DEVELOPMENT OF AN INSTREAM VELOCITY BARRIER TO STOP SEA LAMPREY (PETROMYZON MARINUS) MIGRATIONS IN GREAT LAKES STREAMS

By

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A Thesis
Submitted to the Faculty of Graduate Studies
in Partial Fulfilment of the Requirements
for the Degree of

MASTER OF SCIENCE

Department of Civil Engineering, at the
University of Manitoba
Winnipeg, Manitoba

ISBN 0-612-13352-4

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DEVELOPMENT OF AN INSTREAM VELOCITY BARRIER TO STOP SEA LAMPREY (PETROMYZON MARINUS) MIGRATIONS IN GREAT LAKES STREAMS

BY

THOMAS C. MCAULEY

A Thesis/Practicum submitted to the Faculty of Graduate Studies of the University of Manitoba in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Abstract

One of the many applications of hydraulic engineering is in the area of inland fisheries management. Engineers are typically involved in the design and construction of hydraulic structures such as dams, fishpasses, and weirs. The use of instream barriers is a growing part of an ongoing program to control parasitic sea lamprey (Petromyzon marinus) in the Great Lakes watershed where hundreds of streams are treated with chemical lampricide on a cyclic basis in order to protect a valuable sport and commercial fishery worth $3 billion annually. The Great Lakes Fishery Commission aims to reduce the use of lampricides through the development and use of alternate technologies such as instream barriers.

This thesis develops a new hydraulic structure, a velocity barrier, to control sea lamprey. The goal of a velocity barrier is to block sea lamprey spawning runs while permitting passage of non-jumping adult migratory fish, thereby eliminating the need for chemical lampricide treatments. The velocity barrier concept proposed in this thesis is comprised of a chute of water flowing over a surface to which sea lamprey cannot attach, such that the combination of water velocity over distance surpasses the swimming performance of sea lamprey. The faster the water, the shorter the length of barrier required, since swimming endurance varies inversely with velocity. Conversely, longer velocity chutes designed for lower velocities can be used. Following an inter-disciplinary approach, this research begins with a synthesis of the literature regarding the

hydrodynamics and physiology of swimming fish, and testing of sea lamprey swimming performance in an open channel flume. Hydraulic analyses and the results of swimming performance tests are combined in development of a conceptual velocity barrier design. Hydraulic modelling is conducted to confirm and improve the design hydraulics. A candidate river, the McIntyre River in northern Ontario, is used to demonstrate the velocity barrier design process under conditions of a real stream. Finally, an experimental velocity barrier, constructed on the McIntyre River in summer, 1993, is used as a velocity barrier prototype case study. It is currently being evaluated for fish passage and sea lamprey blockage by other researchers.

Acknowledgements

Many people have assisted me in this project over the course of the past years. I would like to thank my thesis advisors Dr. Barbara Lence at the University of Manitoba, Faculty of Engineering, and Mr. Chris Katopodis at the Freshwater Institute, Department of Fisheries and Oceans, for their time, commitment, questioning, suggestions and patience. I would also like to thank Mr. Vic Gillman of the Department of Fisheries and Oceans for his support and for being instrumental in arranging the thesis leave and Mr. Larry Schleen for also supporting the goal of this research. Thanks go to Mr. Robert Young who, after contributing biological and statistical advice, now has the task of evaluating the effects of the first velocity barrier on the lamprey and fish communities.

Without the confidence and funding of the Great Lakes Fishery Commission, both this thesis and the new barrier would not have happened. The Department of Civil Engineering at the University of Manitoba permitted the use of the hydraulics lab and Professor Cas Booy made some helpful suggestions for the model and hydraulics. Time was spent building the test flume and model by Art Carter, Dave Holmberg and Brian Greene, while Dave Moore and Manuel Pimentel assisted in the swim tests. Thanks also to Andrew Hallett who assisted in taking velocity measurements at the new barrier.

One essential ingredient has been the loving support and patience of my wife Esther. Thank you Samuel, Rebecca, Jonathan and Daniel for having endured a rarified dad during two semesters mostly away.

Dedication

À Esther et bébé Jean-Nicolas,

et la vraie joie dans le Bon Dieu qui nous soutient.

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Notation

ATP	adenosine tri-phosphate	
D	swim distance	L
°C	degrees Celcius	
C_c	Chezy roughness coefficient	
F_f	dimensionless swim speed	
g	gravitational constant	L/T^2
H	upstream stage with velocity head	L
H_s	upstream stage (water level)	L
k	coefficient, weir formula ($kLH^{3/2}$)	
k_s	equivalent sand roughness	L
L	fish length, length dimension	L
n	Manning roughness coefficient	
q	unit discharge	$L^3/T/L$
Q	discharge	L^3/T
R_h	hydraulic radius	L
s	bed slope	L/L
s_e	slope of energy grade line	L/L
t	endurance time	T
t_*	dimensionless endurance time	
T	muscle contraction time	T
V	velocity	L/T
U	swim speed	L/T
y'	relative depth	

CHAPTER 1

INTRODUCTION AND BACKGROUND

General Background

One of the many applications of hydraulic engineering is in the area of inland fisheries management. Engineers are typically involved in the design and construction of hydraulic structures such as dams, fishpasses, and weirs. In the Great Lakes watershed, a fisheries management program to control sea lamprey requires engineering expertise for the design and construction of barrier dams to block spawning migrations of this harmful parasite in tributary rivers.

The invasion of the sea lamprey has provided a major challenge to the fisheries in the Great Lakes watershed. Within this large drainage area covering 774,000 square kilometres (Environment Canada, 1992) , sea lamprey have used more than 400 streams for reproduction. The location of these streams can be seen in Figure 1.1. The majority of these streams are still being treated on a regular basis with a chemical lampricide in order to control sea lamprey. This thesis develops a new kind of instream barrier for lamprey control based on stopping sea lamprey passage with water velocity. The velocity barrier concept proposed in this thesis is comprised of a chute of water flowing over a material to which sea lamprey cannot attach, such that the combination of water velocity over distance surpasses the swimming performance of sea lamprey. The faster the water, the shorter the length of barrier required, since swimming endurance varies inversely with velocity. Conversely, longer velocity chutes can be chosen which will require lower velocities to stop sea lamprey. The structure is sized and sloped to fit stream hydrology and to produce the required velocities during the sea lamprey migration period. It is coupled with an overflow crest to convey higher flows. Reliable swimming performance data for sea lamprey are a prerequisite for velocity barrier design. Such a barrier could be deployed in certain Great Lakes tributaries and could reduce the use of chemical lampricides in those streams.

History

Sea lamprey from the Atlantic Ocean arrived in the Great Lakes through the canal systems built in the nineteenth and early twentieth centuries (Smith and Tibbles, 1980). They adapted to life in fresh water and, after improvements to the Welland Canal in 1920, spread through Lake Erie and the upper Great Lakes. They were first seen in Lake Erie in 1921, Lake Huron in 1936, Lake Michigan in 1937, and Lake Superior in 1946. A large scale fisheries problem resulted from the invasion of the parasitic sea lamprey into the Great Lakes watershed. Adult parasitic sea lamprey attach to fish with their suction disc mouth, and, after rasping a hole with their teeth and tongue, feed on the fish's blood and internal fluids.

Sea lamprey flourished in their new territory. They soon became a source of large scale mortality in fish stocks in the Great Lakes. Characteristic wounds and scars from sea lamprey predation began appearing on larger fish of a variety of species. Lake trout

(Salvelinus namaycush) catches in Lakes Huron, Michigan, and Superior drastically declined by more than 90% between the late 1940's and early 1950's.

The gravity of this fisheries problem required a coordinated response. In 1955, the Great Lakes Fishery Commission (GLFC) was created by the governments of Canada and the United States to advise governments on measures to improve fisheries, to control sea lamprey, and to develop and coordinate fisheries research programs for the Great Lakes (Fetterolf, 1980). Agencies that implement GLFC policies and programs are the Canadian Department of Fisheries and Oceans (DFO) and the United States Fish and Wildlife Service (USFWS). Chemical treatments of streams infested with sea lamprey larvae with a selective lampricide, 3-trifluoromethyl-4-nitrophenol (TFM) soon became the principal tool (1958) in the control programs of these agencies. Regular lampricide treatments are carried out in order to remove sea lamprey larvae from streams before they enter the parasitic phase and move downstream to feed on fish in the Great Lakes region. It has not been possible to completely eradicate sea lamprey from the Great Lakes basin. This is because, in a number of areas in various rivers, larvae are shielded from lampricide by the presence of upwelling groundwater, and because some deltaic and large river locations cannot be adequately treated using existing methods.

The ongoing control program lead by the GLFC has achieved a significant degree of success. The numbers of lamprey have been sufficiently suppressed to permit the recovery of important sports and commercial fisheries with an annual economic value estimated at three to four billion dollars (Talhelm, 1986).

Alternative Technologies to Reduce Lampricide Use

The GLFC has established a goal of reducing the use of TFM by 50% by the year 2005 (Great Lakes Fishery Commission, 1992). This is to be achieved through the development and use of alternative technologies. The GLFC also encourages and funds research aimed at the development of alternative sea lamprey control techniques. TFM has increased rapidly in price over the last two decades, and currently costs $83 per kg of active ingredient. Also, it is not known whether it will always be available for use in the future. Currently, TFM is undergoing re-registration with the United States Environmental Protection Agency. The re-registration process is lengthy and complicated, costing $US 3.72 million for the part of the work between 1994 and 1996 (Great Lakes Fishery Commission, 1994). With changing public attitudes toward the use of chemicals in the environment, the long term future of lampricide treatments is uncertain.

There are basically two different alternative mitigation technologies available at present. These alternatives are barrier dams and the use of sterile male lampreys. The release of sterilized male lampreys is currently being tested in Lake Superior (Great Lakes Fishery Commission, 1994). The evaluation of the sterile male program, however, will take ten to twenty years because a number of consecutive generations of lamprey need to be affected. The use of barrier dams to block spawning runs of sea lamprey is currently the best tested alternative to chemical stream treatments.

Use of Instream Barrier Dams

The use of barrier dams to block and trap sea lamprey spawning runs has been encouraged by the GLFC since the mid 1970's. The Commission's policy statement on barrier dams is presented in Appendix A. As of 1993, barrier dams have been installed on 41 Great Lakes tributaries, 29 in Canada and twelve in the United States. Seven of the installations are remedial works to existing dams and bedrock chutes and two are electric barriers. The locations of these barriers are shown in Figure 1.1. Since 1980, all but one of the Canadian sea lamprey barriers have been built with hydraulic heads of less than 1 m (called low-head barrier dams). Barrier dam designs in Canada usually incorporate built-in sea lamprey traps to collect and assess populations. The development and use of barriers with hydraulic heads of less than 1 m was due in part to a study in outdoor flumes in New York state, where a 30 cm drop with a stable tail-water level proved to be a definitive barrier to 3000 sea lamprey (Hunn and Youngs, 1980).

Application of electric barriers and trapping weirs has also been attempted, but with limited success. Alternating current electric barriers used in the 1950's in Lakes Superior and Huron were phased out after the introduction of chemical control since their use had only minor effect on sea lamprey populations. A newer gradient-field direct current design has been tested since the late 1980's. Three of these barriers have been installed in Michigan. However, only one of these three is currently being operated. The reason for this is that the electric field, when operated during the sea lamprey migration, stops passage of fish both upstream and downstream. This causes conflicts with sports fishing groups. Designs for a pump-driven channel were developed in 1994 and 1995 to assist fish passage at the electric barrier on the Pere Marquette River, but the tenders all came in above budget. The only currently operated electric barrier is located on a river where the blockage of migratory fish is a management policy.

Benefits of Barrier Dams and Potential for Future Barrier Dam Construction

Barrier dams reduce the use of lampricides and the lengths of stream requiring chemical treatment (Biette et al., 1988). Overall, barrier dams are economically efficient. Benefit - cost ratios of 1 to 7 are most common when comparing barrier construction and maintenance costs to cyclical chemical treatments. TFM treatments have been eliminated on nine Canadian streams and considerable reductions in lampricide use have been accomplished on other streams since the construction of barrier dams.

A recent report to the GLFC by its bi-national agents (Koon and McAuley, 1994) indicates a potential for barrier dams on 163 streams that are regularly treated with lampricide. An investment of approximately 41 million (1995$US) to construct these barriers could bring about whole basin reductions of current TFM use in the order of 54%. Given the large potential for reductions in chemical use, the barrier program will undoubtedly expand in the future.

Need for Low Environmental Impact Barrier Designs

Low-head barrier dams constructed in the 1970's and 1980's complied with fishery management directives to pass migratory salmonids (Biette et al.,1988; McDonald and Johnson, 1984). However, non-jumping fish cannot pass upstream at these dams. An expanded barrier program, without special fish passage considerations, could have considerable impact on the ecology of Great Lakes streams. Therefore careful consideration of barrier types and designs is warranted in order to minimize impacts, particularly on non-target fish passage. Development of innovative barrier designs capable of passing non-jumping fish is a necessary component in an expanding GLFC barrier program. The use of fishways may also take on a greater role in the future. Vertical slot and Denil fishways (Katopodis et al., 1988) can be used to pass non-jumping fish. However, sea lamprey are also able to pass through these fishways. Development of an instream velocity barrier to sea lamprey that can pass non-jumping migratory fish would therefore be an important advancement for the barrier program.

The Velocity Barrier Concept

The basic concept of a velocity barrier is to use water velocity to stop the upstream spawning migrations of sea lamprey. This is achieved by exploiting a difference in swimming ability between sea lamprey and other fish species. The anguilliform mode of swimming employed by sea lamprey is reported to be relatively inefficient compared to the method of swimming used by most fish species (Lighthill, 1969; Lindsey, 1978; Webb, 1975).

The idea of lamprey velocity barriers was introduced by researchers concerned with lamprey control (Bergstedt et al., 1981; and Hanson, 1980; and Hunn and Youngs, 1980). Support for the concept faded after some tests of the swimming ability of sea lamprey. It was discovered that the maximum sprint speed of sea lamprey was about 4 m/s (Hanson, 1980). At that time it was considered that velocities greater than the maximum swimming speed of sea lamprey would be required in a velocity barrier. Creating velocity barriers with velocities of 4 m/s seemed less practical than building low barrier dams.

In addition, researchers at that time did not consider the possibility of differentiating between sea lampreys and other fish on the basis of swimming endurance. Sea lamprey have an important advantage over other fish when passing through areas of rapid water in streams in that they can attach to solid surfaces such as rocks or logs with their oral suction disk (Applegate, 1950). In this way they can secure incremental swimming gains in fast water with intermittent short sprints followed by resting periods while attached to the substrate. Other fish in the same circumstances have to continue swimming to hold station or advance. This well known oral disk attachment was probably an additional reason why the early velocity barrier idea did not advance very far.

This thesis work develops a velocity barrier that eliminates the attachment advantage of sea lamprey through the use of selected surface materials to which lamprey cannot attach. If lamprey swim to the limit of their endurance and do not succeed in attaching, they will wash back downstream. In this way, differences in swimming endurance between sea lamprey and other fish can be exploited. Eliminating the lamprey's attachment advantage thus permits the use of water velocities in a velocity barrier that are lower than their maximum sprint velocity. The velocity barrier concept proposed in this thesis is comprised of a chute of water flowing over an "attachment-preventing" surface material such that the combination of water velocity over distance surpasses the swimming performance of sea lamprey. The faster the water, the shorter the length of barrier required, since endurance time varies inversely with velocity. Conversely, the longer the velocity chute, the lower the velocity required to stop lamprey. This concept permits flexibility in design and planning. The length and velocity of a barrier can be selected according to fish passage, budget and site criteria.

Scope of Work

The development an instream sea lamprey velocity barrier is described in this thesis. Chapter 2 summarizes the literature on fish swimming analyses that provides the underlying knowledge required to develop a velocity barrier. Among the topics covered in this chapter are the biomechanics of locomotion in fish and sea lamprey and all previous work related to the swimming performance of sea lamprey.

An essential requirement in velocity barrier planning and design is accurate information regarding the swimming ability of adult sea lamprey over a wide range of water velocities and of other factors, such as temperature, that affect swimming performance. Previous swimming performance research did not measure distance travelled before washing back downstream. Nor did it yield information about behaviourally preferred swim speeds relative to the ground and the water velocity. Behaviourally preferred swimming speed is an important factor in the actual swim distances achieved since different distances can be attained in the same current by fish swimming at different velocities. Therefore, in this research, new swimming performance tests were carried out with sea lamprey in an open channel flume lined with a lamprey attachment-preventing material. These tests are described and analyzed in Chapter 3.

Chapter 4 describes the hydraulic model tests conducted on a preliminary conceptual velocity barrier design. Chapter 5 describes engineering and planning factors related to velocity barrier design for a candidate river, the McIntyre River in Thunder Bay, Ontario, and describes the first velocity barrier built as a case study prototype on that river. Chapter 6 presents the summary, recommendations, and conclusion of this research.

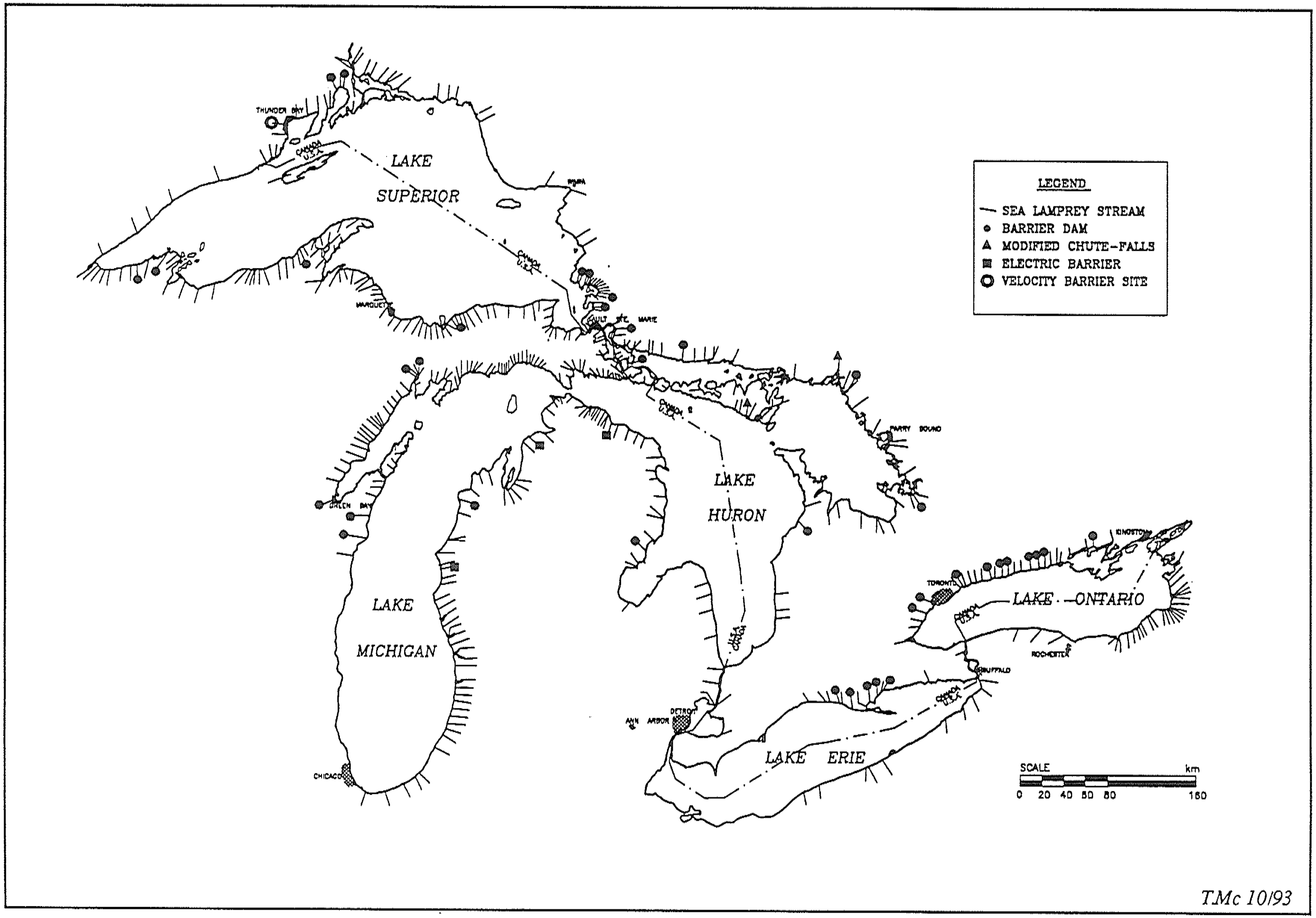

Fig. 1.1 Great Lakes streams used by sea lampreys and streams where lamprey barriers have been constructed. (Also shown is the McIntyre River where the first sea lamprey velocity barrier has been constructed.)

CHAPTER 2

REVIEW OF FISH SWIMMING ANALYSES

Swimming Biomechanics

Since, in the design of velocity barriers, swimming performance is used to contain sea lamprey while allowing the passage of other fish, a basic understanding of the mechanics and physiology of swimming is necessary. Swimming performance depends on a number of factors, both physiological and environmental. The principal factors are swimming mode, species type, length of fish, body morphology, water velocity and temperature, and acclimation temperature (Webb, 1975). The literature on the analysis of such factors is summarised in this chapter.

Force Balance on a Swimming Fish

For a fish to move through water at constant velocity, the thrust developed by the fish must be equal to the drag force on the fish. The weight of a fish must be counterbalanced by the lift developed either by a swim bladder or by fin or body movements. The force balance on a swimming fish is shown in Figure 2.1.

The total drag resisting forward motion is composed of the sum of the skin friction drag and the pressure drag. Skin friction drag is proportional to the square of swimming velocity. The pressure drag is the sum of the form drag and the vortex drag.

The skin friction drag is normally the major drag component for swimming fish (Blake, 1983).

The power required of the muscles to generate thrust to overcome drag is exponentially proportional to the fish's swimming speed by a power of 2.8 (Webb, 1975) or 3 (Blake, 1983). For this reason, increases in speed require much larger increases in power. A doubling in swimming speed from 0.5 m/s to 1.0 m/s requires an eight-fold increase in power. High speed swimming activity is demanding in terms of energy use and fatigue. Because of this, sprint swimming can be maintained for short durations only.

Most fish are slightly denser than water. Those fish that have swim bladders can maintain neutral buoyancy without muscular effort. Fish such as tuna and sea lamprey have no swim bladders. Tuna achieve lift to balance body weight during swimming by exploiting a pressure difference over their extended pectoral fins. Sea lamprey overcome their negative buoyancy by including undulations in the vertical plane along with those in the horizontal plane. This requires an additional energy expenditure for sea lamprey to hold their vertical position while swimming in the water.

Swimming Energetic Levels

There are three basic energetic levels in swimming that have been traditionally recognised: (1) sustained; (2) prolonged; and (3) burst or sprint swimming (Webb, 1975). Swimming energetic levels are commonly defined by the length of time that fish can endure at different swimming speeds. The three energetic levels are shown in Figure 2.2. They are defined as follows:

Sustained swimming refers to low levels of routine activity that can be maintained over long periods of time such as migration, station holding and foraging. Swimming activity which can be maintained longer than 200 minutes is generally considered as sustained swimming.

Prolonged swimming is an activity level between burst and sustained swimming. It is commonly defined as an activity that leads to fatigue between 20 to 30 seconds and 200 minutes. The energy required for prolonged swimming comes from both aerobic and anaerobic metabolism.

Burst swimming refers to relatively high speed swimming at which the fish can endure for short periods of time, i.e., 20 or 30 seconds or less (Beamish, 1978). Burst, or sprint swimming, is used in attempts to traverse rapid water, leaping at falls, fast-start accelerations and sprints required to capture prey or to avoid capture. The largest part of the muscle mass of most fish is geared to support burst swimming.

Metabolism and Muscles

Fish metabolism and muscle systems are adapted to supply the power required to swim at different velocities. Power for swimming comes from the muscles where metabolic fuel is converted into mechanical work. Fish exhibit what is called a "two-geared" metabolic system (Blake, 1983) to better function over the large range of required swimming levels. The total muscle mass is made up of red muscle and white muscle. These distinct fibre types, also called the slow and fast muscle fibres, are designed to operate at lower and higher swimming speeds, respectively.

Red muscle fibre supports lower speed, long endurance activities. It is a slower, more phasic type of muscle that is highly vascularized and well furnished with myoglobin, large mitochondria, and oxidative enzyme systems (Bone, 1978). Energy for the red muscle is produced by **aerobic metabolism** whereby the fuels, e.g., carbohydrates and lipids, are completely oxidized. The red muscle is usually found in thin bands along the outside walls of a fish's body. It generally constitutes 10 % or less of the total muscle mass but can be as much as 20 to 25 % in fish that normally swim at high levels of sustained activity such as Scombridae and Carangidae.

White muscle is used to deliver power for swimming at higher speeds. It has a high intrinsic speed of shortening with contraction times as short as 0.02 seconds. White muscle generally constitutes 80 to 90 % or more of the total muscle mass in most fish. White muscle fibres are larger in diameter than red muscle fibres, are poorly vascularized, and function with anaerobically active enzymes. Energy is produced in white muscle by anaerobic metabolism which is often referred to as glycolysis, i.e., with glycogen being the prominent fuel. Anaerobic burst swimming lasts only for short durations at a time since the build-up of lactic acid produced by glycolysis and depletion of fuel soon necessitate largely reduced activity until internal concentrations are equilibrated.

Swimming Modes

The majority of fish depend on lateral movements in the body and caudal fin for forward propulsion. The principal modes of swimming of Great Lakes migratory species and most other fish are commonly named anguilliform, subcarangiform, and carangiform modes.

The anguilliform swimming mode, which is typified by the eel, is also employed by the sea lamprey. Characteristic to this mode are flexible long, slender bodies with compressed posteriors. Lateral undulations pass backwards with increasing amplitude from head to tail as the body segments push against the water. There is usually one or more wavelengths visible in the body. The anguilliform swimming pattern can be seen in Figure 2.3. Williams et al. (1989) found the mechanical swim wave length for sea lamprey to be 0.72 body lengths($\pm$0.07 SD). This implies about 1.4 wavelengths for the entire body while swimming. The transverse wave, caused by successive muscle contractions, passes down the body faster than the forward speed of the fish. The ratio of forward velocity (U) in the water to the speed of downstream transmission of the body wave is about 0.65 in the eel and 0.8 in the sea lamprey (Sigvardt, 1989).

Anguilliform swimming is relatively inefficient from the hydromechanical point of view (Weihs, 1982). The relatively large sideways motions of the body required to produce backwards motion of the water increase frontal area and hence drag during swimming. Lighthill (1969) calculated that the drag on an anguilliform swimmer is 4 times greater when swimming as opposed to when being towed, i.e., stretched straight, at the same speed. Anguilliform swimmers also lose more energy to the wake of their motion (Webb, 1975). Burst-and-glide swimming, which can allow significant energy reductions in teleosts (Weihs, 1982), has not been reported in sea lamprey. This is probably due to the fact that slender swimmers have a relatively lower ratio of mass and thus momentum to skin friction drag. Sea lamprey tend instead to stop and rest frequently during upstream migrations and migrate at very low rates of 0.06 to 0.11 m/s (Wigley, 1959).

Subcarangiform swimmers advance using both caudal fin oscillations and undulations which occur principally in the posterior half of the body. Their body shapes are fusiform and they have a fairly deep caudal peduncle. The subcarangiform swimming pattern is also shown in Figure 2.3. The propulsive wave comes to a maximum amplitude of about 0.2 body lengths (*L*) in the tail (Lindsey, 1976) with between one half and one wavelength visible on the body. Most common among Great Lakes basin fish, the subcarangiform swimming mode is employed by Salmonidae, Cyprinidae, and Esocidae.

Carangiform swimming is similar to sub-carangiform swimming but has undulations confined to the posterior third of the body. Caudal fin movement increases the wave amplitude to a maximum of 0.3 *L*. The fish are fusiform and have a greater anterior concentration of mass. The peduncle, which supports the caudal fin, is fairly narrow to avoid excessive drag and turbulence in the important caudal fin movements. Members of Carangidae and Clupeidae swim in this mode. The drag increment factor of active swimming as compared to gliding is about 3 to 5 in subcarangiform swimmers and 1.5 in carangiform swimmers.

Other Considerations Affecting Performance

Swimming Near the Bed of a Channel

Fish swimming closer to a channel boundary can take advantage of lower water velocities. The Manning or Chezy equations can be used to calculate average channel velocity only. Local velocity v' at relative depths y' can be fairly closely estimated using the Log Flow Formula (Rouse, 1946). That is

$$v' = (8.5 + 5.75 \text{ LOG } (y'/k_s))\,(gR_h\,s)^{1/2} \qquad 2.1$$

where k_s is equivalent sand roughness, g is the gravitation constant, R_h is the hydraulic radius, and s is the bed slope. This formula was derived and verified extensively for circular pipes but has also been used for open channels where the general shape of the cross section is not a major consideration (Booy,1995). An example of an application of Equation 2.1 to sea lamprey swimming is for a case of a sea lamprey swimming with its body centre-line at a relative depth of 3 cm (y') above the channel bottom. Using for the example a 2% slope, a depth (y) of 14 cm, a k_s of 4 mm for the bed surface, and an R_h of 0.14 m, the average velocity in the water column would be 2.2 m/s. According to the log flow formula, the sea lamprey swimming at 3 cm from the bottom would face a velocity (v') of 2.06 m/s, approximately 6% less than the average velocity.

Swimming near the Surface

Swimming at or near the water surface causes surface waves. The energy required to form the surface waves results in an additional cost for propulsion (Hertel, 1966; Webb et al., 1991). This effect is greatest when the mid-line of the fish body is about 0.3 to 0.5 body depths below the air-water interface, with the dorsal fin breaking the surface. At this depth the increase in propulsive work required could be as much as 70% (Webb et al., 1991). As swimming depth increases, surface energy loss decreases to the point where there is no effect at 3 body depths below the surface. Video-filmed rapid acceleration tests with rainbow trout indicate no significant difference in swim distance achieved between trials at 1.92, 2.73 and 7.56 caudal fin depths below the surface after 70 milliseconds (Webb et al., 1991). Sea lamprey depend much less on caudal fin movements than do rainbow trout. A drag increase is expected to occur for sea lamprey swimming near the surface, however this effect has not yet been investigated.

Temperature and Body Length Effects on Performance

Temperature has an important effect on swimming performance (Beamish, 1978; Webb, 1975). Physiological changes such as acclimation, muscle fibre recruitment and ATPase activity changes (Bone, 1978) can act to reduce the effect of temperature change. The extent of the effect of temperature acclimation has been studied in muscle isolate work carried out with short-horned sculpin, (Myoxocephalus scorpius) (Johnson and Johnston, 1991). It was found that a fish that is acclimated to colder winter temperatures could produce 83% as much fast muscle power at 4°C as when it is acclimated in the summer and swimming at 15° C. An earlier example of acclimation effects showed that sockeye fingerlings acclimated at 15° C exhibited only a 4% reduction in swimming speed in 10° C water (Brett, 1967). However, the maximum burst swimming speeds attainable by fish are more directly affected by temperature (Wardle, 1980). This is because of the effect that temperature has on the contraction times of the white muscles. Other responses such as changes in stride length may also come into play in burst swimming (Wardle and Videler, 1980). A stride is the distance a fish moves forward per complete tail beat cycle which consists of two caudal fin beats, i.e., one to each side.

Performance dependence on length and temperature is quantified in an approach taken by Wardle (1980). Maximum swim velocities (Umax) are projected from measurements of the contraction times (T) of isolated anaerobic fast white muscle from different species and sizes of fish. Fish have been found to have an average stride length of about 0.7 *L* which is usually constant over a range of speeds. Thus, $Umax = 0.7L/2T$, where T is the fast white muscle contraction time at a given temperature. Maximum velocities are lower at colder temperatures since cold muscle contracts less quickly than warm muscle. A somewhat smaller length effect also occurs since muscles of larger fish contract less rapidly than those of small fish at the same temperature. Wardle's approach and projections have been found to agree fairly well with other studies (Blake, 1983). Based on changes in fast muscle contraction times from about 0.033 seconds at 15°C to 0.078 seconds at 4°C for 35-40 cm long fish of several species, Wardle projected significant declines in maximum swimming speeds for a temperature decrease of 10°C.

