, D. 1999. Movement of channel catfish in the Lower Wisconsin River and pool numbers 10 and 11 of the Mississippi River using radiotelemetry. Pages 177-185 *in* E. R. Irwin, W. A. Hubert, C. F. Rabeni, H. L. Schramm, Jr., and T. Coon, editors. Catfish 2000: Proceedings of the International Ictalurid Symposium. American Fisheries Society, Symposium 24, Bethesda, Maryland.

Hegrenes, S.G. 1992. Age, growth, and reproduction of channel catfish in the Red River of the North. Master's thesis. University of North Dakota, Grand Forks, North Dakota.

Hubert, W.A. 1999. Biology and management of channel catfish. Pages 3-22 *in* E. R. Irwin, W. A. Hubert, C. F. Rabeni, H. L. Schramm, Jr., and T. Coon, editors. Catfish 2000: Proceedings of the International Ictalurid Symposium. American Fisheries Society, Symposium 24, Bethesda, Maryland.

Lysack, W. 1986. The angling fishery of the lower Red River. Manitoba Department of Natural Resources, Fisheries Branch Manuscript Report 86-16.

Macdonald, D. 1990. The channel catfish sport fishery of the lower Red River. Master’s thesis. The University of Manitoba, Winnipeg, Manitoba.

Michaletz, P.H. and J.G. Dillard. 1999. A survey of catfish management in the United States and Canada. Fisheries 24:6-11.

Murray, L., and D.S. MacDonnell. 2009. Red River floodway expansion acoustic telemetry study. Report by North/South Consultants for the Manitoba Floodway Authority, Winnipeg, Manitoba.

Pellett, T.D., G.J. Van Dyck, and J.V. Adams. 1998. Seasonal migration and homing of channel catfish in the lower Wisconsin River, Wisconsin. North American Journal of Fisheries Management 18:85-95.

Pflieger, W.L. 1997. The fishes of Missouri. Missouri Department of Conservation, Jefferson City, Missouri.

Robert, L. 1992. Upper Red River channel catfish tagging report. Manitoba Department of Natural Resources, Fisheries Branch, Manuscript Report 20.

Stewart, K., and D. Watkinson. 2004. Freshwater fishes of Manitoba. University of Manitoba Press, Winnipeg, Manitoba.

Wendel, J.L., and S.W. Kelsch. 1999. Summer range and movement of channel catfish in the Red River of the North. *in* E. R. Irwin, W. A. Hubert, C. F. Rabeni, H. L. Schramm, Jr., and T. Coon, editors. Catfish 2000: Proceedings of the International Ictalurid Symposium. American Fisheries Society, Symposium 24, Bethesda, Maryland.

CHAPTER 2

AGE, GROWTH, AND MORTALITY OF A CHANNEL CATFISH *ICTALURUS PUNCTATUS* POPULATION IN MANITOBA, CANADA

ABSTRACT

We studied population dynamics of Channel Catfish in the Red River of the North (Red River). The lower Red River lies at the northern extent of the Channel Catfish's distributional range and is known for producing many trophy Channel Catfish; individuals greater than 800 mm and 10 kg are common. The objectives of this study were to: 1) document the dynamic rate functions (i.e., growth and mortality) and the age structure and size structure of Channel Catfish in the lower Red River, and 2) compare current population dynamics to historical conditions in the lower Red River and other populations. We documented a maximum age of 27, and ages greater than 20 were common (7%). We estimated a low annual mortality rate (0.11), similar to a study in the late 1980s, and lower than mortality estimates for Channel Catfish in the Red River in the USA. Growth rates for individuals ages 3-10 were similar among our study, historical growth estimates, and upstream estimates. However, observed annual growth increments (from mark-recapture) were lower than predicted growth increments from back-calculated mean lengths-at-age, suggesting aging structures are underestimating true ages of individuals. Conservative harvest regulations appear to be an

effective strategy for preserving the desired age structure and size structure of Channel Catfish in the lower Red River, and this study may provide insight into management possibilities for other systems.

INTRODUCTION

Channel Catfish *Ictalurus punctatus* are widely distributed across North America throughout all types of freshwater systems (Pflieger 1997, Hubert 1999). Channel Catfish are a popular sport fish and are often harvested by anglers (Hubert 1999, Michaletz and Dillard 1999). In a survey of Mississippi River basin catfish anglers and biologists, Arterburn et al. (2002) documented that 61% of anglers commonly targeted Channel Catfish and 63% of these anglers harvested Channel Catfish annually. However, trophy catfish fisheries with more restrictive regulations on harvest are becoming popular throughout North America (Michaletz and Dillard 1999).

Perhaps the most well-known fishery for trophy Channel Catfish is in the Red River of the North (Red River), which lies at the northern extent of the Channel Catfish's distributional range (Macdonald 1990). The lower Red River is known for producing trophy Channel Catfish; individuals greater than 800 mm and 10 kg are common. This fishery gained notoriety in the 1980s and, as fishing pressure increased, fisheries managers felt the need to place regulations on harvest

to protect the size structure of Channel Catfish (Macdonald 1990). Manitoba enacted the first harvest regulations in 1981, when a creel limit of eight individuals was implemented. A creel study in 1986 reported almost 4,000 kg of Channel Catfish were harvested in just 16 km of the lower river that year, and most of the catfish harvested were greater than 750 mm (Lysack 1986). In 1986, Manitoba further reduced the creel limit to four Channel Catfish, only one of which could exceed 750 mm. The lower Red River is now managed primarily for catch and release, and since 1992, Manitoba regulations allow the harvest of four Channel Catfish less than 600 mm per day (Drewes et al. 2008). However, few catfish less than 60 mm are caught by anglers on the lower Red River (Chapter 2, this thesis).

Another unique aspect of this fishery is that the Red River is one of few large rivers in North America that has not been subjected to commercial catfish harvest (Macdonald 1990). Commercial fishing can influence size structure (Mestl 1999, Pitlo 1997, Olsen et al. 2004), age structure (Ricker 1981, Mestl 1999), and abundance (Colombo et al. 2007), and ultimately alter life-history characteristics such as age at maturity (Ricker 1981, Law 2000, Olsen et al. 2004), maximum size (Pitlo 1997, Ricker 1981, Olsen et al. 2004), and mortality rates (Mestl 1999). Determining the population dynamics of the Channel Catfish population in the Red River will increase our understanding of how aspects of population dynamics (i.e., age structure, size structure, growth, and mortality)

may differ when a Channel Catfish population does not experience a great deal of commercial or recreational harvest.

The objectives of this study were to: 1) document the dynamic rate functions (i.e., growth and mortality) and the age structure and size structure of Channel Catfish in the lower Red River, and 2) compare current population dynamics of the Channel Catfish population to historical conditions on the Red River (Macdonald 1990, Hegrenes 1992) and to other populations (Hubert 1999). Comparing these data will allow managers to optimize management strategies that sustain the catfish fishery in the Red River and provide insight into management possibilities for other systems.

METHODS

Study Area

The Red River is formed at the confluence of the Bois de Sioux and Otter Tail rivers along the Minnesota-North Dakota border and is part of the Hudson Bay drainage (Figure 2-1). The Red River flows north for 640 km to the international border, forming the boundary between Minnesota and North Dakota (Koel and Peterka 2003). The lower Red River continues north another 233 km before emptying into Lake Winnipeg in southern Manitoba. Within the USA, the drainage basin encompasses parts of western Minnesota, eastern North Dakota,

and a small portion of northeastern South Dakota, draining a total of 108,800 km^2. The Red River drains an area of 185,474 km^2 in Canada, most of which is in the Assiniboine River watershed. The Assiniboine River, a major tributary to the Red River, originates in Saskatchewan and joins the Red River in the city of Winnipeg, Manitoba.

Sampling Locations

Sampling effort was focused on a 15-km reach between the St. Andrews Dam in Lockport, Manitoba downstream to the town of Selkirk, Manitoba (Figure 2-1). This area encompasses the majority of the recreational fishing effort for trophy Channel Catfish, including the majority of the pressure by local fishing guides (S. Siddons, personal observation). Channel Catfish were sampled throughout this reach during 2011-2014. During 2012-2014, the sampling area was expanded to encompass a 5-km reach near the mouth of the Red River at Lake Winnipeg.

Data Collection

We collected Channel Catfish using hoop nets and rod-and-reel during May-August during 2011-2014. Hoop nets had seven, 0.9-m diameter hoops and were baited with a soy bean mash. Angling was primarily conducted with ≥ 6/0 barbless circle hooks baited with cut Goldeye *Hiodon alosoides* or White Sucker

Catostomus commersonii. Channel Catfish were weighed to the nearest g and measured for maximum total length to the nearest mm. We collected sagittal otoliths and pectoral spines from a subsample of Channel Catfish (10 of each structure from each 10-mm size group) in 2011, 2012, and 2013.

Aging Structure Preparation

Ages from Channel Catfish were determined from both sectioned spines and sanded otoliths using methods similar to Buckmeier et al. (2002). Pectoral spines were disarticulated (Quist et al. 2012) and placed in uniquely labeled envelopes. In the lab, spines were cleaned of remaining tissue, set in modeling clay, and placed in plastic centrifuge vials which were filled with clear epoxy. Sections, approximately 30 µm thick, were cut using a low-speed isomet saw anterior to the basal recess. Sections were mounted on glass microscope slides using Cytoseal (Thermo Scientific) and examined through a 10-22x dissecting microscope.

Otoliths were removed by cutting across the top of the head (Buckmeier et al. 2002) about 3-5-mm anterior to the base of the pectoral spines and placed in labeled envelopes. In the lab, otoliths were cleaned of remaining tissue and placed on a hotplate on medium-high heat until they turned brown, usually less than two minutes. Otoliths were mounted, anterior side up, on a glass microscope slide using crystal-bond epoxy then sanded to the center of the nucleus using 600- and

800-grit wet-dry sandpaper. A drop of mineral oil was placed on the sanded face of the otolith and viewed through a 10-22x dissecting microscope with the aid of an adjustable-power light directed at an angle onto the oiled surface.

Aging-Structure Analysis

Ages from both structures were determined by a single reader counting presumed annuli, including the edge for spring captured Channel Catfish. Channel Catfish collected during fall were aged to the last visible annulus. We compared age estimates from each structure for individual Channel Catfish from which both structures were removed. We used a microscope-mounted digital camera to capture an image of each otolith and spine section. Photographs were uploaded to FishBC (Ball State University) for analysis. Distances were measured from the center of the nucleus or spine to the outer edge of each annulus and to the edge of the structure. We used the Dahl-Lea formula to back calculate length-at-age estimates for each individual:

$$\frac{L_i}{L_c} = \frac{S_i}{S_c},$$

where L_i= fish length at annulus formation, L_c= fish length at capture, S_i= radius at annulus formation, and S_c= radius at capture (Quist et al. 2012).

Growth Rate Comparison

We fit von Bertalanffy growth equations to back-calculated growth data using:

$$l_t = L_\infty * (1 - e^{-K(t-t_0)}),$$

where l_t=length at time, L_∞= the asymptotic length, K= a growth coefficient, and t_0= a time coefficient at which length would theoretically be zero (Isely and Grabowski 2007). We also estimated mean annual growth increments from back-calculated lengths-at-age from all individuals that were directly aged.

We compared growth data to published historical Channel Catfish data from the Red River (Macdonald 1990, Hegrenes 1992) and other populations (Hubert 1999). We derived von Bertalannfy growth curve parameters and mean length-at-age data from the previous studies (Macdonald 1990, Hegrenes 1992) for comparisons. Macdonald (1990) reported mean fork-length-at-age, variance (i.e., standard deviation), and von Bertalanffy growth parameters in fork length (FL) for lower Red River Channel Catfish in the late 1980s. To make direct comparisons, we converted FL to maximum total length (MTL) using the equation: $MTL = 1.08 * FL$ (Page and Burr 1991). Mean lengths-at-age (FL) were recalculated as MTL and, using the means and variance reported in Macdonald (1990), updated von Bertalanffy growth curve parameters to reflect MTL. The same procedure (using reported means and standard error) was used to calculate mean length-at-age and von Bertalanffy growth curve parameters for Hegrenes

(1992). We used an ANCOVA to compare Channel Catfish growth characteristics among studies. We limited the age range to ages 3-10 because direct comparisons could be made to range-wide growth data (Hubert 1999), and these age ranges primarily reflect purely somatic growth because most Red River Channel Catfish are not sexually mature before age 10 (Stewart and Watkinson 2004) and have not begun to divert energy resources to gonad development.

We also calculated observed growth (standardized to an annual rate) from mark-recapture efforts (Chapter 4, this thesis) in an attempt to corroborate growth estimates from aging structures. Observed annual growth increments of Channel Catfish were calculated using methods similar to Hamel et al. (2014) as:

$$G_i = \frac{(L_r - L_c)}{Y_i},$$

where G_i is the annual growth for fish i, L_r is the total length at recapture, L_c is the total length at initial capture, and Y_i is the time at large (years). We used observed growth measured with recapture data from Channel Catfish tagged during 2012-2015 and were at large for at least 30 days. We used the latest recapture event only for Channel Catfish that were recaptured multiple times to maximize time-at-large and minimize the effects of measurement error. Recapture measurements that resulted in negative growth were adjusted to zero and were assumed to be measurement error (Hamel et al. 2014). Recaptured Channel Catfish were sorted into 50-mm length groups (initial tagging length), and mean observed annual growth increments were calculated for each length group.

Mortality

We created an age-length key using age estimates from otoliths and applied the key to all Channel Catfish that were not directly aged. We used a log-transformed catch curve on combined hoop net and rod-and-reel caught Channel Catfish from those captured during 2011-2014 (Ricker 1975). The slope of the linearized catch-curve regression is equal to the instantaneous mortality rate (Z), which was then converted to an annual mortality rate using the formula:

$$A = 1 - e^{-z},$$

where *A*= annual mortality and *e*= the base of natural logarithms.

Mortality rates were not reported in Macdonald (1990) or Hegrenes (1992). However, we calculated annual mortality estimates for their studies using catch curve analysis on the reconstructed length-at-age raw data from their growth analyses. We used Channel Catfish ages 6-25 for our study, ages 9-23 for Hegrenes (1992) and ages 3-21 for Macdonald (1990) to calculate mortality rates, as they had recruited to the gear and had sufficient sample sizes at those ages (Miranda and Bettoli 2007).

RESULTS

Age Structure Comparison

Pectoral spines and otoliths produced similar age estimates through age 18, after which otoliths tended to estimate older ages than pectoral spines (Figure 2-2). We therefore chose to use age estimates from otolith-aged fish for calculating dynamic rate functions. Otoliths are not influenced by deterioration like pectoral spines (i.e., expansion of the central lumen) and are believed to be more accurate for older fish.

Age Structure and Size Structure

We collected Channel Catfish during 2011 (N= 66), 2012 (N= 1,743), 2013 (N= 3,561), 2014 (N=6,170). Lower Red River Channel Catfish ages ranged from 2 to 27 years (mean= 11.7, SE=0.015) and lengths ranged from 93 to 995 mm (mean=509, SE=2.3). Catfish greater than age 20 were present in both hoop net (2% > age 20, n_{total} =8,857) and angling samples (25% > age 20, n_{total}=2,683). Catfish became susceptible to angling around age 10 and a mean length of 500 mm, but ages ≥ 15 (≥ 700 mm) were most commonly caught by angling (Figure 2-3).

Growth

Von Bertalanffy parameter estimates for Channel Catfish in the lower Red River were L_∞= 1161 (95% confidence interval: 1018-1305) and K= 0.061 (95% confidence interval: 0.045-0.077; Table 2-1). Von Bertalanffy parameter estimates from Macdonald (1990) data, regenerated and adjusted to MTL, were L_∞= 1427 (95% confidence interval: 1319-1536) and K= 0.05 (95% confidence interval: 0.043-0.056). Von Bertalanffy parameter estimates from the regenerated Hegrenes (1992) data were L_∞= 2113 (95% confidence interval: 1726-2501) and K= 0.025 (95% confidence interval: 0.019-0.031).

Channel Catfish growth rates (i.e., slopes) calculated from mean lengths-at-age of individuals between ages 3-10 were not different between Macdonald (1990), Hegrenes (1992), and this study (Figure 2-5; F=0.3, df=2, P=0.7474). The mean annual growth increment, determined from otoliths, of age-1 catfish from this study was 122 mm. Annual growth increments declined to 76 mm for age-2 catfish and down to 46 mm for age-5 catfish. Annual growth increments ranged between 31 and 15 mm for catfish ages 10-27 (Figure 2-6).

Observed annual growth rates from mark-recapture events were generally less than those predicted from back-calculation procedures (Figure 2-7). Maximum observed annual growth was approximately 50-mm, for the 300-mm size group. A number of fish (n=13) that were recaptured in this study exhibited no growth during the time at large, 10 of which were > 600 mm.

Mortality

Instantaneous mortality was 0.12 and the annual mortality rate was 0.11 for otolith-aged Channel Catfish in the lower Red River. The annual mortality rate estimate derived from reconstructed Hegrenes (1992) data was 0.18, and was 0.09 for the Macdonald (1990) data (Figure 2-8).

DISCUSSION

Channel Catfish in the Red River are among the longest-lived individuals from known Channel Catfish populations across North America. Hubert (1999) reviewed 102 studies and reported that 36 studies had populations with individuals > age 10 and only 7 studies with fish > age 15; a maximum age of 22 was reported from the Green and Yampa rivers in Utah and Colorado (not including the Red River). Channel Catfish greater than age 20 were also identified in the Ottawa River in Ontario (Haxton and Punt 2004). Aging methods for all reviewed studies were not consistent; yet our age data from both pectoral spines and otoliths revealed a much older age-structure for Channel Catfish in the lower Red River than elsewhere. Channel Catfish greater than age 20 were commonly encountered in this study (7%) and catfish up to age 27 were observed. Macdonald (1990) found a slightly younger age structure (maximum age = 21), but used pectoral spines, which likely underestimate ages compared to otoliths

(Figure 2-2). However, Macdonald's (1990) study was conducted in the late 1980s when greater harvest occurred and the province of Manitoba had just begun taking measures to preserve the size structure of Channel Catfish (i.e., more restrictive harvest regulations). Greater exploitation rates may explain the younger age structure seen at the time of Macdonald (1990), as harvest of large individuals (> 750 mm) was still allowed. Therefore, our results indicate the longevity of Channel Catfish in the Red River has likely been maintained or even increased by the implementation of restrictive harvest regulations.

Growth rates of Channel Catfish in the Red River have not changed since the late 1980s and mean lengths-at-age are slightly less than average when compared to Hubert's (1999) range wide evaluation (Figure 2-9). Growth coefficients from von Bertalanffy curves were similar between this study and Macdonald (1990), but lower in the Hegrenes (1992) data (Figure 2-4). Asymptotic maximum lengths (L_∞) were not similar among the studies, but this is likely an artifact of differences in age estimates for the longest-lived individuals due to differing age structures. These results indicate the current lengths of trophy Channel Catfish in the Red River are the result of many years of about average growth.

Comparisons between our observed growth rates from mark-recapture events and growth rates from back-calculation procedures were not similar in most cases. Observed annual growth appears to be substantially less than what we predicted from back-calculation (Figure 2-7). Other studies have reported a

disconnect between observed growth and the use of aging structures to estimate age and growth of fish species (Paragamian and Beamesderfer 2003, Bruch et al. 2009, Hamel et al. 2014). Though these issues have often been associated with other 'long-lived' species (e.g., *Acipenseridae*, *Gadidae*), Channel Catfish are not often placed in this category. However, the Red River population is unique to Channel Catfish where they appear to live much longer than other populations. As such, otoliths and spines do not appear to be providing reliable estimates of age and growth. Therefore, continued research to attempt to validate the full range of ages for Channel Catfish is warranted. Further collection of mark-recapture data will provide additional information needed to accurately characterize Channel Catfish age and growth, while providing additional evidence for corroborating age structure analysis for these long-lived individuals. If mark-recapture growth rates are accurate, Channel Catfish in this population are likely older than previously believed and estimates of dynamic rate functions for this population may need to be interpreted with caution.

Annual mortality rates of lower Red River Channel Catfish were low (0.11) compared to other studies. Hubert (1999) reported a range of 0.13 to 0.88 for all reviewed studies, but admitted differences in aging methods and low sample sizes may have influenced mortality calculations. The low annual mortality rate (0.09) calculated from Macdonald (1990) is unusual because fishing mortality was likely greater at that time due to the more liberal regulations in place. The low mortality rate could be due to a variety of reasons, such as

differences in sampling gear or effort (i.e., more large fish were sampled, creating a flatter mortality curve). Another possibility is that fishing mortality within the lower Red River is compensatory, which has been suggested for other sport fish populations (Allen et al. 1998), and low levels of exploitation do not contribute in increased annual mortality. The slightly greater mortality rate found upstream in the Hegrenes (1992) data (0.18) could be an artifact of the less restrictive harvest regulations in North Dakota and Minnesota, and may indicate harvest functions as an additive mortality source in the USA portion of the river. Goble (2011) reported mortality rates as high as 0.54 for Channel Catfish in the Missouri River, Nebraska and Colombo (2007) reported mortality rates as high as 0.67 in the Wabash River, Indiana. These higher mortality rates may be the result of increased recreational and commercial fishing mortality (i.e., liberal harvest regulations). Within the lower Red River, reduced mortality rates allow for an increase in the age structure, and by consequence, an increase in the size structure of the Channel Catfish population. The size structure of Channel Catfish in the lower Red River has shifted to contain more large individuals through time (M. Pegg, unpublished data), and managers interested in promoting larger individuals in a Channel Catfish population may benefit from controlling fishing mortality by implementing more conservative harvest regulations.

The lower Red River is the only lotic Channel Catfish population in North America managed solely with maximum length limits (as opposed to minimum length limits). A creel limit of four Channel Catfish with a maximum length of

600 mm regulation has been in place since 1992 and has maintained a Channel Catfish population that allows individuals to grow to trophy sizes while still providing opportunities for harvest. The benefits of preserving maximum longevity and size within a fishery include greater fecundity (Hsieh et al. 2010), greater larval survival and recruitment (Berkeley et al. 2004a, Hsieh et al. 2010), and increased larval growth (Berkeley et al. 2004a). These benefits are likely the result of older, larger females that invest more energy toward reproduction (Longhurst 2002, Berkeley et al. 2004a, Hsieh et al. 2010). Additionally, fisheries managed for a large age structure and size structure are likely to be more resilient to variable recruitment (Murphy 1968, Longhurst 2002, Berkeley et al. 2004b) and exploitation (Birkeland and Dayton 2005). The lower Red River Channel Catfish fishery should serve as an example of what can happen when managers are able to protect aspects of a fishery, which we believe has sustained one of the premier catfish fisheries in North America.

LITERATURE CITED

Allen, M.S., L.E. Miranda, and R.E. Brock. 1998. Implications of compensatory and additive mortality to the management of selected sportfish populations. Lakes & Reservoirs: Research & Management 3:67-79.

Arterburn, J.E., D.J. Kirby, C.R. Berry Jr. 2002. A survey of angler attitudes and biologist opinions regarding trophy catfish and their management. Fisheries 27:10-21.

Berkeley, S.A., M.A. Hixon, R.J. Larson, and M.S. Love. 2004a. Fisheries sustainability via protection of age structure and spatial distribution of fish populations. Fisheries 29:23-32.

