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Spawning Migration and Habitat Selection by Steelhead and Longnose Suckers in the Pere Marquette and St. Joseph Rivers, Michigan

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SPAWNING MIGRATION AND HABITAT SELECTION BY STEELHEAD AND LONGNOSE SUCKERS IN THE PERE MARQUETTE AND ST. JOSEPH RIVERS, MICHIGAN

By

Robert Douglas Workman

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ABSTRACT

SPAWNING MIGRATION AND HABITAT SELECTION BY STEELHEAD AND LONGNOSE SUCKERS IN THE PERE MARQUETTE AND ST. JOSEPH RIVERS, MICHIGAN

By

Robert Douglas Workman

I investigated the migratory behavior of steelhead (*Oncorhynchus mykiss*) and longnose suckers (*Catostomus catostomus*) in the Pere Marquette River using radio telemetry to provide base-line information prior to the construction of a proposed electrical sea lamprey (*Petromyzon marinus*) barrier. Steelhead arrived at the barrier vicinity on average within 8 days in 1997 and 18 days in 1998, and moved upstream quickly through the barrier vicinity, averaging 6 minutes (1997) and 32 minutes (1998). Longnose suckers arrived at the barrier on average within 17 days in 1998 and passed through the barrier vicinity within an average of 20 minutes. Steelhead and longnose sucker migrations corresponded with increasing water temperature and stream flows.

In addition to the Pere Marquette data, I used steelhead fishway passage data from the St. Joseph River, Michigan to develop a temperature-based movement rule to quantitatively predict the probability of upstream movement. Exponential, logistic and power functions were evaluated as a means to express the probability of movement. Of these, the power function provided the closest fit between observed and predicted movement. Stream flow was also evaluated as a means of expressing the probability of movement, but did not increase the predictive power of the model. Therefore, I used water temperature to predict

upstream movements. The temperature-based movement model incorporates an increasing probability of movement for increasing water temperatures above the minimum temperature threshold for movement. By using data from two Lake Michigan tributaries, I was able to demonstrate that the modeling approach is transferable to other Great Lakes tributaries and that the model consistently demonstrates the upstream movement probability of steelhead in systems where upstream migration is governed by water temperature.

Finally, I evaluated features (groundwater presence, substrate particle size, etc...) associated with the selection of steelhead spawning habitat the Pere Marquette River. Steelhead redds were evaluated for the presence of groundwater using a GIS-based groundwater prediction model and another method based on intragravel temperature to provide insight to the importance of groundwater as a means of spawning habitat selection. The GIS model and probe-based evaluation were inconclusive as means to identify groundwater associated with steelhead redds. Steelhead preferred to construct redds in a substrate consisting of small gravel, large gravel, and small cobble particle sizes disproportionately to clay, silt, sand, and large cobble. Steelhead redds were located in areas where the stream velocity was significantly higher (F = 97.77, $P < 0.0001$) than velocities that were recorded at reference sites, and redds were located in water that was significantly shallower than what was typically found in the study reaches (F = 113.84, $P < 0.0001$). Stream temperature did not appear to influence the selection of redd locations.

For Krissy, Madeline, Ryan, and Logan.

ACKNOWLEDGEMENTS

Funding for this research was provided by the Michigan Department of Natural Resources and the Great Lakes Fisheries Commission.

I would like to thank my advisor Tom Coon for providing me the opportunity to conduct this research, and for his guidance and assistance throughout this learning process. I would also like to thank Dan Hayes for his guidance and assistance above and beyond the call of duty. My gratitude is also extended to my committee members Stuart Gage and Rich Merritt for their guidance.

I would like to thank Bill Taylor for his assistance, Jim Bence for his statistical advice, Amos Ziegler for GIS assistance, Jim Dexter for the St. Joseph River data, and Ellie Koon for some Pere Marquette data and her guidance. In addition, I would like to thank Jim Willson and the College of Business and for their assistance, and Chuck Wolverton and the staff of Northern Ecological Services, Inc. for their encouragement and support.

I need to thank my fishing buddies (they were also my field crew), Jamie Ladonski, Mike Wilson, Aaron Snell, Dan Weisenreder, and Mike Wilberg. The best part about having to fish for my research, was having your company, "quick wit", and your expertise. Mmm, smoked BKD salmon.

I would like to thank Ken Smith for providing me access to the Pere Marquette River and the Pere Marquette Watershed Council for their interest and assistance in this research.

Because of this research project, I was fortunate to meet and become good friends with a family from Ludington. The world could use more people like the Soberalskis. Thanks for your friendship and help.

Finally, I would like to thank my wife Krissy and our kids Madeline, Ryan, and Logan for their love and support, and for tolerating my mood swings. It's been difficult raising a family while trying to complete school, but I couldn't have done it without you. I would also like to thank my mom and dad, and Gary and Hallie for their love and support.

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CHAPTER 1

INTRODUCTION

INTRODUCTION

The general topic for my research is the migration and spawning habitat use of steelhead (*Oncorhynchus mykiss*) and the migration of longnose suckers (*Catostomus catostomus*). I evaluated steelhead and longnose sucker migrations in the Pere Marquette River, Michigan to address concerns for the successful upstream passage of both species beyond an electrical sea lamprey (*Petromyzon marinus*) barrier and fishway in the Pere Marquette River, Michigan. Previous operations of another electrical barrier in the Pere Marquette River did not permit the upstream passage of either species (Rozich 1989), and created concern among recreational anglers who targeted these species.

Rainbow trout (steelhead are the migratory form of rainbow trout) have been a popular sport fish among Pere Marquette River anglers for many years. Rainbow trout were first introduced to the Pere Marquette River in 1887, and were naturalized in this and other Lake Michigan tributaries shortly after initial introduction (Krueger et al. 1985). The steelhead was among the strains established in Lake Michigan tributaries.

The predominant life history form of steelhead expressed in Lake Michigan tributaries is one that includes 2 years of growth in the river after hatching, followed by a spring migration of smolts to the lake, and then 3 years of growth in the lake before returning to spawn in the spring of the fifth year (Harbeck 1999).

Other variants are expressed in some Lake Michigan tributaries, including some fish that out-migrate after 1 year of stream growth and others that grow 3 years in the stream before out-migrating. Lake growth ranges from 1 to 5 years. One other variant, the Skamania strain, was introduced in Michigan waters in the past 20 years (Dexter and Ledet 1997). Fish of this strain also spawn in the spring (March - May), but unlike the original strain, these fish migrate into their spawning stream late in the summer preceding spawning (Behnke 1992). Fish of the original or winter strain delay migration to their spawning stream until late winter or early spring of its spawning year (March - April).

I evaluated longnose sucker movements with steelhead movements to provide a comparison between a native non-game species (longnose suckers) and an introduced game species that migrate at similar times in the Pere Marquette River. Although sucker species were not considered in the design of the fishway around the barrier, it was important to document the movement of a non-game species and determine if they migrated upstream before it began operation, and to have a reference for comparison after operation began.

Similar to steelhead in Michigan waters, longnose suckers have been observed spawning in April and May in Wisconsin waters (Eddy and Surber 1947), and initiated spawning migrations in rivers when water temperature rose above 5° C (Geen et al. 1966). In addition to spawning in rivers, longnose suckers may spawn in some shoal waters of the Great Lakes (Bailey 1969). Although juvenile steelhead spend one to two years in the river after hatching, larval longnose suckers spend little time in rivers and drift to lakes soon after hatching (Bailey 1969). Longnose suckers are a slow-growing fish that reach maturity in 4 to 9 years (Bailey 1969).

There is a strong body of literature that suggests stream flow and water temperature may regulate the upstream movements of steelhead and other salmonids (Northcote 1962; Shephard 1972; Miller 1974; Power and McCleave 1980; Power 1981; Smith et al. 1994). The degree to which water temperature and/or stream flow regulate upstream migrations depends on the many factors including watershed size, geology, and weather patterns (Jonsson 1991). To further evaluate the effect of stream flow and water temperature on fish migrations, I developed a model to predict the upstream movement of steelhead based on stream flow and water temperature.

For the final segment of my research, I examined steelhead spawning habitat use in the Pere Marquette River. Pacific Coast steelhead exhibit preferences for specific water velocities and water depths (Smith 1973), and for coarse-particulate substrates small enough to be moved during redd construction, yet large enough to accommodate sufficient water flow through the redd for oxygenation of eggs and alevin emergence (Cooper 1965; Fraser 1985; Sowden and Power 1985, Kondolf 1988). Although spawning habitat selection by steelhead is well understood in the Pacific Coast region, little is known about spawning habitat selection in the Great Lakes region.

In addition, little is known about the influence of groundwater on the selection of spawning habitat by steelhead. Groundwater is important to the reproductive success of the brook trout (*Salvelinus fontinalis*) and chum salmon (*O. keta*) by protecting eggs from ice and infiltrating surface water (Kogl 1965; Fraser 1985; Curry and Noakes 1995; Curry et al. 1995), and may be important to reproductive success of steelhead by providing a thermal refuge to developing alevin from warm water in the summer and more stable flows (Shepherd et al 1986). Locations where groundwater is abundant in a river may be preferred by steelhead as spawning areas. Identifying groundwater locations within a river system where steelhead reproduce could provide insight to the importance of groundwater and its role in the selection of steelhead spawning sites.

I examined spawning microhabitat (substrate particle size, flow velocity above the redd, etc...) use characteristics of steelhead in relation to their occurrence in selected sections of the river. Identifying habitat features that are important to spawning site selection in a Great Lakes tributary can be used to help identify other areas within the same tributary that may be used by spawning steelhead, or could be improved to accommodate steelhead by habitat improvement projects that commonly occur throughout the watershed.

In summary, I addressed three topics in this dissertation:

- Steelhead and longnose sucker movements in the Pere Marquette River were examined as part of a preliminary evaluation of movement in the vicinity of an electrical sea lamprey barrier prior to its construction and operation.

- The upstream migration of steelhead was modeled in relation to stream flow and water temperature in two Lake Michigan tributaries.

- Steelhead spawning habitat was described in relation to areas of groundwater input and was characterized according to microhabitat characteristics such as substrate particle size, flow velocity.

By addressing these topics, I will provide baseline information for future evaluations of steelhead and longnose sucker movements in the vicinity of the electrical barrier and of the effectiveness of the steelhead passage device that was installed at the barrier. I will also further evaluate the influence of stream flow and water temperature on steelhead spawning migrations and provide information on steelhead spawning habitat use within a tributary of the Great Lakes.

CHAPTER 2

STUDY AREAS

STUDY AREAS

Movement data from radio-tagged steelhead in the Pere Marquette River (Figure 2-1) were used in the studies presented Chapters 3 and 4, and count data of fish passing through a fish ladder on the St. Joseph River (Figure 2-1) were used in the study presented in Chapter 4. Steelhead spawning habitat use data in the Pere Marquette River was used in the study presented in Chapter 5.

The Pere Marquette River is located in west-central Michigan and the main stem of the river is approximately 154 km long (MDNR/IFR 1988). The river drains 1,955 km^2 of watershed and is one of the last large free-flowing Great Lakes tributary streams in Michigan. The Pere Marquette River is primarily dominated by a cold-water fish community, and receives spawning migratory steelhead during the fall, winter, and spring.

The St. Joseph River is located in southwest Michigan and northwest Indiana. The mouth of the St. Joseph River is approximately 200 km south of the Pere Marquette River and is separated by at least three major tributaries (Muskegon, Grand, and Kalamazoo Rivers) of Lake Michigan. The St. Joseph River is 493 km long and drains a watershed of approximately 11,098 km^2 in Michigan and Indiana (Brown 1944). Six dams located along the river's mainstem regulate stream flow. In 1975, a fishway was constructed in the downstream-most dam at Berrien Springs, located 39 km upstream of Lake Michigan (Figure 2-1).

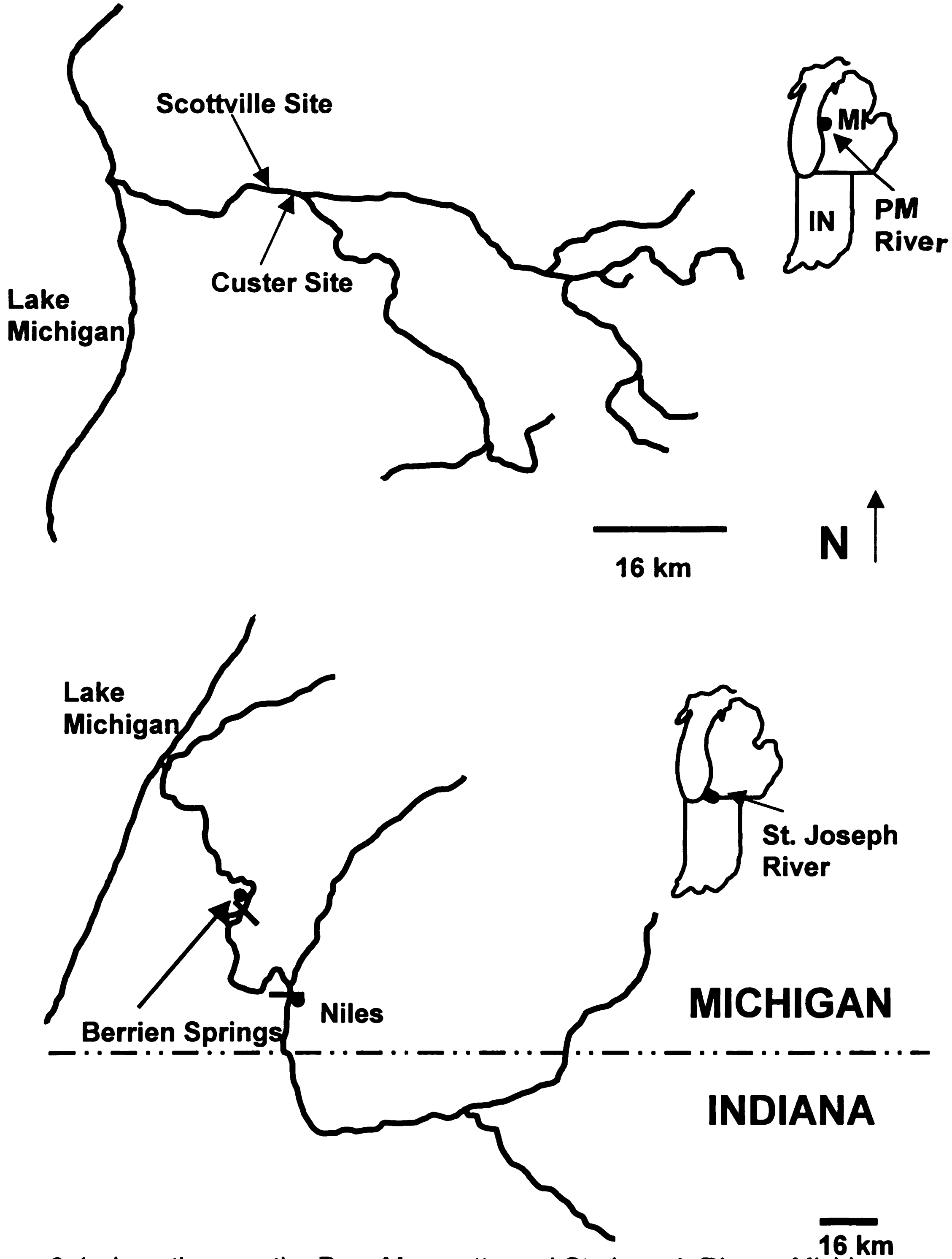

Figure 2-1. Locations on the Pere Marquette and St. Joseph Rivers, Michigan where steelhead migration, water temperature, and stream flow data were collected. Radio-tagged steelhead passage and water temperature data were collected at Custer and stream flow data was collected at Scottville on the Pere Marquette River, Michigan. The bars on the St. Joseph River map indicate where camera-recorded steelhead passage and water temperature data (Berrien Springs), and stream flow (Niles) data were collected.

CHAPTER 3

A description of the migratory behavior of steelhead (*Oncorhynchus mykiss*) and longnose suckers (*Catostomus catostomus*) in the Pere Marquette River, Michigan

Abstract

I evaluated steelhead (*Oncorhynchus mykiss*) and longnose sucker (*Catostomus catostomus*) movements in the vicinity of a proposed electrical sea lamprey (*Petromyzon marinus*) barrier and fishway, and throughout the Pere Marquette River during 1997 and 1998, using radio telemetry. Radio-tagged steelhead moved upstream quickly ($\bar{x}$ = 6 minutes, n = 4) through the barrier reception area from 23 March to 4 April 1997, and from 6 January to 17 April ($\bar{x}$ = 32 minutes, n = 26) during spring 1998, and the upstream passage times between 1997 and 1998 were not significantly different (F = 0.84, P = 0.37). There was no significant difference in the mean time from release to arrival at the barrier between the spring 1997 and spring 1998 radio-tagged steelhead (F = 1.12, P = 0.30). Radio-tagged longnose suckers also were recorded moving quickly ($\bar{x}$ = 20 minutes, n = 8) upstream from 23 March to 10 April 1998. The upstream passage of radio-tagged steelhead did not differ from longnose sucker for the 1997 and 1998 data (F = 0.09, P = 0.77). The percent passage of radio-tagged steelhead through the 150-m long barrier reception area was not significantly different (P=0.22) between 1997 (57%, n=14) and 1998 (63%, n=54). At least 24% of the radio-tagged longnose suckers passed through the barrier area.

Radio-tagged fish movement indicated that there was a general correspondence between increasing stream flow and water temperatures. My telemetry data demonstrated that radio-tagged fish moved upstream quickly through the electric sea lamprey barrier vicinity, and provided a basis for evaluation fish movement in the vicinity of the barrier following the construction and operation of the barrier.

Introduction

Migration barriers can be detrimental to the reproductive success of adult steelhead (*Oncorhynchus mykiss*) and other salmonids (Raymond 1979; Powers and McCleave 1980). Barriers such as hydroelectric dams that do not provide adequate passage for migrating anadromous steelhead will significantly decrease the number of adult returns and delay their upstream migration, resulting in a decrease in the number of steelhead that successfully reproduce (Raymond 1979). Because barriers can be detrimental to the reproductive success of steelhead, barriers should be designed to facilitate swift migrations through barrier areas.

An electric sea lamprey (*Petromyzon marinus*) barrier and fishway were constructed in the Pere Marquette River in 1999, and were designed to selectively prevent sea lamprey spawning migrations while allowing steelhead to migrate upstream to spawning locations. Previous operations of an electric lamprey barrier in the same location as the current barrier did not allow steelhead to successfully migrate around or through the barrier (Rozich 1989). Although the newly constructed barrier and fishway were designed facilitate steelhead spawning migrations, the operation of the electric barrier may cause delays or block the spawning migrations of fish species.

The passage of sucker species was not considered as a design element of the proposed electrical barrier, but suckers are an exploited species in the Pere

Marquette River. Shortly after the river ice has melted, fishers can be found in abundance along the banks of the river near Branch, Michigan, and downstream to the mouth of the river, pursuing migratory suckers well into the month of April. The operation of the electrical barrier may adversely affect future populations of migratory suckers in the Pere Marquette River.

Steelhead and longnose suckers (*Catostomus catostomus*) have similar migration patterns making the two species a likely combination for a dual examination of their migration patterns. Steelhead and longnose suckers share spawning migrations during the first half of the year (primarily February through May) in Michigan rivers. Successful introductions of steelhead into the Great Lakes region have created opportunities to examine the interactions of non-native fish with native fish species such as the longnose sucker. The study of steelhead and longnose sucker migrations in the Pere Marquette River provided a unique opportunity to examine the movement and behavior of two fish species in a Michigan river where there were no physical barriers to migration for either species.

The goal of my study was to evaluate steelhead and longnonse sucker migrations prior to the construction of an electrical lamprey barrier and fishway on the Pere Marquette River. I evaluated three aspects of adult movement: migration timing, movement rates of fish over large distance (10^3 m), and the proportion of migrants that passed upstream of the barrier. Specifically, my objectives were to:

1) Describe the timing of migration initiation by adult steelhead and longnose suckers by describing the temporal distribution of steelhead capture in the reach immediately upstream of Pere Marquette Lake and by describing the date of arrival of radio-tagged fish at the proposed electric barrier site.

2) Determine the speed of upstream movement by adult steelhead and longnose suckers through selected sections of the Pere Marquette River, and;

3) Determine the percent passage of radio-tagged fish at the proposed electric barrier.

The information from this study was used to evaluate the effectiveness of the fish passage device located at the barrier during 2000 and 2001 (Snell 2001). Information on the speed and duration of the spawning migrations of steelhead and longnose suckers was used to determine if the electric barrier had an effect on the number and timing of steelhead and longnose suckers that passed upstream after the barrier was constructed and went into operation.

Methods

Fish Capture

I collected steelhead in the Pere Marquette River (Figure 3-1) for use in the telemetry study of fish movement from February to May 1997 and collected steelhead and longnose suckers from November 1997 to April 1998. I used hook-and-line fishing continually throughout the study within an 8 km reach of the river immediately upstream of Pere Marquette Lake (Figure 3-2). I fished with steelhead spawn, Wiggle Warts ®, and Hot-N-Tots ® in stretches of river that were thought to contain steelhead. I also captured fish in fyke nets measuring 122 by 183 cm with a 5-cm stretch mesh.

A 33-m long lead with a 5-cm stretch mesh was attached to each fyke net. I fished the fyke nets at various locations within 1 km upstream of Pere Marquette Lake during the spring 1997 field season. By the end of the spring 1997 field season, I chose a location 0.25 km upstream of Pere Marquette Lake, where three fyke nets placed adjacent to each other blocked almost the entire width of one channel of the river (Figure 3-3). I used the adjacent net configuration for the spring 1998 field season and I placed the nets in the river from February to April as soon as ice conditions permitted their use. Fyke nets were not used during the 1997 fall months (October – December), due to heavy amounts of leaf material in the river. I checked the nets daily for the presence of steelhead and longnose suckers. All fish that I captured in the nets were identified and I measured the length and weight prior to their release.