Burst Swimming Ability of Fish

A velocity barrier, if it is not to be extremely costly in terms of structure length, would normally be designed so that it separates fish from sea lamprey on the basis of swimming at higher speeds, i.e., at burst or near-burst swimming. However, there are fewer data available in the literature for burst swimming of adult fish of the size that would be encountered migrating in Great Lakes streams. Most swimming tests have been carried out in tunnel respirometer apparati at sustained and prolonged swimming speeds (Beamish, 1978). Confined tunnel apparati are not well suited to the study of burst swimming. General and specific studies pertaining to burst swimming are summarized below.

Bainbridge (1958) established a typical burst speed for fish of 10 body lengths per second (*L*/s). Blaxter (1969) considered that small salmonids, cyprinids, and percids could achieve 9 to 12 *L*/s while salmonids of 35 to 70 cm in length could sprint at 10 to 8.5 *L*/s. At 10 *L*/s, a 30 cm fish would be able to sprint at 3 m/s and a 50 cm fish at 5 m/s. Small haddock and sprats, 10 cm in length, have been recorded on videotape at speeds of 26 *L*/s at 12°C (Wardle, 1975). Juvenile coho salmon (Oncorhynchus kisutch) can swim as fast as 21 *L*/s at 13.5°C and maintain speeds of 7 *L*/s for periods of 9 to 105 minutes (Taylor and McPhail, 1985). Burst swimming speeds show less variation between different teleost species than do prolonged and sustained swimming (Webb, 1975).

Paulik and Delacey (1957) tested migrating rainbow trout (Oncorhynchus mykiss) averaging 60 cm in length, and coho salmon averaging 57 cm in length, in a rotating annular ring that was 3 m diameter at 11° C water temperature. At a velocity of 3 m/s rainbow trout and coho were able to endure for an average of 82 seconds and 24 seconds, respectively. Because the fish had to swim while turning continually in one direction, these results may possibly underestimate actual swim performance. Weaver (1963) tested a large number of instream migrant salmonids in large 26 m long flumes at the Bonneville testing facility on the Columbia River. In those tests it was found that 0.6 m adult steelhead were able to swim at 5.5 to 6.3 m/s (8.3 to 9.4 *L*/s) for 19 seconds at 19° C while 0.7 m long chinook (Oncorhynchus tshawytsha) could maintain 7 *L*/s for about 22 seconds and 8.3 *L*/s for 8 seconds. The effect of warmer water enabling more rapid white muscle contraction (Wardle, 1980) appears to be demonstrated by the speeds attained by salmonids at 19° C in the tests conducted by Weaver. Data for migrating adult salmonids (Brett, 1982; Paulik and Delacey, 1957; Weaver, 1963) can be seen in Figure 2.4.

Some marine fishes, such as tunas and billfish, which maintain an internal body temperature above water temperature, have a performance advantage. For example, a yellowfin tuna (Thunnus albacares, $L = 0.98$ m) was recorded moving at 20.8 m/s and a wahoo (Acanthocybium solanderi, $L = 1.13$ m) at 21.4 m/s (Walters and Fierstine, 1964). It has also been proposed that these fish make changes in their swimming body wave-length and stride length to arrive at such sprinting prowess (Wardle and Videler, 1980).

Swimming Ability of Great Lakes Migratory Fish

Rainbow trout, which is also known as steelhead, and coho and chinook salmon from the Pacific coast have been introduced into the Great Lakes basin and reproduce there. These fish, which are commonly between 40 and 70 cm in length, migrate up many streams that are also used by sea lamprey in the Great Lakes basin. These strong swimmers normally leap over the crests of low-head sea lamprey barriers on their way upstream. Their burst swimming ability is similar to that described for rainbow trout, coho, and chinook in the preceding section.

Also found migrating up Great Lakes tributaries are migratory species which do not jump over low-head barrier crests, such as walleye (Stizostedion vitreum), and white suckers (Catostomus commersonii). Passage for walleye in particular, but also suckers, which are labelled as coarse fish, would be desirable at a sea lamprey velocity barrier. These are somewhat smaller fish, commonly between 30 and 50 cm in length. Jones et al. (1974) found regressions for the swimming speeds that walleye and white suckers of different lengths can endure for a period of 10 minutes. These are,

for walleye, $$U = 1.369L^{0.51} \qquad 2.2$$

for white suckers $$U = 1.309L^{0.552} \qquad 2.3$$

Temperature (7° to 20°C) did not have a significant effect in these low speed tests.

From Equation 2.2, a walleye of 35 cm in length can endure for 10 minutes at 0.8 m/s. From Equation 2.3, a white sucker of 35 cm in length can endure for 10 minutes at 0.71 m/s. Walleye and white suckers of 45 cm in length can endure for 10 minutes at 0.91 and 0.86 m/s, respectively. These points can be seen on the graph in Figure 2.4.

Sea Lamprey Swimming Ability

The anguilliform swimming mode employed by sea lamprey is relatively inefficient from the hydromechanical point of view (Lighthill, 1969; Lindsey, 1978; and Webb, 1975). Some swimming performance analyses have been conducted for sea lamprey by Beamish (1979), Bergstedt et al. (1981), and Hanson (1980). Beamish (1979) found that all marine teleosts (e.g. Atlantic cod, redfish, winter flounder, longhorn sculpin, sea raven, and ocean pout) in his preceding tests of swimming endurance were able to swim for longer periods at higher speeds than could sea lampreys.

Bergstedt et al. (1981) tested adult sea lamprey in 1977 at water velocities of 1.0 to 1.5 m/s and temperatures of 6 and 10° C in a tunnel respirometer. Endurance times for the four sea lamprey tested at 1.4 m/s were 4, 9, 32, and 0 s. However, at 1.5 m/s, three out of the four sea lamprey tested were not able to swim and one endured for 15 s. Bergstedt et al. noted that the dimensions and nature of the tunnel apparatus used were not ideally suited for burst swimming tests and that 1.5 m/s exceeded the maximum current velocity for which it was designed.

Hanson (1980) tested migrating sea lamprey ranging from 37 cm to 55 cm in length in a horizontal 3 m long flume that was set up beside a stream from which the sea lamprey were trapped. A large irrigation pump fed a storage tank at the upstream end of the flume. A total of 792 sea lampreys were placed in a reservoir box from which they could freely attempt to ascend the flume in nineteen tests conducted over the course of two months. Distance and elapsed time until sea lampreys attached to the flume were measured for each swim attempt.

Temperature had a significant effect on the number of sea lamprey swimming attempts in Hanson's work. Relatively few sea lamprey attempted to ascend the flume at lower temperatures. In the six tests conducted at temperatures below 15° C, only four out of 202 sea lampreys, i.e., 2%, attempted to challenge the flume which had currents ranging from 1.5 m/s to 4 m/s. In the 13 tests conducted at temperatures between 16 and 24° C, 98 of the 590 sea lampreys, i.e. 17%, attempted to swim the flume. Only at water temperatures greater than 16.5°C, were sea lamprey able to swim as fast as 4 m/s. However, they could only endure at this speed for an average of 1.3 seconds.

A dimensionless equation representing the mean endurance of anguilliform swimmers was developed by Katopodis (1992). The equation is based on existing endurance data for sea lamprey and burbot (Lota lota). The relationship found between dimensionless fish speed, F_f, and dimensionless endurance, t_*, for anguilliform swimmers is:

$$F_f = 3.006\, t_*^{-0.347} \qquad 2.4$$

where $F_f = U\,(gL)^{-½}$ 2.5

and $t_* = t\,(gL)^{½}$. 2.6

In these equations, U is the fish swimming speed (m/s), t is endurance time (s), L is fish length (m), and g is the gravitational constant (m s^{-2}). Equation 2.4 has the unique advantage of combining endurance and speed, and, at the same time, being applicable for all lengths of anguilliform swimmers.

Endurance data for sea lamprey from previous researchers are plotted together in Figure 2.4. Also included is a plot of the mean endurance curve for an anguilliform swimmer, 50 cm in length, based on Equation 2.4.

Discussion

Conducting swimming tests on non-jumping teleost species is not feasible for the scope of this research. Being aware of the biomechanical, physiological, and environmental aspects of swimming summarized in this chapter provides the necessary background for conducting and interpreting swim performance analyses which are an essential component in the concept and design of velocity barriers. Relevant swim performance data from tests and analyses conducted with migratory fish and sea lamprey are summarized in the graph in Figure 2.4.

In this figure, a notable difference in swimming endurance can be seen between migratory salmonids and sea lamprey. However, the situation is more problematic for fish like walleye and white suckers. Figure 2.4 would indicate that these fish are somewhat better swimmers than sea lamprey at prolonged times of 600 s. But there is no swimming test data for these fish at speeds above approximately 1 m/s. How much better these fish swim than sea lamprey at burst or near-burst speeds is not known.

There is also some uncertainty pertaining to sea lamprey swimming performance. Sea lampreys were able to attach to the flume in tests conducted by Hanson (1980).

It is not known how much longer the sea lamprey would have swam in these tests if attachment to the substrate was not an option for them. It is reasonable to expect that sea lamprey maintain some kind of a reserve between the point in time when they attach to the substrate and the point in time when they are tired enough to wash back downstream. These tests therefore, which are the only ones conducted with sea lamprey at speeds above 1.5 m/s, only give an indication of endurance.

No swimming performance data are available for sea lamprey at stream temperatures normally occurring during their spawning run, i.e. 10 to 20°C , over the important swimming speed range of 0.6 and 2.7 m/s. Beamish's tests (1979) at 15°C were conducted at speeds up to 0.6 m/s. The tests of Bergstedt et al. (1981) with a small number of lamprey were carried out at lower temperatures of 6 and 10°C. In those tests, sea lamprey were not able to swim at speeds above 1.5 m/s. The effect of temperature is important here since sea lamprey did attain higher speeds in Hanson's tests, but only at water temperatures above 16°C. Because of these gaps and uncertainties, it is considered important to further test sea lamprey swimming performance over velocities and temperatures that are the most likely values in streams during their spawning migrations. An accurate knowledge of sea lamprey swimming performance is a prerequisite for future velocity barrier designs.

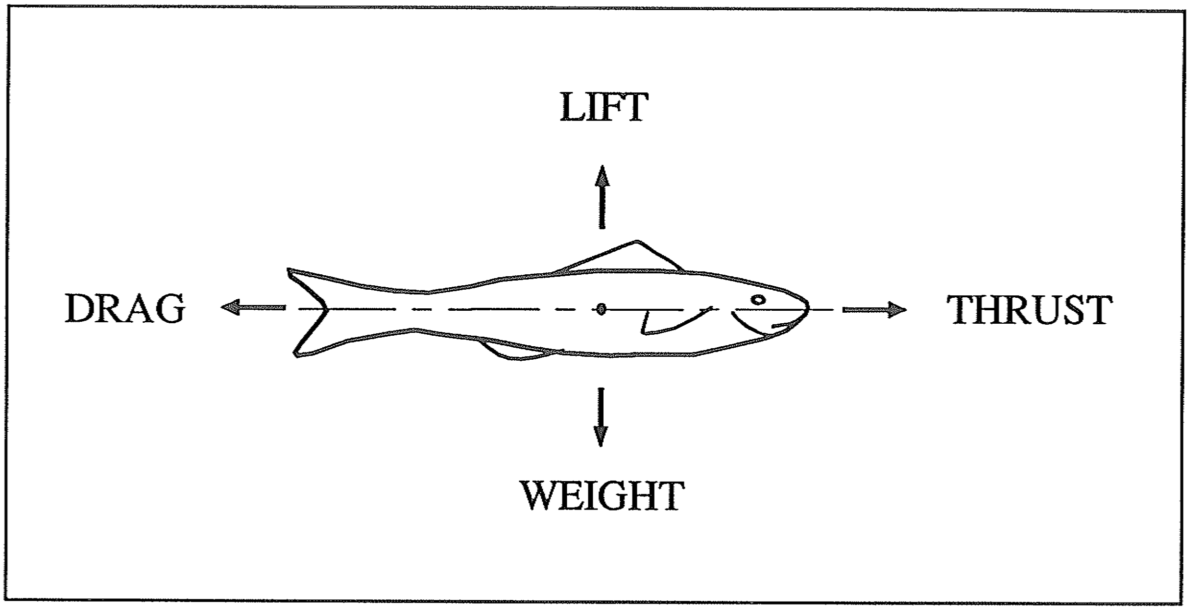

Figure 2.1 Force balance on a swimming fish.

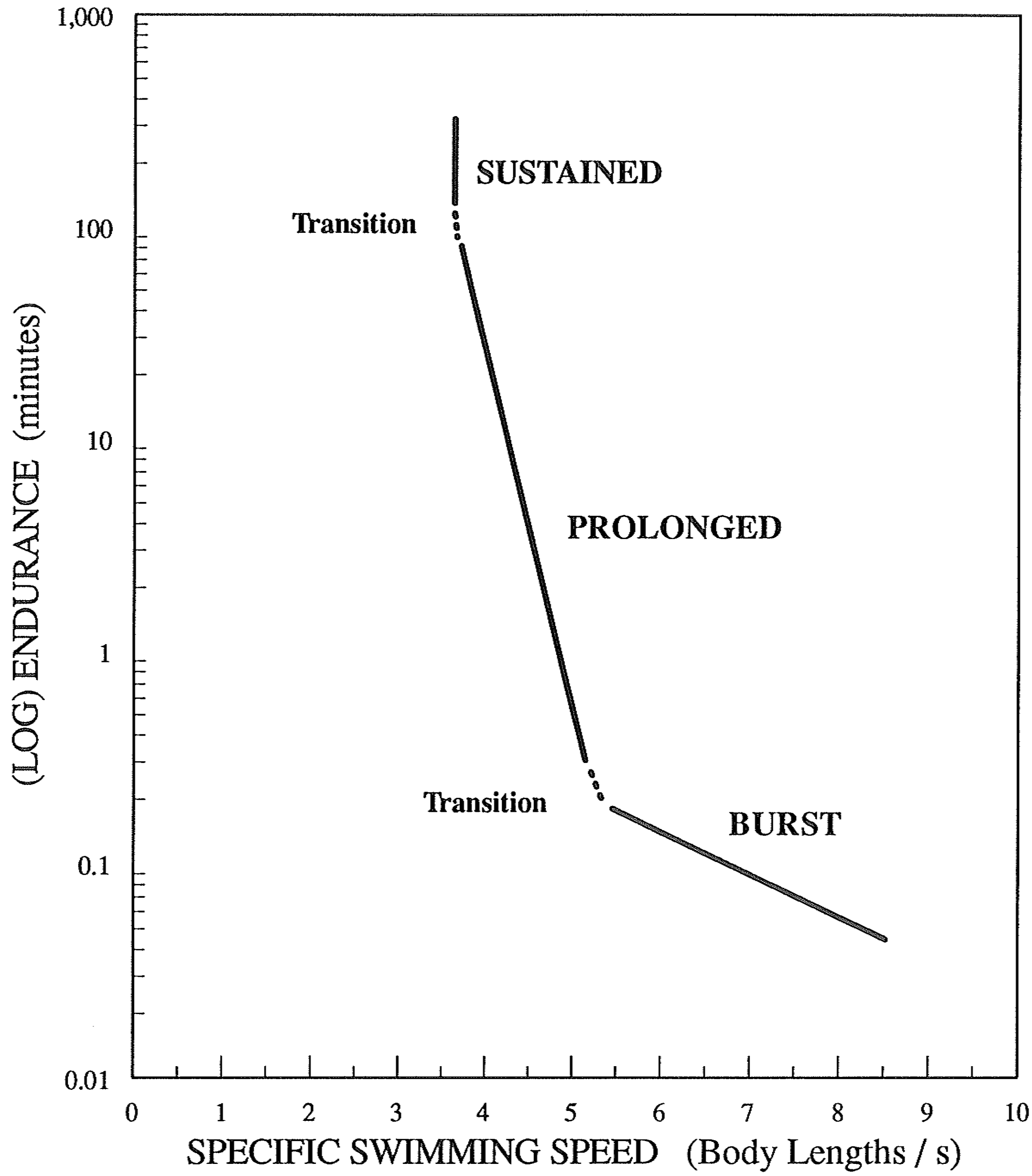

Figure 2.2 Typical swimming speed - endurance curves for a swimming fish. (Modified from Brett, 1967.)

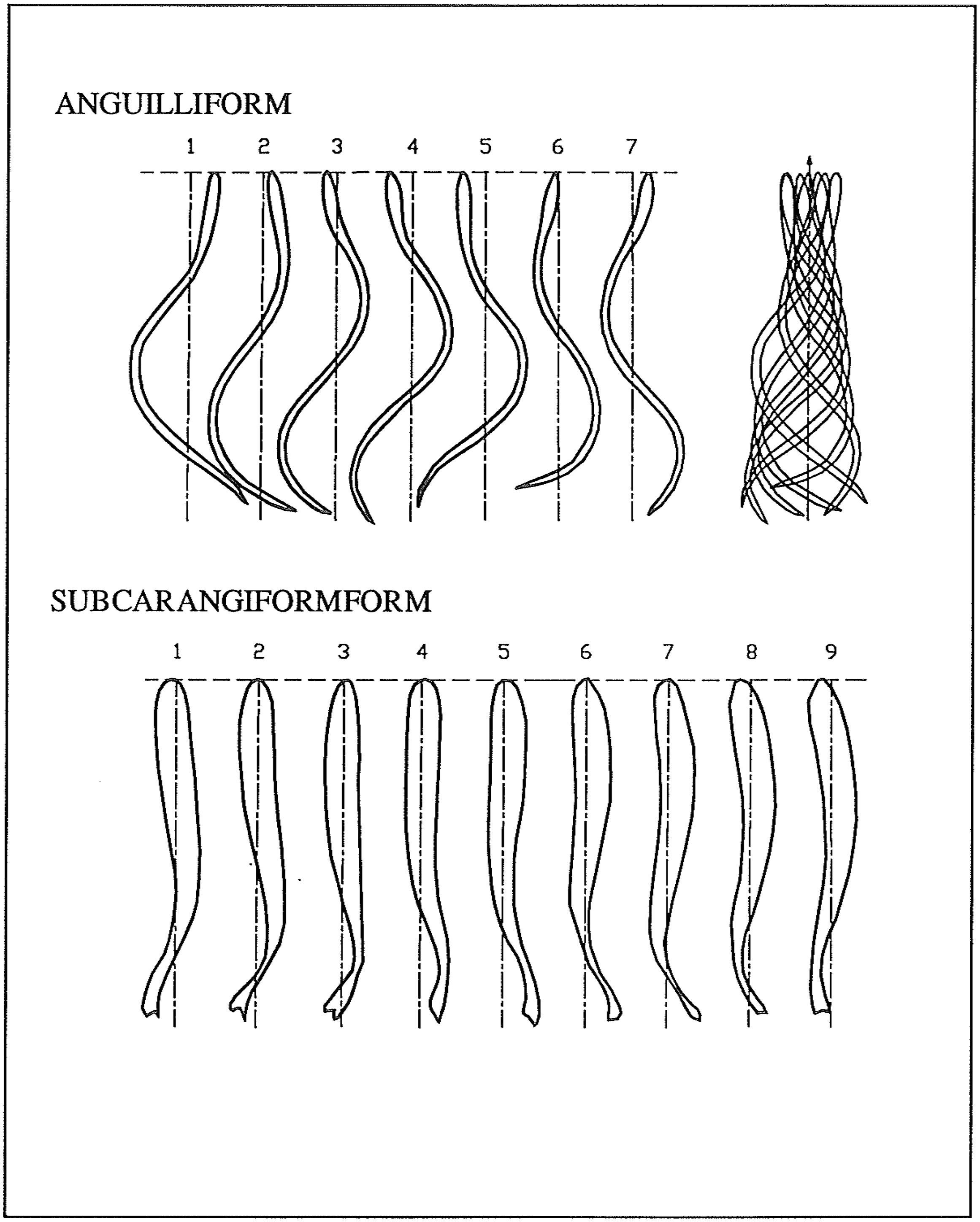

Figure 2.3 Anguilliform and subcarangiform swimming modes.
(Modified from Gray, 1933; and Webb,1975.)

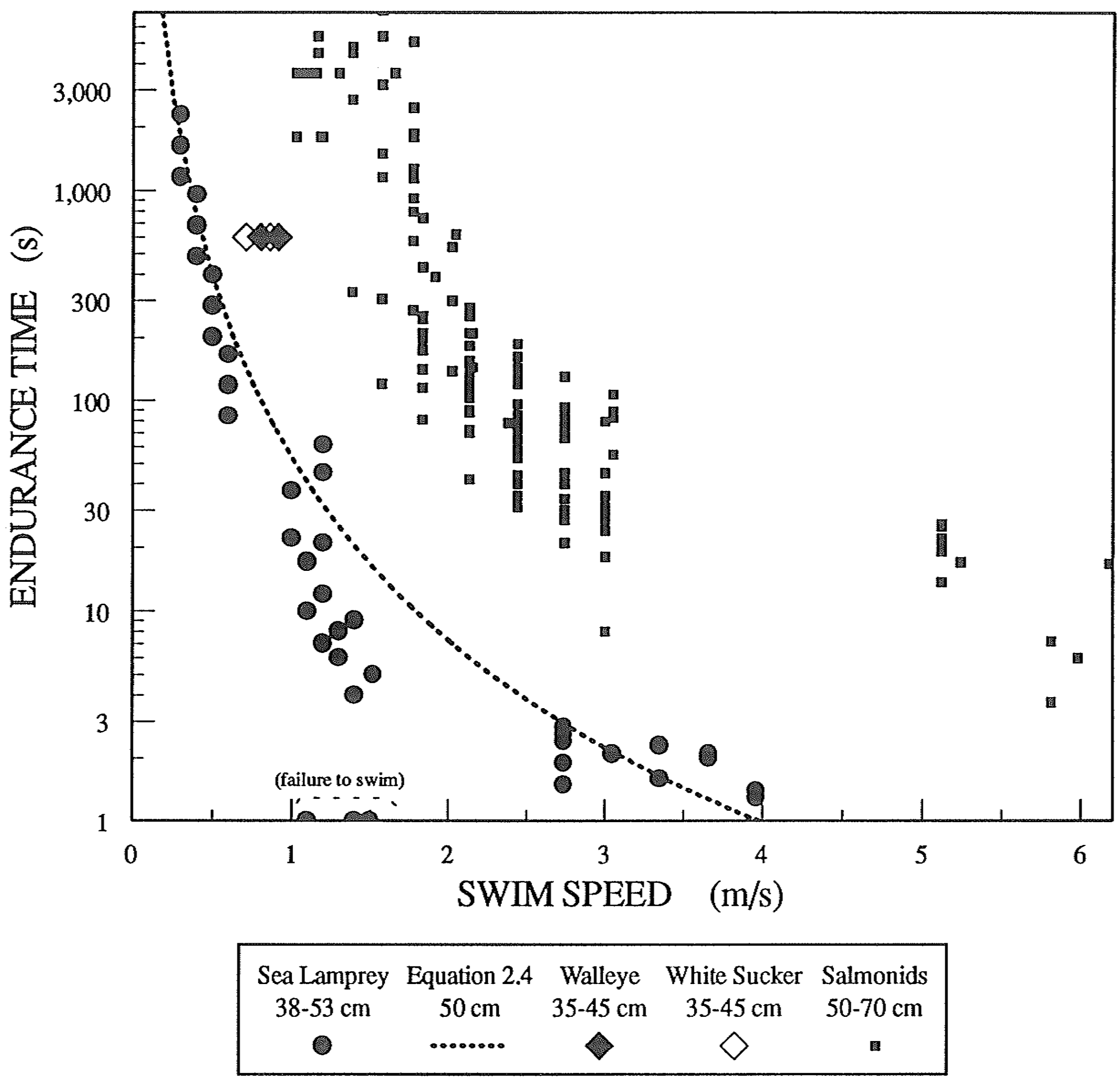

Figure 2.4 Endurance of sea lamprey and migratory fish common to Great Lakes tributaries.

CHAPTER 3

PERFORMANCE TESTS OF SEA LAMPREY

Introduction

A review of the literature pertaining to sea lamprey swimming performance summarized in Chapter 2 showed that no data exists for lamprey swimming between speeds of 0.6 and 2.7 m/s at water temperatures above 10°C. However, in the Great Lakes region, sea lamprey spawning migrations begin in the spring when the rivers reach approximately 10° C. In some rivers, adult lamprey are present until the temperature is slightly above 20° C. Preferred spawning temperature is in the range of 14 to 16° C (Applegate, 1951). For the design of velocity barriers, it is considered important to obtain data in this essential range of velocities and temperatures. Also, in some previous tests sea lamprey could attach to the flume (Hanson, 1980). It is not known how much further lamprey would have swam if attachment to the substrate were not possible for them. In order to fill in these information gaps and to provide accurate swimming endurance and distance data for future velocity barriers, new tests of sea lamprey swimming performance were conducted.

Open channel flumes covered with surfaces to which sea lamprey cannot adhere were chosen for the tests since swimming tunnels are not well suited for testing at burst swimming speeds (Bergstedt et al., 1981). An additional advantage of the new open flume tests is that both swim distances, and endurance time can be measured to the point of fatigue, i.e., wash-back, thus yielding additional information about preferred rates of travel and behaviour.

Tests were conducted in the summer of 1992 in Sault Sainte Marie, Ontario, in a 30 m long flume with average water velocities of 0.66 to 1.48 m/s. Swim tests with sea lamprey for a related study had also been carried out during the previous summer at velocities of 1.85 to 2.8 m/s. Data from these tests are included in this analysis for comparison and to broaden the velocity range. The 1991 test methods and results are summarized in Appendix B.

Experimental Flume

Figure 3.1 shows the 30 m long flume and the introduction reservoir for lamprey at the downstream end of the flume that were constructed in Sault Sainte Marie in 1992. The flume was constructed of plywood and pine with a uniform cross section.and surfaced with materials that prevented sea lamprey oral disk attachment. These materials consisted of red PVC rough-top conveyor belting, black rubber rough-top conveyor belting, and high density polyethelene aqua-net grid. These are called surfaces A, B, and C, respectively. Measurements of the cross sectional area were also taken at the 1, 6, 11, 16, and 21 metre stations along the flume by measuring vertically every 3 cm at 10 locations across the width of the flume. These measurements are listed in Appendix C, Table C1 and were used to calculate the flow areas for the flume. The flume slope was set using a surveyor's level and shims were placed where required at the supports which were spaced every 2.44 m along the flume. At each support, the flume was within ± 5 mm of the ideal slope. To change water velocities, the flume slope was changed. Slopes of 0.75, 1.5, 2.5, and 3.5% were used.

For each test period, water was pumped from the nearby St. Mary's River into a baffle box built at the top end of the flume. From there it moved through the flume and into the introduction reservoir (1.2 x 1.2 x 0.6 m in dimension) attached at the downstream end of the flume (Figure 3.1). This reservoir served as an introduction chamber to hold sea lampreys before their attempts to swim upstream in the flume. A V-notch weir was built into a wall of the introduction reservoir to provide for discharge measurement. Water flowing through the flume system passed over the weir outlet and returned to the river by way of a culvert. The flume was under uniform shading during the tests since it was situated along the north outside wall of a 30 m long building.

Determining Water Velocities

A combination of two methods are used to determine water velocities in the flume. The discharge-area method consisted of calculating average velocity from flow area in the flume and a stage-discharge relationship that was developed from a calibration of the outflow weir. The other method used was that of measuring velocities with a current meter.

Weir Calibration and Discharge-Area Method

Discharges through the flume were determined from a stage-discharge relationship developed for the flume reservoir outflow weir. The outflow weir was calibrated by means of repetitive volumetric flow timing for a range of discharges. For each discharge in the calibration series, the water level in the introduction box was recorded from a staff gage installed at a distance of greater than 3 H upstream from the weir, where H is the head on the weir crest. To measure the discharges producing the reservoir water level upstream of the weir, the hose carrying the discharge into the flume was diverted into a 60.5 cm cubic box. The time to fill the box to a pre-marked level was recorded by stopwatch. The volume of water delivered in the elapsed time was then calculated by measuring the average water depth in the four corners of the box and multiplying by the length and width of the box. A series of 20 tests were done for the calibration with discharges ranging from 8.3 to 14.9 l/s. Appendix C, Table C1, shows volumes, flow timing, discharges, and associated water levels above the outlet weir for this calibration. The best fit regression equation relating stage to discharge for the outflow weir is:

$$Q = 0.326\ H^{1.390} \qquad R^2 = .99 \qquad 3.1$$

To determine average test velocity values, the discharge calculated from the outflow weir relationship was divided by the cross-sectional area of flow in the flume. Cross-sectional area of the flume for the 1, 6, 11, 16, and 21 metre stations along the flume was calculated from measurements every 3 cm across the flume. These measurements, seen in Appendix C, Table C2, were used to calculate the flow areas for various water depths in the flume. The relationship between flow area and centre-line water depth is illustrated graphically in Appendix C, Figure 1. Average test velocities could thus be found using discharge and area calculated from water depths above the outflow weir and in the flume.

Current Meter Measurements

In order to better determine cross section velocity distribution, local velocities were measured in cross sections using a current meter at different flume slopes. These sections help to determine more accurately the velocities encountered by sea lamprey in the swim tests. The average cross section velocities from the meter work were also used as a check on the discharge-area method. These cross-sectional velocity measurements are found in Table C3 of Appendix C.

A recently calibrated Novonics Streamflo velocity gage (type 412) with a 1 cm diameter Nixon (type 404) high speed probe was used to measure velocity. The current meter measurements were spaced on a grid of 1 cm vertical by 3 cm horizontal. This yielded 17 or more velocity measurements per cross-section. Six of these velocity cross-sections were conducted.

Iso-velocity plots of the velocity distributions were produced based on these data using the SAS software program. In order to compare these iso-velocity plots to find the velocities most representative of the zones in which lamprey usually swam, the plots were developed in units relative to the mean section velocity. The local velocities (V) were divided by the average section velocity (Vavg) for each cross section . An example of these plots is shown in Figure 3.2.

Test Methods and Analysis

Along with the water velocity methods previously mentioned, adult sea lamprey were received from traps nearby in the St. Mary's River. They were held in indoor tanks at the Sea Lamprey Control Centre for a minimum of 24 hours before tests. Lamprey sizes were dependant on the catch available from the control centre trapping program. The performance tests were carried out over eight weeks starting in late June, 1992. Normally 20 to 30 lamprey were moved into the introduction box at the downstream end of the flume for each test. Tests consisted of a period of observation of 1 to 2 hours, during which data were taken for sea lamprey attempting to swim upstream in the flume. Handling for the tests was minimized with lamprey being moved in a tub of water from the holding tank to the introduction box about 20 m away. The water temperature was the same in the holding tank, transfer tub, and introduction box, having originated from the St. Mary's River.

Figure 3.3 shows a sea lamprey swimming into the flume from the introduction reservoir box with discharge reduced for photographic purposes. Sea lamprey were observed when they attempted to swim the flume. Whenever possible, an attempt was made to observe ten or more lamprey per test. On days when the water was near 10°C and less, fewer lamprey attempted to swim the flume. In order to achieve testing of about 10 lamprey in those tests, sea lamprey were placed in the flume and chased upstream. Apart from the days when this method was applied, all other lamprey attempted to swim the flume of their own volition. Distance achieved for each swim attempt was measured to the nearest tenth of a metre from a scale along side of the flume. The duration of the swim attempts, i.e., the endurance time, was measured using a stopwatch. Lamprey were considered fatigued when they could no longer advance in the flume and started washing backwards in the current. The length of each lamprey was measured (to the nearest one half centimeter) after its swim attempt. Water temperatures were taken at the start with a 20 cm Canlab thermometer. Temperature was also taken at the end of each observation period as a check for temperature change. For each test, water levels were recorded from the staff gage located in the reservoir near the outflow weir.