Berkeley, S.A., C. Chapman, and S.M. Sogard. 2004b. Maternal age as a determinant of larval growth and survival in a marine fish, Sebastes melanops. Ecology 85:1258-1264.

Birkeland, C. and P.K. Dayton. 2005. The importance in fishery management of leaving the big ones. Trends in Ecology and Evolution 20:356-358.

Bruch, R.M., S.E. Campana, S.L. Davis-Foust, M.J. Hansen, and J. Janssen. 2009. Lake sturgeon age validation using bomb radiocarbon and known-age fish. Transactions of the American Fisheries Society 138:361–372.

Buckmeier, D.L., E.R. Irwin, R.K. Betsill, and J.A. Prentice. 2002. Validity of otoliths and pectoral spines for estimating ages of channel catfish. North American Journal of Fisheries Management 22:934-942.

Colombo, R.E. 2007. Demographics and the ecological role of the channel catfish (Ictalurus punctatus) in commercially exploited and un-exploited reaches of the Wabash River with implications for the flathead catfish (Pylodictis olivaris). A Dissertation. Southern Illinois University. Carbondale, Illinois.

Colombo, R.E., J.E. Garvey, N.D. Jackson, R. Brooks, D.P. Herzog, R.A. Hrabik, and T.W. Spier. 2007. Harvest of Mississippi River sturgeon drives abundance and reproductive success: a harbinger of collapse? Journal of Applied Ichthyology 23:444-451.

Drewes, H., M. Ermer, S. Gangl, and D. Kroeker. 2008. Red River of the North Fisheries Management Plan. Manitoba Water Stewardship, Minnesota Department of Natural Resources, North Dakota Game and Fish Department, and South Dakota Department of Game, Fish, and Parks.

Goble, C.W. 2011. Ecology and management of channel catfish Ictalurus punctatus and flathead catfish Pylodictis olivaris populations in the Missouri River, NE. Master's thesis. Univeristy of Nebraska. Lincoln, Nebraska.

Hamel, M.J., J.D. Koch, K.D. Steffensen, M.A. Pegg, J.J. Hammen, and M.L. Rugg. 2014. Using mark–recapture information to validate and assess age and growth of long-lived fish species. Canadian Journal of Fisheries and Aquatic Sciences 71:559-566.

Haxton, T., and K. Punt. 2004. Abundance and demography of channel catfish in a large northern river. North American Journal of Fisheries Management 24:1440–1446.

Hegrenes, S.G. 1992. Age, growth, and reproduction of channel catfish in the Red River of the North. Master's thesis. University of North Dakota, Grand Forks, North Dakota.

Hsieh, C., A Yamauchi, T. Nakazawa, and W. Wang. 2010. Fishing effects on age and spatial structures undermine population stability of fishes. Aquatic Sciences 72:165-178.

Hubert, W.A. 1999. Biology and management of channel catfish. Pages 3-22 *in* E. R. Irwin, W. A. Hubert, C. F. Rabeni, H. L. Schramm, Jr., and T. Coon, editors. Catfish 2000: Proceedings of the International Ictalurid Symposium. American Fisheries Society, Symposium 24, Bethesda, Maryland.

Isely, J.J., and T.B. Grabowski. 2007. Age and Growth. Pages 187-228 *in* C.S. Guy and M.L. Brown, editors. Analysis and Interpretation of freshwater fisheries data. American Fisheries Society, Bethesda, Maryland.

Koel, T.M. and J.J. Peterka. 2003. Stream fish communities and environmental correlates in the Red River of the North, Minnesota and North Dakota. Environmental Biology of Fishes. 67:137–155.

Law, R. 2000. Fishing, selection, and phenotypic evolution. Journal of Marine Sciences 57:659-668.

Longhurst, A. 2002. Murphy's law revisited: longevity as a factor in recruitment to fish populations. Fisheries Research 56:125-131.

Lysack, W. 1986. The angling fishery of the lower Red River. Manitoba Department of Natural Resources, Fisheries Branch Manuscript Report 86-16.

Macdonald, D. 1990. The channel catfish sport fishery of the lower Red River. Master's thesis. The University of Manitoba, Winnipeg, Manitoba.

Mestl, G. 1999. Changes in Missouri River channel catfish populations after closing commercial fishing. Pages 455-460 *in* E. R. Irwin, W. A. Hubert, C. F. Rabeni, H. L. Schramm, Jr., and T. Coon, editors. Catfish 2000: Proceedings of the International Ictalurid Symposium. American Fisheries Society, Symposium 24, Bethesda, Maryland.

Michaletz, P.H. and J.G. Dillard. 1999. A survey of catfish management in the United States and Canada. Fisheries 24:6-11.

Miranda, L.E. and P.W. Bettoli. 2007. Mortality. Pages 229-277 *in* C.S. Guy and M.L. Brown, editors. Analysis and interpretation of freshwater fisheries data. American Fisheries Society, Bethesda, Maryland.

Murphy, G.I. 1968. Pattern in life history and the environment. American Naturalist 102:391-403.

Olsen, E.M., M. Heino, G.R. Lilly, M.J. Morgan, J. Brattey, and B. Ernande. 2004. Maturation trends indicative of rapid evolution preceding the collapse of northern cod. Nature 428:932-935.

Page, L.M. and B.M. Burr. 1991. A field guide to freshwater fishes of North America north of Mexico. Peterson Field Guide Series, Houghton Mifflin, Boston, Massachusetts.

Paragamian, V.L., and R.C.P. Beamesderfer. 2003. Growth estimates from tagged white sturgeon suggest that ages from fin rays underestimate true age in the Kootenai River, USA and Canada. Transactions of the American Fisheries Society 132:895–903.

Pflieger, W.L. 1997. The fishes of Missouri. Missouri Department of Conservation, Jefferson City, Missouri.

Pitlo Jr., J. 1997. Response of upper Mississippi River channel catfish populations to changes in commercial harvest regulations. North American Journal of Fisheries Management 17:848-859.

Ricker, W.E. 1975. Computation and interpretation of biological statistics of fish populations. Fisheries Research Board of Canada Bulletin 191.

Ricker, W.E. 1981. Changes in the average size and average age of Pacific salmon. Canadian Journal of Fisheries and Aquatic Sciences 38:1636-1656.

Stewart, K., and D. Watkinson. 2004. Freshwater fishes of Manitoba. University of Manitoba Press, Winnipeg, Manitoba.

Quist, M.C., M.A. Pegg, and D.R. DeVries. 2012. Age and growth. Pages 677-731 *in* A.V. Alexander, D.L. Parrish, and T.M. Sutton, editors. Fisheries techniques, 3rd edition. American Fisheries Society, Bethesda, Maryland.

Table 2-1. Von Bertalanffy growth curve parameters and associated 95% confidence intervals for Channel Catfish in the lower Red River of the North.

Study	L_∞ (95% CI)	K (95% CI)
This Study	1,161 (1,018-1,305)	0.061 (.045-.077)
Macdonald (1990)	1,427 (1,318-1,536)	0.05 (.043-.056)
Hegrenes (1992)	2,113 (1,726-2,500)	0.025 (.019-.031)

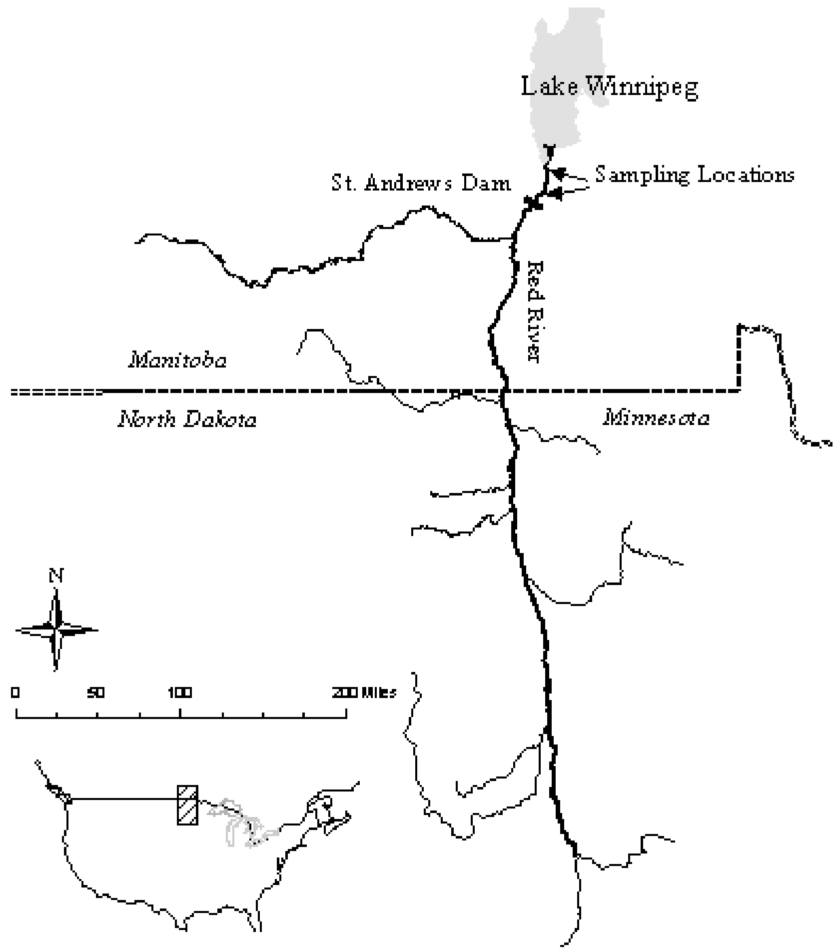

Figure 2-1. Map of the Red River of the North watershed and sampling locations for Channel Catfish during 2011-2014. Insert at lower left shows location of Red River in North America.

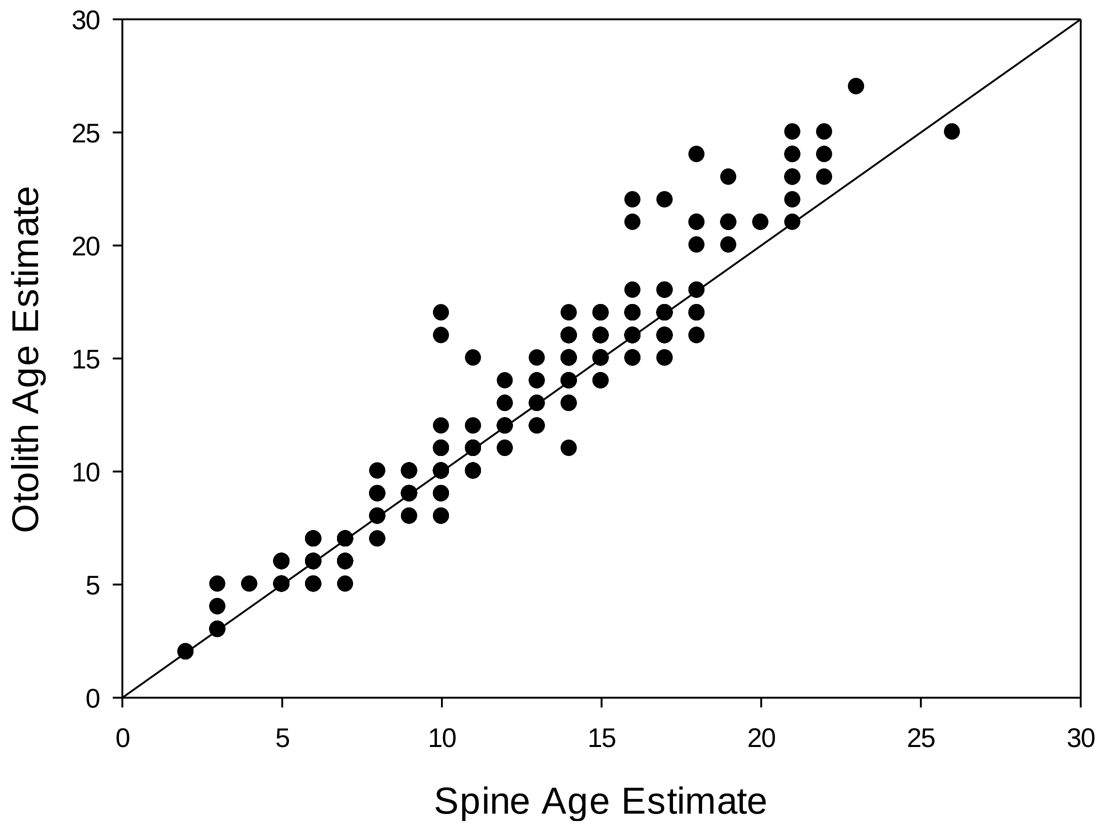

Figure 2-2. Comparison of spine and otolith age estimates for individual Channel Catfish from the lower Red River of the North during 2011-2013 (n=336). The 1:1 line is provided for reference.

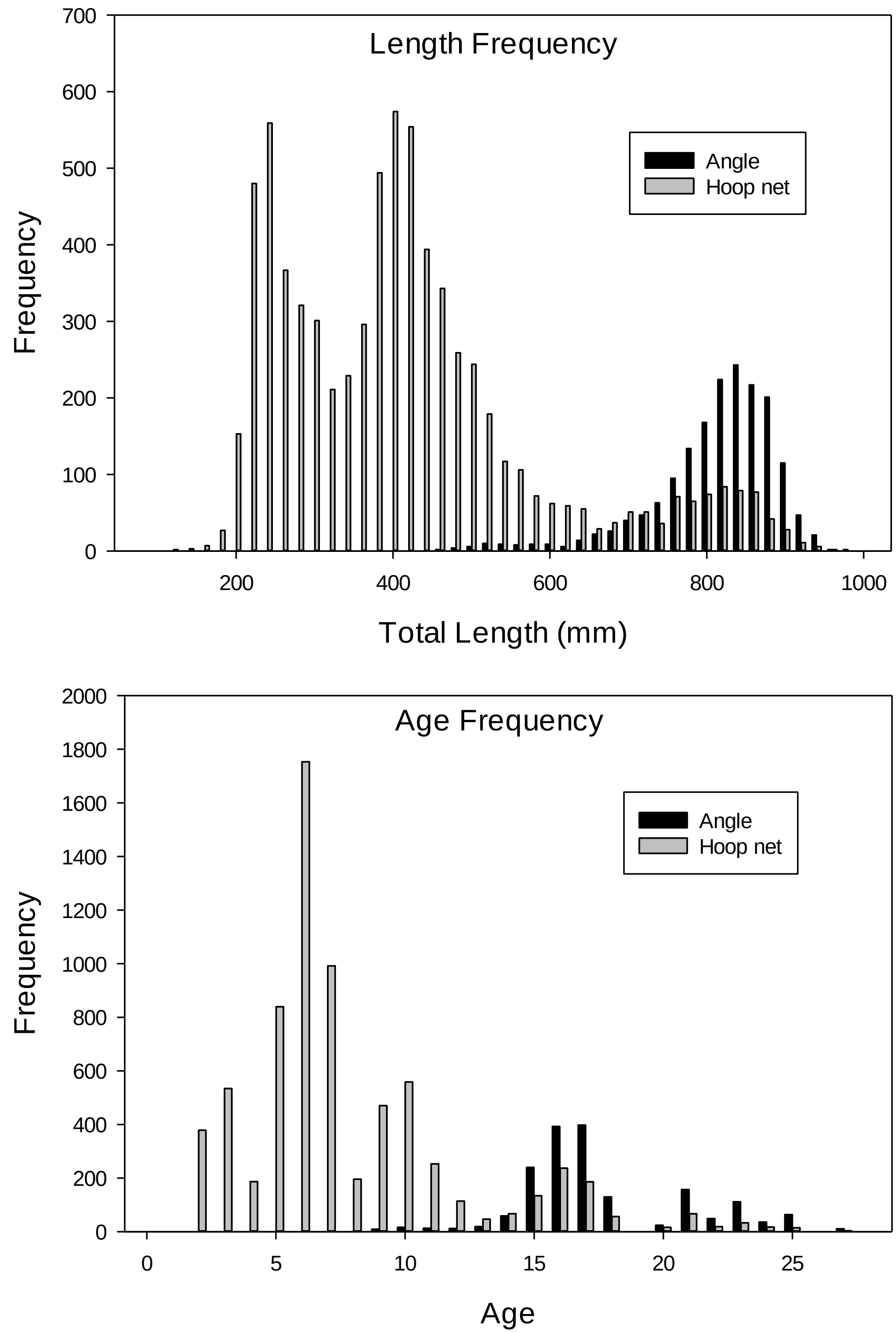

Figure 2-3. Size (top, 20 mm length groups) structure and age (bottom) structure of Channel Catfish sampled in the lower Red River of the North using hoop nets and angling during 2011-2014.

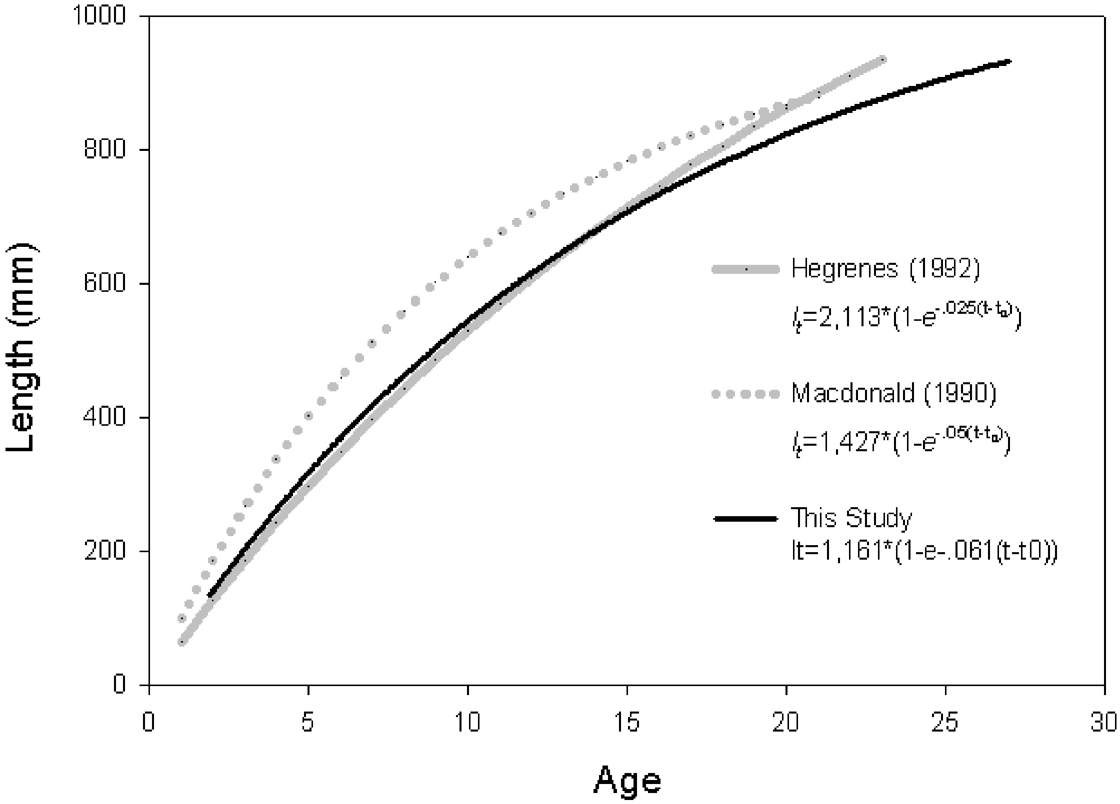

Figure 2-4. Von Bertalanffy growth curves and equations for Channel Catfish in the lower Red River of the North (this study), and past Red River of the North Channel Catfish studies (Macdonald 1990, Hegrenes 1992).

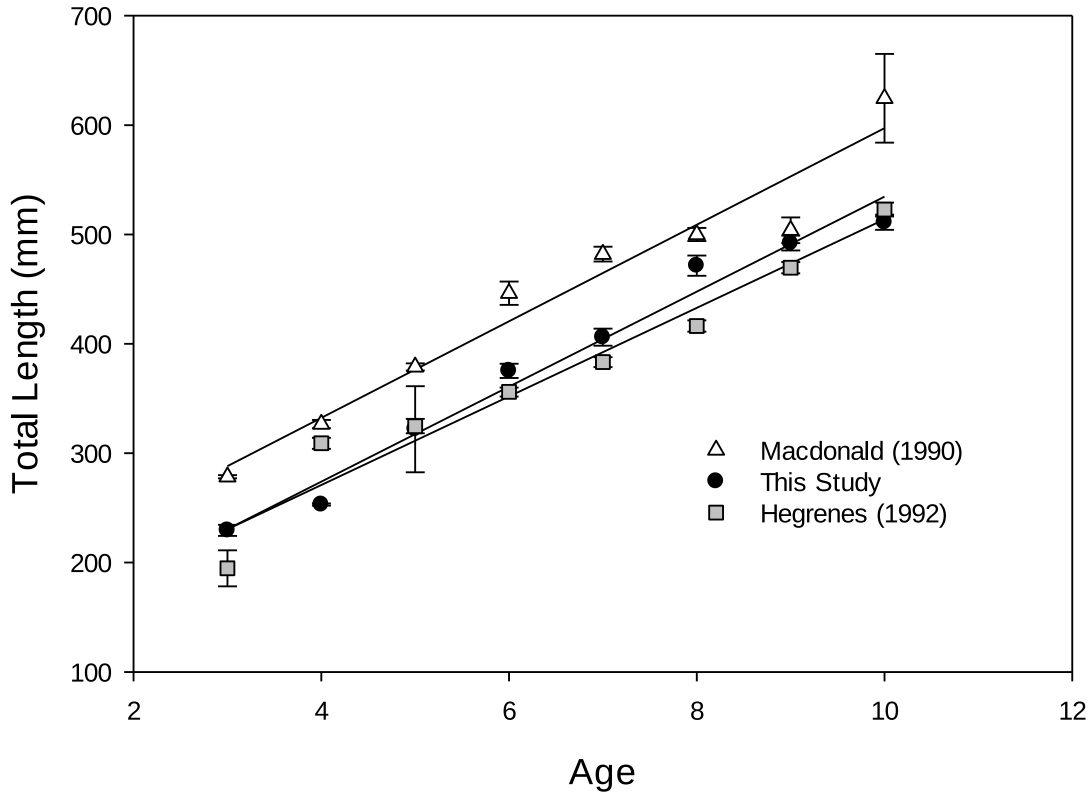

Figure 2-5. Regressions of growth trajectories from mean lengths-at-age (ages 3-10; ± SE) from Macdonald (1990), this study, and Hegrenes (1992) for Channel Catfish from the Red River of the North.

