FISHWAYS FOR WARMWATER SPECIES:

UTILIZATION PATTERNS, ATTRACTION EFFICIENCY, PASSAGE EFFICIENCY, AND RELATIVE PHYSICAL OUTPUT

by

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A thesis

presented to the University of Waterloo

in fulfillment of the

thesis requirement for the degree of

Doctor of Philosophy

in

Biology

Waterloo, Ontario, Canada, 1999

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ABSTRACT

Upstream migration and fishway use by anadromous species are fairly well documented and understood. Very little information exists about similar behaviour among riverine warmwater species. Because many of these species use fishways, a better understanding of fishway effectiveness can be used to offset dam and weir blockage effects, by providing improved upstream passage. Several fishways on the Grand River, Ontario were monitored for five years (1995-1999) and utilization patterns were documented for 30 warmwater fish species relative to seasonal, thermal and hydraulic dynamics. There were seasonal species shifts, with some overlap, from percids, to catostomids, to cyprinids, to ictalurids, back to percids and then centrarchids as water temperatures increased from 4 º C to 25 º C in the Grand River. Maximum fishway use by several species occurred during periods of decreased water clarity during or after storms. More proximately, water velocity and species-specific swimming/position holding abilities affected fishway use. Using digital radiotelemetry, movement patterns of 109 radiotagged fish (smallmouth bass *Micropterus dolomieu*, white suckers *Catostomus commersoni* and walleye *Stizostedion vitreum*), as well as attraction and passage efficiency of three Denil fishways were collectively examined. Attraction efficiency for white suckers was between 50 and 59 %, and passage efficiency was between 38 % and 55 %. Attraction efficiency for smallmouth bass was 55 – 82 % and passage efficiency was 33 – 36 %. For walleye, attraction efficiency was 21 %, and passage efficiency was between 0 and 4.2 %. Variability among species-specific efficiencies was related to fishway design, water velocity, turbulence, swimming ability and swimming strategy. There was an exponential decline in the numbers of smallmouth bass and white suckers that used each fishway relative to water velocity. The maximum water velocities used by white suckers and smallmouth bass were 0.96 m/s and 0.99 m/s, respectively.

Distracting flows upstream from the fishway entrances appeared to affect attraction, particularly for smallmouth bass. To address this problem, the entrances to two of the fishways were modified. An experiment was then designed to illustrate the effect of the modifications on attraction rates of pumpkinseed *Lepomis gibbosus*. Overall attraction rates increased by a factor of three after entrance modifications. Median relative attraction rates also increased significantly from 0 % to 2 % after fishway entrances were modified. Further experiments were then conducted with electromyographic (EMG) telemetry and smallmouth bass to attempt to evaluate physical output associated with passage through both of the modified fishways. EMG levels from areas near the fishway exits were significantly greater than maximum EMG levels recorded during critical swimming speed trials. Smallmouth bass appeared to exceed their aerobic scope of activity during ascent of both fishways. EMG data reflected combinations of burst and prolonged swimming activity and indicated the relative differences in muscular activity and physical output required to use each fishway type. Finally, positive biological effects of dams were investigated, after evidence suggested that some fish spawn in habitat immediately downstream. Radiotagged walleye occupied areas with suitable spawning substrate downstream from the Dunnville dam. At the Mannheim weir, creation and maintenance of microhabitats that supported large numbers of greenside darters *Etheostoma blennioides* and stonecats *Noturus flavus*, occurred downstream. These unique riffle habitats, with unembedded substrate, were maintained by pulsed river discharges associated with precipitation, upstream reservoir regulation, freshets, and ice scour.

ACKNOWLEDGEMENTS

This work was made possible through the continued financial support of the Natural Sciences and Engineering Research Council of Canada. Funding was also provided by the Ontario Graduate Scholarship program, the University of Waterloo and a Davis Memorial Scholarship in ecology. Franklin Smith, Lane Stevens and the Regional Municipality of Waterloo graciously provided laboratory space, living facilities and freedom to experiment with Municipal property. Several people participated in field operations and they are acknowledged at the end of each chapter. In particular, I want to extend my deepest thanks and appreciation for the many individuals that sacrificed their summers to live with me at my research site. The fruits of our efforts and indelible memories would not have been possible without the dedication and commitment of Gabrielle Held, Sean Clancy, Steven Cooke, Lin Wong, Brett van Poorten and Danielle Knight. Cheers to you all! My experiences on the banks of the Grand River were also enhanced by meeting great new friends who often helped me install a trap, build an antenna, clear a screen, carry a cooler of fish, hold a light during surgery, canoe with me downstream during tracking sessions, etc, etc. In particular, I thank Danny Sack, Jeff Danylyk, Ingrid Danylyk, Peter Kaune, Troy Spinney, Rick Auiler, Richard Booth, Jason Held, Brett Raven and Drew Gwilliams. I thank my graduate supervisor, Scott McKinley, for the opportunity to conduct this research. Geoff Power provided advice and valuable reviews of my manuscripts. I thank my graduate committee (Dr.'s Scott McKinley, Geoff Power, William Taylor and George Dixon), internal examiner (Dr. Steven Murphy), external examiner (Dr. David Noakes) and Val Butler for logistic support. Finally, I am grateful to my dear Mum and Dad (Maureen and Reginald Bunt), who must have sat me in front of someone's aquarium at a critical imprinting stage in my development. How else could I be so fish crazy? My parents always encouraged my interest in all living things, and without their love and support my life would not be the same. I thank my sister, Rachel, and all my friends for listening to endless fish stories, tales of misadventure and bad jokes. I especially thank Penny Wilson for her love, laughter, enthusiasm, passion for life and spirit of adventure.

What did the little fish say when she banged her head while swimming upstream?

"Ahh dam!"

><> Bugs and Fishes <><

DEDICATION

This thesis is dedicated to the memory of my mum (Maureen Montgomery-Bunt), who passed away on Saturday December 27th 1997, when I was just over half way through my studies on the Grand River. She was not able to see the final product, but she was with me the whole way.

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CHAPTER 1

General Introduction: AN UPSTREAM BATTLE [1]

For millennia, fish have leaped and struggled upstream, past logjams and small cascades following the relentless, uncontrollable urge to spawn. These awesome migrations are well known among anadromous species such as salmon, trout, herring and shad. Similar movements by warmwater fishes are, however, somewhat less well understood. Although upstream migrations among warmwater fish may not be as extensive as they are for anadromous species, there is a growing body of literature that challenges the restricted movement paradigm (see Gowan *et al.* 1994), proposed for riverine fishes by Gerking (1959). A surprising number of warmwater species migrate up rivers and streams in search of suitable spawning habitat. During some of these migrations, movement is blocked by natural obstructions such as waterfalls and beaver dams. More commonly, as modern development spreads, rivers and streams are blocked by artificial dams and weirs. Dams disrupt the rhythm of rivers by transforming free flowing waterways into a series of impounded pools. Removal of old dams is a growing management tool used to restore river connectivity, but it is not always an appropriate or possible option. As an example of a situation where dam removal was deemed appropriate, the state of Maine recently began dismantling the Edwards Dam on the Kennebec River (Anonymous 1999). This project will allow the river to flow freely for the first time in 160 years and should restore nine species of migratory fish such as striped bass *Morone saxatilis*, shad *Alosa* spp., herring *Alosa* spp. and sturgeon *Acipenser* spp. These fish will soon have access to 27 km of river that they have been prevented from using since the late 1830's. The cost of dam removal is often three to five times less than the

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[1] Published - Fisheries 24(12): 36-37.

cost of repairing or maintaining dams (Wisconsin Department of Natural Resources, unpublished data). Despite this, dams continue to be built and maintained worldwide.

Fishways allow fish to swim upstream past dams and weirs (Clay 1995; Beach 1984). In recent years, dam owners have been legislated to provide adequate fish passage as a result of studies that have shown that river obstructions can negatively affect fish by preventing access to spawning areas. Examples include the collapse of the commercial salmonid industries of France (Dumas *et al.* 1981), Denmark (Lonnebjerg 1980), and along the Pacific coast of North America (Geen 1975; Raymond 1988). Most research in the field of fishway design and monitoring has focused on salmonids. As a result, most fishways incorporate features related to our knowledge of salmonid behaviour and swimming performance despite the fact that this group of fish represents only a small proportion of all North American riverine fish species (Scott and Crossman 1973). Only in the past decade has any information on the use of fishways by warmwater species been documented (Schwalme *et al.* 1985; Katopodis *et al.* 1991). The literature does however contain numerous reports of rheotactic behaviour (Pavlov 1989; Arnold 1974) and upstream migration for many warmwater fishes such as northern pike *Esox lucius* (Schultz 1955), walleye *Stizostedion vitreum* (Rawson 1956) and smallmouth bass *Micropterus dolomieu* (Dexter and Ledet 1997).

There are three major types of fishways, each associated with particular hydraulic conditions. Pool and weir fishways are the most widespread, and function best for leaping species, where no large fluctuations in river levels exist. Some pool and weir fishways incorporate submerged orifices to allow passage of non-leaping fish. Vertical-slot fishways operate well across a wide range of river levels, but may become blocked in some rivers that carry large amounts of debris. Denil fishways also operate well across a wide range of river levels, have a relatively low water demand (Beach 1984) and experience less of a problem with debris blockage. Denil fishways are generally used to pass fish over obstructions with a head less than 2 m (Clay 1995).

Some recent studies have demonstrated that non-leaping species such as northern pike *Esox lucius*, prefer Denil fishways over vertical slot types (Schwalme *et al.*1985). The reasons for such preferences are not clear but are likely related to swimming ability, water velocities and flow patterns within the fishways.

Denil fishways employ baffles to decrease the velocity of flowing water. Denil baffles create vortices (Rajaratnam *et al.* 1984) and turbulence which dissipates large amounts of kinetic energy. An experimental fishway consisting of a rectangular concrete channel with baffles, decreased the average water velocity by 86 - 89% compared to velocities expected in a channel of equal dimensions without baffles (Katopodis and Rajaratnam 1983). Velocity profiles indicate that a region of reduced water velocity (similar to a boundary layer) exists towards the bottom of the channel, which may allow smaller fish, and weaker swimming species to ascend Denil fishways.

Studying fishways from a biological perspective, with the required large sample sizes, has been a notoriously difficult challenge (Beach 1984). Historically, the methodology (i.e., trap studies) used to examine fishway effectiveness has not been able to provide information on partial, or unsuccessful fishway use (Schwalme *et al.* 1985; Katopodis *et al.* 1991). Detailed behaviour of individual fish, timing of fishway use, and an appreciation of just how well fish can locate fishway entrances were unknown. When an operational fishway is being assessed from a biological perspective, the explanations for differing species-specific usage patterns may not be obvious. The underlying principles behind successful use may be elucidated through physiological, ecomorphological and behavioural studies. Examination of fish musculature may help explain the physiological reasons why one group of fishes may outperform another (see Hudson 1973). Species with reduced amounts of red, well-oxygenated muscle, such as northern pike and muskellunge *E. masquinongy*, are not physically designed to sustain the rapid swimming speeds necessary to cope with many large fishway designs. From an ecomorphological perspective, salmonids, for example, are fusiform, making them much more hydrodynamic than laterally flattened centrarchids, which include smallmouth bass. The gibbose centrarchid shape trades hydrodynamic optimization, for agility and maneuverability. Differences in agility may allow some fish to outperform others during fishway use. Although difficult to quantify, behavioural factors may be as important as physical ability (Lucas and Frear 1997) in determining whether fish will be successful at using a particular fishway configuration.

Tracking fish with radio transmitters and receivers has been a standard method of investigating *in situ* behaviour of fish for some time (Trefethen 1956; Hooton and Lirette 1986; Lirette 1988). Recent technological advances have produced small, affordable, digitally coded transmitters that provide unique numerical identification. These tags optimize the use of limited frequency space because coded transmissions may occur on the same frequency. This permits simultaneous tracking of large numbers of individuals. Moreover, coded transmitters minimize sampling time, which may concomitantly eliminate or reduce uncontrolled time-series effects within a dataset. Encoding also enhances the detection of signals in instances where background noise produced by generators, pumps or transmission lines near dams, can obscure accurate collection of data at certain frequencies.

In this dissertation, I used digital radio telemetry, videography, and trap studies to monitor the behaviour and movements of wild fish near and within Denil fishways. Various laboratory and field experiments were devised to determine patterns of fishway use, attraction efficiency, passage efficiency and relative physical output required for smallmouth bass, white suckers and walleyes to move upstream through three different Denil fishways at weirs on the Grand River, Ontario (Figure 1.1). Prior to this work, fishway utilization patterns by warmwater species were largely limited to anecdotal reports and records of incidental bycatch (except Schwalme *et al.* 1985;

Katopodis *et al*. 1991). No studies presented information that could be used to increase passage rates by matching velocities to species-specific swimming abilities at times of the year when these species were known to migrate. In the series of studies that follow, fishway use by 30 species was examined. Without the fishways, each weir represented an impassable barrier for fish that were predisposed to move upstream. Fishway efficiency was subdivided into two components – attraction and passage. Attraction efficiency was calculated by determining the number of individual fish that located a fishway entrance relative of the total number of potential fishway users downstream. Passage efficiency was determined by comparing the number of individual fish of a particular species that passed completely through a fishway, to the number of fish that located and entered the fishway entrance. Research focused on warmwater species for which fishpass data are generally lacking. An outline of the projects assembled for this thesis is shown in Figure 1.2.

Data collected in 1995 indicated that some fish experienced difficulty locating fishway entrances. Fish were consistently monitored upstream from the fishway entrances, near distracting regions of high discharge from one of the weirs. I realized that it was possible to improve attraction by modifying the entrances so that they were relocated and re-sized in a simple and economical manner. In 1996, the owners of the weir (Regional Municipality of Waterloo) modified the fishway entrances according to recommendations derived from this research. The reconfigured fishways were subsequently evaluated, and attraction efficiency had, in fact, increased. Other modifications to the fishways included the installation of debris deflection devices, which also stabilized flow conditions within the fishways. Solid cover plates that kept the fishways dark during the daytime were replaced with grates. And finally, adequate signage was posted to indicate that angling was prohibited immediately downstream from the fishway entrances.

It was clear that my research made it easier for fish to find the fishways on their journey upstream. The next step was to understand how to make the fishways easier to use. Relative physical output and stress experienced by fish should be minimal if the full potential for upstream passage is to be realized. By determining how hard fish must swim to successfully use a fishway, we may begin to understand the relative importance of physical ability versus behavioural motivation. By behavioural motivation, I collectively refer to the many behavioural factors that may determine whether or not fish are able to use a particular fishway configuration. A limiting factor that fish may experience during fishway use, such as turbulence, may be referred to as a behavioural barrier. In an attempt to separate the effects of physical and behavioural barriers, physiological telemetry and videography were used. Physiological data were collected from smallmouth bass implanted with transmitters that relayed contraction rates of axial swimming muscles. Field experiments revealed the relative degrees of exertion required for smallmouth bass to move upstream through the fishways during various flows. Comparisons were then made between muscular activity and maximum sustainable swimming speeds of fish from swim-chamber experiments. This was the first measurement of difficulty associated with the use of fishways by warmwater species. Using miniature video cameras, I determined that turbulent flows in fishways disoriented fish and large amounts of energy were expended while fish swam through them. Reducing turbulence and back-flows by smoothing corners and by implementing baffles in strategic areas within fishways, may reduce the energy required for fish to swim upstream past dams and weirs. If less energy is expended to reach spawning areas, more energy is available for nest building, spawning and care of the developing brood.

This work is of particular importance to fisheries biologists and managers, because it provides a basis for the construction and modification of fishways for the passage of warmwater fishes. It also provides methodology and field data that can be used to measure fishway efficiency and difficulty associated with fishway use by examining the detailed responses of individual fish. The results may then be used to support ideal entrance location and fishway design concepts to maximize fish passage rates worldwide. Reducing the negative effects associated with blocking migratory pathways will improve the quality of river fisheries for future generations to exploit and enjoy.

Figure 1.1. Aerial photographs of the Mannheim weir and two Denil fishways (top), and the Dunnville fishway (bottom), on the Grand River, Ontario.

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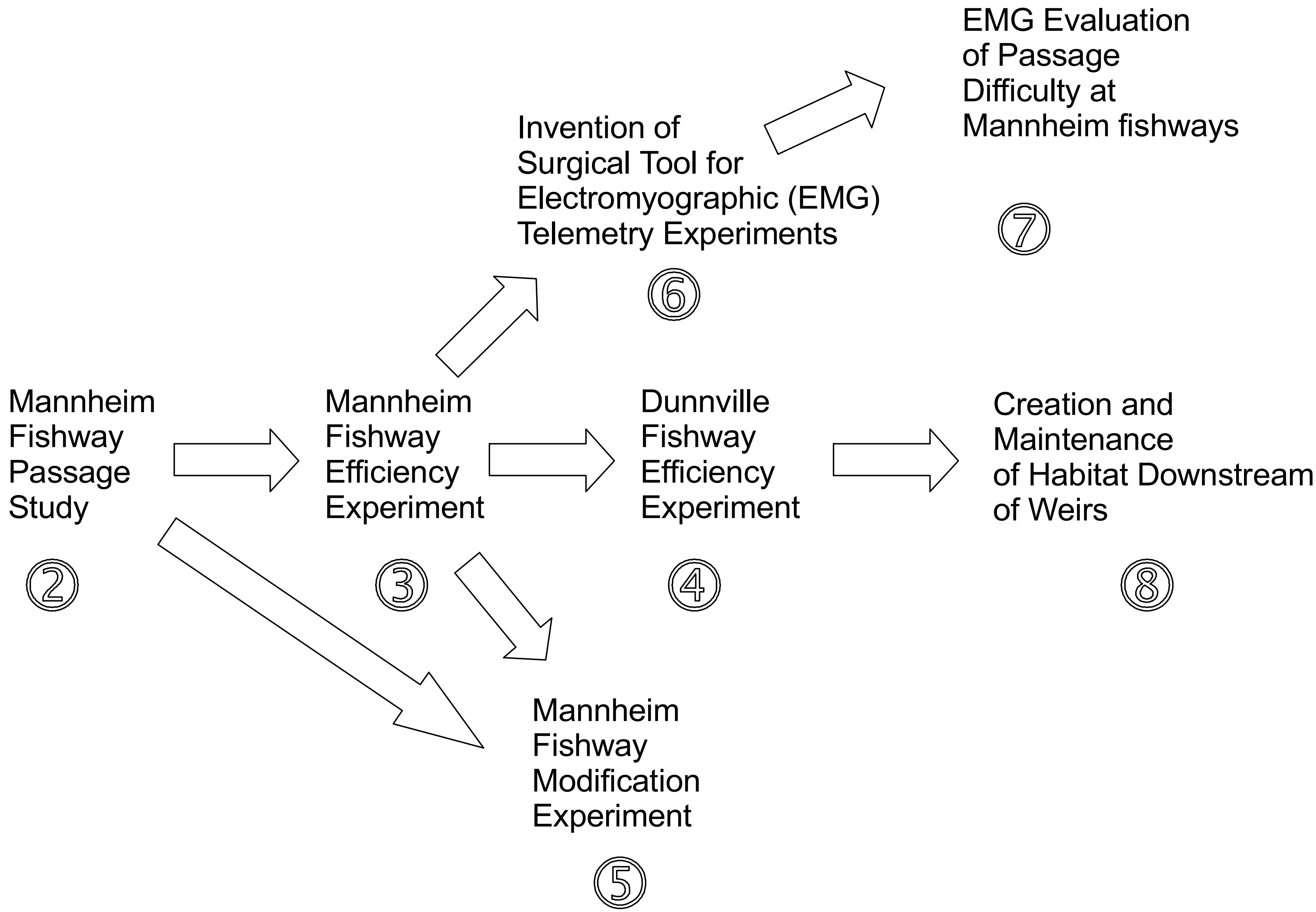

Figure 1.2. Development of fishway studies at the Mannheim weir and the Dunnville dam from 1995 to 1999. Numbers indicate chapters where details of each study can be found

CHAPTER 2

Denil fishway utilization patterns and passage of several warmwater species relative to seasonal, thermal and hydraulic dynamics [2]

Abstract

Fishways that allow passage of as many constituents of local ichthyofauna as possible are necessary if the concept of sustainable development is to be realized. In the present study, two Denil fishways on the Grand River, Ontario, were used as check-points to evaluate the transfer of fishes over a low-head weir and to examine the proportions and inferred swimming performance of 29 warmwater fish species that used each fishway type. Traps installed at fishway exits were used to collect fish over 24 hour sampling periods, during 40 – 51 days each year from 1995 to 1997. Passage rates, mean temperature, water velocity and turbidity for the date of maximum passage for each year were analyzed. General species composition from trap samples shifted from catostomids to cyprinids to ictalurids to percids and centrarchids, with some overlap, as water temperatures increased from 8 – 25 ° C. Due to variable accumulations of debris on upstream trash racks, water depths and therefore water velocities in each fishway were independent of river discharge. Correlations between water velocity and swimming/position-holding abilities by several species emerged. Turbidity was directly related to river discharge and precipitation events, and many species demonstrated maximum fishway use during periods of decreased water clarity. This study 1) provided evidence of migratory tendencies among several species which were previously considered non-migratory and 2) may assist fishery managers in matching physical and biological conditions within fishways with expected patterns of use by a large array of "coarse" fish, bait fish and sport fish.

[2] Presented at the 60th Midwest Fish and Wildlife Conference – Cincinnati Ohio, December 1998

Introduction

Only within the past 15 years have researchers focused on swimming abilities of non-salmonid warmwater fish and their utilization of fish by-pass structures (e.g., Dexter and Ledet 1997; Schwalme *et al.* 1985). The pertinent literature contains numerous reports of rheotactic behaviour and upstream migration of several non-salmonid or non-clupeid species such as common carp *Cyprinus carpio* (Rodriguez-Ruiz and Granado-Lorencio 1992), northern pike *Esox lucius* (Schultz 1955; Nelson 1983), white suckers *Catostomus commersoni* (Nelson 1983) and walleye *Stizostedion vitreum* (Rawson 1957). These studies indicate that water temperature and discharge are the primary factors that control migration. Several researchers have shown that fishway use by freshwater fish is related to reproduction. Fish that used a ladder on the Parana River, Brazil (Borghetti *et al.* 1994) and fishways in Alberta, Canada (Schwalme *et al.* 1985) had gonads in advanced stages of development. This is also true among darters (Etheostomidae) and members of several other families in the Grand River, Ontario (Bunt *et al.* 1998). To maintain healthy populations of migratory fish, access to spawning and feeding areas must not be restricted. In cases where fish by-pass facilities have been constructed at river obstructions, it is not only vital for fish to ascend or descend successfully, but they must also remain in good physical condition so that their reproductive success is not compromised.

Migration has both temporal and spatial scales. For any species, there may be several life-stage specific habitats. These may include overwintering areas, spawning areas, nursery areas, post-spawn (foraging) areas, refugia during drought or spates and corridors between all of these areas. For the purpose of this paper, fishway use was equated with a strong urge to move (displacement) and this was considered to be evidence of migratory tendencies.

Monitoring fishway use provides data that may be used to increase attraction and passage rates. It is also possible to trap fish within fishways to identify migratory species and the environmental variables that promote or encourage fishway use. It is the purpose of this paper to review springtime movement patterns of 29 warmwater fish species in the Grand River, Ontario, based on data collected from two Denil fishways that were used as migratory checkpoints. Fishway use was related to water temperature, turbidity and water velocities within the fishways.

Methods

Study area

This study was conducted at the Mannheim weir on the Grand River, near Kitchener, Ontario. The Grand River is a mid-order stream that flows 297 km from its source in Dundalk, Ontario to the eastern basin of Lake Erie near Port Maitland (Smith 1994). The Mannheim weir is located approximately mid-way along the river and creates an impound pool for the extraction of regional drinking water. In the spring and summer, the mean depth downstream from the weir is approximately 0.5 m, mean annual discharge is approximately 33 m^3/s and primary substrates consist of cobble and broken rock (Bunt *et al.* 1998). To facilitate upstream movement of fish, the weir was constructed with a Denil fishway at each bank. The construction of the 2.2 m high weir and fishways was completed in 1990. Prior to 1990, fish movements were not restricted at this site. Characteristic of Denil fishways, those at the Mannheim weir use baffles to turn the flow of water back on itself to reduce the velocity of a primary flow through which fish must swim. Water velocities in Denil fishways are low towards the bottom of each fishway flume and increase upward to the water surface where a layer of fast water exists. This implies that fish using these fishways may face varying water velocities depending on swimming depth.

A 27 m Denil fishway that doubled back on itself twice was constructed from reinforced concrete along the west bank of the river. Each of three parallel flumes (slope 10 %) were fitted with metal baffles spaced approximately 25 cm apart. Two resting pools were provided between the flumes. On the east bank of the river, a much simpler and less expensive Denil fishway was constructed. It consisted of a single 11 m reinforced concrete flume with baffles along a 20 % slope. All flumes were 0.6 m wide, 2.15 m deep and were originally completely covered with removable steel plates that did not allow light to penetrate. In the autumn of 1997, the solid cover plates were replaced with grates that allowed consistent lighting inside and outside the fishways.

Preliminary trap data were available from the Mannheim fishways in the form of a consultant report that summarized fish activity from 1990 to 1994. For the present study, fish activity at the Mannheim fishways was monitored from 30 March to 17 July 1995, 15 April to 12 July 1996, and 24 April to 17 July 1997. Water temperature and turbidity were monitored and recorded constantly as part of normal operating procedure at the Mannheim weir pumping station. The Grand River is well mixed and there are no major differences in temperature within the region immediately upstream or downstream from the weir. Headwater and tailwater elevations were recorded daily, as were the water depths at 10 stations within the west fishway and 5 stations within the east fishway. Data collected in the field consisted of measurements of the vertical distance from a series of fixed points along the fishway to the water surface using a calibrated rod to the nearest cm. Water depths were calculated by subtracting the field measurement values from the previously measured vertical distance to the baffle crests for the various measurement locations. Depth data were later converted into water velocities according to equations derived from scale models of the two fishways. Denil fishway water depths, discharge, velocities, and water surface profiles are interdependent and relationships among them have been developed through hydraulic studies of scale and prototype models (Katopodis and Rajaratnam 1983; Rajaratnam and Katopodis 1984; Katopodis *et al.* 1997). In these studies, two model scales (1:6 and 1:3) were investigated and compared with a prototype scale (1:1) for the standard Denil design, similar to those at the Mannheim weir. The similarity of the results from the three model scales was demonstrated and the three sets of data fit the same curve. Results were also confirmed in a field study (Rajaratnam *et al.* 1992) which demonstrated the reliability of these relationships and the use of depth measurements to estimate fishway discharges and velocities. In addition, concordance between estimated velocities and actual velocities at the Mannheim weir was verified with direct measurements of water velocity within the fishways using a Sigma PVM ultrasonic Doppler-shift velocity meter. Discharge and velocity were directly related to water depth within each fishway. Maximum water velocities were present within the upper layer (0.8 x water depth) of the primary flow approximately 3 m downstream of each fishway trap. These water velocities are reported. The minimum velocities yielded by the rating curves were 0.24 m/s and 0.33 m/s for the west and east fishway, respectively. Water depths and water velocities in each fishway were linked to river levels and debris accumulation on upstream trash-racks and blocking screens. I attempted to keep the fishway traps and blocking screens clear of debris for the duration of the study to reduce fluctuations in water velocities within the fishways. This was accomplished with limited success; however, the reductions in depth that occurred in response to debris accumulation, provided a range of water velocities that fluctuated over several hours. Upstream passage was correlated to distinct ranges of water velocities for each species that used the fishways.

Both fishways allowed fish to pass freely until they entered the top pool, where fish larger than juvenile cyprinids and centrarchids (approximately > 60 mm TL) were prevented from escaping upstream by a wire mesh blocking screen (mesh size approximately 1.5 cm). I assumed that no fish caught in the fishway traps were of upstream origin. Escape downstream from the upper pool was prevented with a wire mesh funnel-trap. The screens and the funnel-trap were usually cleared of debris two or three times daily. Fishway traps were checked daily or twice daily between 09:00 and 12:00 and from 17:00 to 20:00 from mid-April to mid-July for each of the study years. During sampling episodes, a small diameter blocking mesh (mesh size 0.5 cm) was used to minimize the loss of trapped fish (particularly small cyprinids). Fish were removed from the fishway traps with dipnets and were placed in coolers for examination and enumeration before being released back into the river.

Results and Discussion

There was some variability in the weather in Southern Ontario during the three study years and this affected conditions at the Mannheim weir. River levels remained constant during the investigation except for two peaks during storms at the end of April and beginning of June 1995, during several occasions from May to July 1996, early May 1997 and the first week of June 1997. When river levels were high, turbidity values were concomitantly elevated.

White suckers, northern hog suckers *Hypentelium nigricans* and large common shiners *Luxilus cornutus* and striped shiners *L. chrysocephalus* began using the west fishway when water temperatures were consistently above 8 °C. Spawning among white suckers and northern hog suckers usually begins when water temperature is about 10 °C (Barton 1980; Curry and Spacie 1984; Matheney and Rabeni 1995). Although data are not shown, observations from the Grand River suggest that males migrate first, as also reported by Barton (1980). Timing of migrations at the Mannheim fishways corresponded with literature reports that indicate white suckers spawn first, followed shortly thereafter by northern hog suckers (Curry and Spacie 1984).

Fish usually began to use the east fishway 2 – 3 d after they began to use the west fishway. Smallmouth bass *Micropterus dolomieu,* and all other species began using the fishways when water temperatures were consistently above 10 °C. The maximum temperature of the Grand River in July of each of the study years was approximately 25 °C. The mean turbidity for each year combined was 7.3 ± 0.6 FTU (median 4.4 FTU, n = 259). The range of recorded turbidity was 0.4 – 95.7 FTU.

Under the observed physical and hydraulic conditions, 29 species of fish used the Mannheim fishways. Over 11 800 fish were sampled from the fishway traps. The diversity of fish species that used the fishways increased annually since 1994. In 1995, greenside darters *Etheostoma blennioides,* and green sunfish *Lepomis cyanellus* were observed to use the Mannheim fishways for the first time. Species first captured in the fishway traps in 1996 included black crappie *Pomoxis nigromaculatus*, bluegill *Lepomis macrochirus*, largemouth bass *Micropterus salmoides*, bluntnose minnow *Pimephales notatus* and golden shiner *Notemigonus crysoleucas.* Each of these species is often considered to be more lacustrine and better adapted to lentic habitat in impounded waterways (Martinez *et al.* 1994).

West fishway

The west fishway accommodated approximately 67 % (7961) of total fish passage at the Mannheim weir. There were two patterns of use by the species that were represented in the trap samples. Some species demonstrated constant or sustained use (e.g., striped shiner, common shiner). Other species used the west fishway in a more punctuated or protracted fashion (e.g., greater redhorse *Moxostoma valenciennesi*, largemouth bass and green sunfish). Twenty-five species used the west fishway and 22 of these were common to both fishways. Three species (stonecats *Noturus flavus*, greenside darters and black crappie) used the west fishway exclusively. The species that used the west fishway, the date of peak usage, temperature during peak usage and water velocity associated with peak usage over the three year study period are summarized in Figure 2.1. For example, both largemouth bass and green sunfish used the west fishway most intensively during the first and second week of June in each of the study years. During this period, water temperatures ranged between 16 and 18 º C and water velocities in the fishway varied between 0.24 and 0.4 m/s. Smallmouth bass used the west fishway most intensively between the last week of May and the first week of June. Water temperature was 15 – 16 º C and water velocities in the fishway varied between 0.24 and 0.65 m/s. In Wisconsin rivers, smallmouth bass adults also migrate upstream in May when temperatures are near 15 °C (Langhurst and Schoenike 1990). In July, modest numbers of juvenile smallmouth bass (< 100 mm TL) also used the fishways (data not shown).

Turbidity was strongly correlated with precipitation events at the study site and upstream. Table 2.1a summarizes the relationships between use of the west fishway and river turbidity. Several species demonstrated maximum use of the west fishway during periods of increased turbidity (i.e., turbidity values greater than the mean turbidity for each year combined). These species included brown bullhead *Ameiurus nebulosus*, black crappie, green sunfish, greenside darter, largemouth bass, pumpkinseed sunfish *L. gibbosus*, rock bass *Ambloplites rupestris* and striped shiners. The turbidity during use by brown bullhead, black crappie, greenside darter, rock bass and striped shiners was highly variable. In contrast, several other species used the west fishway most when turbidity was low. These species included bluegill, common carp, common shiners and common shiner/striped shiner hybrids, emerald shiners *Notropis atherinoides*, hornyhead chub *Nocomis biguttatus*, golden redhorse *M. erythrurum*, northern hog suckers, river chub *Nocomis micropogon*, rosyface shiners *N. rubellus*, smallmouth bass, stonecats and white suckers. The turbidity of the river during use by common shiners, common shiner hybrids, smallmouth bass and stonecats was highly variable. Too few bluntnose minnows, creek chub *Semotilus atromaculatus*, golden shiners and greater redhorse suckers used the west fishway for any generalizations to be made.

There is some controversy regarding the relative importance of temperature and stream discharge on the initiation of fish migration and spawning. Some authors indicate that sucker migrations begin after a sudden increase in stream discharge with water temperatures near 10 ºC (Barton 1980). Conversely, Curry and Spacie (1984) observed that initiation of spawning coincided with an increase in water temperature followed by a decrease in stream discharge. Geen *et al.* (1966) reported no correlation between temperature and discharge, while other authors suggest that discharge is most important (Walton 1979).

