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EVALUATION OF FIXED-LOCATION, RIVERINE HYDROACOUSTICS FOR ENUMERATING OUT-MIGRATING CHINOOK SALMON SMOLTS

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EVALUATION OF FIXED-LOCATION, RIVERINE HYDROACOUSTICS FOR ENUMERATING OUT-MIGRATING CHINOOK SALMON SMOLTS

By

Jeremy Dean Price

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ABSTRACT

EVALUATION OF FIXED-LOCATION, RIVERINE HYDROACOUSTICS FOR ENUMERATING OUT-MIGRATING CHINOOK SALMON SMOLTS

By

Jeremy Dean Price

Limited information regarding natural chinook production in Lake Michigan tributaries complicates management of this economically important fishery. Various techniques have been used to quantify smolt production in Michigan streams, each having strengths and weaknesses in its application. Fixed-location, riverine hydroacoustics are proposed as an additional method for quantifying chinook production in the Muskegon River, Michigan.

Evaluation of the hydroacoustic systems and processing software performance was qualitatively achieved through spatio-temporal comparisons of results from visual inspection of echograms and data processing results. This comparison revealed a perceived inability to detect targets and create tracks where many were expected and a propensity towards creating fish tracks from noise echoes.

Passage estimates were compared from concurrent hydroacoustic and auger-type, smolt trapping surveys conducted in 2001 and 2002. Simple linear regression was used to examine the relationship between trap and acoustic daily passage estimates. The relationship between corresponding daily passage results from 2001, 2002, and both years combined proved to be statistically insignificant (ANOVA, $p = 0.94$, 0.59, and 0.61 respectively). The methods used herein may be worthy of further development for use on smaller streams. However, use in their current form for management would be premature.

For my parents, who set the bar high for me and gave me everything I needed to achieve my goals. For my wife, Kathy, whose love and friendship I could never be without. And finally, for my children. You are my hope, my joy, and my inspiration. May each of your lives be full of the same.

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I would like to thank my entire family for their endless support. Thanks to my brother, Jim, for talking me off the ledge at a critical time. You're my man! Special thanks to my wife, Kathy, for her patience in this process. I never could have finished this without your help. I owe you big!

Last, but not least, I would like to thank God for the abilities and opportunities that I've been given in life. You've blessed me far beyond what any man deserves despite my inadequacies. Thank you for everything.

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KEY TO SYMBOLS OR ABBREVIATIONS

Symbol/ Abbreviation	Meaning/Unit
cm	centimeters
dB	decibels
ft	feet
FTA	Fish Tracking Algorithm
GB	Gigabytes
in	inches
kHz	kilohertz
m	meters
max	maximum
min	minimum
mm	millimeters
ms	millisecond
m/s	meters per second
μPa	micropascals
PLDL	Pulse Length Determination Level
STDA	Single Target Detection Algorithm
TS	Target Strength
TL	Total Length

Chapter 1

A Brief History of Chinook Salmon in the Great Lakes

Introduction

Chinook salmon *Onchorhyncus tshawytscha* were first introduced into the Great Lakes in 1873 (Emery 1985). However, it was not until 1967 that a rigorous stocking program was developed to establish chinook as a major predator in the Great Lakes ecosystem (Carl 1982). The purpose of the 1960's reintroductions was to control the overabundant alewife *Alosa psuedoharengus*, an exotic invader whose population exploded following the decline of lake trout *Salvelinus namaycush* in the Great Lakes and to establish a substantial sport fishery (Tody & Tanner 1966; Emery 1985).

Chinook are pacific salmon which are generally anadromous in their native range, spending most of their lives in the ocean and returning to freshwater streams to spawn. Great Lakes chinook are actually potamodromous, meaning they spend the majority of their lives in freshwater lakes. There are two variants of the chinook life cycle: the ocean type and the stream type. These variants are distinguished by the residence time of juveniles in their natal stream with the ocean type characterized by relative short stream residence during the early life history stages while stream type remain in streams in excess of one year after hatching. In general, Great Lakes chinook are of the "ocean type". A typical ocean-type adult chinook in the Great Lakes basin returns to its natal stream to spawn in the fall. Juveniles hatch, emerge, and out-migrate as fingerlings within a year of spawning. In the Muskegon River, the majority of smolts have usually emigrated by the end of June. This life cycle is well suited for successful reproduction in streams that provide marginal thermal habitat during the late summer months such as the tributaries of southern Lake Michigan.

Today, the results of the stocking efforts of the late 1960's are felt strongly in the Great Lakes region. The Great Lakes support a sport fishery of immense economic value. The fishery generated approximately $2 billion for the regional economy in 1985 (Talhelm 1988). A substantial portion of that number can be attributed directly to salmon angler expenditures. At nine index ports in the Michigan waters of Lake Michigan alone, salmon fishermen accounted for more than 25 million angler hours and nearly 3.2 million salmonines harvested from 1985 to 1994 (Rakoczy & Svoboda 1997). Chinook salmon accounted for nearly 44% of the total salmonine harvest during that period (Rakoczy & Svoboda 1997).

The successful development of the sport fishery can be partially attributed to the species itself. Chinook salmon adapted quickly to the Great Lakes ecosystem and soon began to reproduce naturally in Lake Michigan tributaries. Carl (1982) estimated that in 1979 natural recruits contributed 23% of the fishery. Hesse (1994) later estimated that 30% of age I and age II chinook harvested in 1992 and 1993 were naturally produced. In 1993 and 1994, Rutherford et al. (1999) estimated that between 76% and 96% of adult chinook returning to the Muskegon and Manistee Rivers to spawn were non-stocked fish. These studies show that natural salmon production is occurring and is on the rise. Further increases in natural production of chinook are expected with new guidelines imposed upon hydropower facilities (i.e. run-of-the-river discharge; O'Neal 1997). Such guidelines have improved the quality of nursery habitat below the dams and should only enhance the ability of salmon reproduce naturally in impounded rivers such as the Muskegon and Manistee.

Beginning in the late 1980's, angler harvest of chinook salmon and angler hours targeting salmonines declined precipitously in Lake Michigan (Rakoczy & Svoboda 1997). Returns from stocked fish plummeted approximately 70% between the 1984 and 1985 year-classes to the 1989 and 1990 year-classes (Rakoczy & Svoboda 1997). Bacterial Kidney Disease (BKD) *Renibacterium salmoninarum* was identified as playing a key role in the increased mortality observed (Nelson & Hnath 1990). Factors contributing to the increased susceptibility of salmon to BKD included: increased salmon density, reduced prey abundance (specifically alewife), and parasitic stress (Holey et al. 1998). Evidence suggested that predator density had exceeded sustainable levels and that stocking rates should be reduced (Holey et al. 1998; Wesley 1996).

Problem Statement

Fishery managers continue to stock chinook into the tributaries of Lake Michigan without the benefit of knowing the magnitude of the contribution of natural recruitment to the system in a given year. The resulting time lag could have detrimental effects upon the trophic balance within the lake due to a very strong or very weak naturally produced year class. Ideally, managers could alter stocking rates based on current prey abundance with the knowledge of natural inputs of predators into the system and reduce the need for a reactive management strategy. The need for a method of quickly and accurately estimating natural predator inputs to the system is evident.

With the collapse of salmon in the late 1980's and early 1990's, we have come to understand the potential impacts of overly ambitious stocking practices. The Fish-Community objectives for Lake Michigan (Eshenroder et al. 1995) outline several guiding principles for decision-making regarding the future of the lake's fisheries resources. Two of these principles have tremendous implications for stocking policies. The first of which is "recognizing the limits on lake productivity." In the discussion of this principle, the authors highlight excessive stocking as a practice that may lead to trophic imbalance and high levels of mortality. The second principle is "enhanced natural reproduction of desirable introduced fishes." Here the authors acknowledge the importance of natural feedback mechanisms and the drawbacks of time lags associated with their artificial counterparts. Both principles underline the importance of predator inputs into the system and, thus, an understanding of all sources of those inputs.

Project Objectives

Given the economic value of the Lake Michigan salmon fishery and the need for improved information regarding natural recruitment occurring in Lake Michigan tributaries, we are proposing a novel method for estimating natural production of chinook salmon. Here I evaluate fixed, riverine, hydroacoustic technology for enumerating naturally produced out migrant chinook salmon smolts. For this evaluation, we have selected the Muskegon River, a large tributary to Lake Michigan in central, lower Michigan. The Muskegon was selected as our study river to complement data being collected in related studies and because the Muskegon is suspected to be a major contributor of chinook to the Lake Michigan fish community (Carl 1980; Carl 1982; O'Neal 1997). The specific objectives of this thesis are:

1.) To comprehensively evaluate fixed-location riverine hydroacoustic methods for enumerating out migrant chinook salmon smolts.

2.) To estimate the number of naturally produced chinook salmon smolts contributed to Lake Michigan from the Muskegon River.

In chapter two, these objectives will first be addressed through comparisons of visual inspection and software processing results to determine the ability of the method to detect and track chinook smolts as they pass the deployment site. Also in chapter two, hydroacoustic estimates of daily smolt passage will be compared with daily passage estimates from a mark- recapture smolt trapping study that was conducted concurrently. The results of this should provide a mode of comparison by which to evaluate the application of hydroacoustics for quantifying smolt production and passage.

Chapter 2

Evaluation of Fixed-Location, Riverine, Hydroacoustics for Enumerating Out-migrating Chinook Salmon Smolts

Introduction

Laurentian Great Lakes support a recreational sport fishery of vast economic importance, however; this billion-dollar fishery (Talhelm 1988) is not completely self-sustaining. Fishery managers artificially augment the abundance of the system's top predators through stocking of hatchery-raised salmonids. Hatchery production capabilities, rather than the system's carrying capacity, have determined the number of salmon stocked. Public demand can also lead to increases in hatchery production and stocking rates. However, natural predator populations often exhibit a numerical response to fluctuations in the abundance of prey available in the system through density dependent feedback mechanism (Lotka 1925, Volterra 1926, Carpenter and Kitchell 1998). Without consideration of prey abundance, system perturbations from stocking can prove to be excessive and result in piscivore populations exceeding the carrying capacity of the system. This can lead to catastrophic mortality in the salmonid populations and tremendous impacts to the recreational fishery. One such decline in the late 1980's was attributed to bacterial kidney disease *Renibacterium salmoninarum* (Nelson and Hnath 1990). In recent years, fishery managers have considered prey abundance when determining stocking rates. However, other unknowns can contribute to instability within the system. Specifically, increases in natural salmonid production coupled with stocking rates based solely on prey abundance could easily lead to an overabundance of predators. Thus, a better understanding of natural salmonid production is necessary for efficient management of the fishery as well as maintaining the overall health of the system.

Several methods are used to quantify the natural recruitment of salmonids in the Great Lakes basin. Two common methods are pre-smolt electro-fishing surveys and out-migrant smolt-trapping surveys. While these methods have been used extensively and evaluated on several occasions (Carl 1982, Newcomb and Coon 2001, Kennen et al. 1994, Thedinga et al. 1994, Peterson et al. 2004), the potential biases associated with capture efficiencies in each method highlight the need for additional sampling options. Another approach to measure the natural recruitment/production of smolts is fixed-location riverine acoustics. We have proposed that fixed-location riverine hydroacoustics can be used to quantify smolt out-migration. This type of survey has a similar concept to that of the smolt trapping survey. Out-migrant smolts are counted as they move past a point along the migration route to the outlet. However, hydroacoustics have the ability to sample a much larger volume of water to provide increased coverage of the river cross-section relative to that of the smolt trap. Other benefits of using hydroacoustics include remote sensing of smolts (i.e. no handling stress/mortality), limited obstruction of waterways, less labor intensive than the aforementioned methods, and the availability of high resolution temporal migration data. Also, while the system does require daily monitoring, deployments can be set up to allow remote monitoring of the system and its components.

Fixed-location riverine hydroacoustics have long been used in a wide range of stream sizes to measure spawning migrations of adult salmon (Johnston and Steig 1995; Ransom et al. 1998). It has also been shown to be an effective method of estimating the abundance of salmon migrating upstream (Enzenhofer et al. 1998; Ransom et al. 1998). Therefore, we propose to use split-beam hydroacoustic technology deployed in a fixed location to estimate the abundance of out-migrating smolts. We have chosen split-beam technology over single and dual beam technology because of the superior fish tracking capabilities of the split-beam system.

Methods

Study Site

The Muskegon is located in north-central Michigan and flows westward to Lake Michigan. The river is 212 miles long and drains an area of 2,350 square miles. Croton Dam, a hydroelectric facility at the town of Croton, restricts passage of potamodromous fish to the lower 45 miles of the Muskegon.

The Muskegon River fish community below Croton Dam is comprised of cold, cool, and warmwater fishes. This stretch supports good sport fisheries for walleye, brown and rainbow trout, chinook salmon, and steelhead (O'Neal 1997). Annual stockings of chinook salmon in the lower Muskegon have ranged from 97,000 to 530,000 since the program's inception in 1967 (O'Neal 1997, www.michigandnr.com). Over the last five years, stocking rates have not exceeded 150,000 (www.michigandnr.com).