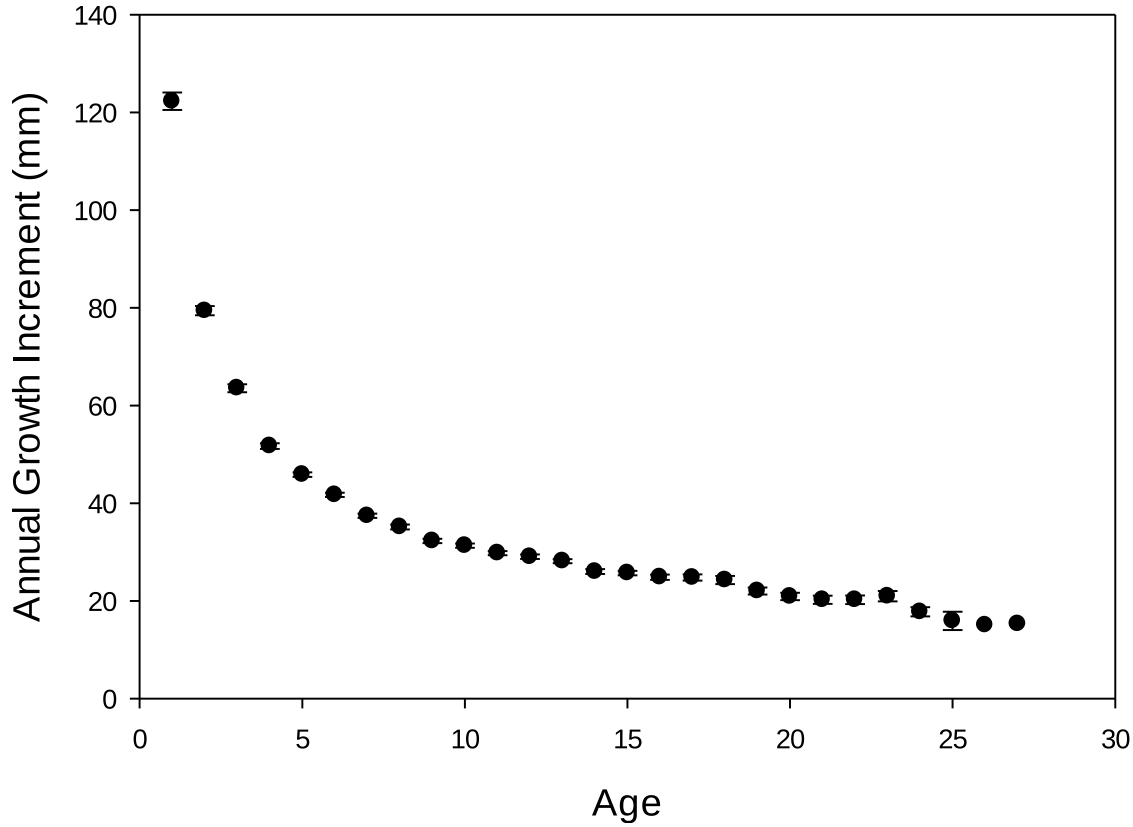

Figure 2-6. Estimated mean annual growth increments (± SE) of Channel Catfish from the lower Red River of the North using otoliths (n=345).

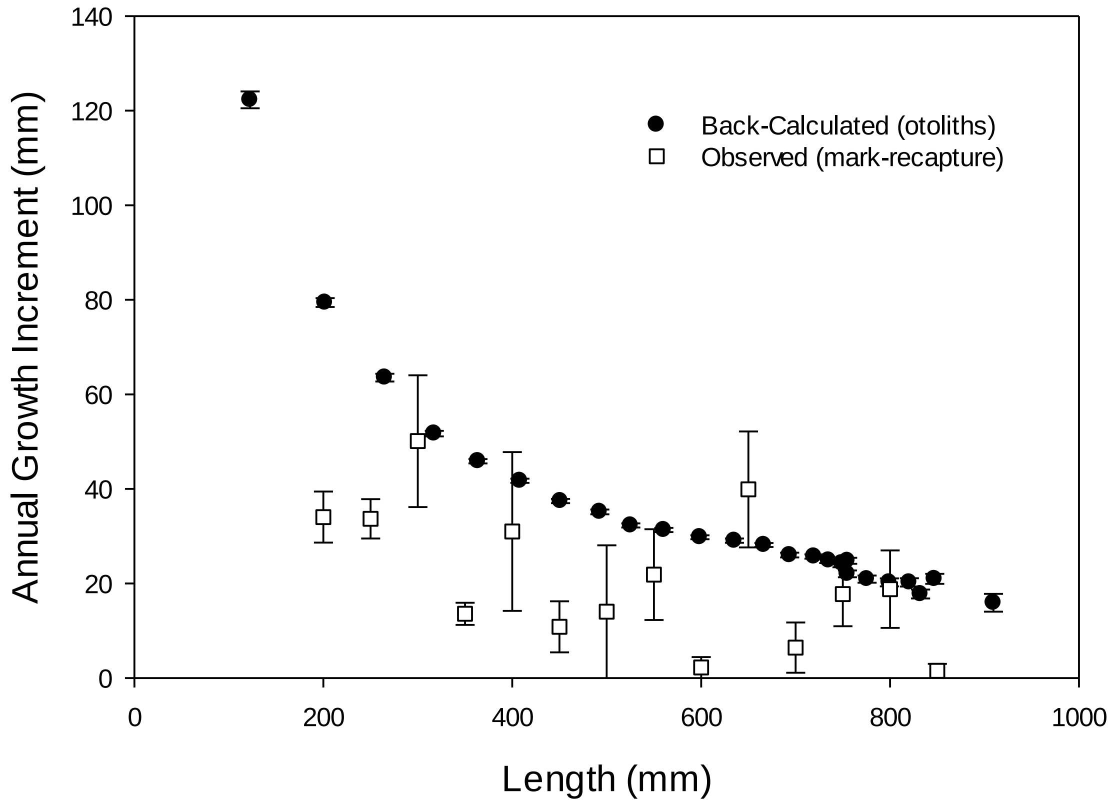

Figure 2-7. Estimated mean annual growth (± SE) from observed mark-recapture events (open squares) and back calculated mean annual growth (filled circles) from otoliths.

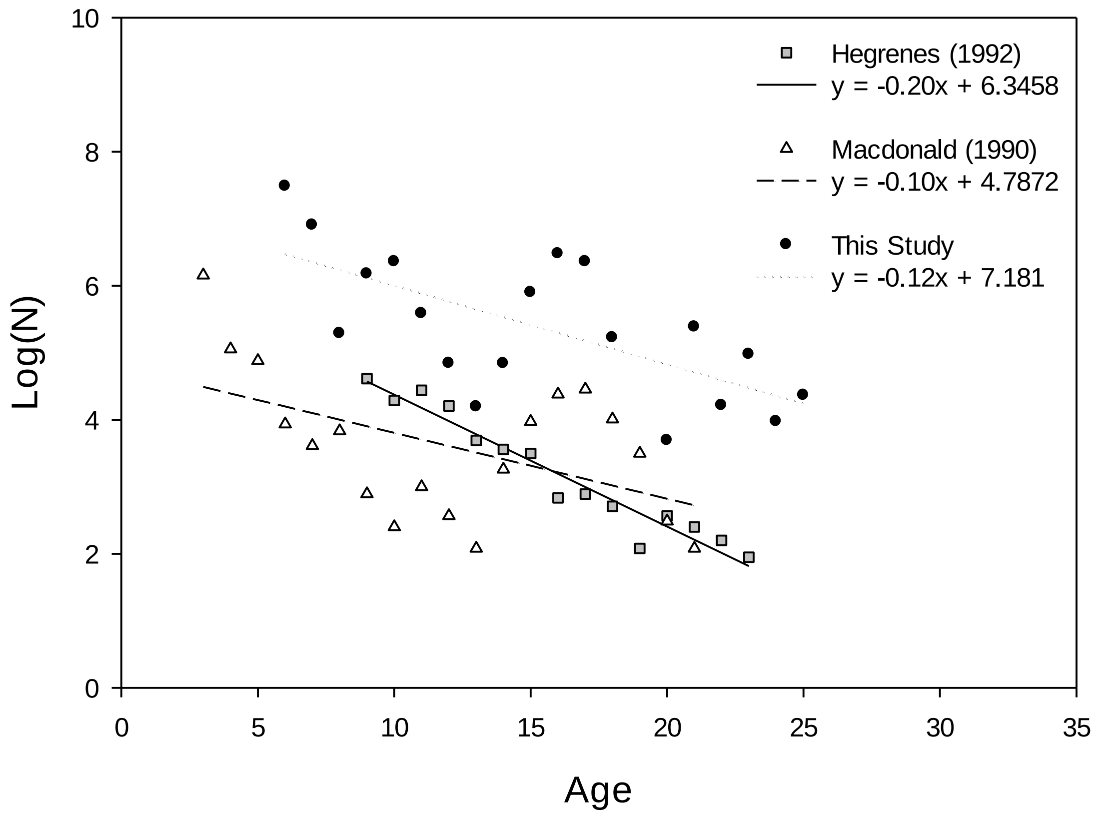

Figure 2-8. Ricker Catch Curve comparison of mortality rates from Hegrenes (1992), Macdonald (1990), and this study for Channel Catfish in the Red River of the North.

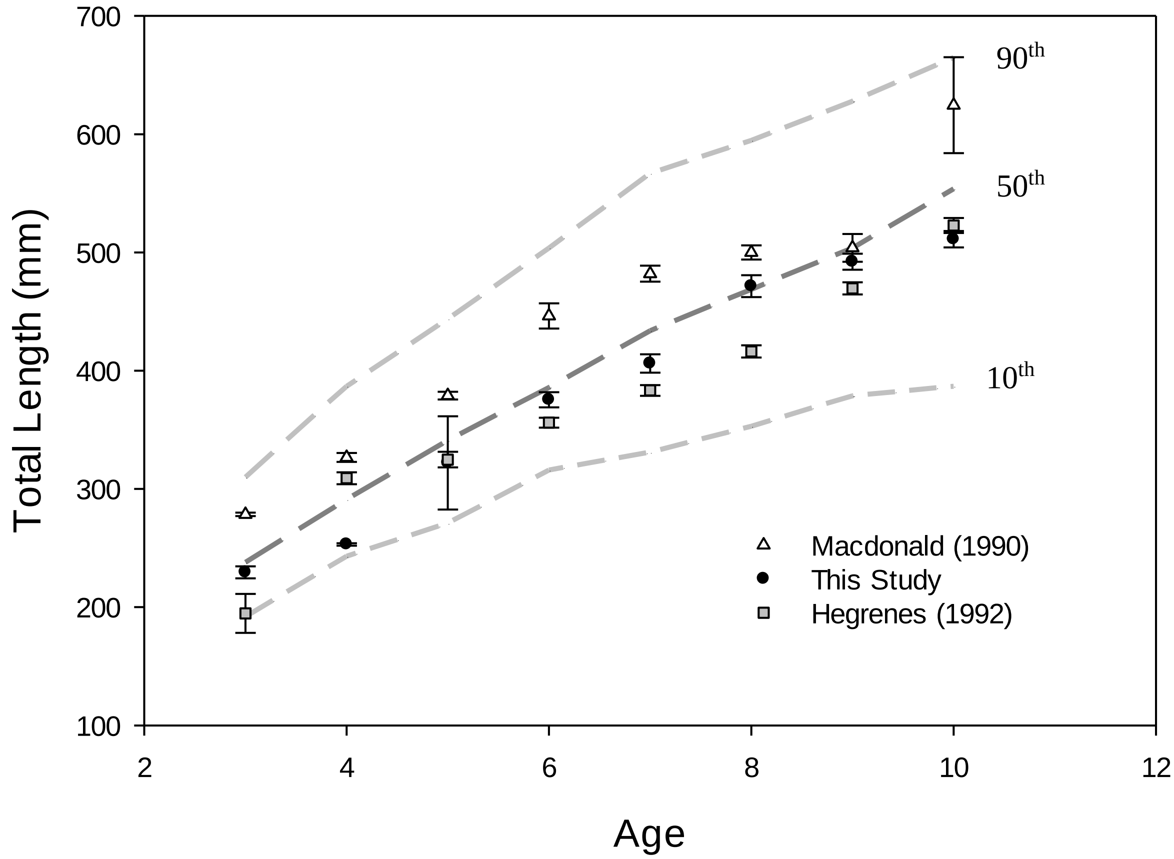

Figure 2-9. Mean length-at-age (± SE) comparisons between this study, Macdonald (1990), Hegrenes (1992), and data summarized by Hubert (1999). The Hubert (1999) percentiles (10^{th}, 50^{th}, and 90^{th}) represent the wide range of summarized Channel Catfish length data.

CHAPTER 3

ASSESSMENT OF CHANNEL CATFISH *ICTALURUS PUNCTATUS* POPULATION CHARACTERISTICS THROUGHOUT THE RED RIVER OF THE NORTH, MANITOBA, CANADA

ABSTRACT

The lower Red River of the North (Red River) in Manitoba, Canada supports an abundance of large (> 600 mm) Channel Catfish *Ictalurus punctatus*, and regulations are now in place to protect larger individuals within this fishery. The most popular reach for angling trophy Channel Catfish is below the St. Andrews Dam, near Selkirk, Manitoba. The Red River in Manitoba, from the St. Andrews Dam to the USA-Canada border is managed under the same regulations as the more popular area downstream. However, it is not known to produce trophy Channel Catfish in the same abundance as below St. Andrews Dam. Therefore, it is important to evaluate this fishery along the length of the Red River to determine the population characteristics of Channel Catfish. The objective of this study was to determine if there are differences in abundance, size structure, and condition of Channel Catfish at selected reaches (Netley Marsh, Selkirk, Winnipeg, and Emerson) throughout the Red River in Manitoba. We estimated abundances of greater than 5,000 Channel Catfish per river kilometer throughout the Red River and size structure generally increased downstream. Channel Catfish susceptible to

angling (≥ 668 mm) were found in greater proportions below the St. Andrews Dam. Intermediate-sized (400-600 mm) catfish were common in the Winnipeg reach, but underrepresented elsewhere. Given the variable size structures among reaches, some areas of the Red River may be more suitable for different life stages of Channel Catfish than others, which may explain differences in population demographics throughout the Red River. As such, management strategies for Channel Catfish in the Red River should encompass the entire river and account for variability in population dynamics.

INTRODUCTION

The Red River of the North (Red River) in Manitoba, Canada supports an abundance of large (> 600 mm) Channel Catfish *Ictalurus punctatus*, and regulations are now in place to protect larger individuals within this fishery (Macdonald 1990). Popularity for this fishery grew internationally in the late 1980s. A 1986 creel survey reported that harvest of Channel Catfish greater than 750 mm was common (Lysack 1986, Macdonald 1990). Manitoba moved to protect this fishery and instituted a creel limit of eight Channel Catfish in 1981, followed by a creel limit of four individuals (only one of which could be > 750 mm) in 1986. Current regulations allow the harvest of four catfish less than 600 mm per day. However, other than two previous studies (Macdonald 1990, Robert 1992) conducted amid the regulation changes, little information exists on the current population dynamics of Channel Catfish in the lower Red River.

The most popular reach for angling trophy Channel Catfish is below the St. Andrews Dam, near Selkirk, Manitoba (Figure 3-1). The Red River above St. Andrews Dam is not known to produce trophy Channel Catfish in the same abundance as below it, despite being managed under the same regulations. Movements of individuals throughout the Red River (Macdonald 1990, Hegrenes 1992, Robert 1992, Murray and MacDonnel 2009) suggest there is a single, panmictic population. Therefore, it is important to evaluate this fishery throughout the river to fully assess the population characteristics of Channel Catfish. The

objective of this study was to determine if there are differences in abundance, size structure, and condition of Channel Catfish in selected reaches throughout the Red River in Manitoba.

METHODS

Study Area

The Red River is formed at the confluence of the Bois de Sioux and Otter Tail rivers along the Minnesota-North Dakota border. The Red River flows north for 640 km forming the boundary between Minnesota and North Dakota (Koel and Peterka 2003). The Red River drainage basin within the USA encompasses parts of western Minnesota, eastern North Dakota, and a small portion of northeastern South Dakota, draining a total of 108,800 km^2. In southern Manitoba, the lower Red River continues flowing north 233 km before emptying into Lake Winnipeg. The Assiniboine River, a major tributary to the Red River, originates in Saskatchewan and joins the river in the city of Winnipeg, Manitoba. The Red River drains an area of 185,474 km^2 in Canada, most of which is in the Assiniboine watershed.

Hydrologic Description

The Red River is a low-gradient, warm-water river with high sinuosity. Over the entire 880-km mainstem, the Red River descends 70 m in elevation. Slopes range from 0.04% in the upper reaches to 0.003% as it enters Canada. The shallow gradient, draining of wetlands, and ditching of tributaries contribute to make this a flood-prone river (Aadland et al. 2005). The lower Red River near Selkirk has a mean flow of approximately 800 $m^3{\cdot}s^{-1}$at the peak of run off in April. Mean flow declines through the summer to an autumn average of about 120 $m^3{\cdot}s^{-1}$ and falls to just under 75 $m^3{\cdot}s^{-1}$ in the winter (Environment Canada, station 050J010). The lower Red River averages about 75 m in width with a maximum depth of about 9 m (Drewes et al. 2008). Peak summer water temperatures are reported at 24-25 °C (Macdonald 1990).

Sampling Locations

The focus of this sampling effort was divided among four reaches (Figure 3-1). A 5-km reach near the mouth of the Red River at Lake Winnipeg has been sampled regularly since autumn 2012 (hereafter, Netley Marsh). The second reach, encompassing the most popular Channel Catfish angling area on the Red River in Manitoba, is a 15-km reach from the St. Andrews Dam downstream to the town of Selkirk, Manitoba (hereafter, Selkirk), has also been sampled since autumn 2012. Sampling effort was expanded to encompass two more reaches

upstream of the St. Andrews Dam in 2014. One was a 5-km reach on the north side of the city of Winnipeg (hereafter, Winnipeg), and the other was a 5-km reach near Emerson, Manitoba at the Canada-USA border (hereafter, Emerson).

Sampling Periods

Channel Catfish were captured using hoop nets and rod-and-reel at Selkirk and Netley Marsh during a two-week period in August 2012. A similar sampling effort occurred during spring 2013 (May 25-June 22) at the same locations. Additional sampling also occurred during August 2013 at Selkirk (hoop nets and rod-and-reel) and at Netley Marsh (rod-and-reel). In 2014, sampling occurred during the spring and summer (May-August; netting and angling) in all four locations, where five visits were made to each sampling location (Netley Marsh, Selkirk, Winnipeg, and Emerson). Each visit yielded 20 net-nights of netting effort and at least 4 person-hours of angling effort. Sampling efforts in 2015 largely focused on the Selkirk reach, but some sampling did occur at Netley Marsh and Emerson reaches as well.

Data Collection

Hoop nets used for this study had seven, 0.9-m diameter hoops and were baited with soy bean mash. Angling was primarily conducted with 6/0 barbless circle hooks baited with cut Goldeye (*Hiodon alosoides*) and White Sucker

(*Catostomus commersonii*). At two reaches (Selkirk and Emerson), additional terminal tackle (size 2 J-hooks baited with nightcrawlers) was incorporated to target smaller catfish and increase catch rates. Channel Catfish were weighed to the nearest g, measured for maximum total length to the nearest mm, and tagged with a T-bar anchor tag inserted through the pterigiophores on the left side (Guy et al. 1996). Channel Catfish that were 200-500 mm received a smaller tag (Floy mfg, 68-B), and Channel Catfish greater than 500 mm received a larger tag (Floy mfg., 67-F). Each tag was labeled with a toll-free phone number for anglers to report caught fish and a unique serial number to identify each individual fish.

Abundance

We used the Jolly-Seber super-population model (Schwarz and Arnason 1996) to estimate abundance of Channel Catfish in the Red River with Program MARK (POPAN model; White and Burnham 1999). The POPAN model allows estimation of apparent survival at time *i* ($\boldsymbol{S_i}$, *phi* in MARK), probability of entry into the study area at time *i* ($\boldsymbol{\beta}_i$), capture probability at time *i* ($\boldsymbol{p}_i$), and a single parameter for the estimate of all individuals that entered the population over the study period (super-population estimate, $\boldsymbol{N}$). We included models with apparent survival and capture probability as either constant values (***S*., *p*.**), or allowed to vary by time ($\boldsymbol{S_t}$, $\boldsymbol{p_t}$; Appendix 1). These parameter possibilities were chosen because the survival parameter in this model is the function of both mortality and permanent emigration from the study area, which we know occurs (Ch. 4, this

thesis), but could be consistent or vary by time. We also included models that allowed capture probability to vary through time to account for inconsistent sampling effort. The probability of entry ($\boldsymbol{\beta}_i$) was only used as a function of time ($\boldsymbol{\beta}_t$) because we expected seasonality to influence movement rates.

All fish tagged or recaptured in each reach were assigned a '1'. If a fish was not encountered in a given period, it was assigned a 0. Hence, an example encounter history of "01000001000000", would be assigned for a fish captured and tagged during the second period in a given reach and not encountered again until it was recaptured in the eighth period (and not recaptured again). A total of 14 monthly periods were used to cover sampling events as equally as possible for models at Selkirk (Appendix 2). The same periods were used at Netley Marsh except for the final period (13 periods; no fish were tagged or recaptured there during the final month). Three monthly periods were used for modeling abundance at Emerson and Winnipeg as only the summer of 2014 was used for a focused effort at these locations (periods 7-9; Appendix 2). We accounted for disparities in time between encounter occasions by designating appropriate time intervals between periods in the model design.

Abundance of Channel Catfish was estimated for each reach and for two different size groupings: an "all-inclusive" size group (> 200 mm) and an "angler-susceptible" size group (≥ 668 mm). We chose the angler-susceptible size group to represent the size group commonly targeted by anglers, as 95% of the Channel Catfish that were angled from the Selkirk reach were at least 668 mm. We

determined a standardized abundance estimate of Channel Catfish per river km (rkm) by dividing our abundance estimates by the length of our study areas. We also calculated density per ha by determining area of the study reach from satellite imagery.

Tag Retention

A subset of Channel Catfish were double tagged to estimate tag retention. The first tag was inserted from the left side of the dorsal fin and the second, consecutively numbered, tag was inserted from the right side. The tag loss probability was calculated by fitting a logistic regression to binomial tag return data (i.e., a '1' was assigned to a tag loss, and a '0' was assigned to fish that retained both tags). Time at large (days) was used as the independent variable. The annual probability of losing a tag was calculated by a natural log back transformation of the logistic equation where time = 365 days.

Relative Abundance

Mean catch per unit effort (CPUE) for hoop nets was calculated as the mean number of Channel Catfish caught per net night (± SE) and used as an index of relative abundance. We chose to restrict our evaluation of CPUE to 2014 data only because all four reaches were sampled evenly in 2014. Nets that fished improperly (e.g., collapsed) were removed from this analysis. Catch data were not

normally distributed, variance was high, and zero catches were prevalent. As such, we conducted relative abundance comparisons among all reaches using a generalized linear model (SAS 9.4) based on a negative binomial distribution (Powers and Moser 1999). We used Tukey's test for multiple comparisons to further determine differences in relative abundance between reaches. We used an alpha value of 0.05 to determine significance for all tests.

Condition

Condition was indexed by calculating relative weights (W_r) for individual fish from both gears during 2014 using the formula:

$$W_r = \frac{W}{W_s} * 100,$$

where, W_r = relative weight, W = weight, and W_s = a length-specific standard weight predicted from a weight-length regression developed as a species standard. The formula for standard weight (W_s) for Channel Catfish is:

$$log_{10}(W_s) = a' + b * log_{10}(L) \ ,$$

where, a' = -5.8, b = 3.294, and L = length (Brown et al. 1995). We calculated mean W_r values for all size groups (i.e., Proportional Stock Distribution; Gabelhouse 1984) and all reaches. We compared W_r values between reaches by PSD groups (e.g., stock, quality, etc.) using Kruskal-Wallis tests for non-normal distributions (Pope and Kruse 2007).