Comparison of Velocity Methods

Results from the area - discharge velocity method and the current meter measurements were compared in order to verify accuracy. The average flume velocities of the current meter sections averaged 3.7% higher (0.9 - 5.7%) than the velocities indicated by the area - discharge method. The comparisons can be found in the rectangular boxes of Table C3. The difference may have been due to the extra bend needed to divert the pumped flow from the flume to the measuring box during the volumetric calibration. This bend could have caused a small velocity head loss in the delivery hose. Because of the location of the building and terrain, the hose bending was unavoidable.

An important element of any swim tests, whether in a flume, a flow tunnel, or any other apparati, is to know as well as possible what water velocities the test animals are swimming against. Sea lamprey throughout the tests swam fairly consistently in the central lower part of the water column. This area is outlined in the sections in Figure 3.2. An examination of the velocity distributions showed that the velocity most typical of the zone in which the lamprey swam was best represented by the 1.1 x V_{avg} iso-velocity line. Since the flume section remained constant, and the velocity distributions of V/V_{avg} in all sections measured were fairly similar, it was decided to use 1.1 x V_{avg} as the most representative velocity faced by lamprey in flume tests.

Summary of Test Results

A summary of the swim tests is shown in Table 3.1. This table lists the test dates, average water velocities, water temperatures, the number of sea lamprey attempting to swim the flume, water velocities at the 1.1 x V_{avg} iso-velocity line, median and maximum swim distances and endurance times achieved in the swim attempts, median swim velocities, and median lengths of the lampreys. Swim velocity (U) is calculated as the sum of water velocity (1.1 x V_{avg}) and the rate of travel against the water velocity. The rate of travel is the maximum distance attained divided by the time to swim that distance. Individual lamprey performance data can be found in Table C4 of Appendix C.

The summer was cooler than normal allowing for 7 tests at or near 10°C. No tests were done at temperatures greater than 16.8°C since that was the maximum temperature attained by the river water in 1992.

Swim Distance versus Water Velocity

The distances that sea lamprey could swim decreased with increasing water velocity. Figure 3.4 illustrates the distances which lamprey could attain in the flume tests. The data can be found in Tables 3.1 and B1 (the 1991 tests were included for comparison and to extend the velocity range covered). The effect of temperature on performance was also evident in the swim tests with sea lamprey. Greater distances were attained in the warmer water tests of 14.3 to 21°C than in the tests grouped around 10°C (9.5 to 10.5°C). This effect was prominent enough to merit pooling the data into the two temperature groups.

Significant relationships were found to exist between swim distance, D, in metres, and water velocity, V, in metres per second. For the tests in cooler water near 10°C (9.5 to 10.5°C), a regression was found to represent the relationship between median swim distance and water velocity. It is:

at 9.5 to 10.5°C, $D = 6.95\ V^{-3.31}$ $R^2 = .90$ 3.2

In the tests in warmer water (14.3 to 21°C), lamprey were able to attain greater swim distances. The regression found to represent the median swim distance - water velocity relationship in these tests is:

at 14.3 to 21°C, $D = 25.0\ V^{-3.21}$ $R^2 = .92$ 3.3

Equations 3.2 and 3.3 are shown plotted in the graph of Figure 3.4.

Figure 3.5 shows the maximum swim distances attained in the tests, D_{max} , versus water velocity. These also were pooled into the same two temperature groups as the median distances. Regressions found best representing maximum swim distances for the two temperature groups are:

for 9.5 to 10.5°C, $D_{max} = 11.46\ V^{-2.97}$ $R^2 = .92$ 3.4

at 14.3 to 21°C, $D_{max} = 35.7\ V^{-2.77}$ $R^2 = .92$ 3.5

Equations 3.4 and 3.5 are can be seen plotted in the graph of Figure 3.5.

Swimming Endurance

Swimming endurance data for the velocity barrier development tests is listed in Tables 3.1 and B1 and are plotted in the graph in Figure 3.6. In Figure 3.6, the swimming endurance of sea lamprey can be seen to decrease with increasing swim velocity. A regression equation representing the endurance of sea lamprey in the tests at 14.3 to 21°C was found to be:

$t = 172.1\ U^{-3.60}$ $R^2 = .94$ 3.6

Equation 3.6 could be used in a limited way for swimming speeds greater than 1.5 m/s at temperatures greater than 14° C.

Comparison with Work of Previous Researchers and Discussion

The results of the swim performance tests compare very well with data for sea lamprey from previous researchers. Figure 3.7 shows the sea lamprey endurance data from theswimming performance tests, i.e., all the data of Figure 3.6, plotted together with the results of previous researchers. The comparison is made on the basis of endurance versus swimming speed since these are the type of data that are common to all previous research.

From Figure 3.7, it can be observed that there is fairly close agreement in all of the swimming tests carried out with sea lamprey. A certain amount of variation is normally to be expected given the challenge of testing live animals from different sources with differences in size, temperature, test apparati, and methods. Tests at 9.5 to 10.5°C plot fairly closely to the 6°C and 10°C data of Bergstedt et al. (1981). Some improvement in endurance at speeds over 1.2 m/s can be seen confirming that the stamina tunnel of Bergstedt et al. was probably impeding performance. The tests at 14.3 to 21°C and Equation 3.6 which is derived from them fit very well with the higher speed tests of Hanson (1980). Lamprey appear to have attached before being fully fatigued in all of Hanson's tests except where lamprey were required to swim between 3.3 and 3.96 m/s. At those higher speeds, it appears that lamprey had to exert themselves to levels similar to those of the 1991 tests in which they could not attach to the substrate.

In comparing the test results to those of Beamish (1979), it can be seen that the 1991 and 1992 tests represent the burst swimming component of the classic plot of swimming energetic levels (see Figure 2.1), while Beamish's tests represent prolonged swimming. A schematic analysis of prolonged and burst swimming of sea lamprey from all swim performance tests can be seen in Figure 3.8.

A transition zone is also shown in Figure 3.8. This would represent the area in which sea lamprey are beginning to employ white muscle and anaerobic metabolism to a larger extent. In this transition zone, it also appears that sea lamprey diminish the amplitude of the body wave from the large amplitude basic anguilliform swimming, as seen in Figure 2.3, to a narrower amplitude "improved" mode. This was observed often during the tests. In the downstream reservoir boxes, lamprey would move about with characteristic wide amplitude anguilliform swimming. However,when swimming the more rapid water in the flume, the body wave amplitude was visibly diminished as can be seen in Figure 3.3. Because of the interesting nature of this phenomenon, measurements were made from several photographs. It was found that the body wave amplitudes were about 0.07 L at the head and 0.11 to 0.14 L at the tail. The effect of temperature on contraction time in white muscle appears to be important in enabling effective burst swimming. The improved endurance for burst swimming, which is seen clearly in the data for tests above 14°C and in equation 3.6, confirm this drag-reducing body wave adjustment. Similar improvements in swimming body wavelength and stride length have been proposed to explain how some adult marine fish attain speeds well above 10 L/s (Wardle and Videler, 1980).

The individual test data for 1992 and 1991 (found in Appendix B and C) were analyzed together with the data from Beamish (1974,1993) for the purpose of formulating comprehensive equations for endurance of sea lamprey in prolonged and burst swimming. The data of Hanson (1980) and Bergstedt et al. (1981) were not included in the endurance regressions developed because lamprey could either attach, or were impeded from burst swimming due to the tunnel apparatus. The data of Beamish, which are for mean endurance for groups of 10 or more, were given a weight of ten. Endurance time was regressed against swimming speed and body length for the two temperature groups. Significant relationships were found to exist.

The first equation, found to represent swimming endurance at or near 10°C (±0.5°C) is,

$$t = 293.51\ U^{-3.077}\ L^{2.602} \qquad R^2 = .96 \qquad 3.7$$

where t represents endurance time in seconds, and L is body length. This equation could be used for endurance at swimming speeds between 0.3 and 2.3 m/s. From observations over two summers of testing, very few lamprey will swim faster than 2.3 m/s at 10°. The equation found to represent sea lamprey swimming endurance for temperatures above 14°C is:

$$t = 630.95\ U^{-2.822}\ L^{2.701} \qquad R^2 = .95 \qquad 3.8$$

Equations 3.7 and 3.8 are plotted in Figure 3.9 for sea lamprey 40 and 50 cm in length. It is interesting to note that endurance in these equations varies with swimming speed to the powers of -2.82 and - 3.08. The propulsive power required by swimming fish to overcome drag increases in proportion to swimming speed to the power of 2.8 (Webb, 1975) or 3 (Blake, 1983). With all other factors being the same, an endurance curve for fish should tend to follow the inverse of the demand for power. That is, endurance should tend to vary with speed to the inverse power of 2.8 or 3 ($U^{-2.8}$ to U^{-3}). This appears to be the case resulting from this analysis of sea lamprey swimming.

Table 3.1 Summary of 1992 sea lamprey swim performance tests at the St. Mary's River.

Test Date	Average Water Velocity (Vavg) *m/s*	Swim Zone Velocity *m/s*	Water Temp. *°C*	Number of Lamprey Observed	Distance Swam (median) *m*	Distance Swam (max) *m*	Endurance Time (median) *s*	Swim Velocity (median) *m/s*	Lamprey Length (median) *m*
Jun. 19	0.66	0.73	9.5	13	13.9	23.6	16.0	1.33	0.51
Jun. 19	1.15	1.27	9.3	10	2.65	5.2	5.5	1.69	0.52
Jun. 23	0.93	1.02	9.5	12	7.0	10.1	15.5	1.45	0.51
Jun. 24	0.97	1.07	10.0	11	6.2	11.2	12.0	1.58	0.52
Jun. 26	1.45	1.59	10.0	8	2.05	3.0	6.5	1.86	0.51
Jul. 7	0.99	1.09	9.0	12	7.95	13.5	12.0	1.62	0.50
Jul. 10	0.66	0.73	10.3	12	26.65	30	44.6	1.24	0.50
Jul. 23,24	1.04	1.14	14.3	20	17.8	25.7	44.0	1.55	0.50
Jul. 31	1.22	1.34	15.5	10	11	13.8	20.6	1.82	0.52
Aug. 4	1.22	1.34	15.8	18	9.2	20.9	22.9	1.73	0.49
Aug. 7,10	1.22	1.34	16.8	20	10.15	15.3	16.4	1.96	0.51
Aug. 13,14	1.35	1.49	16.0	13	5.35	10.1	11.9	1.92	0.48

Figure 3.1 The 30 m swim test flume with sea lamprey in downstream reservoir.

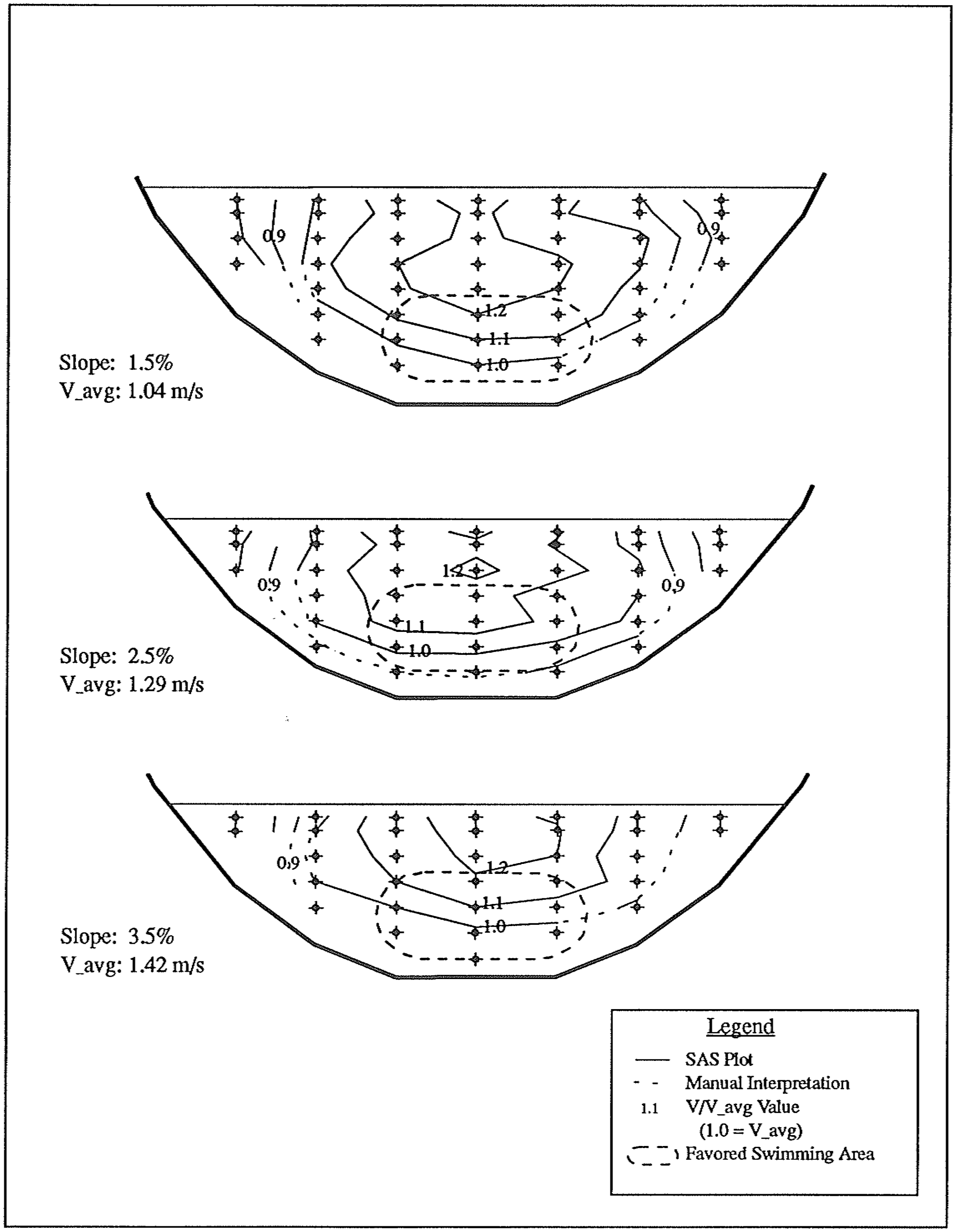

Figure 3.2 Example of plots of V / V_avg for test flume.

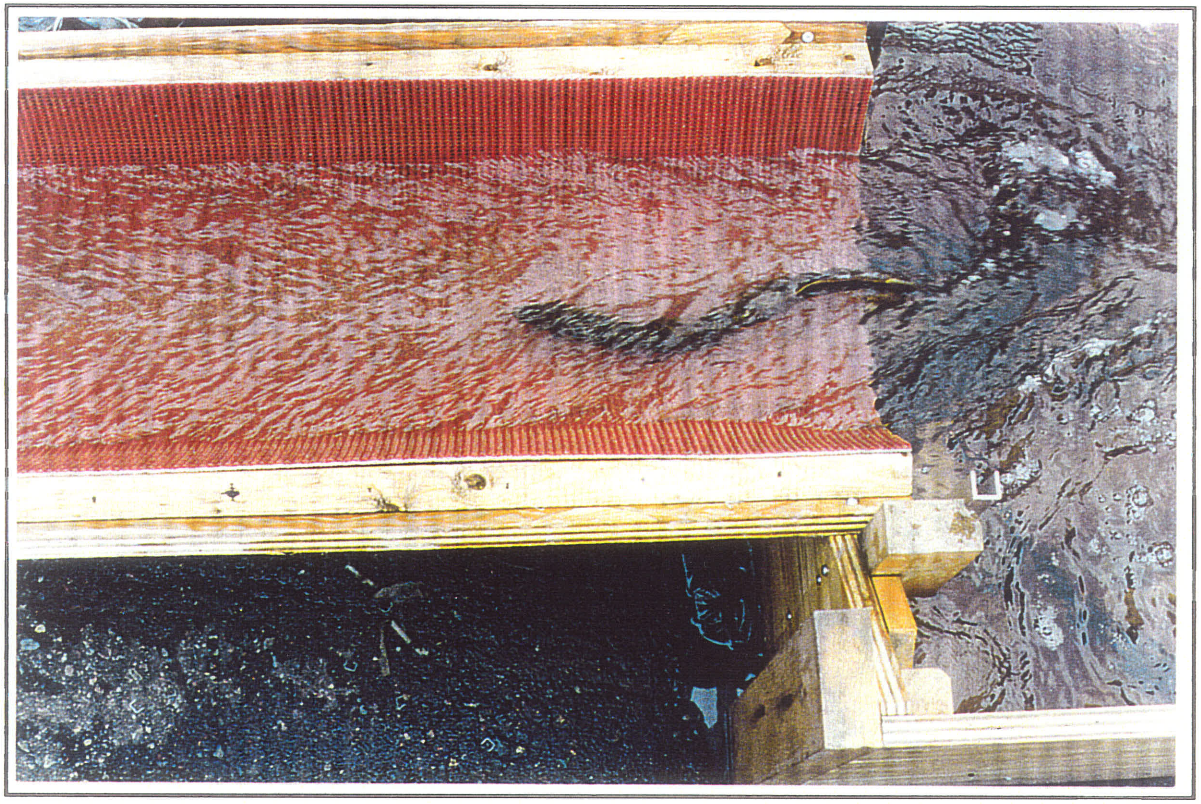

Figure 3.3 A sea lamprey swimming into the velocity flume. (Flow was reduced for photographic purposes.)

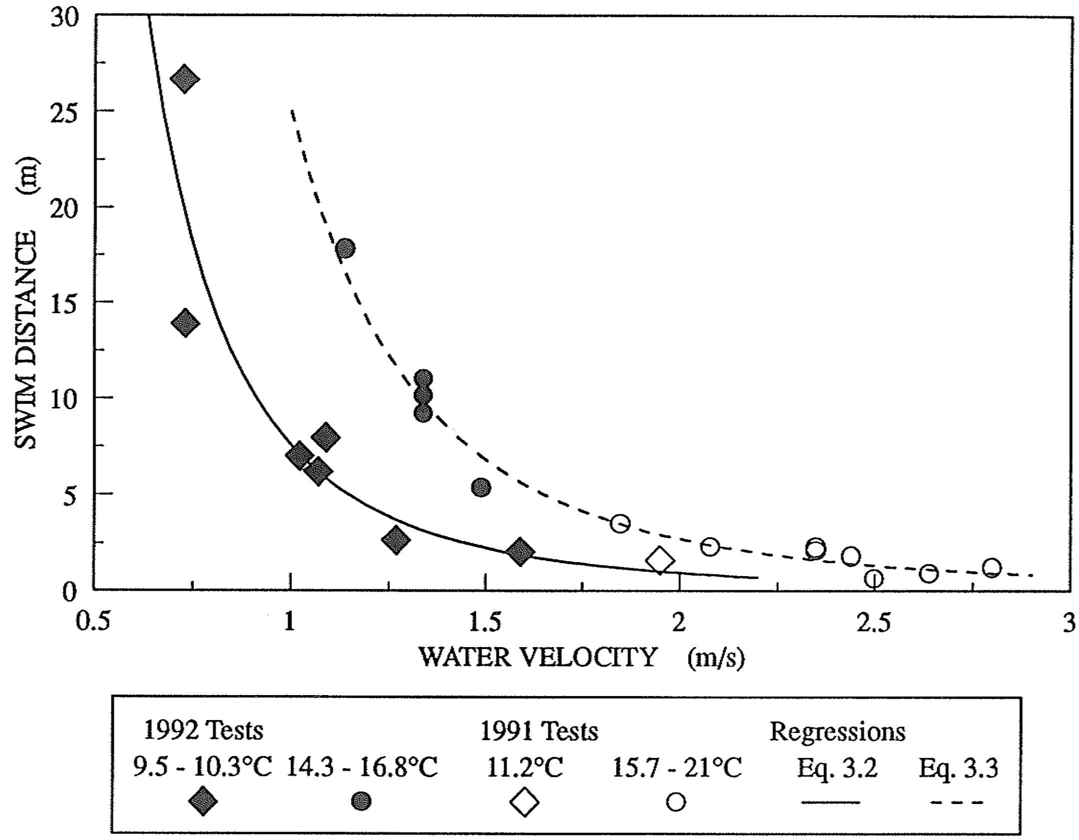

Figure 3.4 Median swimming distances achieved by sea lampreys in the swim tests.

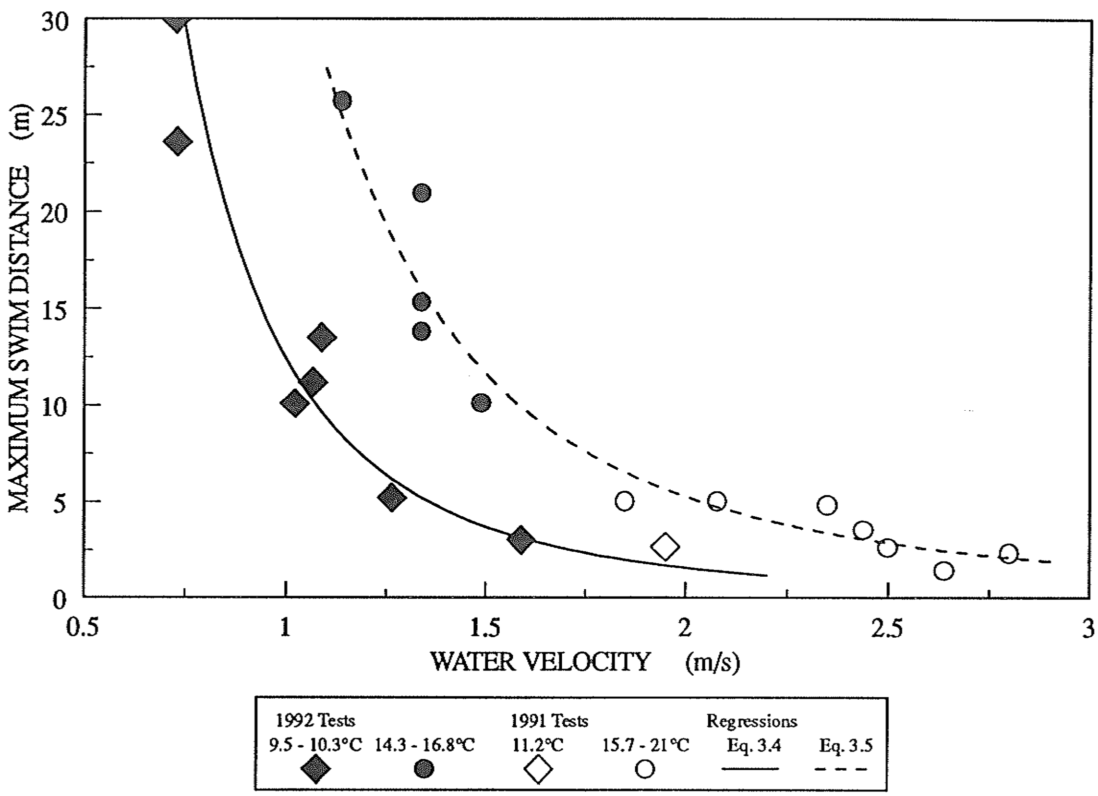

Figure 3.5 Maximum swimming distances achieved by sea lampreys in the swim tests.

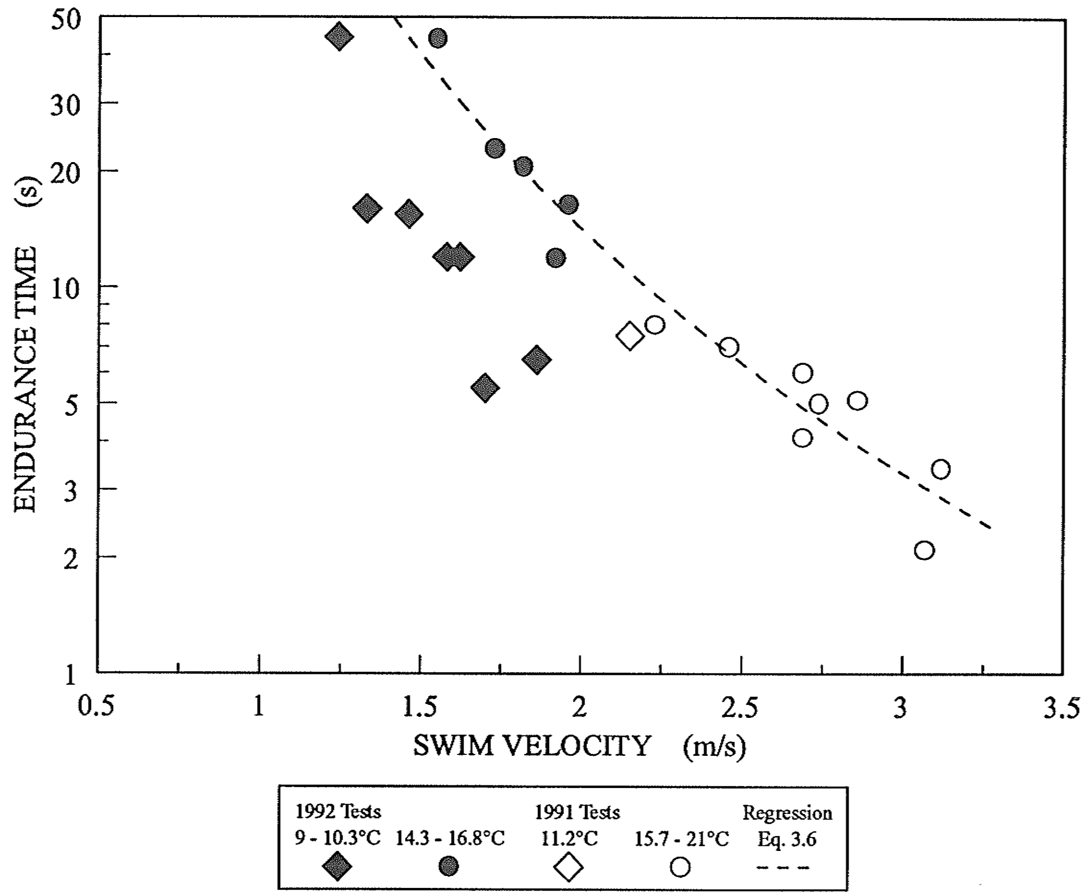

Figure 3.6 Endurance of sea lampreys versus swimming speed in the swim tests..

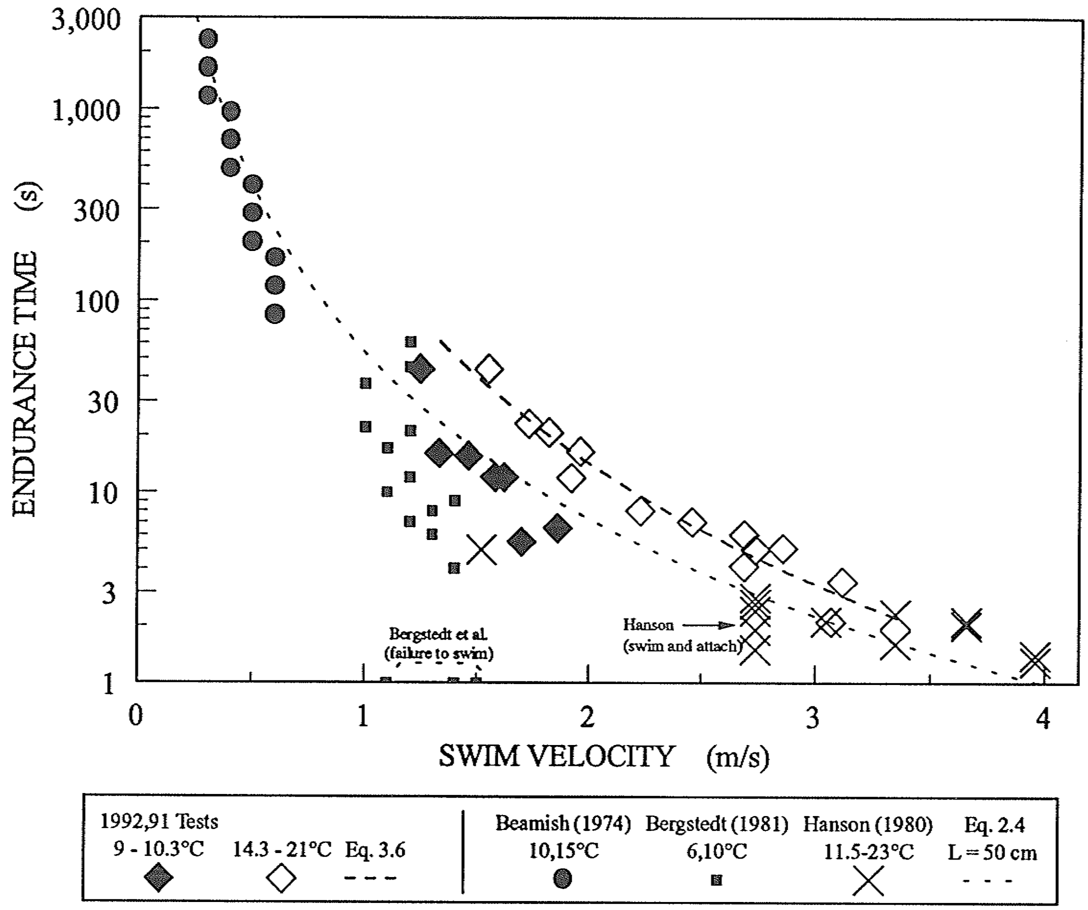

Figure 3.7 Comparison of endurance data found for sea lamprey with data from previous sources.

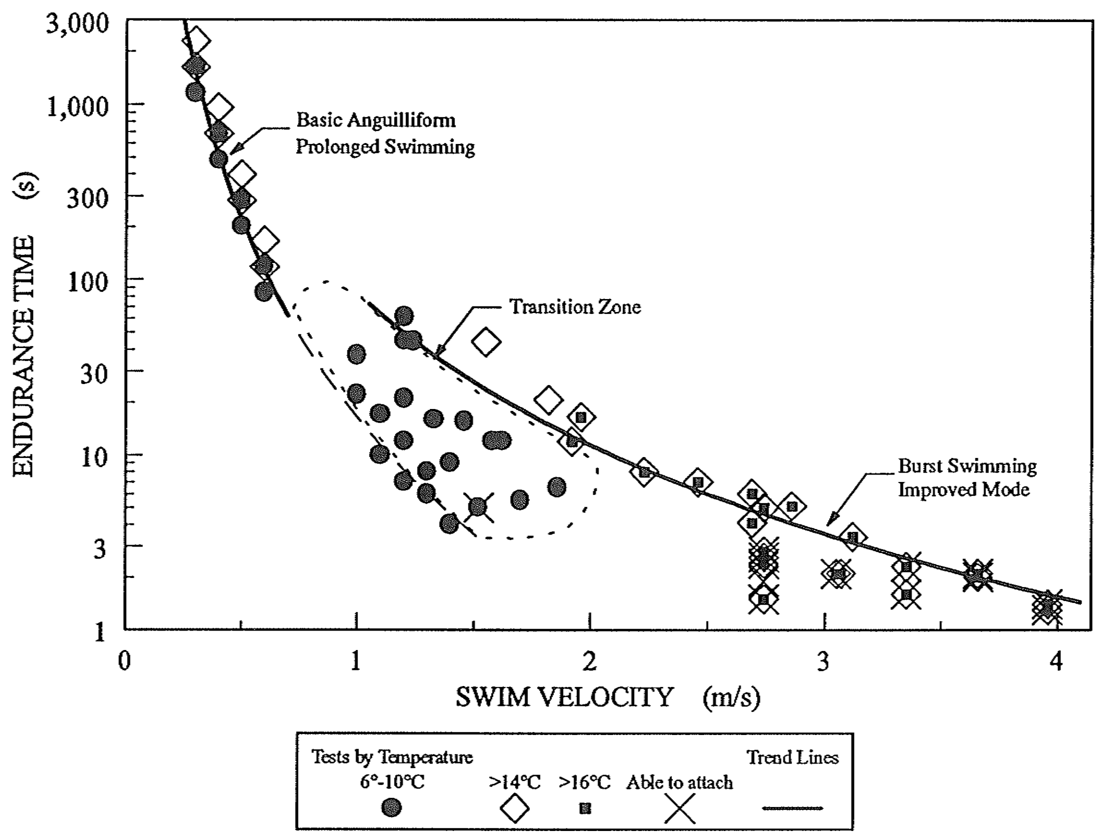

Figure 3.8 Schematic analysis of sea lamprey swimming endurance.