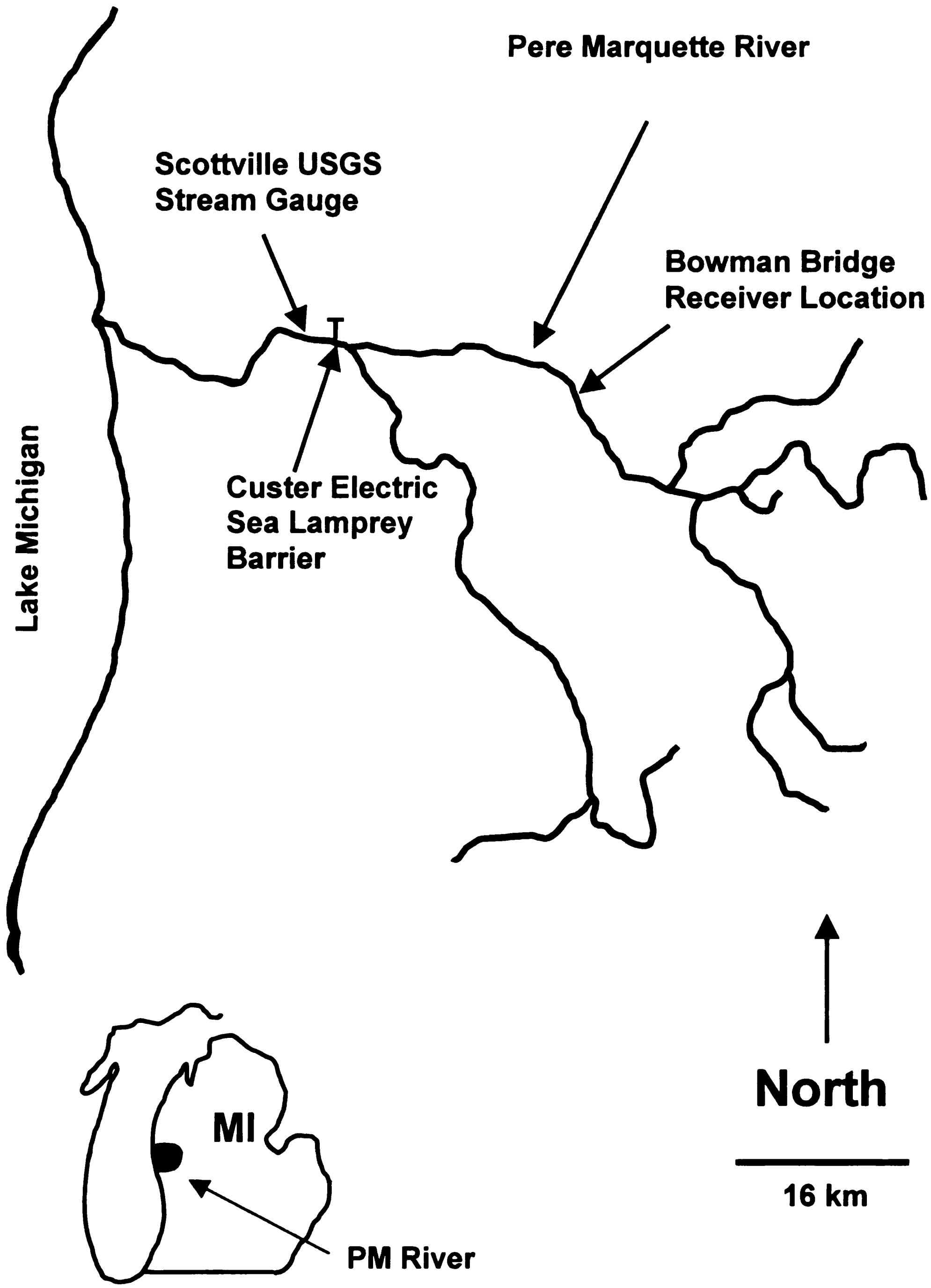

Figure 3-1. The location of Pere Marquette River within Michigan (MI), and notable sites of data collection within the River. The water temperature sampling location is indicated by "T".

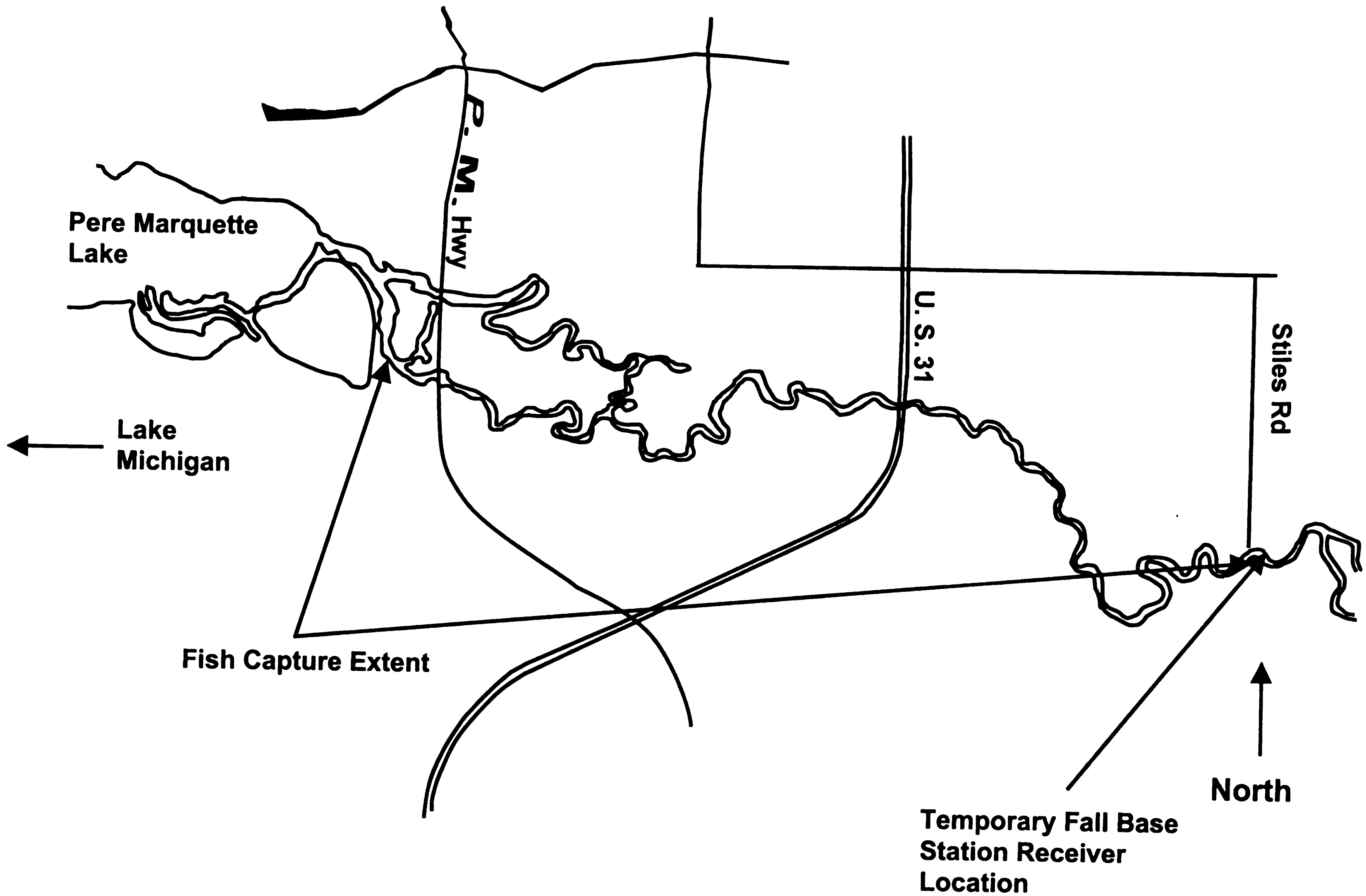

Figure 3-2. Hook-and-line steelhead capture area in the Pere Marquette River 1997-1998.

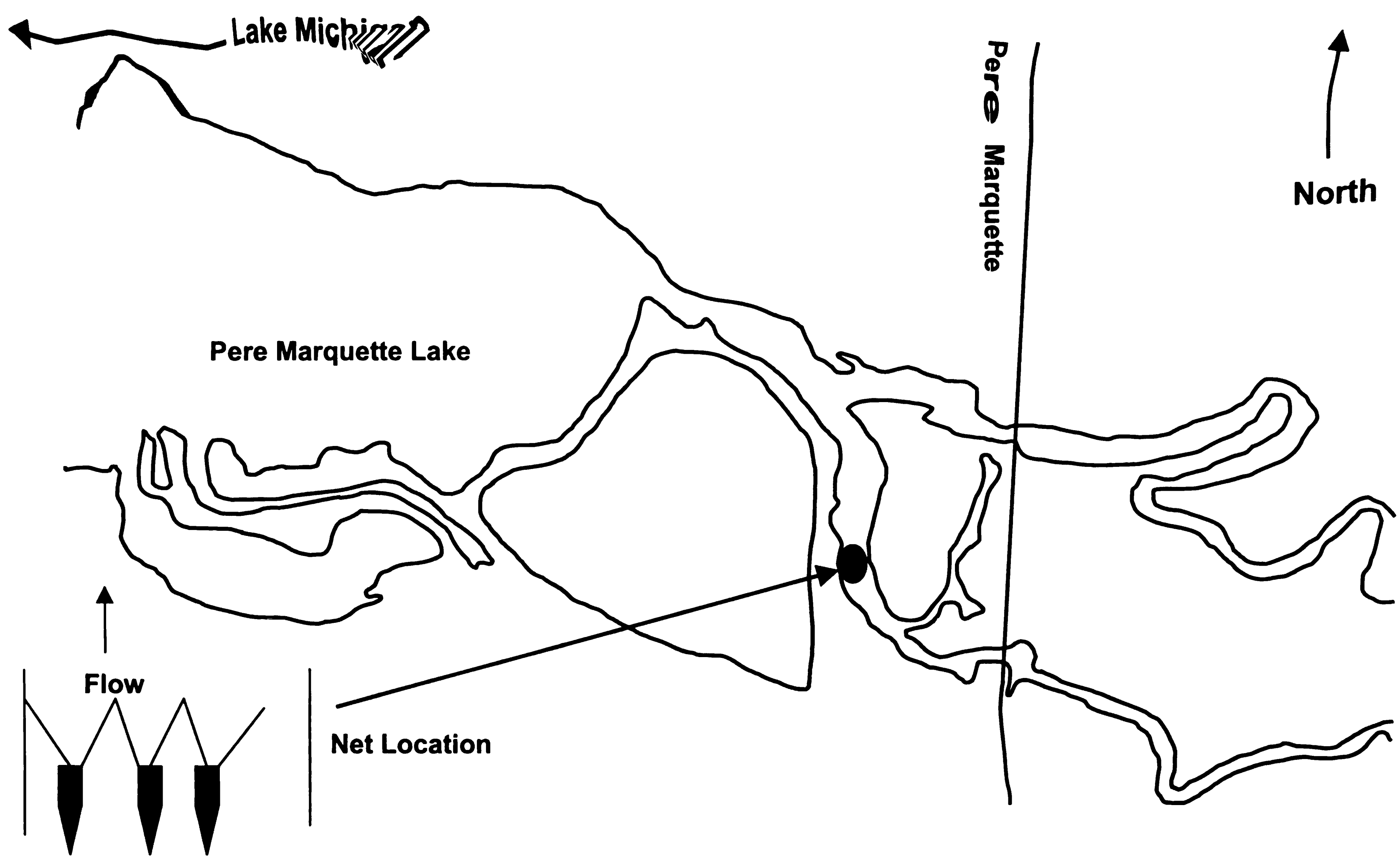

Figure 3-3. Fyke net set location in the Pere Marquette River, Michigan 1997 and 1998. Inset indicates the spatial arrangement of the Fyke nets.

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Radio Tag Implant Procedure

I selected steelhead and longnose suckers larger than 1 kg for radio tag implants. I anesthetized fish that were suitable for implants in a 150 L tank filled with 60 mg/L tricaine methanosulfate (MS-222) dissolved in river water. I recorded the weight, length, and sex from the fish when they were no longer able to maintain an upright posture within the anesthetic tank. I also recorded time and location of capture for each fish that was suitable for radio tag implant. I attempted to implant radio transmitters at a ratio of 50% males to 50% females. I determined the sex of the steelhead using several factors: the presence of a pronounced kype (indicative of males); the ease of scale removal (scales detach with little effort indicates female, not readily detachable indicative of male); and by visual inspection of the gonads during the surgical implant procedure. I determined the sex of longnose suckers using visual inspection of the gonads during the surgical implant procedure, and the presence of pronounced lateral band coloration and tubercles on the anal fin (indicative of males). I inverted the fish and placed them in a V-trough surgical table lined with indoor-outdoor carpet, and removed scales from a longitudinal row for 4 cm along the abdomen approximately 2 cm posterior of the pelvic fins, and from a small area adjacent to the dorsal fin. I made a 4-cm long incision in the abdomen region where I removed the scales and implanted the fish with a LOTEK Engineering, Inc. CFRT-7A digitally encoded radio transmitter into the peritoneal cavity. The digitally encoded radio transmitters were used because of the ability of the receiver to simultaneously monitor multiple radio signals. The radio tags measured 16.0 mm in diameter by 83.0 mm long, and weighed 29 gm in air and 12.8 gm in water. I made an incision the width of a surgical blade posterior to the larger incision and pulled the radio transmitter antenna through. The radio tags were rated to last for 282 days at a 5-second burst rate. I closed the incisions with 000 gut suture and inserted a numbered floy tag in the area where the scales were removed adjacent to the dorsal fin. I irrigated the gills of the fish with river water during the surgical procedure. I transferred the radio-tagged fish to another tub with river water where the fish remained until it maintained an upright posture within the tub. I released the radio tagged fish as close to the point of capture as possible and I released fish captured in the fyke nets approximately 200 m upstream of the nets. I used a portable hand-held SRX-400 receiver to verify that each radio tag was functioning prior to and following surgical implantation.

Monitoring Movements of Radio-Tagged Fish

The movements of steelhead that were radio-tagged during the spring 1997 were monitored at the site of the electrical barrier in Custer, Michigan (Figure 3-4). Radio tagged fish were monitored using an SRX-400 receiver with W-17 firmware that allowed for scanning of multiple channels and numerous frequencies developed by LOTEK. Two yagi antennae were mounted 100 m apart to detect direction of movement, the date and time of arrival of a radio-tagged fish into the reception area, and the date and time of departure when

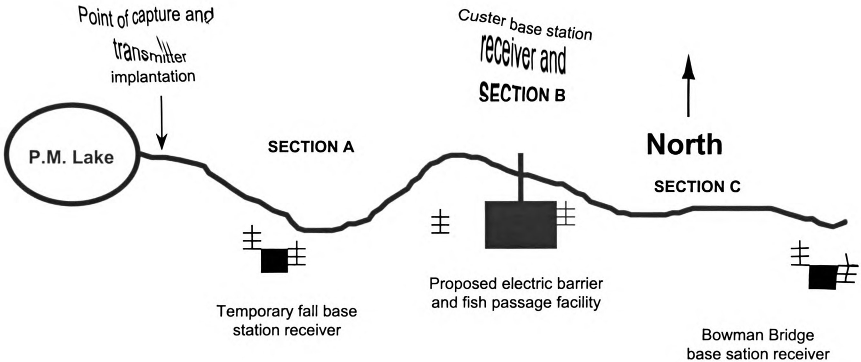

Figure 3-4. Approximate spatial arrangement of 1997 and 1998 radio telemetry study sections and relative locations of receivers (black boxes) and antennae placement along the Pere Marquette River, Michigan. The bar across the river in section B indicates the location of the electric sea lamprey barrier. The figure is not drawn to scale.

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the radio-tagged fish left the reception area. I programmed the receiver to scan antennae sequentially and record the presence of all coded transmitters that were in the listening range of the antenna. The use of coded transmitters increased the time resolution possible for detecting movements of individual fish. All data were logged in the memory of the receiver, and then downloaded periodically to maintain a continuous record. The Michigan Department of Natural Resources provided me a power supply and a structure to house the receiver.

I monitored the movements of fish radio-tagged during the 1997-98 field season using two base stations (one was located at the Custer site and one was portable), each equipped with a scanning, continuously recording receiver and a series of fixed-direction antennae. I positioned a portable base station approximately 12 km downstream of the proposed electric barrier on private property (43° 55' 9.5"N, 86° 21' 33.7" W, WGS-84), on the north side of the river, near the end of Stiles Road (Figure 3-2). The portable base station consisted of a LOTEK SRX-400 receiver with W-17 firmware and a weatherproof secured enclosure. I used a solar panel to supply power to the receiver at the remote site. I mounted two yagi antennae 20 m apart to detect direction of movement, the date and time of arrival of a radio-tagged fish into the reception area, and the date and time of when the radio-tagged fish left the reception area. The primary purpose of using the downstream base station was to gain more information about the movement of fall radio-tagged steelhead. I left the portable base station at this location until radio-tagged fish were detected at the Custer site. I relocated the portable base station approximately 40 km upstream of Pere Marquette Lake to a site 2 km upstream of the Bowman Bridge public access site that marks the downstream end of a reach that contains much of the spawning habitat used by steelhead in the Pere Marquette River (Figure 3-1). The portable base station remained at this location for the remainder of my study. I used a portable hand-held SRX-400 receiver to verify the location of the radio-tagged steelhead downstream of the fall-placed base station.

Study Area

I established three study sections as a means of assessing movements of radio-tagged fish to provide base-line data for comparison with a follow-up study after the electric lamprey weir was in operation (Figure 3-4). Some of the key features of the spatial arrangement were:

-Section A (from a point approximately 28 km downstream of the barrier to a point 100 m downstream of the barrier) is unaffected by the barrier operation. Thus, rates of fish movement and percent of fish passing through this zone acted as a reference site for the duration of this study and follow-up studies.

-Section B (within the 150 m-long detection zone including the barrier and extending 100 m downstream from the barrier) provided a control during years the barrier was not operating and provided the data needed for estimating the impact of the barrier during years of barrier operation.

–Section C (approximately 28 km upstream of the barrier) provided a reference during years when the barrier was not operating. During years of barrier operation, data from this zone could be used to determine if fish compensate movement rates if the barrier facility delays their migration. If no compensation was observed, data from this zone could also serve as a control.

I used the time for passage from the release location of the radio-tagged fish to the downstream antenna at the barrier to calculate movement rates through Section A. To estimate fish movement rate through the barrier section (Section B), I measured the time required for a fish to move from the lower antenna to the time it arrived immediately upstream of the barrier. For the final movement rate estimate (Section C), I used the time from the last record of the fish being immediately upstream of the barrier to the time it was first detected at the upstream base station. A determination of the direction of movement was necessary to assess movement rates through each section. A minimum of two records from one base station (one record from each antenna) were necessary to determine the direction of movement for a radio-tagged fish.

From these antennae arrangements, I was able to determine the dates when much of the migration of steelhead and longnose suckers occurred, as well as the time required for transit between the fixed base stations and the proportion of fish that completed each segment of the migration. Radio-tagged fish whose direction of movement could not accurately be determined from the record of the base station receivers were not used in the speed of movement through section analyses.

Data Analysis

I used a General Linear Model (SAS v. 8.01) to compare movement rates of steelhead and longnose suckers between sections and years. I determined the passage through each section as the number of radio-tagged fish that reached the upper limit of a section as a percent of those that moved upstream of the lower (downstream) limit of the section. I used Fisher's exact test (Zar 1984) to compare the percent passage of radio-tagged steelhead in 1997 and 1998.

Environmental monitoring

Because stream discharge and stream temperature data were likely to be important cues in the migratory process, I monitored stream discharge, and stream temperature. Stream discharge data were obtained from the U.S. Geological Survey gauge station at located in the river at Scottville (Figure 3-1). Stream temperature was monitored by means of an Onset Hobo electronic thermograph located at Custer (Figure 3-1).

Results

Fish Capture

I captured 18 steelhead and implanted 14 with radio transmitters from 18 February to 6 April 1997 (Table 3-1). Six of the 14 steelhead (eight males:six females) were caught by hook-and-line and eight were caught in fyke nets (Table 3-1). I radio-tagged 54 steelhead (26 hook-and-line:28 fyke net capture, and 16 males:38 females) from fall 1997 to spring 1998. Ten of the 54 steelhead were captured and implanted from 24 October to 16 December 1997, and all fall radio-tagged fish were captured by hook-and-line. I captured the spring 1998 steelhead from 6 February to 8 April.

The steelhead that I captured during the spring 1997 ranged from 270 to 800-mm long, and the steelhead captured during the fall 1997 and spring 1998 ranged from 535 to 800-mm long (Table 3-1). From 1997 to 1998, the smallest steelhead that was radio-tagged weighed 1.6 kg, and the largest weighed 5.8 kg.

The movements of longnose suckers were not evaluated during 1997. A total of 200 longnose suckers were captured in fyke nets from 24 February to 20 April 1998, and 33 longnose suckers were radio tagged from 24 February to 28 March 1998. The longnose suckers ranged from 420 to 550-mm long and their weight ranged from 1.0 to 2.0 kg (Table 3-1). Eighteen of the 33 longnose suckers that I implanted with radio transmitters were males and 15 were females (Table 3-1).

Table 3-1. Catch statistics of steelhead and longnose suckers from the Pere Marquette River, Michigan, 1997 - 1998. The statistics include the mean weight and length of the captured fish as well as the number of male and females that were radio-tagged each year.