Size Structure

We constructed length-frequency histograms (20-mm length groups) for each reach and gear type from 2014 to test whether length-frequency distributions were different among reaches (Neumann and Allen 2007). We only used hoop-net caught catfish at each reach for this comparison because effort and methods for angling were different between reaches.

Proportional size distribution (PSD) was calculated for each reach by both gear types from 2014 for comparisons. PSD was calculated with the formula:

$$PSD = \frac{\#\ fish \geq specified\ length}{\#\ fish \geq minimum\ stock\ length} * 100 ,$$

The following length groups were used: stock length (≥ 280 mm), quality length (≥ 410 mm; PSD), preferred length (≥ 610 mm; PSD-P), memorable length (≥ 710 mm; PSD-M), and trophy length (≥ 910 mm; PSD-T; Gabelhouse 1984). We determined approximate 95% confidence intervals using Gustafson (1988).

RESULTS

We tagged 13, 720 Channel Catfish during 2012-2015. Abundance estimates for the angler susceptible size group were highest at Selkirk (Table 3-1). We were unable to estimate abundance for the angler susceptible size group at Emerson due to too few recaptures. Density estimates (per ha) were highest at Netley Marsh, but were similar among Selkirk, Winnipeg, and Emerson. Density

estimates (per ha) for the angler susceptible sized catfish were highest in the Selkirk reach.

Over the course of this study, 3,796 (27%) Channel Catfish were double tagged. We confirmed 123 double tagged catfish were recaptured, and 14 had lost a tag. The y-intercept of the derived logistic regression equation was -4.28 and the beta value was 0.00734. Annual tag loss was estimated to be 16.8% 365 days post-tagging (Figure 3-2).

We collected 8,248 Channel Catfish from the Red River using hoop nets and rod-and-reel during 2014. Relative abundance was lower upstream, where mean CPUE was 15.6 (± 2.5) at Selkirk and 14.8 (± 4) at Winnipeg. The CPUE (mean ± SE) was greatest at Netley Marsh (22 ± 3). The lowest mean CPUE was at Emerson (8 ± 1.5). Mean CPUE was different between Selkirk and Emerson (Tukey's test; $P = 0.0439$) and Netley Marsh and Emerson (Tukey's test; $P < 0.001$).

Relative weight values were different for each of the size groupings among reaches ($P \leq 0.01$; Table 3-2). The lowest relative weight values were observed at Emerson, and the greatest relative weights were observed for individuals at Selkirk. Catfish in the stock (280-409 mm) and quality (410-609 mm) size groups had the lowest relative weights (range: 87-92) across all reaches, and Winnipeg and Emerson had lower relative weights than Selkirk and Netley Marsh.

Length-frequency distributions for hoop-net samples were different among reaches (*P* < 0.01; Figure 3-3): Channel Catfish greater than 800 mm were most common at Selkirk, whereas Channel Catfish less than 520 mm were most common at Netley Marsh and Emerson. The Winnipeg reach comprised fish that were predominantly between 400 and 640 mm. Size structure indices differed across reaches for both hoop net and rod-and-reel data (*P* < 0.01; Table 3-3). For angling catches, PSD values were 100 for every reach but Emerson, which was 37. Proportional size distribution values (P, M, and T size groups) for angling generally increased moving downstream. Selkirk had the largest Channel Catfish of all four reaches (hoop net PSD-M, Table 3-3), but PSD values for hoop net catches were varied.

DISCUSSION

The greater abundance of fish in the angler-susceptible size group at the Selkirk reach may be due to river conditions (*e.g.*, refuge, forage availability, and water quality) and the influence the dam has on concentrating fish. Other studies have reported changes in relative abundance of fish species related to changes in habitat (Torgerson et al. 2006, Paukert and Makinster 2009), greater densities of predator fish species below dams (Beamesderfer and Rieman 1991), and high-quality catfish populations below dams (Jolley and Irwin 2011). Beamesderfer

and Rieman (1991) noted densities of Northern Squawfish *Ptychocheilus oregonensis* were greatest immediately below a dam, and Walleye *Sander vitreus* were most common in the upper third of a reservoir below a dam. Jolley and Irwin (2011) reported larger Blue Catfish *Ictalurus furcatus* individuals and greater abundance of Flathead Catfish *Pylodictis olivaris* in tailrace than in reservoir habitats. We were not able to determine how far downstream the effects from the dam are seen in the fish community, but the relative abundance of Channel Catfish was highest below St. Andrews Dam, and abundance estimates from POPAN models corroborated this trend. The St. Andrews Dam provides a unique habitat feature on the lower Red River that concentrates Channel Catfish.

Few studies have attempted to estimate density or absolute abundance of Channel Catfish, and no studies found Channel Catfish at densities as high as this study. Goble (2011) reported standardized abundance estimates of about 4,200 Channel Catfish (≥ 200 mm) per rkm in one bend of the Missouri River, Nebraska. Haxton and Punt (2004) reported much lower densities per ha (highest density from all reaches = 31.7 Channel Catfish/ha) for Channel Catfish in the Ottawa River, Ontario. Our estimates are likely somewhat inflated by the presence of transient individuals, as the super-population parameter is an estimate of all individuals that entered the study area throughout the sampling period, but they indicate a density of Channel Catfish not currently observed elsewhere.

We did not incorporate tag loss and angler reporting rates into abundance estimates. Tag loss and failure to report tags would reduce the number of

recaptures reported, which would negatively influence abundance estimates. Anchor tag retention was also greater in this study than observed in the literature for Channel Catfish (Greenland and Bryan 1974, Timmons and Howell 1995, Buckmeier and Irwin 2000). Angler reporting rates have been reported as low as 28% (Matlock 1981), and as high as 63% (Denson et al. 2002). We expect reporting rates for this study to be comparable to Denson et al. (2002) because angler perception and participation appeared to be cooperative. It is likely that our abundance estimates are positively biased by not accounting for reporting rates and tag loss, but accounting for our low tag loss rate would likely produce estimates within the confidence intervals of our current abundance estimates.

The size structure of Channel Catfish was unexpectedly different among the reaches we sampled. There was a general longitudinal increase in the size distributions from Emerson to Selkirk, where a smaller proportion of large fish (> 668 mm) were found at Winnipeg and Emerson (Figure 3-3). Samples from the Winnipeg reach were primarily comprised of 400-640 mm long Channel Catfish, and smaller Channel Catfish (< 400 mm) were underrepresented compared to all other reaches. This could be indicative of ontogenetic shifts in habitat (Irwin et al. 1999) and foraging needs (Mol 1995) that likely occur throughout the lifetime of Channel Catfish, and may account for variations in population demographics among reaches (Quist and Guy 1998, Tedesco et al. 2009). Quist and Guy (1998) reported spatially explicit variation in population characteristics (i.e., growth rates, size structure, and relative abundance) of Channel Catfish along the Kansas

River. Continued documentation of movement of Channel Catfish to or from the Winnipeg and Emerson reaches should increase our understanding of the Channel Catfish population dynamics occurring along the length of the Red River.

Current regulations on the Red River in Manitoba allow anglers to harvest four Channel Catfish per day, all of which must be less than 600 mm. This regulation was intended to maintain the trophy-oriented size structure that has historically been present in the Red River. Our results suggest the regulation has been successful at maintaining the trophy size structure of the catfish population, at least at Selkirk and Netley Marsh, but is likely protecting few individuals at Emerson if anglers are inclined to harvest there. Management strategies should account for variation in habitat requirements throughout the life-cycle of Channel Catfish (Irwin et al. 1999, King 2004) and possible variation in population characteristics along the length of the Red River (Quist and Guy 1998, Paukert and Makinster 2009, Tedesco et al. 2009). Further investigation of the age and growth characteristics of Channel Catfish within the Winnipeg Reach, further evaluation of movement patterns, and assessing how interdependent catfish are in the Red River all warrant further investigation. Insights of this nature will facilitate appropriate management strategies to be put in place in the proper locations.

LITERATURE CITED

Aadland, L.P., T.M. Koel, W.G. Franzin, K.W. Stewart, and P. Nelson. 2005. Changes in fish assemblage structure of the Red River of the North. Pages 293-321 *in* J.N. Rinne, R.M. Hughes, and B. Calamusso, editors. Historical changes in large river fish assemblages. American Fisheries Society Symposium 45, Bethesda, Maryland.

Beamesderfer, R.C., and B.E. Rieman. 1991. Abundance and distribution of northern squawfish, walleyes, and smallmouth bass in John Day Reservoir, Columbia River. Transactions of the American Fisheries Society 120:439-447.

Buckmeier, D.L., and E.R. Irwin. 2000. An evaluation of soft visual implant tag retention compared with anchor tag retention in channel catfish. North American Journal of Fisheries Management 20:296-298.

Denson, M.R., W.E. Jenkins, A.G. Woodward, and T.I. Smith. 2002. Tag-reporting levels for red drum (Sciaenops ocellatus) caught by anglers in South Carolina and Georgia estuaries. Fishery Bulletin 100:35–41.

Drewes, H., M. Ermer, S. Gangl, and D. Kroeker. 2008. Red River of the North Fisheries Management Plan. Manitoba Water Stewardship, Minnesota Department of Natural Resources, North Dakota Game and Fish Department, and South Dakota Department of Game, Fish, and Parks.

Gabelhouse Jr, D.W. 1984. A length-categorization system to assess fish stocks. North American Journal of Fisheries Management 4:273-285.

Goble, C. 2011. Ecology and management of channel catfish Ictalurus punctatus and flathead catfish Pylodictis olivaris populations in the Missouri River, NE. Master's Thesis. University of Nebraska, Lincoln, Nebraska.

Greenland, D.C., and J.D. Bryan. 1974. Anchor tag loss in channel catfish. The Progressive Fish-Culturist 36:181-182.

Gustafson, K.A. 1988. Approximating confidence intervals for indices of fish population size structure. North American Journal of Fisheries Management 8:139-141.

Guy, C.S., H.L. Blankenship, and L.A. Neilsen. 1996. Tagging and Marking. Pages 353-384 *in* B.R. Murphy and D.W. Willis, editors. Fisheries techniques, 2nd edition. American Fisheries Society, Bethesda, Maryland.

Haxton, T., and K. Punt. 2004. Abundance and demography of channel catfish in a large northern river. North American Journal of Fisheries Management 24:1440–1446.

Hegrenes, S.G. 1992. Age, growth, and reproduction of channel catfish in the Red River of the North. Master's thesis. University of North Dakota, Grand Forks, North Dakota.

Irwin, E.R., M.C. Freeman, and K.M. Costley. 1999. Habitat use by juvenile channel catfish and flathead catfish in lotic systems in Alabama. Pages 223-230 *in* E. R. Irwin, W. A. Hubert, C. F. Rabeni, H. L. Schramm, Jr., and T. Coon, editors. Catfish 2000: Proceedings of the International Ictalurid Symposium. American Fisheries Society, Symposium 24, Bethesda, Maryland.

Jolley, J.C., and E.R. Irwin. 2011. Catfish population characteristics in tailwater and reservoir habitats of the Coosa River, Alabama. Pages 155-166 *in* P.H. Michaletz and V.H. Travnichek, editors. Conservation, ecology, and management of catfish: the second international symposium. American Fisheries Society, Symposium 77, Bethesda, Maryland.

King, A.J. 2004. Ontogenetic patterns of habitat use by fishes within the main channel of an Australian floodplain river. Journal of Fish Biology 65:1582-1603.

Koel, T.M. and J.J. Peterka. 2003. Stream fish communities and environmental correlates in the Red River of the North, Minnesota and North Dakota. Environmental Biology of Fishes. 67:137–155.

Lysack, W. 1986. The angling fishery of the lower Red River. Manitoba Department of Natural Resources, Fisheries Branch Manuscript Report 86-16.

Macdonald, D. 1990. The channel catfish sport fishery of the lower Red River. Master’s thesis. The University of Manitoba, Winnipeg, Manitoba.

Matlock, G.C. 1981. Nonreporting of recaptured tagged fish by saltwater recreational boat anglers in Texas. Transactions of the American Fisheries Society 110:90-92.

Mol, J.H. 1995. Ontogenetic diet shifts and diet overlap among three closely related neotropical armoured catfishes. Journal of Fish Biology 47:788-807.

Murray, L., and D.S. MacDonnell. 2009. Red River floodway expansion acoustic telemetry study. Report by North/South Consultants for the Manitoba Floodway Authority.

Neumann, R.M. and M.S. Allen. 2007. Size Structure. Pages 375-422 *in* C.S. Guy and M.L. Brown, editors. Analysis and Interpretation of freshwater fisheries data. American Fisheries Society, Bethesda, Maryland.

Paukert, C.P., and A.S. Makinster. 2009. Longitudinal patterns in flathead catfish relative abundance and length at age within a large river: effects of an urban gradient. River Research and Applications 25:861-873.

Pope, K.L. and C.G. Kruse. 2007. Condition. Pages 423-471 *in* C.S. Guy and M.L. Brown, editors. Analysis and interpretation of freshwater fisheries data. American Fisheries Society, Bethesda, Maryland.

Power, J.H., and E.B. Moser. 1999. Linear model analysis of net catch data using the negative binomial distribution. Canadian Journal of Fisheries and Aquatic Sciences 56:191-200.

Quist, M.C., and C.S. Guy. 1998. Population characteristics of channel catfish from the Kansas River, Kansas. Journal of Freshwater Ecology 13:351-359.

Robert, L. 1992. Upper Red River channel catfish tagging report. Manitoba Department of Natural Resources, Fisheries Branch, Manuscript Report 20.

Schwarz, C.J., and A.N. Arnason. 1996. A general methodology for the analysis of capture-recapture experiments in open populations. Biometrics 52:860-873.

Tedesco, P.A., P. Sagnes, J. Laroche. 2009. Variability in the growth rate of chub Leuciscus cephalus along a longitudinal river gradient. Journal of fish biology 74:312-319.

Timmons, T.J., and M.H. Howell. 1995. Retention of Anchor and Spaghetti Tags by Paddlefish, Catfishes, and Buffalo Fishes. North American Journal of Fisheries Management 15:504-506.

Torgersen, C.E., C.V. Baxter, H.W. Li, and B.A. McIntosh. 2006. Landscape influences on longitudinal patterns of river fishes: spatially continuous analysis of fish-habitat relationships. Pages 473-492 *in* R.M Hughes, L. Wang, and P.W. Seelbach, editors. Influences of landscape on stream habitats and biological assemblages. American Fisheries Society Symposium 48. American Fisheries Society, Bethesda, Maryland.

White, G.C., and K.P. Burnham. 1999. Program MARK: survival estimation from populations of marked animals. Bird study 46:S120-S139.

Table 3-1. Abundance estimates of Channel Catfish derived from POPAN models in Program MARK for four areas of interest on the Red River of the North, Manitoba, Canada.

Reach and Size Grouping	Estimate	Standard Error	95% Confidence Interval	Abundance per rkm (Density per ha)
Netley Marsh				
≥ 668 mm	5,894	4,755	1,622 – 24,051	1,179 (38)
≥ 200 mm	1,173,558	542,077	496,460 – 2,780,309	234,712 (7,481)
Selkirk				
≥ 668 mm	47,217	5,923	37,068 – 60,452	3,148 (134)
≥ 200 mm	178,776	19,624	144,434 – 221,753	11,918 (507)
Winnipeg				
≥ 668 mm	5,015	2,456	2,086 – 12,580	1,003 (56)
≥ 200 mm	43,474	10,811	27,042 – 70,478	8,694 (488)
Emerson				
≥ 668 mm	N/A			
≥ 200 mm	29,792	13,168	13,189 - 68,520	5,958 (650)

Table 3-2. Mean (± standard error) relative weight values by reach and size group of Channel Catfish sampled in the Red River of the North, Manitoba, Canada. Kruskal-Wallis test results indicated differences between size groups among reaches (*P*<0.01).

	Selkirk	Netley Marsh	Winnipeg	Emerson
Stock	92 (± 0.8)	92 (± 0.4)	89 (± 0.8)	90 (± 0.3)
Quality	88 (± 0.6)	90 (± 0.4)	90 (± 0.4)	87 (± 0.6)
Preferred	98 (± 2.2)	96 (± 1.6)	94 (± 0.8)	90 (± 1.7)
Memorable	108 (± 1.5)	107 (± 2)	93 (± 1.2)	96 (± 3)
Trophy	108 (± 3.7)	.	.	.

Table 3-3. Proportional size distribution values (± 95% confidence intervals) for Channel Catfish in the Red River of the North sorted by gear and reach.

Reach	PSD (± 95% CI)	PSD-P (± 95% CI)	PSD-M (± 95% CI)	PSD-T (± 95% CI)
Hoop nets				
Netley Marsh	51 (49-53)	5 (4-6)	2 (1-3)	0
Selkirk	61 (58-64)	21 (19-23)	17 (15-19)	1
Winnipeg	85 (83-87)	25 (23-27)	9 (7-11)	0
Emerson	37 (33-41)	11 (9-13)	5 (3-7)	0
Angling				
Netley Marsh	100	94 (88-100)	85 (77-93)	5 (0-10)
Selkirk	100	97 (96-98)	94 (92-96)	7 (5-9)
Winnipeg	100	77 (65-89)	33 (20-46)	1
Emerson	37 (26-48)	18 (9-27)	8 (1-15)	1

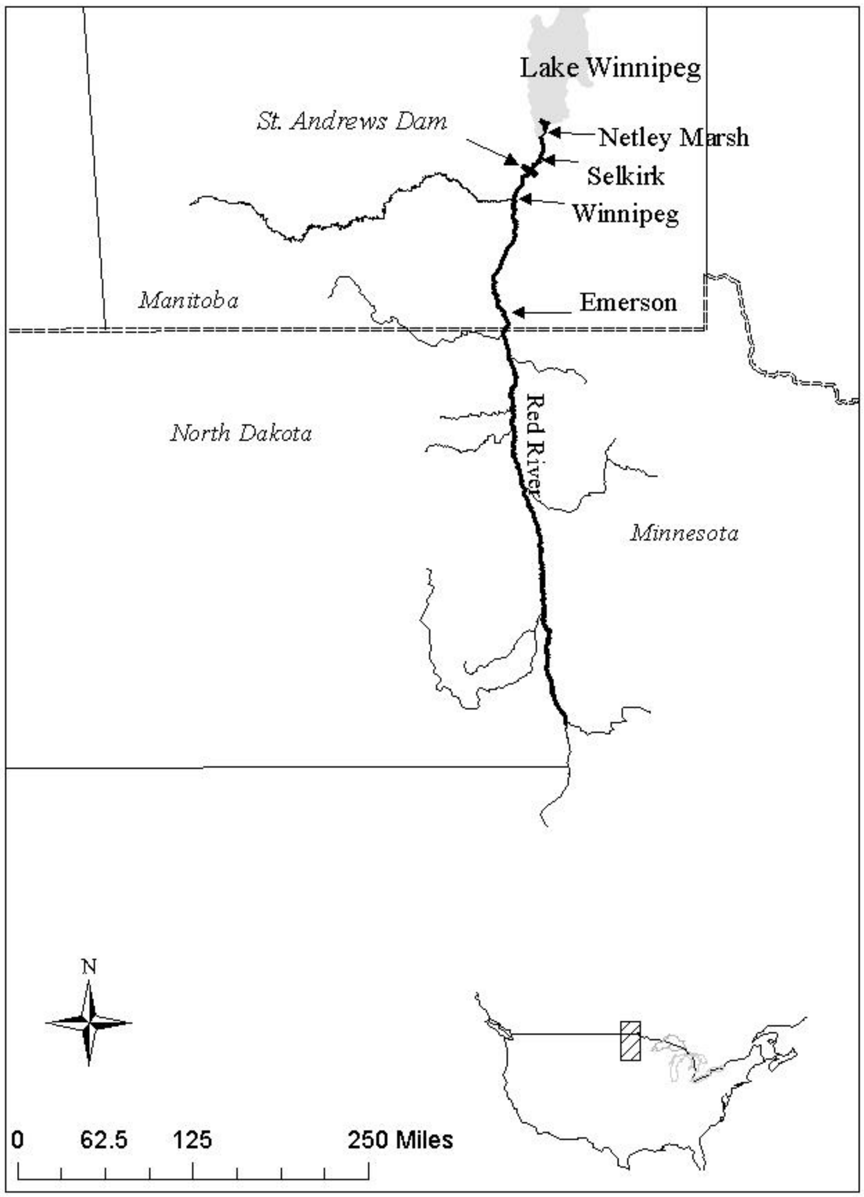

Figure 3-1. Map of the Red River of the North watershed. Sample reach locations are indicated by name and arrow. Insert at lower right shows location of Red River in North America.

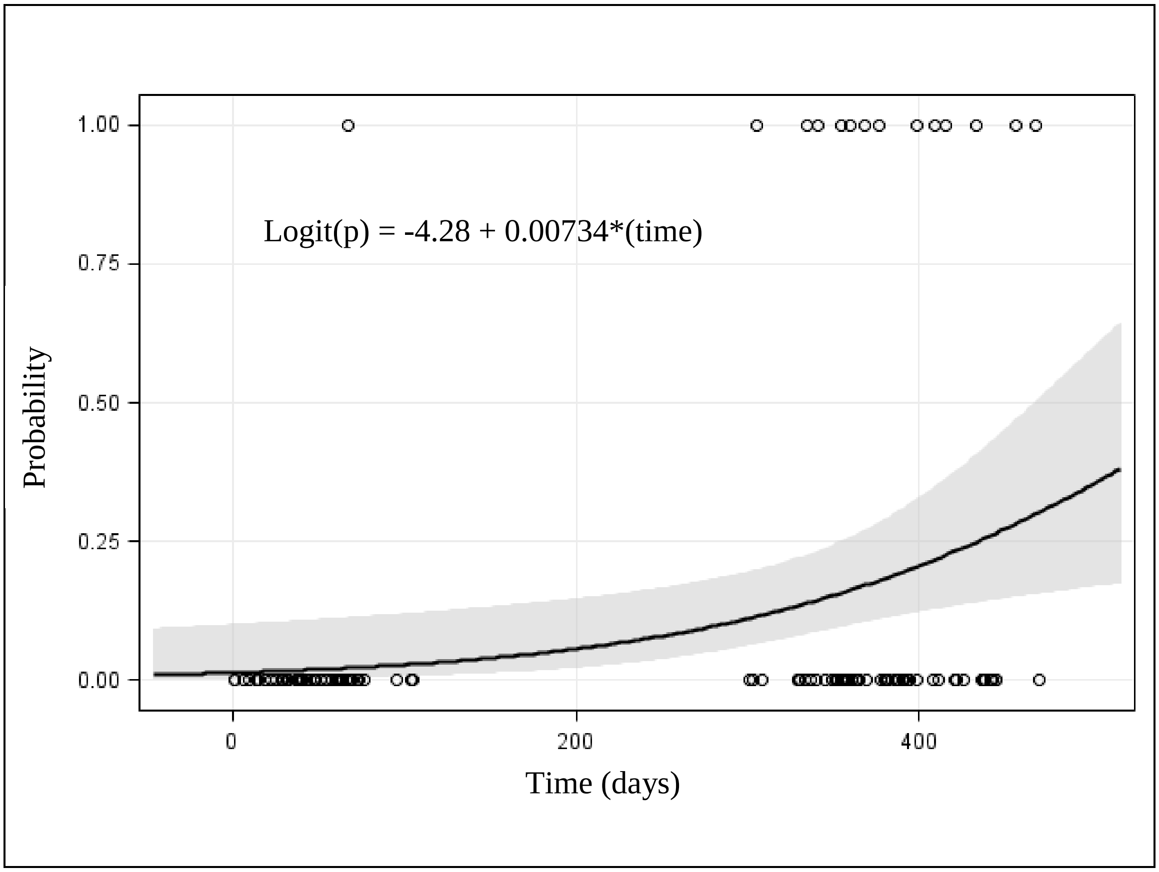

Figure 3-2. Logistic regression of probability of tag loss by time at large (days) for Channel Catfish in the Red River. The black line is predicted tag loss; grey line is 95% confidence intervals (indicated in grey); and open circles are observed results from recaptured Channel Catfish.