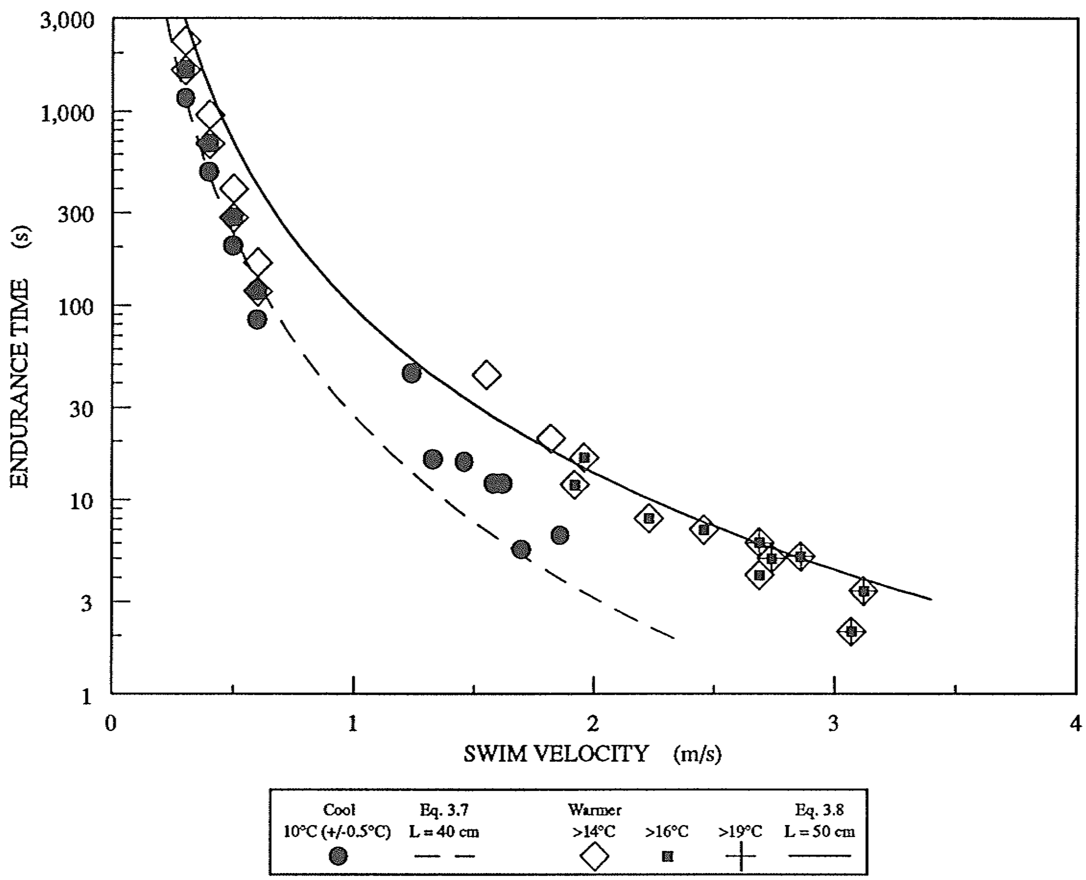

Figure 3.9 Plot of equations relating endurance, swim speed, and length of sea lampreys.

CHAPTER 4

HYDRAULIC MODELLING WORK

Introduction

A conceptual design for a first velocity barrier was developed. Hydraulic modelling of the principle sections of the design was carried out at the University of Manitoba Civil Engineering Department Hydraulics Laboratory. The purpose of the modelling work was principally to test and improve a basic design that was considered for the velocity barrier. This design consists of a single slope velocity chute with a trapezoidal cross-section along with an overflow crest adjacent to the velocity chute for the passage of higher discharges and flood flows. Hydraulic modelling of the basic design was performed to estimate: the discharge coefficient for the proposed chute design; the discharge coefficient for the proposed weir crest; and water surface and velocity profiles along the velocity chute.

Conceptual Design Considerations

The choice of a combination of length and target velocities for the velocity chute conceptual design is the result of a feedback loop between the velocity ranges appropriate to the stream fish species and the length of chute feasible according to budget and site constraints. Calculations from Equation 3.5 indicate that at a water velocity of 1.2 m/s, sea lamprey can swim a maximum distance of 21.5 m, and at 2.4 m/s, their maximum swim distance diminishes to 3.2 m. A length safety factor should also be added to the chute design to cover for the possibility of sea lamprey swimming near the bottom (Equation 2.1) and for uncertainty about migratory discharge ranges. The safety factor amount, however, needs to be evaluated along with the requirements for passage of other fish species.

For the first conceptual design, velocities in the higher end of this range and supercritical flow were chosen after a preliminary investigation of the probable candidate site size and construction budget. Velocity barriers could be designed to function at supercritical or subcritical flows. One advantage of supercritical flow is a decreased sensitivity to changes in downstream water levels. A barrier functioning at supercritical flows would normally be shorter in length with higher velocities. It would require slightly more head because of higher slope and Carnot losses (Booy, 1992) at the downstream end. At sites constrained to use a minimal head, a barrier functioning at subcritical flows would be worth investigating. Incorporating smooth upstream and downstream transitions of the floor and walls of a subcritical regime velocity barrier would greatly reduce hydraulic head loss at both ends. Downstream transition walls at a recommended 1:10 widening rate to eliminate flow separation (Booy, 1992) would add lengths of 20 m, or more, to the barrier length, even on small streams. The transitions, therefore, would constitute an important part of both length and cost of a barrier.

More complex velocity chute section designs, such as those illustrated in Figure 4.1, could also be used. However, considering the uncertainty about the behaviour of sea lamprey when faced with a choice of various flow patterns and velocities, complexity should be avoided. The flat bottom trapezoidal cross-section chosen for the first velocity chute design should provide a uniform velocity pattern and depth across the section. The sloping segments between the floor and sidewalls are included to reduce the lower velocity areas that would have occurred in right angle corners. The design includes a rounded section below the upstream entrance sill and on the upstream ends of the chute sidewalls (piers) to help ensure effective flow coefficients.

For the overflow crest section, a gentle (1:5) adverse slope with a rounded upstream edge was chosen. This design should have a fairly efficient crest discharge coefficient and help minimize upstream water level changes. A small overhanging "lip" at the downstream end of the overflow crest is included for increased protection against sea lamprey passage. The overhanging "lip" is a standard feature in lamprey barrier design. It helps prevent sea lamprey from attaching above the downstream water level and moving over the crest.

Choice of Model Type and Scale

A scale of 1:5 was used to model the two principal sections of the conceptual barrier design described above. This scale permitted testing a 40 cm long (cross-flow direction) section of the chute along with a 40 cm long section of overflow crest in the available 90 cm wide hydraulic flume. The sections represented 2 m sections of each in prototype scale. In order to photograph flow profiles through the plexiglass windows in the side of the hydraulic flume, a model velocity chute length of 83 cm, representing 4.15 m in prototype, was used. A drawing of the model showing dimensions can be seen in Figure 4.2.

A Froude model was chosen since flow in the prototype will be dominated by the forces of gravity and inertia (Booy, 1992). Froudian scale relationships for length (L), velocity (V), discharge (Q), and equivalent sand roughness (k_s) for the model scale of 1:5 are:

L: 5^1

Q: $5^{5/2}$

V: $5^{1/2}$

k_s: 5^1

The model was built of pine and plywood in a modular manner so that the piers at the outside ends of the velocity chute and crest could be removed. This permitted photos and helped to determine the effect of the piers. Figure 4.3 shows the model in place in the flume with one pier removed. Figure 4.4 shows a profile of flow through the model velocity chute as seen through the flume side window. Multiple calibrations were conducted with the end piers removed and then in place to give an indication of the sensitivity of flow over the model to the pier shapes. The centre pier remained fixed.

Although it is challenging to scale surface roughness, an attempt was made to reproduce the roughness in the velocity chute by using a uniform fine sand of about 0.7 to 1 mm diameter in the final sealing coat. The anti-lamprey-attachment surface most likely to be used in the prototype has a projected Manning roughness of approximately 0.017. This translates to an equivalent sand roughness of 4 mm. This is approximately equivalent to the sand size in 1:5 scale.

Discharge ranges typical of the lamprey spawning run in a stream like the McIntyre River were used for the prototype discharge range. In this barrier candidate stream, the lamprey run normally occurs at discharges of 0.77 to 3.0 m^3/s. For the range of discharges and hydraulic radii to be used in the tests, Reynolds numbers were calculated for the model chute to be 4×10^4 to 7×10^4. This corresponds to Chezy C values of 30.8 to 32.2. Since the flow was found to be hydraulically rough throughout, there was no danger of Reynolds number distortion in the modelling.

Eliminating Chute Entrance Shock Wave

In preliminary trials with the model, a shock wave of up to several cm in height, corresponding to approximately 0.1 m in prototype, occurred in the chute running diagonally across the surface from the upstream pier ends. This was caused by the transition of flow from subcritical to supercritical as it came around both the pier and the rounded end of the triangular corner segments simultaneously. The pier was then extended in the upstream direction by 14 cm. As a result, the wave was reduced to being barely visible. This extended pier version was used in the model tests.

Model Stage-Discharge Relationships

Stage-discharge calibrations were performed with the chute and the weir crest individually using a volumetric timing apparatus and repetitive measurements over the discharge range. An electronic point gage installed 5 m upstream of the model indicated the upstream water level. For each discharge, the upstream water level was measured in relation to the weir crest elevation and the associated flow was timed as it filled two alternate large measured concrete bins called the north and south gages. The volume filled divided by the fill time yielded the discharge. Generally four repetitions were conducted and averaged per discharge. The resultant data can be found in Tables D1 and D2 of Appendix D.

Table D1 shows the levels of the upstream point gages associated with their respective average discharges in the two columns on the right side. Each discharge is the average of 6 or 8 timed flows into the north and south gages. The elapsed times and individual flows are listed in columns two to six, with the first column being the number of the run. The volumetric calibrations were conducted for the different components of the model; 1) the chute alone with an extended centre pier, 2) the weir crest alone, 3) the overflow crest and chute with one chute sidewall (pier) removed, 4) the same as 3), but with a shallower ramped sand and stone approach upstream, 5) the chute and weir with extended centre pier, 6) the chute with both side piers, and 7) the same condition as 6) with flow over the weir crest.

From the flow depth and cross-section area at the point gage, the upstream velocity head was calculated. Velocity head was added to the depth above the crest to get values for H for the weir discharge relationship

$$Q = k\,L\,H^{3/2} \qquad 4.1$$

Table D2 shows the weir coefficients k calculated using Equation 4.1 with the data of Table D1 for the key component tests which are the weir crest alone (2), the chute alone with the extended centre pier (1), and the chute with both side piers (6). The value of the constant k was calculated for each discharge using the width L and the values of H. Since k varies principally with H, the values of k were regressed against respective H values for both the chute and the overflow crest. Simple linear equations were found to fit the data. For the chute, the equation relating k to H was found to be:

$$k = 0.641*H + 1.571 \qquad R^2 = .88 \qquad 4.2$$

For the overflow weir, the equation relating k to H was found to be:

$$k = 2.35*H + 1.737 \qquad R^2 = .97 \qquad 4.3$$

Plots of the k and H values and Equations 4.2 and 4.3 can be seen in Figure 4.5. Figure 4.6 shows plots of the stage-discharge relationships in the weir formula format $k\,L\,H^{3/2}$ using k values from Equations 4.2 and 4.3 for the chute and overflow crest. The actual test data are also plotted in the figure as a visual check on the goodness of fit of the equations.

Section Stage-Discharge Coefficients

In preparing the preliminary weir plan, it was projected that discharge coefficients would fall between the values of 1.705 and 2.18 which are the general values for broad-crested and standard ogee crested weirs (Rouse, 1946).

For this model, it was found that the coefficients for the chute varied from about 1.6 to 1.68 (depending on depth). The maximum value attainable with a well-rounded entrance could be 1.705. The shape and size of the corner triangular elements probably account for much of the coefficient decrease. If they were any larger, calculations would be required for the individual segments of the velocity chute section. For the model overflow crest, the values for k ranged from 1.81 to 1.97.

Robustness and Applicability of Model Data

To verify the robustness of the model data in relation to minor design changes, calibration combinations were carried out with several different configurations:

1) removing a side pier in the velocity chute;

2) adding a sand and stone bottom ramping up to the chute and crest entrances; and

3) adding and removing a centre pier upstream extension.

The results of the calibrations for these different configurations can be found in Figure 4.7. The stage-discharge relationship for the sections was found to be quite robust with the coefficient depending to the greatest extent on the upstream water depth and the structural roughness for flow at the upstream face of the weir entrance.

Since changes in the coefficient for all of the calibration combinations were less than +/- 5%, the coefficient formulae from the regressions in Equations 4.2 and 4.3 would be fairly reliable for prototype use. For prototype designs with different crest lengths, effective weir length (L_{eff}) adjustments for pier or abutment roughness should only be required if the upstream pier and abutment ends are not streamlined.

Chute Surface Profiles

Water surface profiles were measured in the model at three different discharges; 0.0136, 0.0255, and 0.0487 m^3/s. These discharges, called Q_1, Q_2 and Q_3 respectively, correspond to prototype flows of 0.76, 1.43, and 2.72 m^3/s (Q_{1_p}, Q_{2_p} and Q_{3_p}). These prototype flows are similar to flows that would be encountered in the McIntyre River which is a candidate stream for the first velocity barrier.

The downstream water level in the flume for each flow was arranged, using a downstream gate, to be somewhat similar to estimated levels in the prototype stream. The downstream levels were not precise since a downstream stage-discharge relationship for this stream was not available. The flow surface elevation profiles for the model can be seen in Figure 4.8 and their prototype translation can be seen in Figure 4.9.

Supercritical flows occur for the three discharges with Froude numbers at the midpoint of the chute of 1.21, 1.23, and 1.14 for low, mean, and high flows respectively. The Froude numbers would be the same in both model and prototype.

The surface profiles indicate that gradually varied flow occurs in the upstream portion of the chute. As the water flows along the chute, depth continues to diminish at an increasingly slower rate. The surface thus follows an S2 curve as the flow approaches normal depth. Flow is also non-uniform in the downstream portion when the downstream water level is both lower and higher than the water level coming out of the chute as seen in the Figure 4.8 and 4.9 profiles. An hydraulic jump occurs at the downstream end of the chute for the three flows tested.

Regarding Use of the Chezy or Manning's Equations

The presence of non-uniform flow means that one should be cautious in the use of equations such as those of Chezy or Manning. It may, however, be a fair assumption that the flow has reached and holds normal depth for a certain distance near the midpoint of the chute. This normal depth distance is longer as discharge decreases. In the parts of the chute where the depth varies minimally, the Chezy or Manning Equations could prove useful. In using Manning's equation where there are significant changes in hydraulic radius R_h, such as model - prototype differences, it is recommended that the roughness n, which varies with $R_h^{1/6}$, be converted by use of equivalent sand roughness k_s (Booy, 1992). The n value for the model velocity chute segments where flow was of nearly uniform depth was found to be 0.0195. This is the average of values of 0.020, 0.0184, 0.020 calculated for Q_1, Q_2 and Q_3 respectively. Roughness factor adjustments can be made to portray average velocity profiles in prototype scale according to:

$$Vp = (n_{model}/n_{barrier}) * V_m * 5^{1/2} \qquad 4.4$$

Usefulness of the Model

The hydraulic modelling work based on the conceptual design was found to be quite worthwhile. It contributed:

useful discharge coefficients for the chute and overflow crest;

an description of the coefficient robustness under small design changes;

a design improvement for the flume side piers to avoid a surface shock wave; and

a portrayal of the depth and velocity changes in the surface profile curves at the upstream and downstream ends of the chute.

Hydraulic modelling increased understanding of, and gave a fair representation of, what the hydraulic performance of the conceptual design would be in prototype scale. A projection of velocities for a 1:5 prototype of the model can be seen in Figure 4.9. From this graph, it can be seen that there will be an important variation of velocity with discharge in the prototype chute. Because of this variation, a good knowledge of the discharge ranges characteristic of the candidate stream's migratory runs will be required. The velocity sensitivity to discharge may possibly be buffered in prototype by a judicious choice of chute elevation in relation to tailwater elevation variations. Final design work can consider variations in the velocity chute slope, roughness, and length for optimum performance. In designing a longer chute, the velocities of the central uniform flow region would be characteristic in the extended middle portion of the velocity chute.

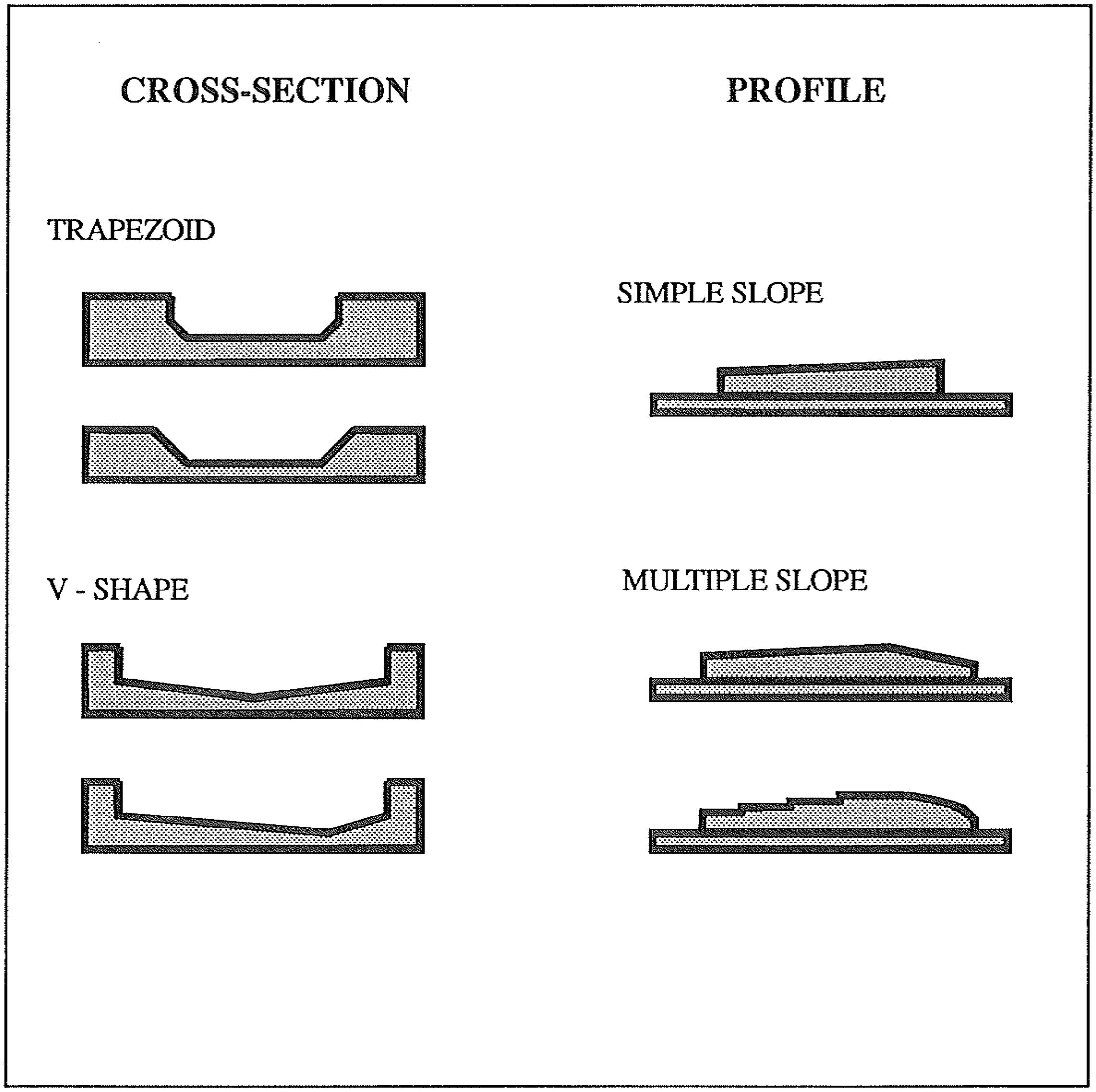

Figure 4.1 Several basic sections that could be used in a velocity barrier design.

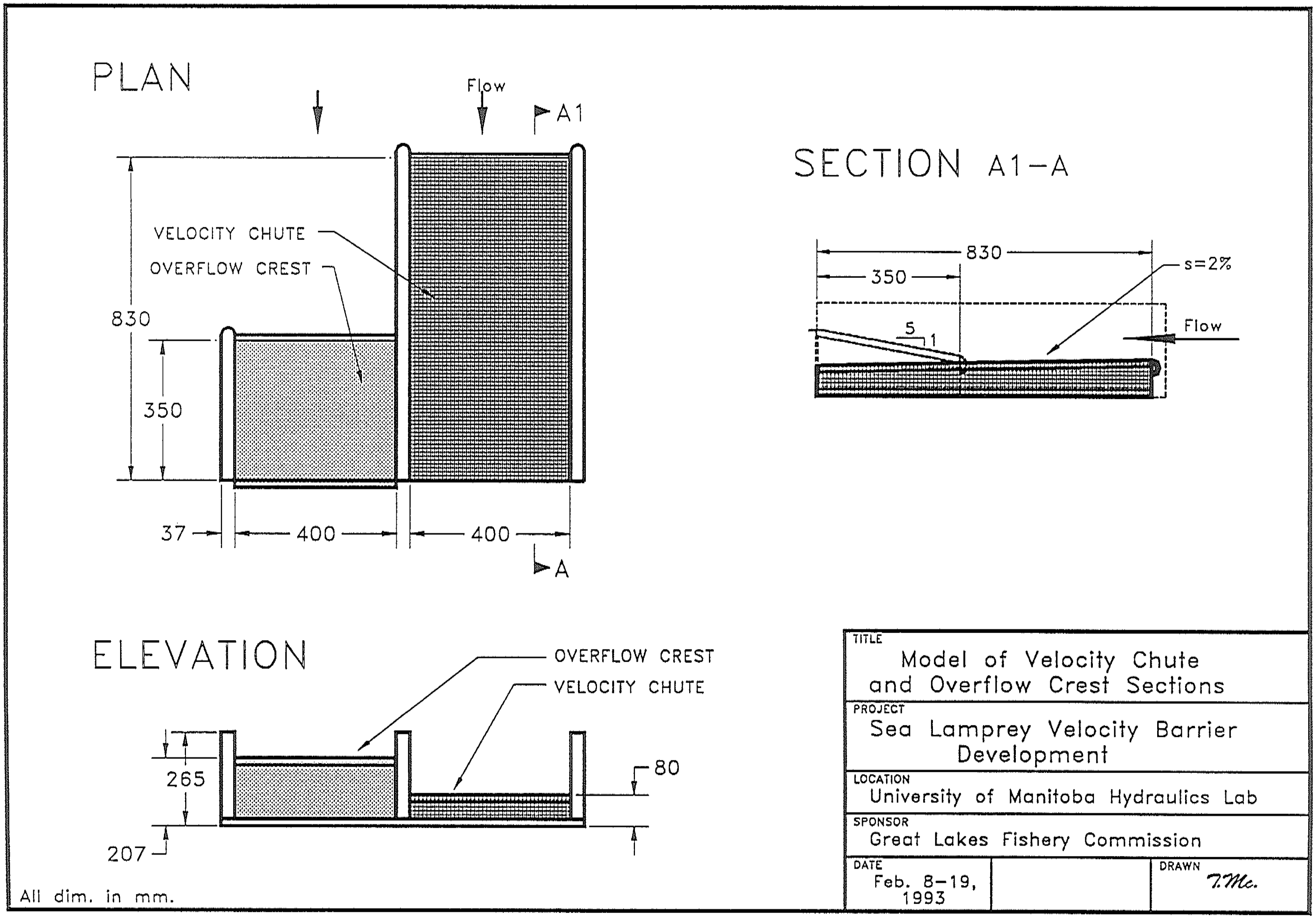

Figure 4.2 Plan and dimensions of the hydraulic model.

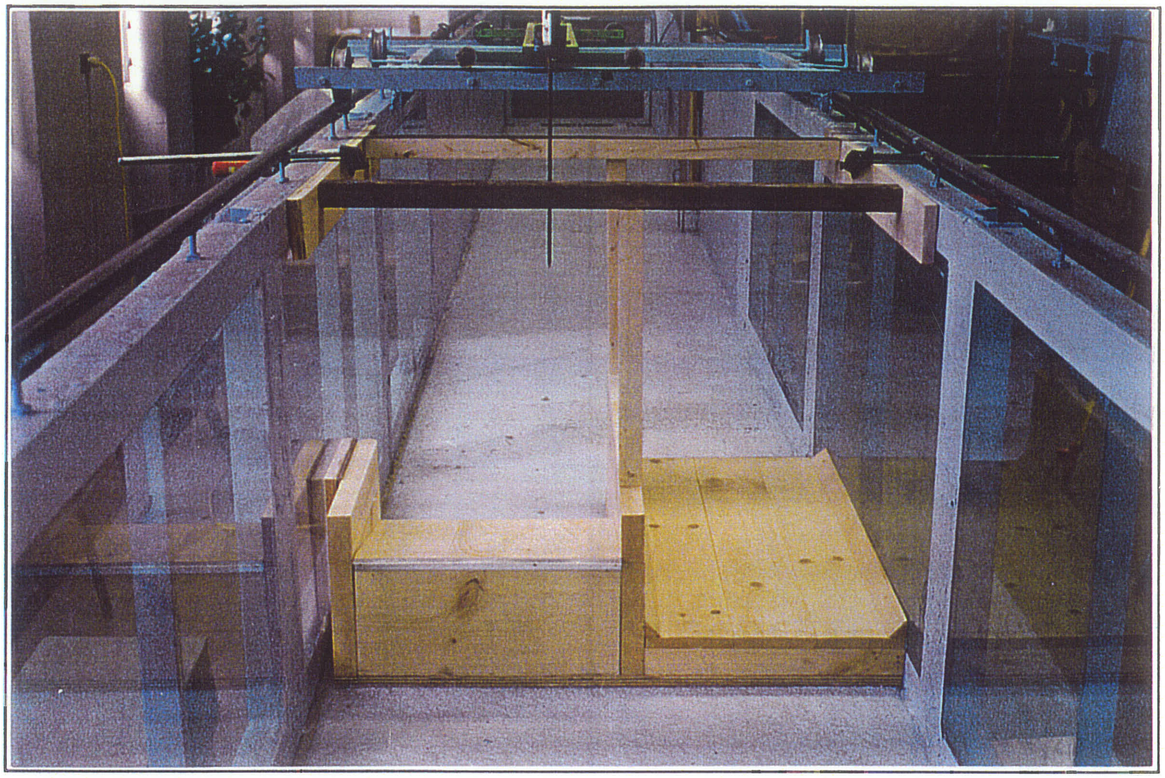

Figure 4.3 A view of the model in the hydraulic flume at the University of Manitoba.

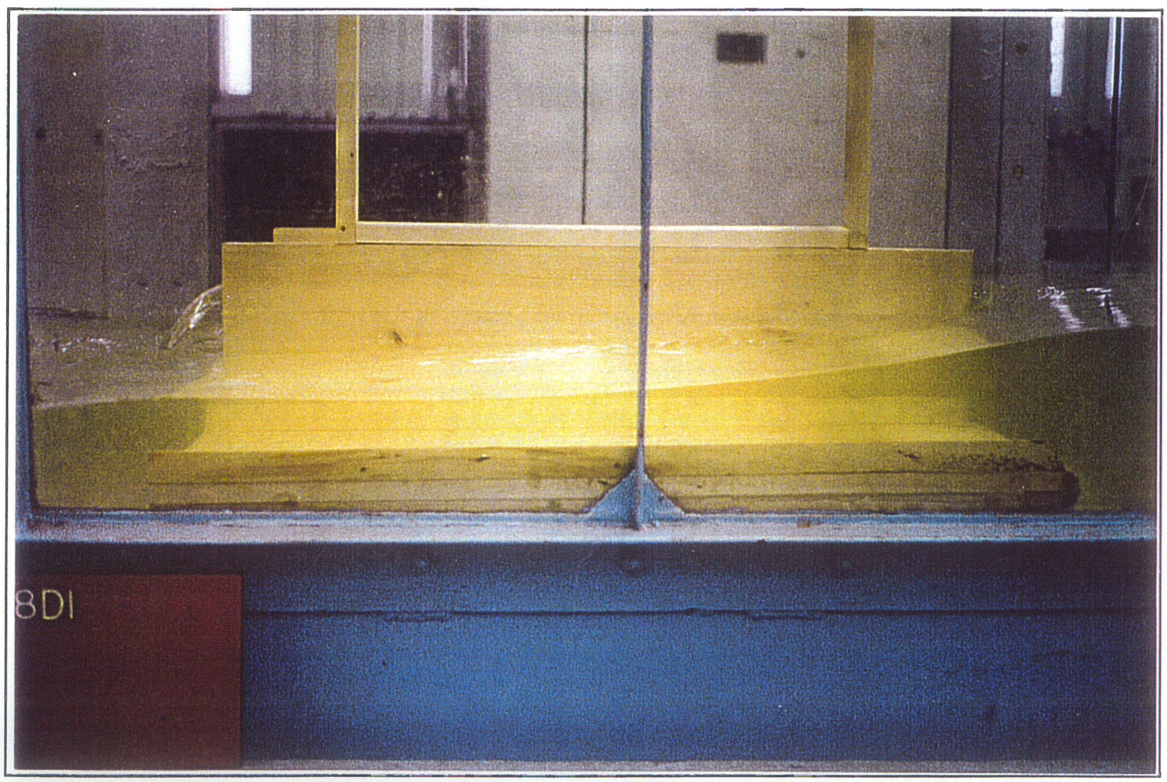

Figure 4.4 Profile of flow over the velocity chute.

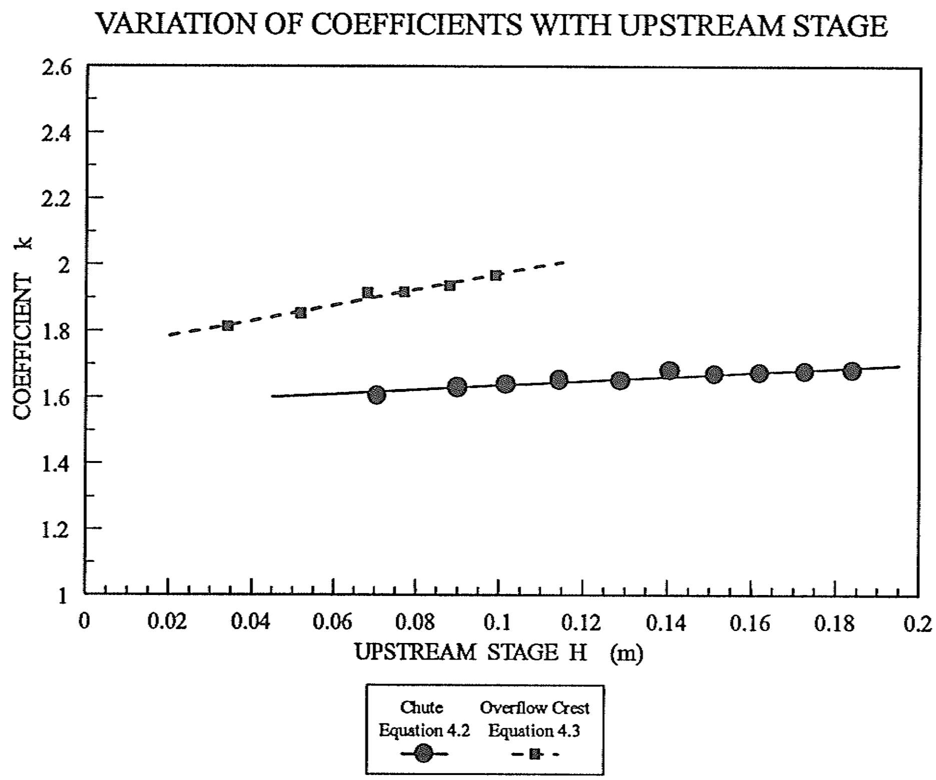

Figure 4.5 Relationship of the discharge coefficients (k) for the model velocity chute and crest sections to the upstream stage (H).