Sample	Number of Fish		Mean Length		Mean Weight		Number of	
Period/Species	Caught	Tagged	(mm)	range (mm)	(kg)	range (mm)	Males	Females
Spring, 1997 Steelhead	18	14	651 n=18	270-800	3.7 n=17	0.8-5.8	8	6
Winter-Spring 1997-1998 Steelhead	84	54	679 n=54	535-800	3.2 n=54	1.2-4.6	16	38
Spring 1998 Longnose Sucker	200	33	471 n=197	420-550	1.37 n=197	1.0-2.0	18	15

Timing of Migration

Radio-tagged steelhead were recorded moving upstream through the Custer reception area (Section B) from 23 March to 4 April 1997 (Figure 3-5), and were recorded moving upstream through the Custer reception area from 6 January to 17 April 1998 (Figure 3-6). Although the 1998 movement occurred over a longer period than 1997, much of the upstream movement occurred over a brief period, from 25 March to 17 April 1998. Radio-tagged longnose suckers were recorded moving upstream from 23 March to 10 April 1998 (Figure 3-7).

Radio-tagged steelhead and longnose suckers were recorded at the Custer base station when water temperatures were greater than 3.5°C and stream flows were greater than 20.8 m^3/s, for 1997 and 1998 (Figures 3-5, 3-6, and 3-7). In 1997 and 1998, temperature and discharge data indicated that there was a general correspondence between fish movement and increasing stream flow and water temperatures.

Speed of Movement Through Base Station Reception Areas

Section A

The mean number of days between release of marked fish and arrival at Custer was 7.8 days ($n = 8$, $s = 11.1$ days), with a range of 0.5 to 33 days for steelhead radio-tagged during spring 1997 (Table 3-2). The mean number of days between release of marked fish and arrival at Custer was 18 days ($n = 26$, $s = 26.6$ days), with a range of 2 to 126 days, for the fall 1997 and spring 1998 radio-tagged

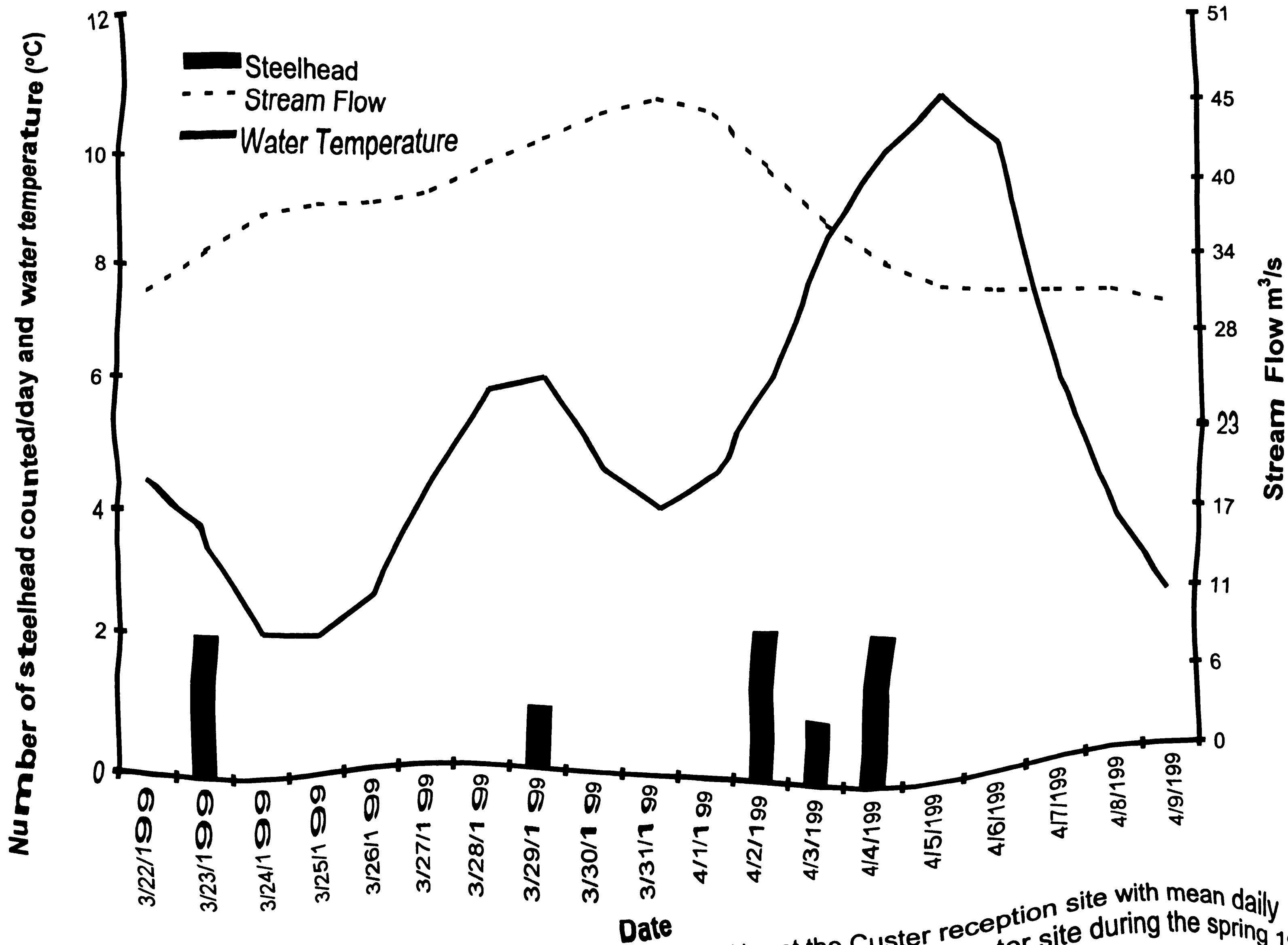

Figure 3-5. The number of radio-tagged steelhead counted/day at the Custer reception site with mean daily stream flow (dashed line) and mean daily water temperature (solid line) at the Custer site during the spring 1997 migration on the Pere Marquette River, Michigan.

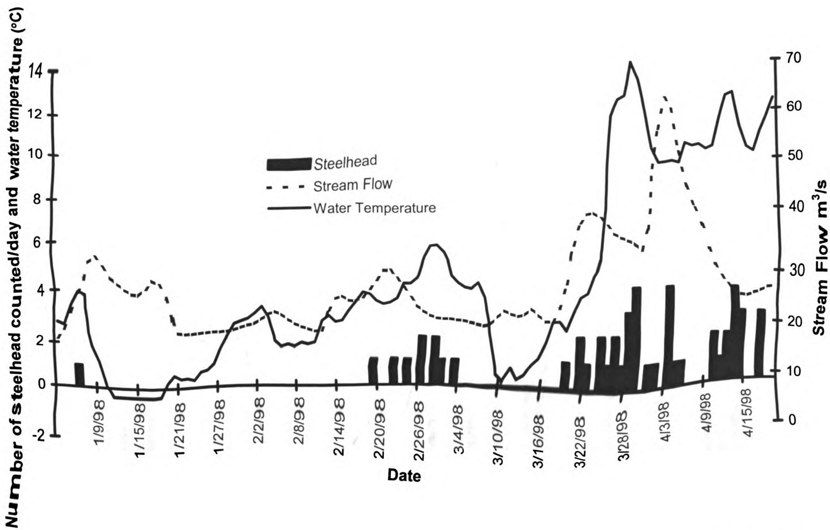

Figure 3-6. The number of radio-tagged steelhead counted/day at the Custer reception site with mean daily stream flow (dashed line) and mean daily water temperature (solid line) at the Custer site during the spring 1998 migration on the Pere Marquette River, Michigan.

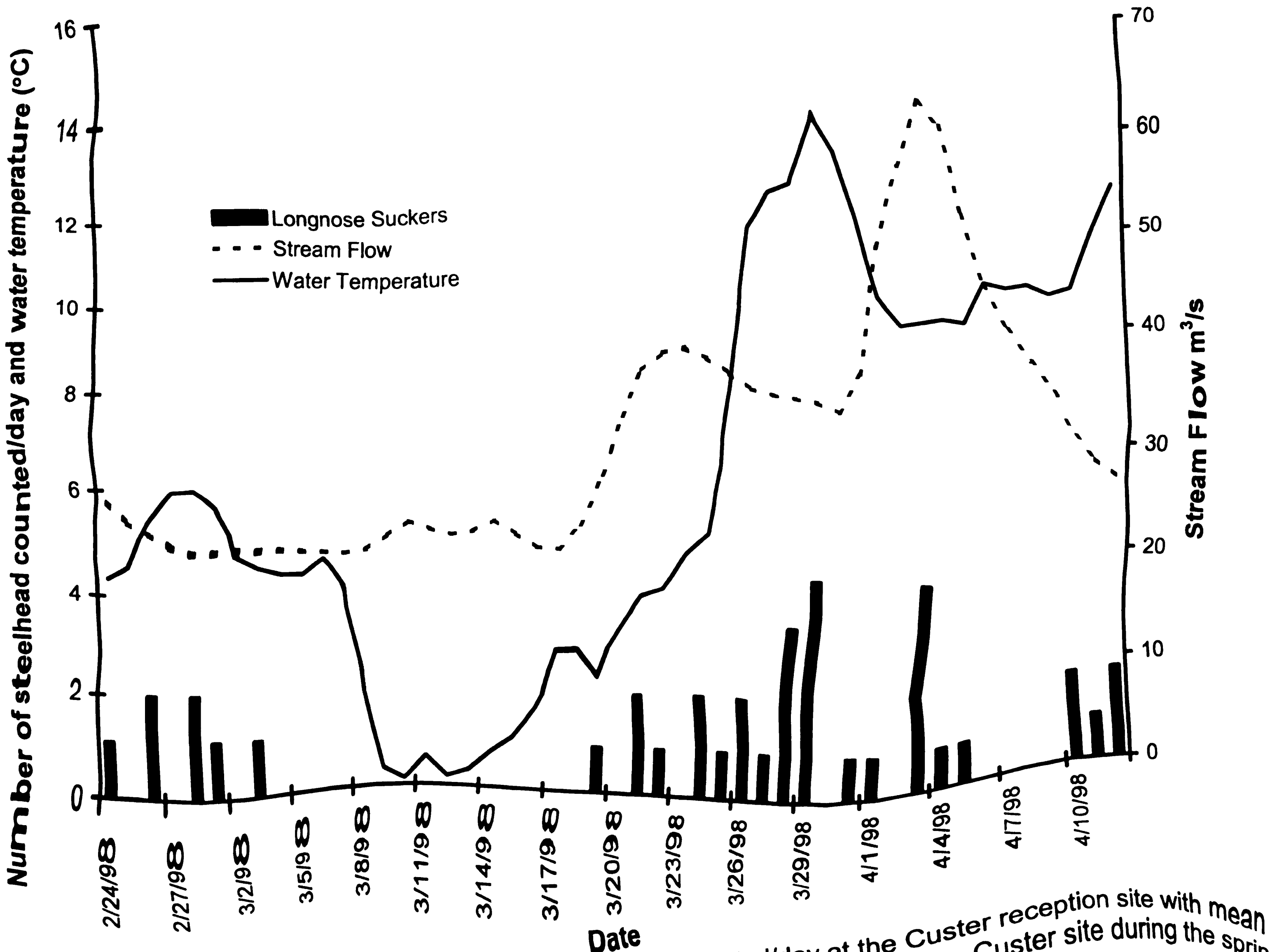

Figure 3-7. The number of radio-tagged longnose suckers counted/day at the Custer reception site with mean daily stream flow (dashed line) and mean daily water temperature (solid line) at the Custer site during the spring 1998 migration on the Pere Marquette River, Michigan.

Table 3-2. Number of fish arriving at base stations and time taken to reach base station for steelhead in 1997 and 1998 and longnose suckers in 1998.

No. of fish implanted	No. of fish counted at Custer	Mean no. of days from release to Custer and range (Section A)	No. of fish at Bowman	Mean no. of days from Custer to Bowman and range (Section C)
Spring 1997, Steelhead 14	8	8 (0.5 - 33)	Not monitored	
Fall 1997 to Spring 1998, Steelhead 54	34	18 (2 - 126)	14	9 (1-28)
Spring 1998, Longnose Suckers 33	8	17 (2 - 24)	0	

steelhead. However, if the fish tagged in fall 1997 were excluded, the mean number of days between release of marked fish and arrival at Custer was 11 days (n = 24, s = 12.7 days), with a range of 2 to 51 days. The mean time from release to arrival at Custer was not significantly different between the spring 1997 and spring 1998 radio-tagged steelhead (F = 1.12, P = 0.30).

Three of the 10 fish that I radio-tagged during the fall 1997 were recorded at the temporary base station located downstream of Custer. Two of the three fish recorded at the temporary base station were later recorded upstream at the Custer base station. Of the seven radio-tagged steelhead that were not recorded at the temporary base station, five were not found in the river within 3 days after radio tag implantation, and using a portable receiver, I observed two approximately 0.25 km upstream of Pere Marquette Lake 1 day after I implanted them with radio transmitters.

Section B

When steelhead arrived at the Custer station, they moved through the section quickly. The mean duration of passage through the 150 m section during spring 1997 was 7 minutes (n = 8, *s* = 6.9 minutes) for upstream-bound fish, and 7 minutes (n = 4, *s* = 6.0 minutes) for downstream-bound fish (kelts returning to the lake after spawning). Six of the eight fish that arrived at Custer passed upstream through the monitored section quickly (less than 1 day), and arrived within a 7-day period from 23 March to 4 April. This suggests that the fish were responding to similar cues to initiate upstream migration and they can make the passage from near Pere Marquette Lake to Custer in one day or less.

The mean duration of passage for the fall 1997 and spring 1998 radio-tagged steelhead was 32 minutes (n = 27, *s* = 72 minutes) for upstream–bound fish, and 11 minutes (n = 9, *s* = 13 minutes) for downstream-bound fish. One steelhead took 11 hours and 12 minutes to move downstream through the Custer reception area. I excluded data from this fish in the calculation of downstream movement time, because I believed that the longer duration was atypical when compared to the other nine fish that were moving downstream. There was no significant difference ($F = 0.84$, $P = 0.37$), in the time of upstream passage between the spring 1997 and fall 1997-spring 1998 data.

The mean duration of passage for longnose suckers through the Custer reception area was 20 minutes (n = 8, s = 16 minutes) for upstream-bound fish and 90 minutes (n = 1) for downstream-bound fish. The mean number of days between release of tagged suckers and arrival at Custer was 16.6 days (n = 8, s = 9.1 days), with a range of 2 to 24 days. There was no significant difference in the mean recorded time to pass through the 150 m long Custer station ($F = 0.09$, $P = 0.77$), or in the mean time from release through the Custer station ($F = 2.46$, $P = 0.12$) between the radio-tagged suckers and steelhead.

Section C

The mean number of days between leaving Custer and arriving at the Bowman Bridge base station was 9 days (n = 10, s = 9), with a range of 1 to 28 days during 1998. The mean time radio-tagged fish moved through the 600 m reception area of the base station was 22 minutes (n=7, s = 17 minutes), going upstream and 186 minutes (n=1) in a downstream direction. No fall radio-tagged steelhead were recorded at the Bowman Bridge receiver site. Radio-tagged longnose suckers were not recorded at the Bowman Bridge base station during 1998.

Percent Passage Through Base Station Reception Areas

At least 57% (n = 14) of the radio-tagged steelhead passed upstream of the Custer barrier location in the spring 1997 and 63% (n = 54) of radio tagged fish passed upstream of the Custer location in the spring 1998 (Table 3-2). The percent passage of radio tagged fish through the Custer reception area (Section B) was not significantly different between 1997 and 1998 ($P = 0.22$).

During 1998, there were seven radio-tagged steelhead recorded at Custer who's direction of travel I could not determine using only the Custer base station data. However, using the Bowman Bridge receiver data, I determined all but one of the steelhead that reached Custer moved upstream of Custer. One of the seven fish was within receiver range at Custer for 10 days. The receiver at the Bowman station recorded 26% of 54 radio-tagged steelhead (Table 3-2).

At least 24% (n = 33) of the radio-tagged longnose suckers passed by the Custer station (Table 3-2). Ten of the 33 radio-tagged longnose suckers were presumed dead after they had been repeatedly located at their release location for one month or longer.

Discussion

Timing of Migration

The timing of migration initiation corresponded to increasing water temperature and increasing stream flow for steelhead and longnose suckers. Shepard (1972) and Miller (1974) found water temperature and stream flow influenced the timing of steelhead migrations. Northcote (1962) found water temperature regulates the upstream movement of rainbow trout. Steelhead initiate upstream migrations over a range of temperatures and have been reported to spawn in water temperatures from 5.0 to 12.5°C (Shepard 1972; Miller 1974; Beschta et al. 1987). Another salmonid, the Atlantic salmon (*Salmo salar*) also initiates migrations over a range of water temperatures and may enter rivers during periods of increased flows (Power and McCleave 1980; Power 1981; Smith et al. 1994). Longnose sucker migrations intensified as a result of increasing temperature in a Wisconsin stream (Bailey 1969), and Geen et al. (1965) found that rising stream temperature may be associated with the onset of upstream migration.

Because steelhead and longnose sucker migrations were influenced by water temperature and stream flow, the shorter duration of upstream migration for steelhead in 1997 than in 1998 was probably due to the colder water temperature during the months of January and February. Water temperature was less than 3.5°C in January and February 1997, and water temperature exceeded 3.5°C for periods in January and February 1998. Although the duration of upstream migration differed from 1997 to 1998, the peak of upstream migratory activity appeared to be similar for the 1997 and 1998 field season, occurring during the last two weeks of March and the first two weeks of April.

Radio-tagged fish appeared to be more likely to move upstream as water temperature and stream flow increased. Leider (1985) suggested that the propensity to migrate upstream increases as the migration season progresses. Later in the season, the increased temperature and flow effect was most pronounced in steelhead that migrated upstream of Custer in as little as 0.5 days, and past the Bowman Bridge base station in as little as 5 days from release.

Percent Passage Through Base Station Reception Areas

Radio-tagged fish moved quickly upstream through the Custer and Bowman base stations. The short passage time through the base station reception areas indicated that the base stations were located in areas that did not impede upstream passage and did not provide adequate spawning habitat for radio-tagged steelhead and longnose suckers.

Longnose suckers were not as successful as steelhead at reaching the Custer and Bowman base stations. It is possible that the spawning habitat for longnose suckers was downstream of the habitats used by steelhead, thereby accounting for their absence at the Bowman Bridge receiver. In addition, at least 30% of the longnose suckers implanted with radio tags did not survive long enough to migrate to Custer. The suckers may have suffered higher mortality or impairment from the radio transmitters, which were larger, relative to the fish size than they were for steelhead. Winter (1996) suggests that fish should not be equipped with transmitters that weigh more than 2% in air of the fish's weight out of water. The radio tags used in my study weighed 1.8% of mean weight, and measured 17% of the mean length of the longnose suckers I implanted with radio tags. Even so, the suckers that did reach Custer were moving almost as quickly as the steelhead. A smaller radio tag would probably reduce incidence of mortality from the surgical implant procedure.

Most of the steelhead that were radio-tagged during fall 1997 did not remain in the Pere Marquette River. Whether this represents typical behavior for staging steelhead or a response to the transmitter implantation procedure cannot be determined. Winter (1976) found 89% of fall-run steelhead that were radio-tagged in Lake Superior streams left the streams following radio-tagging, and returned the following spring to spawn. However, the fact that fish tagged in February to April rarely left the river suggests that steelhead in the river in September to December are more prone to return to the lake.

Migrating steelhead in Pacific coast rivers are known to use holding or staging areas that are also referred to as overwintering areas (Burger et al. 1983). Hooton and Lirette (1986) observed immigrating steelhead that occupied a heavily fished area within a western Canadian river for an extended period of time 3 to 4 months prior to spawning. Little is known of the significance of the staging areas. It is possible that they may serve as a source of energy, such as a location with an abundant food supply, or possibly a refuge from harsh winter river conditions such as icing.

Evaluation of Capture Methods

The combination of fyke nets and hook-and-line methodology were successful and necessary in acquiring enough fish for the implantation of radio tags. Using the multiple net configuration to ensure successful steelhead capture, I blocked as much of the river as possible. I was careful to maintain complete blockage from the surface to the bottom of the river in any location where the fyke net was placed.

Radio tags were implanted in fish far downstream of the proposed barrier so that any immediate responses of the fish to the surgery would be likely to abate by the time they were ready to ascend the river. Because some radio-tagged fish arrived at the Custer base station relatively quick (0.2 to 2 days), it is unlikely that the surgical implant procedure adversely affected the steelhead's ability to migrate upstream.

Future Considerations

The telemetry data that I collected from 1997 to 1998 demonstrated that steelhead and longnose suckers moved quickly upstream in the Pere Marquette

River when they began their final ascent of the river for spawning. Furthermore, both species moved quickly past the site where the electric barrier was constructed. These data allowed for an evaluation of how long the barrier and fish passage structure delay movement for both species (Snell 2001). Likewise, the percent of fish traversing each section will be used as a measure of the number of fish unable to traverse the barrier/fish ladder and “balking” or dropping back out of the section, or being caught by anglers.