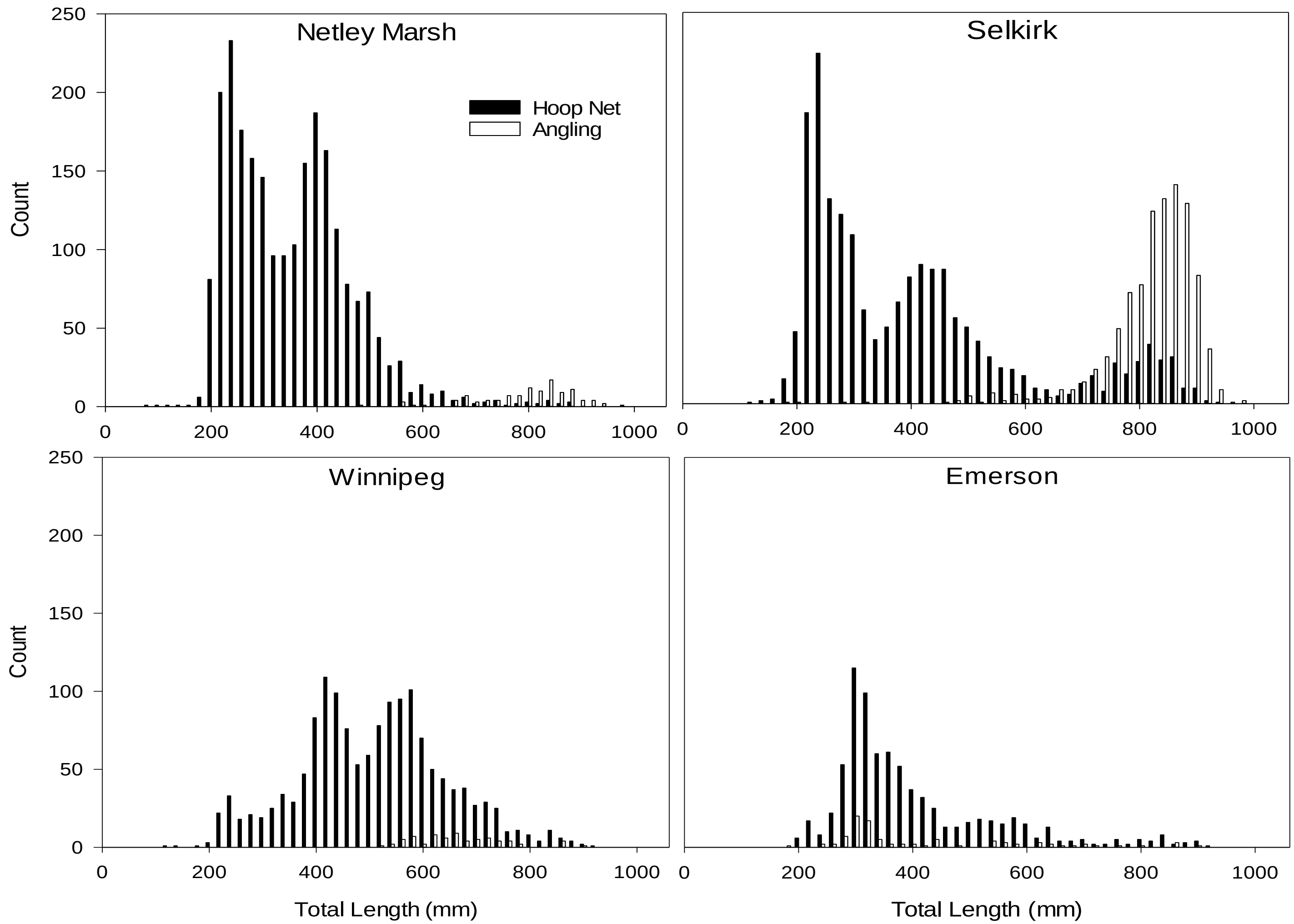

Figure 3-3. Length-frequency histograms of Channel Catfish caught with hoop nets and angling for all reaches in 2014. Additional angling effort occurred at Selkirk, contributing to greater total catch.

CHAPTER 4

QUANTIFYING MOVEMENT OF CHANNEL CATFISH *ICTALURUS PUNCTATUS* IN THE RED RIVER OF THE NORTH

ABSTRACT

Channel Catfish *Ictalurus punctatus* are known to travel long distances in rivers. Many of these movements have been proposed to fulfill some life need, such as spawning or finding overwintering habitat. Like many other large rivers in North America, the Red River of the North (Red River) has been altered, and two dams along the main stem may at least partially inhibit Channel Catfish movement. The primary goal of this study was to determine large-scale movement patterns of Channel Catfish in the Red River. The specific objectives were to determine the frequency of Channel Catfish passage through the St. Andrews Dam, the frequency of movement to or from Lake Winnipeg, the frequency of movement to and from the USA portion of the river, and assess if size of the fish influences movement. We tagged13, 892 Channel Catfish and collected 553 recaptures. We documented Channel Catfish moving throughout the lower Red River and Lake Winnipeg. Most (79%) of the Channel Catfish that moved to the lake were less than 668 mm, whereas, only large (> 600 mm) Channel Catfish moved upstream through St. Andrews Dam. No downstream movement through the dam was documented in this study. Many (88%) Channel Catfish that passed the dam were recaptured upstream in the USA. Our results suggest Manitoba portion of the Red River may be functioning as a

source population for the upstream fishery. The complex nature of Channel Catfish movements in the Red River, across international borders, and the resulting implications suggests management of this fishery should focus on the entire watershed.

INTRODUCTION

Channel Catfish *Ictalurus punctatus* are known to travel long distances in rivers (Dames et al. 1989, Robert 1992, Pellett et al. 1998, Fago 1999, Shrader et al. 2003, Murray and MacDonnell 2009). Many of these movements have been proposed to fulfill some life need, such as spawning (Hubert 1999) or finding overwintering habitat (Dames et al. 1989, Pellett et al. 1998, Fago 1999, Butler and Wahl 2011). However, dams have been shown to inhibit catfish passage in several systems (Siegwarth and Johnson 1994, Pellett et al. 1998, Gerhardt and Hubert 1991, Wendel and Kelsch 1999). Habitat fragmentation by dam construction within larger rivers is common (Nilsson et al. 2005), and has negatively influenced aquatic biota by altering fish assemblages (Taylor et al. 2008, Liermann et al. 2012) as well as preventing fish passage (Santucci et al. 2005, Liermann et al. 2012). Like many other large rivers in North America, the Red River of the North (Red River) was altered through the construction of dams, ditching of wetlands and tributaries, and water diversion projects to reduce flood damage (Aadland et al. 2005). Efforts to mitigate influences of the nine dams on the main-stem Red River have led to either removal or modification of all but two of the dams to facilitate fish passage (Drewes et al. 2008). The remaining two dams (St. Andrews Dam in Manitoba and Drayton Dam in Minnesota-North Dakota) are not complete barriers, but may hinder fish movement at some discharge levels.

Connectivity throughout a watershed is an important consideration in fisheries management, as it allows genetic exchange (Raeymaekers et al. 2009), movements to

important habitats (Sheer and Steel 2006), and can maintain biodiversity (Perkin et al. 2015). For example, isolation of fish populations due to fragmentation can lead to a loss of genetic diversity (Raeymaekers et al. 2009), and in extreme cases, extirpation (Winston et al. 1991, Perkin et al. 2015). Crucial habitat components, such as cavities for spawning and overwintering areas, may not be evenly distributed throughout a watershed, and isolation from these habitats could also have negative consequences for individuals or their offspring that are not able to access them. Therefore, the predictability of fish movement within a watershed may very well depend on the availability and spatial arrangement of habitats (Dunning et al. 1992, Schlosser and Angermeier 1995). Connectivity can also influence population dynamics at multiple spatial and temporal scales (Fullerton et al. 2010). For example, Channel Catfish may find suitable habitat as juveniles in a localized area, but may require access to other parts of the watershed to fulfill some life stage requirement, such as spawning (Hubert 1999). Determining where barriers to connectivity may exist, their influence on population characteristics, life stages that are affected, and their spatial and temporal occurrence allows managers to develop meaningful management actions.

Previous studies on the Red River have shown that Channel Catfish are capable of making long distance movements, and can freely move between the USA and Canada (Macdonald 1990, Hegrenes 1992, Murray and MacDonnell 2009). Given previous movement studies, Channel Catfish within the Red River basin may be functioning as one panmictic population. However, no conclusive studies have evaluated the influence of barriers or attempted to capture population-wide movement tendencies of Channel

Catfish in the Red River, highlighting the need to determine the degree of connectivity and the influence of fragmentation on this population. The primary goal of this study was to determine large-scale movement patterns of Channel Catfish in the Red River. The specific objectives were to determine the frequency of Channel Catfish passage through the St. Andrews Dam, the frequency of movement to or from Lake Winnipeg, the frequency of movement to or from the USA portion of the Red River, and determine if fish size has an influence on movement patterns. Defining the amount of movement within the Red River Channel Catfish population will inform managers on the influence of fragmentation and allow for knowledgeable decisions on future management regulations.

METHODS

Study Area

The Red River is formed at the confluence of the Bois de Sioux and Otter Tail rivers along the Minnesota-North Dakota border and is part of the Hudson Bay drainage of Canada. The Red River flows north for 873 km, ultimately emptying into Lake Winnipeg (Koel and Peterka 2003). The river forms the border between Minnesota and North Dakota in the USA for 640 km, and the final 233 km is in southern Manitoba. The Red River drainage basin within the USA encompasses parts of western Minnesota, eastern North Dakota, and a small portion of northeastern South Dakota, draining a total

of 108,800 km^2. The Assiniboine River, a major tributary to the Red River, originates in Saskatchewan and joins the river in the city of Winnipeg, Manitoba. The Red River drains an area of 185,474 km^2 in Canada, most of which is in the Assiniboine watershed.

Fish Passage Barriers

There are two possible barriers to fish passage along the main stem of the Red River. St. Andrews Dam is located near Selkirk, Manitoba, 44 km upstream from the mouth of the Red River at Lake Winnipeg. The other potential barrier is Drayton Dam, 332 km upstream of the river mouth, located at Drayton, North Dakota. Both structures function as incomplete barriers to passage (Macdonald 1990, Hegrenes 1992, Robert 1992, Murray and MacDonnell 2009, this study). However, low or summer flows, likely create a situation where both dams serve as near complete barriers to at least upstream passage.

Sampling locations

The focus of this sampling effort was divided among four reaches (Figure 4-1). A 5-km reach near the mouth of the Red River at Lake Winnipeg has been sampled regularly since the autumn of 2012 (hereafter, Netley Marsh). The second reach, containing the most popular fishing areas on the Red River in Manitoba, is a 15-km reach between the St. Andrews Dam downstream to the town of Selkirk, Manitoba (hereafter, Selkirk). In 2014, the sampling area was expanded to encompass two more reaches

upstream of the St. Andrews Dam. One reach was a 5-km reach on the north side of the city of Winnipeg (hereafter, Winnipeg), and the other was a 5-km reach at the Canada-USA international border (hereafter, Emerson). These sampling locations allowed sampling of the Channel Catfish population in selected reaches along the length of the Red River in Manitoba and focus on key areas such as the mouth of the river and the international border to capture movement. We considered observed movements of Channel Catfish less than 15 river km (rkm) as localized movements, because our largest sampling reach (Selkirk) was 15 rkm long.

Data Collection

Channel Catfish were collected from the lower Red River using hoop nets and rod-and-reel during 2012-2015. Hoop nets had seven, 0.9-m diameter hoops and were baited with soy bean mash. Terminal tackle was primarily 6/0 barbless circle hooks baited with cut Goldeye (*Hiodon alosoides*) and White Sucker (*Catostomus commersonii*). At two reaches (Selkirk and Emerson), additional terminal tackle (size 2 J-hooks baited with nightcrawlers) was incorporated to target smaller catfish and increase catch rates. Channel Catfish were weighed to the nearest g, measured for maximum total length to the nearest mm, and tagged with a T-bar anchor tag inserted through the pterigiophores on the left side (Guy et al. 1996). Channel Catfish that were 200-500 mm received a smaller tag (Floy mfg, 68-B), and Channel Catfish greater than 500 mm received a larger tag (Floy mfg., 67-F). Each tag was labeled with a toll-free phone number for anglers to report caught fish and a unique serial number to identify each

individual fish. Channel Catfish were also collected using experimental gill nets on Lake Winnipeg by Manitoba Conservation and Water Stewardship staff during June 2013 and 2014. Channel Catfish were not specifically targeted in Lake Winnipeg, but were caught as bycatch while conducting annual Walleye *Sander vitreus* sampling. Tagging sites on Lake Winnipeg were located at 10 sites throughout the south basin of Lake Winnipeg (Manitoba Conservation and Water Stewardship, unpublished data).

Sampling Periods

Channel Catfish were captured and tagged with hoop nets and angling at Selkirk and Netley Marsh during a two-week period in August 2012. A similar sampling effort occurred during the spring 2013 (May 25-June 22) at the same locations. Additional sampling also occurred during August 2013 at Selkirk (hoop nets and angling) and at Netley Marsh (angling). In 2014, sampling occurred during the spring and summer (May-August; hoop nets and angling). Five visits were made to each sampling location (Netley Marsh, Selkirk, Winnipeg, and Emerson) so that each visit yielded 20 net nights and included at least 4 person-hours of angling effort. Additional effort at Selkirk was included to continue tagging Channel Catfish in this area. Sampling efforts in 2015 largely focused on the Selkirk reach, but some sampling did occur at the Netley Marsh and Emerson reaches as well.

Movement Analysis

We used multi-state models (a modification of the Cormack-Jolly-Seber model) in program MARK (multi-state recaptures only model; White and Burnham 1999) to estimate movement rates of Channel Catfish in the Red River to address our objectives. Multi-state models use maximum likelihood estimation procedures to estimate survival (***S***), movement (***Ψ***), and capture probability (***p***) parameters in this model. Angler recaptures for all objectives were grouped into the reach closest to where fish were recaptured and the sampling period closest to the recapture date. We estimated movement rates for all catfish > 200 mm and also for an "angler-susceptible" size group of catfish ≥ 668 mm. The angler-susceptible size group was used to represent fish commonly captured by anglers within this fishery, as 95% of the Channel Catfish that were angled from the Selkirk reach were at least 668 mm. A total of 14 monthly periods were used to cover sampling events as equally as possible (Appendix 2) and used for movement analyses in Program MARK. We accounted for disparities in time between encounter occasions by designating unequal intervals between periods in the models.

St. Andrews Dam Passage

The first objective was to estimate movement rates through St. Andrews Lock and Dam. Only the angler-susceptible size group was used because only one catfish less than 668 mm passed through the dam. All fish tagged or recaptured above the dam were pooled into an 'A' (Above) group, and all fish tagged or recaptured below the dam were

pooled into a 'B' (Below) group. If a fish was not encountered in a given period, it was assigned a 0. Hence, an example encounter history of "0B00000A000000", would be assigned for a fish captured and tagged below the St. Andrews Dam in the second period and not encountered again until it was recaptured above the dam in the eighth period (and not recaptured again). We tested two hypotheses regarding survival by including models where the survival parameter was set to constant among periods and groups ($S_{AB\cdot}$), and where survival was set to constant among periods, but different between groups ($S_{A\cdot}$ and $S_{B\cdot}$; Table 4-1). We assumed survival would be constant over the length of this study because of the longevity displayed by Red River Channel Catfish (Ch. 2, this thesis), but may be different above and below the dam. Movement from above the dam to below the dam was fixed to zero, as no downstream movements through the dam were observed. We hypothesized that movement rates may vary throughout the year, so upstream movement through the dam was analyzed as both a function of time (Ψ_{BAt}), and as a constant ($\Psi_{BA.}$). We hypothesized that capture probabilities may be greater below the dam due to the greater densities of angler-susceptible sized Channel Catfish (Ch. 3, this thesis) and that they could vary throughout the year. Therefore, we tested models with capture probabilities as a function of time and as a constant, but varied among groups (p_{At}, p_{Bt}, $p_{A.}$, $p_{B.}$). The first three periods were constrained to zero for Ψ_{BA} and p_A, as no fish were observed above the dam during those periods.

Manitoba-USA Movement

The second objective was to estimate movement rates of Channel Catfish to or from Manitoba and the USA. Only the “angler-susceptible” size group was used for this analysis because few Channel Catfish less than 668 mm moved to the USA (n=12). Channel Catfish were assigned either an ‘M’ (Manitoba), or a ‘U’ (USA) based on where they were tagged and recaptured. The same movement parameters as the dam passage exercise (constant versus time variation by group) were analyzed for models in this objective because we hypothesized that movement rates may vary throughout the year (Table 4-2). We included models with survival parameters set as a constant through time among groups and constant through time but different between groups. We did not expect survival to vary over our monthly periods, given the longevity seen in this population of Channel Catfish, but it may be different in either region because different management strategies are used to manage Channel Catfish in Manitoba compared to USA. We chose to hold capture probability as a constant through time with differences between groups in this model because there was little difference in capture probability estimates for the dam passage model, and all recaptures in the USA were from recreational anglers. No Channel Catfish were tagged in the USA, therefore we fixed capture and movement parameters to zero until Channel Catfish were known to move into that state (i.e., recaptured there). Only one Channel Catfish was documented moving from the USA to Manitoba. However, the movement parameter from the USA to Manitoba was still constrained to zero because one data point did not fully inform the model.

Lake Winnipeg Connectivity

The final objective was to estimate movement rates of Channel Catfish between Lake Winnipeg and the lower Red River. Channel Catfish were assigned either an 'R' (river) or an 'L' (lake) based on where they were encountered. Only data from the reaches below St. Andrews Dam (Netley Marsh and Selkirk) were used because no downstream movement from above St. Andrews Dam was observed. We only used the small size grouping (200-667 mm) for this objective because few large fish were tagged and recaptured in the lake (n=6 tagged, n=3 recaptured). We tested two survival hypotheses; first, as a constant through time and equal between the lake and the river ($S_{RL.}$), and second, as a constant through time but different between areas ($S_{R.}$ and $S_{L.}$; Table 4-3). The movement parameter from Lake Winnipeg to the river was constrained to equal zero, as only one fish was documented moving from the lake to the river. We tested the hypothesis that movement may depend on the time of year, so the movement parameter from the river to the lake was allowed to vary by time (Ψ_{RLt}), but also modeled as a constant through time ($\Psi_{RL.}$). Capture probabilities were also modeled as both a function of time, and as constant through time, but different for both groups (p_{Rt}, p_{Lt}, $p_{R.}$, $p_{L.}$). We hypothesized that different capture probabilities could occur because recreational angling for Channel Catfish in the river is believed to be greater than the lake. We used 13 monthly periods because no Channel Catfish in the small size group were recaptured in either location during the final period.

RESULTS

Movement Summary

Over the course of this study, we tagged13, 892 Channel Catfish (n_{2012}= 461, n_{2013}= 3,478, n_{2014}= 8,248, n_{2015}=1,705), and collected 553 recaptures. A number of these fish were captured multiple times, including 28 Channel Catfish that were recaptured twice, and three that were recaptured three times. Catfish tagged in Manitoba were recaptured as far away as tributaries in the upper watershed (Red Lake River, Sheyenne River, and Forest River; Figure 4-1). The greatest distance observed was 703 km, from Selkirk, MB to the Sheyenne River, near Harwood, ND. The mean time at large was 279 days (range: 0-1122 days, Figure 4-2). We documented a distinct trend where large Channel Catfish (approximately > 600 mm) moved more than smaller individuals (Figure 4-3). Upstream movements were often (55%) through the St. Andrews Dam, but no downstream movement through the St. Andrews Dam occurred. Additionally, 19 % of recaptures were reported from the USA. Localized recaptures (n=356; < 15 rkm movement) were more common than long distance movements (n=197; > 15 rkm movement). Excluding fish tagged and recaptured in Lake Winnipeg, upstream movements (n=137; upstream movements > 15 rkm) were more common than downstream movements (n=27; downstream movements > 15 rkm). Mean distance traveled was 95 rkm (median=7.9 rkm; range: 0-703 rkm). Mean distance moved of angler susceptible Channel Catfish (≥ 668 mm) was 116 km (median=8.6 rkm; range: 0-703 rkm), and mean distance moved by small (< 668 mm) Channel Catfish was 47 rkm (median=5.8 rkm; range: 0-675 rkm).

St. Andrews Dam Passage

The model with the most support for movement through St. Andrews Dam estimated a constant monthly probability of movement at 9.4% (95% CI: 6.1 - 14.2%; model weight= 71%; Table 4-1). The survival estimate was constant through time and equal above and below the dam at 95% monthly (95% CI: 94 - 97%). Capture probabilities varied by time, but were similar above and below the dam with a mean of 2% (estimate range: 0.4 - 5.7%; Appendix 3).

Manitoba-USA Movement

The model with the most support for "angler-susceptible" fish movement between Manitoba and the USA estimated movement rates that varied by time, with a range of estimates from 0 to 21.9% monthly (mean = 5.6%; model weight=97%; Table 4-2, Appendix 3). Survival estimates were constant, but different between the USA (82.9% monthly; (95% CI = 68 – 91.7%) and Manitoba (97.5% monthly; 95% CI = 95.9 – 98.5%). Capture probabilities were constant and greater in the USA (3.7% monthly; 95% CI = 1.8 – 7.3%) than in Manitoba (1.3% monthly; 95% CI = 1.1 – 1.5%).

Lake Winnipeg Connectivity

The model with the most support estimated a constant movement rate from the lower river (Selkirk and Netley Marsh combined) to Lake Winnipeg for small catfish

(200-667 mm) at a monthly rate of 2.2% (95% CI: 0.5 – 8.8%; model weight= 83%; Table 4-3). Monthly capture probabilities were similar between both areas with most estimates below 1% (Appendix 3). Monthly survival estimates were constant and equal between the lower river and the lake at 98.8% (95% CI: 78.0 – 100%). Extrapolated to an annual rate, annual survival for the lower river and Lake Winnipeg is estimated at 86.5% (or 13.5% annual mortality rate).

DISCUSSION

St. Andrews Dam Passage

Channel Catfish are able to pass the St. Andrews Dam in both the upstream and downstream directions. Though this study did not document any downstream movement over the St. Andrews Dam, Hegrenes (1992) and Robert (1992) did report such movement. We know of no recent structural or operational changes to the dam that may prevent downstream dam passage by Channel Catfish. However, individuals may be avoiding downstream passage through the dam, as has been reported for other populations (Behrmann-Godel and Eckmann 2003, O'Connor et al. 2006), which may have implications for the Channel Catfish fishery in the Red River.