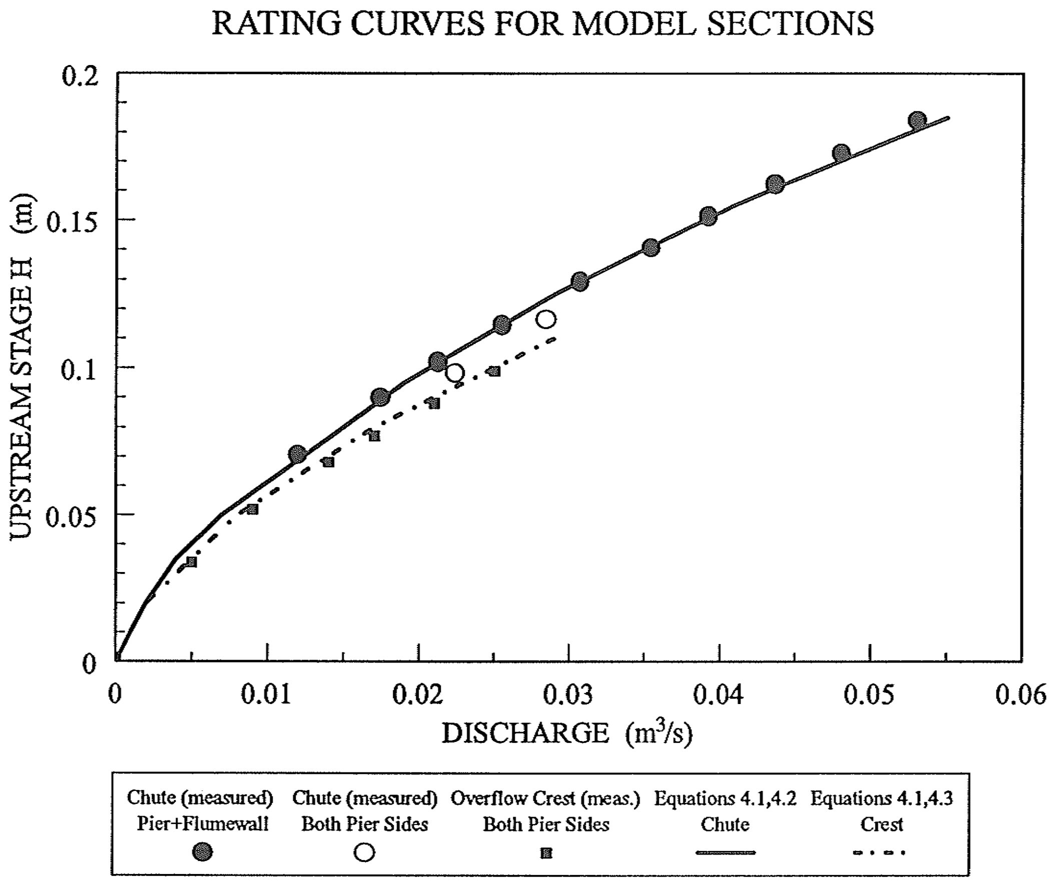

Figure 4.6 Graph of model stage-discharge calibrations. Curves from Equation 4.1 for the chute and crest using H-dependant constants from Equations 4.2 and 4.3 are plotted along with the measured data points.

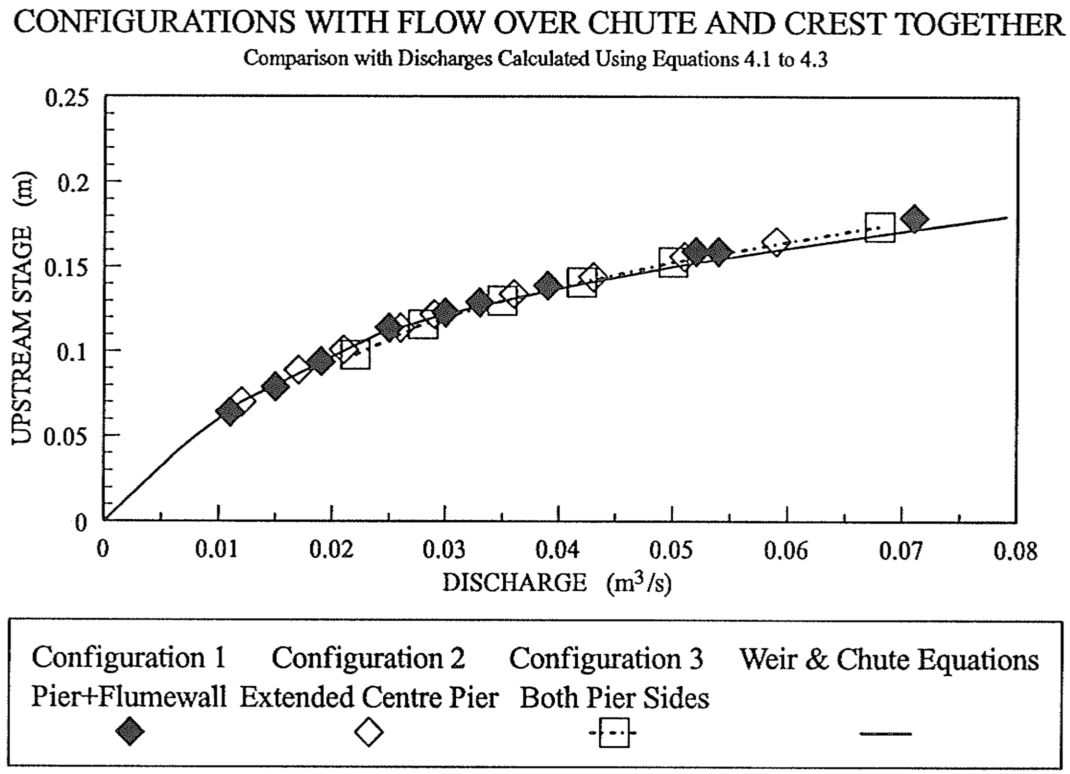

Figure 4.7 Robustness of equations for several different model configurations. Stage-discharge calculations from Equations 4.1 to 4.3 are compared to measurements for several different configurations of flow over the chute and crest together.

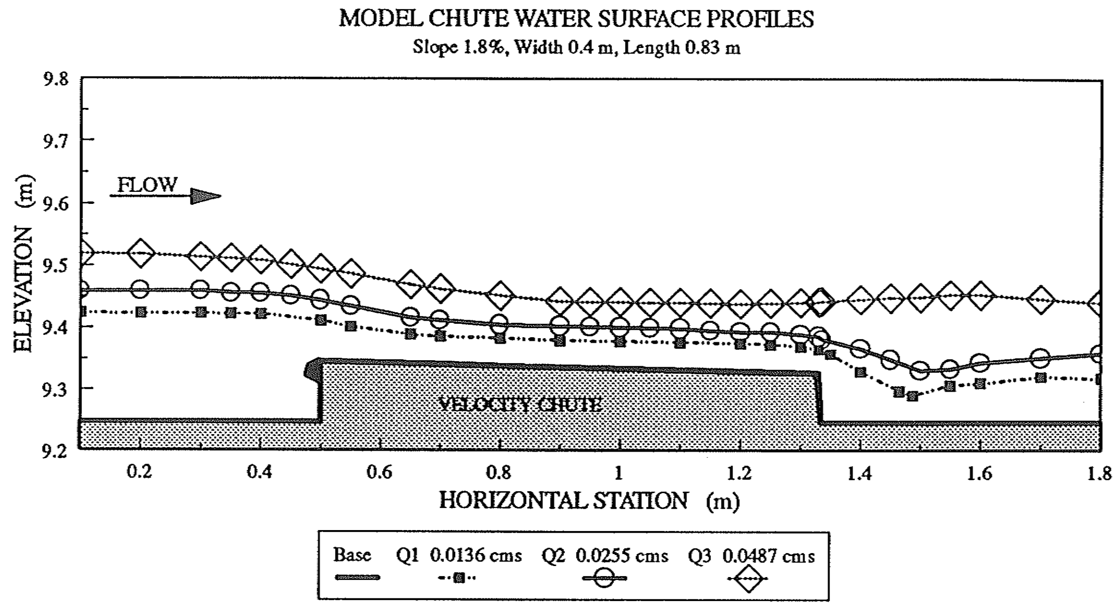

Figure 4.8 Water surface profiles for the model velocity chute.

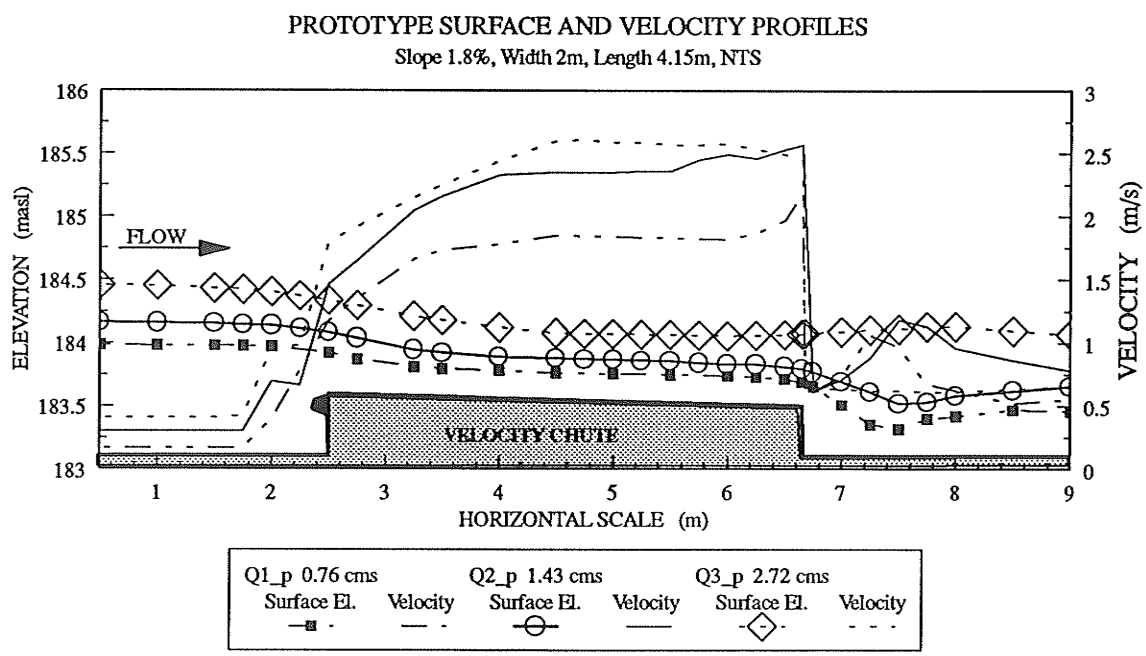

Figure 4.9 Translation to prototype scale of water surface profiles and velocities.

CHAPTER 5

AN EXPERIMENTAL INSTREAM VELOCITY BARRIER

Introduction

A decision was made to design and build a velocity barrier of an experimental nature on a stream in which the continued performance of the structure for fish passage and sea lamprey blocking could easily be evaluated. The experimental barrier itself is to be an instrument to be used to further explore the swimming ability of adult non-jumping migratory fish at sprint velocities. The design for the experimental velocity barrier should therefore present a swimming challenge that narrowly exceeds the ability of sea lamprey so that fish that are only slightly better swimmers may pass. Although barrier design methods are not the intended thrust of this thesis, several important design considerations are necessarily mentioned in this chapter.

Choice of a Candidate River and Site

The McIntyre River, which drains into Lake Superior at Thunder Bay, Ontario, was chosen as the candidate river for the experimental velocity barrier. This lamprey producing stream has a history of lampricide treatments dating back to 1960. The principal spring and fall migratory fish species in the McIntyre River are rainbow trout and common white suckers, sea lamprey, chinook and coho salmon, and longnose suckers. White suckers and rainbow trout are the largest of the migratory runs.

A site for installation was chosen at the furthest downstream riffle area on the river. Stream reaches downstream of the site are effected by seiche and annual fluctuations in Lake Superior. The location of the site can be seen in Figure 5.1. The site is less than 10 m downstream of a major bridge. It was chosen, however, since the next location upstream would have been above the spawning substrate and would also impact the water levels along a number of private residences. The selected site also has a 0.3 to 0.4 m drop over a 15 m horizontal distance. A barrier could use this head and have minimal impact on water levels further upstream. Given success at stopping sea lamprey, the site is favorably located for achieving elimination of future lampricide treatments.

The McIntyre River Velocity Barrier

Description

The experimental velocity barrier was built on the McIntyre River at Thunder Bay, Ontario in the summer of 1993. A photograph of the barrier and site can be seen in Figure 5.2. The velocity chute is 8.5 m long and 2.44 m wide and has a 2% slope. An overflow crest 7 m in length was constructed on one side of the chute. A sea lamprey trap with flow-through attractant water was built into the east bank side of the structure. The structure was built of tightly fit pressure treated timber cribs and framework anchored to a 2.44 m deep steel sheet piling wall that crosses the stream bottom from bank to bank. The velocity chute is stabilized by rock-filled gabions attached under its floor, and is bolted to two 3.7 m long "H" piles at either side of the upstream end. A 0.23 m diameter round pile was placed 2 m upstream of the upstream end of the chute to stop larger trees or logs carried occasionally by high flows. Upstream and downstream banks on both sides were stabilized with rip-rap and geotextile. The construction cost of the barrier was $66,176. This amount is similar to the cost of a low-head lamprey barrier dam on a stream of the same discharge in Ontario ($68,000 in 1993 Canadian dollars) found from a regression of existing barrier costs (Koon and McAuley, 1994).

To prevent sea lamprey from attaching, the bottom and side surfaces of the velocity chute are lined with a commercially produced high density polyethylene grid with 4 mm x 16 mm rectangular spacing oriented with the current. This material had proved to be quite effective in tests conducted with 5 different materials with potential to prevent oral disc attachment (McAuley, 1993).

Stream Hydrology and Fish Migration Periods

The McIntyre River drains an area of 145 km^2 with a mean annual discharge of 1.46 m^3/s. Velocity in the barrier velocity chute varies with discharge. Because of this, knowledge of flows characteristic of the various fish migrations was essential to the design process. Biologists from the Ontario Ministry of Natural Resources in Thunder Bay, and from the Sea Lamprey Control Centre in Sault Ste. Marie, were queried for the calendar periods associated with the fish and sea lamprey migrations in the McIntyre River. It was found that in the spring, the rainbow trout migration occurs between April 15 and May 14, followed by the migration of various sucker species (May 1 to May 30) and sea lamprey (May 11 to June 30). The several salmon species migrate in the early fall (September 8 to October 7), or late fall (October 8 to November 7). The complete record of daily mean discharges from the McIntyre River recording staff gage (Environment Canada, Gage #02AB016) was ranked for the respective periods, and plotted against the probability of exceedence. The Q_{80} and Q_{20} discharges, which are equaled or exceeded 80% and 20% of the time, respectively, were used to describe the principal flow range of each migratory group. The migratory groups, and the associated migration periods and characteristic flows, can be seen in Table 5.1. The choice of the Q_{80} and Q_{20} was influenced by the fact that, in a number of Great Lakes streams where sea lamprey are trapped (McDonald, 1992), the discharges most characteristic of sea lamprey migrations are between one half to two times the streams' mean annual discharges. For the McIntyre River, this would infer the sea lamprey migration to occur between approximately 0.7 and 2.9 m^3/s. This range is quite close to the Q_{80} and Q_{20} values of 0.77 and 2.9 m^3/s found in Table 5.1.

The sea lamprey migration in Great Lakes streams occurs during the latter part of the spring flow recession between snow-melt maximums and summer base flow. Highest annual discharges usually occur in April with lowest flows in mid to late summer and January. Sea lamprey move upstream in the Neebing-McIntyre system principally between the second or third week of May and the end of June (McDonald, 1992). The lamprey run is influenced by water temperature and velocity conditions and can vary by more than a week at the start or the end in any year. There is little upstream movement of sea lampreys until the water temperature reaches 10°C.

Rainbow trout move upstream from mid April to about mid May when flows are higher (George, 1993). Common white and longnose suckers move upstream throughout most of the month of May. In the fall, coho and chinook salmon, along with rainbow trout, move up the McIntyre River. These fish favor part or most of the period between the first week of September and the second week of November. Fall migrating salmonids often remain in the lower reaches, or off the mouth of a stream, until freshets attract them to move upstream. In the McIntyre River, these fish probably move upstream in the upper part of the range listed in Table 5.1.

Hydraulics of the Velocity Barrier

Velocity Measurements and Chute Flow

In the fall of 1993 and spring of 1994, velocity-discharge measurements were taken over a range of discharges within which a large part of the sea lamprey and other migratory fish runs were observed to occur. Measurements were taken with an electromagnetic current metre (Marsh McBirney - Flo-mate 2000). Three separate cross sections were measured within the velocity chute at the 1.0, 4.5, and 8.0 m stations (0 m being the downstream end of the chute). An example of velocity and depth measurements taken in the velocity chute can be found in Table E1 of Appendix E.

Longitudinal and cross sections of the velocity chute showing the discharge of Table E1 can be seen in Figure 5.3. As seen in the Figure 5.3, flow within the velocity chute was found to be non-uniform. It is supercritical over most of the chute length with Froude numbers varying from 1.0 between the 7 and 8 m stations to about 1.5 at the 1 m station.

The velocity and discharge measurements were used to find equations relating the average velocity in the barrier chute (V_{avg_chute}) to the upper staff gage reading (H_s), and the discharge in the velocity barrier chute (Q_{chute}) to the same upper staff gage reading (H_s). These equations are:

$$V_{avg\_chute} = 2.67\ H_s^{\ 0.383} \qquad R^2 = 0.99 \qquad (5.1)$$

and, $$Q_{chute} = 4.425\ H_s^{\ 1.58} \qquad R^2 = 0.99 \qquad (5.2)$$

where $$H_s = (\text{upper staff reading}) - 0.3655\ . \qquad (5.3)$$

All of the velocity and discharge data were used in these regressions, and can be seen in Table E2 of Appendix E. The accuracy of the discharge measurements in the flume is fairly high since the average of the discharges at the 1.0, 4.5, and 8.0 m stations were used. The average error from the means for the six different days in which discharges were taken is 1.5 %. Individual discharge errors were up to 5% in the first discharge measurements. Accuracy increased later with 13 of the last four section discharges being less than ±1% from their respective mean discharges. The data from Table E2 are also illustrated in the stage-discharge and stage-velocity graphs of Figures E1 and E2.

Mitigation of the Risk of Sea Lamprey Passage at Low Discharges

A graphic illustration of the relation of average chute velocity to total stream discharge is shown in Figure 5.4. In this figure, the average velocities in the chute range from 1.8 to 2.1 m/s for the Q_{80} to Q_{20} range of discharges characteristic of the sea lamprey migration. Velocity in the chute drops at an increasing rate as discharge diminishes, particularly below flows of 1 m^3/s. At a discharge of 0.65 m^3/s the water velocity is 1.68 m/s. At this velocity, according to Equation 3.5, the best sea lamprey swimmers can swim a distance of 8.5 m (the length of the chute). This minimum average velocity allowing for possible sea lamprey passage is illustrated as V_1 in Figure 5.4. According to the McIntyre River flow ranking that was carried out, discharges are below 0.65 m^3/s for 16 % of the time during the sea lamprey calendar migration period. The risk of potential passage at low flows required a design solution. In order to mitigate the low flow lamprey passage risk, the chute downstream entrance was designed such that a drop progressively emerges as discharges recede below about 1 m^3/s. An overhanging "lip" (0.1 m long) was also placed across the entrance base. The combination of these conditions, according to lamprey barrier design experience, is likely to block lamprey entrance into the flume. The entrance is submerged, however, at the higher discharges more frequently used by early spring migratory fish.

Comparison with the Hydraulic Model

There are a number of similarities between the McIntyre River velocity barrier and the hydraulic model of Chapter 4, although there is not an exact prototype-model relationship. The hydraulic model in prototype (5x) scale would have a 2 m wide by 4.15 m long velocity chute. Attached to this is a 2 m wide sample section of overflow crest which was used mainly for testing weir design coefficients. The actual McIntyre River barrier chute is a similar 2.44 m wide, but is longer at 8.5 m. The model and barrier chutes have similar slopes of 1.8% and 2%, respectively. An adverse slope of 1:5 leads up to the overflow weir crests in both model and barrier. Both the velocity chute and the weir crest have a 0.35 m diameter half-round at the upstream end to help streamline water entry.

A simple comparison was made for the weir formula coefficients, k (Equation 4.1), using average values from two measured barrier stream discharges (2.54 and 3.07 m^3/s). Equations 4.2 and 4.3 were used to obtain the values of k at the model scale for the chute and crest. The value of k was found to be about 3 % lower for the model chute (1.64 as compared to 1.68) than in the McIntyre barrier chute. The weir crest coefficient , however, is about 14.8 % lower in the model (1.83 as compared to 2.10) than at the McIntyre River barrier. The higher coefficient at the river barrier weir crest is probably due to both a diminished proportion of abutment wall flow reduction, and to relatively higher upstream approach velocities. The design features causing this relatively high coefficient help buffer higher velocities in the chute by taking a relatively high proportion of increasing flows.

Average water velocities in the barrier chute were compared to velocities at the midpoint of the model prototype as seen in Figure 4.9. For the same three discharges of Figure 4.9, average velocities for the barrier chute were calculated using Equations 5.1 and 5.2. Velocities in the theoretical model prototype were an average of 10.6 % higher for the same flows than in the barrier. Taking into account the ratio of the square roots of the slopes, the actual difference is about 17 %. The roughness coefficient due to the fine sand placed in the model chute was therefore less (scale respected), than that of the surface in the actual barrier chute.

Effectiveness of the Mcintyre River Velocity Barrier

Ongoing evaluation of the the effectiveness of the barrier for blocking sea lamprey and its effects on the fish community is being carried out by biological staff supervised by Mr. Robert Young, assessment supervisor at the Sea Lamprey Control Centre in Sault Sainte Marie, with the cooperation of the Lake Superior Programs Office in Thunder Bay. The passage of fish at the barrier, particularly that of sucker species, has become the subject of an M.Sc. research project by Ms. Marilee Chase of the University of Guelph. There are no specific studies reporting on the numbers of salmonids that pass at the velocity barrier. The high water conditions that occur during the rainbow trout migration make successful trapping of these fish very difficult.

Sea Lamprey

A sea lamprey run of 378 animals estimated by tag-recapture studies challenged the velocity barrier in 1994 (McAuley and Young, 1994; 1996). In the spring of 1993, before construction of the barrier, 78 sea lamprey spawning nests were counted in the reaches upstream of the barrier site. In 1994, a total of three nests were found upstream shortly after an extreme rainfall-flood event had inundated the barrier on June 17. In 1995, no nests were found upstream of the barrier and electro-shocking for sea lamprey larvae confirmed the effectiveness of the barrier at stopping the sea lamprey migration. No sea lamprey larvae were found upstream of the barrier in the 1995 electro-shocking surveys.

Salmonid Passage

The Thunder Bay Salmon Association, the North Shore Steelhead Association, and Ontario Ministry of Natural Resources (OMNR) capture salmon and rainbow trout upstream of the velocity barrier in the McIntyre River for hatchery and transfer reproduction programs. These programs have continued in the years since construction of the velocity barrier. Forty-four rainbow trout were captured below the Lakehead University dam in 1993; while 25 rainbow trout were taken in 1994, and 44 in 1995. These fish were transfered to Ferguson Creek, a tributary to the Current River (Johnson, 1995; George,1995). Angling for salmonids, which is a popular sport in the McIntyre River, has also continued since the installation of the velocity barrier.

Chinook and coho salmon, which constitute a fairly small run in the river (George, 1995) are netted from the reaches upstream of the velocity barrier by OMNR and the fishing clubs for hatchery eggs. A random observation of salmon passage by the author while taking discharges on October 21, 1993. Four or five chinook salmon were noticed in the pool downstream of the barrier. Soon after, two large chinook salmon swam through the chute in rapid succession. The average chute velocity at the time was 1.94 m/s and the discharge was 1.48 m^3/s. The two fish were timed over 8.5 m long chute at ten and eleven seconds, respectively.

White Suckers

The swimming ability of white suckers, which are generally smaller and weaker swimmers than migratory salmonids, can also be indicative of the ability of other non-jumping migratory fish, such as walleye, until further data becomes available.

A study of the passage of white suckers was conducted over a wide variety of flow conditions through two spring migrations by netting fish downstream and upstream of the velocity barrier (Chase and Beamish, 1996). In 1994, it was found that 45% of 722 white suckers marked downstream were recaptured upstream of the velocity barrier. In 1995, 13% of 842 suckers marked downstream of the barrier were recaptured upstream. Passage success was observed to decrease with increasing water temperature from 9 to 14°C and to decrease with increasing fish size. Water temperature increase was generally accompanied by decreasing discharges of the spring to summer flow recession.

During some of the more favorable flow conditions (3.07 m^3/s) on May 12, 1994, 37 white suckers were observed swimming in the velocity chute by the author and M. Chase. A stopwatch was used to record the time for fish to swim through the chute, or the time until a fish began washing back downstream. The distance attained by the fish was measured from markers on the chute sidewall; 8.5 m being a successful passage through the chute. Water temperatures at the time were 10 to 11°C. Records of net catches closest to the period of these observations were analyzed for comparative fish sizes caught above and below the barrier. On May 13, the 46 white suckers taken in the net downstream of the barrier averaged 41.6 cm in length (range 34.9 to 46.2) (Chase, 1994). On the same day, 71 white suckers taken from the net upstream of the barrier averaged 41.1 cm in length (range 30.9 to 50.9). The following day, 74 white suckers taken upstream averaged 42.1 cm in length (range 35.8 to 49.3). A summary of catch numbers, and fish lengths for the fish retrieved on May 13 and 14 can be seen in Table E3 of Appendix E. Further details of the methods along with swim endurance data by individual and size groups can be found in Tables E4 and E5 in Appendix E. A photograph taken on May 12 of a white sucker swimming near the 1 m station in the velocity chute can be seen in Figure 5.5.

For the purpose of estimating swimming performance of white suckers for future velocity barrier work, the endurance times of the group of small white suckers swimming in the velocity chute on May 13, 1994, were plotted against swim speed. This is seen in Figure 5.6, along with other available data for the species (Jones et al., 1974). An equation was found to indicate the probable swimming endurance of white suckers (*L*=35 cm) at 10°C from the data available at this point in time. It is:

$$\mathbf{t = 224.6\ U^{-2.87}} \qquad R^2 = 0.997 \qquad (5.1)$$

where t is endurance in seconds and U is swim speed in m/s.

Discussion

In order to assist in the planning of future velocity barriers, the swimming endurance of sea lamprey (Equation 3.7), white suckers (Equation 5.1), and steelhead (rainbow trout)(Paulik and Delacy, 1957) are compared in the graph in Figure 5.6. All data are for the same water temperatures (10 to 11°C). Also shown in the graph is the endurance of sea lamprey in warmer water (Equation 3.8). It is interesting to note that for white suckers, endurance was found to vary with the inverse of swimming speed to the 2.87 power (Equation 5.1), a value similar to the 3.077 and 2.822 powers found for sea lamprey in Equations 3.7 and 3.8.

At lower discharges, white suckers face the same increasingly difficult entrance conditions that were designed to prevent sea lamprey from entering when velocities are lower. A significant increase in propulsive work is required for fish swimming close to the surface (Webb et al., 1991; see Chapter 2), as would be the case at the velocity barrier entrance in low flows. Depths at the 1.0 m station were 0.13 m and 0.21 m at discharges of 0.59 to 1.48 m^3/s. At these depths, a loss of energy to the production of surface waves is probable. Although white suckers have better swimming endurance than sea lamprey, the difficulty involved in separating the two species at the velocity barrier is due to the wide range of discharges possible during their migrations. Since velocity approaches zero in the velocity chute as discharge approaches zero, an entrance drop was designed to prevent sea lamprey access to the chute at lower discharges. However, this same drop creates conditions that negatively impact white sucker access to the velocity chute. A better solution for this problem will be required in future designs of velocity barriers.

Species	Period	Exceedence Discharge m^3/s		
		Q_{80}	Q_{50}	Q_{20}
Sea lamprey	May11-Jun30	0.77	1.53	2.90
Rainbow trout	Apr15-May14	2.30	4.70	8.8
Suckers (sp.)	May1-May30	1.2	2.4	5.1
Early fall salmonids	Sep8-Oct7	0.2	0.68	2.0
Late fall salmonids	Oct8-Nov7	0.36	1.0	2.2

Table 5.1 Characteristic discharges of McIntyre River spawning migrations.

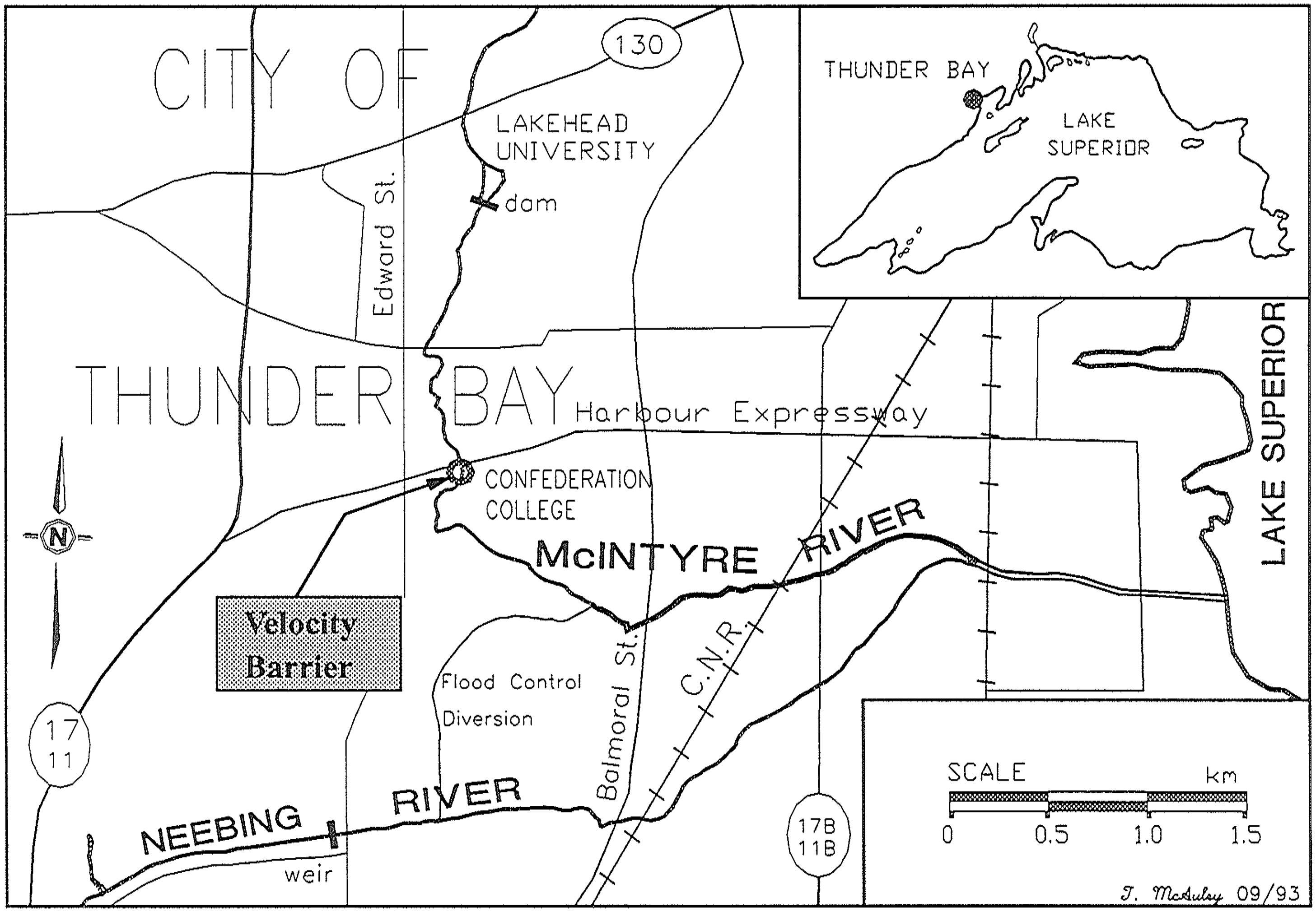

Figure 5.1 Location of the McIntyre River velocity barrier.