CHAPTER 4

A Model of Steelhead Movement in Two Lake Michigan Tributaries in Relation to Water Temperature

Abstract

I used movement data from two Lake Michigan tributaries to develop a new approach for analyzing upstream adult steelhead migration. My data included 28 radio-tagged steelhead (*Oncorhynchus mykiss*) on the Pere Marquette River and a larger (5,876 to 10,083 steelhead), multi-year (1993-1999) data set of camera recorded steelhead passage through a fishway on the St. Joseph River. My model used a temperature-based movement rule developed from the data to quantitatively predict the probability of upstream movement. Exponential, logistic and power functions were evaluated as a means to express the probability of movement. Of these, the power function resulted in the closest fit between observed and predicted movement. Probability of movement increased over increasing water temperatures above a movement-threshold water temperature. Stream flow was incorporated into the temperature-based movement (TBM) model, but did not add substantially to the model's ability to describe the migratory behavior of steelhead in the Pere Marquette and St. Joesph Rivers. The TBM modeling approach is broadly applicable and transferable to other Great Lakes tributaries, and may work well for describing the migratory behavior of other species whose migration is also dependent on water temperatures. Furthermore, the TBM model could be used to predict percent passage by a fixed location, forecast run size early in the migration season, and aid in the timing of operation of sea lamprey (*Petromyzon marinus*) control structures such as electric migration barriers.

Introduction

Several approaches have commonly been used to characterize fish movements. One approach is to collect sequential descriptions of the location of individual fish while taking note of environmental conditions such as water temperature, pH, dissolved oxygen, stream flow and others (Doerzbacher 1980; Schulz and Berg 1992; Workman 1994). Descriptive statistics such as the mean and range are then used to characterize observed movement patterns of fish. The information gained from this approach tends to be fish specific and largely descriptive in nature. Another approach is to determine the timing of movement relative to environmental thresholds (Geen et al. 1966; Bailey 1969; Power 1981; Jonsson 1991). Environmental thresholds can be thought of as cues (e.g., water temperature, dissolved oxygen level, etc.), above which fish movement is observed. Typically, little or no movement is associated with levels below a minimum threshold point and movements are observed at the threshold point and increase until a maximum movement rate is reached. Other approaches make use of regression analyses, analysis of variance (ANOVA), and multivariate analyses to identify environmental cues and their relation to fish movement (Clapp et al. 1990; Trepanier et al. 1996; Giorgi et al. 1997; White and Knights 1997). The information gained from these studies partially describes fish movement by linking exogenous (environmental) cues to movement, or identifying a range of conditions where many fish are likely to move. However, these analyses generally provide a static picture of fish movement, and do not provide a base for predictive models using the range of one or many environmental cues.

Because of the important role migration plays in fish population dynamics, improvements to our understanding are critical to the management of migratory fishes. One aspect of fish migratory behavior that is of particular interest is the timing of migration and its relation to environmental cues. Understanding migratory behavior thus may help fishery biologists better manage these species by limiting exposure to mortality sources.

My objective is to develop an alternative approach for describing fish migratory behavior that is based on a dynamic model that treats migratory behavior in a probabilistic manner. I illustrate the application of this modeling approach using a case study of steelhead (*Oncorhynchus mykiss*) in two Lake Michigan tributaries. In this model, we gain a better understanding of how water temperature and stream flow affect the probability of upstream movement of steelhead in these streams. I also evaluate how the model performs for two different types of data collection; radio telemetry passage data on the Pere Marquette River and fishway passage observational data on the St. Joseph River.

Steelhead were chosen because of their high value to anglers and resultant need for management, and their well known migratory behavior through previous studies. The majority of previous studies have focused on the energetic cost of migration (Hinch and Rand 1998), migration timing between separate runs of the same species in the same river (Burger et al. 1984), factors that influence the migration of juveniles (Northcote 1962; Muir et al. 1994; Zabel et al. 1998), and factors that influence upstream migrations of adults (Shepard 1972; Miller 1974; Jensen et al. 1986; Trepanier et al. 1996). My study focuses on adult steelhead movement behavior over a range of exogenous cues.

Many fish migrate up Great Lakes tributaries for the purpose of reproduction, and initiate upstream migrations to spawning areas based upon exogenous and endogenous (physiological) cues. While endogenous cues are difficult to identify and measure in the field, exogenous cues are more readily identified. Water temperature and stream flow are the most frequently cited exogenous cues that initiate upstream migration (Peters et al. 1973; Miller 1974; Power and McCleave 1980; Power 1981; Jensen et al. 1986; Trepanier et al. 1996). In my model, I test the influence of both of these factors.

Methods

Migration Data Sources

Methods of data collection differed on the Pere Marquette and St. Joseph Rivers. On the Pere Marquette River I radio-tagged steelhead, whereas, a camera was used to observe fish passage on the St. Joseph River. Fifty-four steelhead were implanted with radio transmitters from 15 October 1997 to 11 April 1998 in the lower Pere Marquette River. Fyke nets and angling were used to capture the fish. Steelhead larger than one kilogram were anesthetized in a tank filled with 60 mg/L tricaine methanosulfate (MS-222) dissolved in river water, and a LOTEK Engineering, Inc. CFRT-7A digitally encoded radio transmitter was surgically implanted into the peritoneal cavity (Winter 1996). The gills of the fish were irrigated with river water during the surgical procedure. The radio tags measured 16.0 mm in diameter by 83.0 mm long, and weighed 29 gm in air and 12.8 gm in water. The radio tags were rated to last for 282 days at a 5-second burst rate. The incisions were closed with 000 gut suture, and the radio-tagged fish was transferred to another tub with fresh river water where the fish remained until it maintained an upright posture within the tub. The radio-tagged fish was released as close to the point of capture as possible. Fish captured in the fyke nets were released approximately 200 m upstream of the nets.

Radio tagged fish were continually monitored for passage at a fixed location at the Custer public access site approximately 29 km upstream of Pere Marquette lake, the downstream terminus of the Pere Marquette River (Figure 2-1). The

Custer public access site is the location of an electric sea lamprey (*Petromyzon marinus*) barrier that is intended to block the spawning migrations of sea lamprey, and maintain the integrity of salmonine spawning migrations.

Twenty-eight of the 54 radio-tagged steelhead were recorded moving upstream at the Custer monitoring site and were subsequently used in this study. Of the 26 fish not recorded at Custer, seven were recorded moving out of the Pere Marquette River, and the status of the remainder was unknown. Stream temperature was monitored at 90-minute intervals using an Onset HOBO® Temp Logger at the Custer site for the purpose of movement analyses. Stream flow was monitored hourly at a United States Geological Survey flow recording station located in the river in Scottville, Michigan (Figure 2-1).

The Michigan Department of Natural Resources provided me with seven years (1993 to 1999) of steelhead passage data through the fish ladder at Berrien Springs, on the St. Joseph River, Michigan (Figure 2-1). Fish passage was continually recorded over 24 hours using a camera mounted in a viewing window of the fishway, typically beginning on 1 March and continuing through April in most years except in 1999, when fish passage was monitored for a one-week period from 12 through 19 February and resumed again on 1 March, and 1998 and 1997 when monitoring began on 23 and 18 February, respectively. Because of the gap in data collection during the month of February 1999, I only used data that had been collected beginning on 1 March 1999 for purposes of model simulation. Water temperatures were recorded once daily at 8:00 am, 1.2 km below the Berrien Springs fish ladder. Annual fish migrations in the St. Joseph River data ranged from 5,876 steelhead during 1994 to 10,083 steelhead in 1997.

Model Development

Upstream migration begins when exogenous and endogenous conditions are appropriate to stimulate the movement of a few or a group of fish from a source location such as a lake or ocean, into and upstream. The model portrays the passage of fish upstream beyond a detection site to spawning locations based upon changes in water temperature and stream flow, by drawing daily from a population of fish from the source. The source population of fish (N_t) includes individuals that will migrate upstream to the spawning area, but does not include the portion that will remain in the lake and not participate in spawning migrations during the current year. Once upstream migration begins, the source population continually declines until there are no more fish left to move upstream. The number of fish available to move upstream each successive day (N_{t+1}) is determined from the number of fish available to move the previous day (N_t) minus the number of fish passing the detection site. The number of fish passing the detection site varies daily, and is expressed as the number of fish available to move (N_t) times a probability of movement (PM_t). For the purposes of this model, the probability of movement is based upon a function of water temperature alone, or water temperature and stream flow.

The initial model development included water temperature as the exogenous factor upon which movement was based. A time step of one day, which was in accordance with the data collected from the Pere Marquette River study, was used for the simulation. The differential equation representing movement was solved using a fourth order Runga-Kutta integration (Press et al. 1992). Three functions were evaluated as a means to express the relationship between temperature and the probability of upstream movement (PM). These functions represented the general concept that as water temperature increases, fish are more likely to migrate upstream. An assumption of my model is that steelhead will migrate before stream temperatures are warm enough to inhibit upstream spawning migrations. Therefore, the functions I used to depict the probability of movement do not account for a decreasing probability of movement as water temperature increases. The functions explored were:

Exponential function: PM = $ae^{b(T-h)}$

Power function where PM = $a(T-h)^b$

Logistic function where PM = $\frac{1}{[1+e(-b(T-h)+a)]}$

a = rate variable

b = rate variable

T = mean daily water temperature

h = Minimum water temperature threshold for steelhead movement.

The Solver feature in Excel was used to minimize the sum of squared differences between the observed and predicted number moving (RSS: residual sum of squares) by varying the natural log (Log_e) values of h, and the a and b parameters in the migration functions. By varying the natural log values of my model parameters, the model parameters were constrained to positive values. Best-fitting parameter values were determined by performing a non-linear search to minimize RSS. The non-linear search was initiated with several different values to ensure that the search had achieved a global minimum. The functions tested were compared for goodness of fit by evaluating the sum of squared differences between the observed and predicted number of steelhead moving.

After selecting the best fitting function, I examined how the effect of water temperature varied among years for the St. Joseph river data using an F-test based on extra sum of squares (Neter and Wasserman 1974). A TBM model with a set of parameters representing each year (full model) from 1993 to 1999 was compared with a model where one set of parameters was used to represent the data among all years (reduced model).

Approximate standard errors for the model parameters were estimated using a likelihood approach (Ratkowski 1983). The standard errors were approximate because I assumed that my data were normally distributed. The concentrated likelihood for each parameter was calculated according to methods described in Seber and Wild (1989):

$$-\text{Concentrated [Log}_e\text{ Likelihood]} = \frac{\upsilon}{2}\ln\left[\frac{2\pi RSS}{\upsilon}\right] + \frac{\upsilon}{2}$$

υ = n – k degrees of freedom

n = *sample size*

k = *number of model* parameters

RSS = Residual sum of squares.

Standard errors for parameters were calculated by perturbing the "best fit" parameter estimates by 1 percent, and determining the change in the concentrated likelihood. I estimated the standard error of each parameter estimate (i.e., $\sqrt{\text{var}(S_x)}$) from the variance-covariance matrix for the parameter estimates (Ratkowsky 1983):

$$\text{Variance-Covariance matrix} = \begin{bmatrix} s_h^2 & \text{cov}(h,a) & \text{cov}(h,b) \\ \text{cov}(h,a) & s_a^2 & \text{cov}(a,b) \\ \text{cov}(h,b) & \text{cov}(a,b) & s_b^2 \end{bmatrix}$$

Where,

h = Minimum water temperature threshold for steelhead movement

a = rate variable

b = rate variable.

I derived the variance-covariance matrix from the inverse of the *information* matrix (Ratkowsky 1983):

$$\text{Information matrix} = \begin{bmatrix} \frac{\partial^2 L}{\partial^2 h} & \frac{\partial^2 L}{\partial h \partial a} & \frac{\partial^2 L}{\partial h \partial b} \\ \frac{\partial^2 L}{\partial h \partial a} & \frac{\partial^2 L}{\partial^2 a} & \frac{\partial^2 L}{\partial a \partial b} \\ \frac{\partial^2 L}{\partial h \partial b} & \frac{\partial^2 L}{\partial a \partial b} & \frac{\partial^2 L}{\partial^2 b} \end{bmatrix}$$

I estimated the second derivatives numerically for the *h*, *a* and *b* parameters from the following equation:

$$\frac{\partial^2 L}{\partial^2 x} = \frac{\frac{\partial L}{\partial x}}{0.5(x_1 - x)}$$

x = best fitting value for parameter estimate *h*, *a*, or *b* from the TBM model

x_1 = The value of each parameter (*h*, *a*, or *b*) when it is perturbed one percent above the best fitting estimate

$$\frac{\partial L}{\partial x} = \frac{L_1 - L}{x_1 - x}$$

L_1 = concentrated likelihood value when one model parameter (*h*, *a*, or *b*) is perturbed one percent above the best fitting estimate

L = concentrated likelihood value for best fitting parameter values.

The second derivatives for the co-varying parameters were derived from the general equation:

$$\frac{\partial^2 L}{\partial^2 x \partial^2 y} = \frac{L_{x+y} - L}{(x_1 - x) + (y_1 - y)}$$

x = best fitting value for one parameter estimate h, a, or b from the TBM model

x_1 = the value of one parameter (h, a, or b) when it is perturbed one percent above the best fitting estimate (x)

y = best fitting value for one of the two remaining parameter estimates h, a, or b from the TBM model that were not used to determine the (x) value in this equation

y_1 = the value of one of the two remaining parameters (h, a, or b from the TBM model) perturbed one percent above the best fitting estimate (y) that was not used determine the (x) value in this equation.

L_{x+y} = the concentrated likelihood value when two parameters (h, a, or b from the TBM model) are perturbed one percent above the best fitting values.

L = concentrated likelihood value for best fitting parameter values.

The effects of stream flow on migratory behavior were incorporated into the temperature-based movement model (hereafter referred to as TBM model), following initial evaluations of the effect of water temperature alone. In order to determine the qualitative relationship between flow and movement, I examined plots of the residuals from the TBM versus flow. For these models, three

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functions were evaluated to describe the probability of upstream movement (PM) as a combination of stream flow and water temperature. These functions were:

Linear - Power function where PM = $(c(F)+d)(a(T-h)^{b})$

Power - Power function where PM = $(c(F)^{d})(a(T-h)^{b})$

Logistic - Power function where PM = $(\frac{1}{[1+e(-d(F)+c))]})(a(T-h)^{b})$

c = rate variable

d = rate variable

F = stream flow

a = rate variable

b = rate variable

T = mean daily stream temperature

h = Minimum water temperature threshold for steelhead movement.

Because stream flow is affected by the size of the watershed, stream channel width, streambed gradient and other factors, the effect of flow on the probability of movement is likely to vary among watersheds. Therefore, I represented stream flow in the TBM model using the relative deviation from the mean daily flow $(X-\overline{X})/\overline{X}$, where X represents flow and $\overline{X}$ represents the mean seasonal flow. Stream flow data were collected from a United States Geologic Survey (USGS) monitoring station located approximately 8 km downstream of the Custer site, near the Scottville public access site on the Pere Marquette River, and were recorded at a USGS gauging station located approximately 71.6 km upstream of Berrien Springs in Niles, Michigan on the St. Joseph River (Figure 2-1). The Solver feature in Excel was used again to determine the best fitting parameter values, and was determined by the smallest sum of squared differences between the observed and predicted movement.

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Results

The number of fish passing by the Custer monitoring site each day showed a general correspondence to stream flow and water temperature (Figure 4-1). Incidence of higher numbers of fish passing generally occurred when stream flow and water temperature were increasing. However, it is difficult to quantitatively describe movement behavior based on stream flow and water temperature using this figure alone. In the St. Joseph River, few fish migrated upstream early in the migration period when water temperatures were low (Figure 4-2). As water temperatures increased, there were many fish available to migrate and many did. Later in the migrating season when the water temperatures continued to increase and there was presumably a stronger propensity to migrate, fewer fish were moving upstream because there were fewer fish available to move.

Water Temperature

Three functions were compared for their ability to represent the relationship between water temperature and the probability of movement. The power function provided the best fit for the Pere Marquette River telemetry data, and for the St. Joseph River count data for 6 of 7 years, except for 1995 where the exponential function provided the best fit (Table 4-1). The average sum of squared residuals for the power function was substantially smaller than for the exponential and logistic functions for the St. Joseph River data. Using the 1996 St. Joseph River data as a typical example, all three functions predicted trends of fish movement that generally corresponded to periods when steelhead were

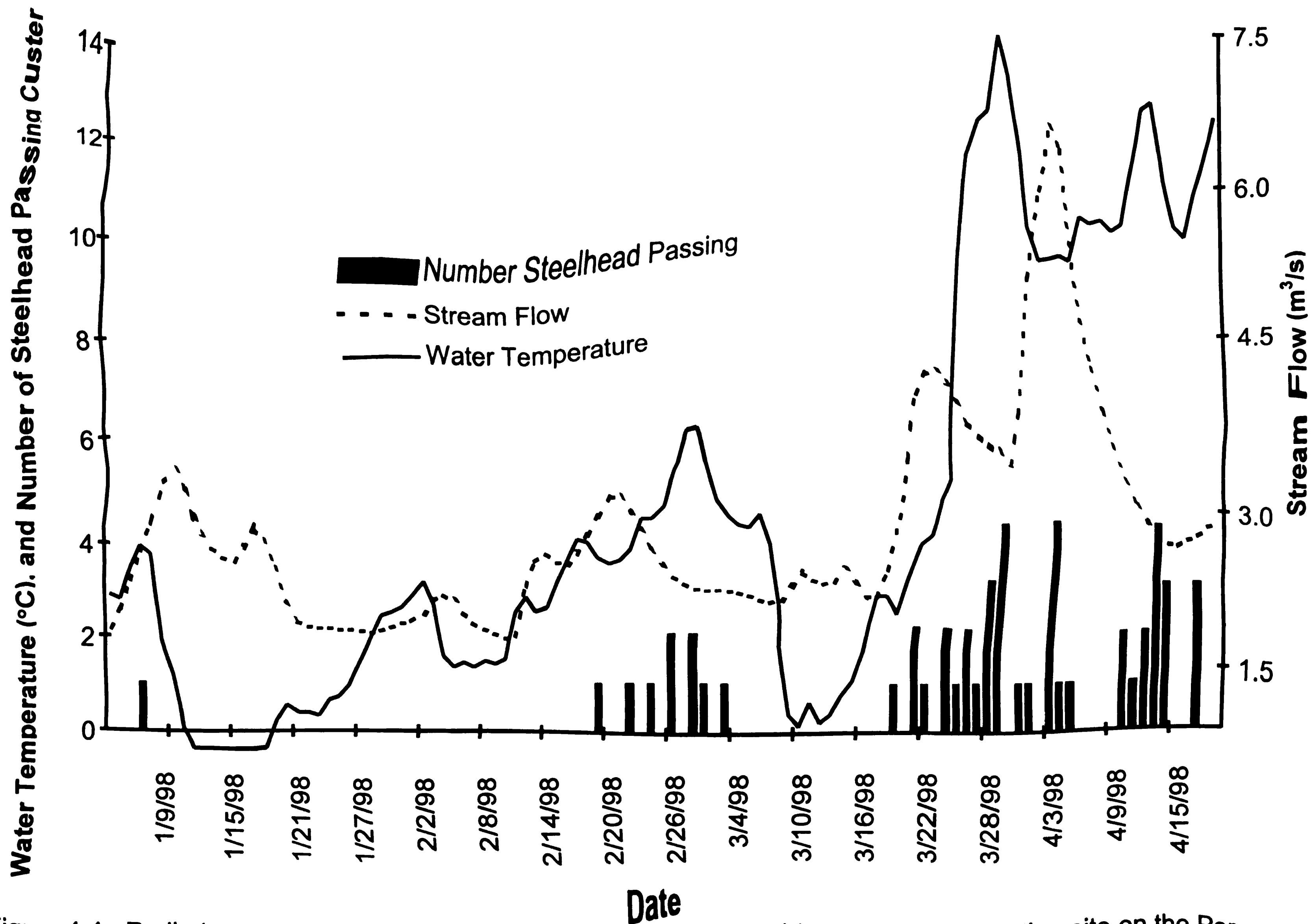

Figure 4-1. Radio-tagged steelhead passage (number/day, solid bars) by the Custer reception site on the Pere Marquette River, Michigan based on the coincident stream flow (m^3/s, dashed line) at the USGS stream flow gauge downstream in Scottville and mean daily mean water temperature (°C, solid line) recorded at the Custer reception site.