The Muskegon River was selected as the river of study due to its large natural contribution to the Lake Michigan salmon population. The Muskegon was found to be one of the most significant producers of chinook salmon in the Lake Michigan Basin (Carl 1980; Carl 1982; O'Neal 1997). Average annual smolt production in the Muskegon is thought to be approximately 350,000 (O'Neal 1997).

Site Selection

Site selection for the acoustic deployment was based on several criteria, which included proximity to the smolt trap, current velocity, cross-sectional profile, and security.

The smolt trap was deployed from the B-31 bridge crossing of the Muskegon on the Muskegon/Newaygo County line (Figure 1). Mortality incurred along the river by the out-migrant smolt population necessitated minimizing the distance between the trap and the acoustic deployment. This ensured maximum comparability between passage estimates derived from trap and acoustic data.

Current velocity is an important factor in the success or failure of a riverine acoustic survey. Very high flow rates tend to entrain air bubbles, decreasing the signal-to-noise ratio, and thus decreasing the probability of detecting a target and the precision and accuracy of angular position estimates (MacLennan & Simmonds 1992; Keiser et al. 2000). Rapid flow can also result in targets passing through the acoustical beam quickly so that multiple detections of the same target are unlikely. Multiple detections are necessary to determine the target's direction of travel and velocity, which are crucial for filtering fish tracks by direction of travel. In very slow flow conditions, sedentary behavior of non-target species is likely to occur in areas of low flow and would likely bias smolt estimates high, due to the inclusion of non-target fish traces (Ransom et al. 1998).

The cross-sectional profile of each site was qualitatively measured using a Humminbird® 200 kHz fish finder. The most desirable channel characteristics are a narrow channel with gradual gradation of smooth streambed to the

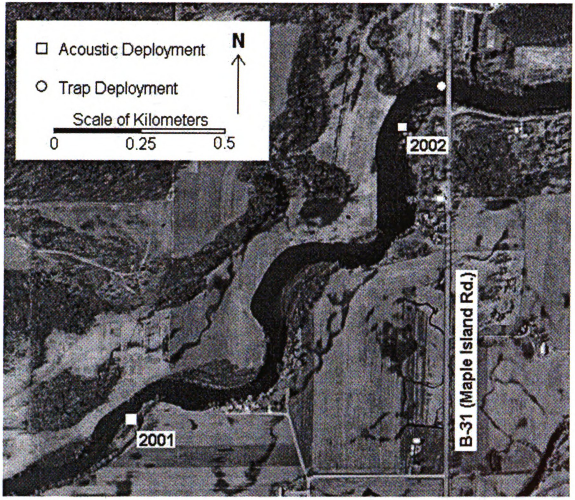

Figure 1. Aerial photo showing location of hydroacoustic and trap deployments.

thalweg (Ransom et al. 1998). The streambed must slope down to the thalweg at slightly greater than the angle at which the sound beam opens on the vertical axis. Streambed slopes greater than the vertical angle of the sound beam will result in a smaller proportion of the channel's cross-section being sampled. If the angle is less than that value, the substrate will interfere with the beam creating long echo traces at the point of intersection. Objects jutting up from the streambed into the beam will also return an echo (Ransom et al. 1998). While echoes created from these issues are easily identified due to their long traces on the echogram, they must be excluded from the analysis. As a result, any targets passing through the beam at that range would also be excluded potentially biasing passage estimates low.

Given the extensive recreational use of the river, site security was also a concern. To minimize the likelihood of vandalism or theft of equipment, a site was sought in close proximity to multiple homes.

Two separate sites were used for the 2001 and 2002 sample seasons. Each year, after obtaining landowner permission for the selected location, a 4' x 7' storage shed was constructed to house the land based portion of the acoustic equipment. In 2001, a location meeting these criteria was found approximately 1.70 km downstream of the B-31 bridge crossing (Figure 1). In 2002, an alternative location 0.27 km downstream of the B-31 bridge. Both sites were similar in usable width, maximum depth, and cross sectional profile (Figure 2).

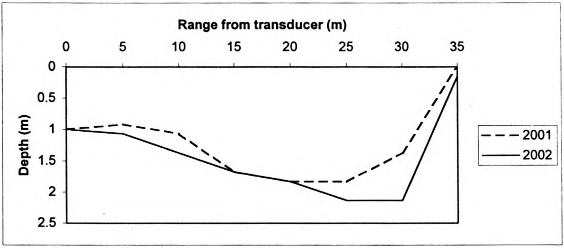

Figure 2. Cross-sectional profile of acoustic sites used in 2001 and 2002.

Data collection

We used a 200 kHz split-beam (3^o x 6^o elliptical beam) digital echosounder (Biosonics DE 6000) to measure acoustic size, swimming direction and velocity, and numbers of fish passing the plane sampled by the echosounder. The echosounder had a 225.5 dB source level (re μPa @ 1m), pulse duration of 0.4 ms and was set at 7 pings per second. The transducer was mounted on a dual axis rotator with the rotator mounted on a frame constructed of 1/2 in. galvanized pipe (Figure 3). The frame, rotator, and transducer were placed close to the riverbank in approximately 1 m of water. The rotator was operated using a control panel (located in the shed) to aim the transducer towards the center of the stream and perpendicular to the main flow. The vertical aiming of the transducer was tuned to maximize range and volume of water sampled.

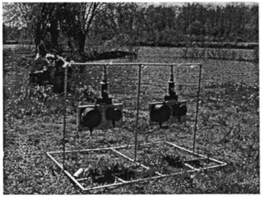

Figure 3. Pipe frame upon which the transducers were mounted.

The system was checked daily in mid to late afternoon. At this time, data were transferred from the laptop to a 120 GB portable hard drive. A deep cycle 12-volt marine battery was used to power the system. The battery was changed daily with a fully charged replacement. The dual axis rotators were also readjusted minimize the signal to noise ratio in the first 20 meters of range.

In May 2001, a major flooding event delayed permanent system deployment until 6-June. Data were collected without significant interruption through 24-June. In all approximately 30 GB of hydroacoustic data were collected.

In 2002 system malfunction and the subsequent repair delayed data collection until 25-May. Data were then collected from 25-May until 9-June, when further equipment failures resulted in a 17-day postponement. During this period, the river receded substantially, thus requiring the shed to be relocated before data collection could resume. To avoid the risk of obstacles imposed by future stage changes in the river, we secured the shed in a 22 ft. johnboat and secured the johnboat using a 3-pt mooring. Data acquisition resumed with this new deployment on 26-June and continued until the system was removed on 2-July.

To limit the volume of data collected, a systematic sampling strategy was adopted for the 2002 season. The echosounder was configured to collect data for a two minute burst. The system would then rest for four minutes between bursts. As a result, we collected 20 minutes of data per hour during the 2002 season.

Additional technical difficulties were encountered during data collection in 2002. Repeated failures of the dual axis rotators and occasional battery depletions resulted in further reductions in the amount of quality data collected. In all, quality data were collected for only seven "full" days and six partial days. This translated to approximately 13 GB of hydroacoustic data.

A VEMCO Minilog TR was deployed prior to commencement of acoustic data collection in 2002 to provide stream temperature data necessary for data file processing. The Minilog was configured to record the temperature at 10-minute increments.

Beam mapping

An *in situ* beam mapping procedure was conducted to determine the extent and location of coverage of the river cross-section. During this process a 38.1-mm tungsten carbide reference sphere was passed through the acoustic beam on a plane corresponding to 0.9 meters below the water surface. Following the same procedures used to process field data, single target data were exported from Echoview, a hydroacoustic data processing software package, and analyzed. The two-dimensional (range and vertical) location of 63 echoes was plotted in relation to the transducer and beam axis. The range of these echoes varied from 10.68 to 19.73 meters. Least squares regression was applied to the range and vertical distance off axis data to determine the location of the line marking the intersection of the 0.9-meter plane and the vertical plane of the beam axis. The regression was constrained to ensure that when plotted relative to the river's cross-section, the position of the transducer was accurate relative to the 0.9-meter plane that the reference sphere was passed through. The beam axis was then geometrically rectified relative to the surface of the water. The upper and lower boundaries of the beam ($\pm 1.5^{\circ}$) were then plotted to show the coverage of the top 1-meter of the river. The proportion of the cross sections coverage was calculated for four 5-meter increment totaling 20 meters from the location of the transducer. These proportions allowed for adjustment of passage estimates based on differences in coverage at varying range. Data from this procedure was also used to calibrate the acoustic data during the processing phase.

Data processing

Data were processed using SonarData Echoview® Version 3.0.80 (www.sonardata.com). The same general procedure was used for all aspects of processing. Raw data files were opened in Echoview. Split-beam data files automatically have three variables associated with them upon opening. These are TS, Angular Positions, and S_v variables. When analyzing single target data, the former two are the variables of interest. Each of these variables was calibrated with data collection settings, sound speed, and the absorption coefficient. Following calibration of the raw variables, a single target variable was created using Echoview's Single Target Detection Algorithm (STDA).

The STDA is a process used to filter echoes based on user-defined criteria. These criteria include: Target Strength thresholds, Pulse Length Determination Level (PLDL), minimum/maximum normalized pulse width, maximum beam compensation, and maximum standard deviation of major and minor-axis angles (Table 1). Echoes passing all criteria are stored in the single target variable for further analysis.

Target Strength (TS). TS, or acoustic size, is a measure of the reflectivity of an individual target and is measured in decibels (dB). Reflectivity has been correlated with length in numerous species of fish. From length/TS relationships we can estimate the

Fish Tracking Algorithm Parameters		Single Target Detection Parameters	
Parameter	Value	Parameter	Value
TS Threshold	-61.0 dB	Alpha (Maj. Axis, Min. Axis, Range)	0.7000
Pulse Length Determination Level	6.0 dB	Beta (Maj. Axis, Min. Axis, Range)	0.5000
		Range Gating Exclusion (Maj. Axis, Min. Axis)	4.0 m
Minimum Normalized Pulse Length	0.8	Range Gating Exclusion (Range)	0.1 m
		Missed Ping Expansion (Maj. Axis, Min. Axis, Range)	0.0 m
Maximum Normalized Pulse Length	1.5	Major Axis Weighting	30
		Minor Axis Weighting	30
Maximum Beam Compensation	6.0 dB	Range Weighting	40
		TS Weighting	0
Max St.Dev. of Minor Axis Angles	1.5	Ping Gap Weighting	0
		Minimum Number of Single Targets in a Track	2
Max St.Dev. of Major Axis Angles	1.5	Minimum Number of Pings in a Track (pings)	2
		Maximum Gap Between Targets (pings)	2

Table 1. List of parameters and values used in processing and analyzing hydroacoustic data.

length of a fish creating an echo that we observe or filter echoes based on the expected length of a target species.

Length/side-aspect TS relationship for chinook salmon smolts for use with a 200 kHz system are currently unavailable. Efforts to determine such a relationship as part of this project failed due to laboratory tank limitations. However, Lilja et al. (2000) developed a side-aspect TS relationship for brown trout *Salmo trutta* (29.0 – 63.0 cm) and Atlantic salmon *Salmo salar* (30.0 - 119.0 cm) for a 200 kHz system:

$$TS = 26.2 * \mathrm{Log}_{10}(TL) - 73.8$$

where TL is total length in cm. While the lengths of fish used to create this relationship were substantially larger than those observed in this field study, no other side-aspect TS relationship for any salmonid was found for use with a 200 kHz system. Therefore, this relationship was used for TS thresholding in this study.

PLDL & Min./Max. Normalized Pulse Length. Pulse length is the measure of the duration of a sound pulse in ms. The normalized pulse length is the length of the received echo pulse divided by the transmitted pulse length (Echoview® 3.0.80 Help File). This value is used to ensure the echo received is from a single target. Echoes with pulse lengths shorter than the propagated signal are noise. Echoes with pulse lengths substantially larger than the propagated signal are due to multiple targets at similar ranges and should not be included in the analysis (MacLennan & Simmonds 1992). Echoes with a Normalized Pulse Length between 0.8 and 1.5 were deemed to be of adequate quality for further candidature. The PLDL is simply the number of decibels down from the peak that an echo's pulse length is measured on the oscilloscope (Figure 4). The PLDL was set to 6 dB. This value is high enough to ensure complete formation of the echo envelope but low enough to allow targets to be detected where background noise might interfere with detection.