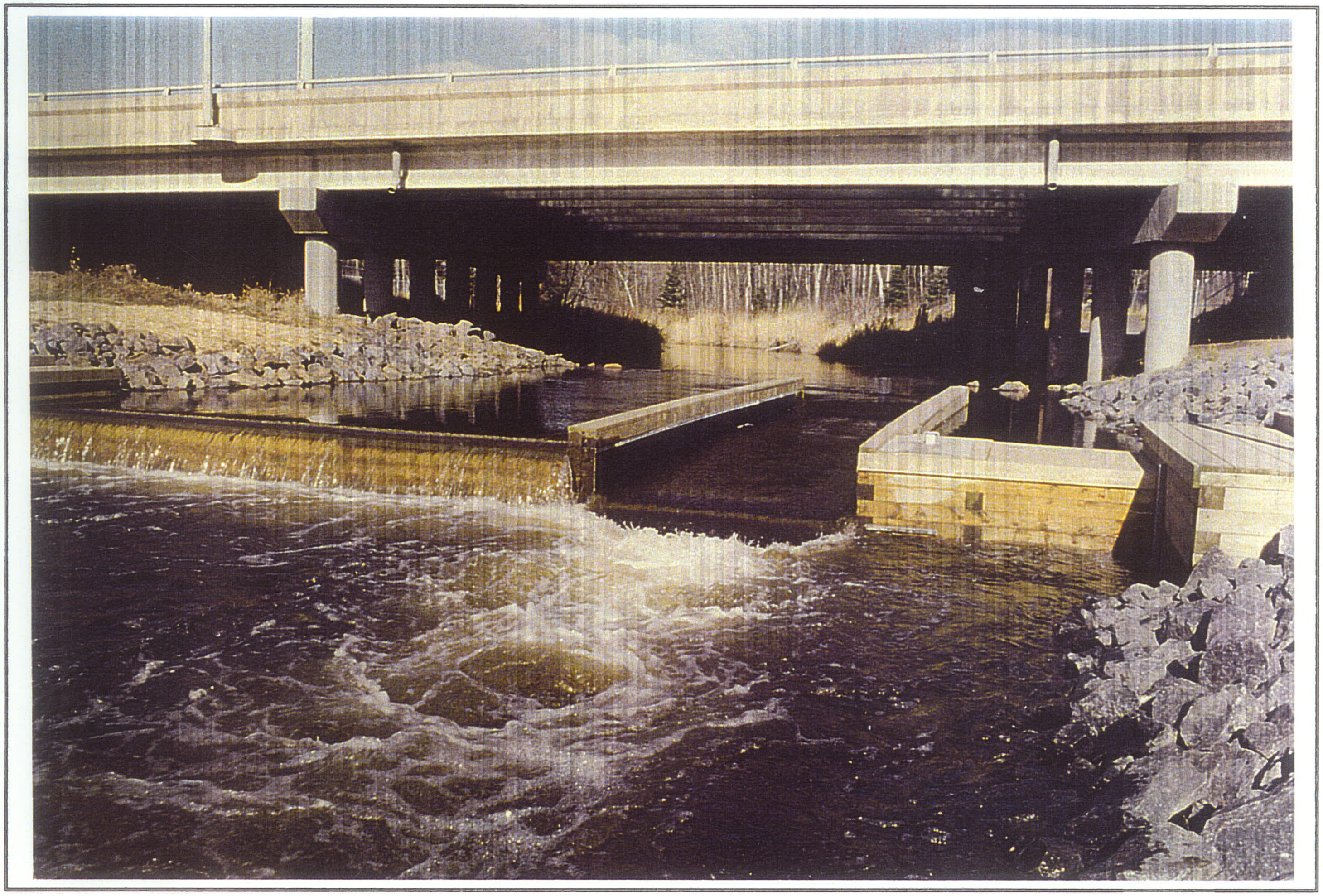

Figure 5.2 The experimental velocity barrier constructed on the McIntyre River in 1993.

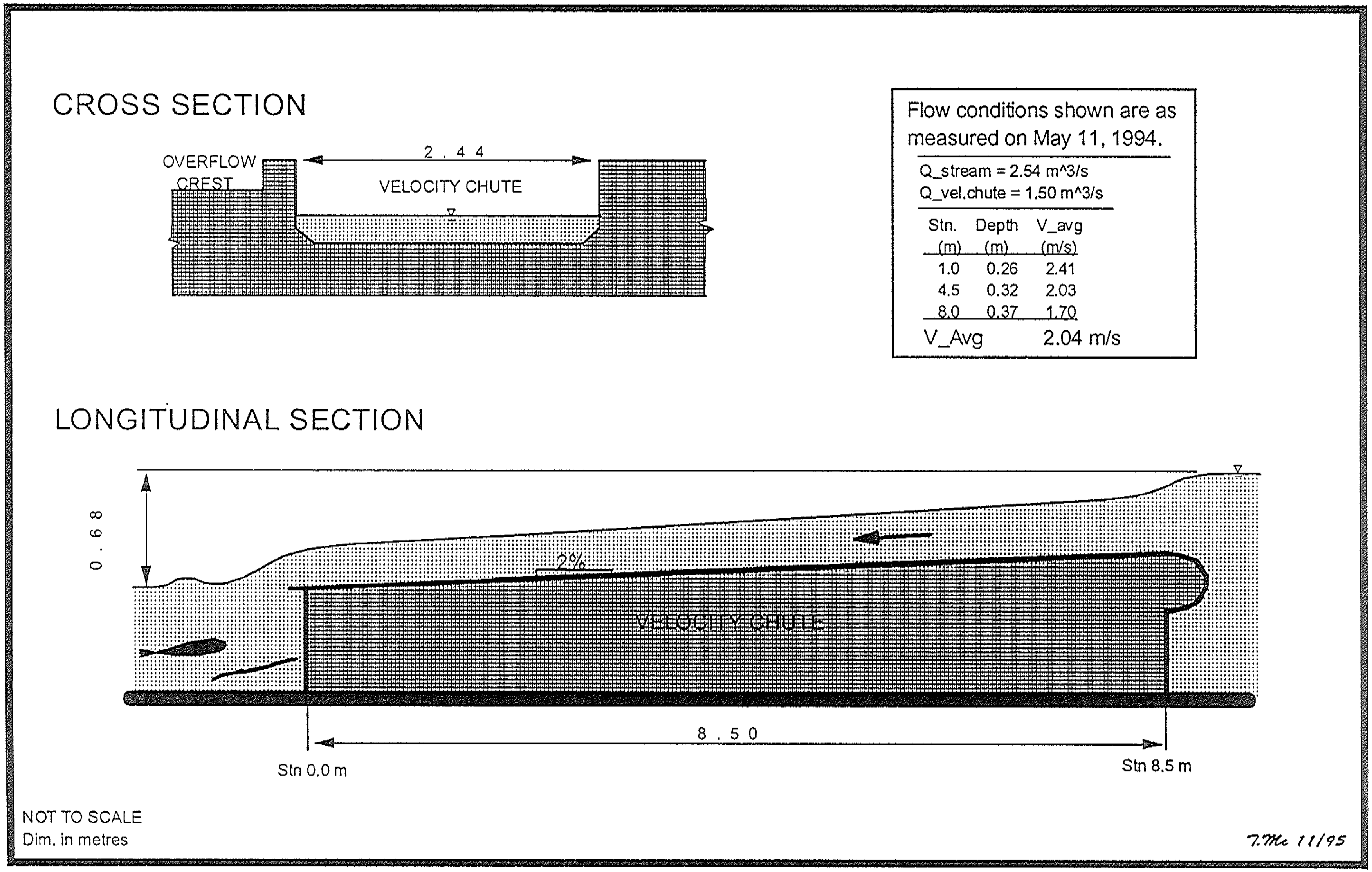

Figure 5.3 Schematic sections of the velocity barrier chute constructed on the McIntyre River.

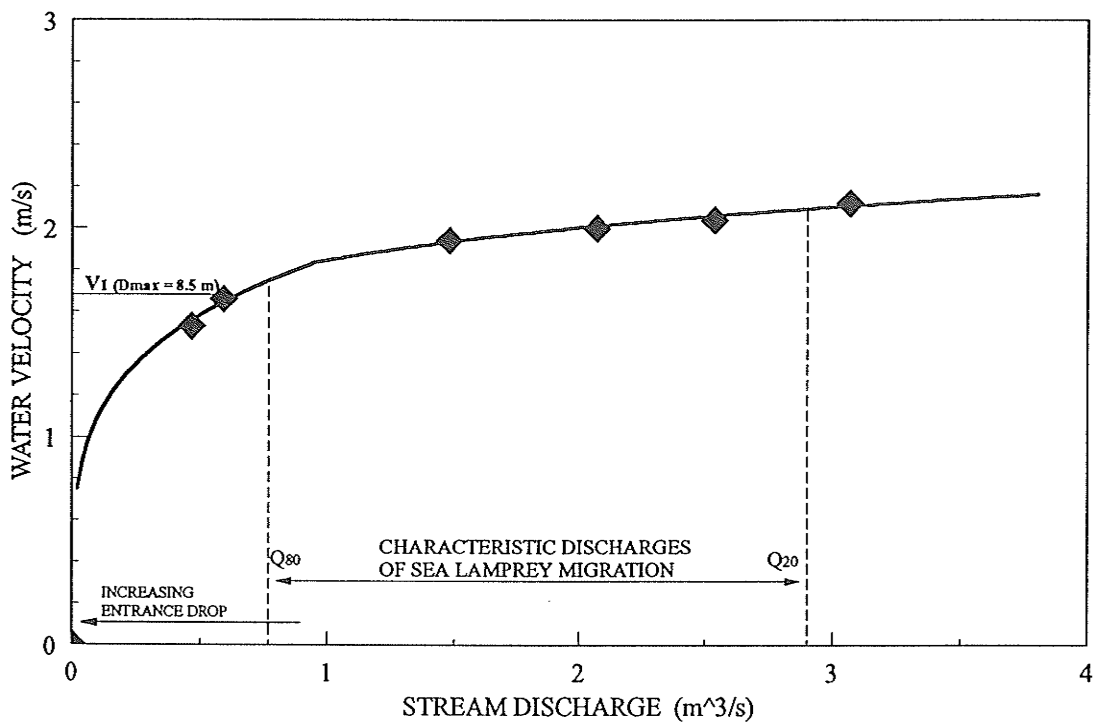

Figure 5.4 Average water velocity in the barrier chute versus discharge in the McIntyre River. Also shown are the Q_{80} and Q_{20} discharges associated with the sea lamprey, migration and the velocity (V_1) at which Dmax (Equation 3.5) equals 8.5 m for sea lampreys.

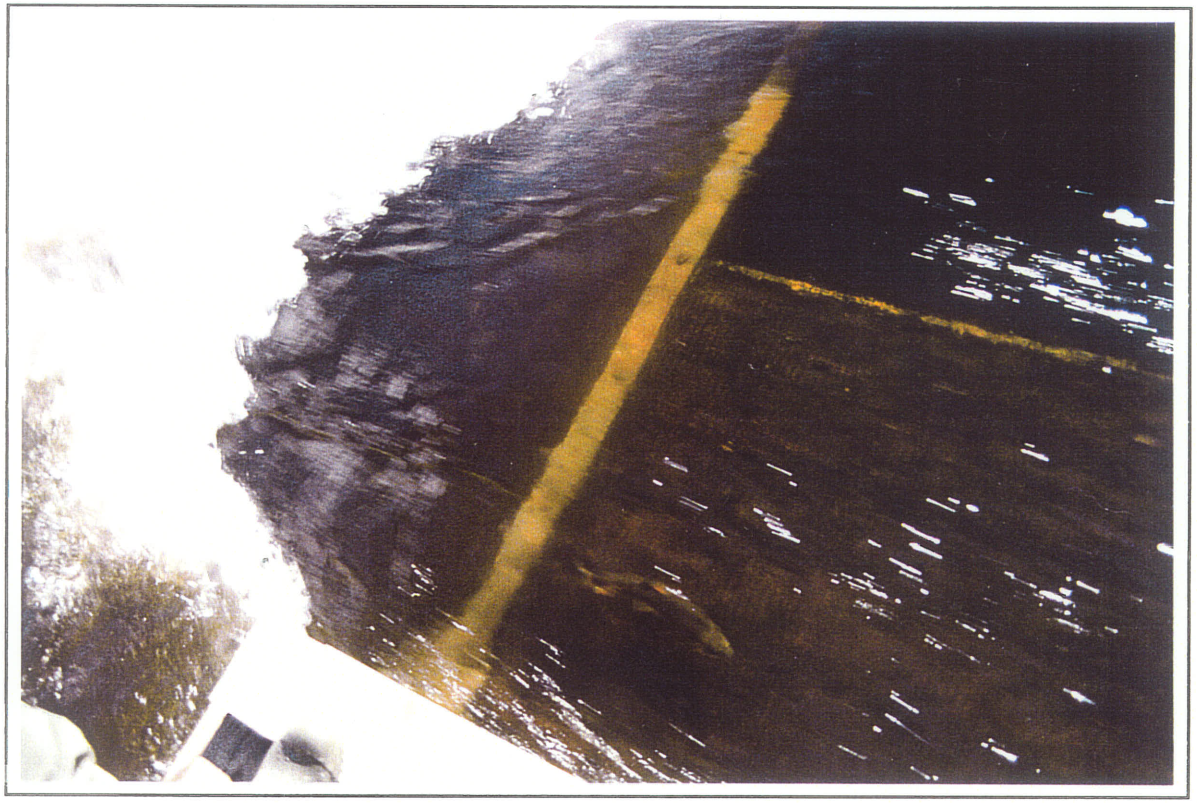

Figure 5.5 A white sucker swimming in the velocity barrier on May 12, 1994.

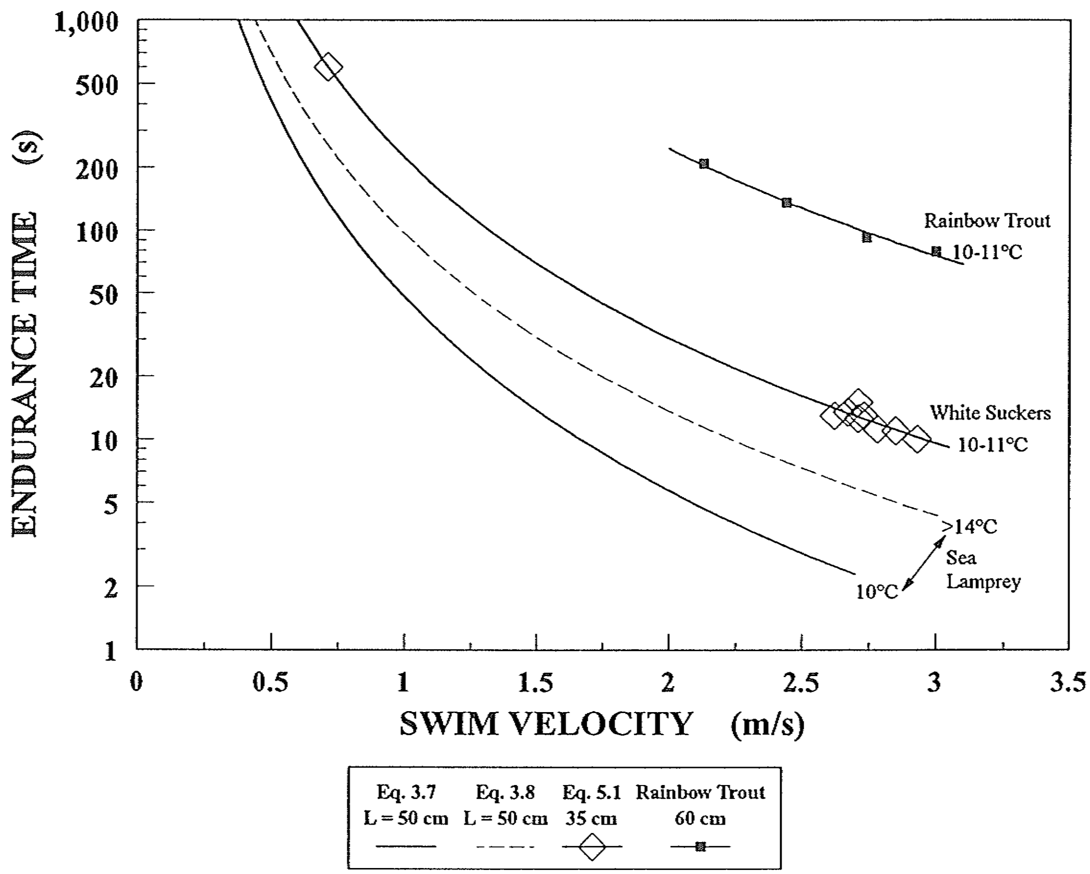

Figure5.6 Swimming endurance of white suckers, sea lamprey, and steelhead (rainbow trout).

CHAPTER 6

SUMMARY, RECOMMENDATIONS, AND CONCLUSIONS

Summary

In this research, the previously unexploited concept of using water velocity as a control for sea lamprey spawning migrations was investigated. The early idea of using velocities beyond the maximum burst swim speed of sea lamprey was replaced by that of exploiting differences in swimming endurance and preventing oral disc attachment. Finally, the concept was demonstrated with an actual velocity barrier functioning on a sea lamprey stream.

With an inter-disciplinary approach, multiple aspects related to the development of a velocity barrier were investigated. An examination of the hydrodynamics and physiology of fish swimming lent support to the idea of selectively stopping sea lamprey on the basis of swimming performance. The swimming performance of sea lampreys was tested in open channel flumes. The swimming test results agreed well with work carried out by previous researchers. They also revealed that, as water temperatures increase above approximately 10 to 12°C, sea lamprey are able to improve their performance by swimming in a more efficient manner. The swim tests of this research project resulted in equations describing the swimming endurance and distances attainable by sea lamprey. They provided knowledge that is essential to the development of velocity barriers.

A conceptual design for a velocity barrier was developed and tested in a scale model in the University of Manitoba Civil Engineering Hydraulics Laboratory. Hydraulic modelling of the basic design components, weir coefficients, and flow profiles were used in confirming and improving the hydraulic aspects of the conceptual design.

The results of the swim tests and hydraulic modelling were used to develop a design for an experimental velocity barrier for a Great Lakes tributary. The characteristic hydrology of the various fish migrations in the candidate river were examined. The design of a fixed structure to provide target velocity ranges over the different discharge ranges associated with the fish and sea lamprey migrations was a serious challenge. The experimental velocity barrier was constructed in the late summer of 1993 on the McIntyre River at Thunder Bay, Ontario. Velocity and discharge measurements were taken on different occasions and equations were developed to describe the hydraulics of the velocity barrier.

Evaluations of the effectiveness of the experimental velocity barrier are currently being carried out by biologists from several agencies and one university. Sea lamprey spawning success was reduced by 96% and 100% in 1994 and 1995, respectively. For the white sucker migration, a tag-recapture study shows a 45% passage rate in 1994, and 13% passage in 1995 (Chase and Beamish, 1996).

Strengths and Weaknesses of the First Velocity Barrier

The experimental velocity barrier constructed at the McIntyre River has a good record at stopping sea lamprey over the past two years. However, it appears to present a serious challenge for white suckers. This may be due largely to the conditions at the downstream entrance to the chute where the water reaches its highest velocities. Water velocity averages 20 % higher at the one metre station than at the 4.5 m station. On May 12, 1994, although the average chute velocity was 2.14 m/s, the fish had to swim much more rapidly to pass the 2.57 m/s velocity at the 1 m station and the estimated 2.7 m/s at the entrance to the chute. It appears that the shallowness of the water over the entrance lip increases the difficulty for white suckers to enter the velocity chute at lower discharges. When swimming near the water surface, fish must expend more energy due to losses to surface waves. It is believed that the design solution of having a drop appear to stop sea lamprey at low discharges is the cause of the higher entrance velocities. A better solution to this problem should be found.

The cost of the McIntyre River velocity barrier is reasonable when compared with other low-head lamprey barriers (Koon and McAuley, 1994). Timber was the material chosen for the construction of the superstructure because of the experimental nature of the barrier. A 20 to 40 year life span is considered reasonable for the structure without a major rebuild. On a number of occasions in 1994, vandals threw rip-rap boulders into the velocity chute. Boulders could permit passage of sea lampreys by reducing the current. The installation of a fence around the site did not help much, but grouting the nearby rip-rap with mortar appears to have eliminated the problem. In future designs, this problem could be avoided by using interlocking blocks instead of rip-rap, or by enclosing the velocity chute with higher sidewalls and an overhead grating.

The high density polyethylene 'non-attachable' material used to surface the chute has not required any cleaning of algae or small detritus in its first two years. Leaves caught in the material can cover up to half of its surface in late fall, but are no longer present in the spring. Several rips of about 1 m long were found in the material near the downstream end in the summer of 1994. These are thought to have occurred during the June 17 flood when some large trees with broken branches were carried downstream. The rips were easily repaired during regular barrier maintenance and the chute surface has functioned since that time. However, it is recommended that a more rugged surface material be found to prevent sea lamprey attachment for use in future velocity barriers. The ideal solution would be to have several materials of both high and low hydraulic roughness.

Recommendations for Future Work

The major challenge in velocity barrier design is that of taking a theoretically logical concept and applying it to the real world of stream hydrology and fish migrations. Given the dynamic nature of stream discharge through various fish migrations, the attainment of target velocity ranges in a fixed structure is a difficult task. Prediction of discharges associated with various spring and fall migrations is at an elementary stage. It is known, however, that several migrations together in a small Great Lakes river can present a range of discharge varying by a factor of as much as four to ten.

Future work is recommended in four areas: 1) development and hydraulic modelling of promising innovative designs; 2) investigations of the hydrology of candidate streams; 3) research into several new rugged surface materials to prevent oral disk attachment; and 4) further research into the swimming ability of non-target fish.

Improvements to the existing design and innovative new designs can be developed and tested as hydraulic models. Suggested ideas in this area include: combining in-line or parallel velocity chutes with fishpass runs where higher hydraulic heads are available; the use of a variable slope velocity chute with an adjusting mechanism; manual installation at low flow of a downstream end drop or upstream trap; combining two channel shapes and slopes in one velocity chute; and the design of a subcritical velocity barrier.

The design of future velocity barriers will depend on the availability of sound hydrological criteria. Basin-wide studies of migratory periods, and associated discharges and temperatures, are recommended. Systematic studies of stage-discharge relationships for the initial rhithron reaches of candidate rivers would provide another essential information component.

Swimming tests are recommended for burst and upper prolonged swimming for species for which passage may be required at future barriers. Several fish of immediate interest are walleye, pike, sturgeon, and smaller salmonids of 10 to 30 cm in length. Velocity barrier chutes may be logical candidates for use in passage of lake sturgeon

(Acipenser fulvescens), a species for which Great Lakes fisheries managers are concerned. Swim tests with all of the species mentioned above would greatly improve the confidence required in planning instream velocity barriers.

Conclusions

The feasibility of using water velocity to control sea lamprey migrations has been demonstrated by this research and thesis. Sea lamprey are poorer swimmers than other fish of comparable size. However, the engineering of velocity barriers to stop the one and pass the other is not nearly as easy as may first appear. Provision must be made for the different velocities and conditions faced by each species at the barrier. The sea lamprey migration continues later into the spring (into late June and early July) than other spring migrations. Because of this, sea lamprey generally encounter lower discharges, and thus lower velocities, at a fixed velocity chute. They also encounter generally higher temperatures. It was found that sea lamprey are able to improve their burst swimming performance at water temperatures above approximately 10 to 12° C by swimming with a more efficient body wave. As a result of these factors, the engineering challenge is considerably increased. The success or failure of future velocity barrier designs could depend principally upon the accuracy of design discharges. Studies to improve the prediction of discharges characteristic of various migratory species will thus be essential to the future implementation of velocity barriers.

The velocity barrier concept has been improved in this work from the early idea of using velocities beyond the maximum burst swim speed of sea lamprey to that of exploiting differences in swimming endurance and preventing oral disc attachment. This revised concept allows much greater flexibility in choosing combinations of barrier length and velocity.

The equations found to describe the swimming ability of sea lamprey from analysis of the swim test data are useful in planning velocity barriers. For instance, if a velocity chute of about 30 m in length is desired, reference to Equation 3.5 indicates that a D_{max} of 30 m for sea lamprey at all temperatures occurs at a water velocity of 1.06 m/s. A safety factor calculated in terms of length or velocity should then be added to cover for the possibility of lamprey swimming near the bottom (Equation 2.1) and for uncertainty about migratory discharge ranges. In another example, at a velocity of 1.8 m/s, a much shorter chute could be used since the D_{max} for sea lamprey at that velocity is 7 m (Equation 3.5).

The first velocity barrier developed on the McIntyre River has shown that the objective of stopping sea lamprey can be realized. With the future work proposed, improved passage of non-jumping fish should be feasible. In the Great Lakes watershed, the use of alternative technology, such as instream barriers, is growing in importance for the control of sea lamprey. The development of hydraulic structures such as the velocity barrier covered in this thesis responds to the need for new non-chemical technology. With further research and design improvements, velocity barriers can become an alternative tool in the control of sea lamprey in the Great Lakes basin.

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APPENDIX A

Great Lakes Fisheries Commission Barrier Policy Statement, 1993

POLICY STATEMENT
THE ROLE OF BARRIERS IN AN INTEGRATED SEA LAMPREY CONTROL PROGRAM

Barriers, natural or man made, play an extremely important role in restricting the potential area used by spawning sea lampreys within a river system. A barrier may be any device or structure which blocks or limits the migration of sea lamprey to spawning habitat in a river. These devices include low-head and electrical barriers which are currently in use and potential new developments, such as, velocity, sound, or pheromone barriers. Since the sea lamprey population in the Great Lakes is dependent upon reproduction which takes place in only about 400 of the 5,750 tributaries entering the Great Lakes, the Commission regards the construction of specifically designed barriers, modification or repair of existing dams or other structures into barriers and research of new barrier design as a valuable and practical supplement to lampricides consistent with its Vision in the development of an integrated sea lamprey control program.

Among the major advantages to be realized through the increased deployment of barriers in sea lamprey producing streams are:

1. lower lamprey populations lake and basin wide that further meet control objectives through reduced spawning area and more efficient control of remaining area;

2. reduced use of lampricides;

3. fewer stream miles that require periodic treatment;

4. increased ability to trap and remove spawning sea lampreys to further enhance Sterile Male Release Program, reduce the number of spawning lampreys and improve assessment to meet control objectives.

5. decreased exposure of nontarget organisms to lampricides;

6. reduced control cost as a result of decreased complexity of the application of lampricides;

7. greater public acceptance of a non-chemical control method.

The benefits from barriers designed specifically for sea lamprey control outweigh the disadvantages. Proper design and knowledgeable selection of streams and sites minimize adverse effects on the ecosystem.

In view of the foregoing, the Commission endorses the installation of barriers, modification of existing structures into barriers, and continued research into new barrier design and technology as part of an integrated control program. The Great Lakes Fishery Commission will develop a barrier program with concern and sensitivity to the conservation of other environmental, ecological, and recreational values. The planning and design process will seek to avoid all impacts or minimize and mitigate significant environmental, ecological, or recreational impacts. The Commission will negotiate agreements with the Great Lakes management agencies to plan, design, construct or modify, operate (trap and remove lampreys) and maintain devices designed specifically for sea lamprey control. The Commission urges the Great Lakes States and the Province of Ontario, in concert with their respective federal governments and in cooperation with this Commission, to actively participate in the barrier program to help the Commission to meet its goals for the sea lamprey control program in the waters of the Great Lakes. The Commission recognizes that action by the States and Province must be taken within the constraints imposed by laws or regulations of the individual agency.

APPENDIX B

Summary of 1991 Sea Lamprey Performance Tests

Summary of 1991 Sea Lamprey Performance Tests

Flume Setup and Method

A 5 m long wooden flume with a gravity water feed was set up at Little Rapids on the Bridgeland River, about 80 km east of Sault Sainte Marie, Ontario. Water from a section of rapids and falls was diverted through a 25 cm diameter PVC pipe to a steel pressure box. From there it passed through a valve and a baffled box into the flume. The flume discharged into an screen gated introduction box from which the water returned to the stream.

To achieve a range of velocities various valve settings and flume slopes were used. Slopes of 7%, 11%, and 14%, were used with a trapezoidal section shape surfaced to prevent lamprey attachment in the flume. Water velocities were taken in the flume with a current meter (Ottmeter C-31) at the centre and 3.5 cm from each side of the 30 cm wide trapezoidal channel at mid depth which represented the part of the cross section in which sea lamprey most commonly swam. When an improved rubber surface was found to prevent attachment, only centre line velocities were taken in the centre of the narrower parabolic shaped section since this was considered representative of the zone in which sea lamprey swam. Measurements were taken at the 1, 2, and 3 m stations.

Sea lamprey taken from a trap on the Bridgeland River beginning in the last week of April were tagged and kept in a tank in the mini-hatchery building on site at ambient stream temperatures. New lamprey were taken periodically from the stream trap to keep a total of about 40 in the hatchery. Toward the latter part of the run (June), fresh lamprey from the cooler St. Mary's River were used. These were given a minimum of 48 hours temperature acclimation time before testing.

On test days, lamprey were were transferred to the introduction box. The screen gate was then removed and lamprey were then free to attempt swimming upstream into the flume. Distances and duration times from the start of the swim attempt to the point of furthest progress in the chute were recorded along with body length and water temperature. After a test period of about 2 hours, lamprey in the flume introduction box were returned to the hatchery tank.

Table B1 summarizes the test dates, water velocities and temperatures, the number of lamprey observed, the median and maximum swim distances, median swim velocity and endurance time, and median lengths of the sea lamprey attempting the flume. Table B2 lists the data for the individual sea lamprey in the tests.

Table B1 Summary of 1991 performance tests with sea lamprey at Bridgeland River.

Test Date 1991	Swim Zone Velocity m/s	Water Temp deg.C	Number of Lamprey Observed	Distance Swam (median) m	Distance Swam (max)	Endurance Time (median) s	Swim Velocity (median) m/s	Length (median) m	Ground Rate m/s
May 3,6	1.95	11.2	16	1.55	2.7	7.5	2.15	0.51	0.20
May 13,14	2.50	16.7	10	0.63	2.6	4.1	2.69	0.50	0.19
May 16	1.85	17.0	13	3.50	5.0	8.0	2.23	0.51	0.38
May 17,21	2.08	15.5	9	2.30	5.0	7.0	2.46	0.51	0.36
May 23	2.35	19.9	28	2.10	4.8	5.0	2.74	0.49	0.40
May 24	2.44	20.7	13	1.80	3.5	5.1	2.86	0.49	0.42
Jun 11	2.35	21.0	14	2.25	4.8	6.0	2.69	0.52	0.34
Jun 13,14	2.80	19.0	25	1.20	2.3	3.4	3.12	0.51	0.32
Jun 21	2.64	19.9	8	0.90	1.4	2.1	3.07	0.49	0.43

Table B2 Performance of individual lamprey in 1991 tests.