East fishway

Approximately 33 % (3849) of total fish passage at the Mannheim weir occurred at the east fishway. Twenty-six species were represented in the fishway trap samples and four species used the east fishway exclusively. These species included rainbow darters *E. caeruleum*, longnose dace *Rhinichthys cataractae*, common/emerald shiner hybrids and Iowa darters *E. exile*. There were two patterns of use at the east fishway, similar to the observations at the west fishway. Some species demonstrated prolonged or sustained use, such as common and striped shiners and river chub. Punctuated or more temporary use occurred among longnose dace, largemouth bass, bluntnose minnow, rosyface shiner and golden shiner. Figure 2.2 summarizes the most intensive periods of use by each species, water temperature, and water velocity during use. For example, peak use by largemouth bass at the east fishway occurred during the second week of June at water temperatures between 19 and 20 º C. During use by largemouth bass, water velocities ranged between 0.32 and 0.4 m/s. Green sunfish used the east fishway most intensively during the second week of June and the first week of July. Water temperatures varied between 19 and 21 º C and water velocities were 0.3 – 0.4 m/s. Smallmouth bass used the east fishway during the same period as the west fishway (i.e., last week of May to the first week of June). During use by smallmouth bass, water temperatures ranged between 16 and 17 º C and water velocities were 0.33 – 0.42 m/s.

Relationships between maximum use of the east fishway and turbidity are summarized in Table 2.1b. Common carp, emerald shiners, hornyhead chub, golden redhorse, northern hog suckers and white suckers used the east fishway during turbidity conditions that did not match turbidity conditions during maximum use of the west fishway. Species that demonstrated maximum use of the east fishway during periods with elevated turbidity included brown bullheads, common carp, creek chub, emerald shiners, longnose dace, largemouth bass, golden redhorse, northern hog suckers, rock bass, and white suckers. Turbidity during use by common shiners and common shiner/striped shiner hybrids, hornyhead chub, northern hog suckers, pumpkinseeds, striped shiners and white suckers was highly variable. Bluegill, bluntnose minnows, green sunfish, Iowa darters, greater redhorse, river chub, rosyface shiners and smallmouth bass used the east fishway most when turbidity was low. It was not possible to generalize relationships between turbidity and use of the east fishway for common shiner/emerald shiner hybrids, golden shiners, and rainbow darters due to insufficient sample sizes.

There were seasonal species shifts with some overlap, from catostomids to cyprinids, to ictalurids, percids and then centrarchids as water temperatures increased from 8 º C to 25 º C in the Grand River. Maximum fishway use by several species occurred during periods of decreased water clarity (during or after storms). Species diversity in the fishway traps was affected by water velocity in the fishways and swimming / position holding abilities of the species that entered the fishways (Bunt, unpublished videographic data). Benthic species probably utilized low velocities in the boundary layer along the fishway walls and floor. Small individuals fit in the spaces between baffles and used burst swimming to progress upstream from refuge to refuge (Bunt, unpublished videographic data). In addition, interspecific interactions (exclusion and predation) likely occurred in the fishways and the importance of this needs to be elucidated in further studies. Of the 29 species that used the Mannheim fishways, the only ones that have been reported to be migratory and use fishways include common carp (Monk *et al.* 1989; Dexter and Ledet 1997), smallmouth bass (Dexter and Ledet 1997), bullheads (Dexter and Ledet 1997), largemouth bass (Dexter and Ledet 1997) and white suckers (Schwalme *et al.* 1985; Katopodis *et al.* 1991). Blackside darters *Percina maculata*, fantail darters *E. flabellare*, northern pike, silver shiners *N. photogenis*, black redhorse *M. duquesnei*, yellow perch *Perca flavescens*, least darters *E. microperca*, johnny darters *E. nigrum,* and brook stickleback *Culaea inconstans* were present downstream from the Mannheim weir (C. Bunt, personal observation) but did not use the fishways. Northern pike and yellow perch have been reported to use other fishways in Canada (Fernet 1984; Schwalme *et al.* 1985). Lack of fishway use by these species in this study may have been related to physical limitations, behavioural limitations, low abundance or lack of detection in the fishways. Northern pike, for example, may have used the fishways in March or April, before monitoring began.

There was evidence of migratory tendencies among several species that were not previously considered migratory. The results of this study may assist fisheries managers in matching physical and biological conditions in fishways with expected patterns of use by warmwater fishes. There are limited data on fishway use by warmwater species and this is important for the development of design criteria and fishway maintenance programs for non-salmonid migrants. Fishway use and the facilitation of upstream passage over lowhead barrier dams, may be enhanced by ensuring that fishways are available (i.e., clear of debris) and easy to locate. Although steeper fishways are cheaper to construct, they may exclude many species. Steeper fishways may also limit use to individuals that are 1) able to swim fast enough and/or 2) individuals that are able to exploit velocity refugia within the fishways. Steeper fishways may also reduce or shift the window for passage. Finally, velocities through which fish must pass may be manipulated through the implementation of “dynamic fishways”. These would use velocity moderators, or gates, to match fishway flows to a species’ swimming abilities at times of the year when these species have been observed to migrate.

Acknowledgements

Thanks to Brett van Poorten and Lin Wong for assistance with trapping and data processing. This work was funded in part by an NSERC graduate scholarship.

Table 2.1. a) Total numbers of each species passed at the west fishway and corresponding mean, maximum and minimum turbidity values for dates of maximum passage between 1995 and 1997. b) Total numbers of each species passed at the east fishway and corresponding mean, maximum and minimum turbidity (n = number of fish passed during various turbidity conditions).

	a) WEST FISHWAY				b) EAST FISHWAY			
Species	Total Passed	Mean Turbidity during dates of Max. Passage	Min. Turbidity during dates of Max. Passage (n)	Max. Turbidity during dates of Max. Passage (n)	Total Passed	Mean Turbidity During dates of Max. Passage	Min. Turbidity during dates of Max. Passage (n)	Max. Turbidity during dates of Max. Passage (n)
Black crappie	153	10.85	1.7 (1)	20 (33)	0	-	-	-
Bluegill	91	2.7	1.7 (1)	3.7 (13)	47	5.3	-	5.3 (18)
Bluntnose minnow	1	10	-	10 (1)	22	1.7	-	1.7 (18)
Brown bullhead	30	10.23	3.3 (2)	20 (9)	10	9.17	2.0 (1)	20.0 (6)
Carp	9	3.9	1.9 (1)	7 (1)	5	16.9	13.8 (2)	20.0 (2)
Common/striped shiner	750	6.27	2.7 (393)	10.9 (50)	1120	4.63	1.2 (450)	10.0 (33)
Common/emerald shiner	0	-	-	-	1	4.2	-	4.29 (1)
Common shiner	1764	3.63	1.0 (54)	7.8 (106)	617	5.27	0.8 (103)	10 (100)
Creek chub	2	5	2.1 (1)	7.9 (1)	33	4.7	2.0 (2)	7.4 (24)
Emerald shiner	516	3.9	2.9 (501)	4.9 (7)	18	34.8	-	34.8 (18)
Golden shiner	1	15.3	-	15.3 (1)	1	1.7	-	1.7 (1)
Greenside darter	323	8.1	2.7 (1)	13.5 (321)	0	-	-	-
Green sunfish	38	4.1	1.0 (3)	8.4 (6)	23	3.3	1.3 (3)	5.3 (8)
Hornyhead chub	81	3.1	0.8 (2)	6.4 (1)	94	6.9	3.3 (5)	10.0 (3)
Iowa darter	0	-	-	-	24	1.2	-	1.2 (24)
Largemouth bass	25	7.1	6.8 (4)	7.4 (3)	13	5.2	0.4 (1)	10.0 (3)
Longnose dace	0	-	-	-	5	10.7	-	10.7 (3)
Golden redhorse	168	3.27	1.9 (34)	5.8 (4)	365	5.23	1.7 (18)	7.8 (166)
Greater redhorse	1	4.3	-	4.3 (1)	4	3.95	1.7 (1)	6.2 (3)
Northern hog sucker	512	3.7	2.9 (81)	5.0 (37)	51	8.9	1.2 (1)	20.0 (15)
Pumpkinseed	408	5.63	1.7 (23)	7.8 (28)	426	6.07	5.3 (97)	7.4 (19)
Rainbow darter	0	-	-	-	1	5.7	-	5.7 (1)
River chub	4	1.95	1.8 (1)	2.1 (2)	3	3.2	2.7 (1)	3.7 (2)
Rock bass	1411	12.83	7.8 (11)	20.0 (147)	315	4.93	1.5 (14)	10.0 (58)
Rosyface shiner	247	4	2.7 (17)	5.3 (179)	5	4.6	-	4.6 (4)
Smallmouth bass	49	5.33	1.5 (5)	7.8 (1)	81	3.57	1.9 (5)	6.7 (8)
Stonecat	221	6.43	0.8 (88)	15.8 (3)	0	-	-	-
Striped shiner	44	10.63	4.8 (2)	16.3 (6)	90	4.9	2.0 (14)	10 (6)
White sucker	1112	3.7	2.9 (67)	5 (92)	475	24.03	6.4 (41)	34.8 (41)

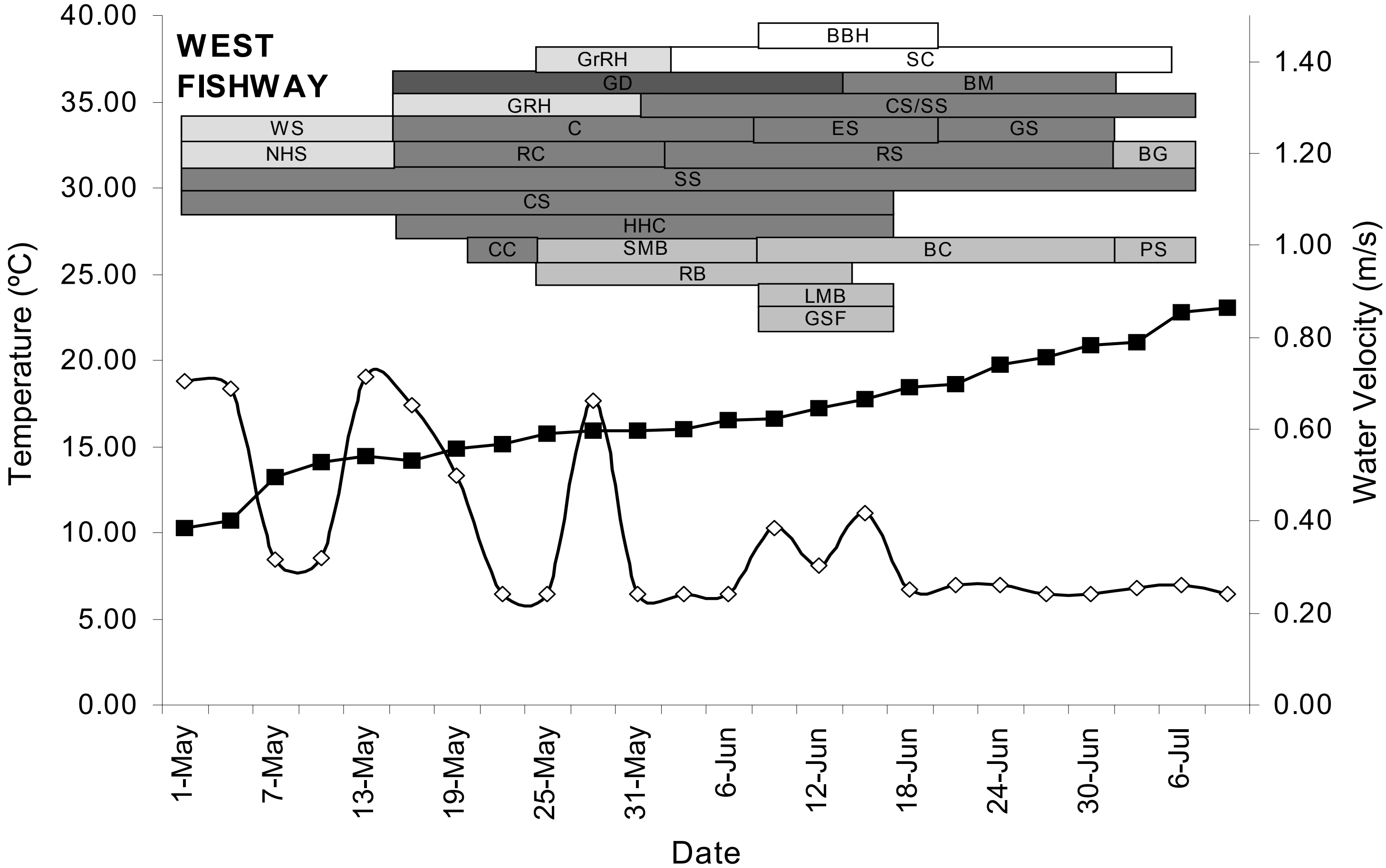

Figure 2.1. Seasonal, thermal and hydraulic conditions during use of the west fishway by 25 species that were passed between 1995 and 1997. Gray and white bars indicate periods of maximum passage by each species. White and shades of gray indicate related families of fish species. Black squares represent mean water temperature and open diamonds represent mean water velocities for days of maximum passage within the fishway. Species abbreviations are as follows: BBH = brown bullhead, GrRH = greater redhorse, SC = stonecat, GD = greenside darter, BM = bluntnose minnow, CC = creek chub, GRH = golden redhorse, CS/SS = common/striped shiner hybrids, WS = white sucker, C = carp, ES = emerald shiner, GS = golden shiner, NHS = northern hog sucker, RC = river chub, RS = rosyface shiner, BG = bluegill, SS = striped shiner, CS = common shiner, HHC = hornyhead chub, SMB = smallmouth bass, BC = black crappie, PS = pumpkinseed, RB = rockbass, LMB = largemouth bass and GSF = green sunfish.

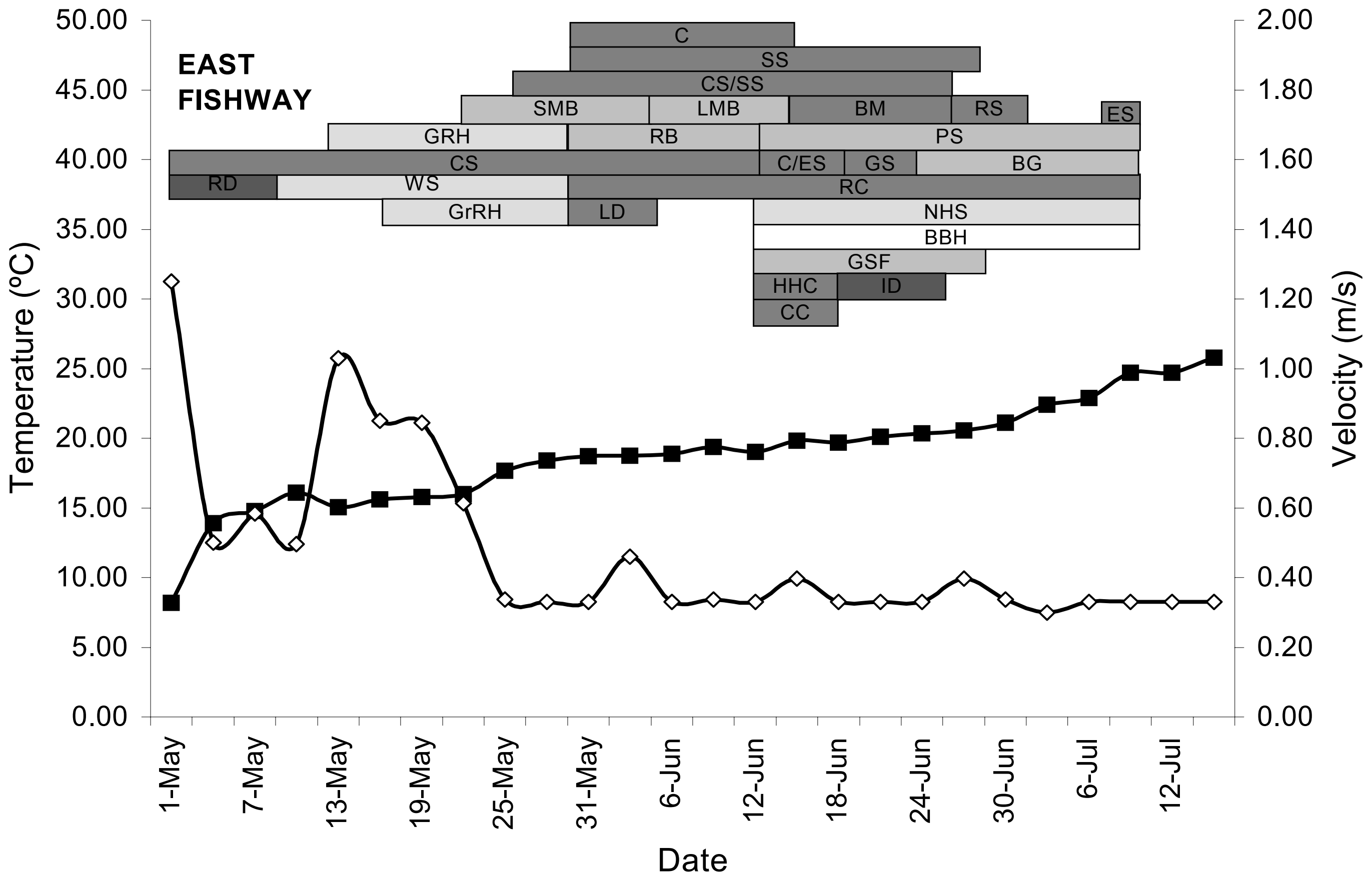

Figure 2.2. Seasonal, thermal and hydraulic conditions during use of the east fishway by 26 species that were passed from 1995 to 1997. Gray and white bars indicate periods of maximum passage by each species. White and shades of gray indicate related families of fish species. Black squares represent mean water temperature and open diamonds represent mean water velocities for days of maximum passage within the fishway. Species abbreviations are as in Figure 2.1 with the following additions: RD = rainbow darter, LD = longnose dace, C/ES = common/emerald shiner hybrids and ID = Iowa darter.

CHAPTER 3

Attraction and passage efficiency of white suckers and smallmouth bass by two Denil fishways[3]

Abstract

I compared two Denil fishways, located on the west (low velocity - 10 % slope) and east (high velocity - 20% slope) side of the Mannheim weir, Grand River, Ontario, for use by upstream migrating white suckers *Catostomus commersoni* and smallmouth bass *Micropterus dolomieu*. Mark-recapture and radiotelemetry were used to assess attraction and fish passage. Movement of 85 radiotagged fish was monitored continuously during spring and early summer of 1995 and 1996. Attraction and passage efficiency of white suckers at the west fishway was approximately 50 %, and 55 %, respectively. Attraction efficiency of white suckers at the east fishway was approximately 59 % and passage efficiency was 38 %. The attraction and passage efficiency of smallmouth bass at the west fishway was approximately 82 % and 36 %, respectively. At the east fishway, attraction efficiency of smallmouth bass was approximately 55% while passage efficiency was 33%. There was an exponential decline in the numbers of both species that used each fishway relative to water velocity. The maximum water velocities used by white suckers and smallmouth bass were 0.96 m/s and 0.99 m/s, respectively. Distracting flows near the west fishway appeared to affect attraction. Both fishways passed equal numbers of smallmouth bass per year, and smallmouth bass that used the east fishway were significantly larger than individuals that used the west fishway. In contrast, more than twice as many white suckers used the west fishway and these fish were significantly larger than those that used the east fishway. Differences in passage were

[3] Published - North American Journal of Fisheries Management 19: 793-803.

related to burst and critical swimming speeds, and the use of velocity refugia within the fishways.

Introduction

Fishways allow upstream migrating fish to bypass natural and artificial river barriers (Beach 1984; Clay 1995). Biologically oriented fishway research has focused on anadromous fishes, such as salmonids and clupeids. As a result, fishways do not usually include design features that are relevant to the behaviour and swimming performance of freshwater fish (Lucas and Frear 1997). This information is vital if fishways designed to accommodate freshwater species are to be successful.

Dams and other river barriers increasingly compromise fish movements in temperate and tropical streams and rivers. Many families of warmwater fishes including centrarchids, catostomids, esocids, percids, cyprinids and ictalurids migrate up streams and rivers, especially during spawning periods (Raney and Webster 1942; Schultz 1955; Rawson 1957). Some members of these families are known to use fishways (Nelson 1983; Derksen 1988; Langhurst and Schoenike 1990; Harris and Mallen-Cooper 1994; Lucas and Frear 1997). Fishway use varies, however, according to fishway design, water velocities within the fishways, water temperature, time of day, fish size and swimming ability (Fernet 1984; Schwalme *et al.* 1985; Derksen 1988; Pavlov 1989; Katopodis *et al.* 1991). Passage efficiency of a limited number of cool and cold-warmwater fishes has been investigated using mark - recapture (Linlokken 1993) and videography (Dexter and Ledet 1997; Haro and Kynard 1997). In a recently published paper, Haro *et al.* (1999) used passive integrated transponder (PIT) technology to compare transit time of American shad *Alosa sapidissima* and blueback herring *Alosa aestivalis*, through Denil and Alaska Steeppass fishways, relative to slope and headpond level. Radiotelemetry has not been used to track individual movements and behaviour of non-salmonid fishes in fishways to determine attraction and passage efficiency.

The objectives of this study were to describe conditions during fishway use, and to quantify attraction efficiency and passage efficiency of white suckers *Catostomus commersoni* and smallmouth bass *Micropterus dolomieu* downstream from a recently constructed weir equipped with two Denil fishways. I chose to study white suckers and smallmouth bass because they are morphologically distinct and differ in swimming ability. The primary null hypotheses for each species was attraction efficiency $_{\text{east fishway}}$ = attraction efficiency $_{\text{west fishway}}$ and passage efficiency $_{\text{east fishway}}$ = passage efficiency $_{\text{west fishway.}}$ I also measured the critical swimming speeds of adult smallmouth bass and used similar data for white suckers from the literature, to help explain successful passage relative to hydraulic conditions within the two fishways.

Methods

Study area

This study was conducted at the Mannheim weir on the Grand River, near Kitchener, Ontario. The Grand River is a mid-order stream which flows 297 km from its source in Dundalk, Ontario to the eastern basin of Lake Erie (Smith 1994). The Mannheim weir is located approximately mid-way along the river (Figure 3.1) and creates an impoundment for the extraction of regional drinking water. Mean depth downstream from the weir is approximately 0.5 m, mean annual discharge is approximately 33 m^3/s and primary substrates consist of cobble and broken rock (Bunt *et al.* 1998). The construction of the 2.2 m high weir and fishways was completed in 1990. Characteristic of Denil fishways, those at the Mannheim weir use baffles to turn the flow of water back on itself to reduce the velocity of a primary flow through which fish must swim. Prior to 1990, fish movements were not restricted at this site.

To allow upstream passage of fish, a 27 m Denil fishway that doubled back on itself twice was constructed from reinforced concrete along the west bank of the river (Figure 3.2). Each of three parallel flumes (slope 10 %) were fitted with metal baffles spaced approximately 25 cm apart. On the east bank of the river, a much simpler and less expensive Denil fishway was constructed. It consisted of a single 11 m reinforced concrete flume with baffles along a 20 % slope (Figure 3.2). All flumes were 0.6 m wide, 2.15 m deep and were completely covered with removable steel plates.

Telemetry

Digitally coded radiotags (1.9 g in water, 10.6 mm x 28 mm x 7 mm, with 2.5 s pulse rates) were externally attached to 32 white suckers and 53 smallmouth bass > 300 mm TL. External tagging was chosen because most fish were ready to spawn and therefore considered unfit for surgical implantation without the risk of affecting normal behaviour. I tagged equal proportions of males and females of each species. The ratio between tag weight and fish weight was less than 2 %, as recommended by Winter (1983). After a brief recovery period, each transmitter was tested and fish were released at randomly chosen sites, approximately 150 m downstream from the weir.

Movement of radiotagged smallmouth bass and white suckers was determined using an array of seven stationary submerged antennas near the weir and within the fishways. One antenna was positioned within each of the three flumes of the west fishway and another was positioned midway within the east fishway. One antenna was also positioned at the entrance of each fishway and the final antenna was positioned between the fishway entrances to record back and forth movement. All seven antennas were scanned every 7.5 ms for telemetry signals. A receiver and digital spectrum processor (SRX_400 and DSP_500, respectively, Lotek Engineering Limited) equipped with fast multiple antenna switching capabilities, were used to determine transmitter locations relative to the focal point of the nearest antenna. Pulse-code discrimination was used to identify valid signals. Signal-strength calibrations permitted accurate determination of the distance between transmitters and receiving antennas to within 0.3 m. The signal reception areas at the weir were verified regularly by manually shifting reference radiotags throughout the zones monitored by the antenna array. Reception cell radii varied between 3 m and 4 m depending on water depth (usually < 1 m) and conductivity (range 450 - 550 µS/cm). Visual observations of radiotagged fish were often possible and were used to corroborate telemetry data.

It was my goal to describe fishway use among a group of smallmouth bass and white suckers that had a propensity to enter and use the fishways but faced variable flow conditions. I recognized that an evaluation of fishway passage efficiency of free swimming fish is a complicated and difficult task. Tagged fish may react negatively in high velocity flows, or radiotagged fish may react variably such that some fish may repeatedly enter a fishway and exit again downstream. For this study, such behaviour was considered to be partial or unsuccessful fishway use. Complete or successful fishway use consisted of trapping or detection of radiotagged fish within the fishway trap. Attraction efficiency was calculated as the ratio between the number of individuals that were detected at each fishway entrance and the number that were released downstream. Passage efficiency was determined from the ratio of successful to overall attempts to use a fishway. I created control groups by anchor-tagging a large number of fish of both species whose recapture patterns were compared to radiotagged fish. It was not possible to collect all fish for anchor-tagging and radio attachment from the fishway traps. I therefore angled 11 smallmouth bass near the fishway entrances and statistically compared their use of the fishways with smallmouth bass that were caught in the fishway traps. If no differences were detected between the number of angled versus trapped smallmouth bass that used the fishways, data for smallmouth bass were pooled.

Mark-Recapture and Data Analysis

Fish that successfully ascended each of the two fishways were trapped just before the upstream exit in fishway traps that consisted of steel blocking screens (mesh size 1.5 cm) and removable aluminum funnels made from 2 cm wire mesh (Figure 3.2). Installation and monitoring of fishway traps began in mid April before any fish were observed near the weir. Water temperatures were recorded each time fishway traps were checked and at midday using a hand held thermometer at the west fishway entrance. The Grand River is well mixed and there is no difference in water temperature on the east or west side of the weir. When the water temperature was warm enough, white suckers were trapped in the fishways and smallmouth bass were either trapped in the fishways or angled near the fishway entrances. These fish were either radiotagged, or externally marked (Floy FD-94 anchor-tag), and released at randomly chosen release sites, downstream. Fishway traps were checked and cleared daily between 0900 - 1400 hours and 1600 - 0200 hours. All trapped fish were removed from the fishway traps with a dipnet and enumerated. Fish were measured (TL, mm), and most were tagged and released downstream. In all situations, fish that returned to either fishway trap a second time were released upstream from the weir. The mean total lengths of white suckers and smallmouth bass, including recaptured fish collected from the fishway traps (excluding juveniles < 200 mm for white suckers and smallmouth bass, Scott and Crossman 1973), were compared with one way analysis of variance (ANOVA). Numbers of anchor-tagged and radiotagged fish that were subsequently recaptured in the fishway traps were compared using chi-square contingency analysis. Radiotagged smallmouth bass and white suckers that were recaptured or detected in the fishway traps were considered to have made a successful attempt at using a fishway. Attempts to use a fishway occurred when radiotagged fish were detected more than 2 m inside either fishway entrance. Attraction and passage efficiencies of both species were compared at each fishway using 2 x 2 contingency analysis for proportions with corrections for continuity, and the power of the performed test was determined according to the methods in Zar (1984). All statistical tests were considered significant at an alpha level of 0.05 and all means are reported ± 1 S.E.

Fishway Conditions

Denil fishway water depths, discharge, velocities, and water surface profiles are interdependent and relationships between them have been developed through hydraulic model studies (Katopodis and Rajaratnam 1983; Rajaratnam and Katopodis 1984). Several extensive laboratory investigations with scale and prototype models of Denil fishways have been conducted (Rajaratnam and Katopodis 1984; Katopodis *et al.* 1997). In these studies, two model scales (1:6 and 1:3) were examined and compared with a prototype scale (1:1) for the standard Denil design, similar to those at the Mannheim weir. The similarity of the results from the three scales was demonstrated and the three data sets fit the same curve. Results were also confirmed in a field study (Rajaratnam *et al.* 1992), thereby validating the reliability of these relationships and the use of depth measurements to estimate fishway discharges and velocities. In addition, concordance between estimated velocities and actual velocities at the Mannheim weir was verified with direct measurements of water velocity within the fishways using a Sigma PVM ultrasonic velocity meter. Water depths were therefore measured directly at the Mannheim weir and used to calculate velocities in the two fishways.

Water depths downstream from each fishway trap were recorded to produce a flow profile and to estimate water velocities from a velocity-rating curve. The minimum velocities yielded by the rating curves were 0.24 m/s and 0.33 m/s for the west and east fishway, respectively. Data collected in the field consisted of measurements of the vertical distance from a series of fixed points along the fishway to the water surface using a calibrated rod to the nearest cm. Water depths were calculated by subtracting the field measurement values from the previously measured vertical distance to the baffle crests for the various measurement locations. Turbulence at the surface of the primary flow compromises true estimates of velocity (Katopodis and Rajaratnam 1983). Calculations of maximum water velocity that any fish would experience during fishway use were therefore derived for a region corresponding to 0.8 x water depth.

Swimming Abilities

I determined the critical swimming speeds (Ucrit) for Grand River smallmouth bass that were similar in size to fish chosen for radiotagging. Critical swimming speed is a measure of prolonged swimming and represents the maximum velocity a fish can maintain for a prescribed period of time (Brett 1964). Fish were held without food for 48 h prior to experimentation. All swimming speed experiments were conducted in ambient river water using a modified 70 L Blazka-Fry respirometer. Fish were acclimated to the respirometer for 24 h at water velocities that approximated 0.5 body lengths (BL)/s. Critical swimming speeds (m/s) were determined using 10 minute increments between constant step-wise velocity increases of approximately 1 - 1.5 BL/s according to the procedures of Brett (1964). Velocities were corrected for blocking effects caused by the flow of water around the bodies of large fish within the swim tube according to Smit *et al.* (1971). The water temperature for all trials ranged between 15 and 20 °C and all fish were acclimated to natural light:dark cycles to minimize the effects of photoperiod and temperature on centrarchid swimming performance (Kolok 1991). Relationships between Ucrit and total length were determined using regression analysis. Information on swimming ability of white suckers was derived from the available literature (Jones *et al.* 1974).

Results

Hydraulic Conditions in Fishways

The mean water velocity in the west fishway was 0.89 ± 0.02 m/s (range < 0.24 - 1.57 m/s, n = 207). This was significantly less than the water velocity in the east fishway (0.99 ± 0.03 m/s, range < 0.33 - 2.05 m/s, n = 162, $P < 0.001$). Water velocities in the east fishway were greater than water velocities in the west fishway except during rare occasions when large amounts of debris accumulated on the east fishway blocking screen. Variable accumulations of debris on upstream blocking screens altered water depths so that a range of water velocities was available in both fishways throughout the study period. Velocities in the fishways varied on a daily basis as debris accumulated and was cleared from the blocking screens. Variations in flow and velocity were most pronounced after mid June, when macrophytes became established upstream. Velocities were greatest after fishway traps and blocking screens were cleaned. Velocities were lowest after large amounts of debris had accumulated on blocking screens after storms. Maximum fishway use occurred at intermediate velocities with some accumulation of debris on blocking screens.

White Suckers

White suckers were first observed at the fishway entrances and began to use both fishways on 3 May 1995, after which, mid-day water temperature was consistently above 9 °C. Maximum passage occurred on 3 May 1995, when 92 white suckers were captured in the west fishway trap. The last recorded passage was on 15 July 1995, when two white suckers were caught in the east fishway, while the water temperature was 23 °C. In 1996, white suckers began to use the west fishway on 6 May, after which water temperature was consistently above 8 °C. Maximum passage at the west fishway occurred on 17 May, when 101 white suckers passed upstream while the water temperature was 11 °C. White suckers began to use the east fishway on 9 May 1996 when the water temperature was consistently above 10 °C. Maximum passage at the east fishway occurred on 11 May 1996, when 76 white suckers used the fishway while the water temperature was 10 °C. The last recorded passage of white suckers at the west and east fishway was on 9 July (temperature = 18 °C), and 15 July (temperature = 21 °C), respectively. White suckers were caught most frequently in the fishway traps from 3 May - 12 May 1995 and 6 May - 18 May 1996. Aggregations of white suckers were observed near the weir and fish often appeared to follow one another. White suckers were periodically located in the vicinity of the weir (within 20 m) for 12 ± 2 d. During this period 50 % (95 % C.I. = 33 – 67 %) and 59 % (95 % C.I. range 42 – 76 %) of radiotagged white suckers were attracted to the west and east fishways, respectively. The attraction efficiency for white suckers at both fishways was not significantly different ($Z = 0.78$, $p > 0.5$). Radiotagged white suckers were detected near the weir and fishway entrances within 1 d of release (mean 0.75 ± 0.25 d). Twenty-two fish approached the weir and 45 % were first detected in the high velocity zone upstream from the west fishway entrance (Figure 3.2). Highly variable exploratory movements (Figure 3.3a) as well as long periods with no movement near the weir and fishways were common.