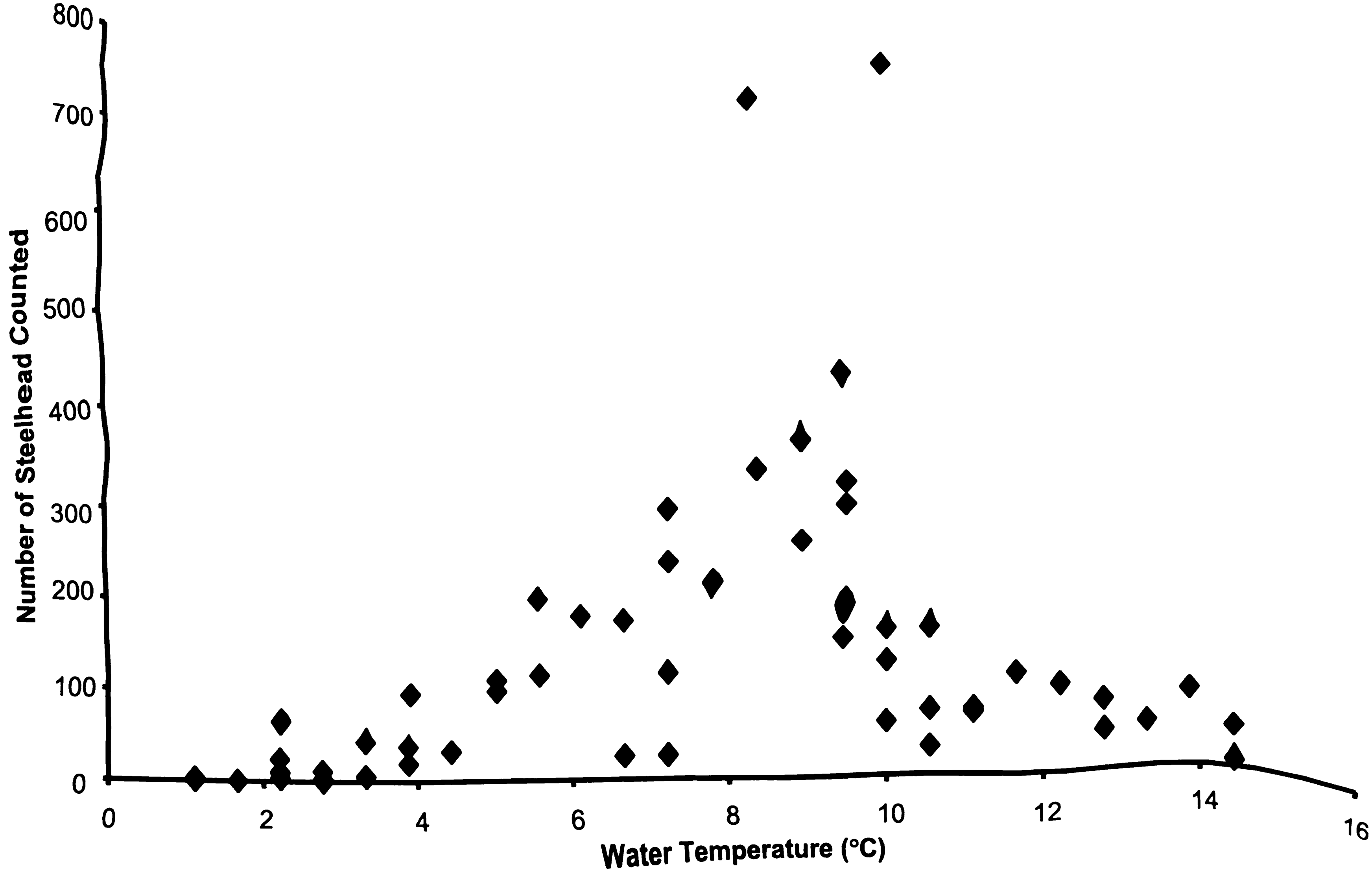

Figure 4-2. The number of steelhead counted using camera-recorded fish passage video during 1993 in relation to *water temperature in the* St. Joseph River, Michigan.

observed to move (Figure 4-3). The observed steelhead movement was variable from day to day, and all three functions did not consistently predict to the extreme maximum and minimum numbers associated with the observed movement. The power function was the best predictor of movement early in the migration period when there was less week-to-week variation in movement, and it consistently did the best job of approximating the observed data. Based on these results, I used the power function for the remaining analyses.

Table 4-1. The sum of squared residual (RSS) values for the power, logistic and exponential form of the temperature-based movement model for the Pere Marquette (1998) and St. Joseph (1993 to 1999) Rivers, Michigan. A low value indicates the best fit for that form of the model and is indicated by an asterisk for each year.

		RSS		
Data Source	**Year**	**Power**	**Logistic**	**Exponential**
Pere Marquette River	1998	21*	23	23
St. Joseph River	1993	232,411*	262,736	290,192
	1994	323,337*	339,036	340,647
	1995	480,621	470,424	470,114*
	1996	369,816*	482,955	518,423
	1997	1,163,361*	1,284,841	1,326,333
	1998	396,918*	607,810	574,139
	1999	582,682*	694,935	694,935
St. Joseph River	**Mean**	**507,021**	**591,820**	**602,112**

The minimum temperature threshold for movement in the St. Joseph River varied from 0.0 °C in 1995 to 6.1 °C in 1996. Across years, the minimum temperature threshold for movement averaged 3.2 °C (Table 4-2). The lowest temperature threshold value (0.0 °C) occurred in 1995 where the logistic (3.4 °C) and the exponential (3.9 °C) functions produced a smaller sum of squares than the power

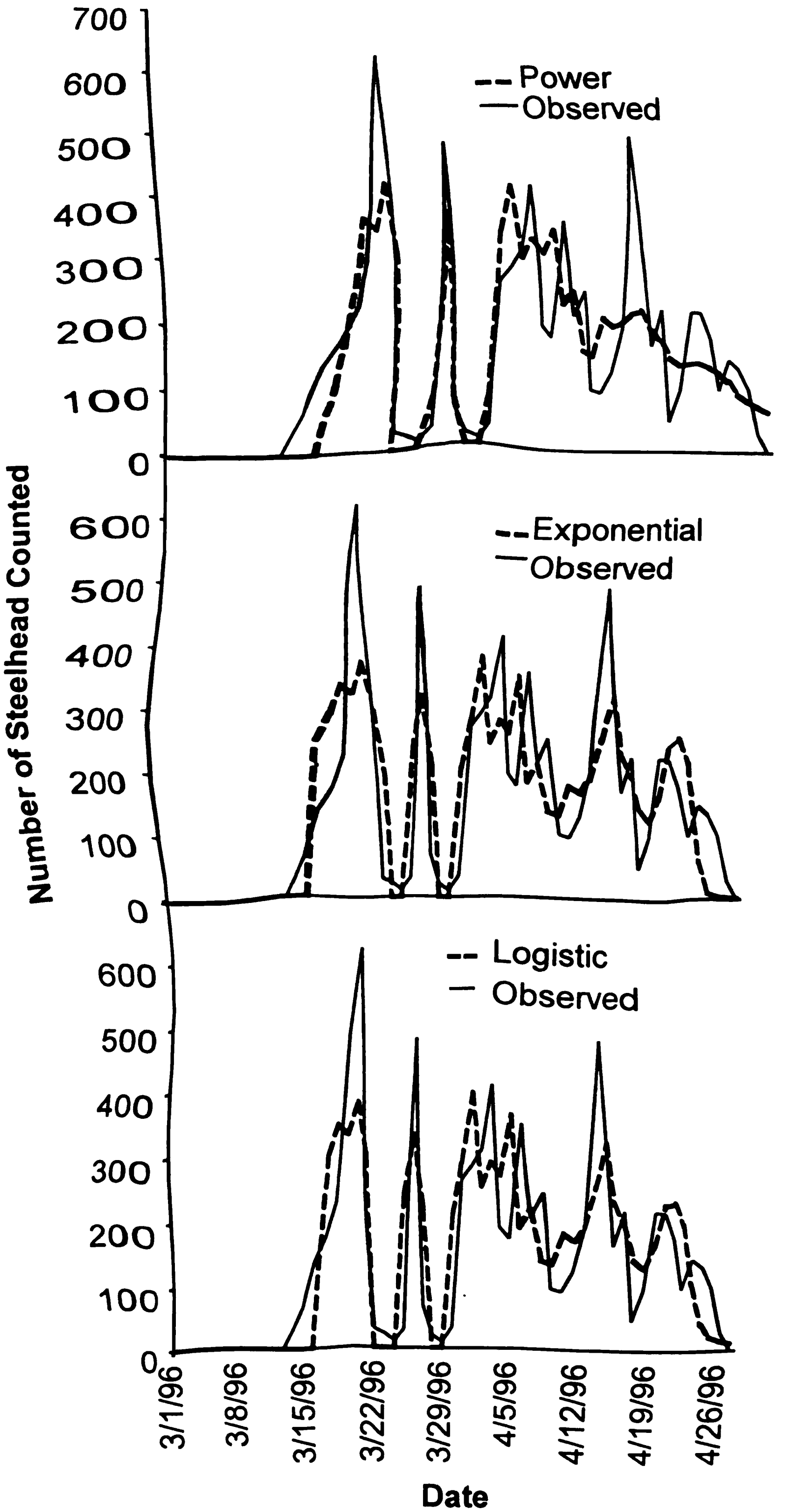

Figure 4-3. Plot of Power, Exponential and Logistic models of temperature-based movement and the observed steelhead movement data in the St. Joseph River, Michigan, 1996.

Table 4-2. Parameter estimates (± 1 standard error) for the power function version of the Temperature-Based Movement model (TBM) for the Pere Marquette River 1998 and St. Joseph River, Michigan 1993 to 1999. The parameter values and approximate standard error estimates for the reduced model (combined 1993 to 1999 St. Joseph River data) that was used in the F test to compare among years for the St. Joseph River data are also included.

		Model Parameters Estimates and Standard Errors		
TBM Model	**Year**	**$T_{empThreshold}$ (°C)**	***a***	***b***
P. M. River	1998	3.2 ± 0.23	0.016 ± 0.0028	0.79 ± 0.072
St. Joseph River	1993	1.6 ± 0.17	0.001 ± 0.0001	2.43 ± 0.031
	1994	4.4 ± 0.07	0.028 ± 0.0029	0.67 ± 0.069
	1995	0.0 ± 0.00	0.001 ± 0.0001	2.35 ± 0.044
	1996	6.1 ± 0.03	0.053 ± 0.0045	0.34 ± 0.068
	1997	3.2 ± 0.24	0.009 ± 0.0012	1.28 ± 0.090
	1998	5.1 ± 0.15	0.018 ± 0.0016	0.98 ± 0.040
	1999	6.1 ± 0.01	0.086 ± 0.0067	0.40 ± 0.037
Reduced Model F test (1993-99)		3.7 ± 0.08	0.011 ± 0.0004	1.25 ± 0.025

function-based TBM model (Table 4-1). The intercept value for the power function (*a*) varied substantially ranging from 0.001 in 1995 to 0.086 in 1996 (Table 4-2). The exponent value for the power function (*b*) also varied substantially from 0.34 in 1996 to 2.43 in 1993. High values of *b* were generally associated with low temperature thresholds and low intercept values (Table 4-2). Despite the variation in parameter estimates, the predicted probability of movement as a function of water temperature for the St. Joseph River was similar most years except 1993 when the probability of movement rose sharply with water temperatures in excess of 10 °C (Figure 4-4).

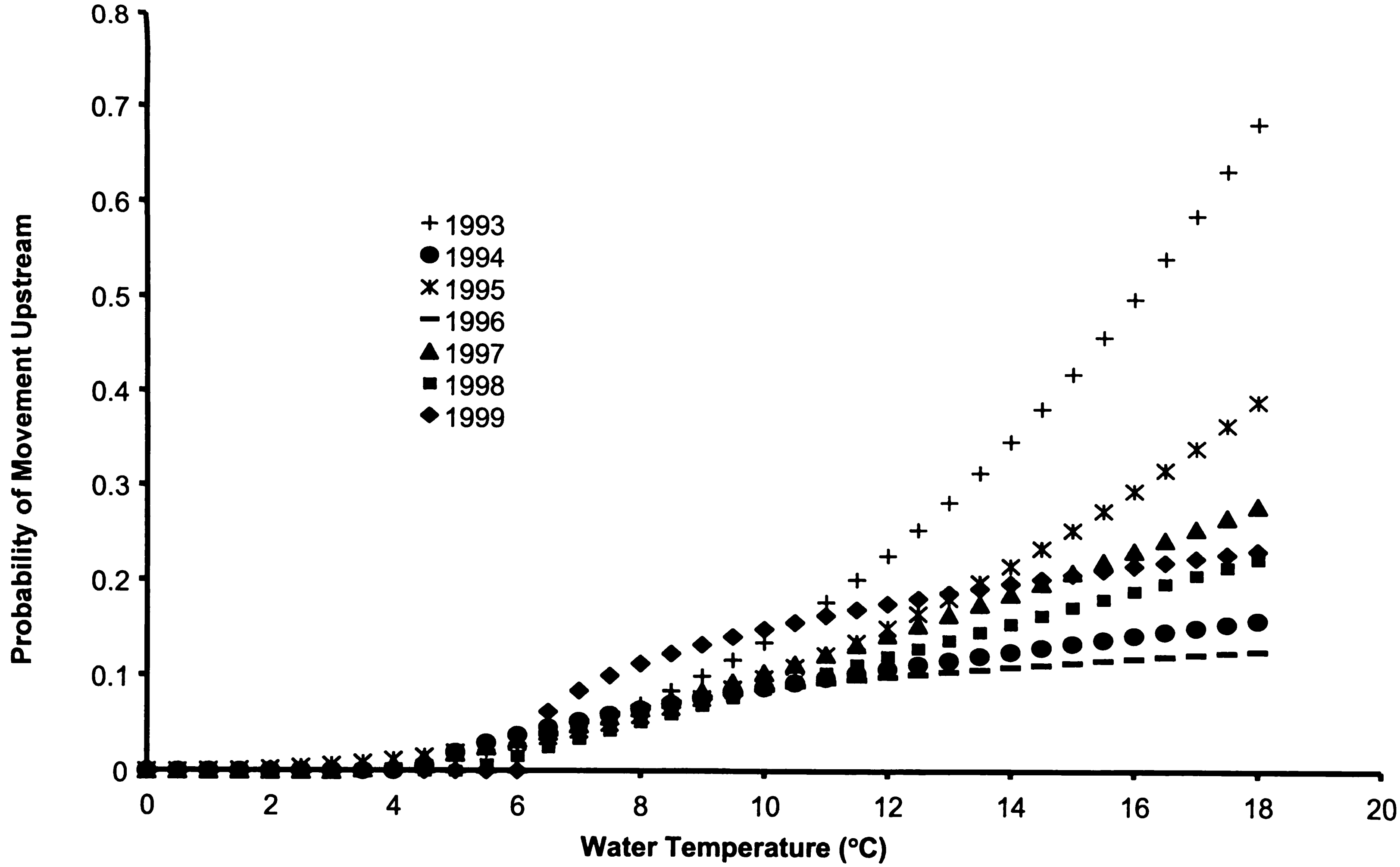

Figure 4-4. Plot of the temperature-based probability of movement curves based on models developed using a power function for the St. Joseph River, Michigan, from data collected from years 1993 to 1999.

A comparison of the RSS for the full TBM model (RSS = 3,549,146) and the reduced TBM model (RSS = 4,336,051) indicated that the parameter estimates for the power function TBM model varied in the St. Joseph River annually ($F_{18,416}$ = 1.57, F_{Calc} = 5.12, $P < 0.001$). The minimum temperature threshold was 3.7 °C for the reduced model from the F test years 1993-99 (Table 4-2).

Water Temperature and Stream Flow

In both the Pere Marquette and St. Joseph Rivers there was generally no relationship between residual errors and flow from the TBM model. This result is illustrated by the results for 1998, which was a typical year (Figure 4-5). The power * power, logistic * power, and linear * power stream flow-water temperature models had the same sum of squared residual values for the Pere Marquette River data and did not result in a substantial improvement in model fit from power function TBM model (Tables 4-1 and 4-3). The average sum of squared residuals for the three stream flow-water temperature functions indicate that the logistic * power function was the best fitting function and was only a slightly better fit than the power * power and logistic * power functions for the St. Joseph River data (Table 4-3). The parameter estimates of the best fitting stream flow-water temperature function (logistic * power) varied from year to year, indicating no consistent effect of flow on movement. Based on these results, additional analyses on the effects of stream flow and water temperature on steelhead migrations were not further considered.

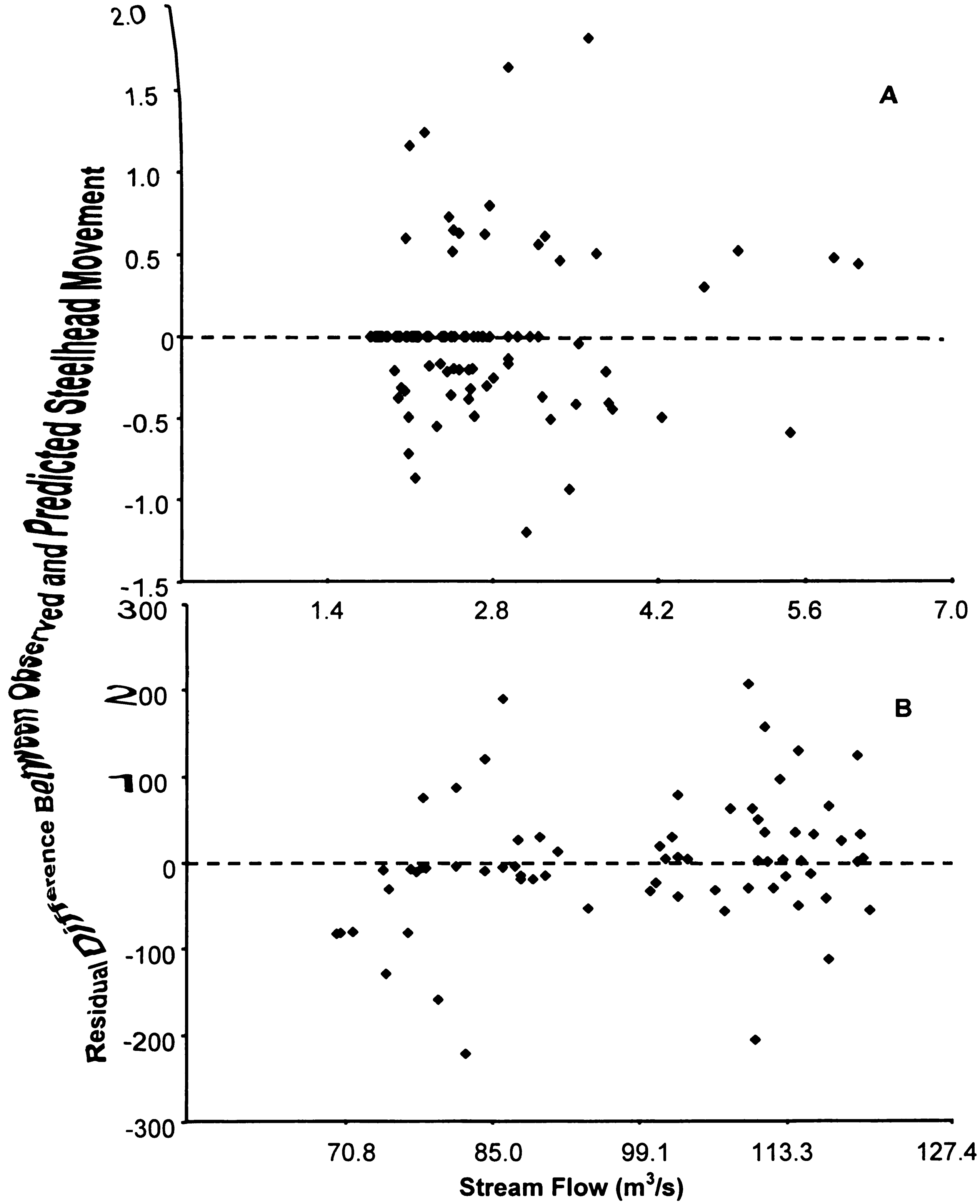

Figure 4-5. The residual plots of the difference between observed and predicted movement using a temperature-based movement model and stream flow for data from the Pere Marquette (A) and St. Joseph Rivers (B), Michigan, 1998.

Table 4-3. The sum of squared residual (RSS) values for the power, logistic and linear function flow-temperature-based movement models, using relative deviation from mean daily flow ($(X - \bar{X})/\bar{X}$) to represent flow for the Pere Marquette (1998) and St. Joseph (1993 to 1999) Rivers, Michigan. A power function was used to describe the temperature portion of the stream flow * water temperature-based function. Power, logistic and linear refer to the flow portion of function used to describe steelhead movement. A low value indicates the best fit for that form of the model and is indicated by an asterisk for each year.

		RSS		
Data Source	**Year**	**Power**	**Logistic**	**Linear**
Pere Marquette River	1998	21*	21*	21*
St. Joseph River	1993	232,411*	232,411*	232,411*
	1994	297,682	284,663*	323,337
	1995	457,889*	459,091	479,475
	1996	396,238	369,816*	369,816*
	1997	1,163,361	1,129,662*	1,134,143
	1998	396,198*	396,853	396,918
	1999	582,682	581,180*	582,682
St. Joseph River	**Mean**	**503,780**	**493,382**	**502,683**

Discussion

Water Temperature

I found the power function-based TBM model was the best fitting model for representing the effect of water temperature on adult steelhead upstream migration in the Pere Marquette and for six of the seven years of the St. Joseph River data. As such, the TBM model serves as a quantitative representation of the migratory behavior of steelhead in relation to water temperature. My model indicated increasing probabilities of upstream movement over a range of water temperatures above the minimum temperature threshold for movement.

The effect of water temperature on fish migration is well studied and varies among systems and species (Banks 1969; Miller 1974; Leggett 1977; Jensen et al. 1986; Jonsson 1991; Lucas and Batley 1996; White and Knights 1997). Steelhead movements have been linked to water temperature during all phases of their life cycle, including upstream spawning migration of adults, downstream movements of juveniles, and distribution of steelhead during their residence in the Great Lakes (Northcote 1962; Banks 1969; Shepard 1972; Haynes et al. 1986; Giorgi et al. 1997). While the upstream movement of adults has been linked to water temperature in some systems, movement has not typically been viewed as occurring over a range of temperatures (Shepard 1972; Miller 1974; Leggett 1977; Jonsson 1991). However, Power (1981) found adult Atlantic salmon (*Salmo salar*) to migrate within a range of temperatures, and also identified a minimum temperature threshold of movement for smolts.

The relation between movement and water temperatures was similar between the Pere Marquette River data and the larger data set from the St. Joseph River. There was an increasing probability of movement associated with increasing water temperatures for steelhead in both systems. The TBM model predicted general trends of movement during periods of observed movement for both rivers. Despite the different data types (radio telemetry and camera count data), and the physical separation (200 km of Lake Michigan shoreline) of the two rivers, the application of the TBM modeling approach to the Pere Marquette and St. Joseph Rivers suggests the possible transferability of this modeling approach to other river systems in the Great Lakes for spring-run steelhead.