Test Date 1991	Swim Zone Velocity m/s	Water Temp deg.C	Distance Swam m	Endurance Time s	Swim Velocity m/s	Length m	Ground Rate m/s
May 3	1.95	11.2	2.50	8.5	2.24	0.51	0.29
May 3	1.95	11.2	1.60	8.5	2.14	0.51	0.19
May 3	1.95	11.2	0.90	6.0	2.10	0.50	0.15
May 6	1.95	11.2	2.20	10.8	2.15	0.56	0.20
May 6	1.95	11.2	1.60	7.0	2.18	0.47	0.23
May 6	1.95	11.2	0.90	4.0	2.18	0.46	0.23
May 6	1.95	11.2	1.50	4.0	2.33	0.46	0.38
May 6	1.95	11.2	1.30	6.5	2.15	0.57	0.20
May 6	1.95	11.2	2.70	7.0	2.34	0.56	0.39
May 6	1.95	11.2	1.05	7.3	2.09	0.51	0.14
May 6	1.95	11.2	1.30	7.0	2.14	0.48	0.19
May 6	1.95	11.2	2.10	10.5	2.15	0.57	0.20
May 6	1.95	11.2	0.65	7.8	2.03	0.47	0.08
May 6	1.95	11.2	1.70	8.0	2.16	0.57	0.21
May 6	1.95	11.2	1.40	9.0	2.11	0.46	0.16
May 6	1.95	11.2	2.10	9.9	2.16	0.56	0.21
May 13	2.50	16.7	0.65	3.0	2.72	0.47	0.22
May 13	2.50	16.8	1.60	4.0	2.90	0.50	0.40
May 13	2.50	16.8	0.60	3.0	2.70	0.53	0.20
May 13	2.50	16.8	2.60	8.0	2.83	0.50	0.33
May 13	2.50	16.6	0.60	3.5	2.67	0.50	0.17
May 13	2.50	16.6	0.80	3.5	2.73	0.49	0.23
May 13	2.50	16.9	0.60	5.0	2.62	0.48	0.12
May 13	2.50	16.5	0.60	4.2	2.64	0.51	0.14
May 13	2.50	17.0	1.10	6.0	2.68	0.53	0.18
May 13	2.50	16.2	0.60	5.0	2.62	0.48	0.12
May 16	1.85	17.0	3.50	8.0	2.29	0.52	0.44
May 16	1.85	17.0	3.00	7.8	2.23	0.51	0.38
May 16	1.85	17.0	3.40	7.5	2.30	0.47	0.45
May 16	1.85	17.0	4.70	12.0	2.24	0.47	0.39
May 16	1.85	17.0	2.70	7.4	2.21	0.51	0.36
May 16	1.85	17.0	3.30	7.0	2.32	0.52	0.47
May 16	1.85	17.0	2.65	7.0	2.23	0.51	0.38
May 16	1.85	17.0	2.80	6.0	2.32	0.51	0.47
May 16	1.85	17.0	4.00	10.0	2.25	0.51	0.40
May 16	1.85	17.0	5.00	13.0	2.23	0.51	0.38
May 16	1.85	17.0	5.00	13.0	2.23	0.47	0.38
May 16	1.85	17.0	4.80	18.0	2.12	0.47	0.27
May 16	1.85	17.0	5.00	14.0	2.21	0.53	0.36

continued...

Table B2 (continued) Performance of individual lamprey in 1991 tests.

Test Date 1991	Swim Zone Velocity m/s	Water Temp deg.C	Distance Swam m	Endurance Time s	Swim Velocity m/s	Length m	Ground Rate m/s
May 17	2.10	15.4	1.70	6.0	2.38	0.51	0.28
May 17	2.10	15.5	3.20	9.0	2.46	0.51	0.36
May 17	2.10	15.5	5.00	7.0	2.81	0.59	0.71
May 17	2.10	15.4	2.00	5.0	2.50	0.45	0.40
May 17	2.10	15.5	2.00	5.0	2.50	0.51	0.40
May 17	2.10	15.4	5.00	12.0	2.52	0.53	0.42
May 21	2.05	16.2	2.00	6.0	2.38	0.53	0.33
May 21	2.05	16.3	3.20	10.0	2.37	0.48	0.32
May 21	2.05	16.3	2.30	9.0	2.31	0.50	0.26
May 23	2.32	19.9	4.60	12.0	2.70	0.58	0.38
May 23	2.36	19.9	1.30	3.5	2.73	0.58	0.37
May 23	2.32	19.8	2.20	5.5	2.72	0.50	0.40
May 23	2.36	19.9	2.40	5.0	2.84	0.47	0.48
May 23	2.36	19.9	2.30	5.0	2.82	0.44	0.46
May 23	2.32	19.7	1.60	4.8	2.65	0.47	0.33
May 23	2.36	19.9	2.00	4.2	2.84	0.49	0.48
May 23	2.32	19.6	2.90	11.5	2.57	0.51	0.25
May 23	2.36	19.9	1.90	3.6	2.89	0.51	0.53
May 23	2.36	19.9	1.40	3.3	2.78	0.50	0.42
May 23	2.36	19.9	2.50	6.4	2.75	0.46	0.39
May 23	2.36	19.9	0.55	3.3	2.53	0.41	0.17
May 23	2.32	19.6	1.10	3.2	2.66	0.55	0.34
May 23	2.32	19.8	0.80	3.0	2.59	0.41	0.27
May 23	2.36	19.9	0.30	3.0	2.46	0.49	0.10
May 23	2.36	19.9	1.30	2.9	2.81	0.49	0.45
May 23	2.36	19.9	2.20	2.9	3.12	0.51	0.76
May 23	2.36	19.9	1.05	1.5	3.06	0.49	0.70
May 23	2.32	19.8	2.90	6.0	2.80	0.46	0.48
May 23	2.36	19.9	2.20	4.0	2.91	0.46	0.55
May 23	2.36	19.9	2.30	6.5	2.71	0.46	0.35
May 23	2.32	19.9	2.60	9.0	2.61	0.46	0.29
May 23	2.36	19.9	2.00	6.6	2.66	0.51	0.30
May 23	2.36	19.9	4.80	8.2	2.95	0.52	0.59
May 23	2.36	19.9	1.80	6.8	2.62	0.47	0.26
May 23	2.32	19.9	4.80	7.7	2.94	0.52	0.62
May 23	2.32	19.8	4.60	9.0	2.83	0.51	0.51
May 23	2.36	19.9	2.00	9.5	2.57	0.48	0.21

continued...

Table B2 (continued) Performance of individual lamprey in 1991 tests.

Test Date 1991	Swim Zone Velocity	Water Temp	Distance Swam	Endurance Time	Swim Velocity	Length	Ground Rate
	m/s	deg.C	m	s	m/s	m	m/s
May 24	2.44	20.8	1.40	5.8	2.68	0.49	0.24
May 24	2.44	20.7	3.50	7.5	2.91	0.49	0.47
May 24	2.44	20.5	0.25	3.9	2.50	0.41	0.06
May 24	2.44	20.8	1.60	4.7	2.78	0.49	0.34
May 24	2.44	20.7	2.95	7.0	2.86	0.48	0.42
May 24	2.44	20.7	1.65	3.6	2.90	0.46	0.46
May 24	2.44	20.8	1.10	3.5	2.75	0.41	0.31
May 24	2.44	20.7	2.30	5.0	2.90	0.51	0.46
May 24	2.44	20.8	3.05	6.9	2.88	0.48	0.44
May 24	2.44	20.8	2.50	5.5	2.89	0.49	0.45
May 24	2.44	20.5	1.10	3.1	2.79	0.51	0.35
May 24	2.44	20.6	3.00	6.7	2.89	0.58	0.45
May 24	2.44	20.5	1.80	5.1	2.79	0.53	0.35
Jun 11	2.35	21.1	1.20	4.0	2.65	0.49	0.30
Jun 11	2.35	21.1	3.30	10.0	2.68	0.52	0.33
Jun 11	2.35	21.0	3.90	8.0	2.84	0.46	0.49
Jun 11	2.35	21.0	2.60	8.0	2.68	0.50	0.33
Jun 11	2.35	21.1	2.40	10.0	2.59	0.54	0.24
Jun 11	2.35	21.1	4.40	8.0	2.90	0.52	0.55
Jun 11	2.35	21.0	4.80	8.0	2.95	0.55	0.60
Jun 11	2.35	21.1	1.40	4.0	2.70	0.54	0.35
Jun 11	2.35	21.1	2.90	6.0	2.83	0.55	0.48
Jun 11	2.35	20.8	0.50	5.0	2.45	0.54	0.10
Jun 11	2.35	21.0	2.00	5.0	2.75	0.52	0.40
Jun 11	2.35	21.1	1.50	5.0	2.65	0.54	0.30
Jun 11	2.35	21.1	2.10	6.0	2.70	0.50	0.35
Jun 11	2.35	21.1	1.30	5.0	2.61	0.46	0.26
Jun 13	2.80	19.5	1.10	3.5	3.11	0.54	0.31
Jun 13	2.80	19.5	1.50	4.0	3.18	0.47	0.38
Jun 13	2.80	19.5	1.10	6.0	2.98	0.50	0.18
Jun 13	2.80	19.5	1.40	5.0	3.08	0.54	0.28
Jun 13	2.80	19.5	1.10	4.0	3.08	0.54	0.28
Jun 13	2.80	19.5	1.40	4.0	3.15	0.53	0.35
Jun 13	2.80	19.5	1.60	4.5	3.16	0.46	0.36

cont...

Table B2 (continued) Performance of individual lamprey in 1991 tests.

Test Date 1991	Swim Zone Velocity	Water Temp	Distance Swam	Endurance Time	Swim Velocity	Length	Ground Rate
	m/s	deg.C	m	s	m/s	m	m/s
Jun 14	2.80	19.0	0.80	2.8	3.09	0.51	0.29
Jun 14	2.80	19.0	0.55	2.5	3.02	0.51	0.22
Jun 14	2.80	19.0	0.60	2.4	3.05	0.50	0.25
Jun 14	2.80	19.0	1.20	2.0	3.40	0.48	0.60
Jun 14	2.80	19.0	0.55	1.8	3.11	0.51	0.31
Jun 14	2.80	19.0	1.70	2.0	3.65	0.44	0.85
Jun 14	2.80	19.0	2.30	4.5	3.31	0.52	0.51
Jun 14	2.80	19.0	1.20	3.0	3.20	0.45	0.40
Jun 14	2.80	19.0	0.60	3.2	2.99	0.51	0.19
Jun 14	2.80	19.0	1.40	3.0	3.27	0.50	0.47
Jun 14	2.80	19.0	1.10	4.5	3.04	0.50	0.24
Jun 14	2.80	19.0	1.60	5.0	3.12	0.54	0.32
Jun 14	2.80	19.0	1.70	5.0	3.14	0.52	0.34
Jun 14	2.80	19.0	1.10	3.4	3.12	0.51	0.32
Jun 14	2.80	19.0	0.40	1.8	3.02	0.50	0.22
Jun 14	2.80	19.0	1.40	6.0	3.03	0.52	0.23
Jun 14	2.80	19.0	0.50	1.0	3.30	0.46	0.50
Jun 14	2.80	19.0	1.40	3.1	3.25	0.46	0.45
Jun 21	2.64	19.9	0.90	2.5	3.00	0.48	0.36
Jun 21	2.64	19.9	1.00	2.0	3.14	0.49	0.50
Jun 21	2.64	19.9	0.85	1.9	3.09	0.50	0.45
Jun 21	2.64	19.9	0.80	2.0	3.04	0.51	0.40
Jun 21	2.64	19.9	1.20	2.0	3.24	0.49	0.60
Jun 21	2.64	19.9	0.85	2.7	2.95	0.49	0.31
Jun 21	2.64	19.9	0.90	2.2	3.05	0.48	0.41
Jun 21	2.64	19.9	1.40	3.0	3.11	0.50	0.47

APPENDIX C

Summary of 1992 Sea Lamprey Performance Tests

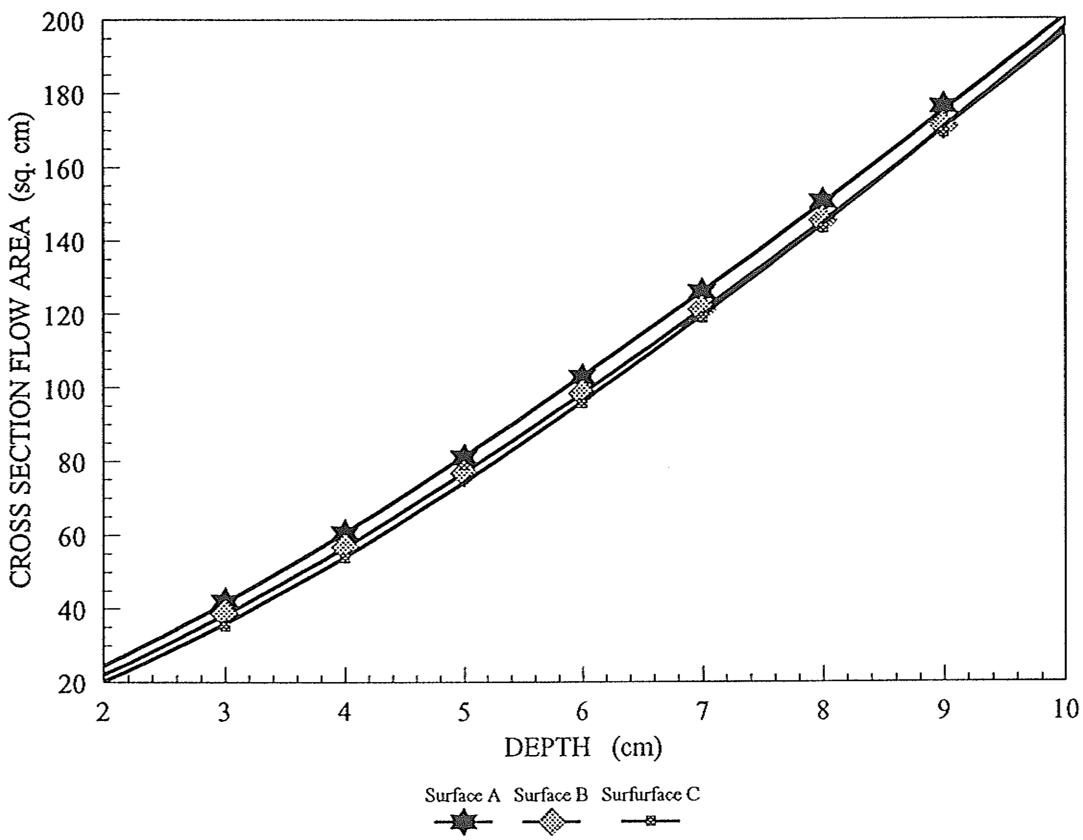

Figure C1 Cross section area versus depth in the test flume.

Table C1 Calibration of test flume outflow weir.

Timing flow into 60.5 cm cubic box

Test	Weir Control	Measured time, depth and volume			
	Intro Box Depth	Time	Box Depth at corners	Water Volume	Discharge
	cm	s	cm	cubic m	cubic m / s
#1a	26.36	18.29	41.9	0.1553	0.00849
			43.3		
			43.1		
			41.4		
b	" "	18.41	41.5	0.1556	0.00845
			42		
			43.3		
			43.2		
c	" "	18.84	41.9	0.1558	0.00827
			43.3		
			43.3		
			41.8		
d	" "	17.6	40.4	0.1504	0.00855
			42		
			41.8		
			40.2		
e	" "	17.9	42	0.1504	0.00840
			41.9		
			40.2		
			40.3		
f	" "	17.85	41.5	0.1512	0.00847
			41.9		
			41.7		
			40.1		
#2a	27.9	14.02	42.8	0.1581	0.01128
			45.3		
			43.7		
			41		
b	" "	14.02	41.5	0.1575	0.01123
			42.3		
			44.5		
			43.8		
c	" "	15	45.4	0.1690	0.01127
			47.7		
			46.9		
			44.7		continued

Table C1 (continued) Calibration of test flume outflow weir.

Test	Weir Control	Measured time, depth and volume			
	Intro Box Depth	Time	Box Depth at corners	Water Volume	Discharge
	cm	s	cm	cubic m	cubic m / s
d	" "	14.46	44.4	0.1657	0.01146
			46.6		
			46.2		
			43.9		
e	" "	13.83	41.4	0.1542	0.01115
			43.5		
			42.9		
			40.7		
#3a	29.65	11.65	45.9	0.1663	0.01427
			43.9		
			46.9		
			45		
b	" "	9.83	35.3	0.1342	0.01366
			38		
			37.7		
			35.7		
c	" "	9.77	37.7	0.1358	0.01390
			38.7		
			36		
			36		
d	" "	9.37	37.7	0.1305	0.01393
			36.1		
			34.1		
			34.7		
e	" "	11.04	44.2	0.1598	0.01447
			45		
			43.1		
			42.3		
f	" "	11.34	44.4	0.1613	0.01423
			45.3		
			43.7		
			42.9		
g	" "	10.25	40.1	0.1448	0.01412
			38.3		
			40.9		
			38.9		
#3a	29.66	9.45	40.5	0.1479	0.01565
			41		
			40.3		
			39.8		
b	" "	10.14	41.2	0.1508	0.01487
			42.2		
			41.2		
			40.2		

Table C2 Velocity calculations from discharge and area.

SLOPE 0.75%

		Jun 12, A, 0.0111 m^3/s			Jul 10, A, 0.0097 m^3/s				
Stn(m)	m	2.5	5	10	1	6	11	16	21
Depth	cm	8.3	8.2	8.5	7.8	7.8	7.8	8	7.7
Area	cm^2	159.6	155.6	164.1	149.24	145.56	146.5	154	146.45
Vel.	m/s	0.697	0.715	0.678	0.653	0.669	0.665	0.632	0.665

SLOPE 1.5%

Setup slope same for tests of Jun 26,30 & Jul 7; surface A.

		June 26, 0.0145 cms			June 30, 0.0142 cms		
Stn(m)	m	1	6	11	1	6	11
Depth	cm	8.1	7.9	7.7	7.9	7.8	7.7
Area	cm^2	151.7	148.055	144.03	151.7	145.6	144
Vel.	m/s	0.956	0.979	1.007	0.936	0.975	0.986

July 7, 0.0146 cms					
	Stn(m)	m	1	6	11
	Depth	cm	7.8	7.9	7.8
	Area	cm^2	149.24	148.06	146.5
	Vel.	m/s	0.978	0.986	0.997

Setup slope same for tests of Jul 14,14,15,16; surface A.

		July 14, 0.0150 cms				July 16, 0.0148 cms			
Stn(m)	m	1	6	11	16	1	6	11	16
Depth	cm	8	8	7.9	7.9	7.9	7.8	7.8	7.7
Area	cm^2	154.27	150.55	148.99	151.5	151.7	145.6	146.5	146.5
Vel.	m/s	0.972	0.996	1.007	0.990	0.976	1.016	1.010	1.010

SLOPE 2.5%

Setup slope same for tests of Jun 15,16,19; surface A.

		Jun 15, 0.014 m^3/s		Jun 16, 0.0142 cms		Jun 19, 0.0142 cms	
Stn(m)	m	1	10	1	10	1	10
Depth	cm	7	7	7	7	7.2	7.1
Area	cm^2	129.6	126.91	129.6	126.91	134.44	129.33
Vel.	m/s	1.080	1.103	1.037	1.098	1.056	1.098

Setup slope same for tests of July 31, 31, August 4, 7, and 10.

Date, surface		July 31, C	Aug 4, C	Aug 7, C	Aug 10, C
Stn(m)	m	6	6	6	6
Depth	cm	6.9	6.8	6.8	7
Area	cm^2	118.81	116.47	116.47	121.16
Vel.	m/s	1.213	1.221	1.221	1.236

SLOPE 3.5%

		Aug 13, C, 0.01422 m^3/s	Aug 14, C, 0.01422 m^3/s
Stn(m)	m	6	6
Depth	cm	6.4	6.3
Area	cm^2	107.26	104.96
Vel.	m/s	1.326	1.355

Table C3 Current meter measurements of test flume cross-sectional velocity distributions.

AUGUST 1992 VELOCITY DATA NOVONICS METER

This file summarizes all Novonics meter velocity data
at slopes of 1.5, 2.5, and 3.5 percent; all tests on surface C.

slope=1.5%
local=1m
depth=8.2cm

DEPTH (CM)	CROSS CHANNEL (3cm intervals) 6.00	9.00	12.00	15.00	18.00	21.00	24.00
SURFACE	0.79	1.06	1.19	1.29	1.19	1.03	0.88
1.00	0.80	1.06	1.23	1.29	1.22	1.08	0.88
2.00	0.79	1.20	1.21	1.26	1.23	1.13	0.91
3.00		1.09	1.20	1.24	1.23	1.11	
4.00		1.09	1.19	1.27	1.26	1.15	
5.00		0.99	1.20	1.26	1.24	1.14	
6.00			1.11	1.19	1.16		
7.00			0.89	1.06	1.04		

Method	V (m/s)	Diff. (%)
Vav.(Q/A)	0.995	
Metre.Avg.	1.04	4.5%

slope=1.5%
local=6m
depth=8.2

DEPTH (CM)	CROSS CHANNEL (3cm intervals) 6.00	9.00	12.00	15.00	18.00	21.00	24.00
SURFACE	0.83	1.05	1.21	1.29	1.18	1.05	0.84
1.00	0.82	1.07	1.18	1.27	1.16	1.07	0.89
2.00	0.81	1.10	1.21	1.27	1.21	1.18	0.91
3.00	0.70	1.12	1.25	1.30	1.27	1.16	0.87
4.00		1.09	1.24	1.30	1.25	1.11	
5.00		0.98	1.17	1.25	1.23	1.07	
6.00		0.82	1.07	1.15	1.13	0.96	
7.00			0.93	1.04	1.00		

Method	V (m/s)	Diff. (%)
Vav.(Q/A)	0.995	
Metre.Avg.	1.04	4.5%

slope=2.5%
local=6m
depth=6.8cm

DEPTH (CM)	CROSS CHANNEL (3cm intervals) 6.00	9.00	12.00	15.00	18.00	21.00	24.00
SURFACE	0.97	1.32	1.50	1.57	1.43	1.24	0.93
1.00	1.01	1.31	1.46	1.52	1.41	1.25	0.95
2.00	1.02	1.37	1.50	1.57	1.49	1.32	0.95
3.00		1.34	1.47	1.50	1.33	1.29	
4.00		1.31	1.47	1.51	1.38	1.26	
5.00		1.14	1.32	1.32	1.26	1.09	
6.00			1.21	1.22	1.12		
7.00							

Method	V (m/s)	Diff. (%)
Vav.(Q/A)	1.22	
Metre.Avg.	1.29	5.7%

continued

Table C3 (continued) Current meter measurements of test flume cross-sectional velocity distributions.

slope=2.5%			CROSS CHANNEL (3cm intervals)				
local=6m	6.00	9.00	12.00	15.00	18.00	21.00	24.00
depth=6.8							
DEPTH (CM)							
1.00	1.05	1.33	1.52	1.59	1.38	1.34	1.07
3.00		1.20	1.07	1.45	1.39	1.28	
5.00		1.05	1.20	1.37	1.26	1.07	

Method	V (m/s)	iff. (%)
Vav.(Q/A)	1.22	
Metre.Avg.	1.231	0.9%

slope=3.5%			CROSS CHANNEL (3cm intervals)				
local=1m	6.00	9.00	12.00	15.00	18.00	21.00	24.00
depth=6.3							
DEPTH(CM)							
SURFACE	0.92	1.38	1.68	1.75	1.69	1.52	1.11
1.00	0.88	1.42	1.69	1.72	1.72	1.49	1.09
2.00		1.42	1.63	1.74	1.71	1.57	
3.00		1.42	1.57	1.69	1.64	1.53	
4.00		1.35	1.42	1.56	1.53	1.40	
5.00			1.31	1.38	1.36		
6.00				1.30			

Method	V (m/s)	iff. (%)
Vav.(Q/A)	1.36	
Metre.Avg.	1.42	4.4%

slope=3.5%			CROSS CHANNEL (3cm intervals)				
local=6m	6.00	9.00	12.00	15.00	18.00	21.00	24.00
depth=6.3cm							
DEPTH(CM)							
SURFACE	1.04	1.49	1.72	1.71	1.67	1.46	1.08
1.00	1.01	1.49	1.70	1.78	1.64	1.46	1.06
2.00	1.00	1.45	1.60	1.75	1.64	1.40	1.05
3.00		1.45	1.64	1.74	1.63	1.47	
4.00		1.34	1.38	1.47	1.37	1.25	
5.00			1.36	1.33	1.26		
6.00			1.16	1.22	1.15		

Method	V (m/s)	iff. (%)
Vav.(Q/A)	1.36	
Metre.Avg.	1.39	2.2%

Table C4 Performance of individual sea lamprey in the swim tests (1992).

Test Date	Average Water Velocity m/s	Swim Zone Velocity m/s	Swim Distance m	Endurance Time s	Water Temp deg.C	Ground Rate m/s	Swim Velocity m/s	Lamprey Length m
19/06	0.66	0.73	7.50	12.0	9.5	0.63	1.35	0.50
19/06	0.66	0.73	9.40	11.0	9.5	0.85	1.58	0.45
19/06	0.66	0.73	23.50	44.0	9.5	0.53	1.26	0.53
19/06	0.66	0.73	22.80	36.0	9.5	0.63	1.36	0.54
19/06	0.66	0.73	4.00	9.0	9.5	0.44	1.17	0.48
19/06	0.66	0.73	18.50	48.0	9.5	0.39	1.11	0.51
19/06	0.66	0.73	23.60	39.0	9.5	0.61	1.33	0.53
19/06	0.66	0.73	13.90	13.0	9.5	1.07	1.80	0.50
19/06	0.66	0.73	10.00	17.0	9.5	0.59	1.31	0.50
19/06	0.66	0.73	8.40	16.0	9.5	0.53	1.25	0.47
19/06	0.66	0.73	16.20	26.0	9.5	0.62	1.35	0.55
19/06	0.66	0.73	8.70	16.0	9.5	0.54	1.27	0.46
19/06	0.66	0.73	14.80	16.0	9.5	0.93	1.65	0.59
19/06	1.15	1.27	2	5.0	9.3	0.40	1.67	0.51
19/06	1.15	1.27	2.80	5.0	9.3	0.56	1.83	0.52
19/06	1.15	1.27	5.2	14.0	9.3	0.37	1.64	0.54
19/06	1.15	1.27	3.50	8.0	9.3	0.44	1.70	0.53
19/06	*1.15*	*1.27*	*4.20*	*7.0*	*9.3*	*0.60*	*1.87*	*0.57*
19/06	1.15	1.27	3.00	7.0	9.3	0.43	1.69	0.49
19/06	1.15	1.27	2.5	6.0	9.3	0.42	1.68	0.53
19/06	1.15	1.27	1.00	3.0	9.3	0.33	1.60	0.39
19/06	1.15	1.27	2.00	4.0	9.3	0.50	1.77	0.49
19/06	1.15	1.27	1.80	4.0	9.3	0.45	1.72	
23/06	0.93	1.02	4.50	25.0	9.5	0.18	1.20	0.50
23/06	0.93	1.02	5.40	12.0	9.5	0.45	1.47	0.50
23/06	0.93	1.02	6.80	14.0	9.5	0.49	1.51	0.47
23/06	0.93	1.02	5.20	13.0	9.5	0.40	1.42	0.50
23/06	0.93	1.02	4.60	11.0	9.5	0.42	1.44	0.50
23/06	0.93	1.02	9.70	44.0	9.5	0.22	1.24	0.53
23/06	0.93	1.02	3.20	10.0	9.5	0.32	1.34	0.54
23/06	0.93	1.02	8.10	16.0	9.5	0.51	1.53	0.55
23/06	0.93	1.02	10.10	17.0	9.5	0.59	1.62	0.58
23/06	0.93	1.02	7.80	16.0	9.5	0.49	1.51	0.45
23/06	0.93	1.02	7.20	17.0	9.5	0.42	1.45	0.53
23/06	0.93	1.02	8.5	15.0	9.5	0.57	1.59	0.54
24/06	0.97	1.07	6.2	12.0	10.0	0.52	1.58	0.56
24/06	0.97	1.07	7.3	14.0	10.0	0.52	1.59	0.55
24/06	0.97	1.07	3	6.0	10.0	0.50	1.57	0.48
24/06	0.97	1.07	3	5.0	10.0	0.60	1.67	0.47
24/06	0.97	1.07	9.1	23.0	10.0	0.40	1.46	0.53
24/06	0.97	1.07	11.2	19.0	10.0	0.59	1.66	0.55
24/06	0.97	1.07	4.5	9.0	10.0	0.50	1.57	0.50
24/06	0.97	1.07	6.5	15.0	10.0	0.43	1.50	0.52
24/06	0.97	1.07	6.5	19.0	10.0	0.34	1.41	0.53
24/06	0.97	1.07	4.1	8.0	10.0	0.51	1.58	0.52
24/06	0.97	1.07	1.7	3.0	10.0	0.57	1.63	0.44

continued

Table C4 (continued) Performance of individual sea lamprey in the swim tests (1992).

Test Date	Average Water Velocity m/s	Swim Zone Velocity m/s	Swim Distance m	Endurance Time s	Water Temp deg.C	Ground Rate m/s	Swim Velocity m/s	Lamprey Length m
26/06	1.45	1.59	2.3	3.5	10.0	0.66	2.25	0.55
26/06	1.45	1.59	3	15.0	10.0	0.20	1.79	0.53
26/06	1.45	1.59	1	3.0	10.0	0.33	1.92	0.45
26/06	1.45	1.59	2.1	8.0	10.0	0.26	1.85	0.53
26/06	1.45	1.59	2.8	11.0	10.0	0.25	1.85	0.53
26/06	1.45	1.59	2	7.0	10.0	0.29	1.88	0.47
26/06	1.45	1.59	1.4	5.0	10.0	0.28	1.87	0.50
26/06	1.45	1.59	1.25	6.0	10.0	0.21	1.80	0.48
07/07	0.99	1.09	4.05	8.0	9.0	0.51	1.60	0.49
07/07	0.99	1.09	4.1	11.5	9.0	0.36	1.45	0.42
07/07	0.99	1.09	10.8	22.6	9.0	0.48	1.57	0.51
07/07	0.99	1.09	11.1	18.0	9.0	0.62	1.71	0.55
07/07	0.99	1.09	10.3	16.2	9.0	0.64	1.72	0.50
07/07	0.99	1.09	10.2	12.0	9.0	0.85	1.94	0.51
07/07	0.99	1.09	6.2	12.0	9.0	0.52	1.61	0.49
07/07	0.99	1.09	7.6	11.0	9.0	0.69	1.78	0.52
07/07	0.99	1.09	8.3	24.0	9.0	0.35	1.43	0.54
07/07	0.99	1.09	4.6	10.0	9.0	0.46	1.55	0.44
07/07	0.99	1.09	5.4	10.0	9.0	0.54	1.63	0.50
07/07	0.99	1.09	13.5	25.0	9.0	0.54	1.63	0.59
10/07	0.66	0.73	28.5	58.4	10.3	0.49	1.21	0.46
10/07	0.66	0.73	30	62.0	10.3	0.48	1.21	0.57
10/07	0.66	0.73	28.5	48.3	10.3	0.59	1.32	0.52
10/07	0.66	0.73	22.1	44.0	10.3	0.50	1.23	0.42
10/07	0.66	0.73	28	53.5	10.3	0.52	1.25	0.40
10/07	0.66	0.73	26.8	48.0	10.3	0.56	1.28	0.53
10/07	0.66	0.73	26.5	45.1	10.3	0.59	1.31	0.53
10/07	0.66	0.73	8.1	14.0	10.3	0.58	1.30	0.42
10/07	0.66	0.73	28.2	43.0	10.3	0.66	1.38	0.50
10/07	0.66	0.73	17.5	40.0	10.3	0.44	1.16	0.50
10/07	0.66	0.73	13.2	27.4	10.3	0.48	1.21	0.50
10/07	0.66	0.73	16.6	33.9	10.3	0.49	1.22	0.49
23/07	1.04	1.14	16.8	48	14.3	0.35	1.49	0.48
23/07	1.04	1.14	19	30	14.3	0.63	1.78	0.51
23/07	1.04	1.14	14.9	44.2	14.3	0.34	1.48	0.51
23/07	1.04	1.14	20.05	43.7	14.3	0.46	1.60	0.58
23/07	1.04	1.14	16.6	40.7	14.3	0.41	1.55	0.48
23/07	1.04	1.14	24.48	42.4	14.3	0.58	1.72	0.50
23/07	1.04	1.14	17.45	36.4	14.3	0.48	1.62	0.47
23/07	1.04	1.14	20.5	36.7	14.3	0.56	1.70	0.57
23/07	1.04	1.14	14.2	45	14.3	0.32	1.46	0.49
23/07	1.04	1.14	18.9	56	14.3	0.34	1.48	0.50
23/07	1.04	1.14	20.25	52.1	14.3	0.39	1.53	0.51
23/07	1.04	1.14	17.1	71.6	14.3	0.24	1.38	
23/07	1.04	1.14	17.5	59.6	14.3	0.29	1.44	0.48
23/07	1.04	1.14	25.7	65.2	14.3	0.39	1.54	0.51
24/07	1.04	1.14	13.5	26.3	15.0	0.51	1.66	0.48

continued

Table C4 (continued) Performance of individual sea lamprey in the swim tests (1992).