Approximately half of all radiotagged white suckers that entered the west fishway ($n = 11$) swam to the exit. Passage efficiency of white suckers by the west fishway was estimated to be 55 % (95 % C.I. range = 25 – 84 %). There were 8 attempts to use the east fishway where passage efficiency of white suckers was estimated at 38 % (95 % C.I. range = 4 – 71 %). Passage efficiency at each fishway did not differ statistically ($Z = 0.17$, $p > 0.5$). Over 69 % of total white sucker passage occurred at the west fishway (Table 3.1). These white suckers were significantly larger than white suckers that used the east fishway ($F = 25.75$, $df = 1328$, $p < 0.001$, Table 3.1).

Approximately 27 % of white suckers caught in the west fishway used velocities < 0.24 m/s. Similarly, approximately 70 % of white suckers used the east fishway while water velocities were < 0.33 m/s. There was an exponential decline in the numbers of white suckers that used both fishways, relative to water velocity. The maximum water velocities used by white suckers was 0.96 m/s. White suckers were located near both fishways at night, but twice as many attempts to use either fishway occurred during daylight hours (Table 3.2).

Smallmouth Bass

Smallmouth bass began to use both fishways on 9 May 1995 when the water temperature was consistently above 10 °C. Maximum passage at both fishways occurred on 5 June 1995, when eight smallmouth bass were caught in each fishway trap. The water temperature was 16 °C. The last recorded passage of smallmouth bass in 1995, was on 27 June (temperature = 20 °C), and 17 June (temperature = 18 °C), for the west and east fishway, respectively. In 1996, smallmouth bass began using the east fishway on 18 May when the water temperature was 14 °C. Maximum passage occurred on 18 May, when nine smallmouth bass used the east fishway. Passage at the west fishway began on 20 May when the water temperature was 16 °C. The last recorded passage for smallmouth bass in the west and east fishways was on 14 July and 15 July, respectively, when the water temperature was 21 °C. Most smallmouth bass were captured in the fishway traps from 15 May - 5 June 1995 and 18 May - 13 June 1996. Frequent freshets and abnormally cool June temperatures interrupted smallmouth bass migrations in 1996. Tagged and untagged smallmouth bass were often observed in the high velocity zone near the west fishway entrance (Figure 3.2). Smallmouth bass were first detected near the weir and fishway entrances 3.0 ± 0.5 d after release. There was no difference in time to detection or attempts to use the fishways among trapped and angled fish. Data for smallmouth bass were therefore pooled.

During the study, 82 % (95 % C.I. = 69 – 95%) of smallmouth bass were attracted to the west fishway while 55 % (95% C.I. = 38 – 72 %) were attracted to the east fishway. The attraction efficiency of smallmouth bass by each fishway was not significantly different ($Z = 1.82$, $0.1 < p < 0.05$, power = 0.43). As with white suckers, exploratory movements were common (Figure 3.3b) and lasted for 16 ± 2 d for fish that did not successfully pass upstream from the weir. The number of attempts to use the fishways during the day exceeded nocturnal use by a factor of four (Table 3.2).

Passage efficiency of smallmouth bass at the west fishway was estimated to be 36 % (95 % C.I. range = 8 – 65 %). Only three radiotagged smallmouth bass entered the east fishway and one swam upstream to the exit. Passage efficiency of smallmouth bass was therefore roughly estimated to be 33 % (95 % C.I. range = 0 – 87 %) at the east fishway. Passage efficiency of smallmouth bass at the west fishway did not appear to differ from passage efficiency of smallmouth bass at the east fishway ($Z = 0.08$, $p > 0.5$). Eighty-five untagged and tagged smallmouth bass were recovered from the fishway traps and 48 (56 %) were caught in the east fishway (Table 3.1). Equal numbers of smallmouth bass used each fishway ($\chi^2 = 1.42$, $p < 0.25$) and equal proportions of radiotagged and anchor-tagged smallmouth bass were recaptured in the fishway traps (Table 3.1). Over 71 % of smallmouth bass used the west fishway while water velocities were < 0.24 m/s. At the east fishway, a similar pattern emerged, as 60 % of smallmouth bass used water velocities < 0.33 m/s. There was an exponential decline in the numbers of smallmouth bass that used each fishway relative to water velocity. The maximum water velocities used by smallmouth bass in the west and east fishway were 0.72 m/s and 0.99 m/s, respectively. Smallmouth bass that used the east fishway were significantly larger than smallmouth bass that used the west fishway ($F = 4.93$, $df = 84$, $p = 0.03$, Table 3.1).

Critical Swimming Speeds

The range of critical swimming speeds recorded for smallmouth bass between 262 mm and 378 mm TL was 0.50 – 1.18 m/s. There was a highly significant positive relationship between critical swimming speed and total length of fish tested ($n = 11$, $r^2 = 0.2$, $p < 0.001$). The relationship was best described as Ucrit (m/s) = 0.009534 x total length $(mm)^{0.7626}$.

Discussion

Studying fishway use and effectiveness from a biological perspective is a notoriously difficult challenge (Beach 1984) and this study was no exception. Various misfortunes confronted me during this project. For example, antennas were temporarily severed twice from debris accumulation during storms, which may have resulted in undetected attempts at the east fishway. I was unable to collect sufficient numbers of fish that were potentially naïve of the weir and this may have affected estimates of attraction and passage. In the context of fishway use, learning among fish has not been shown to exist and I therefore believe that these effects were negligible. Observations suggest that some fish migrate upstream to barriers. Others find habitat that suits them downstream from river barriers that they may never interact with. Clearly, some fish within a spatially distinct area will naturally relocate in the springtime while others will not. It is therefore impossible to know, *a priori*, which individuals have a propensity for physical displacement. Even if fish for this study had been collected from areas away from the weir, there would be no evidence that they had not interacted with the fishways or the weir prior to this work. As such, it is extremely difficult to gauge the importance of fishways, using random samples of fish collected downstream from river barriers. Other problems that I encountered while comparing the Mannheim fishways included the high velocity region upstream from the west fishway that distracted some fish during the study. Also, the modest degree of complete fishway use by radiotagged fish was insufficient for the application of powerful statistical analyses. It is likely, based on limited numbers of white suckers and smallmouth bass that used each fishway annually, that an economically excessive number of fish would have to be tagged to yield statistically adequate data. Nonetheless, this was the first biological assessment and evaluation of fishway use by warmwater species and some intriguing patterns emerged.

A complete assessment of fishway performance should address entrance attraction efficiency, difficulty or physical output associated with upstream passage and finally, passage efficiency. Simple observation or mark-recapture experiments at existing fishways (e.g., Fernet 1984; Schwalme *et al.* 1985; Monk *et al.* 1989; Dexter and Ledet 1997) have not effectively provided information that relates overall attempts to successful attempts, the timing of fishway use, and other factors necessary for a clear understanding of fishway efficiency. One recent study used two receiver check-points or gate-keepers, spaced 50 m apart to monitor the movements and ascent of barbel *Barbus barbus* over a flow gauging weir in England (Lucas and Frear 1997). However, until now, no studies have used radiotelemetry to continuously monitor the detailed behaviour of warmwater fish in fishways. Although the literature contains numerous quantitative and anecdotal reports of anadromous fish passage, there are no studies relating success and failures of individual warmwater fish during fishway use.

The behavioural and physiological impacts of river barriers on white suckers and smallmouth bass are largely unknown. It appears that upstream movements of both species are interrupted and delayed at dams regardless of the presence or absence of fishways. In a recently published report, Kanehl *et al.* (1997) demonstrated the positive effects of low-head dam removal on smallmouth bass abundance and biomass. Numerous other species experience significant delays passing river barriers. For example, delays of several weeks have been reported among northern pike *Esox lucius* in Canada (Fernet 1984), barbel in England (Lucas and Frear 1997), Atlantic salmon *Salmo salar* in Scotland (Webb 1990) and several percid species in Australia (Harris and Mallen-Cooper 1994). At the Mannheim weir, delays were often indefinite and most radiotagged fish did not pass upstream. Delays among salmonid and cyprinid species have been attributed to a reluctance to swim at high speeds (Priede and Holliday 1980), or physical inability to swim at speeds necessary for successful ascent (Lucas and Frear 1997). Regardless of the cause, numerous species of fish have demonstrated a potentially catastrophic tendency to resorb gametes after extensive delays below dams (Shikhshabekov 1971).

In the present study, water velocities in both fishways were usually less than maximum prolonged swimming speeds, which were 1.18 m/s for smallmouth bass (378 mm TL) and 0.73 m/s for white suckers (370 mm FL, Jones *et al.* 1974). Such conditions should have permitted successful fishway use. It is interesting to note that white suckers began using the low velocity fishway earlier in the season and at lower water temperatures than the high velocity fishway. At low water temperatures, fish rely heavily on anaerobic white muscle tissue to support intense swimming activity (Rome *et al.* 1992). Cooler water temperatures reduce aerobic swimming capacity (Jayne and Lauder 1994) such that the onset of burst activity occurs sooner and at lower water velocities. Water temperatures below a species-specific minimum prevent fish from achieving and maintaining swimming speeds necessary to negotiate high water velocities along the lengths of some fishways. Comparisons between swimming performance and passage success in Denil fishways may be further obscured by negative behavioural responses to turbulence, entrained air bubbles, and a high velocity layer of water at the surface of the flow profile. Beach (1984) suggested that fish must swim at least 30 % faster than opposing flows to progress upstream. High water velocities and turbulence in the east fishway may have prohibited successful use by some fish, particularly small smallmouth bass and large white suckers. It should be mentioned that the slope of the east fishway exceeds Clay's (1995) recommended maximum.

The tracking method incorporated in the present study permitted direct measurements of the potential delays associated with locating fishway entrances, time spent in resting pools and total time of passage. Both white suckers and smallmouth bass rested for much longer in the second of the two pools in the west fishway, which may be an indication of fatigue. Visual and videographic observations (Bunt, unpublished data) of smallmouth bass migrating through Denil fishways with water velocities in excess of approximately 0.5 m/s, indicate that fish positions are greatly influenced by turbulence. Non-benthic species, such as smallmouth bass, must withstand a great deal of turbulence while negotiating maximum water velocities near the surface of Denil fishway flows in order to successfully ascend. These maximum velocities and the behavioural effects of turbulence on fish passage should be addressed to refine design criteria for Denil fishways.

Fish that were able to fit in the spaces between baffles without injury sometimes passed upstream when high water velocities should have prohibited successful fishway use. This was accomplished by burst swimming upstream from refuge to refuge, as observed among cyprinids in other Denil fishways (Schwalme *et al.* 1985). Fish that were able to maintain position near the bottom of the flow profile, such as benthic suckers, were able to use the fishways when surface water velocities appeared excessive. The relative importance of burst swimming, position-holding abilities within the boundary layers of flows, prolonged swimming abilities and injury rates caused by impacts with baffles also requires further investigation to maximize passage rates of warmwater species through Denil fishways. Experiments using electromyogram telemetry may help to determine relative physiological costs (McKinley and Power 1992; Demers *et al.* 1996; Hinch *et al.* 1996) associated with the use of different fishways under a variety of conditions.

In summary, the relatively simple and inexpensive fishway design on the east side of the Mannheim weir permitted large smallmouth bass as well as small white suckers, a species with lesser swimming abilities, to pass upstream. Water velocities in both fishways were generally within the range of critical swimming speeds of smallmouth bass and white suckers and equal numbers of smallmouth bass were collected from each of the fishway traps. However, the lower velocity fishway with resting pools, on the west side of the Mannheim weir permitted more white suckers to pass upstream. The number of white suckers and smallmouth bass that used each fishway declined exponentially as water velocities increased. Maximum velocities used by white suckers and smallmouth bass were 0.96 and 0.99 m/s, respectively. Passage efficiencies of each species at both fishways were low to moderate. Future work should address the physiological and behavioural characteristics of fish that affect passage through fishways.

Acknowledgements

I thank Gabrielle Held, Sean Clancy, and Steven Cooke for their assistance in the field, Frank Smith and Lane Stevens from The Regional Municipality of Waterloo, Art Timmerman (Ontario Ministry of Natural Resources) and Val Butler for logistic support.

Table 3.1. Mean total length (± S.E.) of smallmouth bass and white suckers caught in the fishway traps between May and July 1995 and 1996. Numbers of anchor-tagged and radiotagged fish and subsequent recaptures from the fishway traps are shown. For each species, common superscript letters indicate non-significant differences among means and the numbers of fish caught in each fishway trap (n).

	TL (mm) West fishway	TL (mm) East fishway	# Anchor-tagged	# Radiotagged	Anchor-tag Recaptures	Radiotag Recaptures
Smallmouth Bass	326.8 ± 6.3 [a] (n = 37) [a]	348.8 ± 7.2 [b] (n = 48) [a]	51	53	3 (5.9 %)	2 (3.8 %)
White Suckers	321.9 ± 2.2 [a] (n = 919) [a]	302.3 ± 3.2 [b] (n = 410) [b]	818	32	42 (5.1 %)	1 (3.1 %)

Table 3.2. Tracking summary, temporal use of the fishways and patterns of use by white suckers and smallmouth bass. Nocturnal attempts were between 2000 and 0600 hours. Overall attempts may not equal the sum of nocturnal and daytime attempts because some fish resided over night in resting pools of the west fishway.

Parameter	White suckers	Smallmouth bass
# tracked near fishways in 1995 (%)	12 (67 %)	22 (76 %)
# tracked near fishways in 1996 (%)	11 (79 %)	17 (68 %)
Nocturnal attempts (west fishway)	3	2
Daytime attempts (west fishway)	8	10
Nocturnal attempts (east fishway)	2	1
Daytime attempts (east fishway)	6	2
Time in pool 1 (west fishway)	1 - 20 min	2 - 80 min
Time in pool 2 (west fishway)	5 - 176 min	3 -1140 min
Time for full ascent (west fishway)	12 – 85 min	43 – 1240 min
Time for full ascent (east fishway)	4 – 6 min	1 min
Overall attempts (west fishway)	11	11
Successful attempts (west fishway)	6	4
Overall attempts (east fishway)	8	3
Successful attempts (east fishway)	3	1
West fishway attraction efficiency (95 % C.I.)	50 % (33 – 67 %)	82 % (69 – 95 %)
West fishway passage efficiency (95 % C.I.)	55 % (25 - 84 %)	36 % (8 – 65 %)
East fishway attraction efficiency (95 % C.I.)	59 % (42 – 76 %)	55 % (38 – 72 %)
East fishway passage efficiency (95 % C.I.)	38 % (4 - 71 %)	33 % (1 – 87 %)

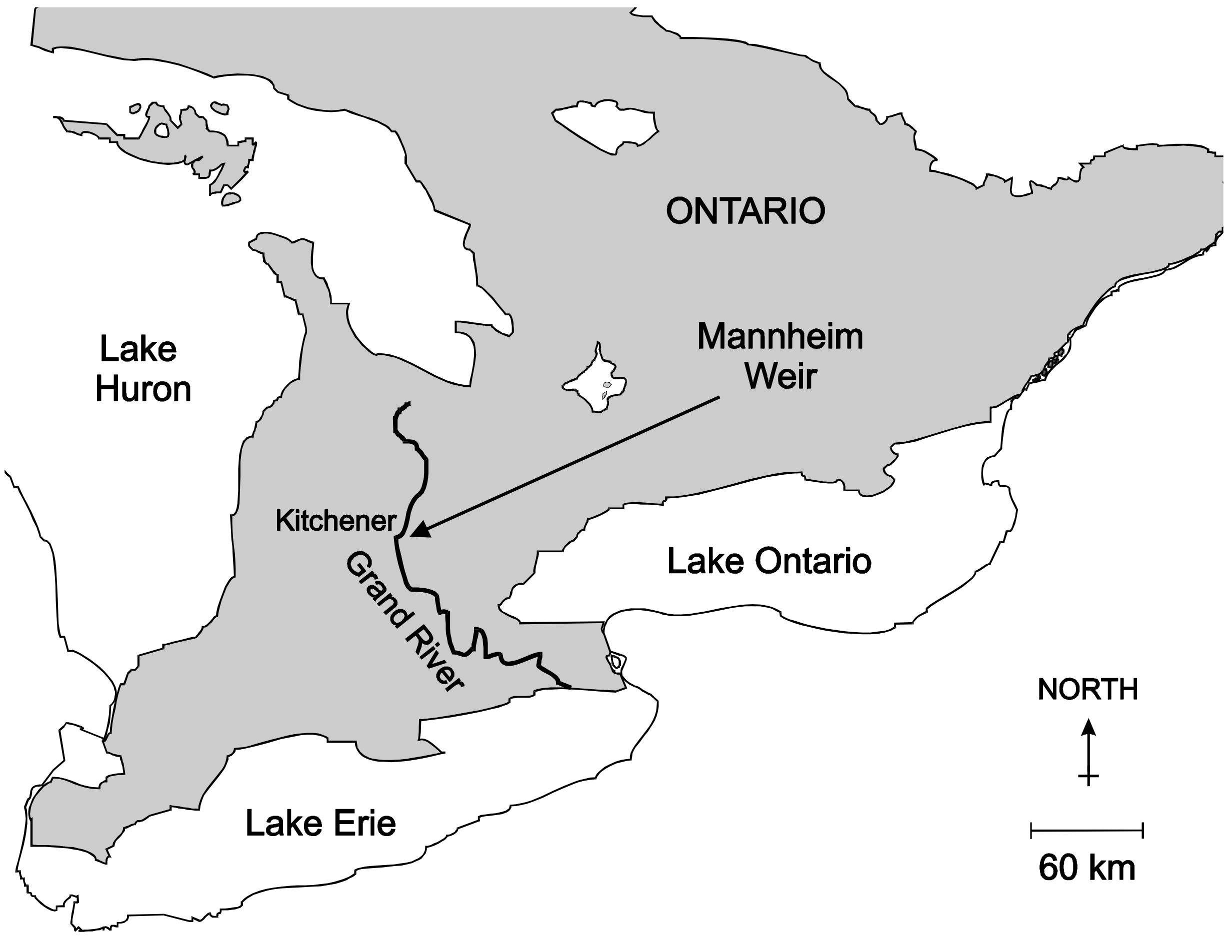

Figure 3.1. The location of the Mannheim weir on the Grand River, near Kitchener, Ontario. Approximately 6700 km^2 are drained into Lake Erie by the Grand River watershed.

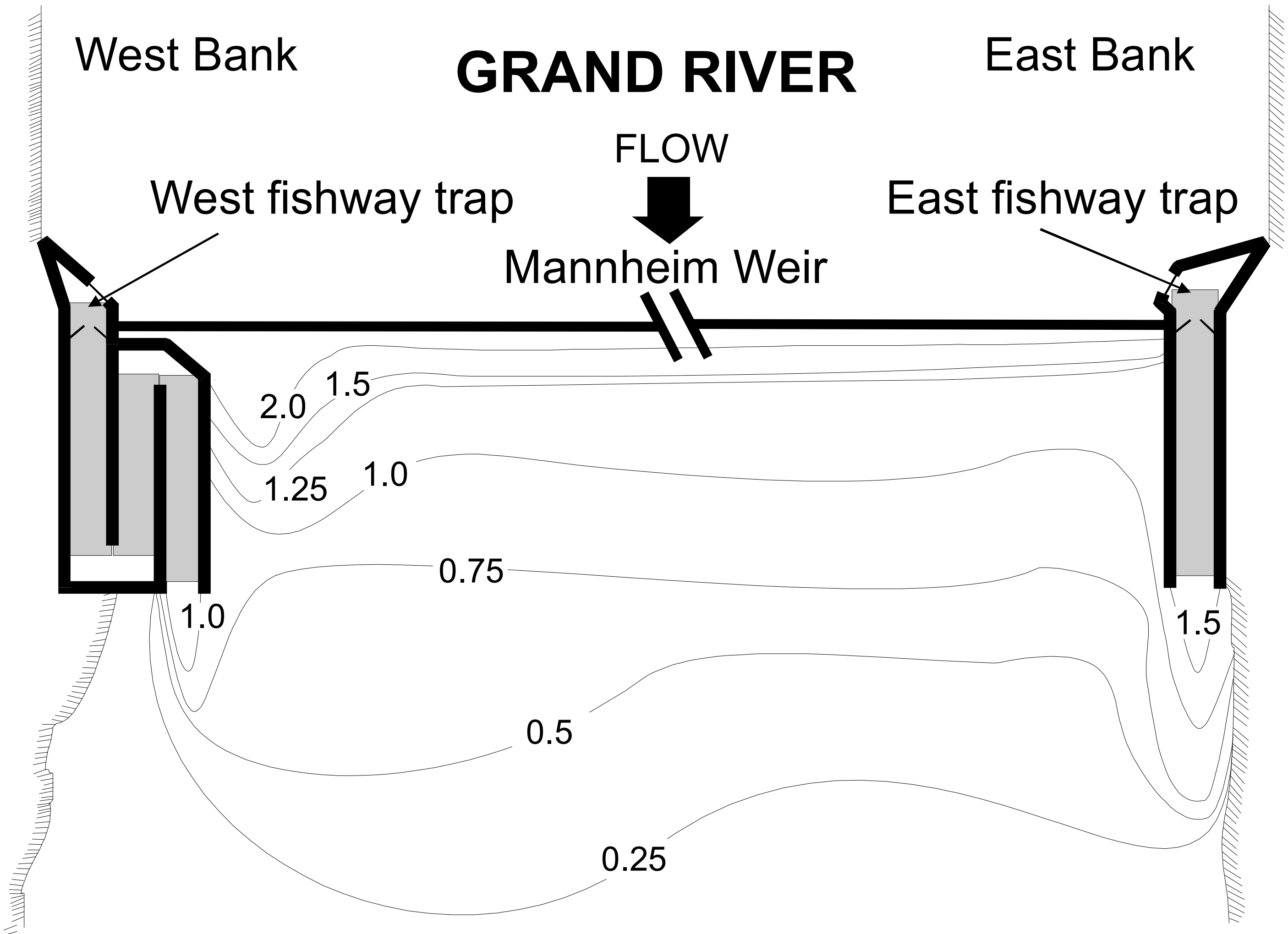

Figure 3.2. Schematic diagram of the fishways (not to scale) and the region immediately downstream from the Mannheim Weir. Shaded areas in the fishways indicate the reception zones monitored by the underwater telemetry antennas. Relative velocity isopleths indicate surface water velocities (m/s) downstream from the weir as measured with an ultrasonic velocity meter.

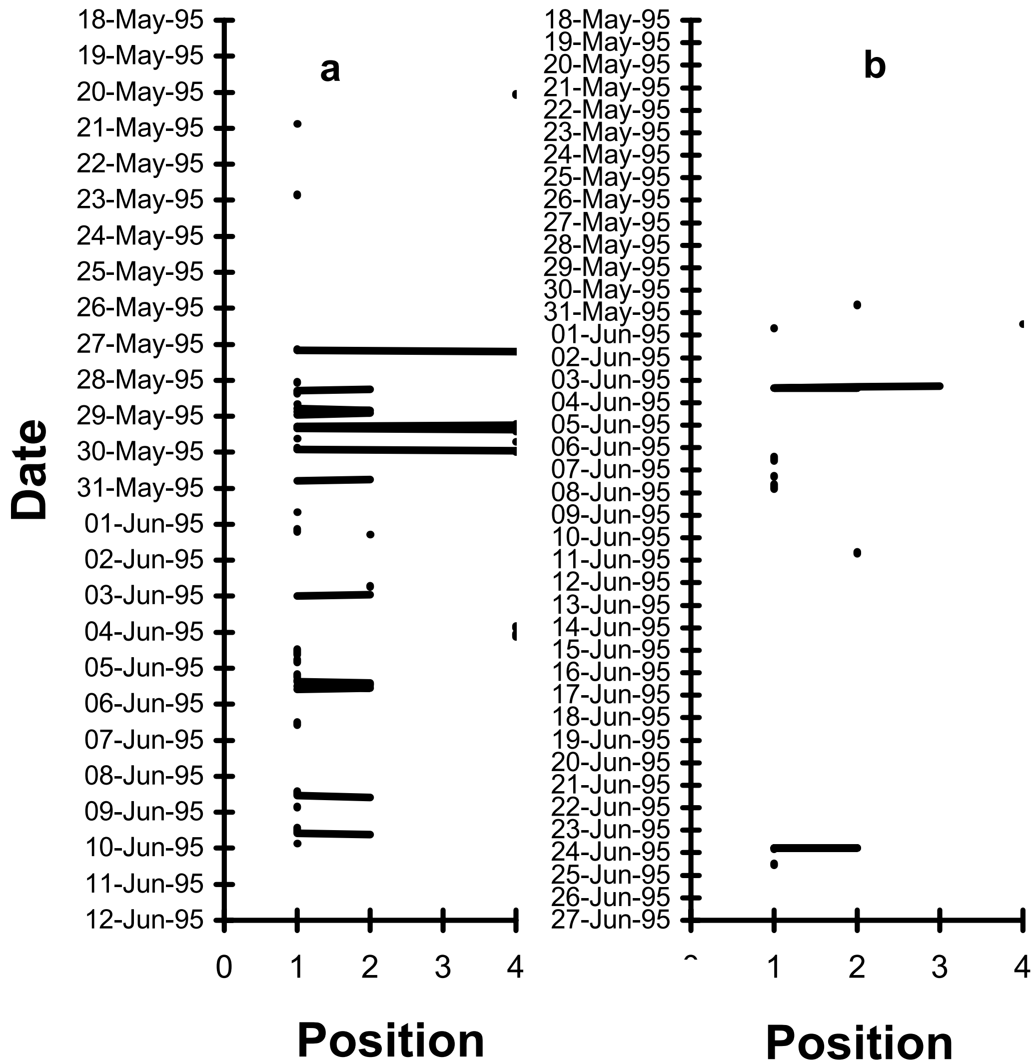

Figure 3.3. Examples of exploratory movements by (a) white suckers and (b) smallmouth bass immediately downstream from the weir during the spring of 1995. Positions along the abscissa are as follows: 1 = west fishway entrance, 2 = high-velocity area in spillway, 3 = region between fishway entrances and 4 = east fishway entrance.

CHAPTER 4

Assessment of the Dunnville fishway for the transfer of walleye from Lake Erie to the Grand River, Ontario [4]

Abstract

A Denil fishway in Dunnville, Ontario was built to provide upstream passage for walleye *Stizostedion vitreum* from Lake Erie to the Grand River. Modest numbers of walleye have been observed to use this fishway. Coded radiotelemetry was used to track 24 adult walleye (12 male, 12 female) downstream from the fishway to explore reasons for limited use. Activity was monitored by a fixed array of three antennas within the fishway that continuously scanned for signals from all radiotagged fish, and by mobile tracking. In April and May 1997, 17 attempts to use the fishway by radiotagged walleye were recorded. During this period, the attraction efficiency of the Dunnville fishway was approximately 21 %. Proportions of female and male walleyes that attempted to use the fishway were not significantly different. All attempts took place in the evening or at night, between 1600 and 0600 hours. Most activity occurred near midnight. Walleye occupied the first resting pool of the fishway for up to 17 h. Subsurface water velocity during the study was approximately 2 m/s. Passage rates of radiotagged fish at the Dunnville fishway were between 0 and 4.2 %. Behaviour modifying hydraulic conditions including turbulence, entrained air, backcurrents and whirlpools in fishway resting areas may delay or prevent successful upstream passage of walleye. There was also evidence of large scale movements (up to 9.6 km/d) by fish that may have spawned in the Grand River below the Dunnville dam.

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[4] Presented at the 59th Midwest Fish and Wildlife Conference – Milwaukee, Wisconsin December 1997

Introduction

Walleye *Stizostedion vitreum* are among the most popular and exploited freshwater fish in North America (Rawson 1957; Ney 1978; McConville and Fossum 1981). Lake Erie is the largest producer of walleye worldwide and supports multiple populations (Todd and Haas 1993). As springtime water temperatures increase to 3 - 4 °C, walleyes return to previously used spawning areas in search of suitable habitat (Crowe 1962; Olson and Scidmore 1962). There is evidence that these migrations are guided by homing (Olson and Scidmore 1962; Olson *et al.* 1978; Todd and Haas 1993) that often consist of movements from lakes into tributaries (Ferguson and Derksen 1971; Todd and Haas 1993). In river systems, dams pose a threat to spawning walleye by impeding upstream migration (Crowe 1962; Behmer 1964). This may result in harvest vulnerability, by preventing access to spawning areas upstream from dams (Schupp 1978; Pitlo 1984; Paragamian 1989). Ultimately, year-class strength may be reduced if the quality or quantity of spawning habitat downstream from the dam is limited. Dams may affect spawning habitat through changes in water temperature, chemistry, flow and bed-load transport (Bunt *et al.* 1998). Unfortunately, barriers that restrict spawning migrations and delay spawning activities can cause fish to resorb gametes and refrain from reproducing (Shikhshabekov 1971). But barriers can also create spawning habitat for some species as discussed in Bunt *et al.* (1998). The Dunnville dam, on the Grand River has been affecting walleye from Lake Erie for well over 150 y. Spawning runs of walleye that currently enter the lower Grand River from Lake Erie may be limited to fish that are relegated to habitat downstream from the dam.

Fishways are mitigative devices that allow fish to swim past otherwise impassable river barriers (Beach 1984; Clay 1995). Percids worldwide have been shown to use fishways to varying degrees (Schwalme *et al.* 1985; Katopodis *et al.* 1991; Harris and Mallen-Cooper 1994; Dexter and Ledet 1997; Bunt *et al.* 1998). However, most fishways appear to be ineffective for passing walleye (Schwalme *et al.* 1985; Katopodis *et al.* 1991; Dexter and Ledet 1997). Reasons for this are unclear but may be related to poor entrance attraction efficiency, supercritical water velocities within fishways that exceed walleye swimming abilities, turbulence that interferes with rheotactic behaviour or a reluctance to enter or remain in artificial channels. The objectives of this study were to 1) examine movement patterns of migratory walleye from Lake Erie to the Dunnville dam on the Grand River, Ontario and 2) to assess the performance of a Denil fishway for passing walleye upstream from the dam. Performance was divided into two main components that included estimates of attraction efficiency and passage efficiency.

Methods

Study area

This study was conducted in Dunnville, Ontario (42° 85' N, 79° 65' W), where four weirs between a series of islands have blocked upstream migrants from Lake Erie into the Grand River for well over a century (Figure 4.1). The lower Grand River valley cuts through a variety of tills and clays. The river is turbid with high levels of suspended solids, large amounts of littoral habitat and several deep pools. The Grand River near Lake Erie is classified as highly productive. To facilitate spawning and the establishment of walleye populations upstream from the Dunnville dam, a Denil fishway was installed in November 1994 near Weir III (Figure 4.1). The fishway consists of a 47 m x 1.35 m concrete channel with two resting pools. Baffles, spaced approximately 0.6 m apart, were fixed along the walls and bottom of three 10.5 % gradient channels. The fishway is not linear and two major direction changes exist between the fishway entrance and exit (Figure 4.2). Vortexes and whirlpools are also produced by walls that comprise a series of traps (Figure 4.2), designed to block the movement of lampreys *Petromyzon marinus* from Lake Erie into the Grand River.

Fishway use

Fishway use was monitored using a removable box trap installed near the fishway exit. Crews lifted the trap every 2 h during weekdays from mid April to mid May. The trap was removed from the fishway from approximately 1700 - 0900 hours due to safety restrictions and manpower limitations. During darkness and on weekends, fish activity was monitored by a radio tracking system that was installed within the fishway (see below). Water temperatures and water velocities within the fishway were continuously recorded with data loggers throughout the study period. Midday temperatures are reported and these were slightly below daily maxima.

Radio-tagging

In early April 1997, 24 walleye were captured 110 m downstream from Weir III using Trammel nets and were held in 8 m^3 pens until the fish were examined and radiotagged. Twelve female walleye (size range 488 - 741 mm TL, Table 4.1) and 6 male walleye (size range 467 - 570 mm TL, Table 4.1) were externally radiotagged on 12 April according to the method described in Bunt *et al.* (1999). Six additional male fish were radiotagged on 19 April (Table 4.1). Coded radio transmitters (1.9 g in water, 10.6 x 28 mm with 2.5 s pulse rate, battery life approximately 30 d) were attached through the dorsal musculature and held in place with surgical wire attached to a neoprene-coated plastic back-plate. This tagging procedure has been shown to have negligible effects on behaviour, movement patterns, or social interactions among walleye at Lake Bemidji, Minnesota (Holt *et al.* 1977). External tagging was chosen because all fish were gravid and/or ripe and therefore considered unfit for surgical implantation without the risk of affecting normal spawning behaviour. By using extremely small, flattened transmitters, I also reduced concerns about altering the normal hydrodynamics around the fusiform bodyshape of walleye. Moreover, this technique has been used without complication to track several other fish species through Denil fishways (Bunt *et al.* 1999). After a 1 h recovery period, all fish were released near the capture site.