While the TBM model predicts the temperature-based migration of steelhead, there are several factors that were not incorporated into the model that may influence steelhead migrations. The TBM model did not generally depict the large day-to-day variability observed in movement for both rivers. Group behavior, where several or many steelhead migrate together upstream at one time may account for the day-to-day variability. Other factors such as neurological and physiological interactions may also account for daily variation in migrations (Leggett 1977; Jonsson 1991). Lorz and Northcote (1965) found that onshore winds and light intensity stimulated river entry by kokanee salmon (*Oncorhynchus nerka*). The winds helped disperse creek odor along the shore, congregate greater numbers of fish in onshore areas. Spending more time in the onshore areas increased the probability of the kokanee salmon locating the river. Other studies suggest high flow or the maturity of the fish may facilitate river entry (Miller 1974; Smith et al. 1994).

The effect of water temperature varied among years 1993 to 1999 in the St. Joseph River. Other factors such as diurnal period may influence the year-to-year variability of the effect of water temperature on steelhead migration.

There are many possible combinations of endogenous and exogenous factors that may stimulate the upstream migration of steelhead. The TBM model demonstrates that we can simplify the complexity of influences on upstream migration by viewing the effect of one exogenous factor (water temperature) on their migratory behavior expressed as an increasing probability of upstream migration with increasing water temperatures once water temperatures increase above the temperature threshold for movement. Previous studies have identified the existence of a threshold for movement based on water temperature for salmonines (Menzies 1939; Power 1981; Jonsson 1991; Jensen et al. 1986). The water temperature threshold serves as a marker between little or no migration and an increasing probability of steelhead to migrate upstream with increasing water temperatures. It is possible that the temperature threshold is a greater barrier to migration earlier in the migratory season when water temperatures are likely to be colder for longer periods of time, than later in the season when the water temperature may drop to or below the threshold for relatively short durations. My TBM model is unique from other movement studies by quantitatively predicting migration behavior over a range of water temperatures and combining the prediction with an identification of a water temperature movement threshold, rather than the qualitative movement description.

The TBM model may work to describe the migratory behavior of other fish that move into rivers for reproductive purposes and time their movements on water temperature and other factors. For example, sea lamprey migrate into Great Lakes tributaries for spawning, and use water temperature as a migratory cue (Morman et al. 1980). Sea lamprey have significantly reduced salmonine game species in the Great Lakes and their impact has resulted in intensive control efforts to reduce their abundance (Smith and Tibbles 1980). If a TBM model is developed for sea lamprey, it could serve to identify the timing of migration and percent passage of sea lamprey into rivers to aid the operators of control structures such as the electric lamprey barriers located on the Pere Marquette River and Jordan Rivers, Michigan (Swink 1999).

Water Temperature and Stream Flow

The combination of stream flow and water temperature did not substantially improve the fit of the TBM model, which was consistent with an examination of the residual distribution of the TBM model compared with stream flow. Jonsson (1991) suggests upstream migration may be a response to a combination of stream flow and water temperature fluctuations. Stream flow and water temperature are important in upstream migration of Atlantic salmon (Power 1981; Jensen et al. 1986). Stream flow has been linked to migratory behavior in other salmonid populations (Ellis 1962; Alabaster 1970; Shepard 1972; Power and McCleave 1980; Smith et al. 1994). Both rivers typically do not exhibit drastic fluctuations in stream flow during steelhead migration that are likely to affect their ability to successfully migrate and subsequently affect their migratory behavior. Therefore, the range in flow and flow fluctuation may have been insufficient to detect how migration would vary in response to flow in streams exhibiting greater variation in flow.

Stream flow is characterized by many factors including, watershed size, streambed morphometry, surrounding topography, weather patterns, groundwater input and others (Bras 1990). Hellawell et al. (1974) found that stream flow and water temperature were secondary to the effect of time-of-year or season on migratory behavior. Shepard (1972) found that stream flow and water temperature are important in steelhead migration, but their influence varies from system to system. Trepanier et al. (1996) found stream flow to be important and water temperature to have little effect on the migratory movement of Atlantic salmon. Stream flow is likely to be a greater factor in steelhead migrations in watersheds that experience drastic changes in flow that may promote movement by creating an avenue of passage over barriers that are typically impassable at low water periods, or inhibit movement during high flows that are strong enough to prohibit upstream movement. In rivers with small fluctuations in water levels, water temperature is important in stimulating upstream migration (Jonsson 1991). The response of steelhead migratory behavior to stream flow is likely to be different among watersheds and difficult to consistently represent in models among different streams or steelhead populations with different life histories. Jonsson (1991) suggests different behavior in different rivers may occur because there is a hierarchy of environmental factors initiating migrations, or the fish adapt the timing of migration to different factors in different rivers.

In conclusion, I developed a new approach to analyzing upstream adult steelhead migrations using a temperature-based movement model that quantitatively predicts the migratory behavior of steelhead over a range of water temperatures. The TBM model demonstrates an increasing probability of movement over increasing stream temperatures for temperatures greater than the threshold of movement temperature. The TBM model predicts migratory behavior in two Lake Michigan tributaries that differ in size, location and other factors. The transferability of the model to the two different tributaries suggests that the modeling approach is broadly applicable and may work well in other Great Lake tributaries and possibly other rivers that receive spawning migrations of steelhead that rely on water temperature as a cue for movement. The TBM model works well for steelhead and can be a useful management tool by predicting of the migratory behavior of nuisance species such as sea lamprey and by synthesizing fish passage data to provide predictive migratory behavioral information on other species of fish.

CHAPTER 5

The spawning habitat selection of steelhead in the Pere Marquette River, Michigan

Abstract

I evaluated features (groundwater, substrate particle size, etc...) associated with the selection of steelhead (*Oncorhynchus mykiss*) spawning habitat in the Pere Marquette River, Michigan 1997 to 1998. Steelhead redds were evaluated for the presence of groundwater using GIS-based groundwater prediction model and another method based on intragravel temperature. In addition to groundwater, microhabitat-scale features associated with the redds (i.e., substrate particle size, redd depth, stream velocity above redds) were evaluated among redd and reference (non-redd locations) data to determine their importance to steelhead spawning habitat selection. The GIS model and probe-based evaluation were inconclusive as a means to identify groundwater associated with steelhead redds during the spring. Steelhead preferred to construct redds in a substrate consisting of small gravel, large gravel, and small cobble particle sizes disproportionately to clay, silt, sand, and large cobble. Steelhead redds were located in areas where the stream velocity was significantly higher ($F = 97.77$, $P < 0.0001$) than velocities that were recorded at reference sites, and redds were located in water that was significantly shallower than what was typically found in the study reaches ($F = 113.84$, $P < 0.0001$). Stream temperature did not appear to influence the selection of redd locations. Although the groundwater data were inconclusive, the microhabitat data can be used to identify specific areas in the Pere Marquette River that may serve as steelhead spawning habitat as part of habitat improvement projects that commonly occur throughout the watershed.

Introduction

Spawning habitat characteristics such as substrate particle size, spawning site water depth and stream velocity of steelhead (*Oncorhynchus mykiss*) spawning sites and other Pacific Coast salmonids such as sockeye (*O. nerka*) and pink salmon (*O. gorbuscha*), are well known (Cooper 1965; Kogl 1965; Smith 1973; Fukushima and Smoker 1998; Groves and Chandler 1999). However, spawning habitat information about Great Lakes steelhead is scarce. In addition, little is known about the influence of groundwater on the selection of spawning habitat by steelhead in the Great Lakes and Pacific Coast regions.

Groundwater is important to the reproductive success of the brook trout (*Salvelinus fontinalis*) and chum salmon (*O. keta*) by protecting eggs from ice and infiltrating surface water (Kogl 1965; Fraser 1985; Curry and Noakes 1995; Curry et al. 1995), and may be important to reproductive success of steelhead by providing more stable flows and a thermal refuge to developing alevin from warm water in the summer (Shepherd et al 1986). Locations where groundwater is abundant in a river may be preferred by steelhead as spawning areas. Identifying groundwater locations within a river system where steelhead reproduce could provide insight to the importance of groundwater and its role in the selection of steelhead spawning sites.

There are several approaches that are typically used for detecting groundwater within river systems. Piezometers are used to detect intragravel water movements and the presence of groundwater (Lee and Cherry 1978; Sowden and Power 1985; Curry and Noakes 1995; Curry et al. 1995). Because the installation and monitoring of piezometers is a time-consuming process, most studies where piezometers are used tend to evaluate small-scale (site specific) groundwater flows rather than flows within a watershed or portions of a watershed (White 1990; Curry et al. 1995; Curry and Noakes 1995).

Intragravel water temperatures can be monitored and compared to stream temperatures to determine the presence or absence of groundwater (White et al. 1987; Silliman and Booth 1993). The thermal regimes of intragravel and stream water can be influenced by groundwater, infiltrating surface water, and solar heating effects. The degree of interaction between the stream and intragravel water influences the water temperature in both environments and may depend on the flow rate, turbulence, gradient, and other factors such as substrate composition (Shepherd et al 1986). To accurately assess the presence of groundwater, water temperature is usually monitored over an extended period (e.g., one year) via data loggers or periodic visits to sample locations (Silliman and Booth 1993). Detecting groundwater by monitoring water temperature can provide information about larger areas of river than piezometer-based studies, because the data collection process tends to be less labor intensive.

Another approach is to evaluate groundwater areas based on predictions from a model. A Geographical Information System (GIS) groundwater model was used to predict areas of groundwater accumulation within the landscape based on surficial geology and digital elevation data within the Great Lakes region (Baker et al. 2000). The groundwater model provided a coarse-scale ($100\ m^2$) landscape prediction of groundwater accumulation within watersheds. The GIS-based groundwater data are readily available without collecting additional field measurements, making it possible to link the groundwater information with steelhead spawning data.

The primary goal of my study was to gain a better understanding of steelhead spawning habitat use in a tributary of Lake Michigan. Identifying groundwater areas in relation to steelhead spawning locations may help determine if groundwater is an important feature of steelhead spawning habitat selection. Because I evaluated steelhead spawning habitat throughout a watershed, I used water temperature monitoring and a GIS groundwater model as surrogates of piezometers to provide evidence of groundwater presence. One objective of my study was to determine if steelhead selected spawning habitat where groundwater was abundant within a stream. I also evaluated the use of water temperature and a GIS model as tools to examine the presence of groundwater.

Groundwater is not the only factor that may influence the selection of spawning habitat by steelhead. Groundwater is low in oxygen and can inhibit the development of embryos (Cooper 1965; Fraser 1985). Spawning site (redd) formations can improve convective patterns and the delivery of oxygenated water to the redd within groundwater areas, and promote convective flow patterns in areas where intragravel flows via groundwater supplies and advective flows are limited or not available (Cooper 1965; Curry and Noakes 1995).

The substrate particle composition of redds vary widely among steelhead and other salmonids (Olsen 1968; Neilson and Banford 1983). However, the substrate particles must be large enough and adequately sorted to accommodate alevin emergence; the substrate must consist of a movable porous material such as gravel so that a female can excavate the redd; and the redd must be located or shaped in a way that promotes the movement of oxygenated water through the redd (Cooper 1965; Fraser 1985; Sowden and Power 1985).

Because water movement (stream flow and intragravel) and substrate composition influence the reproductive success of steelhead, they may influence the selection of spawning habitat by Pacific Coast steelhead and other salmonids (Smith 1973; Fukushima and Smoker 1998; Groves and Chandler 1999), and may influence the selection of spawning habitat by Great Lakes steelhead. Another objective of this study was to evaluate microhabitat-scale features associated with the redds (i.e., substrata particle sizes, redd depth, stream velocity above redds). Specifically, I evaluated the use of microhabitat-scale features in relation to their availability within selected reaches of river. Identifying habitat features that are important to steelhead spawning site selection in a Great Lakes tributary can be used to identify other areas within the river that may be

used by spawning steelhead, or possibly could be modified to accommodate steelhead.

Methods

Sample Locations

The Pere Marquette River is located in west-central Michigan (*Figure 2-1*). Sample reaches (1-2 km reaches) where the bottom was readily observed and the stream was accessible (public access, boat launches, and access permission from riparian landowners) were identified within the Pere Marquette River (Figure 5-1). Five study reaches were randomly selected and sampled in 1997 and 1998, and nine were randomly selected and sampled in 1999. I attempted to collect data from each site between 10:00 and 14:00 hours when the daylight was the greatest intensity to optimize the visual detection of redds. Redds were identified by areas where there was evidence of excavated substrate free of debris, typically shaped with a conical depression in the center, and occasionally by the presence of spawning steelhead. Redds with fish tending them were recorded as active and redds without steelhead present were considered as suspected steelhead redds. The location of the redds with respect to the river channel (river-left, mid-channel, and river-right) were noted, and with respect to run, riffle, and pool habitat types (Hicks and Watson 1985).

Stream temperature, intragravel temperatures, mean column stream velocity, depth of water above each redd, and substrate particle size composition data were collected at each redd. Water temperature was measured using a Yellow Springs Instrument Company (YSI), Inc.™ meter at most redds. For reaches with high redd density, I sampled every fifth redd. Mean column stream velocity, and

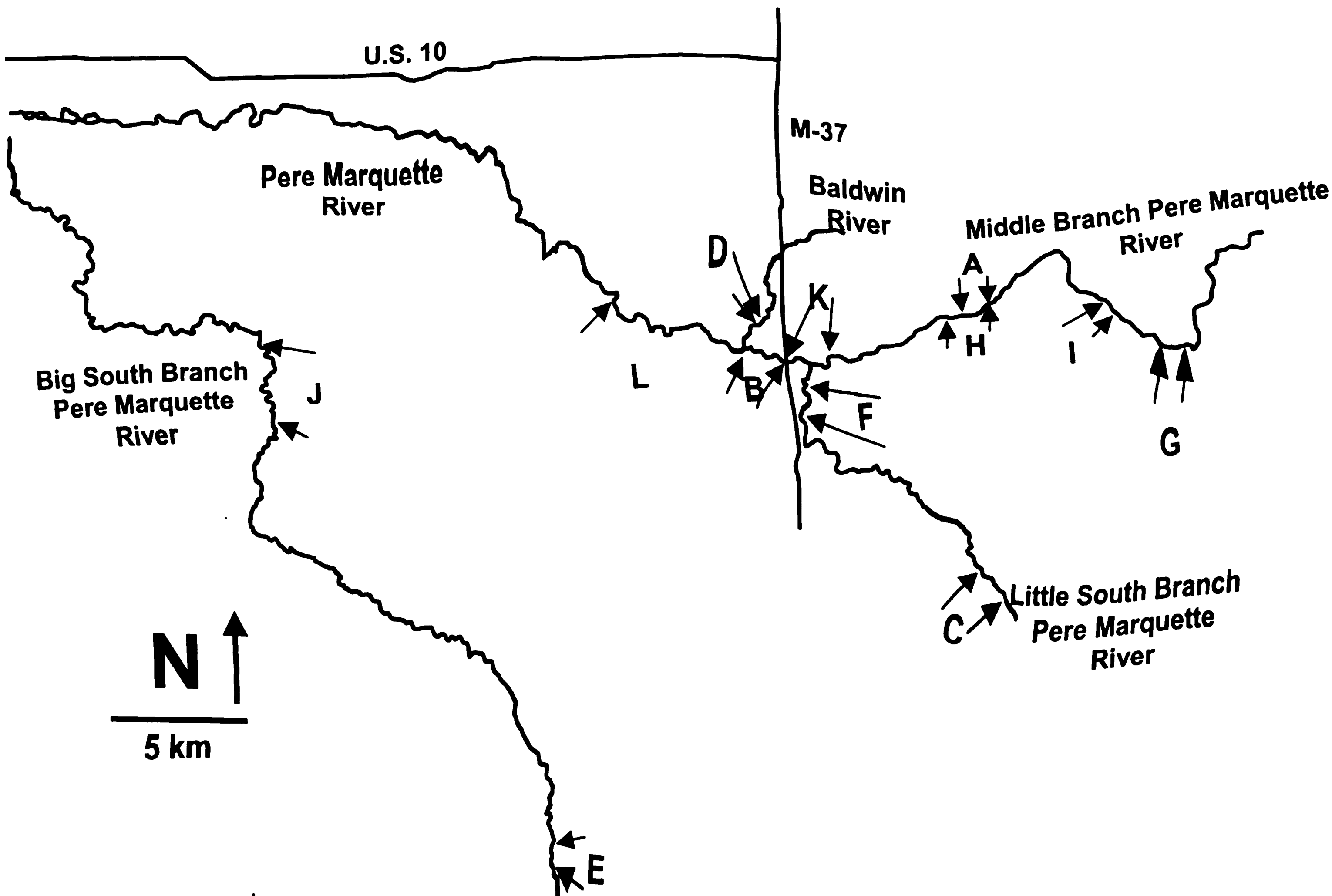

Figure 5-1. Stream reach segments in the Pere Marquette River, Michigan for 1997 through 1999. Arrows indicate approximate study reach extents (A through M). Note: the upstream extent of reach *L is M-37.*

water depth at the measured redds were recorded using a Price AA meter and wading rod. Stream discharge data were obtained from the U.S. Geological Survey gauge station, located in the river at Scottville (Figure 2-1). Intra-gravel temperature was measured in 1998 and 1999 using a YSI series 400, 95-cm long stainless steel temperature probe and thermister. Intragravel measurements were taken at depths of 5, 10, 20, 30, 40, and 50 cm into the substrate at each redd for 1998. All redd measurements were taken in an area that was assumed to be the egg depositional zone, or approximately one-third of the distance between the deepest point of the redd depression, and the downstream edge of the redd.

Substrate particle size composition was visually estimated within a 1 m area centered on the egg depositional zone for each sample site using a modified Wentworth (1922) classification (Table 5-1). The large and small cobble particle size classes were combined during the 1997 sampling and were differentiated during the 1998 and 1999 sampling.

Table 5-1. Particle size classes that were used to classify substrate particle sizes of sample sites in the Pere Marquette River, Michigan 1997-1999.

Particle size description	Particle size
Clay	0.00024-0.004 mm
Silt	0.04-0.062 mm
Sand	0.065-1 mm
Small gravel	1-8 mm
Large gravel	8-64 mm
Small cobble	64-128 mm
Large cobble	128-512 mm

Reference data from non-redd locations (the same information that was collected from redds) was collected within each site for the 1998 and 1999 data, and there were approximately 10 reference locations per kilometer of study reach. Reference locations were equally spaced from each other and alternated from river left (RL) to mid-channel (CH) to river right (RR) locations in a downstream direction (Figure 5-2).

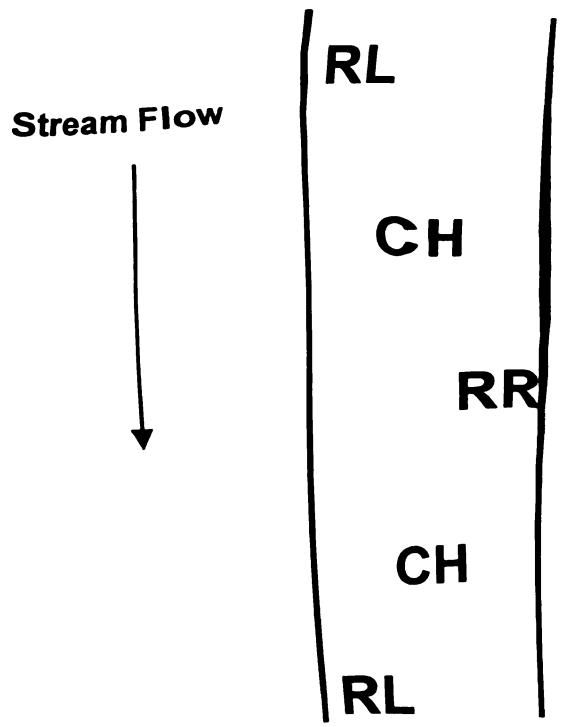

Figure 5-2. Reference sample site configuration where RL indicates river-left, CH indicates channel, and RR indicated river-right.

Groundwater Evaluation

Spawning areas were evaluated based upon the number of redds/m^2 corresponding to the relative area of categorized groundwater flows at 25, 50, and 100-m distance-from-the-river intervals and the groundwater flow values immediately adjacent to the river to determine if the distance from the river influenced the groundwater predictions among stream reaches. The groundwater flow predictions were referenced to distance intervals using Arc View version 3.2 geographical information system software. A correlation analysis of the flow values for each distance interval was performed using Statistical Analyses Software (SAS v8.0) to determine if there were significant correlations among reported flows at each distance interval.

GIS-based predictions

To determine if steelhead redds were linked to areas of groundwater input in the Pere Marquette River, redd data were linked to groundwater accumulation predictions from a model based on surficial geology, digital elevation and Darcy's Law of groundwater flow (Baker et al. 2000). Groundwater predictions varied within each study reach. The Darcy groundwater predictions were categorized as high (1.5 to 3 standard deviations from the mean groundwater potential), medium (0 to 1.5 standard deviations from the mean groundwater potential), and low flows (0 to –1 standard deviations from the mean groundwater potential) from the model predictions to unify the prediction within each stream reach for comparative purposes.

A Mixed-General Linear Model (Littell et al. 1996) was also used to evaluate redd density among study reaches and groundwater predictions. Redd density was evaluated according to the following model:

$$y = \mu + \alpha_i + \beta_j + \gamma_{i,j} + \eta_k + e$$

Where,

y = redd density by year and dary flow prediction

μ = model intercept

α_i = year (fixed effect)

β_j = darcy flow prediction (low, medium, or high flow), fixed model effect

$\gamma_{i,j}$ = interaction parameter

η_k = study reach (random effect with mean zero and σ^2_η)

e = model error.