Maximum Beam Compensation. As targets move away from the acoustic axis, beam pattern effects reduce the amount of sound that they reflect. Split-beam hydroacoustics can account for this loss through beam compensation. By limiting the beam compensation, low quality targets from beyond the nominal beam angles can be

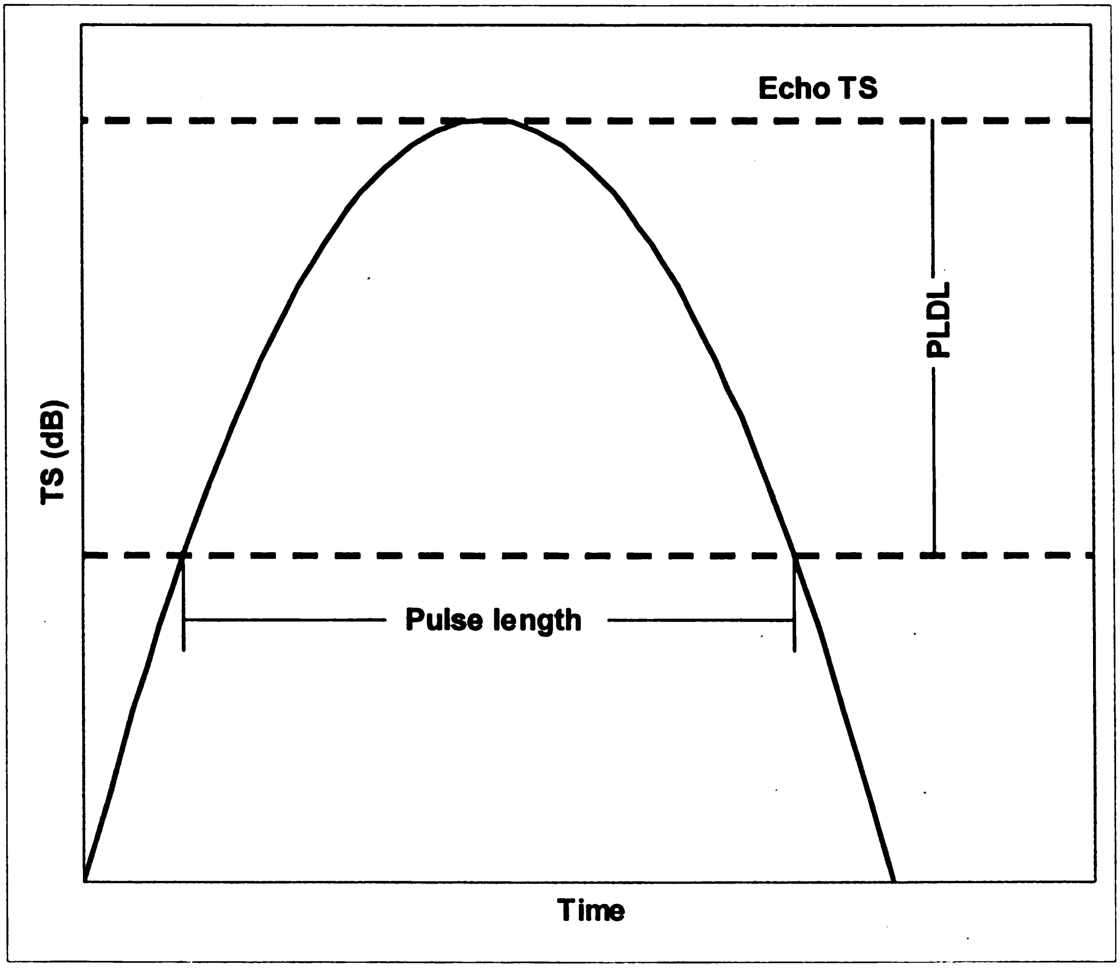

Figure 4. Basic descriptive measurements of a single echo.

excluded from the analysis. Difficulties in detecting single targets led to slight loosening on this criterion. This value was set at 6 dB for this analysis.

Standard Deviations of Axis Angles. Each single target passing the above criteria will have a value describing level of precision associated with its estimates of minor and major axis angles. The precision of these estimates is highly affected by the presence of background noise in the data. Therefore, in a noisy environment like we have in riverine systems, the standard deviations of the angular position estimates will be relatively high. In spite of this, a value of 1.5 was selected for each of these parameters. This value was the lowest value at which adequate numbers of single targets could be detected for fish tracking analysis.

After all single fish targets were identified; a Fish Tracking Algorithm (FTA) was applied. The FTA analyzes each single target variable ping by ping. When the algorithm encounters a single target, a fish track is opened. Echoview then searches for echoes that are likely to be associated with the opening target by creating an ellipsoid to predict the 3-dimensional location of the target on the next ping. If one or more targets fall within that ellipsoid, one can be added to the track. If multiple targets are identified within the ellipse, weighting parameters determine which target is added to the track. These weighting parameters include major and minor axis range (i.e. the proximity to the predicted location of the next sequential target), TS, and ping gap (i.e. the number of sequential pings without an echo). Once the new target is added, the algorithm repeats this process for the next ping. If no target is identified, the algorithm moves to the next ping, increasing the dimensions of the ellipsoid by a user-specified percentage. This process continues until the maximum ping gap parameter is exceeded. When the maximum ping gap has been reached, the track is closed. Tracks including a number of targets and pings greater than or equal to the minimum number of targets and pings required for a track are defined as fish track regions. Tracks not meeting the criteria are discarded.

Performance Analysis

Performance of the FTA was analyzed to parameterize the single target detection and fish tracking algorithms, to qualitatively evaluate the performance of the software, and to provide baseline results that could be applied to the overall processing results to estimate smolt total passage. The process involved:

1.) Trace definition

2.) Data processing

3.) Evaluation of processing results

4.) Adjustment of algorithm parameters

Trace definition. A trace is defined as series of echoes from a sequence of pings that seem to progress in a predictable manner. Since a trace is made up of multiple echoes, the data were evaluated at the trace and echo levels concurrently. Thirty raw data echograms were randomly selected from the data collected from May to July of 2002 and fish traces were visually identified based on characteristics of the echoes and various aspects of trace morphology including pulse width and TS. Pulse width was evaluated in a manner similar to that portion of the STDA. The TS threshold on the echograms was set to exclude echoes from targets too small to be out-migrant smolts after adding the maximum beam compensation. Echoes with TS values falling below this threshold are not visible on the echograms. Thus, they were not identified in the trace definition process. Echoes meeting the visual inspection requirements were considered candidates for trace definition.

Complexities associated with integrating three-dimensional data into the trace definition process prevent filtering of traces by direction of travel. Thus, no consideration was given to angular data in the trace definition process of the performance analysis.

The first range consideration is the maximum change in echo range on sequential pings. Out-migrant chinook generally travel downstream with minimal lateral movement (relative to the direction of flow; Stables & Kautsky 2000). In the trace definition process, echoes showing a high degree of lateral movement relative to each other were only defined as traces if they exhibited a high degree of predictability in that movement.

Range is also used in conjunction with temporal data in determining the minimum number of pings required for formation of a trace. The minimum number of echoes that can constitute a trace is two. The presence of two or more echoes allows for estimation of distance traveled estimates, swimming speed, and direction of travel.

In addition to the minimum number of targets required, there is also a maximum number of targets allowable. Traces in excess of 20 pings (approximately 3 seconds) are unlikely to be smolts exhibiting migratory behavior and were not defined as traces. This type of trace is commonly caused by shifting of the river substrate.

Sequences of echoes that met the aforementioned guidelines were outlined using a polygon. This polygon served as a marker region for spatio-temporal comparisons

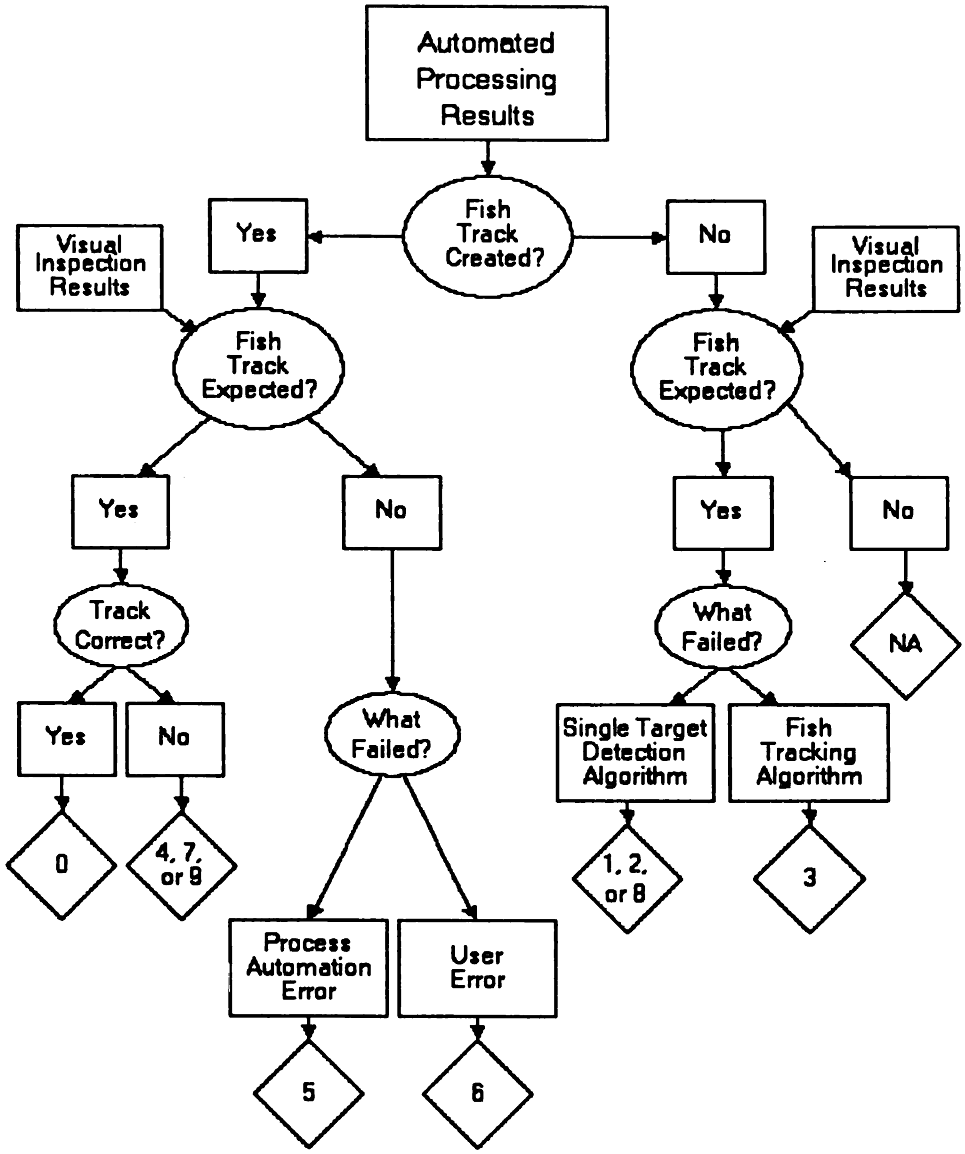

Figure 5. Decision tree for assigning result codes to each track or anticipated track.

between the expected fish tracks identified in the trace ID process and observed fish tracks from the application of the software's algorithms.

Data processing. Data Processing was accomplished in the manner previously outlined. Following the complete inspection and identification of all suspected traces within the raw echogram, the STDA and the FTA were applied to each data file individually.

Evaluation of results. Following the application of the FTA to the single target variable, the raw echograms with the trace polygons and fish tracks overlaid, were inspected to evaluate the performance of software algorithms relative to the expectations defined during the trace definition process. Process result codes are assigned to each user-defined polygon indicating a potential trace. Result codes are also assigned to any fish tracks that were created on areas of the echogram where tracks were not anticipated. The total number of occurrences for each code was then determined for each data file, and the results were evaluated relative to visual expectations (Figure 5). The list of possible result codes included the following:

- Code 0 – A fish track was correctly identified within the trace polygon. This indicates adequate performance of the entire process relative to the visual inspection by the user.
- Code 1 – The STDA failed to identify multiple targets within the trace polygon created by the user. Therefore, no track could be created.
- Code 2 - The STDA identified multiple targets within a trace polygon, but a fish track was not created due to poor STDA performance. This code is generally

reserved for longer traces where few targets are identified and the maximum ping gap is exceeded

- Code 3 – The STDA identified multiple targets within a trace polygon, but a fish track was not created due to poor FTA performance. This code applies to traces that have multiple targets within the maximum ping gap, but the FTA fails to create a track based on target exclusion.
- Code 4 – The FTA created multiple tracks within a single trace polygon. This is usually due to the maximum ping gap being exceeded between two groups of single targets within the same trace.
- Code 5 – The FTA created a track in an unanticipated location using targets that seem to be unrelated. Use of this code is based on the user's visual inspection of the raw data and overlaid fish track following data processing.
- Code 6 – The FTA created a track in an unanticipated location. However, in this case, the user failed to identify a potential track during the initial inspection of the raw data echogram. Therefore, the FTA performed correctly.
- Code 7 – The FTA created a fish track in which non-trace targets were selected over trace targets occurring on the same ping.
- Code 8 – The FTA failed to create a fish track due to the exclusion of targets because of borders (i.e. temporal bounding, bad data, etc.).
- Code 9 - The FTA created a fish track in location as expected with multiple targets within the trace polygon. However, targets external to the trace polygon were also included.