Tracking

To allow behavioural acclimatization to the radio transmitters, I did not begin to collect data until at least 24 h after fish were released. A fixed system that consisted of three sequentially-scanned antennas monitored the fishway entrance, first resting area and exit of the fishway, continuously for 34 d. Pulse-code discrimination software within the receiver (SRX_400, Lotek Engineering Inc.) was used to decode radio signals. Prior to the study, reference radiotags were positioned at various locations within the fishway to calibrate the receiver. Measurements of relative signal strength permitted determinations of transmitter location and fish positions in the fishway to within 1 m. Manual tracking using a scanning receiver and hand-held H-antenna was conducted daily from 0900 - 1800 hours by watercraft. Fish locations were determined to within 5 m and were plotted on aerial photographs (scale 1:8000) to describe movements between the dam and Lake Erie.

Analysis

All means are reported ± 1 S.E. In situations where data were non-parametric (Lilifors test), median values were used. Statistical comparisons (Z-test) were conducted with an alpha-level of 0.05.

Results

Fishway use by walleye increased as water temperatures rose from 4 - 8 °C (Figure 4.3). In total, 22 untagged walleye were caught in the fishway trap from 7 April to 14 May, when water temperatures ranged between 4 and 12 °C. Fishway discharge was invariable (range 1.062 to 1.070 m^3/s) and the subsurface water velocity midway along the length of the fishway was approximately 2 m/s. The water velocity near the bottom of the flow profile was 0.2 m/s and the mean velocity derived from the discharge rating curve was 1 m/s.

The Dunnville fishway was monitored continuously for 816 h, during which time 17 attempts to use the fishway by radiotagged walleye were recorded. Five different fish (3 males, 2 females) entered the fishway. Attraction efficiency was 21 % (95 % C.I. = 5 – 37 %). Since no radiotagged walleye successfully used the fishway, the maximum passage efficiency was estimated to be < 4.2 % (95 % C.I. range = 0 – 12 %). All fishway use (with one exception – code 1459 see below) occurred at night between 1800 hours and 0600 hours. Peak activity occurred between 2100 hours and 0100 hours. Walleye occupied the lower reaches of the fishway for between 1.2 min and 1020 min. The median occupancy time was 1.2 min, and the mean occupancy time was 64 ± 59 min (Table 4.2). One female fish (code 1459, Table 4.1) entered the fishway at 0615 hours on 16 April and remained within the first resting pool (Figure 4.2) for 17 h, until 2313 hours on 17 April.

From 12 April to 8 May 1997, walleye positions were determined 149 times (mean 6 fixes/fish). Distances between fixes were 208 m/d and 313 m/d for females and males, respectively (Z-test, p = 0.23, Table 4.1). Extensive lateral movement near the dams, as well as upstream and downstream movements (e.g., 3 km in < 7.5 h), from weir I to weir IV were common. Walleye spent long periods of time between weir III and weir IV in Sulfur Creek (Figure 4.1). Fish were located in Sulfur creek for up to 11 d. Walleyes were located over areas with previously known deposits of gravel substrate (e.g., submerged gravel roads and areas where gravel had eroded from the river bank). Downstream movements from Weir IV to approximately 1.5 km upstream from Lake Erie (approximately 8 km) occurred over the course of 6 d. Downstream movement was more common than upstream movement after the last week in April. All fish returned to Lake Erie by mid May.

Discussion

There are many variables and assumptions that must be considered before generalizations can be made about the interactions between migratory walleye, river barriers and fishways. In the Grand River, walleye moved extensively throughout the river downstream from the Dunnville dam and attempts to use the fishway were not common. Lack of upstream passage, delay, and extensive exploratory movements by walleye downstream from dams has also been observed in Michigan (Eschmeyer 1950), Iowa (Behmer 1964; Pitlo 1984; Paragamian 1989) and Minnesota (Holt 1977). In agreement with this study, limited or nonexistent use of Denil fishways by walleye has been documented from studies in Alberta (Schwalme *et al.* 1985), Manitoba (Katopodis *et al.* 1991) and Saskatchewan (Katopodis *et al.* 1991). Several fishways of the St. Joseph River in Michigan and Indiana have been monitored annually using time-lapse video (Dexter and Ledet 1997). The authors were surprised by the modest numbers of walleye that used the fish ladders, because walleye were well represented in the St. Joseph River below the dams (Dexter and Ledet 1997).

Attraction efficiency of walleye at the Dunnville fishway was less than half of the attraction efficiencies calculated for other species at similar fishways. For example, Bunt *et al.* (1999) estimated attraction efficiency of white suckers at two Denil fishways on the Grand River to be 50 % and 59 %. In the same study, the attraction efficiencies of smallmouth bass were estimated to be 82 % and 55 % (Bunt *et al.* 1999). Attraction efficiencies of walleye at the Dunnville fishway may have been negatively affected by distracting flows originating upstream of the fishway in Sulfur Creek, near weir IV (Figure 4.1). Some walleye may have found suitable spawning habitat in areas downstream from the dam.

Passage efficiency of walleye was estimated to be < 4.2 %. In other studies, passage efficiencies of white suckers have been estimated to vary between 38 % and 55 % at Denil fishways (Bunt *et al.* 1999). For smallmouth bass, passage efficiencies at Denil fishways range between 33 % and 36 % (Bunt *et al.* 1999). In these studies, water velocities in the fishways were within each species' range of swimming abilities. Low passage efficiencies of walleye likely result from excessive water velocities, turbulence, air entrainment, back-currents and disorienting flows which have been observed to inhibit and delay passage of percids (Schwalme *et al.* 1985; Bunt *et al.* 1998) and other fish species (Haro *et al.* 1999) through Denil fishways. Walleyes also show tendencies to avoid turbulent water, especially when the water temperature is low (Ryder 1977). Furthermore, behavioural studies in an artificial flume, showed that less than 50 % of walleyes swam past each sharp corner (Peake 1997). For walleyes to be successful at using the Dunnville fishway, a minimum of four large corners, or abrupt changes in direction must be negotiated. This would therefore result in the net passage of only 6 % of the total number of walleyes that enter the fishway, if the corner variable was valid and considered independently. It is yet to be determined if corners are either physical or motivational obstacles for walleyes. Spiral fishway designs, and linear fishways with resting pools that minimize the formation of backcurrents and whirlpools, should be considered as a possible alternatives to double-backed, or convoluted fishways.

Larger fish may experience more difficulty when ascending Denil fishways than smaller conspecifics, as appears to be the case with yellow perch (Schwalme *et al.* 1985) and white suckers (Bunt *et al.* 1999). In other studies, walleye have ascended Denil fishways with surface water velocities up to 1.6 m/s (Katopodis *et al.* 1991). The subsurface water velocity, midway along the Dunnville fishway was 2 m/s. The velocity near the bottom of the flow profile was approximately 0.2 m/s. Water velocities in the Dunnville fishway may have had exceeded the maximum swimming speeds of some fish. Cruising speeds range between 0.5 and 1.5 bodylengths/s (Jones *et al.* 1974; Kelso 1975; Bahr 1977; McConville and Fossum 1981). This translates into ground speeds between 0.25 and 0.75 m/s for a 50 cm fish at temperatures at or above those during the spring in Dunnville. It is unclear whether walleye are able to remain within the layer of reduced velocity near the bottom of the flow, or if turbulence affects their vertical position. Since female walleye are usually larger than males, gender-specific passage efficiencies may also exist.

Perhaps it is most obvious to assume that the majority of walleyes may have passed through the fishway at night. Predicted diel passage rates based solely on daytime fishway trap observations would therefore underestimate the true number of fish that used the fishway. However, there have been no reports of increases in angler catches of walleye upstream from Dunnville since the fishway has been operational (Grand River Conservation Authority, personal communication). Eschmeyer (1950) reported that small walleye were native to impoundments upstream from some dams in Michigan, and he provided evidence that fish moved downstream before reaching sexual maturity. This may explain why very few large walleye have been collected upstream from Dunnville even though some large adults have used the fishway, presumably to spawn before returning to Lake Erie.

Walleye home to spawning sites (Stoudt 1939). Except for strays, this behaviour appears to be quite established and non-plastic, and is strengthened by repeated migrations (Ferguson and Derksen 1971; Olson *et al.* 1978). The Grand River today may therefore not attract as many walleye from Lake Erie as it would if the dam had never been constructed. The dam has been affecting Lake Erie walleye for well over 150 y. Since suitable spawning habitat is limited in the Grand River below Dunnville, relatively few adult fish may home from Lake Erie to spawn in the lower Grand River. Only limited numbers of larval walleye were collected in plankton nets towed throughout the Dunnville area of the Grand River in 1995 (Ontario Ministry of Natural Resources, Lake Erie Management Unit, unpublished data).

Pitlo (1984) implanted walleye with radio transmitters and observed them to move upstream to the tailwater of a dam on the Mississippi River. Walleye then dispersed downstream and spawned at several sites (Pitlo 1984). Paragamian (1989) radiotagged walleye and observed them to migrate to the Waverley dam and the Cedar Falls dam on the Cedar River, Iowa. These fish proceeded to spawn exclusively in the dam tailwaters. Recruitment of native walleyes in the Cedar River was poor (Paragamian 1989) and the author speculated that substrate downstream from the dams (e.g., sand and fine gravel) may be a factor, since walleye embryo survival is greatest in areas with clean gravel-cobble substrates (Corbett and Prowles 1986).

Dams often produce hydraulic conditions and ice scour that help unembed substrate thereby producing clean gravel-cobble areas that may function as suitable spawning sites for walleye (Paragamian 1989) and other percids (Bunt *et al.* 1998). In the present study, walleye occupied areas with known gravel deposits as well as tailwater areas of the dams. Although this evidence is largely circumstantial, spawning may have occurred downstream from the dam. If it was easier for walleye to locate and use the Dunnville fishway, more fish would. Further research may show that successful use of the Dunnville fishway, followed by successful spawning upstream from the dam, may result in increased use of the Dunnville fishway in the near future. Lake Erie populations of walleye that spawn upstream from the dam may produce progeny for a spring run of fish that have the ability and behavioural motivation necessary to locate and use the Dunnville fishway. The Dunnville fishway is a relatively new addition to an old dam. Increased fishway use may indicate that a spawning population of Lake Erie walleye has developed in the Grand River upstream from Dunnville.

This paper describes a situation that is site specific – as all fishways are. Lessons learned through the process of fine tuning the Dunnville fishway may, however, be applicable to other fishways that are to be built to pass walleye. Existing fishways may also be modifiable so that attraction efficiencies and passage efficiencies may be improved.

Acknowledgements

I thank the Grand River Conservation Authority for providing fishway discharges, water velocities and temperature data. Trish Nash, Ken Chandler, Lori Richardson, Weldon Dolan and the Dunnville Hunters and Anglers Club assisted with field operations. Erling Holm and Dr. Geoff Power provided comments on an earlier version of this manuscript. Funding for this study was provided by the Department of Fisheries and Oceans (Burlington, Ontario), and the Natural Sciences and Engineering Research Council of Canada in the form of a graduate scholarship.

Table 4.1. Tracking summary of walleye released downstream from the Dunnville fishway.

Code	L (mm)	Wt. (g)	Sex	Release date	Fixes	Mean distance between fixes (m/d)
1454	741	4565	Ò	12-Apr	6	518
152	608	2760	Ò	12-Apr	6	601
1451	488	1145	Ò	12-Apr	4	43
1446	704	4810	Ò	12-Apr	5	141
1121	628	2625	Ò	12-Apr	3	140
1227	690	3405	Ò	12-Apr	6	451
1449	511	1260	Ò	12-Apr	12	253
1226	533	1710	Ò	12-Apr	5	18
1358	665	3190	Ò	12-Apr	3	163
1447	534	1665	Ò	12-Apr	7	100
1459	566	2385	Ò	12-Apr	8	300
1448	574	2060	Ò	12-Apr	6	410
1342	496	1290	ö	12-Apr	8	182
1453	492	1190	ö	12-Apr	7	278
1343	538	1545	ö	12-Apr	11	348
1344	521	1280	ö	12-Apr	12	435
1445	570	1640	ö	12-Apr	1	n/a
1229	478	915	ö	12-Apr	9	559
2179	548	1680	ö	19-Apr	7	473
2177	501	1235	ö	19-Apr	2	n/a
2176	549	1835	ö	19-Apr	4	278
2178	473	945	ö	19-Apr	3	74
2180	467	920	ö	19-Apr	3	387
2181	498	1210	ö	19-Apr	3	146

Table 4.2. Walleye activity at the Dunnville fishway, during 816 h of continuous monitoring using digital telemetry. Proportion of full ascent indicates how far each fish swam into the fishway.

Code	Date	Time	Time to fishway (h)	Time in fishway (min)	Proportion of full ascent	Velocity (m/s)
152	13-Apr	23:47	37	42	< 0.15	2
1343	14-Apr	21:53	59	< 1.2	< 0.15	2
1343	15-Apr	2:29	-	< 1.2	< 0.15	2
1459	15-Apr	18:10	79	4	0.15	2
1459	15-Apr	18:24	-	5	0.15	2
1459	15-Apr	19:49	-	< 1.2	< 0.15	2
1459	15-Apr	19:57	-	< 1.2	< 0.15	2
1459	15-Apr	20:00	-	1.2	0.15	2
1459	15-Apr	20:36	-	2.5	0.15	2
1459	15-Apr	20:40	-	3.7	0.15	2
1459	16-Apr	4:55	-	< 1.2	< 0.15	2
1459	16-Apr	6:07	-	< 1.2	< 0.15	2
1459	16-Apr	6:11	-	1020	0.35	2
2176	20-Apr	0:51	10	< 1.2	< 0.15	2
2179	23-Apr	0:23	152	< 1.2	< 0.15	2
2179	25-Apr	22:27	-	< 1.2	< 0.15	2
2179	25-Apr	22:42	-	4.5	0.15	2

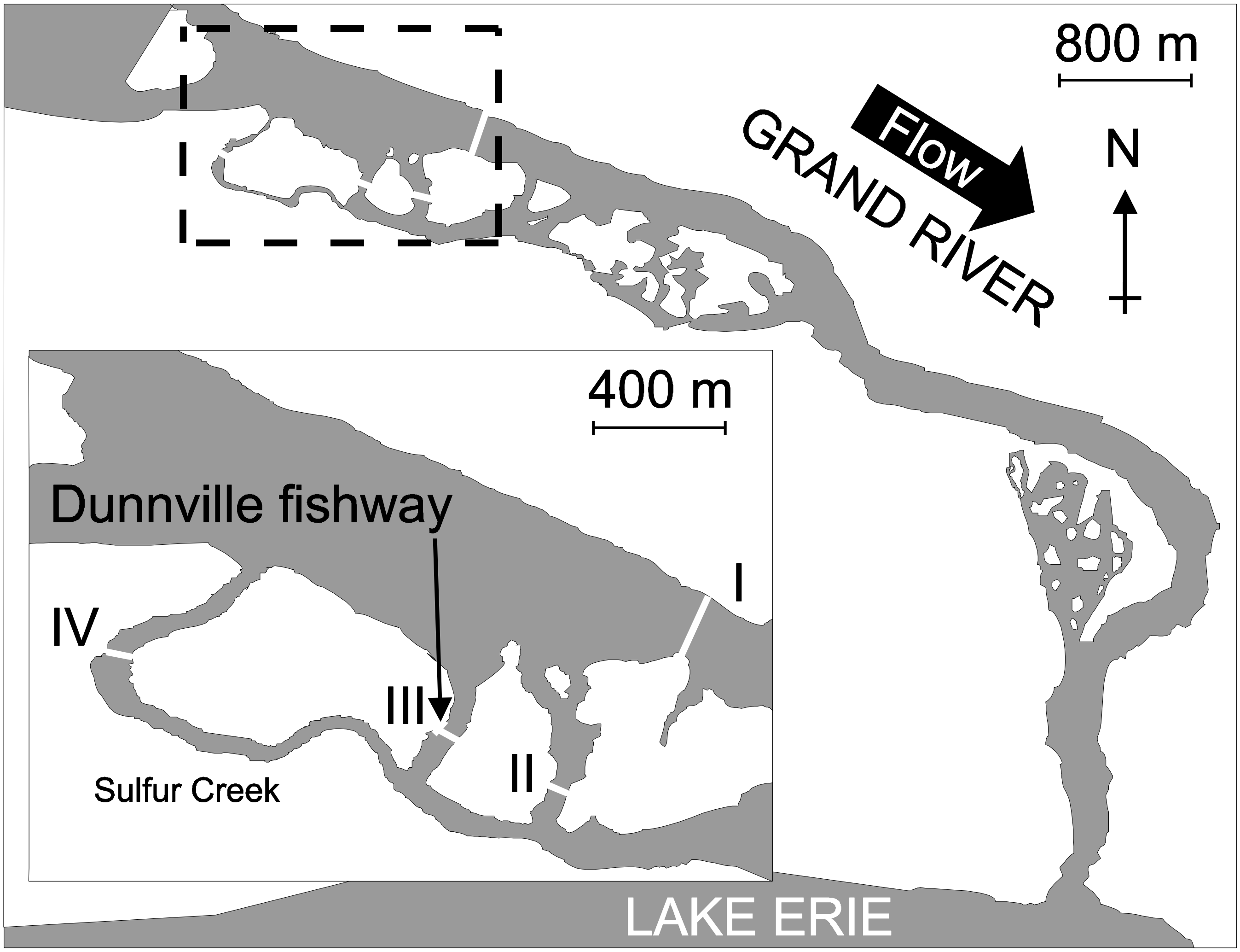

Figure 4.1. The lower Grand River to Lake Erie and the four weirs (I,II,III,IV) that compose the Dunnville dam and island complex (enlargement). The fishway was located at weir III. Sulfur Creek flows between weir III and weir IV.

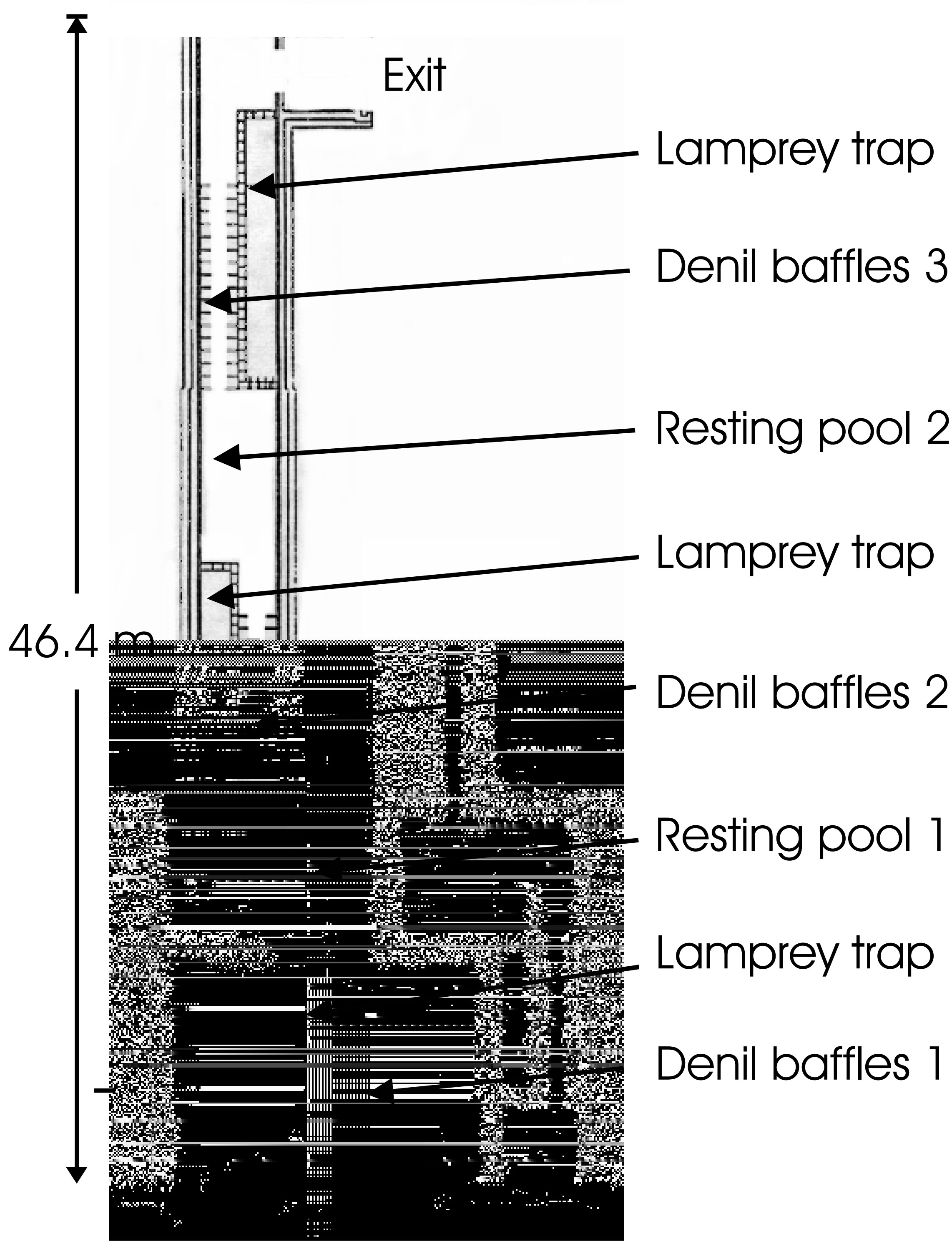

Figure 4.2. Plan view of the Dunnville fishway.

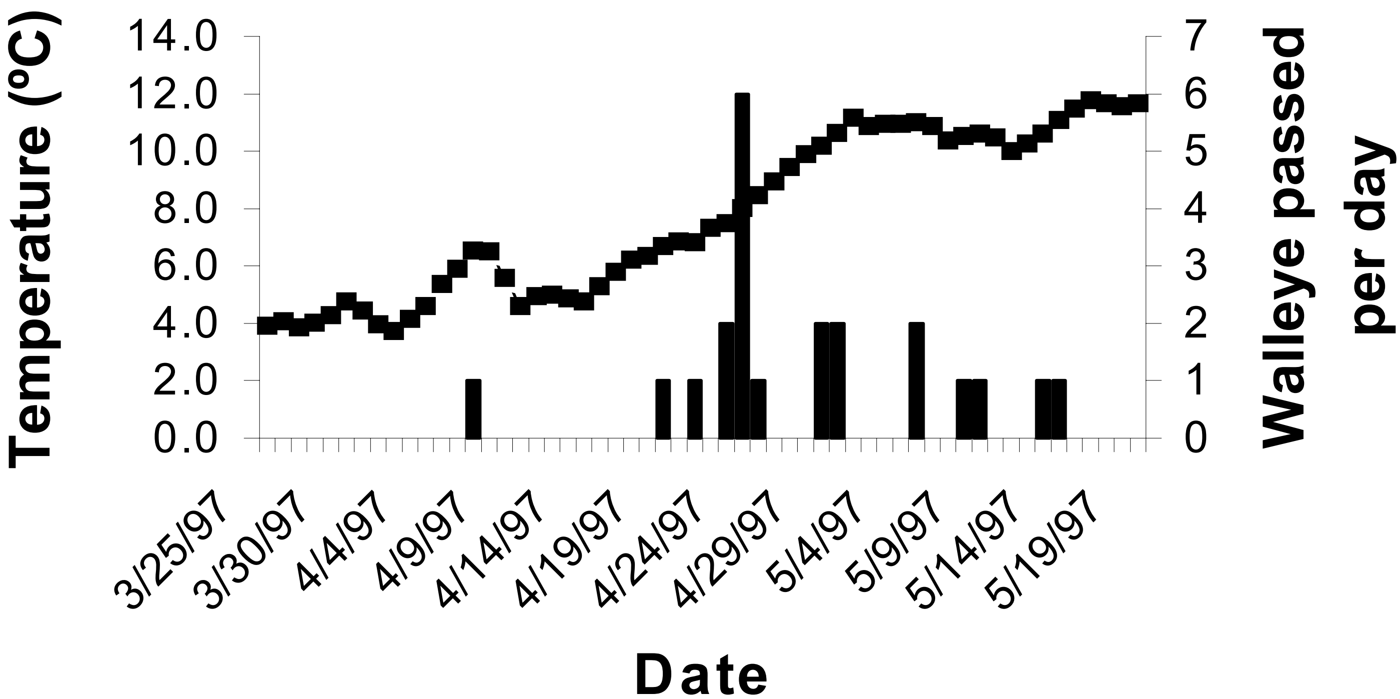

Figure 4.3. Water temperature (°C), and corresponding number of untagged walleye that used the Dunnville fishway.

CHAPTER 5

Fishway entrance modifications enhance attraction [5]

Abstract

Two Denil fishways on the Grand River, Ontario, have been monitored for activity by several dozen fish species annually since 1994. Fishway use was related to water temperature, water velocity, season, and the ease with which fishway entrances were located. Simple modifications to the entrances of two Denil fishways resulted in increased attraction efficiency for pumpkinseed *Lepomis gibbosus*. Entrances were enlarged and repositioned approximately 2 m closer to the weir face, in areas where radiotagged fish congregated. After modifications, overall relative rates of recapture were 39 % (95 % C.I. = 32 – 46 %), representing a 2.6 – 3 fold increase in fishway use relative to pre-modification conditions. Median instantaneous recapture rates also increased significantly from 0 % at both fishways to approximately 2 %, after fishway entrances were modified. Fishway entrances should be located as close to a dam or weir face as possible, but velocity barriers from spillway or tailrace discharge must not compromise access. Similar modifications may be made to other fishways to improve attraction efficiency of warmwater species.

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[5] Presented at the 61st Midwest Fish and Wildlife Conference - Chicago, Illinois, December 1999

Introduction

Satisfactorily effective fishways must attract fish to the entrances, permit fish to swim upstream through the downward flow of water and do so with minimal energetic expense. Most research has focussed on hydraulics, and whether water velocities within fishways are within species-specific ranges of swimming abilities. This is of obvious importance, since non-leaping species (percids, centrarchids, catostomids, esocids, ictalurids and cyprinids) must swim at least 30 % faster than opposing flows to progress upstream (Beach 1984). Fish use a combination of sustained, prolonged and burst modes of swimming while using fishways. On a biochemical scale, energy for swimming through fishways is derived from both aerobic and anaerobic pathways. A good fishway will be easy for fish to find under most flow conditions, and will allow fish to pass upstream without compromising fitness. Access to a fishway may be blocked or restricted by turbulence that disorients fish, supercritical velocity barriers caused by high discharge, or distracting flows in areas away from fishway entrances. The unique features of each fishway site must be considered to ensure that fishway entrances are well positioned (Beach 1984). If fish experience difficulty locating a fishway entrance, and vast amounts of energy are expended while trying, the fishway will be of little value.

Two Denil fishways on the Grand River, Ontario, have been monitored for activity by several dozen fish species annually since 1994. Fishway use was related to water temperature, water velocity, season, and the ease with which fishway entrances were located (Bunt *et al.* 1999). These criteria differed for each species that was observed. In 1995, an intensive radio telemetry study using a submerged array of seven antennas (Bunt *et al.* 1999), indicated smallmouth bass and white suckers were distracted by a high discharge area located upstream of one of the fishway entrances (Figure 5.1). In anticipation of an opportunity to modify the fishway entrances, a mark-recapture experiment was initiated to demonstrate changes in fish activity that could be attributed to effects of fishway entrance modifications. Pre-modification data were collected in 1995 and 1996. Post-modification data from 1997 were compared against data collected during the two previous years. The objective was to illustrate the effects of changes to the fishway entrances using a null hypothesis of no change in attraction for pre-modification and post-modification conditions, and no difference in attraction at either fishway entrance.

Methods

Study area

This study was conducted at the Mannheim weir on the Grand River, near Kitchener Ontario during the spring and early summer of 1995 to 1997. The construction of the 90 m weir and its fishways was completed in 1990. Prior to 1990, fish movements were not restricted at this site. The Grand River is a mid-order stream that flows 297 km from its source in Dundalk, Ontario to the eastern basin of Lake Erie. The Mannheim weir is located approximately mid-way along the river and creates an impoundment for the extraction of regional drinking water. Mean depth downstream from the weir is approximately 0.5 m, mean annual discharge is approximately 33 m^3/s and primary substrates consist of cobble and broken rock (Bunt *et al.* 1998). On the west side of the 2m high weir, there is a 27m long sloped concrete channel which doubles back on itself twice (Figure 5.2a). Two resting pools were provided between three inclined channels. Each of the three channels were fitted with metal baffles spaced approximately 25 cm apart. The baffles dissipate energy and reduce the velocity in a primary flow of water that fish must swim through to pass upstream. The slope of each channel was 10% and the width of all channels was 0.6 m. On the east bank of the river, a much simpler and cheaper Denil fishway was constructed (Figure 5.3a). It was composed of one 12 m sloped channel with baffles on a 20% incline. Each fishway entrance was 0.6 m wide and was located approximately 8 m downstream from the weir.

Fishway entrance modifications

Telemetric and visual data (Bunt *et al.* 1999) indicated that the fishway entrances might be easily re-located closer to the weir in areas where fish were observed to congregate. Signals from the high discharge area (Figure 5.1) dominated the collection of radio telemetry data until an attenuation device was installed between the closest antenna and the receiver. The antenna was actually located within the west fishway. However, until its sensitivity was reduced, it detected signals through the fishway wing wall, from the region of high flow upstream from the west fishway entrance. Fish were also observed visually and videographically (Bunt unpublished data) in the vortex of a whirlpool upstream from the east fishway entrance. Fish located in these areas bypassed the fishway entrances during upstream migration. They seemed reluctant to swim back downstream and were consequently not attracted to the fishway entrances.

In October 1996, a 2 m x 3 m block of concrete was removed from the downstream end of the wing wall near the entrance of each fishway (Figures 5.2b, 5.3b). The new entrance began where the most downstream fishway baffles inserted onto the fishway floor. There were no significant changes in fishway flow characteristics. These modifications 1) enlarged the fishway entrances, 2) changed their shape and 3) re-positioned them 2 m further upstream in the deeper water of the stilling basin.

Biological data

River levels remained constant during the investigation except for two peaks during storms at the end of April and beginning of June 1995, during numerous occasions in May and June 1996 and during the first week of June 1997. Pumpkinseed *Lepomis gibbosus* were relatively unaffected by variable weather conditions over the three year period, because migrations began in early summer. In addition, pumpkinseeds are easy to mark, show few signs of stress when handled, and most importantly, are caught in abundance in fishway traps on the Grand River. In earlier studies, pumpkinseeds used the fishways most frequently from mid-June to Mid-July (Bunt 1999a), and showed no demonstrable preference for either fishway design (chi-square, $0.25<p<0.5$).

Fish activity, marking and recapture patterns were monitored for two years (1995 and 1996) prior to modification of the fishway entrances, to establish a basis for comparison. The effects of the modifications were assessed in 1997. I assumed that changes in recapture ratios among pumpkinseeds, reflected changes in perceived difficulty associated with locating the fishway entrances. If more fish located the fishway entrances, the overall number of fish that used the fishways should also increase. It is difficult to control for annual variation in the number of potential fishway users. This variation may result from changes in year-class strength, or environmental conditions that encourage or favour fishway use (Bunt 1999a). Recapture ratios were therefore deemed to be more accurate indicators of entrance locatability rather than overall passage rates. It was inherently assumed that spatial learning was not a factor that changed fish behaviour from year to year. The nature of the study did not positively reinforce the experience of being in a fishway trap.

Both fishways allowed fish to pass freely until they entered the top pool, where escape upstream into the impoundment was averted by a wire mesh blocking screen (mesh size approximately 1.5 cm). Escape downstream from the exit pool was prevented with a wire mesh funnel-trap. Both the screens and the funnel-trap were cleared of debris two or three times daily. During sampling episodes, a small diameter blocking mesh (mesh size 0.5 cm) was used to ensure that no trapped fish escaped through the funnel. All fish were removed from the fishway traps with dipnets and were placed in aerated coolers for examination, measuring (TL) and marking daily or twice daily between 09:00 and 12:00 and from 17:00 to 20:00 from mid-April to mid-July 1995, 1996 and 1997. Pumpkinseeds from the west fishway trap received upper caudal clips and those from the east fishway received lower caudal clips. Fish were then released randomly at the east or west bank, approximately 150 m downstream of the weir. Equal numbers of fish from each fishway were released at both river banks.

Recapture (or return) patterns from the fishway traps were analyzed for year to year variation with the first two years (pre-modification) treated as a separate factor. I examined overall recapture rates and relative recapture rates (RRR) at both fishways. RRR reflected the percentage of recaptured fish as a function of the number that were available to be recaptured (i.e., running total of marked fish – number previously recaptured). I used the following formulae to generate RRR from samples from each fishway trap:

$$\text{instantaneous RRR} = \frac{a}{\Sigma\, b - \Sigma\, a} \times 100\ \%$$

$$\text{overall RRR} = \frac{\Sigma\, a}{\Sigma\, b} \times 100\ \%$$

where a = number recaptured on day i, b = number marked up to day (i-1), and Σ b > Σ a. RRR were annually independent because fin clips were superficial and evidence of marking lasted for only one season. Changes in attraction efficiency were estimated using median instantaneous RRR. Medians were analyzed for significant differences using the median test (α = 0.05, Zar 1984). Estimates of instantaneous RRR are similar to Schnabel population estimates whereby values fluctuate to a large degree until Σ a and Σ b increase. Fish that returned to either fishway trap more than one time were released upstream from the weir. There was no evidence that fish released upstream subsequently dropped back over the weir and, in my analyses, I assumed that this did not occur.