Probe-based predictions

A Mixed-General Linear Model (GLM) was used to evaluate water temperatures in the stream and intragravel portions of redd and reference site among study reaches. Least square means (Littell et al. 1996) were used to determine where significant differences occurred. The following model was used to evaluate water temperature in the intragravel environment and stream:

$$y = \mu + \alpha_i + \beta_j + \zeta_l + \gamma_{i,j} + \iota_{i,l} + \kappa_{j,l} + \eta_k + e$$

Where,

y = water temperature (intragravel and stream) by year, temperature probe depth, and sample location

μ = model intercept

α_i = year (fixed effect)

β_j = depth of temperature sample (fixed effect)

ζ_l = sample location (fixed effect)

$\gamma_{i,j}$ = interaction between year and depth of temperature sample

$\iota_{i,l}$ = interaction between year and sample location

$\kappa_{j,l}$ = interaction between depth of temperature sample and sample location

η_k = study reach (random effect with mean zero and σ_η^2)

e = model error.

According to Silliman and Booth (1993), a stream reach is considered to be neutral with respect to gaining groundwater or losing stream water to the sediments in stream reaches where the stream temperature is significantly warmer than the intragravel temperature, and the intragravel temperature fluctuates daily. A stream reach where the intragravel temperature is stable and cooler than the stream temperature is considered to gain groundwater, and a stream reach where the intragravel and stream temperature fluctuate over a daily cycle and are not significantly different are considered to lose stream water into the sediments.

Although Silliman and Booth (1993) monitored water temperature at 1 hr intervals over 25 days in their study, I monitored intragravel and stream temperatures within each stream reach approximately 4 hours, or the time it took to sample the redd and reference sites within each reach. Groundwater presence in each stream reach was determined according to the mean difference between the intragravel temperature at each depth and stream temperature. Stream reaches where the mean difference between the intragravel and stream temperature was negative were considered as high groundwater upwelling areas. Stream reaches where the mean difference between the intragravel and stream temperature was positive were considered as low groundwater upwelling areas, and stream reaches where the mean difference was near zero were considered as medium groundwater upwelling areas.

A Mixed GLM was used to investigate the relationship between redd density and intragravel probe-based groundwater predictions among study reaches. Redd density was evaluated according to the following model:

$$y = \mu + \alpha_i + \beta_j + \gamma_{i,j} + \eta_k + e$$

Where,

y = redd density by year and probe-based predictions (low, medium, or high flow), at 5, 10, 20, 30, 40, and 50 cm

μ = model intercept

α_i = year (fixed effect)

β_j = probe-based prediction (fixed model effect)

$\gamma_{i,k}$ = interaction parameter

η_k = study reach (random effect with mean zero and σ^2_η)

e = model error.

Redd Characteristics

Substrate particle size distributions were compared for year-to-year (1997, 1998, and 1999), and reference and redd site differences (1998 and 1999) using the *Kolmogrov-Smirnov two-sample* test statistic (Berry and Lindgren 1996). *Vanderploeg and Scavia's* electivity index (E_i) was used to compare steelhead redd substrate use with reference site substrate data (Vanderploeg and Scavia 1979):

$$E_i = \frac{[W_i - (\frac{1}{n})]}{[W_i + (\frac{1}{n})]} \qquad \text{Where,} \qquad Wi = \frac{r_i / p_i}{\sum r_i / p_i}$$

Where,

ri = the proportion of observations of particle size I in the redd substrate composition

pi = the proportion of observations of particle size I in the reference site substrate composition

n = the number of particle size categories.

The index ranges from +1 to –1. A positive value of E_i indicates a larger proportion of the substrate particle size in the redd than is found in the stream reaches. A negative value of E_i indicates a particle size was used less than was available in the stream reaches. A value of 0 indicates a particle size was used in proportion to availability within the stream reaches.

A Mixed GLM was performed on stream velocity, water depth, and water temperature, to examine differences among years, channel locations, study reaches, and between sample locations (redd and reference sites). Least square means (Littell et al. 1996) were used to determine where significant differences occurred. The following model was used to evaluate stream velocity, water depth, or water temperature:

$$y = \mu + \alpha_i + \beta_j + \zeta_l + \gamma_{i,j} + \iota_{i,l} + \kappa_{j,l} + \eta_k + e$$

Where,

y = stream velocity, water depth, or water temperature by year, channel location, and sample location

μ = model intercept

α_i = year (fixed effect)

β_j = channel location (fixed effect)

ζ_l = sample location (fixed effect)

$\gamma_{i,j}$ = interaction between year and channel location

$\iota_{i,l}$ = interaction between year and sample location

$\kappa_{j,l}$ = interaction between channel location and sample location

η_k = study reach (random effect with mean zero and σ_η^2)

e = model error.

A General Linear Model was used to evaluated differences among years of stream flow data that were recorded at the Scottville USGS gauging station. The Tukey-Kramer pairwise comparison was used to determine where the significant differences occurred.

$y = \mu + \alpha_i + e$

y = discharge recorded at the USGS gauging station in Scottville, Michigan

μ = model intercept

α_i = year

e = model error.

All tests were conducted using $\alpha = 0.05$.

Results

I recorded steelhead redd and reference data from 15 April to 24 April 1997, 15 April to 23 April 1998, and 28 March to 17 April 1999. I observed the greatest redd density (68 redds/ha) in section C (Figure 5-1) during 1999, and the lowest redd density (0 redds/ha) in section E during 1999 (Table 5-2). Redd densities did not vary significantly among years ($F = 0.19$, $P = 0.84$).

Table 5-2. Redd density by stream reach for 1997, 1998, and 1999 in the Pere Marquette River, Michigan.

Year	Stream Reach	Darcy Flow	Redd density (numbers/ha)	Number of Redds
1997	A	High	58.0	37
	C	Medium	26.0	57
	D	Low	61.0	53
	J	High	0.3	4
	L	Medium	5.0	100
1998	A	High	36.0	23
	B	Low	7.0	59
	C	Medium	35.0	76
1999	B	Low	9.0	72
	C	Medium	68.0	149
	E	Low	0.0	0
	F	Low	30.0	72
	G	High	3.0	4
	H	High	4.0	7
	I	Medium	22.0	17
	K	Low	0.3	1

Groundwater

GIS-based predictions

I performed a correlation analysis to evaluate the groundwater flow (as indicated by the Darcy flow model) at the 0, 25, 50, and 100-m distance-from-the-river intervals. Correlations between distance intervals were highly significant (*P* < 0.001) indicating that any of the intervals would be adequate to use in further analyses. Because the correlation coefficients varied little (Table 5-3) and all were significantly correlated, I used the Darcy area estimates from the 0 m category for the additional analysis.

Table 5-3. Correlation coefficients for 0 to 100 m categories of Darcy flow area estimates in study areas from the Pere Marquette River, Michigan.

Category (*n* = 13)	0 m	25 m	50 m	100 m
0 m	1.000	0.986	0.986	0.971
25 m	0.986	1.000	0.997	0.991
50 m	0.986	0.997	1.000	0.993
100 m	0.971	0.991	0.993	1.000

Because of the lack of multiple representatives in each Darcy flow class (low, medium, and high flow) in the 1997 and 1998 data, the test for interaction between year and Darcy flow effects was not possible. Redd density was not significantly different among years ($F = 0.10$, $P = 0.91$) and Darcy flows ($F = 0.14$, $P = 0.88$).

Probe-based predictions

There was no consistent relationship between water temperature, probe depth, redd and reference sites, and years. There were no significant differences between intragravel temperatures of redd and reference sites ($F = 0.04$, $P = 0.84$). However, intragravel water temperatures were significantly different among probe depths ($F = 58.88$, $P < 0.0001$) and years ($F = 520.53$, $P < 0.0001$).

There were significant interactions between redd and reference sites and years ($F = 5.39$, $P = 0.02$), and water temperature at all probe depths ($F = 4.53$, $P <$ 0.0001), and between years and water temperature at all probe depths ($F =$ 10.42, $P < 0.0001$).

Because of the limited availability of temperature probe data at depths greater than 10 cm, the following analyses evaluated intragravel water temperatures at 5 and 10 cm. The mean difference between intragravel temperatures measured at 5 and 10 cm into the substrate and stream temperatures, ranged from –1.6 to 1.0 °C among depths and stream reaches (Table 5–4). Study reaches with a mean difference between the intragravel and stream temperature (ΔT) that ranged from –1.7 to –0.7 °C were categorized as high, and study reaches with a mean difference that ranged from 0.29 to 1.1 °C were categorized as low with respect to groundwater presence throughout the reach. Study reaches with a mean difference between the intragravel and stream temperature that ranged from – 0.69 to 0.2 °C were categorized as medium.

All probe-based predictions were high among study reaches in 1998 and were not consistent among probe depths in 1999. Probe-based predictions were not consistent among study reaches (e.g., study reach B) and years, and were not consistent with the GIS-based groundwater predictions (Table 5-4). Because of unbalanced data, the evaluation of redd density and probe predictions was not possible.

Table 5-4. The mean difference (ΔT ± standard error) between intragravel temperatures measured at 5 and 10 cm into the substrate and stream temperatures, and the probe-based and Darcy groundwater flow predictions in the Pere Marquette River, Michigan study reaches 1998 and 1999.

Year	Study Reach	Darcy Flow	Mean ΔT (°C) 5 cm	Mean ΔT (°C) 10 cm	Probe prediction 5cm	Probe prediction 10cm
1998	A	High	-1.1 ± 0.10	-1.2 ± 0.15	High	High
	B	Low	-0.8 ± 0.13	-1.0 ± 0.18	High	High
	C	Medium	-0.8 ± 0.13	-1.0 ± 0.18	High	High
	J	High	-1.3 ± 0.40	-1.5 ± 0.12	High	High
1999	B	Low	1.0 ± 0.24	0.8 ± 0.26	Low	Low
	C	Medium	-0.7 ± 0.14	-1.0 ± 0.17	High	High
	E	Low	-1.2 ± 0.11	-1.5 ± 0.14	High	High
	F	Low	-0.6 ± 0.27	-1.6 ± 0.35	Medium	High
	G	High	-0.4 ± 0.10	-0.5 ± 0.12	Medium	Medium
	H	High	0.3 ± 0.12	0.7 ± 0.15	Low	Low
	I	Medium	-0.6 ± 0.10	-0.9 ± 0.09	Medium	High
	J	High	0.0 ± 0.19	-0.1 ± 0.20	Medium	Medium
	K	Low	-0.4 ± 0.05	-0.1 ± 0.08	Medium	Medium

Substrate Particle Size

Steelhead did not appear to construct redds in areas with larger particle sizes. I did not observe the small-boulder particle size (256-512 mm) and larger particle sizes (> 512 mm) in redds. I observed large cobble in 6% of redds sampled in 1998 and 1999 (n = 219). Although large particle sizes were more frequently sampled (10% of the samples) in the 1998 and 1999 reference sites (n = 249), larger particles were not common within the study reaches.

Steelhead also avoided smaller particles such as silt and clay occurring in redds. I did not observe silt and clay in any of the active and suspected redd samples, and silt was observed at an average of 3% (1999) and 0.8% (1998) in the reference samples. I observed clay at an average of 0.7% and 0% in the reference samples.

I evaluated the substrate particle size distributions among active and suspected redds, reference sites, and sample years using the Kolmogorov-Smirnov test. The particle size distributions of active and suspected redd locations were not significantly different (*P* > 0.27, for each year) for 1997 to 1999. Thus, I combined the active and suspected redd data from each sample year for further particle size analyses. The particle size distributions of redd (active and suspected) and reference sites were significantly different in 1998 (*P* < 0.001) and 1999 (*P* < 0.001). In 1998 and 1999, steelhead redds were associated with larger particle sizes than reference sites within the study reaches (Figure 5-3), and did not select locations with silt or clay.

The 1998 and 1999 redd substrate data (large cobble was differentiated from small cobble) were not significantly different (*P* = 0.186), and neither were the 1998 and 1999 reference data (*P* > 0.27). The combined 1998 and 1999 redd particle size distributions were not significantly different between run and riffle habitats (*P* > 0.27). I did not observe redds in pool habitat (Table 5-5). I observed pool habitat in 15 reference samples over two years (Table 5-5). The combined 1998 and 1999 reference site particle size distributions were not significantly different among habitat types (*P* = 0.22 for run vs. riffle, *P* > 0.27 for all other combinations).

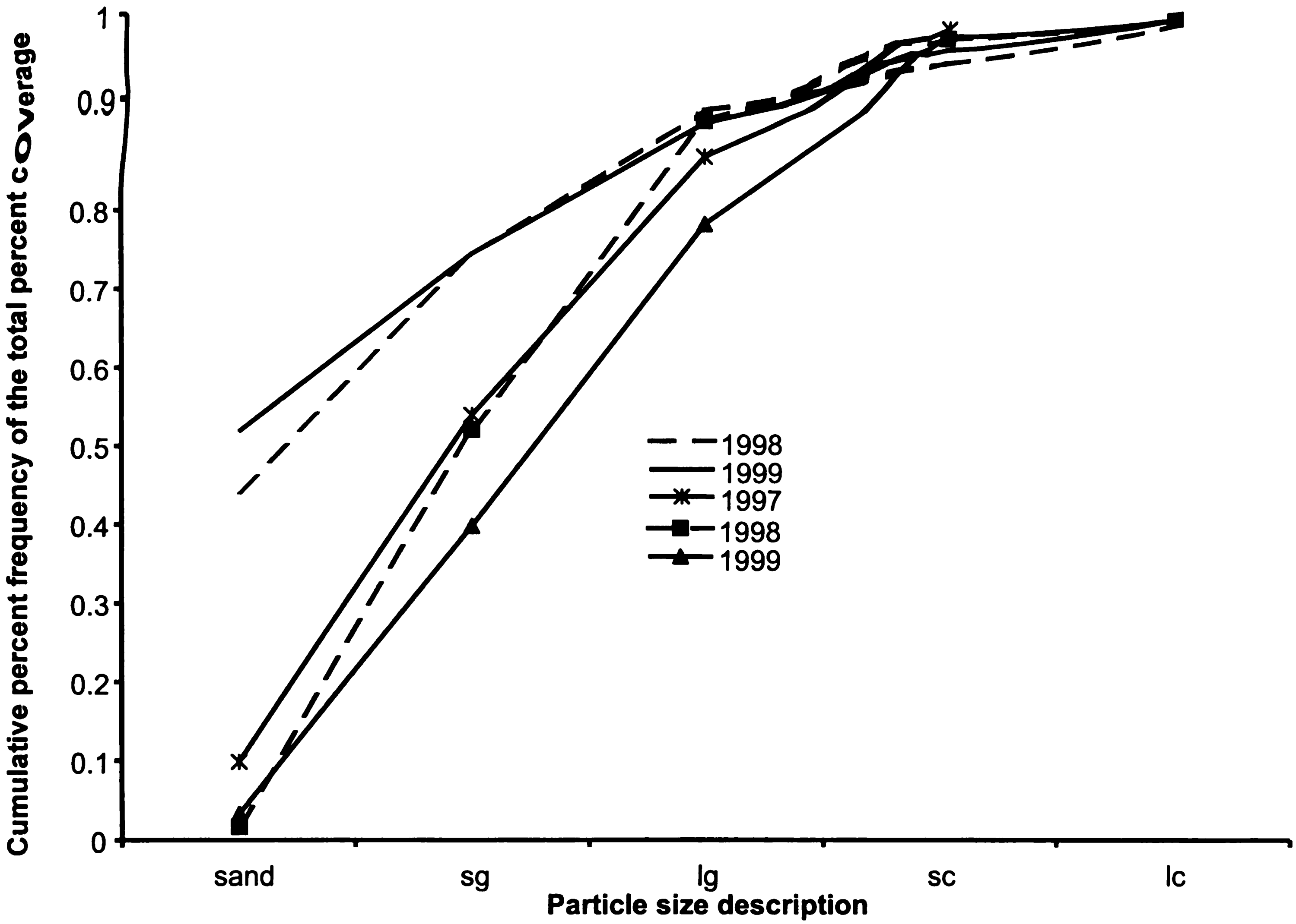

Figure 5-3. The cumulative percent frequency distribution of total percent coverage of small gravel (sg), large gravel (lg), sand (s), small cobble (sc), large cobble (lc), silt (slt) and clay (clay) size classes within redd and reference sites in the Pere Marquette River, Michigan for 1997, 1998, and 1999.

Table 5-5. Redd and reference habitat characteristics in the Pere Marquette River, Michigan 1997, 1998 and 1999.

		Sample Year	
Site Metric	**1997**	**1998**	**1999**
		Redds	
Mean water depth above redd (m)	0.43 (*s* = 0.45)	0.39 (*s* = 0.40)	0.37 (*s* = 0.47)
Mean water temp above redd (°C)	8.5 (*s* = 1.2)	9.4 (*s* = 0.2)	10.3 (*s* = 2.5)
Mean velocity above redd (cm/s)	73 (*s* = 50)	73 (*s* = 44)	64 (*s* = 48)
Mean number redds/ha	30	26	17
Percent of run samples	15 (n = 27)	36 (n = 27)	7 (n = 10)
Percent of riffle samples	85 (n = 151)	64 (n = 48)	93 (n = 140)
Percent of pool samples	0	0	0
		Reference Sites	
Mean water depth above ref site (m)	n/a	0.64 (*s* = 0.71)	0.60(*s* = 0.77)
Mean water temp above ref site (°C)	n/a	10.3 (*s* = 1.4)	10.0 (*s* = 2.3)
Mean velocity above ref site (cm/s)	n/a	60 (*s* = 73)	46 (*s* = 64)
Percent of run samples	n/a	83 (n = 82)	76 (n = 113)
Percent of riffle samples	n/a	11 (n = 11)	18 (n = 27)
Percent of pool samples	n/a	3 (n = 6)	6 (n = 9)

I evaluated the combined 1998 and 1999 data for steelhead electivity of substrate particle size. Steelhead preferred small gravel, large gravel and small cobble disproportionately to their availability within the stream reaches (Figure 5-4). Although sand was frequently observed in the reference samples (Figure 5-3), sand, large cobble, silt, and clay were not preferred within redd substrata (Figure 5-4).

The 1998 data were not significantly different from the 1997 data ($P = 0.23$), and the 1999 data were not significantly different from the 1997 data ($P > 0.27$). All substrate particle size data (1997 to 1999) were combined for further analyses.

The combined 1997 to 1999 redd particle size distributions were not significantly different between run and riffle habitats ($P = 0.12$). Redds were not observed in pool habitat. The combined 1997 to 1999 redd particle size distributions and the

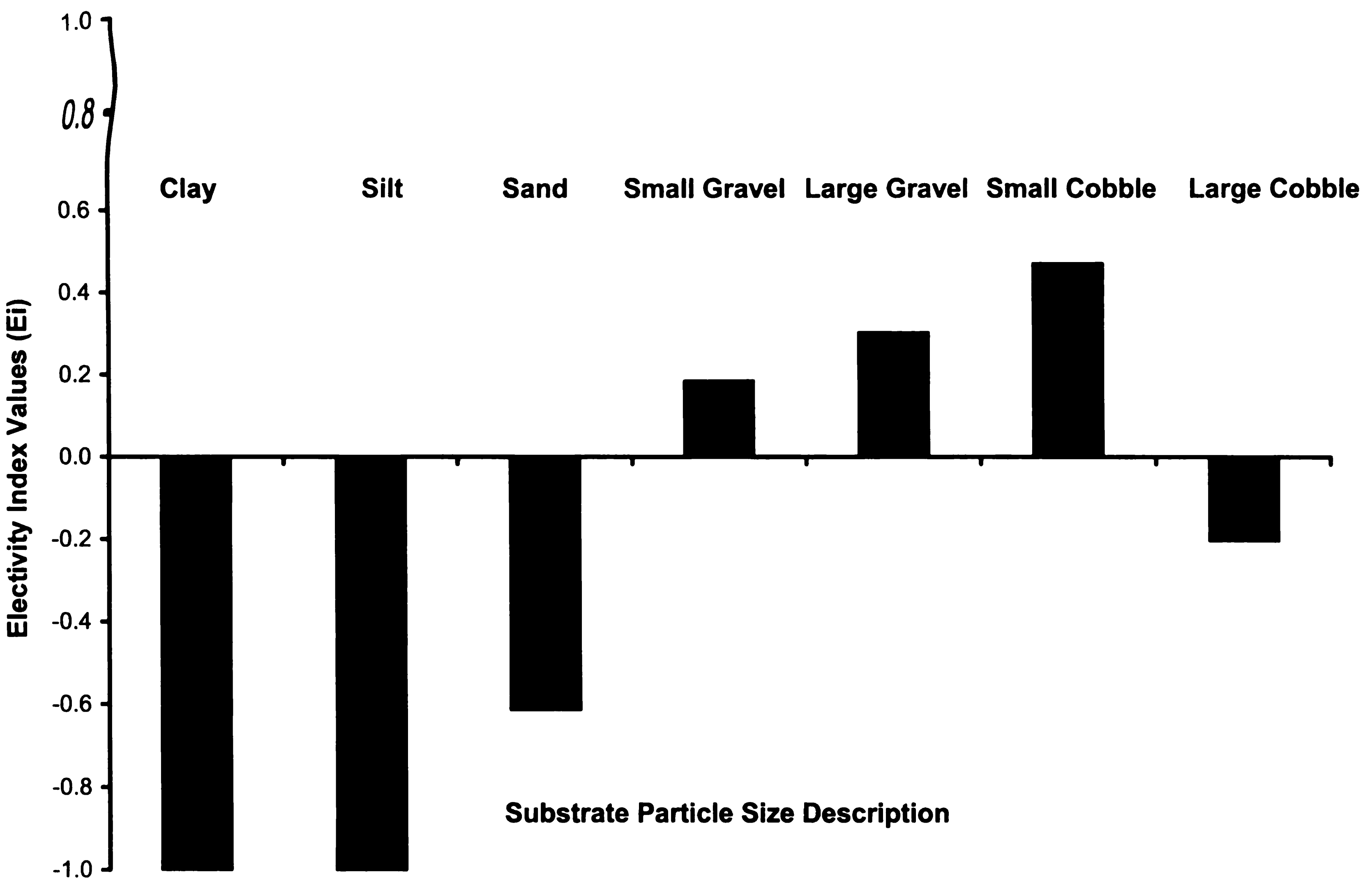

Figure 5-4. Electivity values for steelhead spawning substrate particle size descriptions in the Pere Marquette River, Michigan 1998 and 1999 combined.

location of the redds with respect to the river channel (RR, CH, and RL) were not significantly different ($P > 0.27$) for all possible combinations (RR vs. RL, RR vs. CH, and CH vs. RL).