The St. Andrews Dam likely influences the rate of upstream passage for smaller Channel Catfish in four ways that also likely have a seasonal influence. First, velocity and flow through the St. Andrews dam is high when the curtains are not in place, and

water velocities may exceed swimming capabilities of smaller catfish, effectively preventing passage (Haro et al. 2004). Second, a fish ladder is in place, but is constructed with several drops between resting pools that may be too difficult for small Channel Catfish to traverse. Further, we observed large Channel Catfish in almost every pool of the fish ladder (S. Siddons, personal observation). This observation indicates larger individuals are capable of navigating the ladder successfully, but could also suggest vulnerability of smaller Channel Catfish to predation by larger Channel Catfish or other predators in the confined pools (Unprasert et al. 1999, Agostinho et al. 2012). Third, passage through the locks is possible for all size Channel Catfish, but relies on boat passage that is infrequent. Fourth, a flood-control channel around the city of Winnipeg (and St. Andrews Dam) may be an avenue for passage when operational, but we did not investigate this route because this channel is only active under flood conditions. Other studies have not reported size to have an influence on movement rates for Channel Catfish as we have documented here (Wendel and Kelsch 1999, Schrader et al. 2003, Butler and Wahl 2011), but Wendel and Kelsch (1999; mean length = 614 mm) and Butler and Wahl (2011; mean length = 437 mm) used telemetry which may have been biased towards larger individuals. Recaptures by anglers were probably also biased towards larger individuals due to assumed angler preference and targeting of larger Channel Catfish. However, the limited movement appears to be more a phenomenon of the St. Andrews Dam influence on size-selective movement because we did have Channel Catfish < 600 mm that moved relatively long distances (> 50 rkm) between Emerson and Winnipeg and between Selkirk and Lake Winnipeg.

Manitoba-USA Movement

Eighty-seven percent of Channel Catfish recaptured in the main stem and tributaries in the USA were greater than 668 mm and survival estimates were lower in the USA than in Manitoba (Manitoba-USA multi-state model). Furthermore, annual mortality was estimated to be lower for the lower Red River in Manitoba (11%; Chapter 2, this thesis) than in the USA and is comparable to annual mortality estimates from multi-state models (13.5%, Lake Winnipeg-lower river multi-state model). More liberal harvest regulations for Channel Catfish in the USA may explain the lower survival rate. Minnesota and North Dakota allow the harvest of five individuals (one of which may be greater than 610 mm [24 inches]), whereas Manitoba allows the harvest of only four Channel Catfish less than 600 mm per day. Of the angler reported recaptures for which we had sufficient information, 21% of recaptures were harvested in the USA (n_{total}=82) and 6% of recaptures were harvested in Manitoba (n_{total}=183). If downstream movement from the USA does not occur, as we have seen here, or is limited, then the Channel Catfish fishery in the Red River could be functioning as a source-sink system. Eventually, unidirectional movements could lead to degradation of the trophy Channel Catfish fishery in the lower Red River. We have no evidence that such depletion of Channel Catfish in the lower Red River is occurring, but it would be worth monitoring to ensure viable populations on both sides of the international border.

Lake Winnipeg Connectivity

Movement between Lake Winnipeg and the lower portion of the river may occur more frequently than we were able to document; only one fish was documented moving from the lake to the river. Lake Winnipeg supports many Channel Catfish, as they are commonly caught by commercial fishermen in gill nets (G. Klein, Manitoba Conservation and Water Stewardship, personal communication). Determining the extent of interactions between Lake Winnipeg and the Red River may be crucial in understanding the contribution of each region to the Channel Catfish population. Lake Winnipeg may supplement the Red River population by providing additional food sources or habitat that is uncommon or unavailable within the river (i.e., could provide additional spawning or over-wintering habitat). For example, our study had four recaptures on Lake Winnipeg in September 2014 from fish that were originally tagged in the Red River. Recaptures at this time of year and location could indicate a concerted movement to over-wintering habitats. Butler and Wahl (2011) noted that all radio-tagged Channel Catfish used lentic habitats (i.e., reservoirs) as over-wintering habitat, many of which were tagged in lotic reaches during the summer. Further investigation of Lake Winnipeg's role in the Red River Channel Catfish fishery is warranted, as it is a unique component to this fishery.

Movement Trends and Implications

Given the unidirectional, long distance movements by large Channel Catfish (Figure 4-3) that we regularly documented in the Red River over short time frames (Figure 4-2), we suspect that these movement patterns may be migrations. Pellett et al. (1998) found Wisconsin River Channel Catfish migrate to the Mississippi River in the autumn to overwinter, then return to the Wisconsin River in the spring. The time of year likely plays a significant role in migration patterns for Channel Catfish in the Red River, but we were unable to quantify a seasonal pattern. Not all individuals displayed the same movement patterns and we only documented one downstream movement back to the original tagging location. Several fish were recaptured locally up to a year post-tagging, then recaptured in the USA the following year, signifying that upstream migrations were either blocked, due to St. Andrews Dam, or not attempted in all years for all individuals. It is possible that only a proportion of the population is inclined to migrate (i.e., some individuals are transients and some are locals), which has been documented for other fish species (Gillanders et al. 2015), but the impetus for migration in the Red River is still unclear.

Movement histories of individual Channel Catfish varied in this study, but there was one overriding theme: Channel Catfish (mostly > 600 mm) that moved upstream through St. Andrews Dam continued to the USA and did not return to Manitoba. In this system, catfish from the lower river in Manitoba may be supporting, either in part or total, the population (Appendix 4). Pracheil et al. (2014) found Paddlefish *Polyodon spathula* from an upstream reservoir were substantially subsidizing downstream

populations through downstream dam passage. Channel Catfish are seldom considered a migratory species despite studies to the contrary (Newcomb 1989, Pellett et al. 1998, Butler and Wahl 2011). Our study builds on the idea that Channel Catfish management and conservation should be considered at larger spatial scales than traditionally has been done. In fact, Channel Catfish populations in lotic systems may be subject to the same effects of fragmentation reported for other large river fish species. Specifically, fragmented rivers alter population dynamics (Alo and Turner 2005, Pracheil et al. 2014), impede migrations (Santucci Jr. et al. 2005, Liermann et al. 2012), and reduce biological diversity (Liermann et al. 2012, Perkin et al. 2015). However, conservation and management strategies applied to other large river species are rarely used for Channel Catfish. We suggest the Channel Catfish population in the Red River be considered at the watershed level to address population dynamic issues.

LITERATURE CITED

Aadland, L.P., T.M. Koel, W.G. Franzin, K.W. Stewart, and P. Nelson. 2005. Changes in fish assemblage structure of the Red River of the North. Pages 293-321 *in* J.N. Rinne, R.M. Hughes, and B. Calamusso, editors. Historical changes in large river fish assemblages. American Fisheries Society Symposium 45, Bethesda, Maryland.

Agostinho, A.A., C.S. Agostinho, F.M. Pelicice, and E.E. Marques. 2012. Fish ladders: safe fish passage or hotspot for predation? Neotropical Ichthyology 10:687-696.

Alo, D., and T.F. Turner. 2005. Effects of habitat fragmentation on effective population size in the endangered Rio Grande silvery minnow. Conservation Biology 19:1138-1148.

Behrmann-Godel, J., and R. Eckmann. 2003. A preliminary telemetry study of the migration of silver European eel (Anguilla Anguilla L.) in the River Mosel, Germany. Ecology of Freshwater Fish 12:196-202.

Butler, S.E., and D.H. Wahl. 2011. Distribution, movements and habitat use of channel catfish in a river with multiple low-head dams. River Research and Applications 27:1182-1191.

Dames, H.R., T.G. Coon, and J.W. Robinson. 1989. Movements of channel and flathead catfish between the Missouri River and a tributary, Perche Creek. Transactions of the American Fisheries Society 118:670-679.

Drewes, H., M. Ermer, S. Gangl, and D. Kroeker. 2008. Red River of the North Fisheries Management Plan. Manitoba Water Stewardship, Minnesota Department of Natural Resources, North Dakota Game and Fish Department, and South Dakota Department of Game, Fish, and Parks.

Dunning, J.B., B.J. Danielson, and H.R. Pulliam. 1992. Ecological processes that affect populations in complex landscapes. Oikos 65:169-175.

Fago, D. 1999. Movement of channel catfish in the Lower Wisconsin River and pool numbers 10 and 11 of the Mississippi River using radiotelemetry. Pages 177-185 *in* E. R. Irwin, W. A. Hubert, C. F. Rabeni, H. L. Schramm, Jr., and T. Coon, editors. Catfish 2000: Proceedings of the International Ictalurid Symposium. American Fisheries Society, Symposium 24, Bethesda, Maryland.

Fullerton, A.H., M. Kelly, E. Burnett, A.L. Steel, R.L. Flitcroft, G.R. Pess, B.E. Feist, C.E. Torgersen, D.J. Miller, and B.L. Sanderson. 2010. Hydrological connectivity for riverine fish: measurement challenges and research opportunities. Freshwater Biology 55:2215-2237.

Gerhardt, D.R., and W.A. Hubert. 1991. Population dynamics of a lightly exploited channel catfish stock in the Powder River system, Wyoming–Montana. North American Journal of Fisheries Management 11:200-205.

Gillanders, B.M., C. Izzo, Z.A. Doubleday, and Q. Ye. 2015. Partial migration: growth varies between resident and migratory fish. Biology letters 11:20140850.

Guy, C.S., H.L. Blankenship, and L.A. Neilsen. 1996. Tagging and Marking. Pages 353-384 *in* B.R. Murphy and D.W. Willis, editors. Fisheries techniques, 2nd edition. American Fisheries Society, Bethesda, Maryland.

Haro, A., T. Castro-Santos, J. Noreika, and M. Odeh. 2004. Swimming performance of upstream migrant fishes in open-channel flow: a new approach to predicting passage through velocity barriers. Canadian Journal of Fisheries and Aquatic Sciences 61:1590-1601.

Hegrenes, S.G. 1992. Age, growth, and reproduction of channel catfish in the Red River of the North. Master's thesis. University of North Dakota, Grand Forks, North Dakota.

Hubert, W.A. 1999. Biology and management of channel catfish. Pages 3-22 *in* E. R. Irwin, W. A. Hubert, C. F. Rabeni, H. L. Schramm, Jr., and T. Coon, editors. Catfish 2000: Proceedings of the International Ictalurid Symposium. American Fisheries Society, Symposium 24, Bethesda, Maryland.

Koel, T.M. and J.J. Peterka. 2003. Stream fish communities and environmental correlates in the Red River of the North, Minnesota and North Dakota. Environmental Biology of Fishes. 67:137–155.

Liermann, C.R., C. Nilsson, J. Robertson, and R.Y. Ng. 2012. Implications of dam obstruction for global freshwater fish diversity. BioScience 62:539-548.

Macdonald, D. 1990. The channel catfish sport fishery of the lower Red River. Master’s thesis. The University of Manitoba, Winnipeg, Manitoba.

Murray, L., and D.S. MacDonnell. 2009. Red River floodway expansion acoustic telemetry study. Report by North/South Consultants for the Manitoba Floodway Authority.

Newcomb, B.A. 1989. Winter abundance of channel catfish in the channelized Missouri River, Nebraska. North American Journal of Fisheries Management 9:195-202.

Nilsson, C., C.A. Reidy, M. Dynesius, and C. Revenga. 2005. Fragmentation and flow regulation of the world's large river systems. Science 308:405-408.

O'Connor, J.P., D.J. O'Mahony, J.M. O'Mahony, and T.J. Glenane. 2006. Some impacts of low and medium head weirs on downstream fish movement in the Murray–Darling Basin in southeastern Australia. Ecology of Freshwater Fish 15:419-427.

Pellett, T.D., G.J. Van Dyck, and J.V. Adams. 1998. Seasonal migration and homing of channel catfish in the lower Wisconsin River, Wisconsin. North American Journal of Fisheries Management 18:85-95.

Perkin, J.S., K.B. Gido, K.H. Costigan, M.D. Daniels, and E.R. Johnson. 2015. Fragmentation and drying ratchet down Great Plains stream fish diversity. Aquatic Conservation: Marine and Freshwater Ecosystems 25:639–655.

Pracheil, B.M., G.E. Mestl, and M.A. Pegg. 2014. Movement through dams facilitates population connectivity in a large river. River Research and Applications 31:517-525.

Raeymaekers, J.A., Raeymaekers, D., Koizumi, I., Geldof, S., and F.A. Volckaert. 2009. Guidelines for restoring connectivity around water mills: a population genetic approach to the management of riverine fish. Journal of Applied Ecology 46:562-571.

Robert, L. 1992. Upper Red River channel catfish tagging report. Manitoba Department of Natural Resources, Fisheries Branch, Manuscript Report 20.

Santucci Jr, V.J., S.R. Gephard, and S.M. Pescitelli. 2005. Effects of multiple low-head dams on fish, macroinvertebrates, habitat, and water quality in the Fox River, Illinois. North American Journal of Fisheries Management 25:975-992.

Schlosser, I.J., and P.L. Angermeier. 1995. Spatial variation in demographic processes of lotic fishes: conceptual models, empirical evidence, and implications for conservation. Pages 392-401 *in* J.L. Neilsen, editor. Evolution and the aquatic ecosystem: defining unique units in population conservation. American Fisheries Society Symposium 17, Bethesda, Maryland.

Sheer, M.B., and E.A. Steel. 2006. Lost watersheds: barriers, aquatic habitat connectivity, and salmon persistence in the Willamette and Lower Columbia River basins. Transactions of the American Fisheries Society 135:1654-1669.

Shrader, T.M., B. Moody, and M. Buckman. 2003. Population dynamics of channel catfish in Brownlee Reservoir and the Snake River, Oregon. North American Journal of Fisheries Management 23:822-834.

Siegwarth, G.L., and J.E. Johnson. 1994. Pre-spawning migration of channel catfish into three warmwater tributaries—effects of a cold tailwater. Proceedings of the Arkansas Academy of Science 48:168-173.

Taylor, C.M., D.S. Millican, M.E. Roberts, and W.T. Slack. 2008. Long-term change to fish assemblages and the flow regime in a southeastern US river system after extensive aquatic ecosystem fragmentation. Ecography 31:787-797.

Unprasert, P., J.B. Taylor, and H.R. Robinette. 1999. Role of stocking sequence on survival of fingerling channel catfish cultured in mixed-size populations. North American journal of aquaculture 61:235-238.

Wendel, J.L., and S.W. Kelsch. 1999. Summer range and movement of channel catfish in the Red River of the North. *in* E. R. Irwin, W. A. Hubert, C. F. Rabeni, H. L. Schramm, Jr., and T. Coon, editors. Catfish 2000: Proceedings of the International Ictalurid Symposium. American Fisheries Society, Symposium 24, Bethesda, Maryland.

White, G.C., and K.P. Burnham. 1999. Program MARK: survival estimation from populations of marked animals. Bird Study 46:S120-S139.

Winston, M.R., C. M. Taylor, and J. Pigg. 1991. Upstream extirpation of four minnow species due to damming of a prairie stream. Transactions of the American Fisheries Society 120:98–105.

Table 4-1. Suite of models used to estimate parameters for St. Andrews Dam passage by angler-susceptible Channel Catfish (≥ 668 mm) in the Red River of the North during 2012-2015.

Models	Parameters	Delta AICc	Weight
$S_{AB.}\Psi_{AB=0}\Psi_{BA1-3=0,4-14.}\ p_{Bt}p_{A1-3=0,4-14t}$	30	0	0.71
$S_{A.}S_{B.}\Psi_{AB=0}\Psi_{BA1-3=0,4-14.}\ p_{Bt}p_{A1-3=0,4-14t}$	31	1.8	0.29
$S_{AB.}\ \Psi_{AB=0}\Psi_{BA1-3=0,4-14t}\ p_{Bt}p_{A1-3=0,4-14t}$	41	10	0
$S_{A.}S_{B.}\Psi_{AB=0}\Psi_{BA1-3=0,4-14t}\ p_{Bt}p_{A1-3=0,4-14t}$	42	12	0
$S_{AB.}\ \Psi_{AB=0}\Psi_{BA1-3=0,4-14t}\ p_{Bt}p_{A1-3=0,4-14.}$	30	26	0
$S_{A.}S_{B.}\Psi_{AB=0}\Psi_{BA1-3=0,4-14t}\ p_{Bt}p_{A1-3=0,4-14.}$	31	28	0
$S_{AB.}\Psi_{AB=0}\Psi_{BA1-3=0,4-14.}\ p_{Bt}p_{A1-3=0,4-14.}$	19	31	0
$S_{A.}S_{B.}\Psi_{AB=0}\Psi_{BA1-3=0,4-14.}\ p_{Bt}p_{A1-3=0,4-14.}$	21	32	0
$S_{A.}S_{B.}\Psi_{AB=0}\Psi_{BA1-3=0,4-14.}\ p_{B.}p_{A1-3=0,4-14t}$	19	53	0
$S_{AB.}\ \Psi_{AB=0}\Psi_{BA1-3=0,4-14.}\ p_{B.}p_{A1-3=0,4-14t}$	18	55	0
$S_{AB.}\ \Psi_{AB=0}\Psi_{BA1-3=0,4-14t}\ p_{B.}p_{A1-3=0,4-14t}$	29	58	0
$S_{A.}S_{B.}\Psi_{AB=0}\Psi_{BA1-3=0,4-14.}\ p_{B.}p_{A1-3=0,4-14t}$	8	84	0
$S_{AB.}\ \Psi_{AB=0}\Psi_{BA1-3=0,4-14.}\ p_{B.}p_{A1-3=0,4-14.}$	7	84	0
$S_{A.}S_{B.}\Psi_{AB=0}\Psi_{BA1-3=0,4-14t}\ p_{B.}p_{A1-3=0,4-14.}$	19	86	0
$S_{AB.}\ \Psi_{AB=0}\Psi_{BA1-3=0,4-14t}\ p_{B.}p_{A1-3=0,4-14.}$	18	87	0
$S_{A.}S_{B.}\Psi_{AB=0}\Psi_{BA1-3=0,4-14t}\ p_{B.}p_{A1-3=0,4-14t}$	30	87	0

Table 4-2. Suite of models used to estimate parameters for Manitoba to USA movement by angler-susceptible Channel Catfish (≥ 668 mm) in the Red River of the North during 2012-2015.

Models	Parameters	Delta AICc	Weight
$\boldsymbol{S}_{\mathrm{M}}.\boldsymbol{S}_{\mathrm{U}}.\boldsymbol{\Psi}_{\mathrm{UM=0}}\boldsymbol{\Psi}_{\mathrm{MU1\text{-}3=0,4\text{-}14t}}\ \boldsymbol{p}_{\mathrm{M}}.\boldsymbol{p}_{\mathrm{U1\text{-}3=0,4\text{-}14.}}$	19	0	0.97
$\boldsymbol{S}_{\mathrm{M}}.\boldsymbol{S}_{\mathrm{U}}.\boldsymbol{\Psi}_{\mathrm{UM=0}}\boldsymbol{\Psi}_{\mathrm{MU1\text{-}3=0,4\text{-}14.}}\ \boldsymbol{p}_{\mathrm{M}}.\boldsymbol{p}_{\mathrm{U1\text{-}3=0,4\text{-}14.}}$	8	7	0.03
$\boldsymbol{S}_{\mathrm{MU}}.\boldsymbol{\Psi}_{\mathrm{UM=0}}\boldsymbol{\Psi}_{\mathrm{MU1\text{-}3=0,4\text{-}14.}}\ \boldsymbol{p}_{\mathrm{M}}.\boldsymbol{p}_{\mathrm{U1\text{-}3=0,4\text{-}14.}}$	7	11	0
$\boldsymbol{S}_{\mathrm{MU}}.\boldsymbol{\Psi}_{\mathrm{UM=0}}\boldsymbol{\Psi}_{\mathrm{MU1\text{-}3=0,4\text{-}14t}}\ \boldsymbol{p}_{\mathrm{M}}.\boldsymbol{p}_{\mathrm{U1\text{-}3=0,4\text{-}14.}}$	18	13	0

Table 4-3. Suite of models used to estimate parameters for movement of Channel Catfish (< 668 mm) from the lower Red River of the North (Selkirk and Netley Marsh) to Lake Winnipeg during 2012-2015.