Results

In the pilot year (1995), 214 pumpkinseeds used the fishways and 38 % used the west fishway. Seventy-four pumpkinseeds were marked. Of these, five were recaptured in the west fishway and six were recaptured in the east fishway. The overall RRR was therefore 15 % (95 % C.I. = 7 – 23 %). In 1996, fishway use by pumpkinseed increased by 66 %. A total of 355 fish used the fishways (54 % used the west fishway) and 283 were marked. Of these marked fish, 25 were recaptured in the west fishway and 21 were recaptured in the east fishway. As such, the overall RRR in 1996 was 16 % (95 % C.I. = 12 – 21 %).

There was a spike in instantaneous RRR at the beginning of each pre-modification season up to 14 %. Thereafter, values generally fluctuated between 0 % and 3 % until mid-July (Figure 5.4). Pre-modification RRR at the east and west fishways did not differ statistically for either year ($p > 0.05$). The median instantaneous RRR at both fishways for both years was 0 %. Maximum instantaneous RRR at the west fishway was 2.8 % and 10.5 % in 1995 and 1996, respectively. Maximum instantaneous RRR at the east fishway was 13.8 % in 1995 and 14.0 % in 1996.

In total, 265 pumpkinseeds used the fishways in 1997 and 51 % used the west fishway. Of these, 181 were marked and 31 and 39 fish were subsequently recaptured in the west and east fishway, respectively. The post-modification overall RRR was therefore 39 % (95 % C.I. = 32 – 46 %), representing a 2.6 – 3 fold increase in recaptures relative to pre-modification conditions. In concordance with pre-modification years, there was a spike in instantaneous RRR at the beginning of the season, but in 1997, values for both fishways reached 50 % (Figure 5.5). Instantaneous RRR fluctuated at higher levels in 1997 relative to 1995 or 1996. Unlike previous years, marked pumpkinseeds were recaptured in either of the fishway traps every day except one. Median instantaneous RRR at the west and east fishway were significantly greater in 1997 than either 1995 or 1996 (median test, $0.05 > p > 0.025$ for both fishways). Median instantaneous RRR increased from 0% to 1.9 % and 2.1 %, at the west and east fishway, respectively.

Discussion

Simple modifications to the entrances of two Denil fishways produced significant increases in recapture rates of pumpkinseeds. Assuming that probability of recapture increased proportionally with fishway entrance locatability, increased recapture rates represent concomitant increases in attraction efficiency. Although other species were not investigated in this study, they would likely experience less difficulty locating the fishways as a direct result of entrance modifications. Hydraulic conditions downstream of every fishway are unique. However, similarly simple modifications may help increase passage rates of warmwater fish at other fishways that have been identified as ineffective.

Deficiencies in fishway efficacy for passing fish may be due to severe hydraulic conditions (i.e., supercritical water velocities and extreme turbulence) or poorly positioned or improperly designed entrances (Katopodis *et al.* 1991). One assessment of migration failure by migratory cyprinids (barbel *Barbus barbus*) used stepwise multiple regression analysis to reveal that entrance attractivity was the major factor that allowed barbel to successfully use a Denil fishway in Belgium (Baras *et al.* 1994). Several other researchers have noted that turbulence and high water velocity alters the behaviour of migrating fish and reduces success at locating and using fishways (Barry and Kynard 1986; Kynard 1993).

In a comparative study of vertical slot and Denil fishways, Schwalme *et al.* (1985) noted that fish bypassed the fishways and swam through a spillway that was located several metres upstream from the fishway entrances. To prevent this, access to the spillway was blocked with a sheet of plywood, thereby encouraging modest numbers of fish to begin re-using the fishways. A study of radiotagged Atlantic salmon at the Pitlochry Dam on the River Tummel, in Scotland, indicated that fish sometimes failed to locate the entrance to a pool and orifice fish ladder, and appeared to be distracted by tailrace and turbine flows (Gowans *et al.* 1999). This situation was rectified by screening off the dam tailrace, thereby preventing access to attraction flows from turbine discharge (Gowans *et al.* 1999). Other modifications to fishways have focused on exits. Examples include changes to diffusers on Connecticut River fishways to produce suitable exit face velocity conditions (White and Pennino 1980), and modifications to upper ends of fish ladders at the John Day Dam and Bonneville Dam on the Columbia River, to improve passage times of American shad (*Alosa sapidissima*) and salmonids (Perkins and Smith 1973; Monk *et al.* 1989). The authors indicate that the design changes should enhance fish passage and minimize water consumption, but results from follow-up studies were unavailable.

During upstream migrations, fish become rheotactic and are attracted to currents but avoid highest velocity flows. In cases where a waterfall or other migratory obstruction is angled across a stream, fish tend to gravitate towards the apex of water below the barrier, as described by Power (1989). This is the ideal location for the entrance to a fishway designed to mitigate the blocking effects of such a barrier. If an obstruction is located squarely across a stream, fishway entrances should be placed as close to the face of the obstruction as possible while avoiding velocity or turbulence barriers that may develop during high flow conditions. If possible, entrances should be positioned to maximize the utilization of turbine tailrace, or spillway discharge so that fish are led towards the fishway entrances.

Extensive delays have been reported among fish downstream from dams, regardless of the presence of fishways (Fernet 1984; Webb 1990; Harris and Mallen-Cooper 1994; Lucas and Frear

1997; Bunt *et al.* 1999). Due to limited availability of suitable spawning habitat, successful reproduction of some fishes may be compromised downstream from dams. In some circumstances, however, ice scour and spillway flows may unembed substrate and produce conditions that result in ideal spawning habitat for some species immediately downstream of dams (Bunt *et al.* 1998). More commonly, however, fish are delayed indefinitely and exploratory movements in and around dam spillways are common occurrences. These delays may prevent fish from spawning due to gamete resorbtion (Shikhshabekov 1971). In addition, environmental changes may occur and suitable spawning conditions may be missed, or spawning may be relegated to marginal areas downstream of dams. Reserves of energy may become depleted and injury or mortality may occur as fish repeatedly attempt to swim through or leap past a dam face (Bunt, unpublished data). Delays and crowding downstream from dams may result in increased exposure to communicable diseases such as lymphocystis and lymphosarcoma, and may also leave fish vulnerable to angling (e.g., northern pike – Nelson 1983; Fernet 1984). Conservation regulations that prohibit angling immediately downstream of dams are meant to offset this problem to some extent, and help protect migratory fish during certain periods of the year.

Acknowledgements

Field operations for this project were assisted by Gabrielle Held, Steven Cooke, Brett van Poorten and Lin Wong.

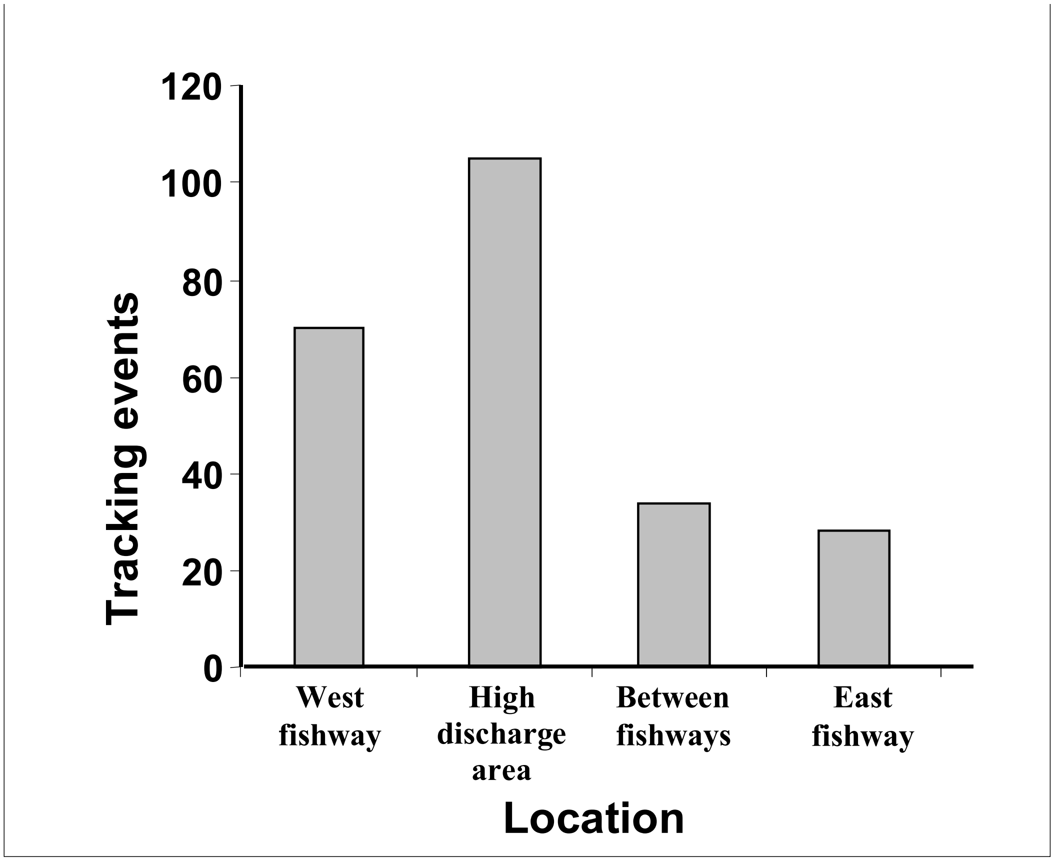


Figure 5.1. Summary of radio-tracking events downstream of the Mannheim weir from 17 May to 31 May 1995. An event was defined as two or more consecutively logged records by up to 53 radiotagged smallmouth bass *Micropterus dolomieu* or selected catostomids (white sucker *Catostomus commersoni*, northern hog sucker *Hypentelium nigricans* and golden redhorse *Moxostoma erythrurum*) from within 3 - 4 m of each location.

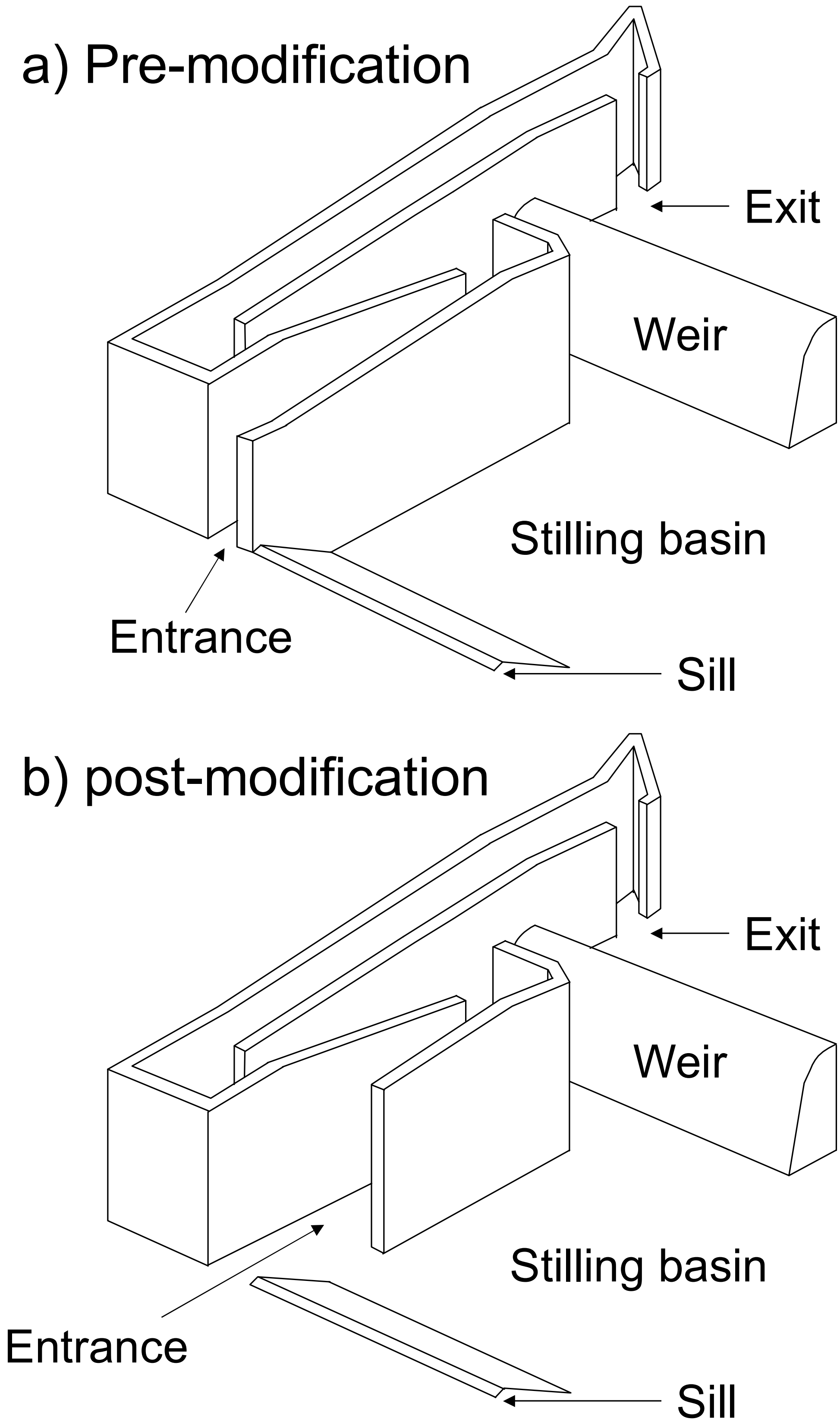


Figure 5.2. a) The west fishway at the Mannheim weir prior to entrance modifications. b) The west fishway after the entrance had been enlarged and re-located.

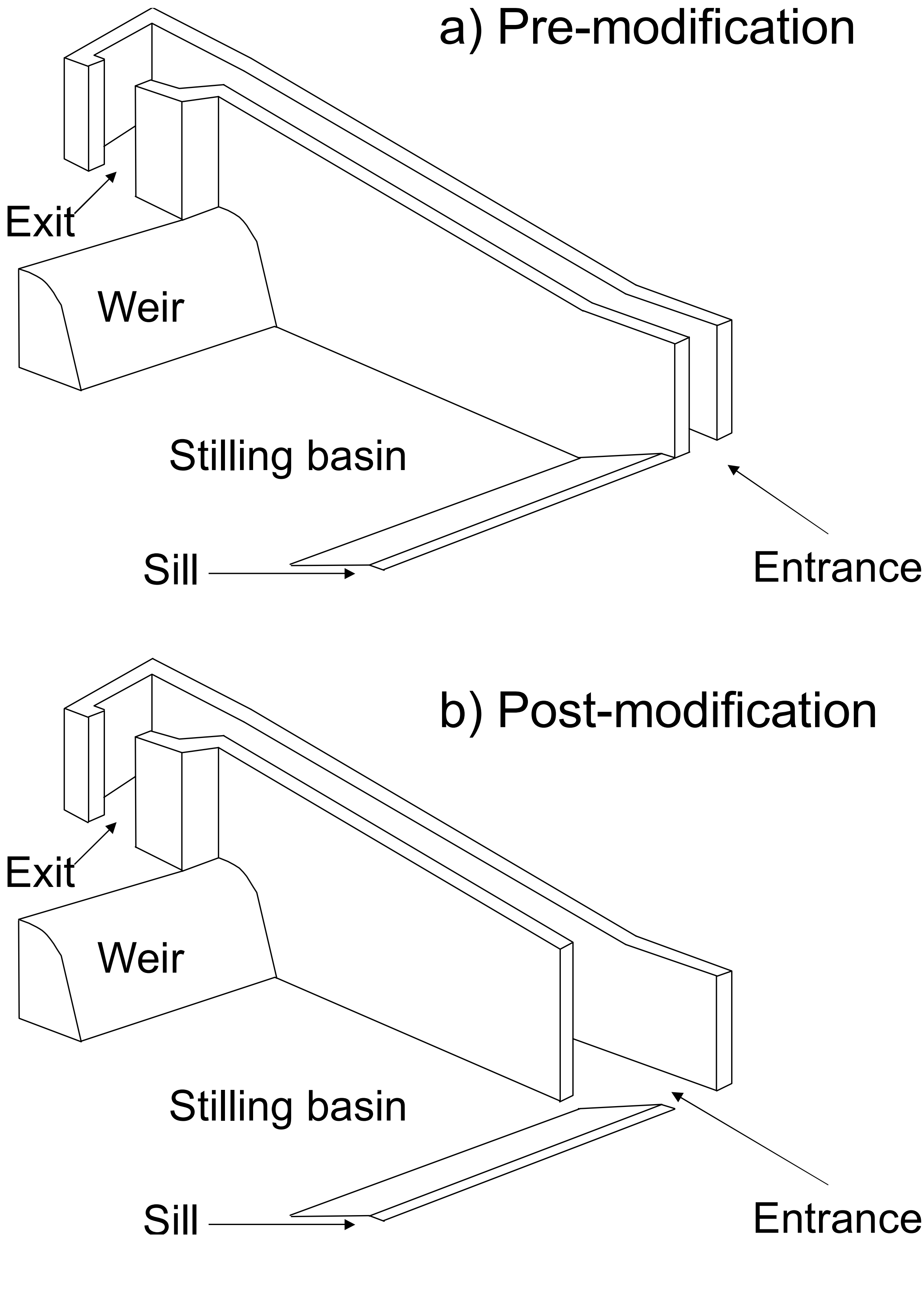
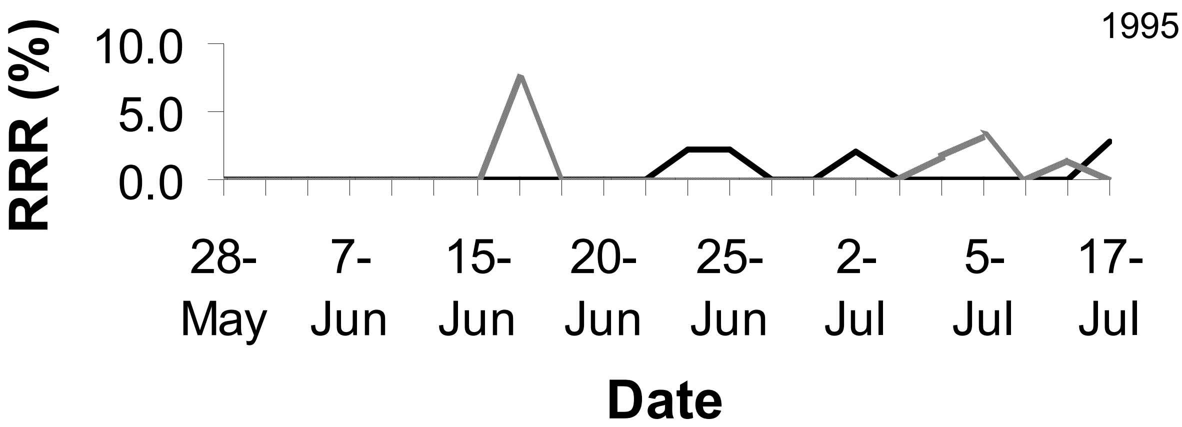


Figure 5.3. a) The east fishway at the Mannheim weir prior to modification of the entrance. b) Post-modification configuration and positioning of the entrance.



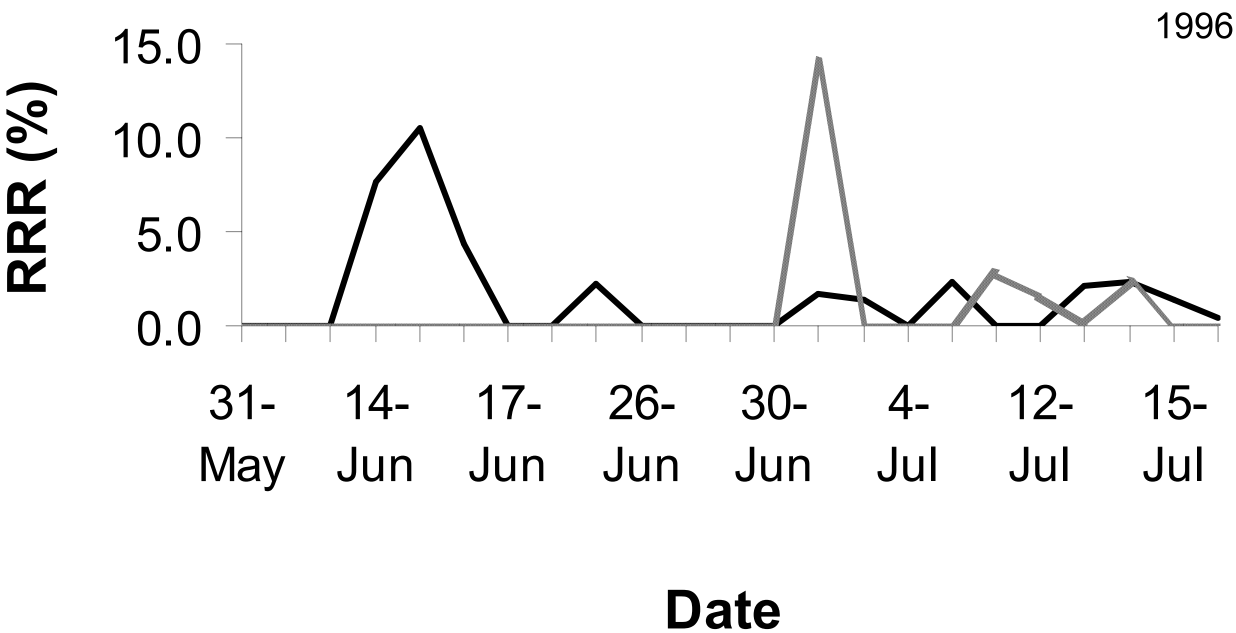


Figure 5.4. Pre-modification instantaneous RRR of pumpkinseed at the west fishway (black line) and east fishway (gray line) for the years 1995 and 1996.

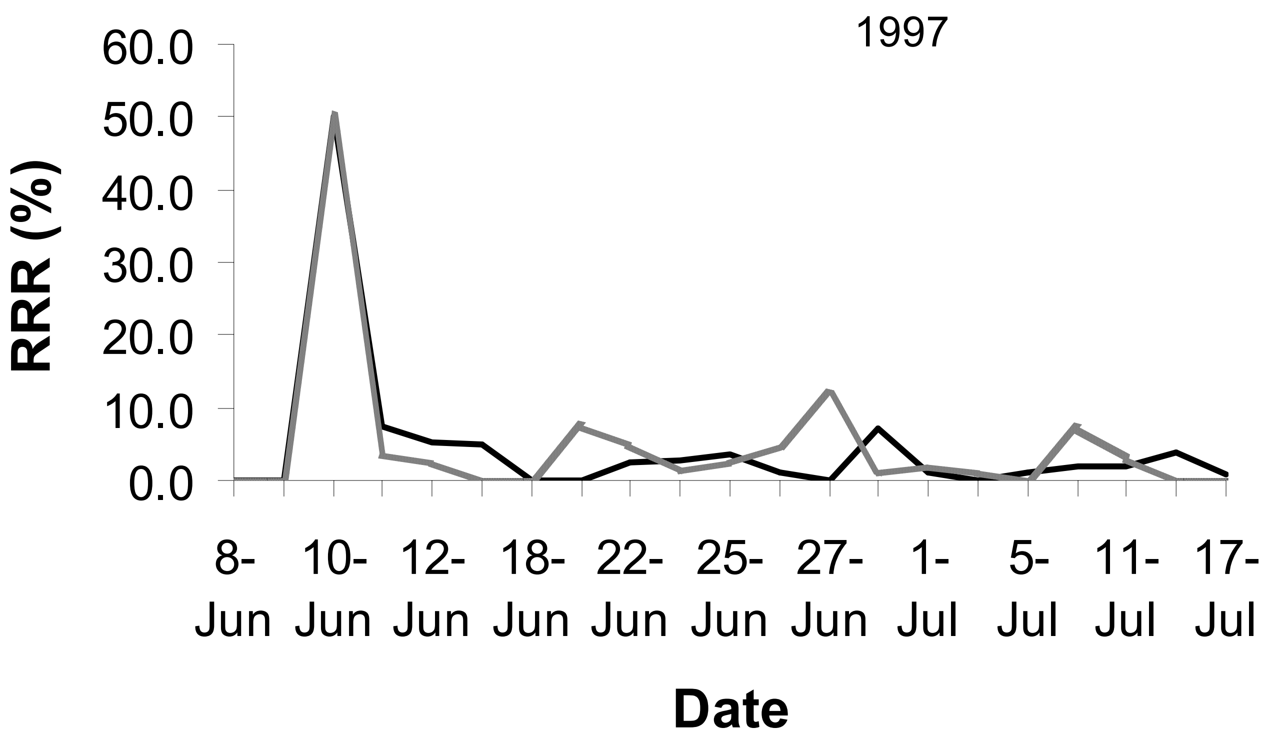


Figure 5.5. Post-modification instantaneous RRR of pumpkinseed at the west fishway (black line) and east fishway (gray line) in 1997.

CHAPTER 6

A tool to facilitate implantation of electrodes for electromyographic telemetry experiments [6]

Abstract

Conventional techniques for implanting electrodes into axial swimming musculature of fish are reviewed. A new device is described that reduces time for electrode implantation, ensures constancy in electrode orientation, implantation depth, and separation distance. This device is inexpensive, simple to build, and easy to use.

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[6] Published - Journal of Fish Biology 55: 1123-1128.

Introduction

Electromyographic (EMG) telemetry involves implantation of transmitters in fish that relay muscular activity to aerial or submerged antennas and receiver systems. Muscular activity rates in free swimming fish are then used to describe physical output associated with fishway use (Bunt 1999b), upstream migrations (Hinch *et al.* 1996), spawning behaviour (Kaseloo *et al.* 1996; Weatherley *et al.* 1996), swimming performance and oxygen consumption (McKinley and Power 1992; Booth *et al.* 1995; Økland *et al.* 1997), diel activity (Demers *et al.* 1996), activity associated with stressors such as pollutants (Weatherley *et al.* 1980) and temperature changes (Beddow and McKinley 1998; Booth *et al.* 1997), metabolic rates (Rogers and Weatherley 1983; Briggs and Post 1997), and to test bioenergetic models (Hinch and Rand 1998).

Typically, EMG transmitters consist of a cylindrical package composed of a printed circuit board and surface mounted components, wrapped around a battery and sealed in epoxy. Trailing from one end of a radio (as opposed to ultrasonic) telemetry package are three leads. One is a broadcast antenna and the other two are electrode attachment wires for the detection of biologically relevant data. Traditionally, electrodes at the end of the attachment wires are implanted into target musculature using a variety of techniques that require several minutes to complete. Usually, these techniques involve two independent needles that are inserted carefully into red musculature beneath the skin and below the lateral line for measurement of aerobic activity, or within glycolitic, white musculature to measure anaerobic, or burst activity. Transmitters accumulate (i.e., integrate) bioelectrical energy from target muscles in a capacitor. When a preset threshold is achieved (e.g. 150 μV), the device transmits a pulse from the broadcast antenna, with a rate that is dependent on the rate of loading of the capacitor. Therefore, radio pulse rates are inversely proportional to muscular activity. The strength of EMG signals is not correlated with electrode separation distances between 5 – 12 mm, however Beddow and McKinley (1998) indicated that abrupt signal differences occurred when electrodes were > 30 mm apart. They also indicated that transmitters malfunctioned when electrodes contacted one another (Beddow and McKinley 1998). Electrode positions within muscle fibers may affect the electrical potential difference between electrodes. In fish, twitch contraction times and EMG signals vary with longitudinal position (Wardle and Videler 1993; Jayne and Lauder 1995) and muscle type (Jayne and Lauder 1994). Therefore, inconsistent electrode implantation could cause biologically irrelevant variation in EMG data. There is no standard separation distance between electrodes (1 mm – Weatherley *et al.* 1982; 5 mm – McKinley and Power 1992 and Booth *et al.* 1997; 10 mm - Hinch *et al.* 1996; 20 mm – Briggs *et al.* 1997; 7 mm – Beddow and McKinley 1998). Most studies use electrode separation distances between 5 and 10 mm. However, conventional techniques for electrode placement result in variable electrode positions and variable implantation depths within target musculature that are difficult to control. Moreover, if the distance between electrodes is not consistent, signal accumulation and capacitor loading may be affected. Inconsistencies in electrode placement may contribute to EMG data variation among groups of fish. Inconsistencies in electrode placement among research projects make it difficult to accurately compare results from different studies. This paper describes a simple device that may be used to significantly reduce time required for electrode implantation, and that ensures constancy in electrode orientation, implantation depth, and separation distance.

Methods

The following examples are based on implantation of EMG transmitters into anesthetized *Micropterus dolomieu* (350 – 500 mm TL). These techniques have also been used with largemouth bass *M. salmoides* (Demers *et al.* 1996; Kaseloo *et al.* 1996), Atlantic salmon *Salmo salar* (Booth *et al.* 1997; Beddow and McKinley 1998), sockeye salmon *Oncorhynchus nerka* (Hinch *et al.* 1996), lake sturgeon *Acipenser fulvescens* (McKinley and Power 1992), rainbow trout *Oncorhynchus mykiss* (Weatherley *et al.* 1982; Briggs and Post 1997), and lake trout *Salvelinus namaycush* (Kaseloo *et al.* 1996; Weatherley *et al.* 1996). Traditional methods of implanting transmitter electrodes into target musculature involve the use of sewing needles (Kaseloo *et al.* 1992), or two grooved needles (approximately 150 mm long, 21-G) and sharpened metal plunger inserts (McKinley and Power 1992). Electrodes are loaded into the grooves and the needles are inserted through the body wall, to beneath the epidermis from inside the body cavity. This eliminates problems associated with abrasion, tangling or angling damage that may occur when electrodes are completely inserted through the body wall and anchored externally (Kaseloo *et al.* 1992; Demers *et al.* 1996; Briggs and Post 1997). Needles are guided visually from above a ventral body cavity incision that secondarily facilitates placement of the transmitter within the body cavity. Placement and spacing of the electrodes is accomplished through palpation of the epidermis adjacent to the site of electrode implantation. Alternatively, electrode placement could be guided by radiography, but this is exceptionally costly. Once the electrodes are in place, excess electrode wire is pushed posteriorly, away from the incision, and the broadcast antenna is threaded from a puncture near the urogenital pore using a modified shielded needle technique as follows. A small puncture is made through the skin near the antenna exit point using an 18-G needle. Then, a 150 mm blunt-tip spinal-tap needle with a solid steel insert is introduced into the puncture and guided carefully past the viscera so the tip protrudes from the ventral incision. The solid insert is removed, the transmitter antenna is pushed into the tip of the spinal-tap needle, and the needle is withdrawn from the puncture, leaving the antenna threaded in its place. The transmitter is inserted carefully into the body cavity and pushed posteriorly away from the incision. In some cases, antibiotic solutions may be applied before the body cavity incision is sutured closed and fish are allowed to recover prior to experimentation. The average time required for electrode placement and transmitter implantation using this technique is approximately 10 min, but could be up to 30 min from initial incision to final suture.

The newly developed device (Figure 6.1) consists of two fused syringes and plungers that expel preloaded transmitter electrodes from modified large gauge needles. Since fish size is often correlated with thickness of the body wall, longer needles and plunger inserts are required to implant electrodes in larger fish.

To expel the electrodes accurately into the target musculature, the syringe plungers were modified to include a length of surgical steel that fitted into the shafts of the grooved needles (steel plunger insert; Figure 6.1a). To build the device, plungers were removed from the syringes and the rubber tips were detached. A length of 20-G surgical steel (approximately 3 cm long, depending on fish size and needle length) was heated with a Bunsen burner and melted into each syringe plunger tip, parallel with the syringe plunger. Surgical steel inserts were secured in place with a small amount of epoxy glue. Then, the rubber tips were forced carefully over the ends of the surgical steel inserts and back onto the syringe plungers. The distal ends of each plunger were glued together so that they functioned as one unit rather than two independent plungers. Then, the plungers with surgical steel inserts were placed into the syringes. The inserts were guided into the needle shafts, and pushed snugly against the ends of the electrodes when they are loaded into the needle grooves. Transmitter electrode wires were held parallel to the electrode needles prior to insertion from inside the body cavity into the axial musculature beneath the epidermis.

To prevent gas bubbles from entering the implantation sites, 4 x 4 mm rectangular vents were cut with a scalpel blade towards the lower end of each syringe. The vents discharge air before it enters the needle shafts. Different sized shims made from styrene foam may be glued between the two syringes so that the distance between needle tips may be varied. Industrial-strength hot glue is the recommended adhesive. The prototype tool consisted of two 40 mm 16-G hypodermic needles that were aligned and glued to the syringe tips with a small amount of epoxy. The needle tips were also slightly blunted with a sharpening stone to prevent puncture of the epidermis and infection (Beddow and McKinley 1998). In this model, needle tips were spaced 7 mm apart and a groove was created in the tip of each needle using a hand-held power rotary tool (Figure 6.1b). These longitudinal grooves measured 1 x 10 mm and permitted insertion of 9 K gold electrodes that measured 0.75 x 7 mm. Each electrode was composed of a cylindrical shaft with a hole for the transmitter electrode wire midway along the length (Figure 6.1c), rather than at one end (Hinch *et al.* 1996). With electrodes loaded into both needle tips, and transmitter attachment wires pushed to the apex of the needle groove, the electrode/needle combination creates a relatively streamlined shape (Figure 6.1c). When the electrodes are ejected from the tool, they become hooked into the target muscle like an anchor tag.