In each file, result codes were recorded for each trace outlined in the trace identification step and all fish tracks created by the software that were not deemed to be associated with an outlined trace. Proportions of the total number of result codes were calculated for each individual result code. The arithmetic mean was calculated for each code's proportion across all data files. The mean proportions were used to determine what algorithm failed most often and why the perceived failure occurred.

These ten result codes were also divided into three broader groups to simplify performance evaluation. These categories were: Good (codes 0 & 6), Bad (codes 4, 5, 7, & 9), and Omitted (codes 1, 2, 3, & 8). "Good" results occur when the algorithms properly identify a fish track. "Bad" results occur when fish tracks are created from or include what appear to be noise echoes. "Omitted" results occur when a trace is identified during the visual inspection process, but no fish track is formed. Proportions of the total number of result codes for each category were calculated for each data file. These proportions were used to evaluate the general performance of the entire process and for comparison across different algorithm parameterizations.

Glaring differences in data quality at different ranges were apparent. Thus, the data were binned out into four 5-meter increments. Names of these increments correspond to their maximum range (i.e. 10 to 15 meter increment is called the 15 meter range bin). ANOVA was used to determine if there was a significant effect of range bin on the numbers of categorical results.

Iterative Parameter Perturbation

Results obtained from the above processes were used to modify parameters in a feedback loop to improve the performance of the FTA. While time constraints prevented most parameters to be iteratively tuned, the process was used to adjust the "range gating" parameter. This parameter restricts the maximum allowable change in range between sequential targets in a track. The starting value was 0.3 meters. Iterations subsequent to the initial run involved perturbations of 0.1 meter. The proportions of categorical results were compared across iterations. The overall goal was maximize the proportion of good results while minimizing the proportion of bad and omitted.

Passage Estimates

Passage estimates for days with more than 10 hours of data from both years were obtained using the parameters from the performance analysis. Each day was processed using the procedure described in the data processing section above. Following the completion of the data processing, fish track regions were exported from Echoview. Fish track data that were exported and used in analysis include: date, time, mean TS, mean target range, horizontal direction of travel, and tortuosity.

Additional filtering was applied to the processed data to determine is targets were likely to be out-migrating chinook smolts. Studies regarding out-migrant smolt behavior provide some guidance on selecting filtering criteria. Passive drifting and active swimming are important components of smolt migration behavior (Fried et al. 1978; Fängstam 1993; Lacroix and McCurdy 1996). Fängstam (1993) observed that active swimming was only used by migratory fish approximately 10% of the time.

Additionally, active swimming speeds of 0.11 to 0.23 m/s are predicted for smolts of the size produced in the Muskegon River. Swimming speeds in this range are not discernable from passive drifting due to the poor precision of angular position estimates for individual echoes. As a result, swimming speed was not used in the filtering process.

Another filter considered was swimming direction. Movements of migratory smolts are strongly oriented towards their destination (Groot 1972; Fängstam 1993; Stables & Kautsky 2000). Generally migratory smolts orient themselves parallel to the current of the stream during out-migration (Stables & Kautsky 2000). Therefore, direction of travel is likely to be a good filtering criteria. The variable providing the most information regarding the direction of travel relative to up/downstream is "horizontal direction". This variable is measured in degrees and is determined for each track by drawing a straight line between the first and last target in the track. As deployed, objects moving from upstream (right) to downstream (left) while looking across the river from the transducer position exhibit a horizontal direction of 270° (Figure 6). Filter thresholds for each day-range bin combination were determined by creating histograms of horizontal direction. Binning of the histograms was set to 5° increments. The increment exhibiting the most fish tracks was determined to be the direction of flow. Each day-range bin

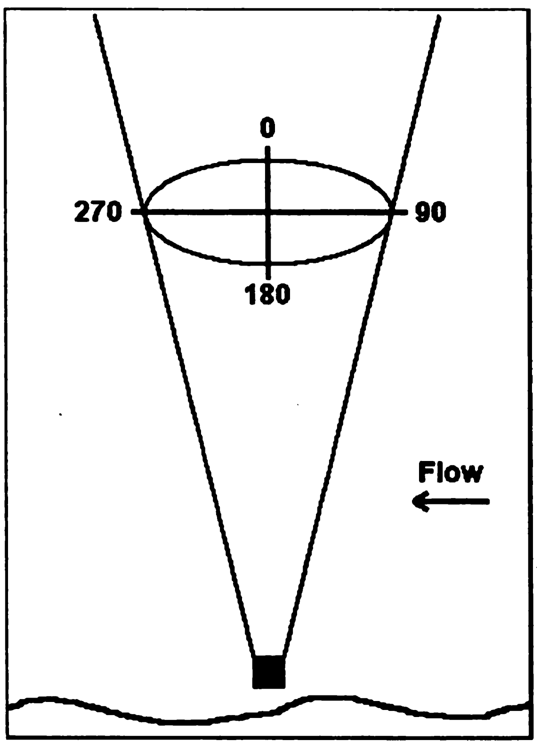

Figure 6. Geometry of direction of travel measurements in the horizontal plane (aerial view).

combination was then filtered to exclude targets outside ±45° of this value. Tracks passing this filter are assumed to be moving primarily in a downstream direction.

Tortuosity is another variable dealing with orientation and the deliberate movements associated with migratory behavior. Tortuosity (unitless) is the sum of the distances in a track divided by the distance from the first to last targets in the track, measured in 3 dimensional space. Tracks with only two targets in them have a tortuosity of 1. Tracks with three or more targets are likely to have a tortuosity greater than 1. The deliberate movements associated with migratory behavior are unlikely to yield tortuosities substantially larger than 1. Thus, tracks with tortuosities greater than 1.5 were filtered from the results.

The final filtering criterion used was mean TS. The side-aspect length/TS relationship developed by Lilja et al. (2000) for trout was used to calculate daily filtering values. The range of lengths for chinook smolts collected in the auger-trap was used for daily upper and lower TS thresholds (Table 2). The trap-catch on 26-May consisted of only three chinook. Thus, the minimum and maximum length of chinook from the previous and subsequent days were used.

	Chinook Lengths (mm)		Chinook TS (dB)	
Date	Minimum	Maximum	Minimum	Maximum
5/26/2002*	58	86	-53.80	-49.32
5/29/2002	64	101	-52.68	-47.49
5/30/2002	52	90	-55.04	-48.80
5/31/2002	65	90	-52.50	-48.80
6/5/2002	52	88	-55.04	-49.05
6/6/2002	54	83	-54.61	-49.72
6/7/2002	56	96	-54.20	-48.06

*Includes minimum and maximum chinook length from the previous and following day.

Table 2. Minimum and maximum length of smolts captured in the trap survey (Rutherford, unpublished data) and the corresponding TS threshold values.

The exported fish tracks were filtered according to the criteria description above. Following the filtering process, total numbers of fish tracks passing the criteria for each day were summed. The temporal and spatial distributions of tracks exported were used to calculate whole river passage estimates for each day.

To estimate total number of fish out-migrating, the number of tracks detected for each 5-meter increment was multiplied by a constant to estimate the total number of tracks that would be detected if the top meter of the water column were completely ensonified for that range. Daily track totals were calculated for the following ranges: 0 to 5 m, 5 to 10 m, 10 to 15 m, and 15 to 20 m. An estimate for the entire river cross-section was also calculated by extrapolating the 0 to 15 m results to the corresponding distances from the opposite shore (Figure 7).

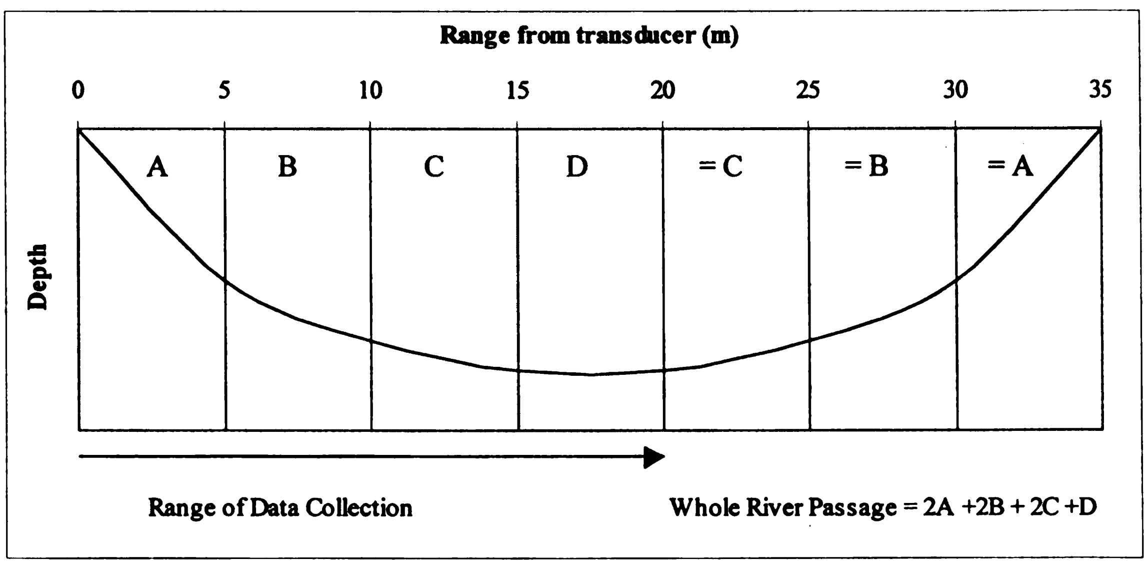

Figure 7. Rationale behind calculation of whole river estimates.

Since less than 24 hours of data were collected on each day, summation of the number of tracks observed would yield daily passage estimates that were biased low due to non-continuous temporal coverage. Thus, it was necessary to calculate a mean hourly passage rate for each day to arrive at a total daily passage estimate for comparison to the results of the trap study.

Data limitations constrained the statistical analyses that could be done. The statistically low number of days for trap and hydroacoustic estimate comparison dictates that a very simplified regression model be used. Thus, simple linear regression was used to determine the relationship between hydroacoustic and smolt trap estimates.

Mean normalized hourly passage rates across all days were calculated for each year to determine if any detectable diel migration pattern existed. These quantities were calculated by dividing each hourly passage estimate by the maximum hourly passage for the corresponding day. The possible range of resulting values was 0 to 1, with 1 representing the hour of maximum passage for each day. Results for each hour of the day (i.e. 0100, 0200, etc.) were then averaged across all days to determine if a trend existed.

RESULTS

Beam Mapping

The transducer was aimed downward approximately 2° to maximize the signal:noise ratio at extended ranges. Accounting for the vertical beam angles, the beam sampled 13% of the top 1 mat the 0 - 5 m range, 38.61% for the >5 - 10 m range, 44.62% for the >10 - 15 m range, and 40.46% for the >15 - 20 m range (Figure 8). Height of the beam (vertical distance ensonified) increased linearly with range, while volume sampled within the upper 1 m only increased slightly between the second and third range increment and decreased from the third to the fourth range increment.

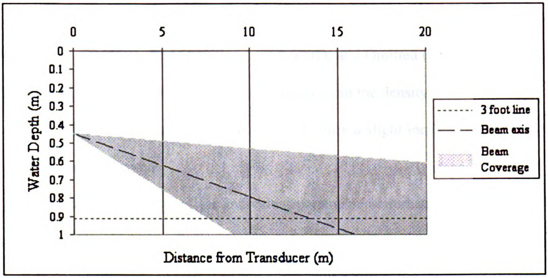

Figure 8. Cross-sectional coverage of the ensonified region.

Performance Analysis

There was a statistically significant effect of range increment on numbers of Good (ANOVA, $p < 0.0001$), Bad (ANOVA, $p < 0.0001$), and Omitted (ANOVA, $p < 0.0001$) tracks per 1000 m^3 (Figure 9). Substantial decreases in the density of Good and Omitted results with increasing range were evident, while only a slight increase was observed in Bad results was observed

A total of four runs of the individual parameter perturbation were necessary to optimize the "range gating" parameter of the FTA. Only slight decreases in total numbers of results were observed as the range gating parameter decreased (Figure 10). Since the loss of results was minimal across iterations, valid comparisons of ratios for categorical results could be made to evaluate the software's performance. As range increased, the range gating parameter had an increasingly positive effect on the ratio Bad to Good results (Figure 11). Little effect of the perturbation was observed on Omitted to Good results across iterations (Figure 12).

Proportions of result code occurrences were used to evaluate the performance of the STDA and the FTA across range bins (Table 3). Result codes 0 and 6 indicate good performance of both algorithms. In general, these codes decrease with increasing range. Codes 1 and 2 indicate perceived failures in the STDA due to a lack of target

Range Bin	Percentages of Result Code Occurrences									
	0	1	2	3	4	5	6	7	8	9
5	30.8	53.4	0.0	0.0	0.0	0.0	15.7	0.0	0.0	0.0
10	21.5	58.1	0.7	0.2	0.1	1.5	17.9	0.0	0.0	0.1
15	15.2	61.5	1.6	0.0	0.0	10.0	11.4	0.0	0.1	0.1
20	12.7	39.0	2.6	0.0	0.8	28.7	16.1	0.0	0.0	0.1

Table 3. Percentages of each result code's occurrence by range bin (0.1 m iteration of range gating manipulation).