Models	Parameters	Delta AICc	Weight
$\boldsymbol{S}_{\mathrm{RL.}}\boldsymbol{\Psi}_{\mathrm{LR=0}}\boldsymbol{\Psi}_{\mathrm{RL1\text{-}2=0,3\text{-}13.}}\ \boldsymbol{p}_{\mathrm{R.}}\boldsymbol{p}_{\mathrm{L1\text{-}2=0,3\text{-}13}t}$	28	0	0.83
$\boldsymbol{S}_{\mathrm{R.}}\boldsymbol{S}_{\mathrm{L.}}\boldsymbol{\Psi}_{\mathrm{LR=0}}\boldsymbol{\Psi}_{\mathrm{RL1\text{-}2=0,3\text{-}13t}}\ \boldsymbol{p}_{\mathrm{R}t.}\boldsymbol{p}_{\mathrm{L1\text{-}2=0,3\text{-}13}t}$	39	4	0.1
$\boldsymbol{S}_{\mathrm{RL.}}\boldsymbol{\Psi}_{\mathrm{LR=0}}\boldsymbol{\Psi}_{\mathrm{RL1\text{-}2=0,3\text{-}13}t}\ \boldsymbol{p}_{\mathrm{R}t}\ \boldsymbol{p}_{\mathrm{L1\text{-}2=0,3\text{-}13}t}$	38	5	0.07
$\boldsymbol{S}_{\mathrm{RL.}}\boldsymbol{\Psi}_{\mathrm{LR=0}}\boldsymbol{\Psi}_{\mathrm{RL1\text{-}2=0,3\text{-}13.}}\ \boldsymbol{p}_{\mathrm{R.}}\ \boldsymbol{p}_{\mathrm{L1\text{-}2=0,3\text{-}13.}}$	7	24	0
$\boldsymbol{S}_{\mathrm{R.}}\boldsymbol{S}_{\mathrm{L.}}\boldsymbol{\Psi}_{\mathrm{LR=0}}\boldsymbol{\Psi}_{\mathrm{RL1\text{-}2=0,3\text{-}13.}}\ \boldsymbol{p}_{\mathrm{R.}}\boldsymbol{p}_{\mathrm{L1\text{-}2=0,3\text{-}13.}}$	8	1427	0
$\boldsymbol{S}_{\mathrm{R.}}\boldsymbol{S}_{\mathrm{L.}}\boldsymbol{\Psi}_{\mathrm{LR=0}}\boldsymbol{\Psi}_{\mathrm{RL1\text{-}2=0,3\text{-}13.}}\ \boldsymbol{p}_{\mathrm{Rt}}\ \boldsymbol{p}_{\mathrm{L1\text{-}2=0,3\text{-}13t}}$	29	2795	0
$\boldsymbol{S}_{\mathrm{RL.}}\boldsymbol{\Psi}_{\mathrm{LR=0}}\boldsymbol{\Psi}_{\mathrm{RL1\text{-}2=0,3\text{-}13}t}\ \boldsymbol{p}_{\mathrm{R.}}\ \boldsymbol{p}_{\mathrm{L1\text{-}2=0,3\text{-}13.}}$	17	2802	0
$\boldsymbol{S}_{\mathrm{R.}}\boldsymbol{S}_{\mathrm{L.}}\boldsymbol{\Psi}_{\mathrm{LR=0}}\boldsymbol{\Psi}_{\mathrm{RL1\text{-}2=0,3\text{-}13t}}\ \boldsymbol{p}_{\mathrm{R.}}\boldsymbol{p}_{\mathrm{L1\text{-}2=0,3\text{-}13.}}$	18	2804	0

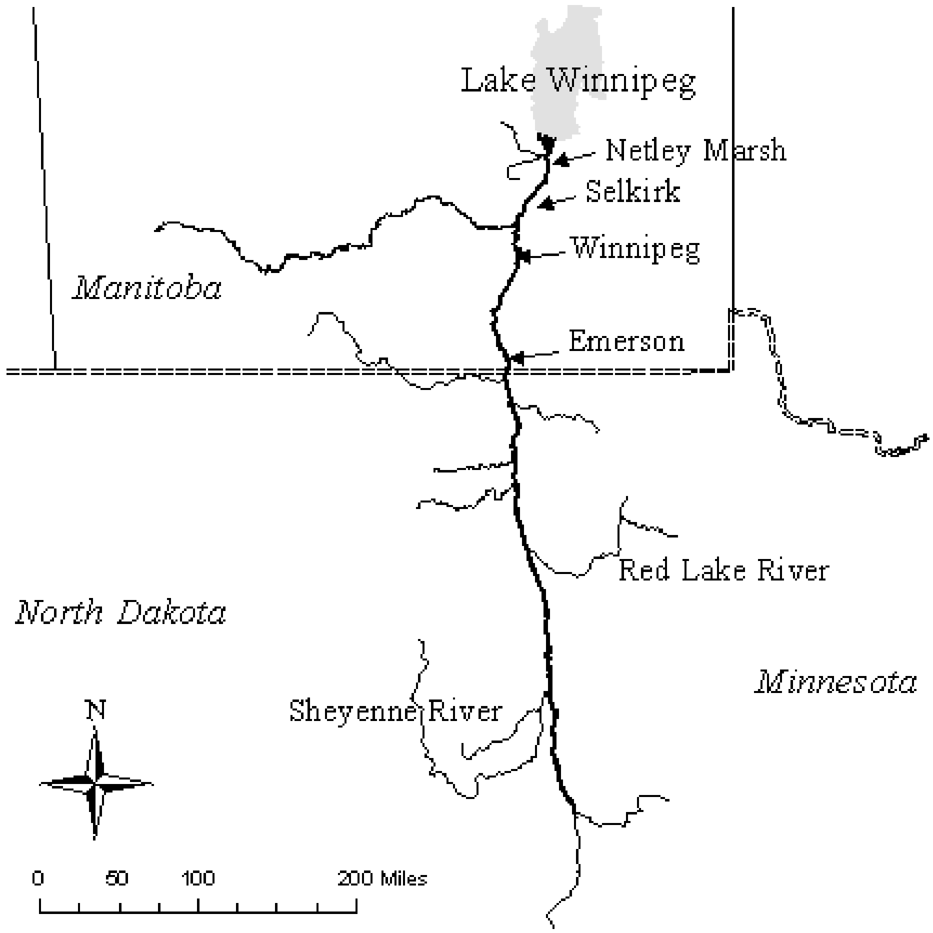

Figure 4-1. Map of the Red River of the North watershed. Sample reach locations are indicated by name and arrow.

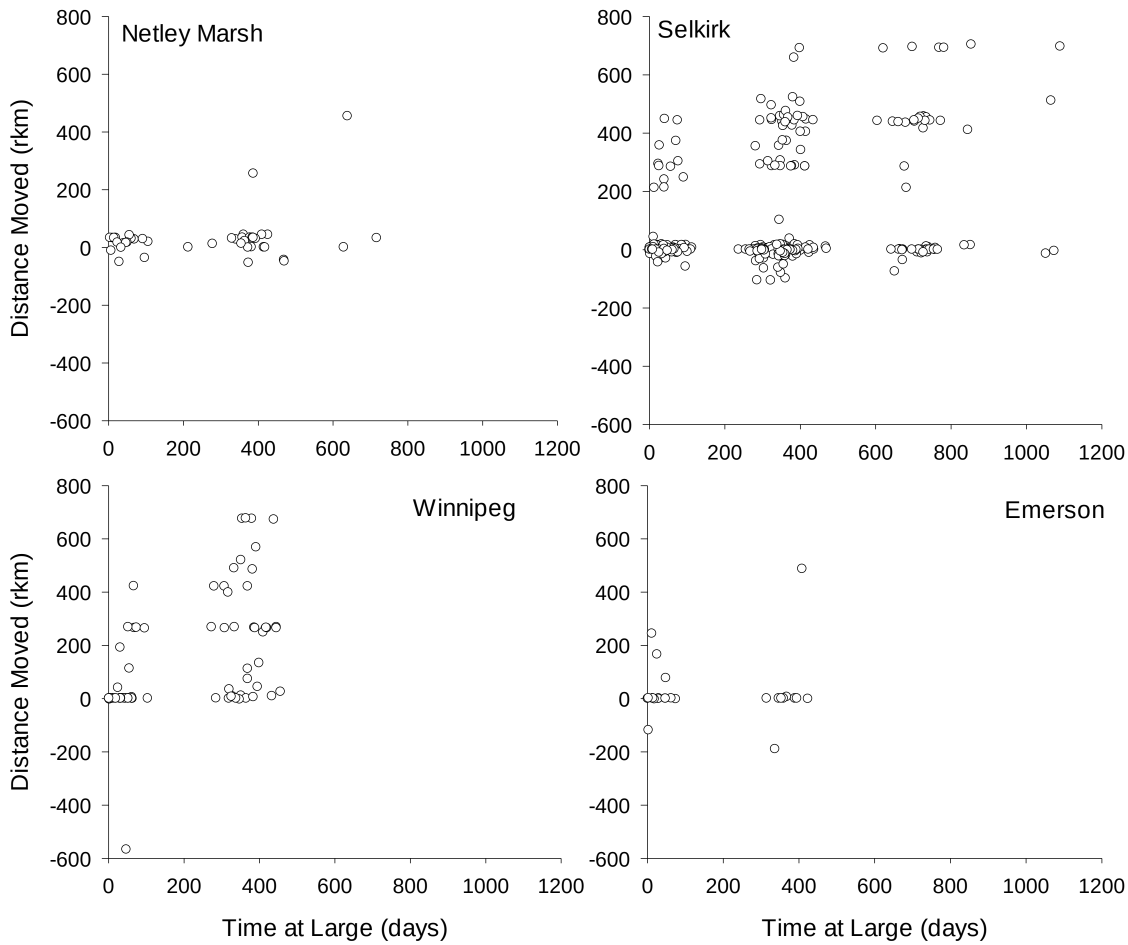

Figure 4-2. Observed distances moved (river km) and time at large (days) by recaptured Channel Catfish in the Red River of the North during 2012-2015. Positive distances are upstream movements, and negative values are downstream movements from initial tagging location.

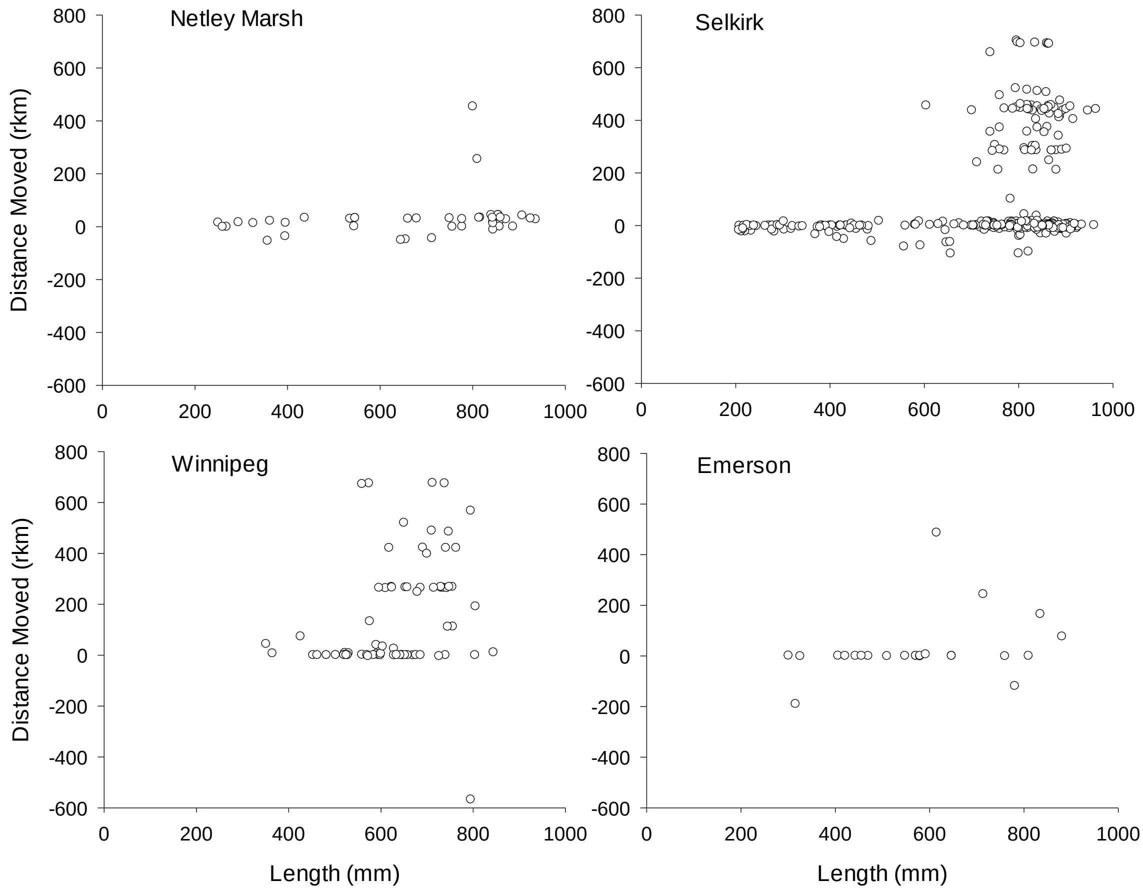

Figure 4-3. Observed distances moved (river km) and length at tagging (mm) by recaptured Channel Catfish in the Red River of the North during 2012-2015. Positive distances are upstream movements, and negative distances are downstream movements from initial tagging location

CHAPTER 5

CONCLUSIONS AND MANAGEMENT IMPLICATIONS

CHAPTER 2

AGE, GROWTH, AND MORTALITY OF A CHANNEL CATFISH *ICTALURUS PUNCTATUS* POPULATION IN MANITOBA, CANADA

CONCLUSIONS

Understanding the basic population characteristics of a fishery is necessary for proper management. This study described the age structure and size structure, and dynamic rate functions (i.e., growth and mortality) of the Channel Catfish *Ictalurus punctatus* fishery in the lower Red River. This fishery has not been studied since the late 1980s, when harvest was greater and restrictive regulations were just being implemented (Macdonald 1990). We found Channel Catfish in the lower Red River were among the largest and oldest known (> 1,000 mm and ≥ 27 years), and regulations are likely protecting the current age structure and size structure. Annual mortality rates were low (annual mortality = 0.11). Predicted growth rates were average compared to range-wide growth rates, but observed growth rates from mark-recapture events were often less than predicted from back-calculation of otoliths suggesting an older population than current aging techniques can detect.

MANAGEMENT IMPLICATIONS

2.1 *Investigate accuracy of aging structures for lower Red River Channel Catfish.*

Fisheries managers rely on accurate aging techniques to properly assess population demographics. Otoliths have only been validated through age-4 for Channel Catfish (Buckmeier et al. 2002). Validating the full age-range of lower Red River catfish (ages 0-27) would be difficult at present, yet it is possible that Channel Catfish in this population are older than we have estimated from aging structures. We found observed annual growth rates from mark-recapture were often less than annual growth rates predicted from back-calculation of age structures. Discrepancies in observed and predicted growth rates are likely due to underestimation of the true age of individuals. Ultimately, a lack of accuracy and precision in aging leads to biases in growth and mortality estimates, and can lead to misinformed management decisions. Annual tagging operations should be continued as mark-recapture techniques may be the most viable method to assess growth characteristics of this long-lived population (Hamel et al. 2014).

2.2 *Maintain current regulations and increase monitoring operations.*

Current regulations in Manitoba allow the harvest of four Channel Catfish less than 600 mm per day, and these regulations have been in effect since 1992 (Drewes et al. 2008). It appears that the current regulations have successfully maintained a large size structure and old age structure below the St. Andrews Dam. Furthermore, restrictive regulations on the lower Red River in Manitoba likely improve angling opportunities

upstream, as many trophy fish were found to move upstream to the USA (Ch. 4, this thesis). It appears the current management strategy has effectively reduced mortality when compared to mortality rates we estimated from Hegrenes (1992) for Channel Catfish upstream in the USA. By using maximum length limits and restrictive creel limits in the Red River, mortality from fishing is targeted towards younger individuals, and the fishery does not suffer from growth overfishing. Future changes in population characteristics, harvest, angler use, or river alteration could be an impetus for managers to reevaluate current regulations.

Given the results of my study, it appears exploitation and movement rates (emigration) are not causing a significant impact on the trophy fishery in the lower Red River; however, establishment of a standardized population monitoring program is necessary to document changes to this fishery. Monitoring should be conducted on meaningful spatial and temporal scales (i.e., throughout the Red River and Lake Winnipeg, and over a short enough time frame to capture changes as they occur). Exploitation rates are currently unknown throughout the Red River and should be determined for both the Manitoba and USA portions of the Red River to establish baselines for future comparisons. The most current threat to this fishery could emerge in Lake Winnipeg from commercial fishing operations. Declining Walleye *Sander vitreus* stocks are leading to increased effort from commercial fishers, ultimately inflicting additional mortality through harvest of Channel Catfish as by-catch (G. Klein, Manitoba Conservation and Water Stewardship, personal communication). This additional source of mortality has not been quantified, but is currently expected to be small, as no large-

scale commercial market exists for Lake Winnipeg catfish at this time. However, if commercial fishing operations targeting Channel Catfish were allowed, it could have substantial impacts on the lower Red River trophy fishery. We do not know whether fishing mortality influences are compensatory or additive at this time, but it would be important to determine where the additive mortality threshold lies, especially if commercial harvest rates were increased. Monitoring should be conducted on a large spatial scale because declines in this fishery may be difficult to capture just in the lower river due to hyper-stability. The area below the St. Andrews Dam has proven to be an aggregation area for Channel Catfish, and samples taken exclusively from this area could fail to reflect true changes in population characteristics or abundance. Also, observed movements between different portions of the river were not reciprocated by movement back to the original location. Therefore, standardized monitoring, perhaps on a biennial time frame across the basin, may help to detect declines in localized areas, which may ultimately impact the fishery in other areas of the river.

CHAPTER 3

ASSESSMENT OF CHANNEL CATFISH *ICTALURUS PUNCTATUS* POPULATION CHARACTERISTICS THROUGHOUT THE RED RIVER OF THE NORTH, MANITOBA, CANADA

CONCLUSIONS

Trophy Channel Catfish were most abundant below the St. Andrews Dam, but were found throughout the Red River in Manitoba. The size structure at Emerson consisted of mostly small individuals (< 400 mm), and the size structure at Winnipeg was predominantly intermediate-sized individuals (400-600 mm). The intermediate-sized individuals found at Winnipeg were underrepresented in all other reaches. Size structure at the Netley Marsh and Selkirk reaches were similar, with trophy (> 700 mm) and small catfish being most common in the samples. Channel Catfish condition was good throughout the Red River (mean relative weight values near 100). Relative abundance of Channel Catfish increased longitudinally (mean CPUE; derived from hoop net catches), and abundance estimates from POPAN models corroborated this trend. However, abundance estimates at Netley Marsh were variable and likely inflated by transient individuals, but suggest high densities of Channel Catfish in this area. Variation in size structure throughout the studied reaches suggests that different portions of the river are more suitable for different life stages of Channel Catfish.

MANAGEMENT IMPLICATIONS

3.1 *Management strategies should account for size-specific life-history needs.*

Discrepancies in size structure throughout the reaches we sampled suggest variations in appropriate habitat for different life-stages of Channel Catfish. Aquatic habitat studies pertaining to fisheries have not been conducted on the Red River in Manitoba. Future research to evaluate the habitat that is present, its spatial arrangement throughout the basin, and how different life stages of Channel Catfish are utilizing habitats within the Red River would increase our understanding of the ecological needs of Channel Catfish. Evaluation of the habitat components of this fishery would allow management efforts to account for ontogenetic shifts in habitat and foraging requirements of Red River Channel Catfish.

3.2 *Determine what function the Winnipeg reach plays in the production of trophy Channel Catfish.*

The size groups of Channel Catfish we sampled at Winnipeg may be the next cohort to recruit to the trophy fishery, as individuals of this size were uncommon elsewhere. However, our movement data showed Channel Catfish that left this area were only recaptured upstream (Ch. 4, this thesis). If none (or few) of these individuals are replenishing the trophy stock below the St. Andrews Dam, then that stock is being supplemented by individuals from an unknown area. Density estimates at Winnipeg were primarily driven by intermediate-sized catfish. Many of these were recaptured locally,

suggesting that this area can support large numbers of intermediate-sized Channel Catfish. One approach to evaluate how the Winnipeg reach functions within this fishery would be to study prey availability and diet habits of Channel Catfish throughout the Red River to determine prey selection. Analyzing differences in prey selection by size group and location may provide insight into habitat selection and life stage needs of Channel Catfish. In addition, incorporating otolith microchemistry (study in progress) and stable isotope analysis of fish tissues would provide further evidence of how long catfish are using different portions of the river, what they are consuming, and where Channel Catfish from the Winnipeg reach are going.

CHAPTER 4

QUANTIFYING MOVEMENT OF CHANNEL CATFISH *ICTALURUS PUNCTATUS* IN THE RED RIVER OF THE NORTH

CONCLUSIONS

Only large (mostly > 600 mm) Channel Catfish traversed the St. Andrews Dam, and all were in an upstream direction. The St. Andrews Dam probably impedes upstream movement of small Channel Catfish (< 600 mm). No downstream movement past the dam was documented in this study. Furthermore, many catfish that passed the dam were recaptured upstream in the USA. A portion of the Channel Catfish population in the Red River may be migratory, but only one catfish was documented returning downstream to the original tagging location from a long distance movement. Movement from the lower river to Lake Winnipeg was documented for several individuals and one individual moved from the lake to the river. Additionally, we found movement was common between the reaches above the dam and had recaptures from multiple tributaries in both the USA and Manitoba. Future work to describe the metapopulation dynamics of Channel Catfish in the Red River would help to determine the degree of connecticity throughout the Red River, and particularly if the Netley Marsh and Selkirk areas are functioning as a source population for the upstream fishery.

MANAGEMENT IMPLICATIONS

4.1 *Continue monitoring recaptures of tagged Channel Catfish.*

Over 13,000 Channel Catfish have been tagged on the Red River since 2012, and angler reported recaptures of tagged Channel Catfish will be commonplace for several years. Future recaptures will provide further insight into movement patterns of Channel Catfish in the Red River.

4.2 *Further investigate the use of Lake Winnipeg by Channel Catfish*

We were unable to satisfactorily document the interaction between Lake Winnipeg and the lower Red River Channel Catfish population. Increasing the amount of tagged Channel Catfish in Lake Winnipeg would provide further empirical evidence of the linkage between the lake and the river. Previous research has shown a linkage between connected lotic and lentic habitats. For example, Shrader et al. (2003) found 48% of the Channel Catfish recaptured in Brownlee Reservoir were originally tagged in the Snake River, Oregon. Evaluation of the lake as potential over-wintering habitat would help to draw further conclusions on the annual movement cycle. Butler and Wahl (2011) reported that lentic habitats (i.e., reservoirs) were important over-wintering habitat in the Fox River, Illinois. However, different sampling methodologies would need to be developed for late fall sampling as our regular sampling methodologies were less successful in the late fall than spring and summer. Methods similar to Richters and Pope (2011), or electrofishing using methods similar to Newcomb (1989), may be effective

options for fall sampling to determine if Channel Catfish are moving from the river to Lake Winnipeg for the winter. Acoustic telemetry would be another viable option for gathering empirical evidence of seasonal movements to Lake Winnipeg.

4.3 *Further investigate the St. Andrews Dam as a barrier to Channel Catfish movement.*

We did not document downstream movement of any Channel Catfish through the St. Andrews Dam, unlike previous studies. Upstream movement through the dam was common, but only for large individuals. It is unknown why movement was unidirectional. If movements were consistently unidirectional, then there is the potential for the trophy Channel Catfish fishery downstream of the St. Andrews Dam to decline. However, our current understanding of population dynamics in this system does not support this scenario. Future evaluations of the St. Andrews Dam as a barrier to fish movement would likely best be accomplished through telemetry to accurately assess when and where catfish are moving through the dam.

4.4 *Management strategies should include the entire watershed.*

Management of the Channel Catfish fishery in the Red River is the responsibility of three different agencies that intersects an international border: North Dakota Game and Fish Department, Minnesota Department of Natural Resources, and Manitoba Conservation and Water Stewardship. Channel Catfish did move into several tributaries

in Manitoba and the USA, as well as between all jurisdictions emphasizing a need for collaborative management. An international Red River fisheries management committee was established in 1990 to protect the Channel Catfish population in the Red River and coordinate assessment work throughout the basin (Drewes et al. 2008), but further collaboration may be necessary to establish meaningful assessments of this fishery.

Tributaries to large rivers have been shown to be an important component to lotic Channel Catfish populations (Dames et al. 1989, Pellett et al. 1998, Fago 1999), often providing habitat not common in the main stem. Dams are common on tributaries of the Red River (Aadland et al. 2005) and likely impact the Channel Catfish population throughout the Red River basin. Further determination of tributary importance and evaluation of passage of barriers on major tributaries could improve the Red River fishery.

4.5 *Increase standardized sampling and use appropriate gears.*

Sampling methods to monitor Channel Catfish in the Red River are not currently standardized among the agencies. An attempt to monitor the population in the USA occurs infrequently (every five years) and is conducted with sampling gears that may not effectively collect Channel Catfish throughout the river. Collaboration between all agencies to establish standardized sampling procedures (utilizing the proper gear), would significantly improve our understanding of the Channel Catfish population in the Red River and provide support for future management strategies. Efforts to that end have

begun with implementation of standardized sampling across all agency jurisdictions in 2015, but additional coordination of management strategies, goals, and objectives are needed.

GENERAL MANAGEMENT IMPLICATIONS FOR CHANNEL CATFISH

Catch-and-release angling is an important component of this fishery. Multiple recaptures of individual fish throughout the lower Red River (including two individuals angled twice in less than 24 hours) suggest that the quality of this fishery is partially maintained through successful releases of angled Channel Catfish. Furthermore, many of the Channel Catfish recaptured in the USA were originally tagged with angling gear below St. Andrews Dam. Age and growth analyses predicted that fish become susceptible to angling around age 15 (≈ 668 mm), and are capable of surviving for another decade once they enter the fishery (Chapter 2, this thesis). Despite protection from harvest, angler susceptible-sized Channel Catfish likely experience an unknown rate of delayed mortality from angling events. We collected two recaptures of tagged Channel Catfish that were found dead, but had been reported by anglers in the previous weeks, and observed several instances of negligent handling practices (S. Siddons, personal observation). Managers may be able to lessen the impacts of delayed hooking mortality

through angler education programs, but evaluation of hooking mortality rates may be important, especially if recreational angling effort increases.