Guiding the needles through the body cavity incision, past viscera and into axial swimming muscles requires care. During experimentation with traditional needles and the new device, muscles often twitched as physical damage occurred in the muscle mass between the body cavity and target musculature beneath the skin. When it is clear that electrodes are placed properly, a 2 - 3 mm withdrawal of the needles prevents puncture of the skin after plunger depression. Using the new device, needles are guided into place quickly, and plunger depression releases the electrodes into the muscles that are to be monitored. The device is then removed from the incision, the antenna is threaded through the body wall, the transmitter is inserted carefully into the body cavity and the incision is sutured closed. Average time required for electrode placement, transmitter implantation and suturing of the incision is approximately 5 min. In trials with the new device, electrodes were implanted quickly and average anesthetization times for *M. dolomieu* were reduced by a factor of two. In each trial, electrodes were oriented and spaced consistently (Figure 6.2). X-ray imaging and post-mortem examinations indicated that electrode placement was well controlled and visual observations showed that post-surgical behavioural effects were negligible. Occasionally, the traditional technique of electrode placement leads to movement of the electrodes and resultant contact between them (Beddow and McKinley 1998). This results in loss of biologically relevant EMG data and waste of a transmitter if the fish has been released for observations of natural behaviour and activity. There was little variation in electrode positions when the new tool was used to implant EMG electrodes. Overly dulled or damaged needles may simply be replaced and the life expectancy of the tool is virtually unlimited. The newly described device is inexpensive and simple to build, easy to sterilize and use, and will allow researchers to accurately compare the results of physiological telemetry experiments by ensuring that electrode placement techniques are standardized.

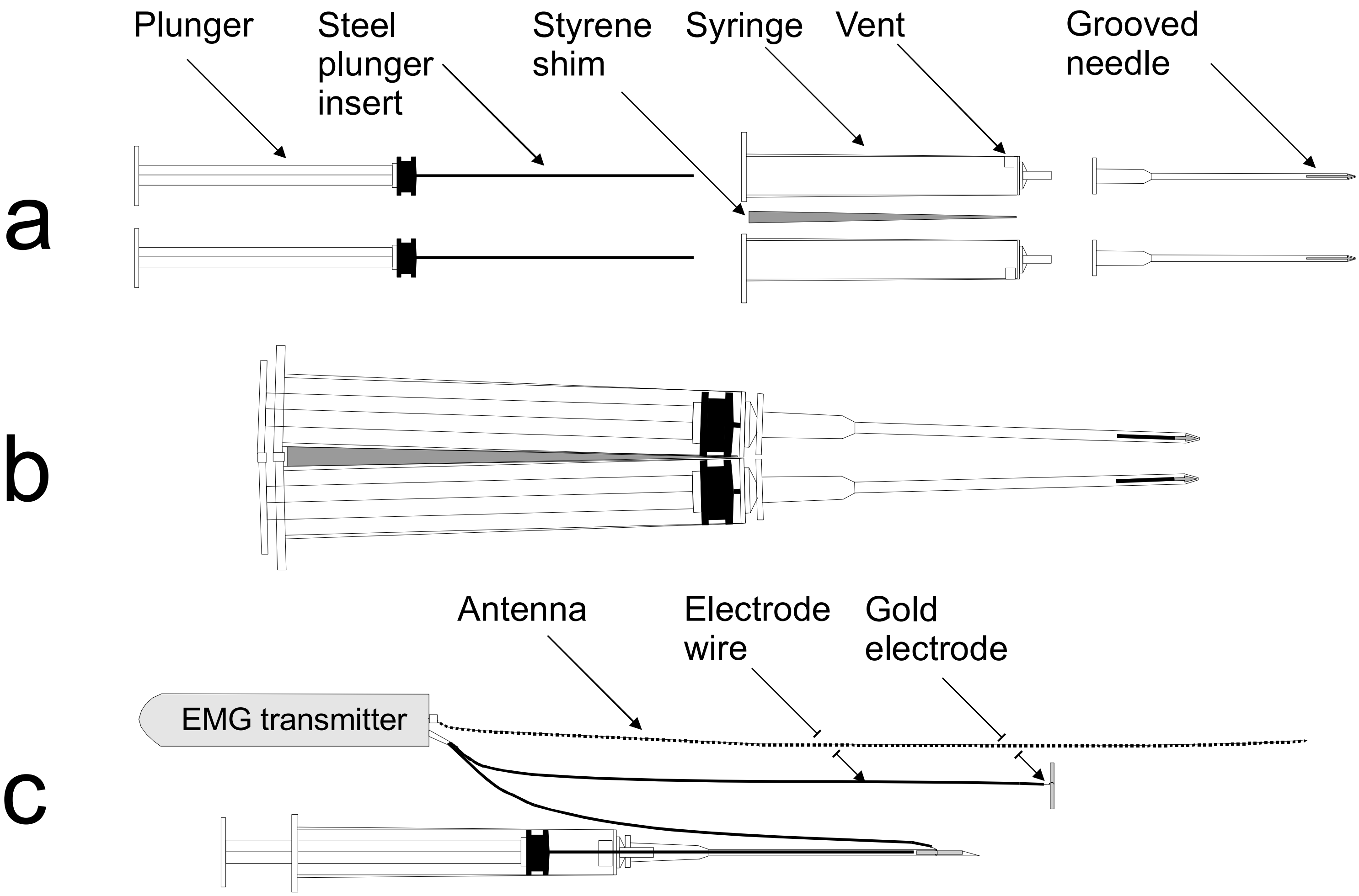

Figure 6.1. a) Components of the tool used to facilitate implantation of EMG electrodes (exploded view). b) Assembled tool (plan view) with syringe and shim held together with hot glue. c) Transparent lateral view of the implantation tool showing EMG electrode loaded into needle groove.

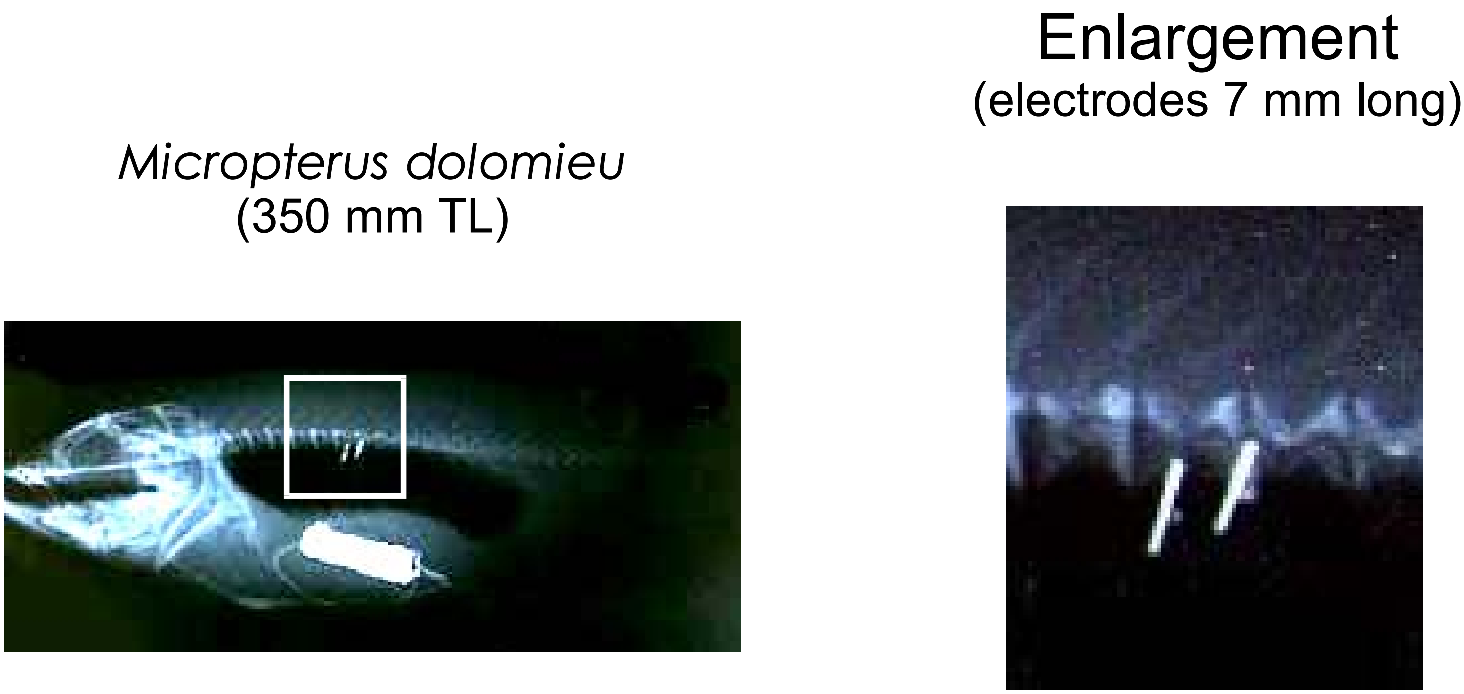

Figure 6.2. X- ray image of *M. dolomieu* (350 mm TL) implanted with electrodes from a typical EMG transmitter using the new tool. Note relative electrode positions in enlargement.

CHAPTER 7

Electromyographic evaluation of difficulty during use of two Denil fishways for smallmouth bass *Micropterus dolomieu* [7]

Abstract

I used electromyogram (EMG) telemetry to measure the relative physical output required for smallmouth bass *Micropterus dolomieu* to ascend two different Denil fishway designs. The fishways differed in length, slope and water velocity. Smallmouth bass (n = 7) were implanted with transmitters that broadcast integrated signals representing axial muscular contraction rates to a submerged antenna array within each fishway. There was a significant positive relationship between activity of the swimming muscles and the position of each fish between the fishway entrance and exit. Mean EMG pulse rates from each fish that swam from the entrance to exit of a short, steep fishway increased by 13 – 55 % relative to basal levels. Maximum subsurface water velocities during fishway use were 0.4 – 1.4 m/s. In a long fishway with reduced slope and resting pools, maximum subsurface water velocities were 0.35 - 0.9 m/s and EMG levels increased by 17 to 47 % of basal levels as fish swam from the entrance to the exit. EMG levels were significantly greater in the upper regions of each fishway compared to the entrances. EMG levels from areas near the fishway exits were also significantly greater than maximum EMG levels recorded during critical swimming speed trials. Smallmouth bass appeared to exceed their aerobic scope of activity during ascent of both fishways. EMG data reflected combinations of burst and prolonged swimming activity and indicated the relative differences in muscular activity and physical output required to ascend each fishway type.

[7] Presented at the 128th American Fisheries Society Conference – Hartford, Connecticut, August 1998

Introduction

Relative physical output and stress experienced by fish should be minimal if the full potential for successful upstream passage through fishways or other fish by-pass facilities is to be realized. Results of recent studies suggest that high degrees of variability among passage rates and low species-specific passage efficiencies through fishways result from a combination of physical and behavioural (i.e., motivational) differences among fish (Haro and Kynard 1997; Lucas and Frear 1997; Bunt *et al.* 1999). The twitch contraction time of lateral swimming muscles is temperature regulated. By measuring contraction times of isolated swimming muscles at preset temperatures, maximum swimming speed can be estimated (Beach 1984). By measuring how hard a fish must swim to successfully use a fishway, we may begin to separate and quantify the relative importance of ability versus proclivity to use a particular fishway type or configuration. Successful studies will provide useful information that may help maximize upstream fish passage.

Several techniques are available to monitor activity of free-living fish including videography (Collins *et al.* 1991), surface or subsurface observation (Monk *et al.* 1989) and electromyogram (EMG) radiotelemetry (Kaseloo *et al.* 1992; McKinley and Power 1992; Kaseloo *et al.* 1996; Hinch *et al.* 1996). EMG telemetry has proved to be an effective tool for the collection and analysis of muscular activity levels from free-living lentic smallmouth bass *Micropterus dolomieu* (Demers *et al.* 1996). Smallmouth bass are one of the most recreationally and economically important potamodromous fish in Canada and the United States. Among lotic populations, spawning-related upstream migrations and fishway use in the northern United States and southern Canada usually occur in May and June (Bunt *et al.* 1999).

Denil-type fishways, are versatile and well suited for non-leaping warmwater species. They are generally considered operational over a wide range of flows and are therefore useful for fish passage where extreme fluctuations in water levels occur (Schwalme *et al.* 1985). Hydraulic conditions within all fishways are often turbulent (Beach 1984; Clay 1995; Haro and Kynard 1997). However, Denil fishways provide reduced water velocities by creating extremely turbulent flows to dissipate energy in the downward stream of flowing water that fish must swim through to pass upstream. Passage efficiencies of adult smallmouth bass through Denil fishways are approximately 30 %, as determined using radiotelemetry (Bunt *et al.* 1999). Low passage rates of American shad *Alosa sapidissima* and sea lamprey *Petromyzon marinus* through a weir and orifice fishway in Massachusetts were attributed to turbulence, high water velocities and entrainment of air bubbles by Haro and Kynard (1997). The goal of this study was to use EMG telemetry to measure the relative activity of the axial aerobic swimming muscles of smallmouth bass during use of two different Denil fishways.

Methods

Smallmouth bass used in this study were angled from the Grand River in southwestern Ontario in the spring of 1997 and 1999. To minimize the effects of body size and gender which may confound the results of physiological experiments, I selected female fish with lengths between 421 and 489 mm TL (n = 7). Each fish was implanted with an EMG transmitter that broadcast an integrated signal representing axial swimming muscle contraction rates. Patterns of muscular activity were collected and analyzed while each fish was at rest, during stepwise increases in water velocity in forced-swim experiments and during use of two Denil fishways located at a low-head weir on the Grand River. Between experiments, all fish were held in 300 L tanks equipped with a 1 L/s flow of river water. Fish were fed crayfish *ad libitum* between experiments. An artificial photoperiod was maintained to match natural conditions during the investigation period (16 L:8 D).

Transmitter Implantation

EMG transmitters (Lotek Engineering Limited, Newmarket, Ontario) measured 5 cm long x 1.5 cm in diameter and weighed 17.5 g in air. Bioelectrical activity was detected by two 9 k gold electrodes which were secured in the band of aerobic swimming muscle, located beneath the skin and approximately 2 cm ventral to the lateral line. Electronics within each transmitter detected, amplified and rectified all signals greater than 1 - 2 μV. The signal was then integrated in a capacitor until a threshold level of 150 μV was achieved, at which point a radio pulse was broadcast from an antenna which trailed from one end of the transmitter package. The integration circuits were then reset until enough signals accumulated to trigger another radio burst. The interval between bursts is inversely related to the frequency of muscular contraction rates. For the purposes of this study, EMG pulse intervals were converted into pulse rates (pulses per min) for analysis. Due to electronic differences within each transmitter, EMG activity was standardized and expressed as percentage increase relative to basal (baseline) EMG levels.

Transmitters were implanted using a modified version of the technique developed by McKinley and Power (1992). Smallmouth bass were anesthetized in a 50 ppm clove oil/ethanol solution (Anderson *et al.* 1997) and were placed ventral side up into a V-shaped foam-lined trough. To maintain a satisfactory state of anesthesia, a 25 ppm maintenance dose of clove oil/ethanol mixed with aerated water was used to continuously irrigate the gills. A 2 cm incision was made into the body cavity posterior to the right pelvic fin, 1 cm to the right of the ventral midline. A small puncture was carefully made in the epidermis using an 18 G hypodermic needle anterior to the urogenital pore. A blunt-tipped spinal-tap needle with a solid metal insert was carefully inserted into the body cavity incision and through the puncture. The solid insert was then removed and the transmitter antenna was threaded through the needle tip. The needle was then withdrawn from the puncture leaving the antenna threaded in its place.

Hard-wired EMG experiments have shown that the intensity of muscle activity varies along the length and at opposite positions on alternate sides of fish (Beddow and McKinley 1999). Other studies have suggested that inconsistent EMG electrode placement in the axial musculature of smallmouth bass may produce somewhat variable results (Demers *et al.* 1996). To minimize these concerns, I developed a simple tool that was used to increase the precision of my electrode placement technique. The device consisted of two fused syringes and plungers (superficially similar to commercially available epoxy resin/hardener kits). Details of the construction and use of the tool are in Bunt (1999c). The tool controls electrode placement by ensuring that the electrodes are expelled at a pre-determined distance apart (approximately 7 mm) and at the same depth within target musculature. Consistency in electrode placement was verified by external palpation of the electrode needle positions, just ventral to the lateral line. When I was satisfied with the needle positions, needles were withdrawn approximately 3 mm and the plungers were depressed, thereby expelling the electrodes within the red muscle. Excess electrode wiring was then inserted into the body cavity incision, followed by the transmitter, which was pushed posteriorly. The incision was then closed with three or four simple interrupted sutures of non-absorbable braided silk. Fish were allowed to recover from surgery in tanks that provided a flow of fresh river water. The surgical procedure generally lasted less than 5 min and recovery required < 3 min. All fish appeared healthy and behaved normally after radiotag implantation and for the duration of the investigation. Incidentally, after the study, fish were released into the Grand River with EMG tags implanted. SMB264 was recaptured in good condition by an angler in July 1998 – nearly one year after release.

Laboratory study

Each fish was allowed to recover for one week prior to the collection of EMG data. This delay allows tissue trauma at the site of the electrodes to heal and for EMG signals to stabilize. Basal, or resting EMG pulse rates were collected and averaged over 2.5 – 5.5 h including periods when peak EMG activity has been recorded from wild smallmouth bass (i.e., mid-late afternoon, Demers *et al.* 1996).

To investigate the relationship between EMG output and swimming speed, I used a 70 L Blazka-Fry swim tube and followed the protocol of Kaseloo *et al.* (1992). Fish were acclimated to water velocities < 10 cm/s for 2 h prior to stepwise increases in water velocity of 10 cm/s at 10 minute intervals. Velocity increases continued until fish fatigued (Ucrit, Brett 1964). A bright halogen light was placed near the rear of the swim tube and this encouraged fish to swim beneath a shaded portion of the swim tube midway along its length. Swimming speeds were corrected to compensate for blocking effects caused by the flow of water around the fish while within the swim tube according to Smit *et al.* (1971). EMG signals were recorded continuously with a Lotek SRX_400 receiver and were averaged for each 10 min interval between velocity increases. All swim speed trials were conducted in river water with temperatures between 20 and 24 °C. The use of fundamental units of measure such as m/s (rather than bodylengths/s), allow direct comparisons to be made with water velocities in fishways (Beach 1984).

Field Study

The east fishway consisted of a 0.6 m wide linear concrete channel on a 20 % gradient with metal baffles spaced 25 cm apart. Turbulence and shear stresses resulting from vortexing flows between baffles (Rajaratnam and Katopodis 1984) slow water velocities in a primary flow that fish swim through by more than 85 % of expected values from channels without baffles (Katopodis and Rajaratnam 1983). The fishway was 11 m long and provided typical subsurface maximum water velocities from 1.5 - 2 m/s when flows were unobstructed by debris. A benchmark position was established approximately 3 m downstream from the fishway trap, where backwater effects were negligible, to represent the region with the greatest water velocities. Water velocities were measured approximately 10 cm below the surface of the flow with a Sigma PVM ultrasonic velocity meter. For the purpose of these experiments, the upstream exit and downstream entrance were blocked to prevent the escape of EMG tagged fish that were released within each fishway at the entrance. The downstream entrance was closed with a wood and chain-link fence corral that was secured flush to the concrete foundation without any large gaps. A velocity refuge was provided behind the end of the outer wall of the fishway to allow fish to swim volitionally without becoming impinged on the downstream blocking screen. The upstream exit was fitted with a removable steel blocking screen with 1.5 cm mesh. A removable aluminum funnel trap (mesh size 2 cm) located 1.5 m downstream from the exit prevented escape of fish from the upper region of the fishway upon successful ascent.

The west fishway was more complex than the east fishway. It was composed of a 22 m concrete channel of equal dimensions to the east fishway except, it was doubled-back on itself twice with a resting pool at each 180° turn. Each of the three channels was set on a 10 % gradient. Typical water velocities measured from a subsurface benchmark position 3 m downstream from the fishway exit ranged between 0.75 and 1.3 m/s without debris on blocking screens. Both the entrance and the exit were blocked in the same manner as the east fishway. Further details of the fishways, the 2.2 m high weir, and the study site are available in Bunt *et al.* (1998) and Bunt *et al.* (1999).

To track the positions of radiotagged fish and to collect EMG data, sequentially scanned submerged antennas were embedded in each of the three channels of the west fishway and at the entrance. The tracking and data collection system in the east fishway consisted of two submerged antennas; one at the entrance and the other midway between the fishway entrance and exit. The receiver (Lotek SRX_400 with W20 firmware) was connected to each submerged antenna via RG-58 A/U coaxial cables that ranged in length between 40 and 150 m. Scanning between antennas was facilitated with a Lotek ASP_8 fast antenna switcher. Individual antenna gains were manipulated using reference signals from manually placed transmitters to fine-tune the system in each fishway before all trials commenced. Transmitters were detectable at any position within all channels. EMG data from midway (± 2 m) along each channel in the west fishway, midway (± 2 m) along the east fishway and at each fishway entrance were analyzed. Data from resting pools in the west fishway where fish were observed to swim irregularly were excluded from analysis. Fish positions were accurate to within 50 cm.

EMG data were continuously recorded from each radiotagged fish that was individually tested in each fishway between 7 July and 30 July 1997 and 11 May to 13 July 1999. All experiments commenced at 13:00 h and were completed when fish were trapped between the funnel trap and blocking screen near the fishway exits.

Average (± 1 S.E.) EMG pulse rates from each antenna were used to compare muscle activity at various regions within each fishway. Single-factor ANOVA was used to test for significant differences in physical output associated with fish location between the fishway entrances and exits. EMG activity levels within the fishways were compared to EMG activity levels recorded during swim tube trials using single factor ANOVA.

Results

Baseline EMG data from each fish were determined to be suitable for parametric analysis (Lilifors test) and mean values ranged between 24.61 ± 0.02 and 32.78 ± 0.01 pulses/min. There was a significant difference between baseline values among individuals (ANOVA, $F = 1929.5$, 12063 df, $p < 0.0001$). Mean baseline values for each fish were each statistically distinct from one another (Tukey-Kraemer HSD). During critical swim speed trials, there was a significant positive relationship between EMG pulse rate (expressed as percentage difference from basal levels) and swimming speed for each fish (ANOVA, $p < 0.001$, Figure 7.1). Maximum percentage differences from basal EMG levels increased between 8 % and 46 % as swimming speeds increased from 0.1 to 0.61 m/s. Maximum prolonged swimming speed (Ucrit) ranged between 0.47 and 0.69 m/s (Table 7.1).

Maximum subsurface water velocities recorded in the east fishway were generally greater than those from the west fishway. Correspondingly, smallmouth bass exhibited greater EMG activity during use of the east fishway (Figure 7.2, Table 7.1). It should be noted that a large mat of *Cladophora* became impinged on the east fishway upstream blocking screen during use by SMB505. The debris reduced the water level and maximum subsurface water velocity to < 0.4 m/s. Maximum EMG activity from within the fishway during this trial was only 1 % greater than swim tube trials and the difference was not statistically significant (ANOVA, $p = 0.84$, Table 7.1). Axial muscle activity increased significantly as smallmouth bass progressed upstream through the east fishway (Figure 7.2, Table 7.2). Maximum pulse rates were recorded from the upper reaches of the fishway, near the exit, where water velocities were greatest. Average EMG pulse rates for each fish increased by 13 % to 55 % as fish progressed from the entrance to the exit (Table 7.1). EMG activity recorded during passage of the upper regions of the east fishway exceeded baseline levels by up to 64 % and were up to 46 % greater than maximum levels recorded during laboratory swim tube experiments (Table 7.1).

EMG pulse rates increased significantly as each smallmouth bass swam from the entrance to the exit of the west fishway (Figure 7.3, Table 7.2). EMG pulse rates increased by 34 – 60 % as fish progressed from the fishway entrance to the exit. Increased activity was attributed to differences in location within the fishway that were related to changes in water velocity. EMG activity levels were lowest midway along the fishway and near the fishway entrance (Figure 7.3). EMG activity was greatest near the upper region of the fishway. Maximum subsurface water velocities approximately 3 m downstream from the fishway exit ranged between 0.35 - 0.9 m/s. EMG activity levels during passage of regions with the greatest water velocities within the west fishway were 39 – 60 % greater than baseline levels (Table 7.1). As smallmouth bass swam through the upper section of the west fishway, EMG activity was significantly greater than maximum values recorded during aerobic swimming speed trials (ANOVA, Table 7.1). EMG activity during fishway use exceeded maximum EMG pulse rates recorded during swim tube trials by up to 39 %.

Discussion

It is generally accepted that fishways which provide water velocities within a species-specific range of prolonged swimming speeds (< Ucrit) will allow passage over a distance equal to the product of Ucrit (m/s) and the endurance @ Ucrit (s) (Beach 1984; Peake *et al.* 1997). The results of the present study, however, suggest that most fish probably depend on several different modes of swimming while using fishways, including burst swimming which uses energy derived entirely from anaerobic processes (Webb 1978; Wardle 1980; Videler 1993).

Swimming activity recorded in the field exceeded maximum levels recorded during aerobic swimming exercises performed by the same fish that were tested in swim tube experiments in the laboratory. Moderately high water velocities and turbulence, which were most apparent approximately 3 m downstream from the exit of both fishways, produced challenging conditions for each smallmouth bass tested. It appears that some fish are able to overcome super-critical water velocities and turbulent flows in fishways using a combination of anaerobic and aerobic modes of swimming.

Measurements of maximum sustained swimming speeds from swim tube experiments produced a range of values of axial muscle activity that was fueled primarily by aerobically fueled metabolic processes (Brett 1964; Hudson 1973; Beamish 1978; Webb 1975). Despite deliberate placement of electrodes in aerobic musculature, EMG electrodes may also be sensitive to bioelectric impulses that are directed to stimulate anaerobic white muscle fibers (Weatherly *et al.* 1982; Sisson and Sidell 1987; McKinley and Power 1992). Burst swimming is accomplished using fast-twitch muscles that derive much of their energy from glycolitic pathways. This results in an oxygen debt that must be repaid. If the energetic costs required to compensate for this debt exceed the aerobic scope of activity (Fry 1971), delayed mortality may occur (Beamish 1978).

Aerobic and anaerobic activity was identified by Hinch *et al.* (1996) using EMG telemetry data from sockeye salmon *Oncorhynchus nerka*. An assessment of difficulty during use of the Hell's Gate fishway was not possible, but white muscle tissue sampled from salmon that passed through the fishway contained high levels of lactate, indicating that burst swimming had occurred (Hinch *et al.* 1996). Results from the assessment in the current study suggest that smallmouth bass use a combination of prolonged and burst modes of swimming when using Denil fishways.

At low water temperatures, fish rely heavily on white muscle tissue to support intense swimming activity (Rome *et al.* 1992). Cooler water temperatures reduce aerobic swimming capacity (Jayne and Lauder 1994) such that the onset of burst activity occurs sooner and at lower water velocities than during this study. The relative importance of aerobic versus glycolytic pathways for the derivation of energy for fishway use depends on intraspecific variables that should be examined in detail to maximize fish passage.

Relatively high water velocities in upper regions of fishways translate into large amounts of turbulence that smallmouth bass must progress through to proceed upstream (Bunt, unpublished videographic data). Despite the obvious relationships between position while within the fishways, swimming speeds and EMG output, major extrapolations beyond the range of the tested independent variable are required to predict actual swimming speeds during fishway use. Nonetheless, EMG output from the field exceeded maximum values obtained from measurements of maximum prolonged swimming speed. Regardless of differences in water velocity, the west fishway appeared to only be moderately less challenging for smallmouth bass to use than the east fishway. This study also clearly demonstrates that the intensity of activity during fishway use cannot be reliably simulated in laminar flow swim tubes.

Observations of smallmouth bass behaviour in swim tubes indicate that they occupy paths of least resistance that form between irregular currents. Videographic evidence from within the fishways (Bunt, unpublished data) also shows that smallmouth bass use paths of least resistance. Fish sometimes appear to "surf" somewhat effortlessly within turbulent flows. As an example, it is sometimes quite difficult to maintain the position of an object such as a velocity probe in turbulent fishway flows. It is considerably less difficult to allow the object to gently drift (usually laterally) within surrounding flows. Fish occupy areas of least resistance, while water flows around their streamlined body shape. By not opposing lateral forces, fish appear to maintain position between a fishway entrance and exit in the same way a kayaker uses gravity and principles of hydro-foiling to surf in rapids. Perhaps fish subtlely contort their bodies to produce a zone of high pressure caudally, while a zone of lower pressure forms where the flowing water splits, immediately in front of the snout. Complete passage may require fish to burst through more intense regions of turbulence. Although difficult to quantify, behavioural factors may be as important as physical ability in determining whether fish will be successful at using a particular fishway configuration.

Variability among fish in the present study may have been due to electronic differences within each transmitter (Demers *et al.* 1996), subtle differences in electrode placement (Beddow and McKinley 1999; Bunt 1999c), or physical differences among fish. Variability may also have been due to subtle differences in the paths taken by each fish during upstream passage. Species with different swimming habits than smallmouth bass may employ different strategies when using Denil fishways. Benthic species, such as those in the catostomid family or darter subfamilies, demonstrate exceptional position-holding abilities in high velocity flows (Bunt *et al.* 1998; Bunt *et al.* 1999). This is achieved by avoiding overhead turbulence, which is greatest near the surface of Denil fishway flows, and by exploiting reduced velocities in boundary layer flows and between baffles. Most species of interest to fishway planners and operators are not benthic. Therefore, turbulence effects, mechanisms to reduce turbulence, and the importance of anaerobic activity during fishway use should be examined.

Acknowledgments

I thank Dan Sack, Brett van Poorten, Lin Wong, Steven Cooke, Jeff and Ingrid Danylyk, Gabrielle Held, and Danielle Knight, for assistance in the field. The Regional Municipality of

Waterloo, Frank Smith and Lane Stevens graciously provided laboratory facilities. This project was supported by a post-graduate scholarship from the Natural Sciences and Engineering Research Council of Canada.

Table 7.1. Maximum prolonged swimming speed (Ucrit) of smallmouth bass implanted with EMG transmitters and maximum subsurface water velocities in the east fishway (top) and west fishway (bottom). Change in EMG activity recorded from each fish between fishway entrances and exits is shown as ΔEMG I. The percentage difference between maximum EMG values recorded during swim tube trials and maximum EMG values recorded during fishway use is shown as ΔEMG II. Change in EMG activity from near fishway exits relative to mean baseline EMG pulse rates is shown as ΔEMG III. F-values and associated probabilities indicate significant differences between maximum EMG activity from swim tube experiments and maximum EMG activity recorded in each fishway.