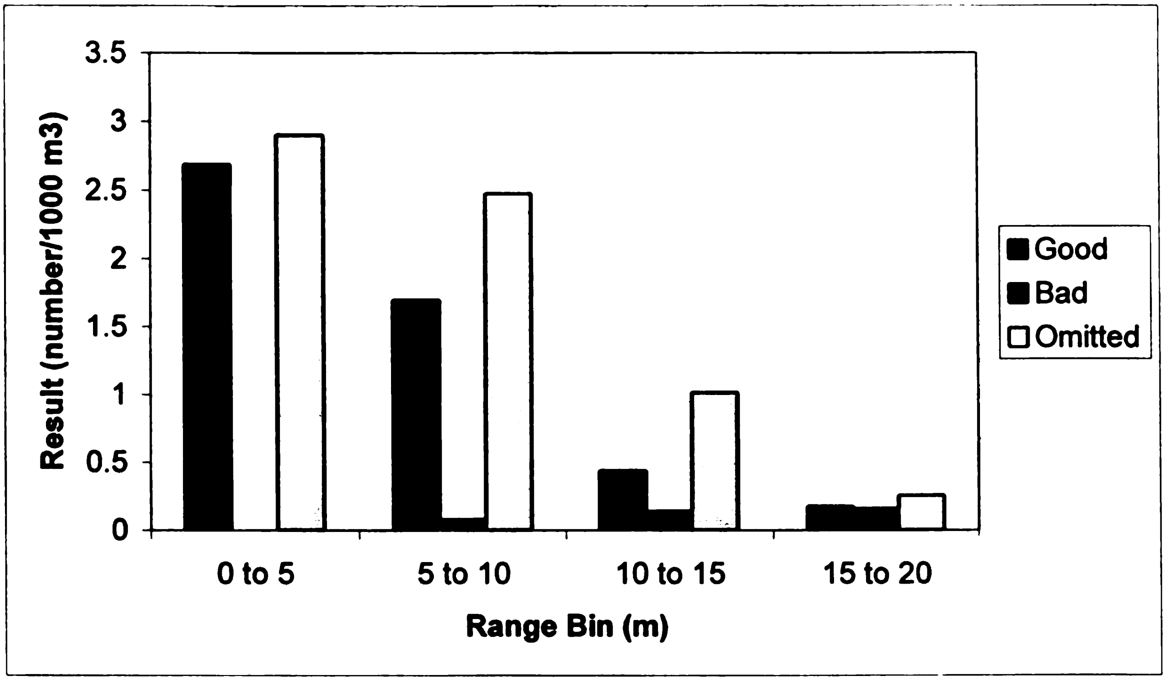

Figure 9. Number of categorical results per volume sampled by range bin (0.1 m iteration of range gating manipulation).

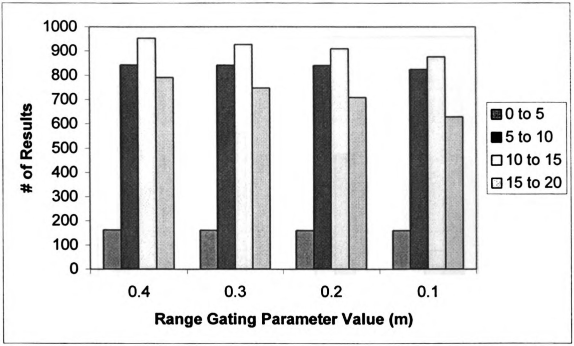

Figure 10. Absolute numbers of results from the four range gating manipulations.

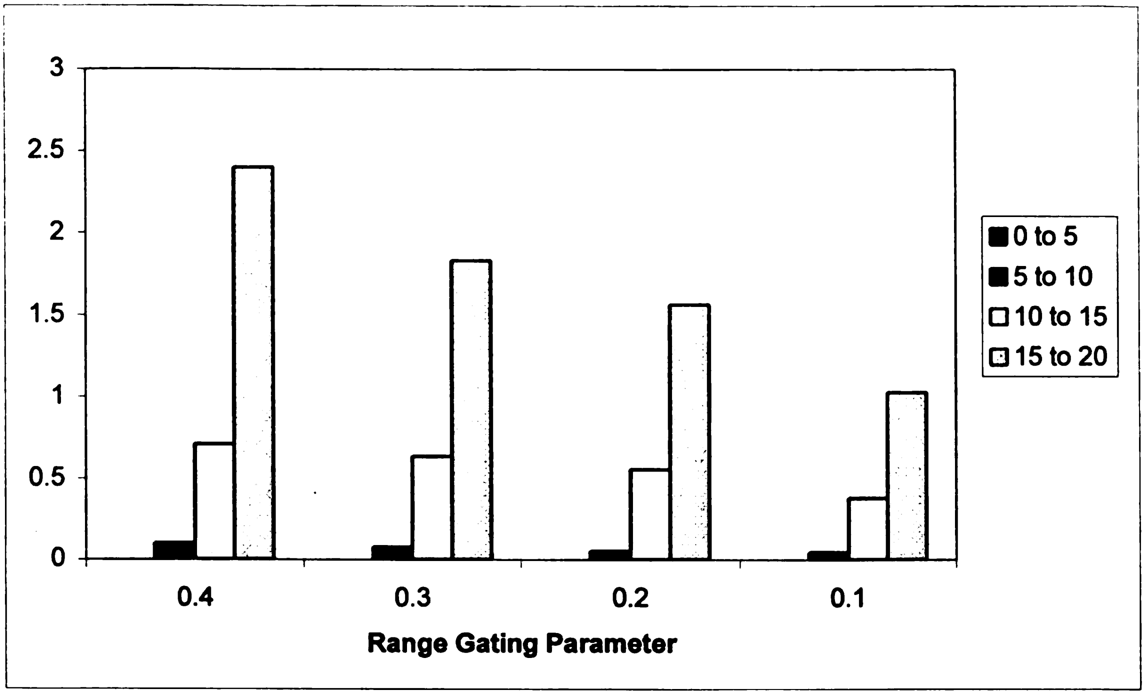

Figure 11. Ratio of bad to good results for each iteration of the range gating parameter manipulation.

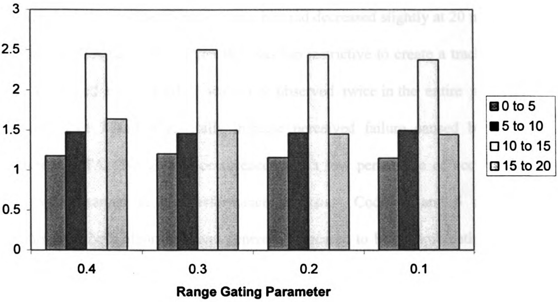

Figure 12. Ratio of omitted to good results for each iteration of the range gating parameter manipulation.

detection. Loosening of STDA criteria reduced these percentages. The percentage of these codes increased to the 15-meter range bin and decreased slightly at 20 meters. Code 3 indicates an FTA parameterization that was too restrictive to create a track associated with an identified trace. Code 3 was only observed twice in the entire performance analysis. Codes 7 and 9 generally indicate perceived failure caused by a loosely parameterized FTA. No code 7 occurrences and a low percentage of occurrences for code 9 was observed in the performance analysis. Codes 4 and 5 can indicate shortcomings of both algorithms and generally appeared to be a combination of STDA and FTA failures. A restrictive STDA and FTA characterize code 4, while code 5 indicates a loose parameterization of both. Occurrences of code 4 were sparse. Code 5 increased with increasing range. Finally, code 8 is an artifact of data bounding and was only observed once in the performance analysis.

Passage Estimates

In 2001, acoustic daily passage estimates ranged from a maximum of 14,791 on June 23 to a minimum of 2,610 on June 21 (Table 4). Acoustic daily passage estimates from 2002 ranged from a maximum of 20,767 on June 5 to a minimum of 9,319 on May 26. Across

	Date	Acoustic Passage Estimate	Trap Passage Estimate
2001	6/8	9,028	4,000
	6/10	7,654	3,351
	6/11	5,773	3,135
	6/12	7,707	3,838
	6/13	7,287	3,189
	6/14	5,945	5,459
	6/19	3,781	1,243
	6/20	5,400	1,838
	6/21	2,610	919
	6/22	6,155	1,405
	6/23	14,791	865
2002	5/26	9,319	317
	5/29	15,991	556
	5/30	13,380	1,349
	5/31	12,782	3,095
	6/5	20,767	1,825
	6/6	13,062	5,793
	6/7	20,232	4,920

Table 4. Daily smolt passage estimates from acoustic and trapping studies.

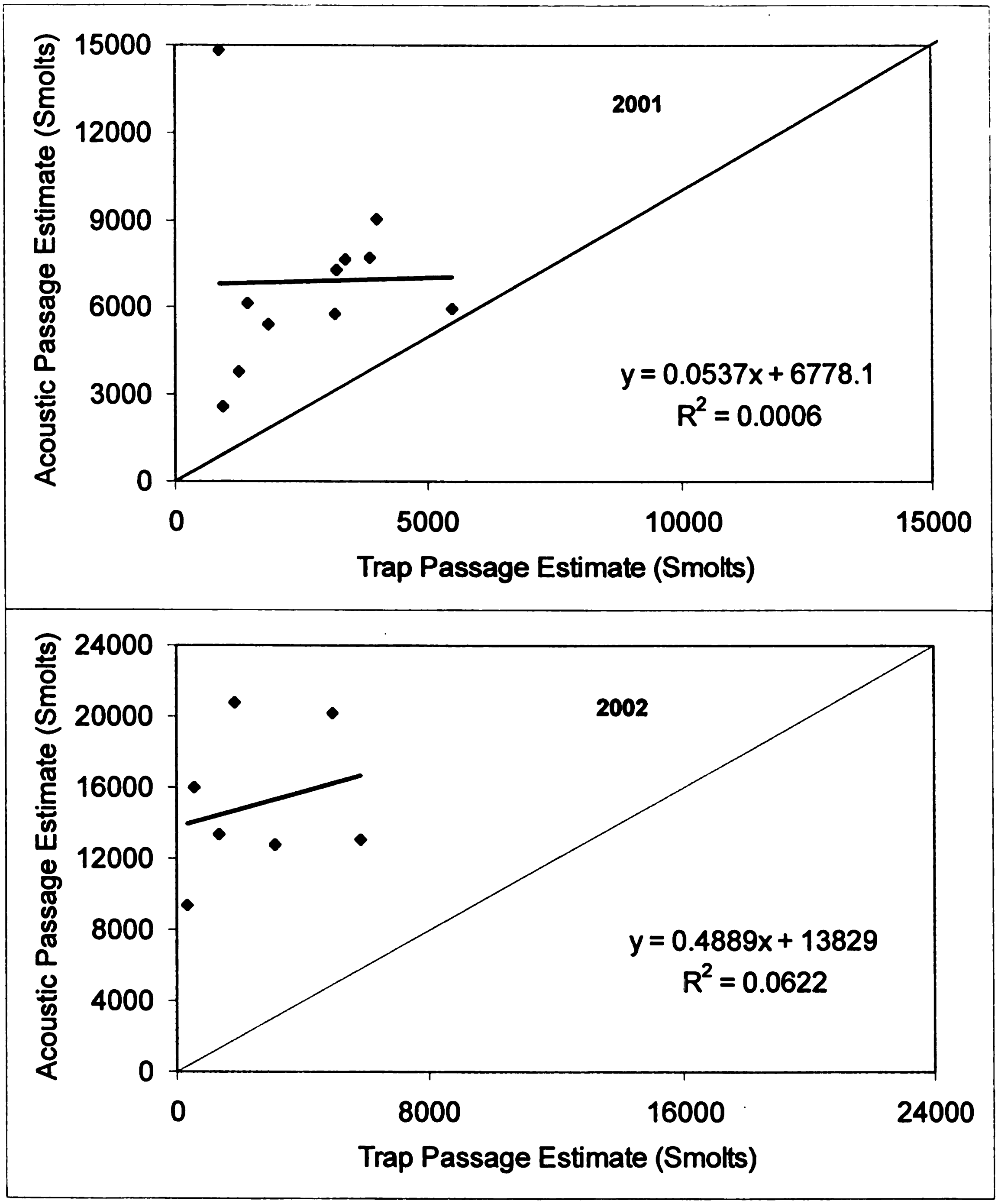

Figure 13. Regression results from comparisons of daily passage estimates from trap and acoustic surveys.