Manitoba is the only agency in North America that manages Channel Catfish populations using maximum length limits. Most populations across North America are managed via daily creel or minimum length limits (Michaletz and Dillard 1999), which can lead to over-harvest of the largest individuals in a population. The benefits of preserving a large size structure and old age structure within a fishery often provides greater fecundity (Hsieh et al. 2010), better larval survival and recruitment (Berkeley et al. 2004a, Hsieh et al. 2010), and increased larval growth (Berkeley et al. 2004a) compared to populations without this protection. Fisheries managed for maximum age structure and size structure are also likely to be more resilient (Pope et al. 2014) to variable recruitment (Murphy 1968, Longhurst 2002, Berkeley et al. 2004b) and exploitation (Birkeland and Dayton 2005). If management goals for Channel Catfish fisheries include maintaining a sustainable fishery and providing angling opportunities for larger fish, then a re-evaluation of the more common Channel Catfish regulations is warranted. Redistributing harvest from the largest individuals in the Red River towards younger cohorts has proven to be an effective management strategy for developing a large size structure. The lower Red River Channel Catfish fishery serves as an example of what can happen when managers are able to provide a viable trophy fishery, and by consequence, sustain one of the premier fisheries in North America.

LITERATURE CITED

Aadland, L.P., T.M. Koel, W.G. Franzin, K.W. Stewart, and P. Nelson. 2005. Changes in fish assemblage structure of the Red River of the North. Pages 293-321 *in* J.N. Rinne, R.M. Hughes, and B. Calamusso, editors. Historical changes in large river fish assemblages. American Fisheries Society Symposium 45, Bethesda, Maryland.

Berkeley, S.A., M.A. Hixon, R.J. Larson, and M.S. Love. 2004a. Fisheries sustainability via protection of age structure and spatial distribution of fish populations. Fisheries 29:23-32.

Berkeley, S.A., C. Chapman, and S.M. Sogard. 2004b. Maternal age as a determinant of larval growth and survival in a marine fish, Sebastes melanops. Ecology 85:1258-1264.

Birkeland, C. and P.K. Dayton. 2005. The importance in fishery management of leaving the big ones. Trends in Ecology and Evolution 20:356-358.

Buckmeier, D.L., E.R. Irwin, R.K. Betsill, and J.A. Prentice. 2002. Validity of otoliths and pectoral spines for estimating ages of channel catfish. North American Journal of Fisheries Management 22:934-942.

Butler, S.E., and D.H. Wahl. 2011. Distribution, movements and habitat use of channel catfish in a river with multiple low-head dams. River Research and Applications 27:1182-1191.

Dames, H.R., T.G. Coon, and J.W. Robinson. 1989. Movements of channel and flathead catfish between the Missouri River and a tributary, Perche Creek. Transactions of the American Fisheries Society 118:670-679.

Drewes, H., M. Ermer, S. Gangl, and D. Kroeker. 2008. Red River of the North Fisheries Management Plan. Manitoba Water Stewardship, Minnesota Department of Natural Resources, North Dakota Game and Fish Department, and South Dakota Department of Game, Fish, and Parks.

Fago, D. 1999. Movement of channel catfish in the Lower Wisconsin River and pool numbers 10 and 11 of the Mississippi River using radiotelemetry. Pages 177-185 *in* E. R. Irwin, W. A. Hubert, C. F. Rabeni, H. L. Schramm, Jr., and T. Coon, editors. Catfish 2000: Proceedings of the International Ictalurid Symposium. American Fisheries Society, Symposium 24, Bethesda, Maryland.

Hamel, M.J., J.D. Koch, K.D. Steffensen, M.A. Pegg, J.J. Hammen, and M.L. Rugg. 2014. Using mark–recapture information to validate and assess age and growth of long-lived fish species. Canadian Journal of Fisheries and Aquatic Sciences 71:559-566.

Hegrenes, S.G. 1992. Age, growth, and reproduction of channel catfish in the Red River of the North. Master's thesis. University of North Dakota, Grand Forks, North Dakota.

Hsieh, C., A Yamauchi, T. Nakazawa, and W. Wang. 2010. Fishing effects on age and spatial structures undermine population stability of fishes. Aquatic Sciences 72:165-178.

Longhurst, A. 2002. Murphy’s law revisited: longevity as a factor in recruitment to fish populations. Fisheries Research 56:125-131.

Macdonald, D. 1990. The channel catfish sport fishery of the lower Red River. Master’s thesis. The University of Manitoba, Winnipeg, Manitoba.

Michaletz, P.H. and J.G. Dillard. 1999. A survey of catfish management in the United States and Canada. Fisheries, 24:6-11.

Murphy, G.I. 1968. Pattern in life history and the environment. American Naturalist 102:391-403.

Newcomb, B.A. 1989. Winter abundance of channel catfish in the channelized Missouri River, Nebraska. North American Journal of Fisheries Management 9:195-202.

Pellett, T.D., G.J. Van Dyck, and J.V. Adams. 1998. Seasonal migration and homing of channel catfish in the lower Wisconsin River, Wisconsin. North American Journal of Fisheries Management 18:85-95.

Pope, K.L., C.R. Allen, and D.G. Angeler. 2014. Fishing for resilience. Transactions of the American Fisheries Society 143:467-478.

Richters, L.K., and K.L. Pope. 2011. Catch of channel catfish with tandem-set hoop nets and gill nets in lentic systems of Nebraska. Pages 573-580 *in in* P.H. Michaletz and V.H. Travnichek, editors. Conservation, ecology, and management of catfish: the second international symposium. American Fisheries Society, Symposium 77, Bethesda, Maryland.

Shrader, T.M., B. Moody, and M. Buckman. 2003. Population dynamics of channel catfish in Brownlee Reservoir and the Snake River, Oregon. North American Journal of Fisheries Management 23:822-834.

APPENDIX 1

All models used for POPAN abundance estimates in Chapter 3 and associated parameter estimates.

Table A1-1. Suite of models used in POPAN abundance estimates for the Netley Marsh reach; all-inclusive size group (≥ 200 mm).

Models	Parameters	Delta AICc	Weight
$S_t\ p_t\ \beta_t\ N$	38	0	1
$S_t\ p.\ \beta_t\ N$	26	26	0
$S.\ p.\ \beta_t\ N$	15	307	0
$S.\ p_t\ \beta_t\ N$	27	460	0

Table A1-2. Suite of models used in POPAN abundance estimates for the Netley Marsh reach; angler susceptible size group (≥ 668 mm).

Models	Parameters	Delta AICc	Weight
$S_t\ p_t\ \beta_t\ N$	35	0	0.99
$S_t\ p.\ \beta_t\ N$	26	9.4	0.01
$S.\ p_t\ \beta_t\ N$	27	62	0
$S.\ p.\ \beta_t\ N$	15	91	0

Table A1-3. Suite of models used in POPAN abundance estimates for the Selkirk reach; all-inclusive size group (≥ 200 mm).

Models	Parameters	Delta AICc	Weight
$S_t\ p_t\ \beta_t\ N$	41	0	1
$S_.\ p_t\ \beta_t\ N$	29	66	0
$S_t\ p_.\ \beta_t\ N$	28	739	0
$S_.\ p_.\ \beta_t\ N$	16	5314	0

Table A1-4. Suite of models used in POPAN abundance estimates for the Selkirk reach; angler susceptible size group (≥ 668 mm).

Models	Parameters	Delta AICc	Weight
$S_t\ p_t\ \beta_t\ N$	41	0	1
$S_.\ p_t \beta_t\ N$	29	31	0
$S_t\ p_.\ \beta_t\ N$	28	440	0
$S_.\ p_{t.}\ \beta_t\ N$	16	2709	0

Table A1-5. Suite of models used in POPAN abundance estimates for the Winnipeg reach; all-inclusive size group (≥ 200 mm). Selected model indicated by '*'.

Models	Parameters	Delta AICc	Weight
$S_t\ p_.\ \beta_t\ N$	6	0	0.61
$S_.\ p_.\ \beta_t\ N$*	5	1.8	0.25
$S_.\ p_t\ \beta_t\ N$	7	3.3	0.12
$S_t\ p_t\ \beta_t\ N$	8	7.1	0.01

Table A1-6. Suite of models used in POPAN abundance estimates for the Winnipeg reach; angler susceptible size group (≥ 668 mm). Selected model indicated by '*'.

Models	Parameters	Delta AICc	Weight
$S_.\ p_t\ \beta_t\ N$	7	0	0.36
$S_t\ p_.\ \beta_t\ N$	6	0.25	0.32
$S_.\ p_.\ \beta_t\ N$*	5	0.34	0.31
$S_t\ p_t\ \beta_t\ N$	8	6.32	0.01

Table A1-7. Suite of models used in POPAN abundance estimates for the Emerson reach; all-inclusive size group (≥ 200 mm).

Models	Parameters	Delta AICc	Weight
$\boldsymbol{S_t\ p_.\ \beta_t\ N}$	6	0	0.75
$\boldsymbol{S_.\ p_.\ \beta_t\ N}$	5	3.1	0.16
$\boldsymbol{S_t\ p_t\ \beta_t\ N}$	8	4	0.10
$\boldsymbol{S_.\ p_t\ \beta_t\ N}$	7	19	0

Table A1-8. Parameter estimates, standard errors, and 95% confidence intervals from top POPAN model for the Netley Marsh reach; all-inclusive size group.

Index	Parameter	Estimate	Standard Error	Lower 95% CI	Upper 95% CI
1	*S*	1	0	1	1
2	*S*	0.999	0.001	0	1
3	*S*	0.471	0.103	0.283	0.668
4	*S*	0.999	0.003	0	1
5	*S*	0.865	0.217	0.144	0.996
6	*S*	1	0	1	1
7	*S*	0.787	0.242	0.179	0.984
8	*S*	0.32	0.087	0.179	0.504
9	*S*	1	0	1	1
10	*S*	1	0	1	1
11	*S*	0.22	0.064	0.12	0.368
12	*S*	0.191	0.095	0.066	0.441
13	*S*	N/A			
14	*p*	N/A			
15	*p*	<0.001	<0.001	<0.001	<0.001
16	*p*	0.037	0.009	0.023	0.0587
17	*p*	<0.001	<0.001	<0.001	0.001
18	*p*	0.019	0.004	0.013	0.027
19	*p*	0.001	<0.001	0.001	0.002
20	*p*	0.012	0.003	0.007	0.021
21	*p*	0.007	0.002	0.004	0.010
22	*p*	0.031	0.004	0.024	0.041
23	*p*	<0.001	<0.001	<0.001	0.001
24	*p*	0.014	0.002	0.011	0.019
25	*p*	0.029	0.008	0.017	0.048
26	*p*	0.267	0.114	0.104	0.534
27	*p*	N/A			
28	*β*	N/A			
29	*β*	<0.001	0.006	0	1
30	*β*	0	0	0	0
31	*β*	0.455	0.092	0.287	0.634
32	*β*	0.001	0.012	0	0.999
33	*β*	0	0	0	0
34	*β*	0.374	0.093	0.214	0.566
35	*β*	<0.001	0.0015	0	1
36	*β*	<0.001	<0.001	0	1
37	*β*	0	0	0	0
38	*β*	0	<0.001	0	<0.001
39	*β*	<0.001	<0.001	0	1
40	*β*	N/A			
41	*N*	178,776	19,624	144,435	221,753

Table A1-9. Parameter estimates, standard errors, and 95% confidence intervals from top POPAN model for the Netley Marsh reach; angler susceptible size group.

Index	Parameter	Estimate	Standard Error	Lower 95% CI	Upper 95% CI
1	*S*	0.416	0	0.416	0.416
2	*S*	0.01	0	0.01	0.01
3	*S*	1	0	1	1
4	*S*	1	<0.001	0	1
5	*S*	1	<0.001	0.999	1
6	*S*	1	0	1	1
7	*S*	0.918	1.26	0	1
8	*S*	0	0	0	0
9	*S*	0.41	0	0.41	0.41
10	*S*	0.041	29.12	0	1
11	*S*	0.908	0	0.9081	0.908
12	*S*	N/A			
13	*p*	N/A			
14	*p*	0	0	0	0
15	*p*	0.999	0.001	0	1
16	*p*	0	0	0	0
17	*p*	0.002	0.002	<0.001	0.009
18	*p*	<0.001	<0.001	<0.001	0.001
19	*p*	0.006	0.004	0.002	0.025
20	*p*	0.02	0.030	0.001	0.306
21	*p*	0.252	3.29	0	1
22	*p*	0	0	0	0
23	*p*	0.443	14.4	0	1
24	*p*	0.999	0.133	0	1
25	*p*	N/A			
26	*β*	N/A			
27	*β*	0.007	0.006	0.001	0.035
28	*β*	0.163	1.6	0	1
29	*β*	0.781	1.64	0	1
30	*β*	<0.001	0.052	0	1
31	*β*	<0.001	0	<0.001	<0.001
32	*β*	<0.001	0.034	0	1
33	*β*	0.011	0.148	0	1
34	*β*	0.008	0.244	0	1
35	*β*	<0.001	0.012	0	1
36	*β*	0.004	0.010	<0.001	0.428
37	*β*	N/A			
38	*N*	5,894	4,755	1,622	24,051

Table A1-10. Parameter estimates, standard errors, and 95% confidence intervals from top POPAN model for the Selkirk reach; all-inclusive size group.

Index	Parameter	Estimate	Standard Error	Lower 95% CI	Upper 95% CI
1	*S*	1	0	1	1
2	*S*	0.999	0.001	0	1
3	*S*	0.471	0.103	0.283	0.668
4	*S*	0.999	0.003	0	1
5	*S*	0.865	0.217	0.144	0.996
6	*S*	1	0	1	1
7	*S*	0.787	0.242	0.179	0.984
8	*S*	0.32	0.0856	0.179	0.504
9	*S*	1	0	1	1
10	*S*	1	0	1	1
11	*S*	0.22	0.0637	0.12	0.368
12	*S*	0.191	0.0952	0.066	0.441
13	*S*	N/A			
14	*p*	N/A			
15	*p*	<0.001	<0.001	<0.001	0.001
16	*p*	0.037	0.009	0.023	0.059
17	*p*	<0.001	<0.001	<0.001	<0.001
18	*p*	0.019	0.004	0.013	0.027
19	*p*	0.001	<0.001	<0.001	0.002
20	*p*	0.012	0.003	0.007	0.021
21	*p*	0.007	0.002	0.004	0.011
22	*p*	0.031	0.004	0.024	0.041
23	*p*	<0.001	<0.001	<0.001	0.001
24	*p*	0.014	0.002	0.01	0.019
25	*p*	0.029	0.008	0.017	0.048
26	*p*	0.267	0.114	0.104	0.534
27	*p*	N/A			
28	*β*	N/A			
29	*β*	<0.001	0.006	<0.001	1
30	*β*	<0.001	<0.001	<0.001	<0.001
31	*β*	0.455	0.092	0.287	0.634
32	*β*	0.001	0.012	<0.001	0.999
33	*β*	<0.001	<0.001	<0.001	<0.001
34	*β*	0.374	0.0935	0.214	0.566
35	*β*	<0.001	0.0015	<0.001	1
36	*β*	<0.001	<0.001	<0.001	1
37	*β*	<0.001	<0.001	<0.001	<0.001
38	*β*	<0.001	<0.001	<0.001	<0.001
39	*β*	<0.001	<0.001	<0.001	1
40	*β*	N/A			
41	*N*	178,776	19,624	144,435	221,753

Table A1-11. Parameter estimates, standard errors, and 95% confidence intervals from top POPAN model for the Selkirk reach; angler susceptible size group.

Index	Parameter	Estimate	Standard Error	Lower 95% CI	Upper 95% CI
1	*S*	1	0	1	1
2	*S*	0.999	0.007	<0.001	1
3	*S*	0.415	0.103	0.235	0.62
4	*S*	0.999	0.005	0	1
5	*S*	0.999	0	0.999	0.999
6	*S*	0.935	0.031	0.843	0.975
7	*S*	0.8245	0.299	0.076	0.996
8	*S*	0.623	0.186	0.259	0.887
9	*S*	0.999	0.013	0	1
10	*S*	1	0	1	1
11	*S*	0.401	0.116	0.206	0.632
12	*S*	0.2	0.098	0.07	0.455
13	*S*	N/A			
14	*p*	N/A			
15	*p*	<0.001	<0.001	<0.001	0.001
16	*p*	0.051	0.014	0.029	0.086
17	*p*	0.001	<0.001	<0.001	0.002
18	*p*	0.034	0.008	0.021	0.052
19	*p*	0.004	0.001	0.003	0.006
20	*p*	0.024	0.008	0.012	0.048
21	*p*	0.007	0.002	0.005	0.012
22	*p*	0.039	0.006	0.029	0.051
23	*p*	<0.001	<0.001	<0.001	0.001
24	*p*	0.017	0.003	0.013	0.023
25	*p*	0.035	0.009	0.021	0.058
26	*p*	0.267	0.113	0.105	0.53
27	*p*	N/A			
28	*β*	N/A			
29	*β*	0	0	0	0
30	*β*	<0.001	<0.001	0	1
31	*β*	0.332	0.089	0.184	0.522
32	*β*	0.002	0.02	0	0.999
33	*β*	0	<0.001	<0.001	<0.001
34	*β*	0.406	0.06	0.296	0.528
35	*β*	0.003	0	0.003	0.003
36	*β*	<0.001	0.004	0	1
37	*β*	<0.001	0	<0.001	<0.001
38	*β*	<0.001	0	<0.001	<0.001
39	*β*	<0.001	0	<0.001	<0.001
40	*β*	N/A			
41	*N*	47,217	5,923	37,068	60,452

Table A1-12. Parameter estimates, standard errors, and 95% confidence intervals from top POPAN model for the Winnipeg reach; all-inclusive size group.

Index	Parameter	Estimate	Standard Error	Lower 95% CI	Upper 95% CI
1	S	0.559	0.037	0.485	0.63
2	p	0.023	0.006	0.014	0.038
3	β	<0.001	0.001	<0.001	1
4	β	0.405	0.019	0.368	0.444
5	N	43,474	10,811	27,042	70,478

Table A1-13. Parameter estimates, standard errors, and 95% confidence intervals from top POPAN model for the Winnipeg reach; angler susceptible size group.

Index	Parameter	Estimate	Standard Error	Lower 95% CI	Upper 95% CI
1	S	0.904	0.148	0.249	0.996
2	p	0.023	0.012	0.008	0.062
3	β	<0.001	0.004	<0.001	1
4	β	0.352	0.099	0.188	0.560
5	N	5,015	2,456	2,086	12,580

Table A1-14. Parameter estimates, standard errors, and 95% confidence intervals from top POPAN model for the Emerson reach; all-inclusive size group.

Index	Parameter	Estimate	Standard Error	Lower 95% CI	Upper 95% CI
1	S	0.957	0.082	0.307	0.999
2	S	0.117	0.02	0.084	0.162
3	p	0.012	0.005	0.005	0.028
4	β	0.001	0.04	<0.001	1
5	β	<0.001	<0.001	<0.001	1
6	N	29,792	13,168	13,189	68,520

APPENDIX 2

Time periods available for Program MARK models in Chapter 3 and Chapter 4.

Table A2-1. Monthly periods used for Program MARK analyses.

Year	Period	Months
2012	1	August
	2	September
2013	3	May-June
	4	July
	5	August
	6	September-October
2014	7	May-June
	8	July
	9	August
	10	September-October
2015	11	May-June
	12	July
	13	August
	14	September-October

APPENDIX 3

Parameter estimates for selected parameters from multi-state models in Chapter 4.

Table A3-1. Time-specific capture probability parameter estimates (above St. Andrews Dam) from the top St. Andrews Dam passage model (“=0” indicates parameters constrained to equal zero).

Period	Estimate	Standard Error	95% CI
1	=0		
2	=0		
3	=0		
4	0.148	0.015	0.002-0.103
5	0.005	0.005	0-0.038
6	0.01	0.008	0.002-0.043
7	0.018	0.007	0.008-0.04
8	0.036	0.01	0.021-0.06
9	0.008	0.003	0.003-0.018
10	0.045	0.013	0.026-0.078
11	0.024	0.008	0.013-0.044
12	0.026	0.008	0.014-0.046
13	0.005	0.003	0.002-0.013

Table A3-2. Time-specific capture probability parameter estimates (below St. Andrews Dam) from the top St. Andrews Dam passage model.

Period	Estimate	Standard Error	95% CI
1	0.008	0.006	0.002-0.032
2	0.057	0.019	0.029-0.108
3	0.004	0.002	0.001-0.012
4	0.015	0.005	0.008-0.028
5	0.007	0.002	0.003-0.014
6	0.027	0.007	0.017-0.044
7	0.009	0.003	0.004-0.018
8	0.019	0.005	0.012-0.03
9	0.007	0.002	0.004-0.013
10	0.035	0.008	0.023-0.053
11	0.025	0.006	0.016-0.038
12	0.035	0.007	0.024-0.050
13	0.011	0.003	0.007-0019

Table A3-3. Time-specific movement parameter estimates (Manitoba to USA) from the top Manitoba-USA passage model ("=0" indicates parameters constrained to equal zero).

Period	Estimate	Standard Error	95% CI
1	=0		
2	=0		
3	=0		
4	0.060	0.043	0.014-0.221
5	0.000		
6	0.018	0.022	0.002-0.178
7	0.070	0.045	0.019-0.225
8	0.114	0.042	0.054-0.225
9	0.000		
10	0.219	0.048	0.014-0.327
11	0.033	0.023	0.008-0.123
12	0.032	0.020	0.009-0.107
13	0.022	0.017	0.005-0.095

Table A3-4. Time-specific capture probability parameter estimates (Red River) from the top Red River-Lake Winnipeg passage model.

Period	Estimate	Standard Error	95% CI
1	0.005	0.005	0.001-0.035
2	0.011	0.008	0.003-0.045
3	0.002	0.001	0.001-0.008
4	0.002	0.001	0.001-0.008
5	0.001	<0.001	0.000-0.004
6	0.008	0.002	0.004-0.016
7	0.003	0.001	0.002-0.006
8	0.004	0.001	0.003-0.007
9	0.001	<0.001	0.000-0.002
10	0.001	0.001	0.000-0.003
11	0.001	0.001	0.000-0.003
12	0.001	0.001	0.000-0.003

Table A3-5. Time-specific capture probability parameter estimates (Lake Winnipeg) from the top Red River-Lake Winnipeg passage model ("=0" indicates parameters constrained to equal zero).

Period	Estimate	Standard Error	95% CI
1	=0		
2	=0		
3	0.000		
4	0.000		
5	0.000		
6	0.006	0.006	0.001-0.05
7	0.006	0.005	0.001-0.03
8	0.000		
9	0.005	0.004	0.001-0.025
10	0.009	0.008	0.002-0.044
11	0.003	0.003	0-0.019
12	0.000		

APPENDIX 4

General summary of number of Channel Catfish recaptures by location within the Red River of the North watershed from 2012-2015.