	EAST FISHWAY					
	Ucrit (m/s)	Velocity (m/s)	ΔEMG I (%)	ΔEMG II (%)	ΔEMG III (%)	F (probability)
smb264	0.66	1.3	+ 55	+ 15	+ 57	2.51 (p = 0.11)
smb440	0.69	1.4	+ 44	+ 46	+ 64	129.24 (p<0.001)
smb505	0.56	0.4	+ 17	+ 1	+ 11	0.04 (p=0.84)
smb034	0.47	0.8	+ 22	+ 2	+ 39	9.22 (p=0.003)
smb055	0.54	1.3	+ 13	+ 6	+ 18	2.54 (p=0.1180)
smb075	0.52	0.7	+ 18	- 3	+ 23	0.28 (p=0.5592)
smb098	0.57	0.8	+ 26	+ 4	+ 44	8.43 (p=0.0045)
	WEST FISHWAY					
	Ucrit (m/s)	Velocity (m/s)	ΔEMG I (%)	ΔEMG II (%)	ΔEMG III (%)	F (probability)
smb264	0.66	0.35	+ 47	+ 15	+ 57	17.15 (p<0.001)
smb440	0.69	0.36	+ 37	+ 39	+ 60	34.60 (p<0.001)
smb505	0.56	0.47	+ 32	+ 32	+ 39	142.5 (p<0.001)
smb034	0.47	0.74	+ 18	+ 8	+ 45	6.53 (p=0.01)
smb055	0.54	0.9	+ 33	+ 34	+ 46	38.10 (p<0.0001)
smb075	0.52	0.8	+ 26	+ 18	+ 44	135.00 (p<0.0001)
smb098	0.57	0.9	+ 17	+ 14	+ 54	59.07 (p<0.0001)

Table 7.2. Results of ANOVA showing F ratios and probabilities of significant increases in EMG activity (pulses per minute) for each smallmouth bass between the fishway entrances and exits.

	smb264	smb440	smb505	smb034	smb055	smb075	smb098
EAST	F = 11.19	F = 37.77	F = 216.82	F = 406.39	F = 35.39	F = 120.75	F = 143.18
FISHWAY	p = 0.0009	p<0.0001	p<0.0001	p<0.0001	p<0.0001	p<0.0001	p<0.0001
WEST	F = 23.95	F = 60.36	F = 293.95	F = 10.94	F = 79.05	F = 137.04	F = 8.34
FISHWAY	p<0.0001	p<0.0001	p<0.0001	p = 0.001	p<0.0001	p<0.0001	p = 0.004

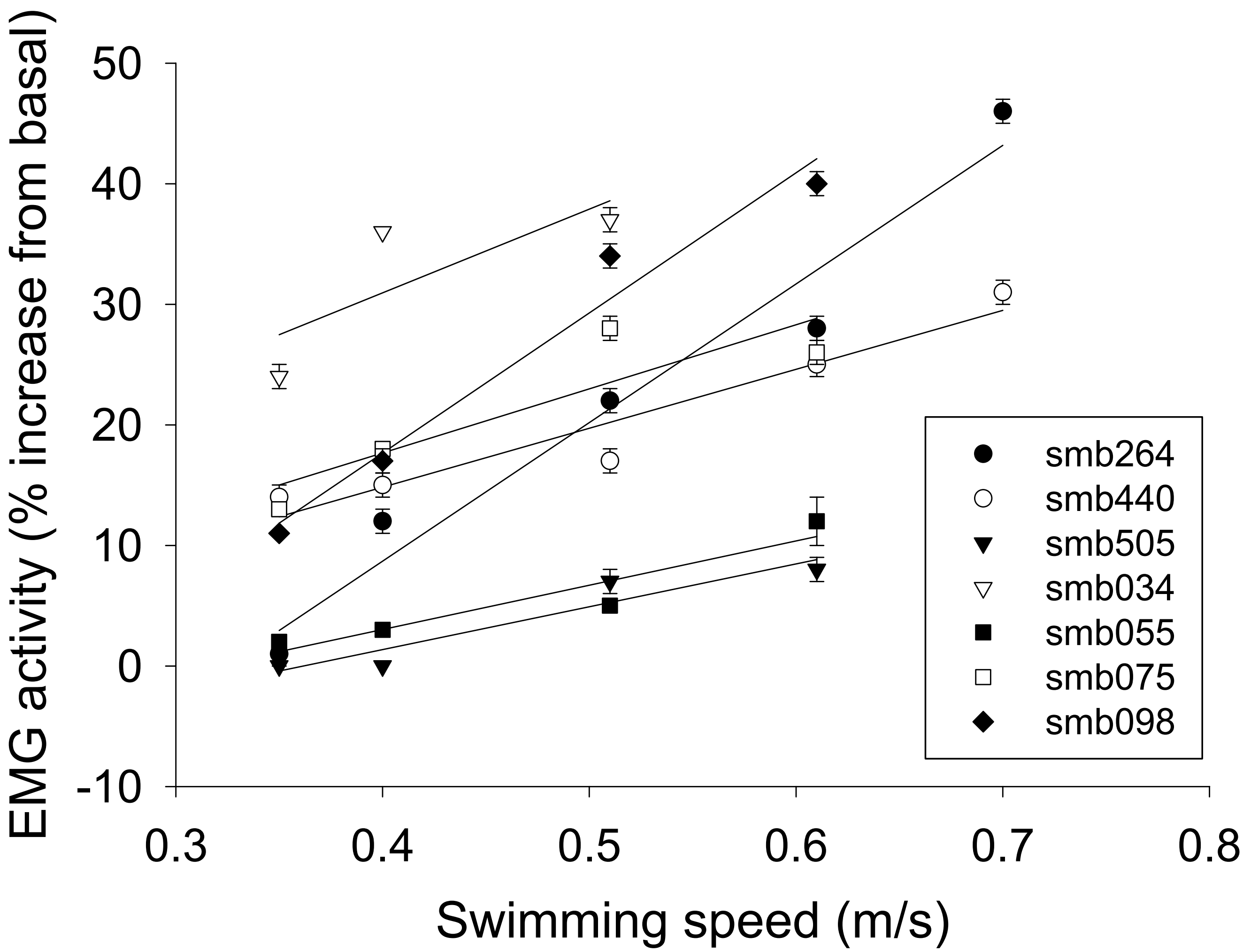

Figure 7.1. Axial muscle activity of each smallmouth bass as a function of swimming speed (m/s).

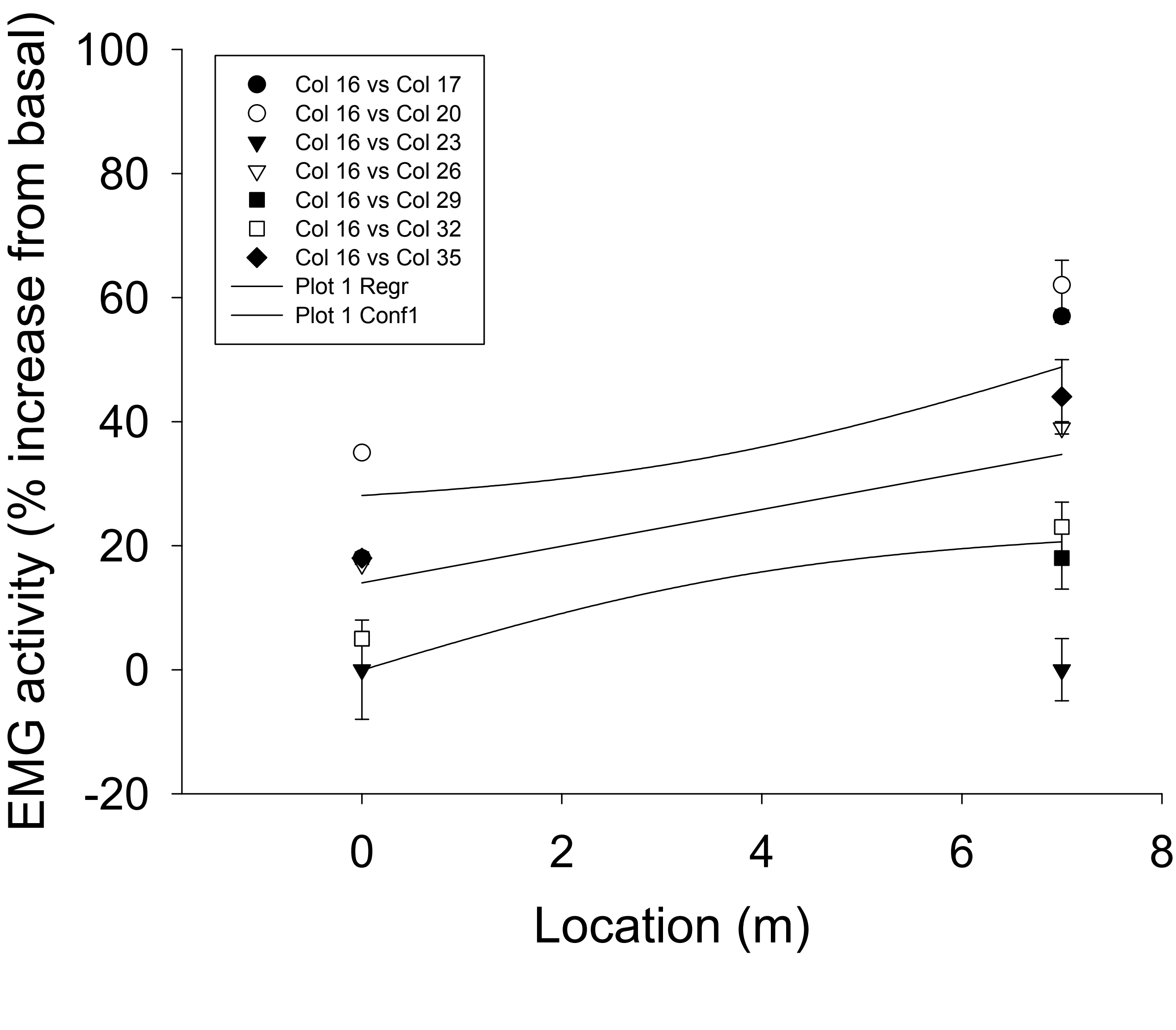

Figure 7.2. Average EMG activity (± 1 S.E.) and 95 % confidence intervals recorded from smallmouth bass during ascent of the east fishway.

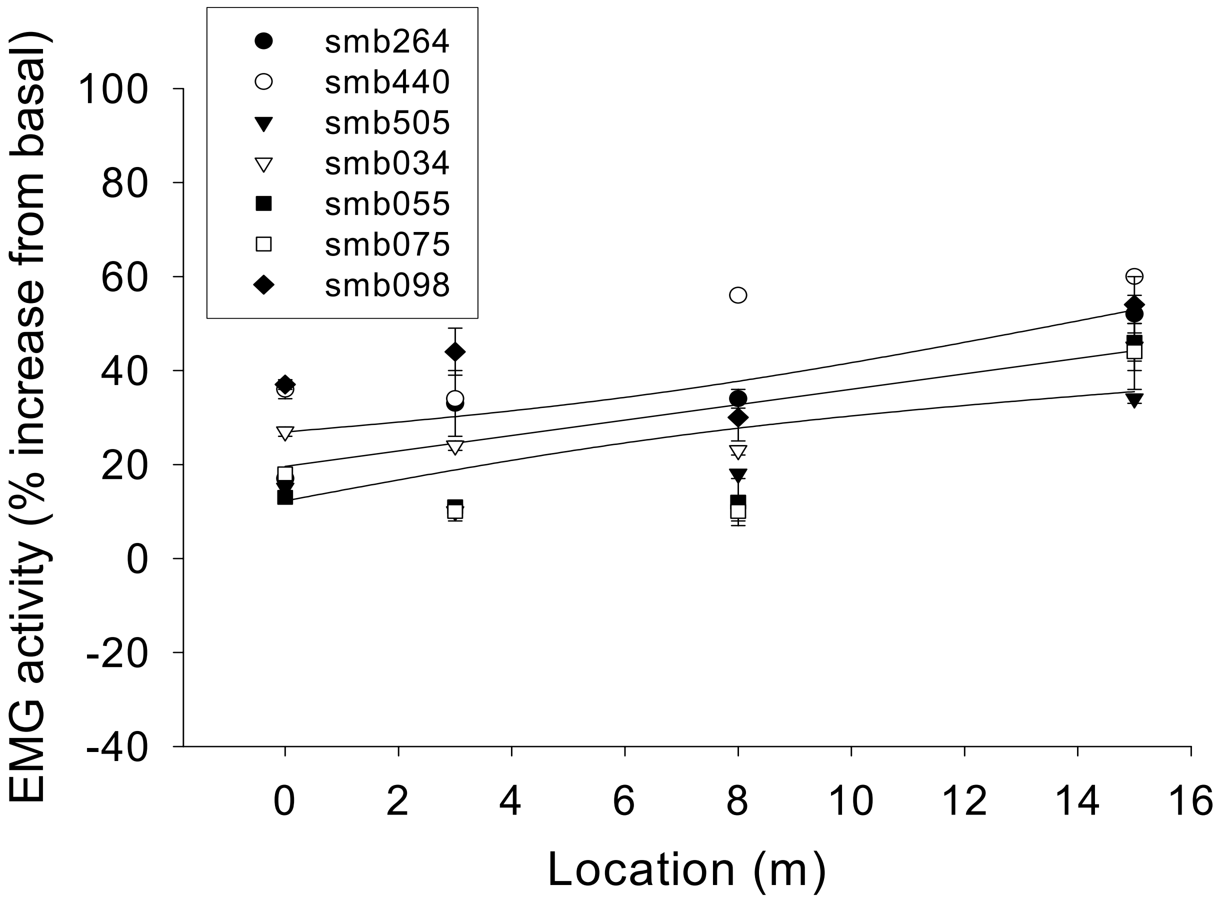

Figure 7.3. Average EMG activity (± 1 S.E.) and 95 % confidence intervals from smallmouth bass between the west fishway entrance (0 m) and the exit (22 m).

CHAPTER 8

Creation and maintenance of habitat downstream from a weir for the greenside darter *Etheostoma blennioides* - a rare fish in Canada [8]

Abstract

The biology, microhabitat use and migratory behaviour of the greenside darter, *Etheostoma blennioides*, was studied at the Mannheim Weir on the Grand River, Ontario during the summer of 1995 and 1996. Officially listed as vulnerable in Canada, greenside darters reached maturity at age 1 and lived up to 4 years. They were found in riffle habitats that consisted of cobble and loose boulders, with large mats of *Cladophora*. This type of unembedded substrate is uncommon in the Grand River watershed. However, local abundance of greenside darters immediately downstream from the Mannheim Weir was likely due to high water velocities from weir discharge, freshets and ice scour which help maintain unembedded riffle areas. Trap data indicated that greenside darters temporally partition this habitat with the stonecat *Noturus flavus*. Other darter species were not commonly found in areas with greenside darters, whose depth selection and habitat choices were influenced by predators and morphology. Denil fishways at the Mannheim Weir rarely passed greenside darters due to prohibitively high water velocities and exclusion by larger fish.

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[8] Published - Environmental Biology of Fishes 51: 297-308.

Introduction

Greenside darters *Etheostoma blennioides*, were thought to be restricted to five river systems and one lake in Canada prior to 1996 (Dalton 1991). The initial appearance and subsequent localized population explosion of the greenside darter in the Grand River was first recorded in 1995 (Bunt, unpublished data). This range extension contrasts the findings of Dalton (1991) who suggested that the Canadian range appeared to be declining, likely as a result of habitat degradation. Following Dalton's recommendations in 1991, the Committee On the Status of Endangered Wildlife in Canada (COSEWIC) recognized the greenside darter as a vulnerable species in Canada due primarily to its restricted range and overall rarity.

Spawning areas of the greenside darter are restricted to boulders and rubble covered with filamentous algae (Fahy 1954; Winn 1958 a, b). Destruction of these habitat types causes a decline in greenside darter populations (Dalton 1991). Impoundments on the Grand River may create areas that are unsuitable as greenside darter habitat. However, river barriers may also help to create and maintain areas immediately downstream with characteristic shallow depths and coarse substrate which is free of silt, as suggested by Ligon *et al.* (1995). The nutrient-rich water of the Grand River may also encourage the lush growth of *Cladophora* on cobble and boulders, which may be important habitat for the greenside darter.

The literature contains one report of greenside darter behaviour and ecology in Canada. Englert and Seghers (1983) examined the habitat segregation among stream darters, including the greenside darter, in the Thames River watershed of southwestern Ontario. They reported that greenside darters were generally found over rubble in shallow water. However, there have been no investigations into the demographics of a greenside darter population in Canada. Reports of upstream dispersion through fishways of small benthic fish, such as darters, are similarly rare.

I present biological and behavioural observations from a large population of greenside darters below an impoundment. Microhabitat preferences and distribution of the greenside darter are discussed as well as factors which contribute to the maintenance of greenside darter populations immediately downstream from a weir. Finally, I examine variables affecting fishway use by greenside darters and implications of fish passage restrictions to the conservation and dispersion of greenside darters in the Grand River.

Methods

The Grand River is a large tributary of Lake Erie in southwestern Ontario. The Grand River watershed covers an area of 6 734 km^2 and extends 297 km from Dundalk in the north to Port Maitland in the south. The topography of the Grand River watershed in the vicinity of the study site can be characterized by rolling and undulating hills and valleys. Medium to coarse textured surface soils are laid over a variety of tills, sands and gravel deposits. Mean annual precipitation in the watershed varies between 813 mm and 965 mm, and mean discharge downstream from the study site (1989 - 1995) was 33.19 m^3s^{-1} (John Bartlett, Grand River Conservation Authority, personal communication). Agriculture and increasing urban development have had major effects on the watershed. In the late 1980's, it was deemed necessary to impound the river, which has subsequently impacted the fish community. Water velocities, water temperature, dissolved oxygen, turbidity, river connectivity and geomorphological processes have all been altered because of river impoundment.

The study site (Figure 8.1) was located on the main stem of the Grand River, near the south end of Kitchener. The site extended 800 m upstream and downstream from the Mannheim Weir (43° 25' N, 80° 25' W), which was constructed in 1990 to provide a pool for the extraction of regional drinking water. Upstream from the weir, the habitat is primarily lentic. The channel was relatively devoid of cover and structure, and the substrate is largely silt. Approximately 800 m upstream from the weir, the channel assumes riverine characteristics and begins to meander. Immediately downstream from the weir, cobble and boulders covered in *Cladophora* form riffle areas. Much of the substrate found here is large broken rock deposited during construction of the weir. Fifty metres downstream, the riffle terminates into a large and deeper run with finer substrates and scattered boulders. Three hundred metres downstream, the river begins to assume a riffle-run-pool sequence and includes back-eddy areas. The next impassable barrier is located 17 km downstream, at the Parkhill Dam in Cambridge, which does not have a fishway or fish-bypass channel.

The Mannheim Weir extends 90 m across the river and is equipped with two different Denil fishways at either bank of the river (Figure 8.1). The west side of the 2 m-high weir was constructed with a 27 m-long reinforced concrete channel which doubles back on itself twice. Two resting pools were provided between the three inclined channels, each of which are 7.5 m long, with a gradient of 10 %. Each channel was fitted with metal baffles designed to dissipate energy through the downward flow of water within the fishway. In contrast, the east bank of the river accommodates a much simpler fishway, composed of one 12 m-reinforced channel with a 20 % gradient. The width of all channels is 0.6 m.

Habitat identification and fish collection

I divided the study site into impoundment, upstream riffle, run and downstream riffle areas where fish were collected and observed (Figure 8.1). A back-pack electrofisher (Smith-Root Mark VII) was used monthly between June and October 1996 to obtain distributional data for over 400 greenside darters. Crews spot-electrofished, moving upstream in a systematic fashion, while observations were made on the habitat types used by greenside darters. Although some authors (e.g., Gatz *et al.* 1987) have suggested that electrofishing may bias habitat descriptions because of displacement of individuals from their natural positions during capture, I felt this was not a valid concern with greenside darters. The darters held tight to the cover and when the electrofisher was activated, it was clear which types of microhabitats greenside darters were using. This is supported by research which suggests that electrofishing appears to be an effective method for habitat characterization in shallow, fast-flowing water with large diameter substrates (Heggenes *et al.* 1990), such as the riffle zone below the Mannheim Weir. Seine nets (15 m long, 5 mm mesh) were also used in the downstream run and backwater areas between June and August, 1996. Seining was ineffective over large cobble substrates and in deep impounded areas upstream from the weir.

After capture, greenside darters were measured (TL, mm), weighed (± 0.001 g) and sexed based on colouration and urogenital pore differences. Random samples were dissected to confirm that sexual determinations were accurate. Scales were removed from a subsample of individuals (n = 69), using the method of Lachner *et al.* (1950). Samples were then cleaned and aged on a projection screen. Ovaries from gravid females were removed and weighed on a digital balance (± 0.001 g). Eggs were refrigerated and later enumerated using the gravimetric method. Additional darters were preserved in 95 % ethanol for stomach analysis and stomach contents were analyzed using the numerical occurrence method as described by Blake (1977). Diet composition was determined in order to illustrate predominant food types from within each sample: frequency of occurrence of each food type was calculated to determine the most commonly consumed food type among individuals.

Direct underwater observations by divers (e.g., Keenleyside 1962; Northcote and Wilkie 1963) were made immediately upstream and downstream from the weir, and to a distance of 400 m downstream, between June and August of 1996. Snorkellers moved slowly upstream by holding onto rocks (Keenleyside 1962) and made qualitative notes where greenside darters were located. Cobble and boulders were carefully lifted to ensure no greenside darters were missed (Chipps *et al.* 1994). Microhabitat preferences of over 200 greenside darters were observed using this method in 1996.

Additional behavioural information was collected by observing fish from the fishways, which were used as overhead vantage points. Fish were observed at the fishway entrances and in the surrounding areas. Qualitative information with respect to position of greenside darters, orientation relative to the water current, proximity to heterospecific fish, proximity to conspecifics and swimming behaviour were documented. Nighttime observations were also made using focused halogen-beam handlights.

Habitat characterization

Habitat variables were collected from the upstream riffle, run and downstream riffle in random 1 m^2 quadrats from areas where greenside darters were generally observed by snorkeling and electrofishing. Depths were measured using a calibrated rod. A Sigma Portable Velocity Meter (PVM) was used to measure water velocity (m/s) at the focal point (Fausch and White 1981; Cunjak and Power 1986). Because greenside darters are benthic, all velocities were recorded at the bottom. Substrate was classified according to a modified Wentworth scale, similar to that of Cummins (1962); where boulders were > 256 mm, cobble 64 - 256 mm, pebble 16 - 64 mm, gravel 2 - 16 mm, sand 0.0625 - 2 mm and silt < 0.0625 mm. Embeddedness was scored using the methods developed by Crouse *et al.* (1981), where substrate was classified as completely embedded, 3/4 embedded, 1/2 embedded, 1/4 embedded, and unembedded. Embeddedness was considered to be important because greenside darters tend to seek refuge in the interstices beneath and between cobble and boulders. Within the same 1 m^2 quadrat where depth and velocity were measured, the amount of *Cladophora* present was recorded as a percentage of substrate covered, while the presence of other aquatic macrophytes was also noted. I compared the upstream and downstream riffle sections, and the upstream riffle section and the run, using t-tests for independent means ($\alpha = 0.05$) with pooled variances.

Fishway entrance trapping

Wire basket minnow traps were set 2 m downstream from the entrance of both fishways (May - July 1996). Minnow traps were checked twice daily (early morning and late afternoon) and all fish were enumerated. Microhabitat characteristics within 10 m^2 of the east and west fishway entrances were examined for differences as described above. Ten random points were selected within the 10 m^2 areas near the entrances to obtain representative habitat measurements. Microhabitat differences at the fishway entrances were analyzed using a t-test for independent means ($\alpha = 0.05$) with pooled variances.

Fishway use

Fishway traps were checked and cleared at least daily in 1995 (April - July) and 1996 (May - July). Dipnets were used to remove fish from fishway traps and on some occasions, attempts were also made to capture fish in resting pools. Greenside darters caught in the fishway traps were measured and released upstream. Hydraulic conditions within the fishways during upstream spring migrations were also recorded.

Results

Distribution and habitat use

No greenside darters were captured or observed immediately upstream from the weir where no riffle areas were located. The mid-channel depth was > 2 m, with shallow areas along the banks. The substrate was composed of silt which supported such macrophytes as *Potomogeton pectinatus*, *Elodea canadensis* and *Myriophyllum* spp. Species observed or collected in the impoundment included smallmouth bass *Micropterus dolomieu*, brown bullhead *Amieurus nebulosus*, golden redhorse *Moxostoma erythrurum*, greater redhorse *Moxostoma valenciennesi*, white sucker *Catostomus commersoni*, common carp *Cyprinus carpio*, central mudminnow *Umbra limi*, common shiner *Luxilus cornutus*, johnny darter *Etheostoma nigrum*, least darter *Etheostoma microperca* and Iowa darter *Etheostoma exile*. All adult cyprinid species were rare within 800 m upstream from the weir.

Snorkeling observations and electrofishing downstream from the weir resulted in the location of greenside darters primarily on unembedded large cobble and boulder substrates covered with *Cladophora*. Most greenside darters were located immediately downstream from the weir across the entire width of the upstream riffle. Other fish species commonly observed or collected in this riffle were stonecats *Noturus flavus*, smallmouth bass, white suckers, northern hog suckers *Hypentelium nigricans*, rock bass *Ambloplites rupestris*, pumpkinseeds *Lepomis gibbosus*, largemouth bass *Micropterus salmoides*, black crappie *Pomoxis nigromaculatus*, common carp, and many other species of cyprinids. Greenside darters were oriented obliquely to the flow at the base of the weir, and along concrete areas where *Cladophora* was present. Where the upstream riffle terminated into a deeper run, the substrate became much finer (e.g., cobble, pebble, and gravel with scattered boulders) and was largely embedded (Table 8.1). The run was significantly deeper ($p < 0.05$) and had significantly less *Cladophora* cover than the upstream riffle, where greenside darters were common ($p < 0.05$). The bottom velocity did not differ significantly between the upstream riffle and the run ($p = 0.40$). No greenside darters were observed in the run section except along the shoreline where larger cobble substrates with *Cladophora* and shallower depths were present. Centrarchid predators and stonecats were all found within the run.

Further downstream (> 200 m), shoreline areas had reduced water velocity and finer substrates (e.g., silt, sand and pebble) where no greenside darters were observed. Several silty backwater areas were seined and electrofished, and no greenside darters were collected. In the most downstream section of the study site, another riffle area was present which also extended across the entire river. Greenside darters were rarely found in this area. However, least darters and Iowa darters, as well as many cyprinids and catostomids used this riffle. The downstream riffle was not significantly different from the upstream riffle (Table 8.1) in terms of bottom velocities ($p = 0.32$), depth ($p = 0.15$) or *Cladophora* cover ($p = 0.98$), but had finer substrates (e.g., small cobble, pebbles and gravel) which were more embedded. The riffles differed mainly in embeddedness, substrate type and proximity to the weir.

Seining was ineffective near the weir where high water velocities and large cobble substrate were present. We successfully seined in shallow areas with finer substrates, where Iowa darters, least darters and johnny darters were captured, but very few greenside darters were found. Snorkeling observations in these downstream areas also resulted in no greenside darter sightings.

Diet analysis

Ephemeropteran and trichopteran larvae were the most important summer food items for greenside darters in the Grand River (Table 8.2). The majority of individuals preyed upon trichopteran larvae (hydropsychids being the most common of these larvae), followed by ephemeropteran larvae, dipterans, ostracods and hemipterans. Ephemeropterans, predominantly baetids, were the most abundant food item. Dipterans included chironomids and simuliids.

Fecundity

Eggs were found only in age 1+ and age 2+ females (Table 8.3). Prior to and during spawning, no females larger than 69 mm, or older than age 2 were collected. Age 2 females contained more eggs than age 1 females, although the range in fecundity overlapped for the two age classes.

Length-weight relationships

The best-fit length-weight regression is described as weight (g) = (1×10^{-5}) x length $(mm)^{2.9011}$ ($n = 30$, $p < 0.0001$, $r^2 = 0.91$) and weight (g) = (2×10^{-5}) x length $(mm)^{2.8644}$ ($n = 39$, $p < 0.0001$, $r^2 = 0.85$) for females and males, respectively (Figure 8.2). The mean length for males was 66.2 mm ± 0.4 (n = 158), while the mean length for females was 60.5 mm ± 0.4 (n = 223). Length-frequency distributions of greenside darters captured in early July were plotted for females and males (Figure 8.3), and the ratio of males to females was 1:1.4.

Fishway entrance habitat

The region near the west fishway entrance had significantly lower water velocities with more diverse and more embedded substrates compared to the region near the east fishway entrance ($p < 0.001$, Table 8.1). There were also small patches of sand near large *Cladophora*-covered cobble and boulders by the west fishway entrance. The east fishway entrance had higher velocities ($p < 0.05$), large unembedded boulders, and was free from finer substrates. The mean depth of the west fishway entrance was significantly shallower than that of the east fishway entrance ($p < 0.05$), and *Cladophora* was significantly less abundant on the east side than on the west side ($p < 0.05$).

Fishway entrance trapping

Significantly more ($p < 0.001$) greenside darters were captured in the minnow traps at the west fishway entrance ($n = 342$) compared to the number of greenside darters collected from traps near the east fishway entrance ($n = 28$). Blackside darters *Percina maculata*, were caught in both traps on rare occasions, while stonecats were found regularly in both traps when first emptied in the morning. All species were more abundant in the west trap, and greenside darters were the most common species captured during the afternoon trapping periods.

Fishway exit traps

On 13 June 1995, approximately 300 greenside darters were captured in the west fishway trap (range 56 - 79 mm TL), but, in 1996, very few greenside darters (< 10) were captured in this area due to high flow conditions. However, greenside darters were captured inside both resting pools of the west fishway between May and mid-July 1996. Within the resting pools, greenside darters were consistently observed against the walls and floor of the fishway in groups of several individuals. These greenside darters were oriented head first, obliquely to the flow, with pectoral fins splayed and angled towards the substrate.

Discussion

Creation and maintenance of microhabitats that support large numbers of greenside darters has occurred downstream from a weir. These unique riffle habitats are maintained by pulsed river discharges associated with precipitation, upstream reservoir regulation and freshets. The impounded area upstream from the dam allows suspended particulates to settle, thereby increasing water clarity. Scouring and perturbation by ice also maintains the unembedded nature of the substrate in these types of riffles. Greenside darters were found only in fast-moving riffle areas immediately downstream from the Mannheim Weir. Riffle habitats consistently appear to be the most important habitat type for greenside darters (Lachner *et al.* 1950; Englert and Seghers 1983). Kuehne and Barbour (1983) reported that greenside darters were relegated to the margins and heads of riffles. In the present study, I found a similar pattern, although greenside darters were present in reduced abundance in the tails of riffles. Several authors have suggested that substrate composition is a major determinant of the distribution and habitat preferences of benthic organisms such as greenside darters (Page 1983; Hlohowskyj and Wissing 1986). Other commonly studied factors include depth and bottom velocity (Englert and Seghers 1983; Greenberg 1991; Chipps *et al.* 1994; Stauffer *et al.* 1996), and macrophytic associations (Englert and Seghers 1983; McCormick and Aspinwall 1983; Greenberg 1991).

Compared to other darter species, greenside darters consistently demonstrate a preference for large substrates (Englert and Seghers 1983; Hlohowskyj and Wissing 1986). In the present study, boulders and cobble were the most commonly selected substrate type. Greenberg (1991) found *E. blennioides* to be associated with rapid currents and the aquatic macrophyte, *Podostemon* spp. In the Grand River, the most common cover types used by greenside darters were cobble and boulders covered with thick mats of filamentous green algae as reported by Greenberg (1991). Hynes (1970) showed that thick growths of *Cladophora* were generally restricted to larger substrates which served as stable attachment sites for the algae. Hlohowskyj and Wissing (1986) suggested that since greenside darters prefer larger substrates, this may have indicated selection for large cobble and boulders which secondarily support attached forms of epilithic algae.

In riffles, greenside darter distributions were strongly influenced by the embeddedness and size of the substrate, and the degree to which it was covered with *Cladophora* - all of which affected the complexity of the area and its value as suitable habitat. Greenside darters require complex habitats with large interstitial spaces that provide cover, as indicated by snorkeling and electrofishing observations. Although the upstream and downstream riffles did not differ significantly with respect to water depth, bottom water velocity or *Cladophora* cover, embeddedness was significantly different. This may have accounted for the abundance of greenside darters in the upstream riffle, and the absence of this species from the downstream riffle. The downstream riffle was much more embedded than the upstream riffle and contained finer substrates, providing very little cover between or under large cobble. Such optimal riffles for greenside darters are relatively rare in a large river such as the Grand River. Only in areas of high gradient or immediately downstream from obstructions were substrates comprised of unembedded boulders and cobble with large mats of *Cladophora*.

Some authors (e.g., Paine *et al.* 1982; Wynes and Wissing 1982; Stauffer *et al.* 1996) have examined resource partitioning between darter species. However, few examples exist that compare habitat use between darters and non-darter species. The only other abundant benthic fish species commonly found in riffles below the Mannheim Weir was the stonecat. However, stonecats were rarely observed in the spillway (where greenside darters were often seen) because they prefer to use riffles with large loose stones (Scott and Crossman 1974; Becker 1983). Unembedded substrates likely provide stonecats, as well as greenside darters, with interstitial cover. During daytime electrofishing collections, stonecats were drawn out from between large cobble and boulders. Minnow traps located at the fishway entrances contained mostly stonecats when first emptied every morning; and afterwards, quickly filled with greenside darters. Stonecats are active during the night, feeding on immature aquatic insects, molluscs, small fish and plant material (Scott and Crossman 1974). Small greenside darters were part of the gut contents of several stonecats that were examined. I suggest that greenside darters and stonecats selected similar habitats, but coexisted through temporal habitat and food partitioning. Paine *et al.* (1982) suggested that food partitioning may be as important as habitat partitioning, although separation of the two is difficult.

Examinations indicated that females reached sexual maturity at age 1. The mean number of eggs produced per female increased with age. Fecundity data presented here are lower than previously reported values. Winn (1958a) reported fecundity for age 1 greenside darters (n = 3, mean egg count = 466, range 404 - 510) and age 2 greenside darters (n = 3, mean egg count = 784, range 773-799). The lower fecundity values observed in the Grand River (Table 8.3) may have resulted from the longer and colder winters of southern Ontario which limit the energy that can be accumulated to produce large numbers of eggs.

Length-frequency distributions for males and females showed evidence of age class patterns (Figure 8.3) supported by scales which had clear annuli. Males and females were divided into 4 overlapping age classes, which showed the overlap to be more pronounced for males. It was difficult to make comparisons with previous studies of southern populations due to problems such as different measurement techniques (e.g., standard length vs. total length). Males in the Grand River grew faster than females as previously reported for other populations by Lachner *et al.* (1950) and Fahy (1954), despite the fact that the largest individual examined was female. Greenside darters collected in fall electrofishing sessions had grown significantly over the four month summer: age 3 fish which were between 70 and 77 mm in May had attained lengths up to 96 mm by late August.

Greenside darters in the Grand River fed primarily upon ephemeropteran larvae at various stages of development. Hydropsychid trichopteran larvae, often associated with large cobble substrates downstream from impounded areas, were also a common food item. Various benthic dipterans including chironomid and simuliid larvae are important to smaller fish. However, larval abundance exhibits extreme seasonal variation. In the greenside darter population I studied, there was an absence of zooplankton in the diet except for the occassional ostracod. Turner (1921) examined the stomach contents of greenside darters in the Ohio waters of Lake Erie and in some Ohio streams. Juveniles in Lake Erie fed primarily on chironomid larvae, cladocerans and copepods, while other age classes fed almost exclusively on chironomid larvae. In streams, chironomid larvae were an important food source; however, the diet also included ephemeropterans, and, to a lesser degree, trichopteran larvae. Studies by Fahy (1954) demonstrated that in New York tributaries of Lake Ontario, simuliid, chironomid and trichopteran larvae were primarily consumed. Wynes and Wissing (1982) reported there was no indication that greenside darters fed on drift organisms. They showed chironomid pupae and larvae accounted for most food items in the annual diet, with hydropsychid larvae also being an important item. Differences in diet composition among these studies likely reflect regional and temporal differences in prey availability.