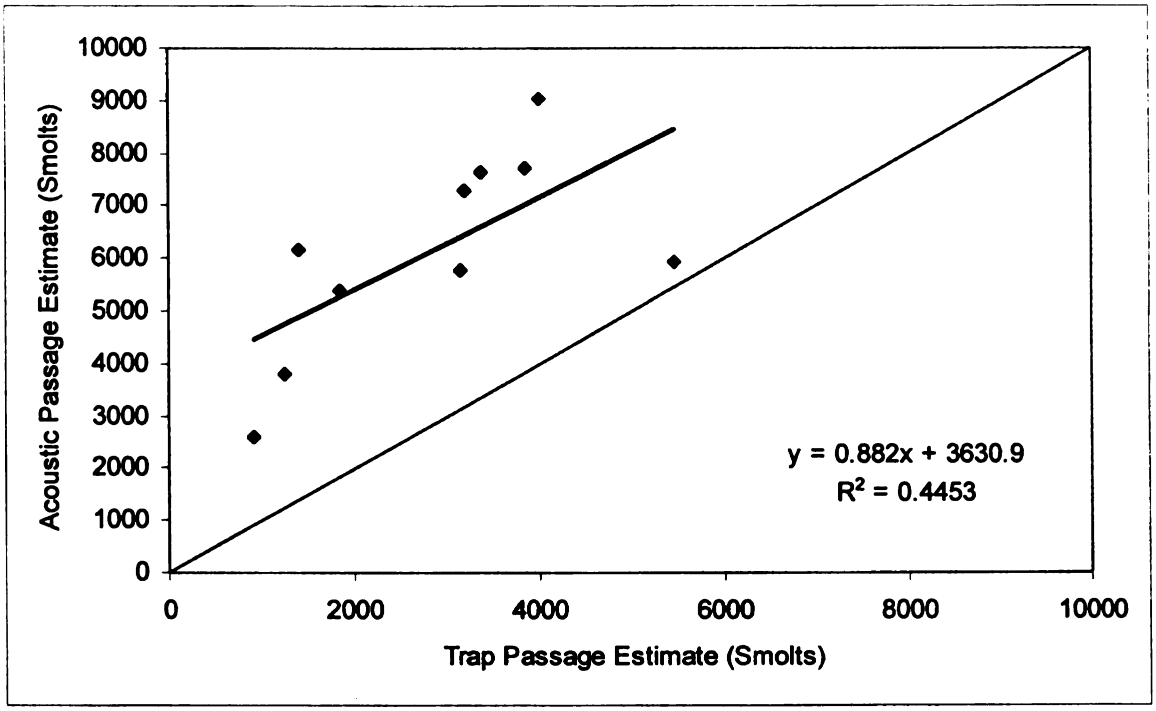

Figure 14. Comparison of daily passage estimates from trap and acoustic surveys from 2001 with an outlier removed.

both years, acoustic daily passage estimates ranged from slightly greater than 1 to nearly 30 times the estimates yielded by the smolt trap study. In general, daily estimate comparisons between methods from 2002 were much more variable than those from 2001 (Figure 13). While the comparison of 2002 daily acoustic estimates and trap estimates of smolt passage appeared to be positively correlated, the correlation was not statistically significant (ANOVA, P = 0.59; Table 5). There was also no significant correlation between the acoustic and trap estimates from 2001 (ANOVA, P = 0.94; Table 5). However, with the removal of a single outlier (23-June) from the 2001 comparison, a statistically significant positive correlation was achieved (ANOVA, P = 0.035; Table 5). The decision to exclude this data point was made solely on its position relative to the other days' comparisons. No apparent change in discharge or data quality was observed. The slope from the regression equation resulting from the 2001 comparison with the

Year	β (± 95% C.I.)	*n*	r	r^2	P-value (ANOVA)
2001	0.054 (1.599)	11	0.0253	0.0006	0.9410
2001*	0.882 (0.802)	10	0.6673	0.4453	0.0350
2002	0.489 (2.182)	7	0.2494	0.0622	0.5897
Combined*	0.419 (1.727)	17	0.1323	0.0175	0.6128

* outlier removed

Table 5. Correlations and significance from comparisons of daily passage estimates from trap and acoustic results.

outlier removed was 0.882, and the intercept was 3,630.9 (Figure 14). A final comparison of the pooled results from 2001 and 2002 (outlier removed) also proved to be insignificant (ANOVA, P = 0.61; Table 5).

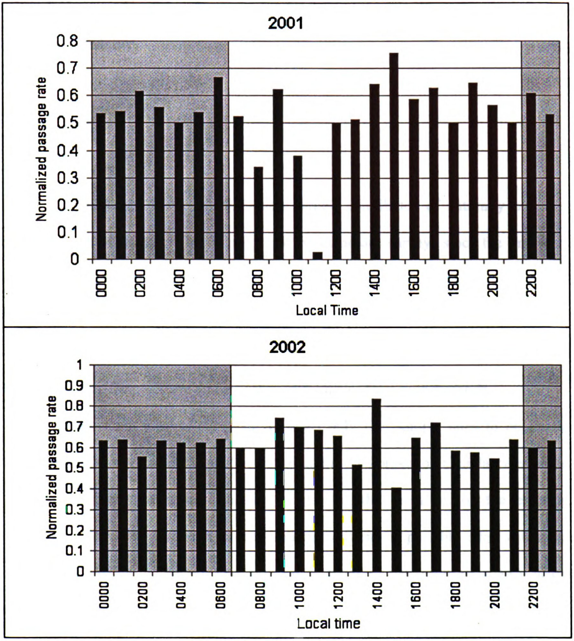

Figure 15. Mean normalized hourly passage rates from 2001 and 2002 acoustic surveys (shading from approximation of sunset to sunrise).

No obvious trends were detected upon examination of the mean normalized hourly passage rates for either year (Figure 15). Passage rates did appear to be more stable during the nighttime hours during the nighttime hours than the day. However, data were collected for fewer days during the late morning and early afternoon hours due to battery depletions. The reduced sample size for these hours probably led to the perceived increase in variability.

Discussion

Gear Comparisons

The Muskegon River is Michigan's largest contributor of naturally produced smolts to Lake Michigan. This is supported by numerous surveys since the first work done by Carl (1982) in the late 1970's. The electrofishing estimates made by Rutherford from 2000 and 2001 are comparable to previous estimates of pre-smolt abundance and lend credence to the smolt trapping methods used in those years. However, concerns still remain regarding the precision and accuracy of estimates from both methods.

The pre-smolt electrofishing survey used only five sample sites to obtain the average smolt density that is extrapolated to reach the total pre-smolt abundance estimate. This low samples size incites questions regarding the precision of the estimate. Additionally, the sites were not chosen randomly from all possible sites within the nursery area. While the survey may provide an index of pre-smolt abundance across years, the validity of the overall estimate is questionable.

The smolt trapping survey is also subject to questions of precision and bias. In larger rivers such as the Muskegon, a very small percentage of the river's cross section is sampled. The magnitude of this percentage varies with changes in river stage. As a result, in years of highly variable river stage, the probability of capturing a given smolt is likely to be variable as well. Additionally, auger-type traps are operated by the pressure exerted by flowing water. As the flow rate decreases, the trap turns slower and provides more of an opportunity for migrating smolts to avoid capture. Depending on the stage changes, flow rates, and the timing of the migration, a real potential exists for the daily estimates to be biased high or low.

Performance Analysis

The results of the performance analysis indicate shortcomings in the parameters used in both the STDA and the FTA. It should be noted that all data used in the performance analysis was collected in 2002 when daily acoustic passage estimates were extremely variable relative to daily trap passage estimates. However, the performance analysis does provide some insight into the problems of 2002.

Foremost, the perceived inability of the STDA to identify multiple targets in many visually identified fish traces caused relatively high numbers of omitted results. The parameters of the STDA were selected to limit the influence of debris such as tree branches and twigs. Any object passing through the beam is likely to create a trace. Without perfect knowledge of both target and non-target objects passing through the acoustic beam, much uncertainty remains regarding the performance of the STDA. Human error in the trace identification process probably led to inclusion of non-target debris traces that were in turn filtered out by the STDA. The magnitude of such error remains a mystery.

Shortcomings of the FTA, while still subject to the same target uncertainties as those of the STDA, can be more concretely identified. The primary error associated with the FTA was the creation of tracks where none had been identified visually. These tracks were often spatially erratic. This irregular pattern was easily identified in the visual inspections, as the change in range from ping to ping was generally unpredictable. This conclusion is also supported by the results of the range gating parameter perturbation where the ratio of bad to good results decreased by approximately half at each of the range bins as the range gating parameter was adjusted from 0.4 m to 0.1 m.

Passage Estimates

The performance analysis results indicate that software was very limited in its ability detect the tracks identified in the visual inspection. Yet, the daily passage estimates derived from the acoustic methods used in this study were still consistently higher than estimates made by Rutherford. Acoustic passage estimates from 2001 ranged from 1.09 to 17.1 times higher than the corresponding trapping estimates. However, with the removal of the outlier, the upper end of that range is lowered to 4.38 (mean = 2.50). Acoustic passage estimates from 2002 ranged from 2.25 to 29.4 times higher than the corresponding trapping estimates (mean = 12.8).

The generally low magnitude of the differences between daily passage estimates from acoustic and trapping methods from 2001 shows some promise for the methods used herein. Additional optimism can be drawn from the significant correlation between the 2001 estimates. However, the variable results from 2002 raise concerns for the immediate implementation of these methods for management purposes. More in depth analysis of this variability will be necessary. River channel morphology and equipment limitations led to gross simplifications in calculating whole river passage estimates. The channel cross-sections for the acoustic sites used in 2001 and 2002 were asymmetrical. However, data cable length, decreased ping rate from running multiple transducers, and the use of a single hydroacoustic system, prevented the deployment of transducers from both riverbanks. As a result, it was necessary to extrapolate results from the half of the channel nearest the transducer in a symmetrical manner to the far half of the channel to estimate total passage. The most probable effect of this strategy is an underestimation of passage on the far side of the river channel where currents are faster and smolts are more likely to out-migrate.

Fixed River Acoustics: Assumptions and Problems

Successfully executing an acoustic survey such as this relies on two primary assumptions. The first is that the hydroacoustic system is consistently able to detect the target species for filtering. This is especially crucial when data on direction of travel and swimming speed data are necessary. Given the inherent noise associated with riverine environments (i.e. turbulence, debris, non-target species, etc.), detectability issues are a significant hurdle to overcome when dealing with small targets such as chinook salmon smolts. Low signal-to-noise ratio substantially limited the system's ability to detect smolts at extended ranges. Therefore in the center of the river channel, an area likely to pass a large portion of migratory smolts, the probability of detecting a given smolt was low.

The second assumption is that the data processing phase can effectively remove, or at least account for, non-target objects without affecting numbers of target traces. Undoubtedly, this assumption is also violated at some level. Through improved parameterization the impact of these violations can be minimized but never eliminated. The regression techniques used in the comparison can account for non-target tracks through the intercept. This implies that non-target track numbers are consistent across days. When river stage and discharge is stable, this may be a valid assumption. However, in the days following a rain event, river stage, discharge, and debris load can all change significantly.

One drawback to the use of hydroacoustic surveys of this type is the need for ground-truthing data. Hydroacoustics cannot be used as a standalone method for quantifying smolt passage. Some additional form of verification that identifies objects passing through the acoustic beam will continue to be necessary. These data can take the form of video surveillance or trapping. Differences in fish communities between streams or between stretches within a stream may result in significant variability. Thus, it may be necessary to reevaluate parameters and deployment configurations to ensure accurate results.

Conclusions

Each of the methods used to quantify smolt production in the Muskegon River has problems associated with its use. However, pre-smolt electrofishing and smolt trapping surveys continue to be the best methods for estimating natural smolt production at this time. While these methods do have biases associated with their use, they have been documented and can be qualitatively considered when evaluating the quality of the estimates they provide. Currently, unknowns surrounding the use of hydroacoustic methods for estimating

This study has shown that fixed location riverine hydroacoustics does have promise as a method for enumerating out-migrating salmonids. Detection issues may limit the use of hydroacoustics methods for enumerating out-migrant chinook. However, in low gradient sections of stream where turbulence is reduced, this ability is likely to be enhanced. This method holds much promise in applications where stream-type, anadromous salmonids such as coho, steelhead, and Atlantic salmon are targeted. Species residing in rivers for a year or more following emergence attain much larger sizes prior to their seaward migration. As a result, they exhibit much larger side aspect TS and greatly improve the signal:noise ratio that impedes the use of acoustics on smaller species.

Future Research

Given the results found in this study, fixed-location, riverine hydroacoustics could potentially become a useful tool for fishery managers concerned with natural salmonid production in streams. Further development of data collection and analysis methods will be necessary but also appears to be warranted.

Foremost, development of side-aspect TS relationships for chinook or other target species would improve track-filtering capabilities. Such advances could translate to more precise estimates of daily smolt passage if detectability issues can be addressed.