Test Date	Average Water Velocity m/s	Swim Zone Velocity m/s	Swim Distance m	Endurance Time s	Water Temp deg.C	Ground Rate m/s	Swim Velocity m/s	Lamprey Length m
24/07	1.04	1.14	16.1	32.1	15.0	0.50	1.65	0.51
24/07	1.04	1.14	14.2	32.2	15.0	0.44	1.58	0.43
24/07	1.04	1.14	24.8	99.4	15.0	0.25	1.39	0.54
24/07	1.04	1.14	9.8	24.5	15.0	0.40	1.54	0.40
24/07	1.04	1.14	24.28	64.8	15.0	0.37	1.52	0.51
24/07	1.04	1.14	18.1	48.5	15.0	0.37	1.52	0.48
31/7	1.22	1.34	13.8	33.5	15.5	0.41	1.75	0.55
31/7	1.22	1.34	11.6	18.9	15.5	0.61	1.96	0.50
31/7	1.22	1.34	13.8	28.3	15.5	0.49	1.83	0.48
31/7	1.22	1.34	8.5	33	15.5	0.26	1.60	0.56
31/7	1.22	1.34	11.45	22.3	15.5	0.51	1.86	0.51
31/7	1.22	1.34	8.4	16.6	15.5	0.51	1.85	0.50
31/7	1.22	1.34	9.1	35.8	15.5	0.25	1.60	0.55
31/7	1.22	1.34	11.2	12.5	15.5	0.90	2.24	0.49
31/7	1.22	1.34	9.3	16.8	15.5	0.55	1.90	0.56
31/7	1.22	1.34	10.8	17.8	15.5	0.61	1.95	0.54
04/8	1.22	1.34	7.4	20.8	15.8	0.36	1.70	0.48
04/8	1.22	1.34	9.4	21.5	15.8	0.44	1.78	0.48
04/8	1.22	1.34	12.3	18.3	15.8	0.67	2.01	0.51
04/8	1.22	1.34	9	13	15.8	0.69	2.03	
04/8	1.22	1.34	8.1	16.2	15.8	0.50	1.84	0.47
04/8	1.22	1.34	8.9	17.7	15.8	0.50	1.84	0.48
04/8	1.22	1.34	6.7	18.3	15.8	0.37	1.71	0.47
04/8	1.22	1.34	9.8	22.6	15.8	0.43	1.77	0.49
04/8	1.22	1.34	20.9	68	15.8	0.31	1.65	0.54
04/8	1.22	1.34	8.8	22.7	15.8	0.39	1.73	0.52
04/8	1.22	1.34	5.4	23.1	15.8	0.23	1.57	0.54
04/8	1.22	1.34	6.7	35.6	15.8	0.19	1.53	0.46
04/8	1.22	1.34	10.8	32.1	15.8	0.34	1.68	0.49
04/8	1.22	1.34	11.2	23.5	15.8	0.48	1.82	0.47
04/8	1.22	1.34	7.7	50.5	15.8	0.15	1.49	0.55
04/8	1.22	1.34	11.1	41.7	15.8	0.27	1.61	0.50
04/8	1.22	1.34	9.9	24.9	15.8	0.40	1.74	0.50
04/8	1.22	1.34	12.5	24.6	15.8	0.51	1.85	0.50
07/8	1.22	1.34	7	8.1	16.8	0.86	2.20	0.44
07/8	1.22	1.34	5.2	8	16.8	0.65	1.99	0.48
07/8	1.22	1.34	7.8	6.4	16.8	1.22	2.56	0.53
07/8	1.22	1.34	8.9	13.2	16.8	0.67	2.01	0.43
07/8b	1.22	1.34	15.3	54.8	16.8	0.28	1.62	0.53
07/8b	1.22	1.34	9.7	15.7	16.8	0.62	1.96	
07/8b	1.22	1.34	8.2	25	16.8	0.33	1.67	0.44
07/8b	1.22	1.34	12.1	47	16.8	0.26	1.60	0.52
07/8b	1.22	1.34	10.15	16.4	16.8	0.62	1.96	0.54
10/8	1.22	1.34	11.05	20.06	16.7	0.55	1.89	0.47
10/8	1.22	1.34	12.4	19.5	16.7	0.64	1.98	0.54
10/8	1.22	1.34	9.5	35	16.7	0.27	1.61	0.52
10/8	1.22	1.34	8.25	12.2	16.7	0.68	2.02	0.43
10/8	1.22	1.34	15.3	64	16.7	0.24	1.58	0.53
10/8	1.22	1.34	9.2	15.5	16.7	0.59	1.93	0.46
10/8	1.22	1.34	9.3	13.8	16.7	0.67	2.01	0.49

continued

Table C4 (continued) Performance of individual sea lamprey in the swim tests (1992).

Test Date	Average Water Velocity m/s	Swim Zone Velocity m/s	Swim Distance m	Endurance Time s	Water Temp deg.C	Ground Rate m/s	Swim Velocity m/s	Lamprey Length m
10/8	1.22	1.34	13.03	19	16.7	0.69	2.03	0.54
10/8	1.22	1.34	10.5	15.6	16.7	0.67	2.01	0.53
10/8	1.22	1.34	12.3	15.8	16.7	0.78	2.12	0.47
10/8	1.22	1.34	10.4	43	16.7	0.24	1.58	0.51
10/8	1.22	1.34	12.35	20.1	16.7	0.61	1.95	0.55
13/8	1.35	1.49	4.1	10.1	16.0	0.41	1.89	0.46
13/8	1.35	1.49	5	11.4	16.0	0.44	1.92	0.43
13/8	1.35	1.49	5.7	15.5	16.0	0.37	1.85	0.50
13/8	1.35	1.49	4.45	9.4	16.0	0.47	1.96	0.49
13/8	1.35	1.49	4.7	11	16.0	0.43	1.91	0.45
13/8	1.35	1.49	2.1	4.7	16.0	0.45	1.93	0.45
13/8	1.35	1.49	7.8	18	16.0	0.43	1.92	0.51
13/8	1.35	1.49	7.4	18.2	16.0	0.41	1.89	0.51
13/8	1.35	1.49	8.5	18.5	16.0	0.46	1.94	0.48
13/8	1.35	1.49	5.35	20.4	16.0	0.26	1.75	0.52
14/8	1.35	1.49	10.1	17.5	16.1	0.58	2.06	0.50
14/8	1.35	1.49	5.6	11.9	16.1	0.47	1.96	0.44
14/8	1.35	1.49	4.8	8.2	16.1	0.59	2.07	0.46

APPENDIX D

Hydraulic Modelling

Table D1 Model volumetric discharge calibration.

Test No.	South Gage Time	South Gage Q	North Gage Time	North Gage Q	Qavg	Upstream Point Gage	Qavg	Upstream Point Gage
	s	*cfs*	*s*	*cfs*	*cfs*	*cm*	*cfs*	*cm*
1) Chute alone, extended centre pier								
1	97.9	1.851	96.7	1.882	1.867	30.02	1.872	30.020
2	97.6	1.857	96.2	1.892	1.874	30.02		
3	97.6	1.857	96.0	1.896	1.876	30.02		
1	108.2	1.676	106.0	1.717	1.697	28.9	1.696	28.900
2	107.4	1.688	106.7	1.706	1.697	28.9		
3	107.6	1.685	106.8	1.704	1.695	28.9		
1	119.0	1.525	116.6	1.561	1.543	27.88	1.542	27.880
2	118.6	1.530	116.8	1.558	1.544	27.88		
3	118.8	1.528	117.2	1.553	1.540	27.88		
1	132.2	1.374	130.0	1.400	1.387	26.79	1.386	26.790
2	131.8	1.378	131.2	1.387	1.383	26.79		
3	131.6	1.380	130.6	1.394	1.387	26.79		
1	147.6	1.232	144.0	1.264	1.248	25.75	1.251	25.750
2	145.8	1.247	144.7	1.258	1.252	25.75		
3	145.8	1.247	144.9	1.256	1.252	25.75		
1	168.0	1.084	167.5	1.087	1.085	24.65	1.084	24.650
2	169.3	1.076	168.2	1.082	1.079	24.65		
3	168.0	1.084	166.4	1.094	1.089	24.65		
1	203.0	0.899	200.2	0.909	0.904	23.16	0.902	23.160
2	203.7	0.896	199.8	0.911	0.904	23.16		
3	205.0	0.891	201.1	0.905	0.898	23.16		
1	244.8	0.748	240.6	0.756	0.752	21.92	0.751	21.913
2	240.0	0.763	246.8	0.737	0.750	21.91		
3	240.4	0.761	245.8	0.740	0.751	21.91		
1	299.6	0.613	294.0	0.619	0.616	20.71	0.616	20.710
2	300.2	0.612	292.9	0.621	0.617	20.71		
3	299.8	0.613	293.6	0.620	0.616	20.71		
1	436.7	0.425	428.8	0.424	0.425	18.82	0.424	18.820
2	441.0	0.421	424.4	0.429	0.425	18.82		
3	442.0	0.420	429.5	0.424	0.422	18.82		
2) Weir crest alone								
1	102.4	0.879	102.8	0.885	0.882	32.81	0.884	32.810
2	102.2	0.881	102.3	0.890	0.885	32.81		
3	102.5	0.878	102.2	0.890	0.884	32.81		
1	124.7	0.722	124.3	0.732	0.727	31.7	0.726	31.700
2	125.4	0.718	123.9	0.734	0.726	31.7		
3	124.6	0.722	124.8	0.729	0.726	31.7		
1	153.3	0.587	150.9	0.603	0.595	30.66	0.592	30.647
2	153.5	0.586	151.7	0.600	0.593	30.66		
3	154.6	0.582	152.7	0.596	0.589	30.62		

continued

Table D1 (continued) Model volumetric discharge calibration.

Test No.	Time *s*	South Gage Q *cfs*	Time *s*	North Gage Q *cfs*	Qavg *cfs*	Upstream Point Gage *cm*	Qavg *cfs*	Upstream Point Gage *cm*
2) Weir crest alone								
1	186.0	0.484	184.3	0.494	0.489	29.72	0.487	29.717
2	187.1	0.481	185.0	0.492	0.486	29.72		
3	187.4	0.480	185.3	0.491	0.486	29.71		
1	294.2	0.306	284.1	0.320	0.313	28.11	0.312	28.103
2	294.6	0.305	285.9	0.318	0.312	28.1		
3	294.8	0.305	286.0	0.318	0.312	28.1		
1	597.0	0.151	539.0	0.169	0.160	26.3	0.159	26.300
2	594.0	0.152	546.0	0.167	0.159	26.3		
3	601.0	0.150	546.0	0.167	0.158	26.3		
3) chute and weir; one chute pier removed								
1	73.4	2.452	72.5	2.510	2.481	29.6	2.491	29.678
2	73.1	2.462	72.1	2.524	2.493	29.7		
3	72.9	2.469	72.0	2.528	2.498	29.72		
4	73.3	2.456	72.1	2.524	2.490	29.69		
1	95.7	1.881	94.6	1.924	1.902	27.72	1.904	27.720
2	95.8	1.879	94.4	1.929	1.904	27.72		
3	95.5	1.885	94.7	1.922	1.903	27.72		
4	95.4	1.887	94.6	1.925	1.906	27.72		
1	154.4	1.166	151.5	1.201	1.184	24.69	1.182	24.690
2	155.3	1.159	152.0	1.197	1.178	24.69		
3	154.5	1.165	151.6	1.201	1.183	24.69		
1	269.6	0.668	259.1	0.702	0.685	21.22	0.684	21.220
2	269.9	0.667	259.0	0.703	0.685	21.22		
3	268.9	0.669	261.8	0.695	0.682	21.22		
1	488.0	0.369	474.4	0.384	0.376	18.22	0.377	18.220
2	491.2	0.366	469.6	0.388	0.377	18.22		
3	488.4	0.369	473.2	0.385	0.377	18.22		
1	348.6	0.516	342.7	0.531	0.524	19.71	0.523	19.707
2	349.6	0.515	343.2	0.530	0.523	19.71		
3	348.8	0.516	345.6	0.527	0.521	19.7		
1	172.0	1.047	167.8	1.085	1.066	24.09	1.065	24.090
2	171.8	1.048	169.3	1.075	1.061	24.09		
3	173.0	1.040	166.4	1.094	1.067	24.09		
1	130.3	1.381	143.1	1.272	1.381	25.7	1.383	25.700
2	130.2	1.382	148.4	1.226	1.382	25.7		
3	129.6	1.389	153.6	1.185	1.389	25.7		
4	130.5	1.379	148.2	1.228	1.379	25.7		

continued

Table D1 (continued) Model volumetric discharge calibration.

Test No.	Time *s*	South Gage Q *cfs*	Time *s*	North Gage Q *cfs*	Qavg *cfs*	Upstream Point Gage *cm*	Qavg *cfs*	Upstream Point Gage *cm*
4) chute and weir; one chute pier removed, ramped upstream substrate								
1	133.0	1.353	153.6	1.185	1.353	25.7	1.362	25.733
2	131.3	1.371	153.6	1.185	1.371	25.75		
3	132.2	1.362	153.0	1.190	1.362	25.75		
1	84.8	2.123	84.4	2.158	2.123	29.67	2.138	29.670
2	83.3	2.161	83.0	2.193	2.161	29.67		
3	84.5	2.130			2.130	29.67		
1	99.4	1.811	97.8	1.861	1.836	27.72	1.835	27.720
2	99.8	1.804	98.9	1.840	1.822	27.72		
3	98.4	1.829	97.7	1.863	1.846	27.72		
1	209.6	0.859	205.8	0.884	0.872	23.16	0.872	23.160
5) chute and weir; one chute pier removed, extended upstream pier								
1	87.9	2.060	86.7	2.099	2.080	28.3	2.075	28.300
2	88.4	2.049	86.9	2.094	2.072	28.3		
3	88.2	2.053	86.9	2.094	2.074	28.3		
1	101.0	1.795	99.6	1.827	1.811	27.4	1.812	27.400
2	100.8	1.798	99.8	1.824	1.811	27.4		
3	100.6	1.802	99.8	1.824	1.813	27.4		
1	121.0	1.500	119.8	1.519	1.510	26.24	1.510	26.240
2	121.2	1.498	119.6	1.522	1.510	26.24		
3	121.0	1.500	119.6	1.522	1.511	26.24		
1	143.6	1.266	142.2	1.280	1.273	25.2	1.270	25.200
2	144.4	1.259	143.2	1.271	1.265	25.2		
3	144.0	1.263	142.0	1.282	1.272	25.2		
1	177.4	1.027	175.2	1.039	1.033	23.96	1.032	23.960
2	177.8	1.025	174.8	1.041	1.033	23.96		
3	178.6	1.020	175.2	1.039	1.030	23.96		
1	203.0	0.899	200.2	0.909	0.904	23.16	0.902	23.160
2	203.7	0.896	199.8	0.911	0.904	23.16		
3	205.0	0.891	201.1	0.905	0.898	23.16		
1	244.8	0.748	240.6	0.756	0.752	21.92	0.751	21.913
2	240.0	0.763	246.8	0.737	0.750	21.91		
3	240.4	0.761	245.8	0.740	0.751	21.91		
1	299.6	0.613	294.0	0.619	0.616	20.71	0.616	20.710
2	300.2	0.612	292.9	0.621	0.617	20.71		
3	299.8	0.613	293.6	0.620	0.616	20.71		
1	436.7	0.425	428.8	0.424	0.425	18.82	0.424	18.820
2	441.0	0.421	424.4	0.429	0.425	18.82		
3	442.0	0.420	429.5	0.424	0.422	18.82		
6) chute alone with both piers								
B2	111.6	0.806	117.6	0.774	0.790	22.22	0.791	22.22
	112.3	0.801	116.4	0.782	0.792	22.22		
B3	89.0	1.011	91.2	0.998	1.005	24.02	1.005	24.02
7) chute alone with both piers and flow over crest								
B4	71.9	1.252	73.4	1.240	1.246	25.38	1.246	25.38
B5	60.6	1.486	61.9	1.470	1.478	26.5	1.478	26.5
B6	51.1	1.761	51.4	1.770	1.766	27.67	1.766	27.67
B7	37.4	2.406	37.9	2.401	2.404	29.91	2.404	29.91

Table D2 Stage discharge calibration of principal model sections.

#	Upstream Point Gage	Upstream Vel. head	H	Discharge	Weir Coefficient
	cm	*cm*	*m*	*cms*	
1) Chute alone, extended centre pier					
	30.02	0.18	0.184	0.053	1.681
	28.90	0.16	0.173	0.048	1.676
	27.88	0.14	0.162	0.044	1.672
	26.79	0.13	0.151	0.039	1.670
	25.75	0.11	0.141	0.035	1.680
	24.65	0.09	0.129	0.031	1.649
	23.16	0.08	0.114	0.026	1.652
	21.91	0.06	0.102	0.021	1.639
	20.71	0.05	0.090	0.017	1.629
	18.82	0.03	0.070	0.012	1.604
2) Weir crest alone					
	32.81	0.03	0.099	0.025	1.968
	31.70	0.02	0.088	0.021	1.937
	30.65	0.02	0.077	0.017	1.918
	29.72	0.01	0.068	0.014	1.915
	28.13	0.01	0.052	0.009	1.853
	26.30	0.00	0.034	0.005	1.814
	23.00	0.00	0.000	0.000	
6) chute alone with both piers					
	21.62	0.07	0.099	0.022	1.802
	23.42	0.09	0.117	0.028	1.775

APPENDIX E

Hydraulic and Fish Passage Data at the McIntyre River Velocity Barrier

Table E1 Discharge measurements on May 11, 1994 at the velocity barrier chute.

Instrument: Electromagnetic (Marsh McBirney Flo-mate 2000)
UWL 0.8735

Stream Discharge	2.538	cms
Chute Discharge	1.497	cms
Chute Vel-avg	2.044	m/s

CHUTE						Qmn 1.497
Stn and distance from wall						Difference
Stn 1 m	@ 0.3m	@ 0.9m	@ 1.5m	@ 2.1m	Avg	from Qmn
Depth (m)	0.265	0.262	0.262	0.26	0.262	
Vel: .8h	2.45	2.6	2.55	2.39	2.498	
Vel: .2h	2.4	2.3	2.36	2.2	2.315	
V_avg					2.406	
Q_chute					1.482	-1.0%
Stn 4.5 m						
Depth (m)	0.315	0.315	0.315	0.315	0.32	
Vel: .8h	2.1	2.06	2.14	2.03	2.08	
Vel: .2h	2.1	1.9	2	1.89	1.97	
V_avg					2.03	
Q_chute					1.507	0.7%
Stn 8 m						
Depth (m)	0.365	0.37	0.38	0.38	0.374	
Vel: .8h	1.65	1.68	1.75	1.6	1.67	
Vel: .2h	1.65	1.68	1.79	1.78	1.725	
V_avg					1.698	
Q_chute					1.502	0.3%
V_avg Chute					2.044	m/s
Q_avg Chute					1.497	cms

Table E2 McIntyre River velocity barrier discharges and chute velocities.

Date	Discharge			Velocity	Staff Gages	
	Total	Chute	Weir	Chute Av.	UWL	DWL
	cms	cms	cms	m/s	m	m
Sept 3, 93	0.592	0.591	0.001	1.66	0.645	0.090
Sept 13, 93	0.467	0.467	0.000	1.53	0.607	0.055
Oct 21, 93	1.482	1.130	0.352	1.94	0.788	0.120
Oct 22, 93	2.069	1.396	0.673	1.99	0.837	0.245
May11, 94	2.538	1.497	1.041	2.04	0.874	0.280
May12, 94	3.067	1.674	1.393	2.14	0.910	0.320

1 m Stn.	Discharge Measured m^3/s	Velocity Average m/s	Depth Average m
Sept 3, 93	0.614	2.015	0.133
Sept 13, 93	0.464	1.790	0.114
Oct 21, 93	1.136	2.294	0.212
Oct 22, 93	1.391	2.340	0.252
May11, 94	1.482	2.406	0.262
May12, 94	1.679	2.574	0.284

4.5 m Stn.	Discharge Measured m^3/s	Velocity Average m/s	Depth Average m
Sept 3, 93	0.600	1.590	0.165
Sept 13, 93	0.495	1.496	0.144
Oct 21, 93	1.124	1.928	0.248
Oct 22, 93	1.400	1.955	0.302
May11, 94	1.507	2.030	0.320
May12, 94	1.687	2.110	0.340

8.0 m Stn.	Discharge Measured m^3/s	Velocity Average m/s	Depth Average m
Sept 3, 93	0.560	1.387	0.176
Sept 13, 93	0.451	1.292	0.152
Oct 21, 93	1.130	1.603	0.308
Oct 22, 93	1.396	1.670	0.352
May11, 94	1.502	1.698	0.374
May12, 94	1.655	1.734	0.403

Table E3 Summary of white sucker catches upstream and downstream of the McIntyre River velocity barrier on May 13 and 14, 1994.

Location	Date	Number trapped	Lengths (Fork Length cm)				
			L_{avg}(cm)	L_{min}	L_{max}	<40cm	<36cm
Downstream	May 13	46	41.6	34.9	46.2	28 %	7.7 %
Upstream	May 13	71	41.1	30.9	50.9	37 %	7.4 %
Upstream	May 14	74	42.1	35.8	49.3	27 %	1.5 %

Summary of Observations of White Suckers Swimming in the Velocity Barrier

White sucker passage through the velocity chute in the springs of 1994 and 1995 was confirmed by net catches upstream of the barrier (Chase, 1994; 1995). On May 13, 1994, 71 white suckers taken from the net upstream of the barrier averaged 41.1 cm in length (range 30.9 to 50.9). The following day, 74 white suckers taken upstream averaged 42.1 cm in length (range 35.8 to 49.3) (Chase, 1994). The sizes of fish caught upstream compare very closely with the catch of 46 white suckers downstream of the barrier on May 13 averaging 41.6 cm in length (range 34.9 to 46.2). The nearly identical mean length would suggest that the barrier was not preferentially blocking smaller fish. However an analysis of the May 13 catch showed approximately one fifth as many fish in the under 36 cm length range. Trap data for the fish retrieved on May 13 and 14 can be seen in Table E1 of Appendix E.

On May 12, 1994, suckers were observed swimming in the chute by the author and M. Chase at water temperatures of 10 - 11° C. A stopwatch was used to record the time to swim through the chute, or the time until a fish began washing back downstream. The distance swam by the fish was measured from markers on the chute sidewall; 8.5 m being a successful passage through the chute. Fish size was visually estimated as small, medium, or large. These sizes relate to a length range of 30 to 50 cm as found by trapping measurements (Table E3). A summary of the values by size group and for all 37 fish observed can be seen in Table E4. Individual swim times and distances can be seen in Table E5.

Generally, the fish did not show a preferred swimming location or depth. From the velocity profiles, it was judged that mean section velocities were fairly representative of the velocities faced by the fish. The average swim velocity for each fish was calculated by distance over time (ground rate) plus the water velocity of the length of chute swam by the fish. For the small fish, only 3 out of 9 attempts passed through the 8.5 m chute. Three of the unsuccessful attempts achieved 7.9 m to 8.4 m. It is known that fish normally make several or many attempts at barriers and these 3 may have passed later on. The group of small fish was attributed an average length of 35 cm by proportioning the trap sizes. This appeared confirmed by the lower catches in the under 36 cm range on May 13.

Table E4 Summary of observations of white suckers swimming in the velocity chute on May 12, 1994. Group sizes are relative to catch length range of 30 to 50 cm as seen in Table E3.

Group	Number observed	Swim Distance *m*		Swim Duration *s*		Ground Speed *m/s*		Swim Speed *m/s*	
		median	mean	median	mean	median	mean	median	mean
Small	9	8	7.9	12.6	12.3	0.65	0.66	2.73	2.76
Medium	16	8.5	8.3	10.0	10.0	0.83	0.85	2.93	2.94
Large	11	8.5	6.8	10.5	10.4	0.73	0.66	3.01	2.87
Xlarge	1	8.5	8.5	5.5	5.5	1.55	1.55	3.62	3.62
All	37	8.5	7.8	10.8	10.6	0.76	0.77	2.85	2.87

Table E5 Performance of white suckers in the velocity flume on May 12, 1994.

Chron. Order	Distance Swam *1 *m*	Swim Time *s*	Size (visual est.*2)	Ground Rate *m/s*	Swim Speed *3 *m/s*
1	6.5	15	sm	0.43	2.71
2	8.5	10.8	med	0.79	2.87
3	8.5	10	sm	0.85	2.93
4	8.5	11.2	med	0.76	2.84
5	8.5	8.85	med	0.96	3.04
6	8	12.6	sm	0.63	2.71
7	4	7	lg	0.57	2.87
8	8.5	9.5	lg	0.89	2.97
9	8.5	7.5	med	1.13	3.21
10	8.4	13	sm	0.65	2.73
11	8.5	9	med	0.94	3.02
12	7	13	sm	0.54	2.62
13	8.5	10	med	0.85	2.93
14	8.5	11	lg	0.77	2.85
15	8.5	11.2	lg	0.76	2.84
16	8	13.5	sm	0.59	2.67
17	8.5	10.4	med	0.82	2.90
18	0.3	6	lg	0.05	2.13
19	8.5	11.2	med	0.76	2.84
20	4.5	17.2	lg	0.26	2.55
21	7.9	11.2	sm	0.71	2.78
22	5.9	10.5	lg	0.56	2.84
23	8.5	9.4	med	0.90	2.98
24	8.5	8.3	med	1.02	3.10
25	8.5	7.5	lg	1.13	3.21
26	8.5	11	sm	0.77	2.85
27	5.5	8.6	med	0.64	2.92
28	8.5	12.6	med	0.67	2.75
29	8.5	13.7	lg	0.62	2.70
30	8.5	9.5	lg	0.89	2.97
31	8.5	13	med	0.65	2.73
32	8.5	5.5	xlg	1.55	3.62
33	8.5	10	med	0.85	2.93
34	8.5	11.7	lg	0.73	2.81
35	8.5	11	sm	0.77	2.85
36	8.5	7.9	med	1.08	3.15
37	8.5	11.4	med	0.75	2.82
Mean	7.8	10.6		0.77	2.87
Median	8.5	10.8		0.76	2.85

*1 8.5 m means passage through the flume of 8.5 m length.

*2 Visual size estimates relate to a range of lengths between 30 and 50 cm (Table 2).

*3 Ground rate plus average water velocity of chute segment.

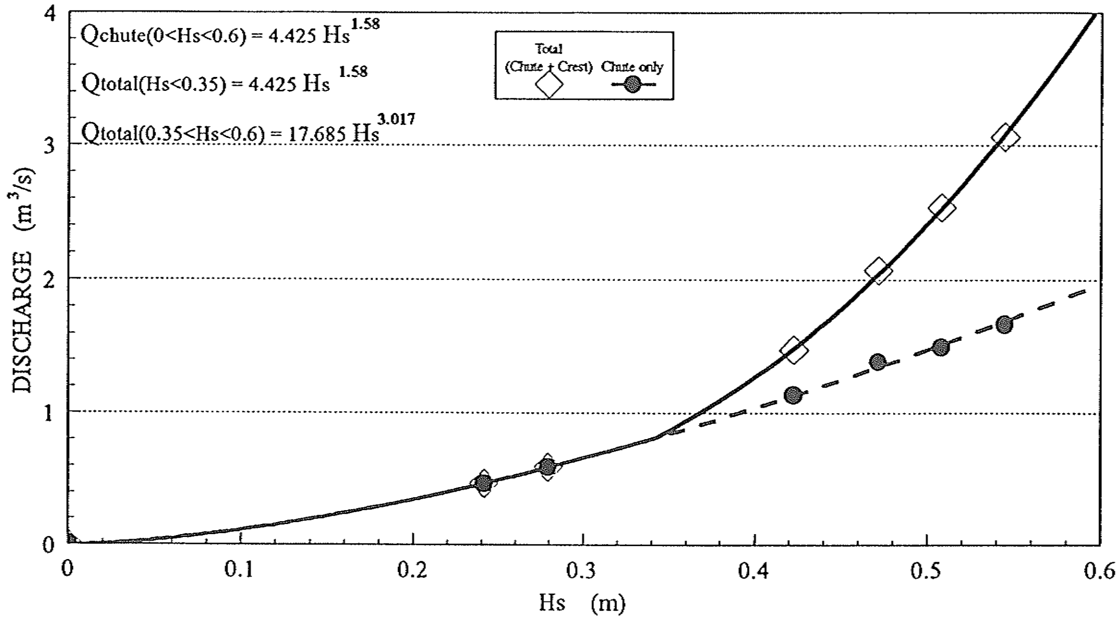

Figure E1 Stage - discharge graph for the McIntyre River velocity barrier.

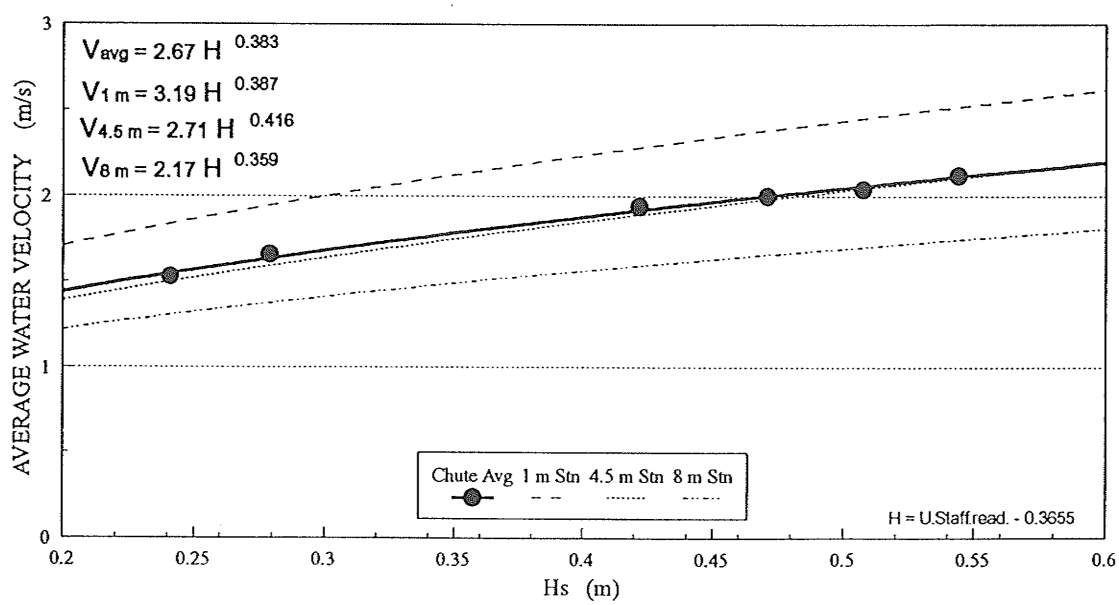

Figure E2 Average water velocity in the chute versus upstream stage.