Previous studies provided evidence that greenside darters exhibited clear upstream migration behaviour associated with reproduction, as supported by observations at the Mannheim Weir. In the Grand River, greenside darters were observed downstream from the weir throughout the spring, summer and early autumn. Winn (1958a) also observed upstream migration to an impassable barrier. During the non-reproductive season, some adult males were present in riffles below the barrier, but in early spring, a significant increase in the abundance of large males was reported.

Significantly more greenside darters were captured in minnow traps downstream at the west fishway entrance compared to the number of greenside darters collected from traps near the east fishway entrance. Greenside darters were observed maintaining positions on sand substrate, among boulders in very shallow water, near the entrance to the west fishway. The depths near the west fishway entrance were shallower than those at the east side, helping to reduce predation risk by large piscivores. Water velocities at the west fishway entrance were also significantly lower than those recorded at the east fishway. However, none of the velocities recorded should have affected the ability of greenside darters to maintain position among the boulders and cobble. There were lesser amounts of *Cladophora* near the east fishway which may have reduced cover availability. Greenside darters were observed to hold positions in *Cladophora* that covered the outside of the east fishway wall, but rarely occupied the areas which would have facilitated attraction to the fishway entrance.

Subtle microhabitat differences may have affected the ability of greenside darters to locate and successfully approach a fishway entrance. It is likely that failed attempts to traverse habitat types not within the optimal range of, for instance, depth and appropriate cover, restricted access to the east fishway entrance. Considerations of the differences in entrance microhabitats may be important, especially in designing natural fish bypass channels and fishways built to pass benthic species.

Only after a precise set of requirements was satisfied, was it then possible for greenside darters to ascend the west fishway while avoiding predation, as supported by videographic evidence collected from within the west fishway and at both fishway entrances (Bunt, unpublished data). For example, during the day of 13 June 1995, following a period when debris was not cleared from upstream trash racks, and fishway water levels were too low for large predators, greenside darters were captured in the fishway exit trap. On this date, no other fish species that may have excluded greenside darters were found in the trap. If escape from the fishway exit was not blocked by debris, greenside darters would have had to traverse > 800 m of impounded lentic habitat before reaching any riffle-like areas. Predation risk and lack of adequate foraging habitat would have limited their success. If the fishways were being properly maintained for larger fish species, suitably low water velocities would not occur to allow successful passage of greenside darters. Greenside darters are able to maintain feeding positions in high velocity flows in the weir spillway, but successful use of the fishways was rare. Therefore, the Mannheim fishways do not contribute to the upstream range extension and dispersion of the greenside darter.

High densities of greenside darters downstream from the weir were a direct result of large amounts of *Cladophora*-covered, unembedded cobble substrate which was maintained by hydraulic disturbance and ice scour from the weir. The ability of the greenside darter to maintain feeding positions in high water velocities permitted use of this unique habitat. Other darter species remained in backwater areas, pools, runs and riffles which contained finer-embedded substrates and fewer predators.

Acknowledgements

I thank Gabrielle Held for field assistance, the Municipality of Waterloo for use of their laboratory facilities, Art Timmerman (Ontario Ministry of Natural Resources) for use of the electrofishing equipment, and John Bartlett (Grand River Conservation Authority) for river discharge data. Previous versions of this manuscript were improved by comments received from Geoff Power, Lin Wong and two anonymous reviewers. I also thank the Natural Sciences and Research Council of Canada for post-graduate scholarship support.

Table 8.1. Habitat variables collected from 1 m^2 quadrats downstream from the Mannheim weir.

Variable	Upstream riffle (n = 45)	Run (n = 26)	Downstream riffle (n = 15)	West fishway entrance (n = 10)	East fishway entrance (n = 10)
Approximate area (m^2)	3,000	24,000	3,000	10	10
Mean depth (cm) ± SE	25.27 ± 1.78	57.27 ± 4.60	19.93 ± 2.61	26.10 ± 4.19	38.20 ± 3.05
Mean bottom velocity (cm/s) ± SE	15.8 ± 2.2	13.1 ± 1.8	20.1 ± 2.5	7.1 ± 1.0	14.2 ± 1.8
Mean *Cladophora* cover (%) + SE	59.88 ± 4.39	15.39 ± 2.29	59.67 ± 6.82	55.00 ± 8.33	23.50 ± 7.23
Primary substrate	Boulder	Cobble	Cobble	Boulder	Boulder
Secondary substrates	Cobble, Sand	Pebble, Gravel	Pebble, Gravel	Cobble, Sand	
Embeddedness value	1/4 Embedded – Unembedded	3/4 Embedded - Embedded	1/2 Embedded – Embedded	1/4 Embedded - 1/2 Embedded	¼ Embedded - Unembedded

Table 8.2. Stomach contents of greenside darters collected during the summer of 1996 (n = 25). Other stomach contents included aquatic hemipterans and terrestrial insects.

Order	Diet composition (%)	Frequency of occurrence
Ephemeroptera	67.6	0.56
Trichoptera	27.0	0.68
Diptera	4.1	0.28
Ostracoda	1.0	0.12
Other	0.3	0.04

Table 8.3. Fecundity summary for greenside darters collected during the spring of 1996. No age 3 females were found during this time, although 3-year-old partially spawned females were collected early in the summer.

	Age 1 (n = 5)	Age 2 (n = 6)
Mean number of eggs (± SE)	335.2 ± 44.39	418.8 ± 81.02
Range in fecundity	181 - 447	231 – 750
Mean ovary weight (g) (± SE)	0.0674 ± 0.0067	0.1308 ± 0.0161
Mean egg weight (g) (± SE)	0.000216 ± 0.000029	0.000355 ± 0.000056
Range in total length (mm)	52 - 60	62 – 69

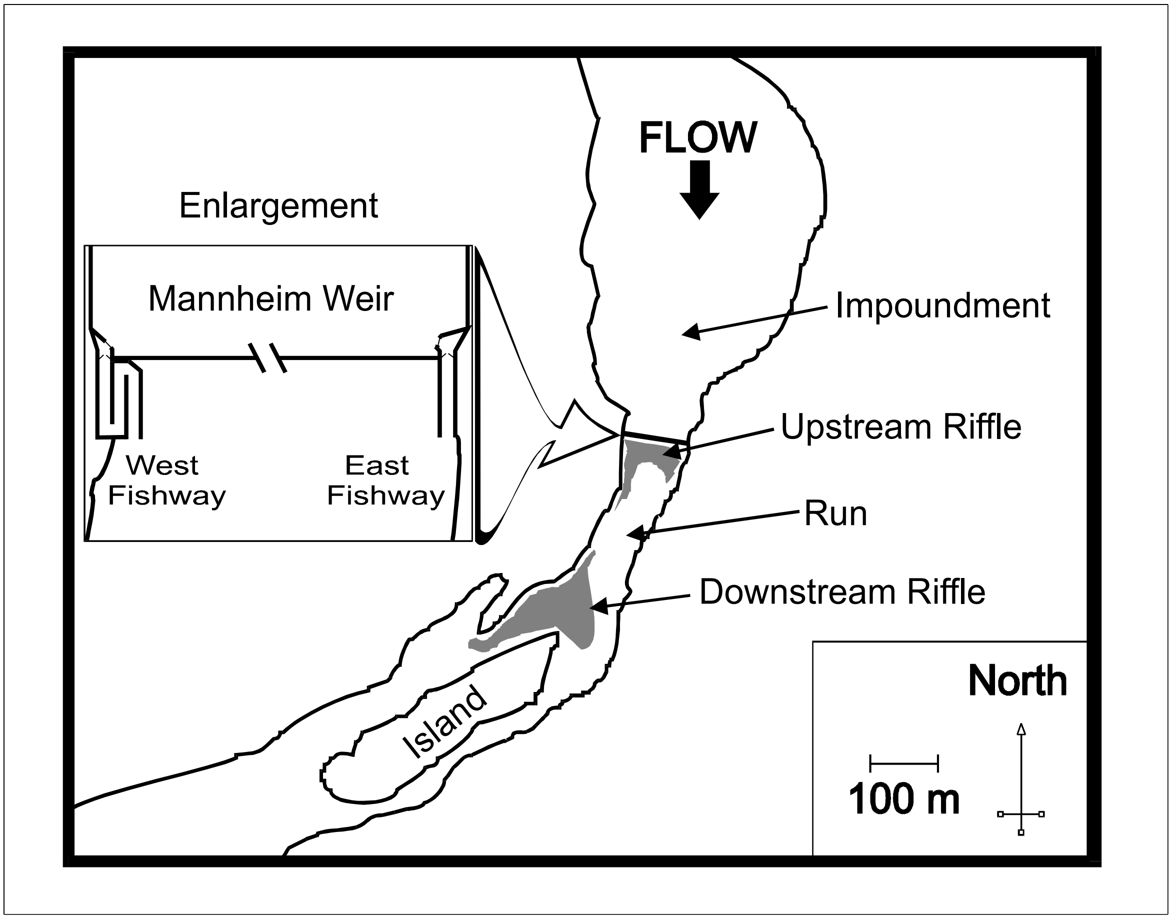

Figure 8.1. The Mannheim weir on the Grand River, near Kitchener, Ontario. The enlargement shows the west and east Denil fishways and areas near the weir where greenside darters were commonly observed.

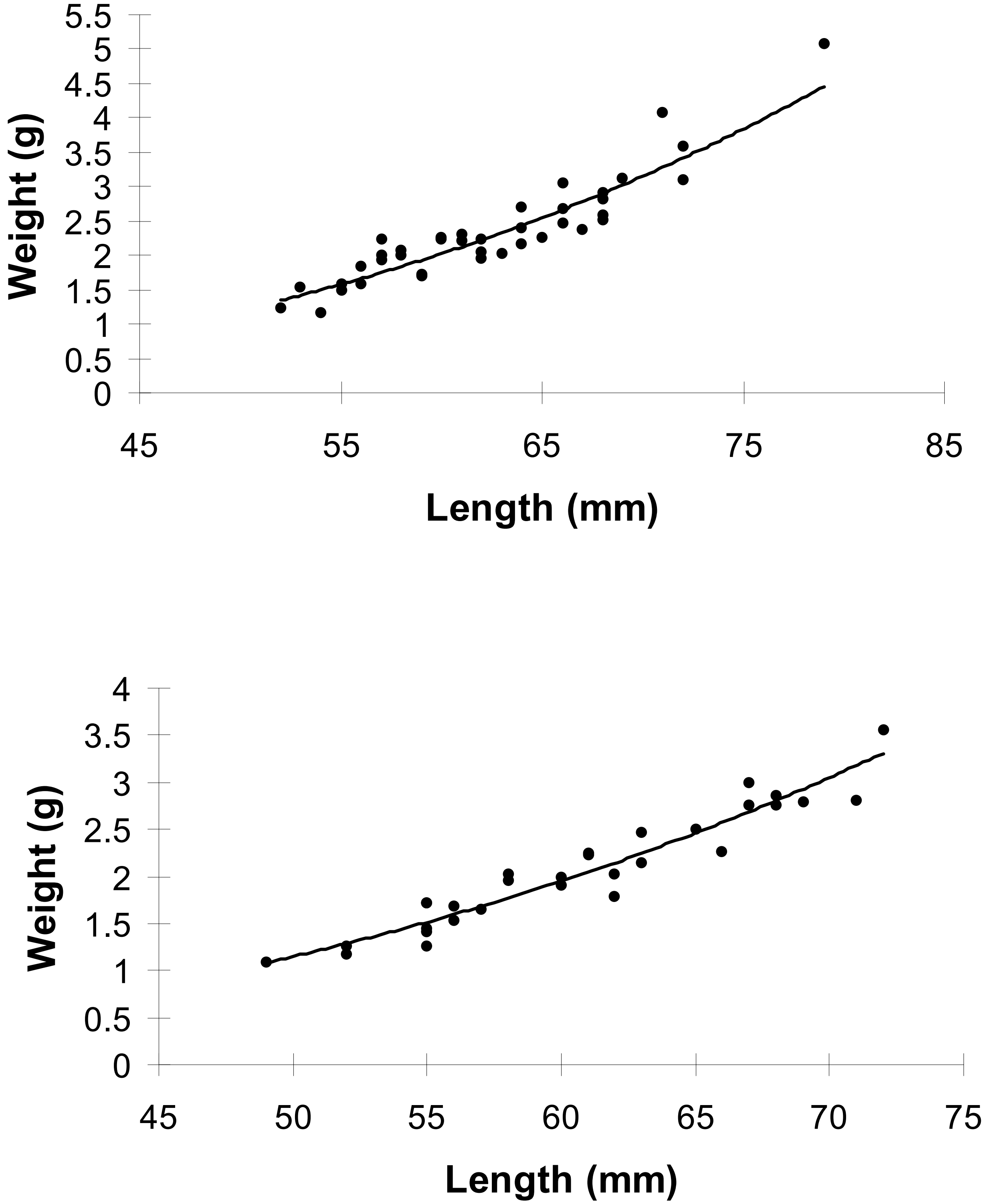

Figure 8.2. Length-weight regressions for female (top) and male (bottom) greenside darters from the Grand River. The relationships are defined as weight (g) = ($1x10^{-5}$) x total length (mm)$^{2.9011}$ and weight (g) = ($2x10^{-5}$) x total length (mm)$^{2.8644}$ for females (n = 30,p < 0.0001, r^2 = 0.91) and males (n = 39 , p < 0.0001, r^2 = 0.85), respectively.

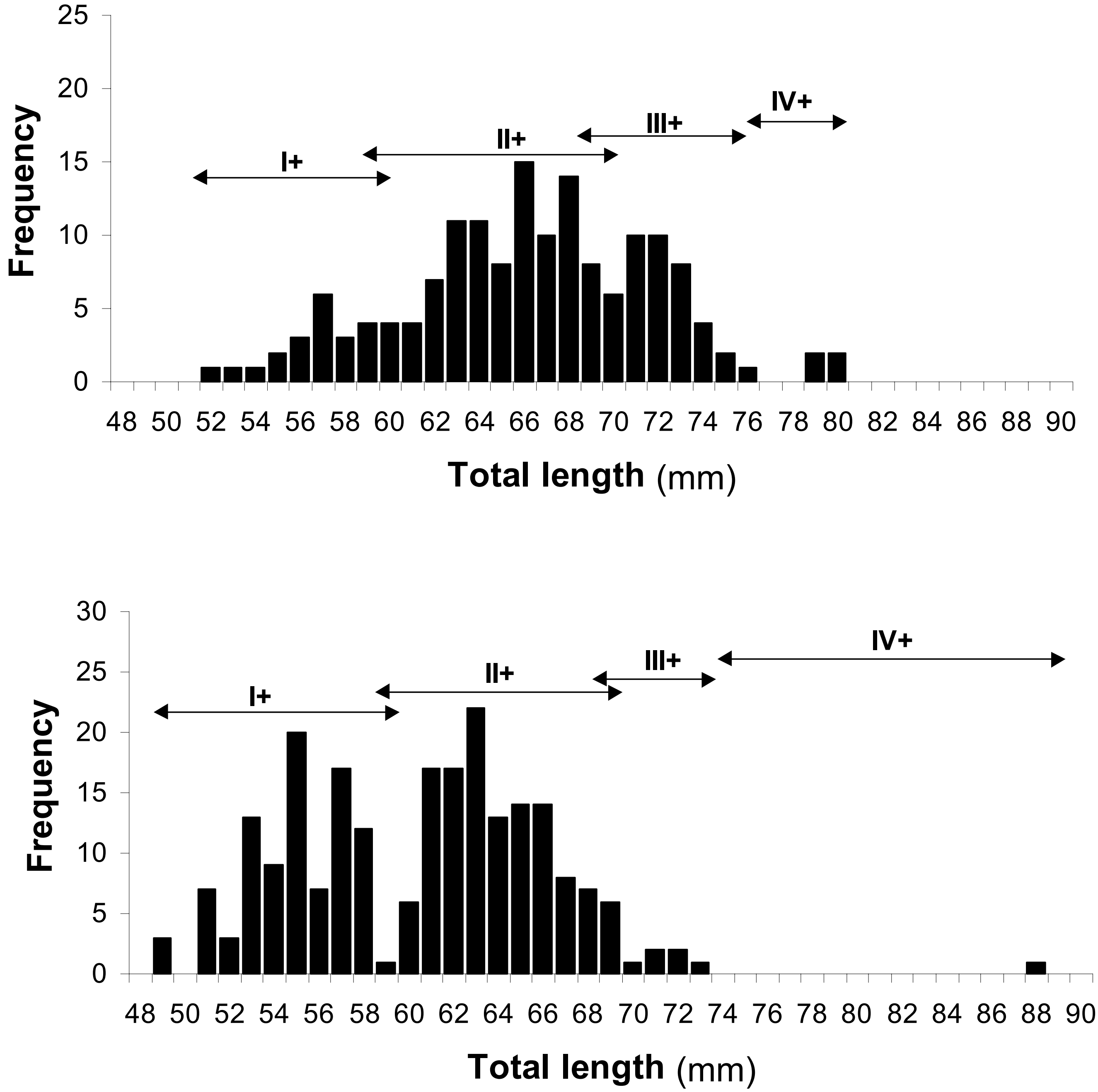

Figure 8.3. Length-frequency distribution of female (top, n = 223) and male (bottom, n = 158) greenside darters collected below the Mannheim Weir during June and July, 1996.

CHAPTER 9

Summary and General Conclusions

Fishways are artificial devices that are designed to provide wild fish with passage around obstructions. Applying experience and knowledge gained from biological insights into fishway effectiveness can improve the frequency and ease of fish passage. Fishway evaluations have been facilitated in recent years through the advent of technology that allows behaviour, movement and activity of numerous individual fish to be monitored simultaneously, in real time. The Mannheim fishway project developed from a series of basic trapping studies (1995, 1996 and 1997), to radiotelemetric surveys of fishway efficiency (1995 and 1996). Radiotelemetry methodology was refined at the Mannheim weir and re-applied for different fish species at another site on the same river (Dunnville) in 1997. Using information derived from the Mannheim fishways during the first two years of study, alterations were made to the fishway entrances to make them easier for fish to find. In 1997 and 1999, a physiological telemetry experiment was designed to assess relative difficulty, or physical output required during fishway use. Finally, some biological advantages of habitat produced and maintained downstream from dams and weirs were examined. There was circumstantial evidence, supported by literature reports, that some fish (e.g., walleye in Dunnville) may use habitat downstream from weirs for spawning. Greenside darters were abundant downstream from the Mannheim weir and it was determined that their presence was associated with hydraulic conditions and habitat produced by weir discharge. Through the application of this research, the Mannheim fishways have been substantially modified and improved. The entrances were modified, cover plates were replaced with grates, debris deflection and flow stabilization devices were installed at the fishway exits, a maintenance program was developed, and signs were posted to reduce illegal harvest of fish that accumulate downstream from the weir, near the fishway entrances. Based on knowledge gained at Mannheim and Dunnville, a fishway for the passage of walleye was designed for the Caledonia dam, located between Mannheim and Dunnville, on the Grand River. Plans are also underway to modify the Dunnville fishway to improve passage of walleye by reducing the intensity of turbulence, and production of vortices and back-currents, especially in resting pools. In a world where economy and ecology are often mutually exclusive, the applied biological studies described in the body of this thesis have the real potential to make a difference to the ecological well-being of the Grand River. Techniques, results and insights from these studies can be applied to nearly every situation where a dam or weir blocks movement of fish from one part of a river to another.

With the exception of undesirable species, such as sea lamprey *Petromyzon marinus*, successful fishway use by as many species as possible is necessary if the concept of sustainable development, or sustainable exploitation, is to be realized. In the first study, two Denil fishways on the Grand River, Ontario, were used as check-points to evaluate the transfer of fishes over the Mannheim weir, and to examine the diversity and inferred swimming performance of 29 warmwater fish species that used each fishway type. Traps installed at fishway exits were used to collect fish over 24 hour sampling periods, during 40 – 51 days each year from 1995 to 1997. Passage rates, mean temperature, water velocity and turbidity for the date of maximum passage for each year were analyzed. General species composition from trap samples shifted from catostomids to cyprinids to ictalurids to percids and centrarchids, with some overlap, as water temperatures increased from 8 – 25 ° C. Due to variable accumulations of debris on upstream trash racks, water depths and therefore water velocities in each fishway were independent of river discharge. Correlations between water velocity and swimming/position-holding abilities by several species emerged. Turbidity was directly related to river discharge and precipitation events, and most species demonstrated maximum fishway use during periods of decreased water clarity. This study 1) provided evidence of migratory tendencies among several species which were previously considered non-migratory and 2) may assist fishery managers in matching physical and biological conditions within fishways with expected patterns of use by a large array of “coarse” fish, bait fish and sport fish.

In the second study, the two Denil fishways, located on the west (low velocity - 10 % slope) and east (high velocity - 20% slope) side of the Mannheim weir, Grand River, Ontario, were compared for use by upstream migrating white suckers *Catostomus commersoni* and smallmouth bass *Micropterus dolomieu*. Mark-recapture and radiotelemetry were used to assess attraction and fish passage. Movement of 85 radiotagged fish was monitored continuously during spring and early summer of 1995 and 1996. Attraction and passage efficiency for white suckers at the west fishway was approximately 50 %, and 55 %, respectively. The overall efficiency of the west fishway for the passage of white suckers was 28 %, or the product of attraction efficiency and passage efficiency. Attraction efficiency for white suckers at the east fishway was approximately 59 % and passage efficiency was 38 %. Overall efficiency of the east fishway for passing white suckers was therefore 22 %. The attraction and passage efficiency for smallmouth bass at the west fishway was approximately 82 % and 36 %, respectively, for an overall efficiency rating of 30 %. At the east fishway, attraction efficiency for smallmouth bass was approximately 55% while passage efficiency was 33%. The overall efficiency of the east fishway for passing smallmouth bas was therefore 18 %. There was an exponential decline in the numbers of both species that used each fishway relative to water velocity. The maximum water velocities used by white suckers and smallmouth bass were 0.96 m/s and 0.99 m/s, respectively. Distracting flows near the west fishway appeared to affect attraction. Both fishways passed equal numbers of smallmouth bass per year, and smallmouth bass that used the east fishway were significantly larger than individuals that used the west fishway. In contrast, more than twice as many white suckers used the west fishway and these fish were significantly larger than those that used the east fishway. Differences in passage were related to burst and critical swimming speeds, and the use of velocity refugia within the fishways.

To illustrate that the methodology used at the Mannheim fishways may have universal application, a similar study was designed to examine the passage of walleye *Stizostedion vitreum* at another fishway on the Grand River. The Denil fishway in Dunnville, Ontario was built to provide upstream passage for walleye from Lake Erie to the Grand River. Modest numbers of walleye were observed to use this fishway. Coded radiotelemetry was used to track 24 adult walleye (12 male, 12 female) downstream from the fishway to explore reasons for limited use. Activity was monitored by a fixed array of three antennas within the fishway that continuously scanned for signals from all radiotagged fish, and by mobile tracking. In April and May 1997, 17 attempts to use the fishway by radiotagged walleye were recorded. During this period, the attraction efficiency of the Dunnville fishway was approximately 21 %. Proportions of female and male walleyes that attempted to use the fishway were not significantly different. All attempts took place in the evening or at night, between 1600 and 0600 hours. Most activity occurred near midnight. Walleye occupied the first resting pool of the fishway for up to 17 h. Subsurface water velocity during the study was approximately 2 m/s. Passage rates of radiotagged fish at the Dunnville fishway were between 0 and 4.2 %. The maximum overall efficiency of the Dunnville fishway for passing walleye was therefore approximately 1%. Behaviour modifying hydraulic conditions including turbulence, entrained air, backcurrents and whirlpools in fishway resting areas may delay or prevent successful upstream passage of walleye. There was also evidence of large scale movements (up to 9.6 km/d) by fish that may have spawned in the Grand River below the Dunnville dam.

Having demonstrated that techniques for monitoring fishway efficiency are not site specific, I re-visited the Mannheim weir and attempted to improve the efficacy of the fishways, particularly with respect to fish attraction. The Mannheim fishways were monitored for activity by several dozen fish species annually since 1994. Fishway use was related to water temperature, water velocity, season, and the ease with which fishway entrances were located. Simple modifications to the entrances of two Denil fishways resulted in increased attraction efficiency for pumpkinseed *Lepomis gibbosus*. Entrances were enlarged and repositioned approximately 2 m closer to the weir face, in areas where radiotagged fish congregated. After modifications, overall relative rates of recapture were 39 % (95 % C.I. = 32 – 46 %), representing a 2.6 – 3 fold increase in fishway use relative to pre-modification conditions. Median instantaneous recapture rates also increased significantly from 0 % at both fishways to approximately 2 %, after fishway entrances were modified. Fishway entrances should be located as close to a dam or weir face as possible, but velocity barriers from spillway or tailrace discharge must not compromise access. Similar modifications may be made to other fishways to improve attraction efficiency of warmwater fishes.

Attraction efficiency and passage efficiency are independent components of fishway performance. Attraction efficiency is affected largely by behavioural factors, whereas passage efficiency may have both behavioural and physical components. To determine how physical output, or effort, compared among smallmouth bass *Micropterus dolomieu* at each of the Mannheim fishways, a physiological telemetry study was initiated. This study involved the use of transmitters that relayed activity patterns from electrodes that were implanted in swimming muscles. Conventional techniques for implanting electrodes into axial swimming musculature of fish were reviewed and a new device was invented that reduced time for electrode implantation, ensured constancy in electrode orientation, implantation depth, and separation distance. Using this device, I used electromyogram (EMG) telemetry to measure the relative physical output (i.e., effort) required for smallmouth bass to ascend the two Denil fishways at the Mannheim weir. The fishways differed in length, slope and water velocity. Smallmouth bass (n = 7) were implanted with transmitters that broadcast integrated signals representing axial muscular contraction rates to a submerged antenna array within each fishway. There was a significant positive relationship between activity of the swimming muscles and the position of each fish between the fishway entrance and exit. Mean EMG pulse rates from each fish that swam from the entrance to exit of a short, steep fishway increased by 13 – 55 % relative to basal levels. Maximum subsurface water velocity during fishway use was 0.4 – 1.4 m/s. In the long fishway with reduced slope and resting pools, maximum subsurface water velocity was 0.35 - 0.9 m/s and EMG levels increased by 17 to 47 % of basal levels as fish swam from the entrance to the exit. EMG levels were significantly greater in the upper regions of each fishway compared to the entrances. EMG levels from areas near the fishway exits were also significantly greater than maximum EMG levels recorded during critical swimming speed trials. Smallmouth bass appeared to exceed their aerobic scope of activity during ascent of both fishways. EMG data reflected combinations of burst and prolonged swimming activity and indicated the relative differences in muscular activity and energetic demands that were required to ascend each fishway type.

Dams and weirs are imposing structures that negatively affect natural flow regimes and resident flora and fauna. Over the course of these studies, there was evidence that some fish adapted to and thrived in impounded areas upstream from weirs. There was also evidence that some fish may have spawned in dam tailraces, or in habitat immediately downstream. To examine positive aspects of the presence of dams and weirs, the biology, microhabitat use and migratory behaviour of the greenside darter *Etheostoma blennioides* was studied at the Mannheim Weir during the summer of 1995 and 1996. Officially listed as vulnerable in Canada, greenside darters reached maturity at age 1 and lived for up to 4 years. They were found in riffle habitats that consisted of cobble and loose boulders, with large mats of *Cladophora*. This type of unembedded substrate is uncommon in the Grand River watershed. However, local abundance of greenside darters downstream from the Mannheim weir was likely due to high water velocities from weir discharge, settlement of suspended silt in the upstream impoundment, freshets and ice scour that help maintain unembedded riffle areas. Trap data indicated that greenside darters temporally partition this habitat with the stonecat *Noturus flavus*. Other darter species were not commonly found in areas used by greenside darters, whose depth selection and habitat choices were influenced by predators and morphology. Denil fishways at the Mannheim weir rarely passed greenside darters due to prohibitively high water velocities and exclusion by larger fish.

By examining utilization patterns, attraction efficiency, passage efficiency, physical demands on fish during ascent, and changes in habitat upstream and downstream, dams and weirs may be designed and managed in a more environmentally-friendly manner. Warmwater fisheries world-wide, especially in developing countries, will be more sustainable if migratory routes are maintained around river barriers. Well-designed fishways have the potential to make river obstructions imperceptible or nearly invisible to upstream migrating fishes. The fishways examined in this series of studies, however, have a long way to go before overall efficiency is 100%. As with most things in life, we get what we pay for. At the Mannheim weir, the steeper fishway was cheaper, but it was outperformed by the fishway that provided the most reduced water velocities. Linear and convoluted fishways appear to be moderately effective, at best, for passing warmwater fish. Maximum attraction and passage efficiency may require a change in design paradigm. The efficacy of spiral fishways should be examined and further research needs to be conducted on the relative performance of natural bypass channels. In recent years, natural bypasses have become the fishpass design of choice among some European engineers. Natural bypasses are more aesthetic and require less maintenance than enclosed fishways. Restoring river connectivity using design concepts based on an understanding of warmwater fish behaviour and swimming abilities, will increase the distribution of fishes within a river system, and will reduce the possibility of extirpation, which may result when access to spawning areas or other critical habitat is blocked.

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Execution of the Mannheim and Dunnville fishway projects

Work at the Mannheim weir began with a feasibility project in November 1994. The adventure began with boat malfunctions, a trip over the weir on Dec. 7th with water temperatures about 2 °C, followed by the temporary loss of the tracking antennas when they became frozen in the river. The following spring, two assistants and myself developed a research station at the Mannheim low-lift pumping station on the banks of the Grand River. We designed wet-lab facilities, a dry-lab area where samples were analyzed and data were entered into our computers, a tracking station where telemetry data from the river were transmitted via an umbilical line of cables embedded in each fishway, and living quarters. We slept in tents outside the noisy pumping station until September.

In April 1996, with one research assistant from 1995 and a new recruit from the University of Waterloo, we again took up residence on the banks of the Grand River. Monitoring passage at the fishways seemed like a never-ending task. The blocking screens and traps accumulated debris from the river so quickly, our hands barely had time to dry before they were immersed in the river again. It was not uncommon for us to check and clear the fishway traps at 2:00 in the morning after scrambling to process, tag and release fish all day long.

Some fascinating things happened during the most obscure hours. For example, during a blue moon on June 30th 1996, I walked down to the west fishway at the Mannheim weir at about 3:00 in the morning. For some reason, every carp between Kitchener and Cambridge must have mobilized and swam upstream to the weir. I could have walked from one side of the river to the other on fish! Other equally memorable, but somewhat less enjoyable events challenged us. We were repeatedly plagued by storms that destroyed the tracking antennas in the river, and security breaches were commonplace. In one case, someone stole a live bass from our holding tanks, and our barbecue on the same day.

In late March 1997, I began development of the Dunnville fishway experiment. I used the same technology and protocols that I had used at the Mannheim weir, but focused on walleye, instead of bass and suckers. Again, I realized that fish do not always conduct business between nine to five on weekdays. It was a bit chilly to sleep all alone in a tent, so I decided to take up residence in a muddy, old equipment trailer, with propane stove heating, until the project was complete. I cooked over an open fire, listened to the radio and watched comet Hale-Bopp skirt the northern sky. By the end of April, it was time to gear up for the third field season 120 km, or so, upstream at the Mannheim weir. My assistants from 1995 and 1996 had moved on to pursue their own studies and were largely unavailable. I posted signs at the University of Guelph and soon met with several keen students who wanted to volunteer at the weir. In early May, we again set up camp and managed to survive a rash of tent thefts, until mid August. By the end of the 1997 field season, we had handled, measured, and released 11 810 fish from the Mannheim fishways. Many of these fish were tagged, and angler recapture data still trickle in.

The volunteers from Guelph were so keen and excited, it was difficult to get rid of them. They harassed me on the phone weekly – they wanted to come back to the weir. In 1998, I embarked on a videographic study of the Mannheim fishways and I kept my assistants busy transcribing tapes, entering data into my spreadsheet files, and recording observations from larval redhorse that we raised from eggs. Instead of living in a tent, I moved up the road from the Mannheim weir into a house with a solid roof.

The fifth field season in 1999, was an extension of the EMG work that I began in 1997. The Guelph volunteers surfaced from winter hibernation as expected and began working with me in early May. In exchange for food, beer and a spot in the backyard to pitch a tent, we worked fastidiously to build a tracking system and wet-lab. My neighbour and another volunteer from a local high school helped catch crayfish to feed the bass and managed the swim tube calibration experiments. After the EMG experiments were complete, the implanted fish were released into the Grand River to examine how physical output within the fishways compared with activity associated with living in a flowing system, where laziness may translate into downstream displacement. Life on the river continues with weekly tracking sessions by canoe.

I completed several unrelated studies during the course of the fishway work described in this dissertation. I examined habitat use and movement of brown trout and brook trout downstream from a hydroelectric generating station in the Rocky mountains of Alberta, spawning behaviour of greater redhorse in the Grand River, post-spawning habitat and movement of greater redhorse in the Grand River, ontogeny and development of larval greater redhorse, trends and derby effects on the smallmouth bass fishery of the Grand River, winter residency of smallmouth bass in a thermal discharge canal of an Ontario Hydro generating station, injury and short-term mortality associated with electroshocking and trapping of benthic stream fishes, effects of various antenna configurations during implantation of transmitters in smallmouth bass, and a comparative assessment of several techniques used for studying mobility and activity of smallmouth bass. These studies have been published, are in press, or are in various stages of review.