Additionally, as technology improves, investigation into alternate deployment configurations should also enhance acoustic capabilities. Use of multiple or multiplexing systems deployed to allow data acquisition from both sides of the channel will increase coverage of the stream's cross-section and eliminate the uncertainty of extrapolating results from one half of the channel to the other. A bottom deployed, stationary, up-looking transducer may also improve coverage and smolt detectability in the center of the river where bank deployed transducers provide data of marginal quality.

Finally, development of fixed-location, riverine, hydroacoustic survey methods should be expanded to other streams and rivers in the Great Lakes basin. Although it is the largest contributor, the Muskegon River is one of many Great Lakes tributaries with naturally reproducing populations of chinook salmon. To gain acceptance as a legitimate technique for quantifying smolt production, this method will require testing on numerous streams throughout the Great Lakes watershed.

Chapter 3

The Future of Fixed-location, Riverine Hydroacoustics in Great Lakes Fisheries Management

Project Summary

This study has shown significant obstacles associated with chinook smolt surveys. The primary obstacle identified is detectability of chinook smolts and is due to their small size at emigration. While with improved site selection and deployment strategies hydroacoustic surveys of chinook smolt passage may be possible, the detectability issue will continue to complicate the process.

With this in mind, what contributions can this method make towards managing Great Lakes fisheries? Results from this study and published literature point to several possibilities. Specifically, riverine hydroacoustics could be applied to quantify spawning stock during adult salmon spawning runs, provide smolt production estimates of coho and steelhead, and potentially provide information for management of non-game species.

Adult salmon returns. Fixed-location, riverine hydroacoustics have provided sound information for use in management of salmonid fisheries on the west coast of North America for over a decade (Ransom et al. 1998). Typical applications of the method are usually implemented to quantify escapement of adults in efforts to maintain adequate spawning stock biomass. Although rivers of the west coast generally exhibit a high gradient and, as a result, are acoustically noisy, the method is well suited for counting adult salmon. Adult salmon migrations consist of fish that exhibit target strength (TS) in the range of -30 dB and higher. With appropriate site selection, such a TS is easily distinguishable from background noise levels. Additionally, the advent of split beam hydroacoustics allows for three-dimensional tracking capabilities (Ransom et al. 1998; MacLennan and Simmonds 1993). Thus, fish migrating upstream are easily distinguished from drifting debris. These factors enhance the ability of hydroacoustic methods to quantify adult salmonid abundance in rivers.

With the current state of technology, hydroacoustics will be best applied to quantifying adult returns to natal streams. Results from adult passage surveys can at minimum be considered a reliable index of abundance. With the prior development of stock-recruitment models for streams making significant natural smolt contributions, adult returns can be used to make preliminary estimates of smolt production nearly six months in advance of stocking. This information combined with the status of Lake Michigan predator and forage populations can be used to make adjustments to stocking rates and reallocate hatchery resources for optimal production of all species. Stocking rates can then be fine tuned with updated information on pre-smolt abundance immediately prior to the planting of fish.

The benefits of this type of management strategy are twofold. Foremost, management actions shift away from relatively static stocking rates and reacting to natural inputs the year after they are added to the lake. Instead, lake conditions and natural smolt contributions are considered prior to stocking, thus, circumventing the time lag associated with the reactive strategy. As a result, lake conditions should remain more stable, decreasing concerns of predator overpopulation forage depletion. Secondly,

Smolt production. Substantially less work has been conducted targeting out-migrating salmon smolts. Obstacles such as small size at out-migration (e.g. low TS) and direction of travel make distinguishing smolts from noise and other non-target objects more difficult as noise levels increase. As a result, high gradient streams are not well suited for this application of the method, and its development has been relatively slow.

However, managers working in low gradient streams like the lower Muskegon could potentially benefit from out-migrant work. Such work will probably be limited to "stream type" species (i.e. steelhead and coho) that out-migrate at much larger size than chinook.

Development of techniques for enumerating out-migrant coho and steelhead is not only promising, but also justified. One of the major difficulties encountered during this study was detectability of the small chinook smolts. The TS corresponding to the observed range of chinook lengths in the Muskegon was approximately –55 dB to –47.5 dB. The background noise levels observed in this study gradually increased with range until it exceeded even the high end of this range (Figure 1). Newcomb and Coon (2001) found that the average length of steelhead smolts emigrating from the Betsie River, Michigan was approximately 195 mm. Using the TS-length relationship of Lilja et al. (2001), a smolt this size would exhibit a TS of approximately –40 dB. This is well above background noise levels and bodes well for steelhead smolt detection (Figure 1).

In addition to improved detectability, coho and steelhead abundance in the Lake Michigan system also provide support for further development. Northwest lower Michigan streams have been known to consistently produce significant numbers of wild coho and steelhead smolts since the late 1970's (Carl 1982, Seelbach and Whelan 1988, Seelbach 1993). Additionally, these species contribute a sizable portion of the Lake Michigan sport fishery. In 1999, the combined coho and steelhead catch from mandatory charter boat reporting of trips in Michigan waters was 21,916 compared to 28,689 for chinook (Rakoczy and Russell 2003a). In a similar comparison of 1998 reporting, coho and steelhead catch exceeded chinook catch by more than 2,000 (Rakoczy and Russell

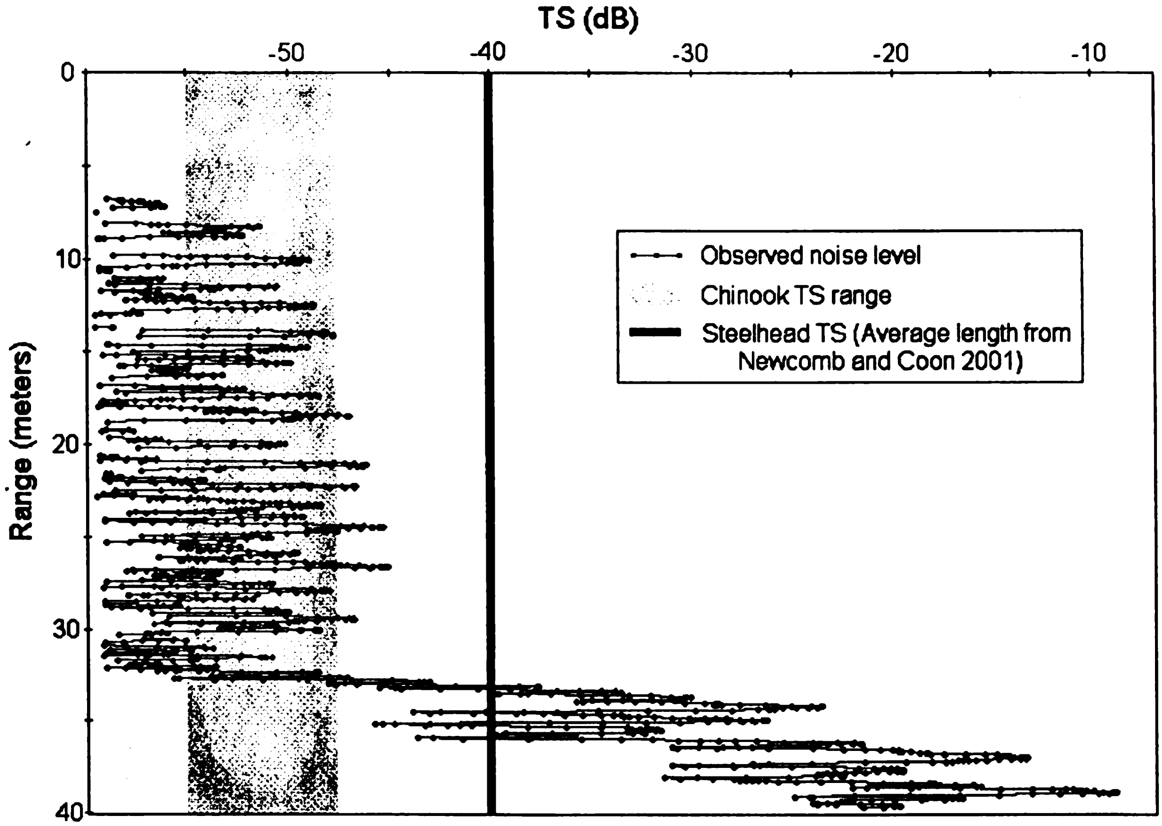

Figure 16. Noise levels typically observed in this study with chinook and steelhead TS shown for reference.

2003b). At these levels of relative abundance, coho and steelhead can significantly influence the trophic balance of the lake.

Non-game species management. Just as it is important to understand the reproductive dynamics of important game and commercial species like salmon and trout, this information is important for conservation of certain non-game species as well. Hydroacoustic surveys could potentially aid in the management of other potamodromous species such as lake sturgeon, which return periodically to their natal streams to spawn.

Conclusions

While the outlook for using riverine hydroacoustics as a method to quantify chinook smolt production is marginal at this time, several other applications hold promise for the technique. Use of hydroacoustics in quantifying adult returns, smolt production of alternate species, and non-game species management is feasible and could be implemented with a reasonable amount of development.

APPENDIX

				% of Filtered Tracks				
Date	Range Bin	Total Tracks	Number	Lower TS	Upper TS	Direction	Tortuosity	Process
6/8/01	0 - 5	618	346	0.0	84.1	13.9	2.0	0.0
	5 - 10	1,622	1,350	0.0	74.7	22.7	1.7	0.8
	10 - 15	9,832	8,708	0.0	77.3	18.4	2.6	1.7
	15 - 20	13,638	13,000	0.0	91.2	7.1	0.8	0.9
6/10/01	0 - 5	367	215	0.0	99.5	0.0	0.5	0.0
	5 - 10	2,897	2,421	0.0	86.5	11.8	1.7	0.0
	10 - 15	12,506	11,487	0.0	82.6	14.9	2.4	0.0
	15 - 20	9,712	9,464	0.0	95.9	3.8	0.4	0.0
6/11/01	0 - 5	978	720	0.1	78.9	20.3	0.7	0.0
	5 - 10	13,105	11,612	0.0	75.8	21.7	2.5	0.0
	10 - 15	34,582	32,938	0.0	84.1	13.9	2.0	0.0
	15 - 20	24,605	24,285	0.0	93.6	6.0	0.4	0.0
6/12/01	0 - 5	1,112	828	0.5	58.0	36.8	4.3	0.4
	5 - 10	9,652	7,982	0.2	73.0	23.1	3.2	0.6
	10 - 15	34,042	30,162	0.1	73.7	21.2	4.4	0.6
	15 - 20	16,632	16,248	0.0	91.1	7.6	0.6	0.8
6/13/01	0 - 5	1,307	927	0.0	52.0	42.7	4.5	0.8
	5 - 10	10,127	8,717	0.0	76.1	19.9	2.9	1.1
	10 - 15	24,268	21,648	0.0	74.8	19.5	4.2	1.5
	15 - 20	11,708	11,514	0.0	93.4	5.6	0.4	0.5
6/14/01	0 - 5	690	446	0.0	84.5	14.8	0.7	0.0
	5 - 10	5,516	4,827	0.0	80.9	17.2	1.9	0.0
	10 - 15	20,312	18,644	0.0	82.2	15.2	2.5	0.0
	15 - 20	15,834	15,581	0.0	94.7	4.9	0.4	0.0
6/19/01	0 - 5	796	622	3.5	70.1	22.7	1.3	2.4
	5 - 10	9,330	8,421	1.1	80.9	15.0	2.4	0.6
	10 - 15	11,509	11,183	0.2	92.6	6.3	0.7	0.2
	15 - 20	8,012	7,969	0.0	98.3	1.4	0.1	0.3
6/21/01	0 - 5	494	302	0.0	82.5	16.2	1.0	0.3
	5 - 10	6,492	5,298	0.9	70.0	24.3	4.5	0.3
	10 - 15	7,636	7,230	0.1	86.3	11.8	1.6	0.2
	15 - 20	8,353	8,227	0.0	95.6	4.2	0.2	0.0
6/22/01	0 - 5	433	347	5.2	85.3	9.2	0.3	0.0
	5 - 10	5,823	5,230	4.4	80.1	13.3	2.2	0.0
	10 - 15	9,928	9,592	1.6	90.1	7.6	0.7	0.0
	15 - 20	9,769	9,699	0.6	96.3	2.6	0.2	0.2
6/23/01	0 - 5	991	818	0.0	92.1	7.3	0.1	0.5
	5 - 10	6,091	5,575	0.0	89.3	9.3	0.9	0.4
	10 - 15	1,224	1,213	0.0	97.7	2.1	0.1	0.2
	15 - 20	1,388	1,369	0.0	96.3	3.4	0.0	0.3
6/24/01	0 - 5	2,309	1,834	6.1	82.2	9.7	1.7	0.3
	5 - 10	5,521	4,843	3.7	83.3	10.9	1.7	0.4
	10 - 15	1,492	1,468	0.9	93.5	4.6	0.4	0.6
	15 - 20	1,545	1,506	0.7	87.7	8.9	1.3	1.4

Table 6. Contribution of post-processing filters to total number of tracks filtered for 2001.