Velocity, Water Temperature, Water Depth

Stream velocity was an important component of steelhead spawning site selection. As illustrated using the 1998 data in Figure 5-5, reference velocities were significantly lower than redd velocities ($F = 97.77$, $P < 0.0001$) and redd velocities were significantly different among years ($F = 15.01$, $P < 0.0001$). There was no significant interaction between redd and reference site velocities and years ($F = 0.23$, $P = 0.63$). Redd velocities varied less than velocities measured at reference sites (Table 5-5). The 1999 redd velocities were significantly lower than the 1997 ($t = 4.57$, $P < 0.0001$) and the 1998 ($t = 3.18$, $P = 0.016$) redd velocities (Figure 5-6). The 1997 and 1998 mean redd velocities were 73 cm/s (Table 5-5) and were not significantly different ($t = 0.10$, $P = 0.22$). Like the redd data, the mean daily discharge recorded at Scottville, Michigan for the month of April was significantly lower in 1999 than 1997 ($t = 3.01$, $P = 0.003$) and 1998 ($t = 4.87$, $P < 0.0001$). The 1997 and 1998 discharge data were not significantly different ($t = -1.80$, $P = 0.08$) for the month of April.

Stream velocities for redds in the center of the channel were significantly greater than redds located in the river-left ($t = 0.008$, $P = 0.02$) and river-right ($t = 0.002$,

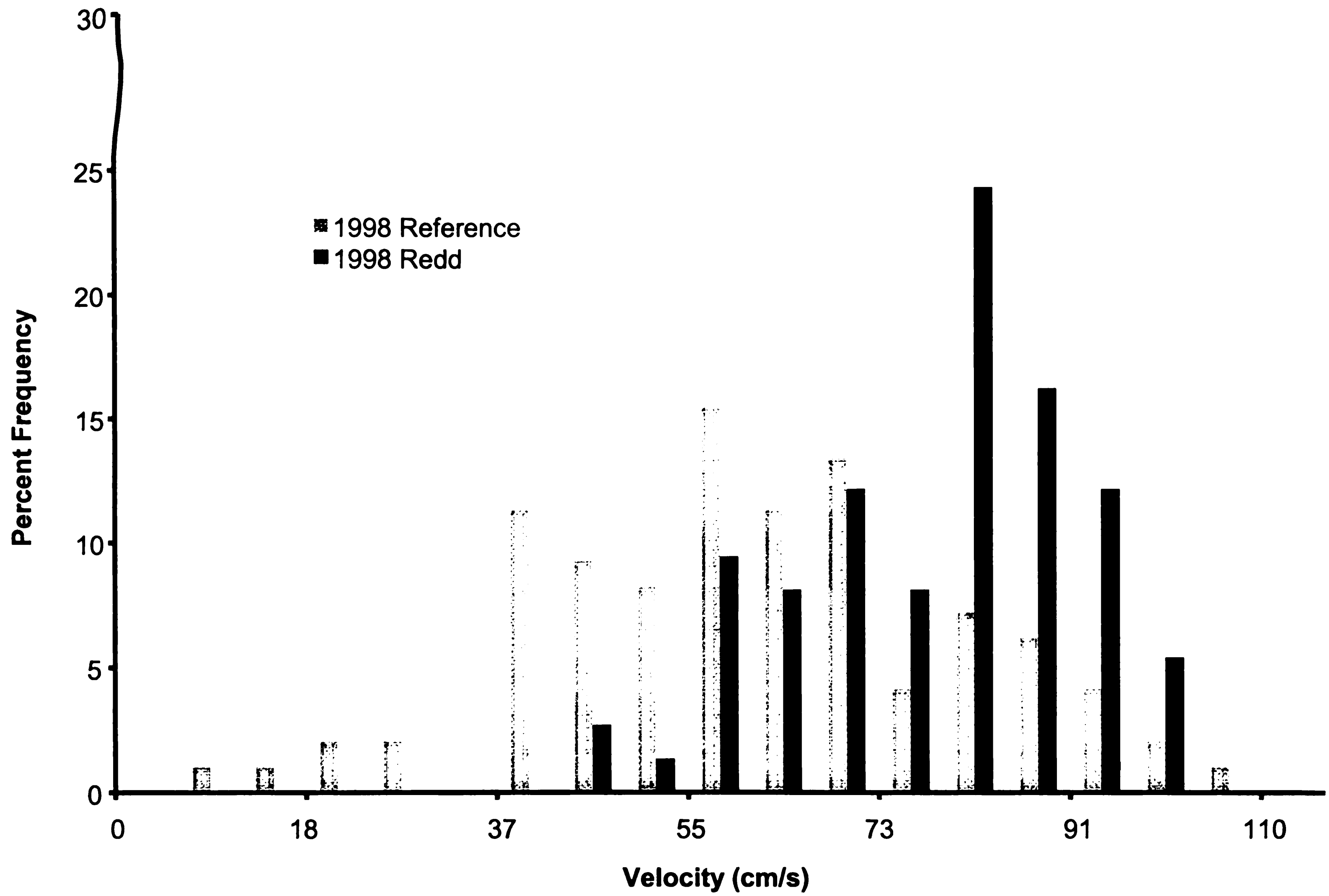

Figure 5-5. Percent frequency of stream velocity recorded at steelhead redd and reference sites during 1998 in the Pere Marquette River, Michigan.

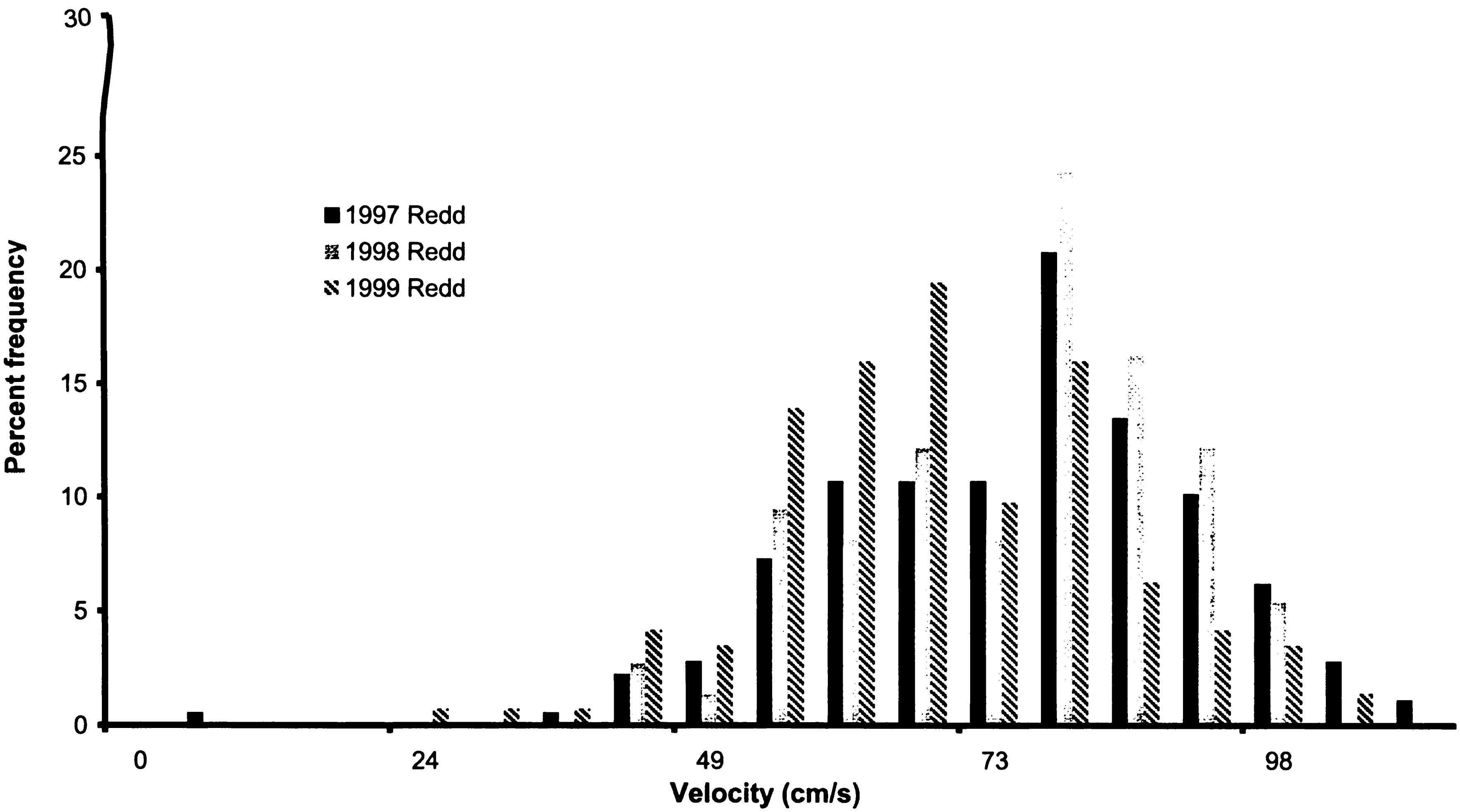

Figure 5-6. Percent frequency of stream velocity recorded at steelhead redds during 1997, 1998, and 1999 in the Pere Marquette River, Michigan.

P = 0.05) channel locations. However, velocities of reference samples were also higher (F = 11.88, $P < 0.001$) in the center of the channel.

Within site deviations of stream temperature was not an important component of steelhead selection of spawning habitat in the Pere Marquette River. Water temperature above the redd was not significantly different between redd and reference sites ($F = 1.16$, $P = 0.28$), but was significantly different among years 1997 ($t = 11.78$, $P < 0.0001$), 1998 ($t = 12.75$, $P < 0.0001$), and 1999 ($t = 15.37$, $P < 0.0001$).

Steelhead redds were located in significantly shallower water ($F = 113.84$, $P < 0.0001$) than reference sites (Figure 5-7). Steelhead constructed redds in approximately 0.20 m shallower than was normally found within the study reaches (Table 5-5). The sample year did not appear to influence the depth of water above redds or reference sites ($F = 1.92$, $P = 0.15$). Redd depth was not significantly different according to the location of the redd within the river channel ($F = 2.65$, $P = 0.07$). The water depth among reference sites was only significantly deeper ($t = 2.29$, $P = 0.02$) in channel locations when compared with river-left locations.

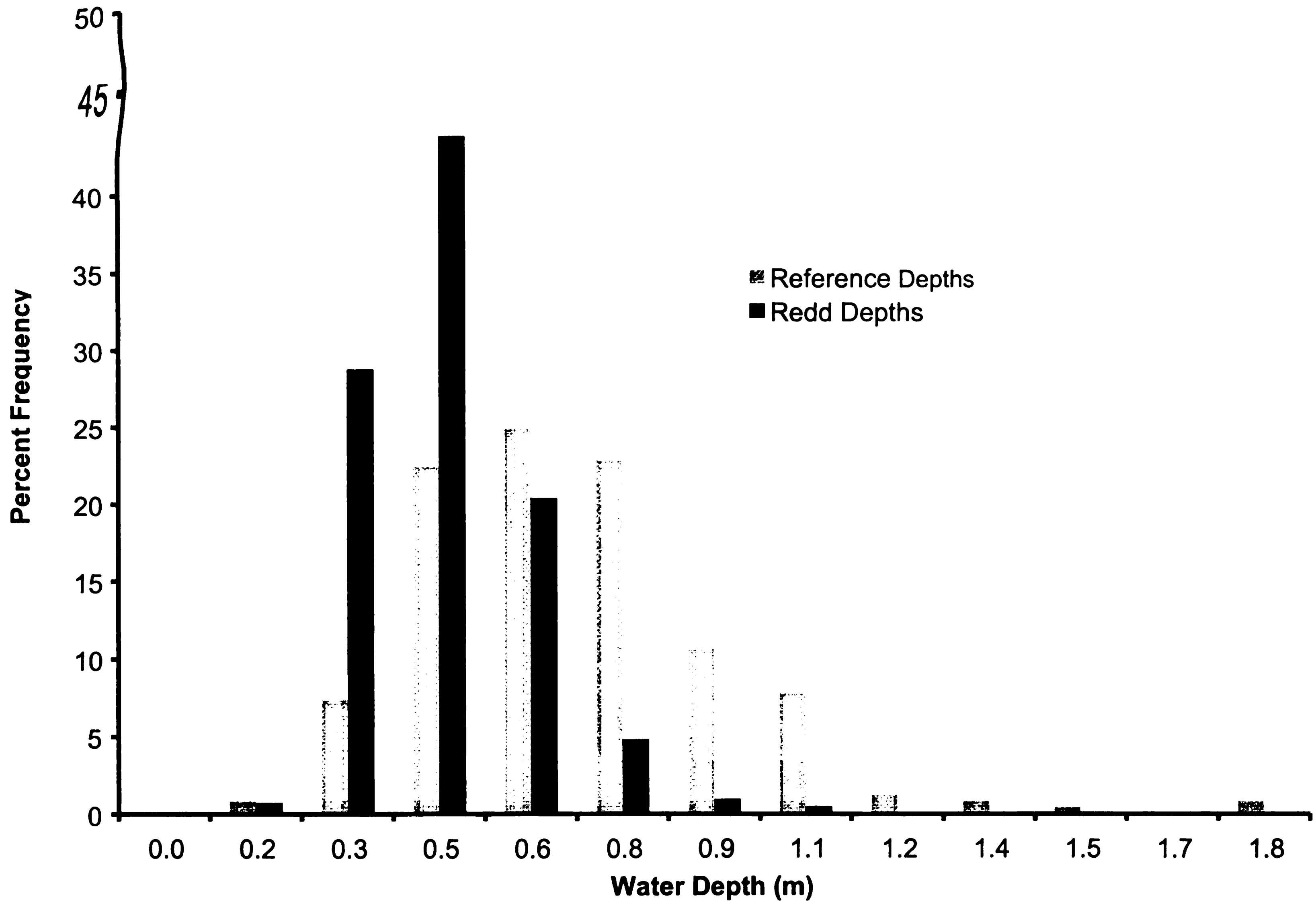

Figure 5-7. Percent frequency of water depth recorded at steelhead redd sites from 1997 to 1999, and from reference sites from 1998 to 1999 in the Pere Marquette River, Michigan.

Discussion

Groundwater

Steelhead redds were not disproportionately located in areas of low, medium, or high groundwater flow within the Pere Marquette River using the GIS–based groundwater predictions. Because the GIS model was designed for coarse-scale predictions (100 m^2) it may not provide enough detail to accurately assess steelhead spawning locations in relation to groundwater areas within the Pere Marquette River (Baker et al. 2000).

In addition to the GIS-based groundwater predictions, the evaluation of intragravel water temperature was inconclusive as a means of identifying groundwater input areas in the river. Silliman and Booth (1993) identified groundwater within a stream reach by monitoring intragravel temperatures over 25 days within a fixed location. I monitored portions of a stream reach for approximately 4 hours by collecting successive observations in a downstream direction. Although my monitoring approach was able to detect differences among stream water and intragravel temperatures in most cases, I was unable to establish the status (stable or fluctuating) of the intragravel temperatures.

Finally, groundwater may be plentiful throughout much of the steelhead spawning habitat within the Pere Marquette River, making the location of a redd with respect to groundwater unimportant. Curry and Noakes (1995) found that groundwater may have drawn brook trout to generalized spawning areas, but did not influence the selection of redd locations in areas where groundwater was abundant within the baseflow of the stream.

Substrate Particle Size

Steelhead exhibited a preference for substrate particles that were larger than sand yet smaller than large cobble. Sowden and Power (1985) indicated that the spawning substrate must be coarse yet small enough that the fish can move it.

Although I visually estimated substrate particle size, I consistently detected a preference for specific particle sizes by steelhead. Another substrate sampling method like the pebble count pebble (Kondolf and Li 1992) where the particles are randomly chosen and physically measured produce data that can be evaluated parametrically. However, because of the large sample areas and the abundance of redds, the pebble count method was too time consuming and not a feasible method given these constraints.

Velocity, Water Temperature, Water Depth

Stream velocity appeared to influence the location where steelhead constructed redds. Steelhead constructed redds in locations with higher stream velocity than average within each study reach. The stream velocities that I recorded at the redds in the Pere Marquette River were consistent with steelhead redd velocities as determined by Smith (1973). Smith found the average mean-column velocities at redds to range from 63 to 70 cm/s, as compared to 64 to 73 cm/s in my study (Table 5-4).

The faster moving water may assist embryo development by providing oxygenated water (Stuart 1953; and Sowden and Power 1985). The delivery of oxygenated water to the redd is also affected by water depth. The velocity of water must be fast enough to penetrate the interstices of the redd and deliver oxygenated water, and the water must remain deep enough to cover the redd until the fry emerge from the redd (Semko 1954, and Smith 1973).

Although steelhead consistently preferred to construct redds in locations with stream velocities that were higher than average, the stream velocity at the redds and river discharge recorded at Scottville varied annually. The annual variation may be attributed to a large-scale effect that influences stream flow (e.g., annual differences in precipitation).

Water temperature was not a deciding factor in the choice of steelhead redd locations. Because steelhead spawn during the spring in Michigan when water temperatures are cooler, water temperature may not influence the location choice for redd construction.

Water depth influenced the location of steelhead redds. As indicated by the disproportionate number of redds located in riffles (Table 5-5), steelhead preferred to construct redds in water that was shallower than the average depth within the study reaches. The steelhead in my study constructed redds in water depths that were consistent with a 1973 Pacific Coast steelhead spawning study (Smith 1973).

Although my study did not provide additional information regarding the relationship between steelhead spawning and groundwater, I have identified substrate particle composition, stream velocity, and water depth features that are specific to steelhead redds within the Pere Marquette River. Should spawning habitat be found to be limiting within the Pere Marquette River, these features could be used as a measure to evaluate other locations within the river where habitat may be suitable for spawning.

Identifying these spawning habitat features and redd densities within each study reach serves as a quantitative description of steelhead spawning habitat preference within a Great Lakes tributary, and may help to guide future monitoring of steelhead numbers within the river. Stream habitat improvement projects are regularly conducted within the watershed (personal communication, Pere Marquette Watershed Council). The habitat improvement projects are often stream-bank stabilization efforts to minimize the amount of fine sediments entering the river. These habitat improvement projects may create opportunities to monitor the effects of the stream-bank stabilization by identifying spawning locations and redd densities prior to the improvement project and evaluating changes to spawning habitat following the work. My results could be used as baseline data to evaluate the improvement project in terms of improving or creating additional steelhead spawning habitat.

CHAPTER 6

SUMMARY

SUMMARY

Steelhead and longnose spawning migrations were described in the Pere Marquette River using radio telemetry as part of an evaluation of an electrical sea lamprey barrier. Steelhead and longnose suckers moved upstream quickly (all radio-tagged fish moved upstream within an average of 32 minutes) through the sea lamprey barrier vicinity, prior to barrier operation. The upstream movements of radio–tagged fish after the barrier was in operation were not evaluated in this study. Radio-tagged steelhead and longnose suckers showed a general correspondence of upstream movements with increasing water temperature and stream flow.

The telemetry data I collected from 1997 to 1998 provided base-line migration information for a future study on the effect of the operation of the electrical barrier on migratory steelhead and longnose suckers. Specifically, the data from my study were used to evaluate migratory delay caused by barrier operation, the speed of passage through each study section, and the percent passage through each section.

A model was developed to evaluate the upstream movements of steelhead in relation to water temperature and stream flow in the Pere Marquette and the St. Joseph Rivers, Michigan. My data for the model included 28 radio-tagged steelhead (*Oncorhynchus mykiss*) on the Pere Marquette River and a larger (5,876 to 10,083 steelhead), multi-year (1993-1999) data set of camera recorded

steelhead passage through a fishway on the St. Joseph River. My model predicted the probability of movement as increasing over increasing water temperatures above a movement-threshold water temperature. Stream flow was incorporated into the model, but did not add substantially to the model's ability to describe the migratory behavior of steelhead in the Pere Marquette and St. Joesph Rivers.

The TBM model may work to predict the migratory behavior of other fish such as sea lamprey that move into rivers for reproductive purposes and time their movements on water temperature and other factors. In addition, my modeling approach could be used to predict the appropriate sampling periods based on migration timing, or predict future run size from percent passage data from the model.

Finally, I described the spawning habitat use of steelhead in the Pere Marquette River. A GIS-groundwater model and an intragravel temperature probe were evaluated as tools to identify areas of groundwater within the river. The methods were inconclusive as a means of identifying groundwater. Groundwater did not appear to be related to redd density in the study reaches.

Steelhead preferred to construct redds in a substrate consisting of small gravel, large gravel, and small cobble particle sizes disproportionately to clay, silt, sand, and large cobble. The selection of coarse particle sizes small enough to move and large enough to allow water to flow through the redd were consistent Pacific Coast salmonids. In addition, similar to Pacific Coast steelhead, Pere Marquette River steelhead exhibited a preference for stream velocities faster than normal, and a preference for water shallower than normal (e.g., riffles) within the study reaches. Although stream temperature influenced the upstream migration of steelhead, it did not appear to influence their selection of redd locations.

Identifying these spawning habitat features and redd densities within each study reach served as a description of steelhead spawning habitat preference within a Great Lakes tributary, and may help to guide future monitoring of steelhead numbers within the river. My study results could be used to monitor the influence of habitat improvement projects that regularly occur in the watershed on steelhead reproduction.

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