				% of Filtered Tracks				
Date	Range Bin	Total Tracks	Number Filtered	Lower TS Threshhold	Upper TS Threshhold	Direction of Travel	Tortuosity	Process Error
5/26/02	0 - 5	112	80	0.0	63.8	36.3	0.0	0.0
	5 - 10	879	663	0.2	56.1	36.3	7.4	0.0
	10 - 15	1,229	1,098	0.0	63.0	30.0	7.0	0.0
	15 - 20	2,304	2,204	0.0	78.3	18.4	3.3	0.0
5/29/02	0 - 5	203	105	4.8	32.4	54.3	8.6	0.0
	5 - 10	941	908	2.1	20.0	70.0	7.8	0.0
	10 - 15	1,342	1,095	0.0	38.1	48.9	13.0	0.0
	15 - 20	1,614	1,462	0.4	51.7	41.9	5.9	0.1
5/30/02	0 - 5	241	149	0.0	59.7	38.3	2.0	0.0
	5 - 10	1,245	1,004	0.0	57.3	37.5	5.2	0.0
	10 - 15	3,304	3,122	0.0	72.6	24.0	3.4	0.0
	15 - 20	6,918	6,843	0.0	94.4	5.3	0.4	0.0
5/31/02	0 - 5	267	168	3.0	51.8	41.1	4.2	0.0
	5 - 10	1,068	866	2.8	51.2	41.5	4.6	0.0
	10 - 15	962	899	1.0	64.4	30.5	4.1	0.0
	15 - 20	1,171	1,124	0.1	77.7	21.0	1.2	0.0
6/5/02	0 - 5	221	146	0.0	65.1	32.2	2.7	0.0
	5 - 10	1,572	1,176	0.0	59.3	34.1	6.6	0.0
	10 - 15	2,280	2,141	0.0	70.1	27.1	2.8	0.0
	15 - 20	1,724	1,646	0.0	76.7	21.9	1.4	0.0
6/6/02	0 - 5	262	185	0.0	72.4	27.0	0.5	0.0
	5 - 10	1,446	1,144	0.0	68.4	28.6	3.0	0.0
	10 - 15	1,755	1,584	0.0	73.5	23.1	3.3	0.0
	15 - 20	2,017	1,893	0.0	81.8	15.3	2.9	0.0
6/7/02	0 - 5	257	128	0.0	46.9	48.4	4.7	0.0
	5 - 10	1,086	717	0.0	38.8	52.7	8.5	0.0
	10 - 15	1,610	1,353	0.0	43.2	43.7	13.2	0.0
	15 - 20	2,524	2,252	0.0	55.4	36.2	8.4	0.0

Table 7. Contribution of post-processing filters to total number of tracks filtered for 2002.

Date	Species	Number*	Minimum Length (cm)*	Maximum Length (cm)*
6/8/2001	Chinook salmon	74	5.4	9.4
	Steelhead (parr)	17	-	<3.5
	Notropis sp.	1	-	-
6/10/2001	Chinook salmon	62	6.5	8.9
	Steelhead (parr)	13	-	<3.5
	Alewife	1	-	13.1
	White perch	1	-	16.2
	Notropis spp.	-	-	-
	Bluntnose minnow	-	-	-
	Rock bass	-	-	-
6/11/2001	Chinook salmon	58	-	-
6/12/2001	Chinook salmon	71	-	-
6/13/2001	Chinook salmon	59	5.0	10.6
	Notropis sp.	3	9.8	11.9
	Rock bass	3	4.5	16.4
	Shorthead redhorse	2	35.0	39.0
	Alewife	1	-	-
	Steelhead (smolt)	1	-	20.9
	Fathead minnow	1	-	7.5
6/14/2001	Chinook salmon	101	5.3	9.6
	Steelhead (parr)	30	-	<3.5
	Alewife	4	13.8	17.1
	Shorthead redhorse	3	34.0	42.0
	Greater redhorse	2	38.0	44.0
	Steelhead (smolt)	2	23.4	24.2
6/19/2001	Chinook salmon	23	6.4	9.3
	Alewife	2	13.5	16.0
	Bowfin	1	-	7.0
	Rock bass	-	-	-
	Fathead minnow	-	-	-
	Notropis sp.	-	-	-
6/20/2001	Chinook salmon	34	6.0	10.2
6/21/2001	Chinook salmon	17	7.0	9.0

*Abundance and length data were not collected for all species on all days.

Table 8. Species composition from smolt trap by trap day in 2001.

Date	Species	Number*	Minimum Length (cm)*	Maximum Length (cm)*
6/22/2001	Chinook salmon	26	5.5	8.5
6/23/2001	Chinook salmon	16	6.7	8.9
	Steelhead (parr)	-	-	<3.5
	Largemouth bass (fry)	-	-	-
	Notropis sp.	-	-	-
	Yellow perch	-	-	-

*Abundance and length data were not collected for all species on all days.

Table 8 (continued). Species composition from smolt trap by trap day in 2001.

Date	Species	Number	Minimum Length (cm)	Maximum Length (cm)
5/26/2002	*Notropis spp.*	5	3.6	9.9
	Chinook Salmon	4	7.0	7.5
	Rock bass	3	3.6	5.6
	Brown trout	1	-	16.2
5/29/2002	Chinook salmon	7	6.4	10.1
	Rock bass	5	3.7	4.9
	Brown trout	4	19.6	20.9
	Shorthead redhorse	3	44.5	47.0
	Notropis spp.	2	4.7	7.2
	Creek chub	2	9.2	11.2
	Bluntnose minnow	1	-	4.7
	Bluegill	1	-	3.3
5/30/2002	Chinook salmon	17	5.2	9.0
	Notropis spp.	10	4.1	8.8
	Steelhead (smolt)	3	16.9	21.8
	Rock bass	3	3.2	4.2
	Brown trout	2	-	23.2
	White sucker	2	38.9	47.6
	Rainbow darter	1	-	3.2
5/31/2002	Chinook salmon	39	6.5	9.0
	Notropis spp.	9	3.6	10.1
	Rock bass	3	4.4	14.4
	Brown trout	1	-	16.4
6/5/2002	Chinook salmon	23	5.2	8.8
	Notropis spp.	6	6.5	8.5
	Rock bass	1	-	4.0
	Steelhead (parr)	1	-	3.0
	Sea lamprey	1	-	45.5
6/6/2002	Chinook salmon	73	5.4	8.3
	Notropis spp.	13	2.9	9.9
	Black redhorse	1	-	43.4
6/7/2002	Chinook salmon	62	5.2	9.6
	Steelhead (parr)	13	2.8	3.3
	Notropis spp.	9	4.1	9.7
	Rock bass	6	2.1	13.2
	Bluegill	1	-	10.5
	Shorthead redhorse	1	-	32.7

Table 9. Species composition from smolt trap by trap day in 2002.

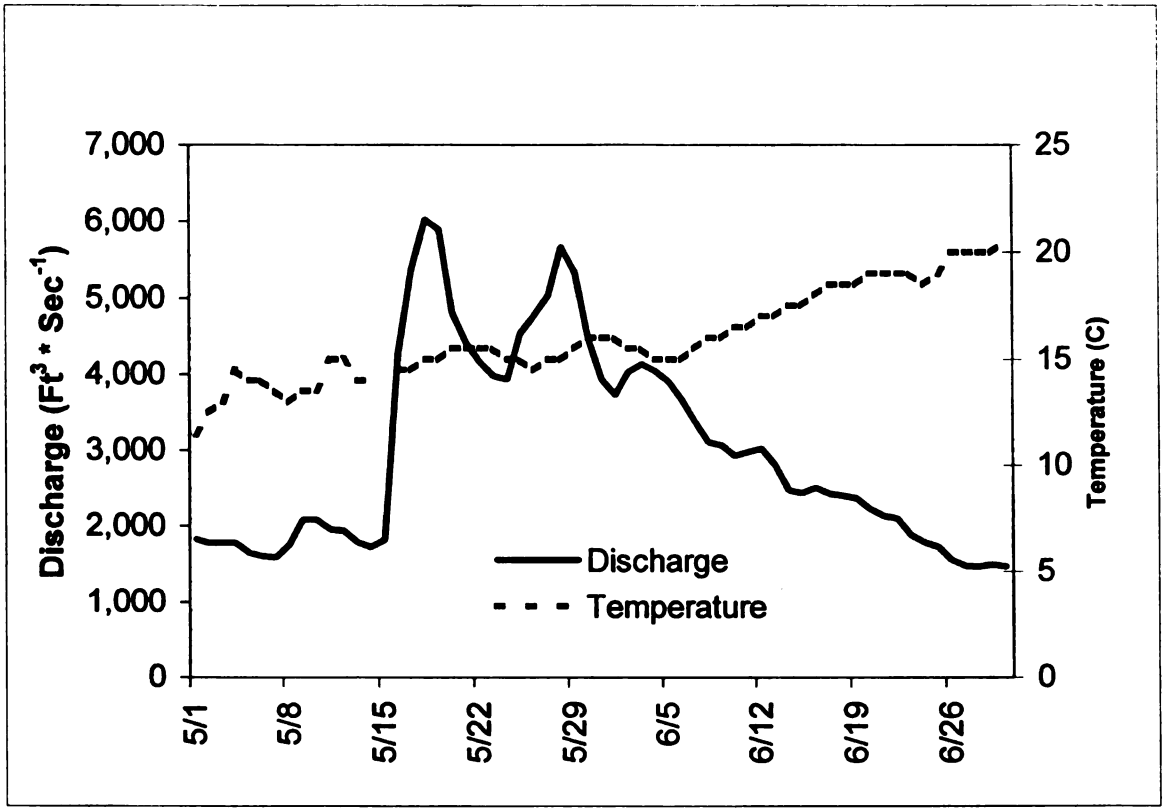

Figure 17. Temperature and discharge from 2001 as measured at Croton Dam (data courtesy of US Geological Survey).

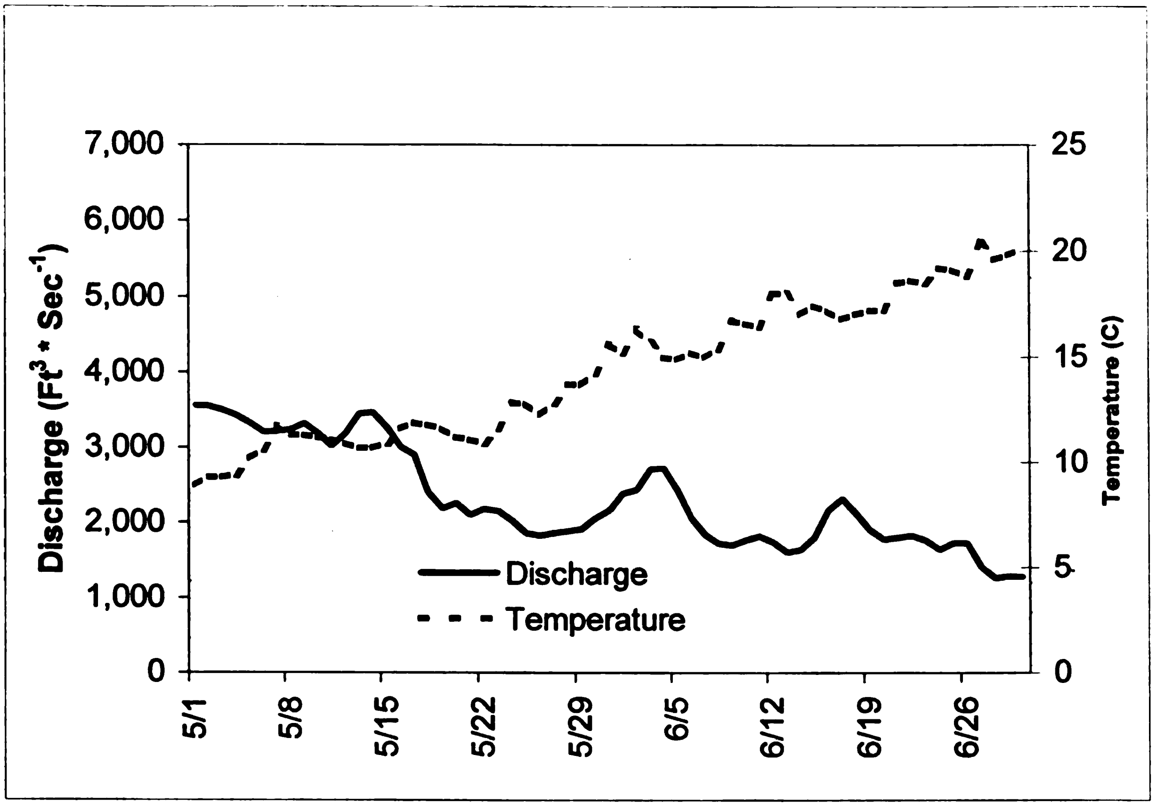

Figure 18. Temperature and discharge from 2002 as measured at Croton Dam (data courtesy of US Geological Survey).

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