Salmonid spawning stock abundance, recruitment and exploitation in the Muskegon River

Project Completion Report

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INTRODUCTION

Classical predator-prey dynamics highlight the numerical response of a predator population to changes in the prey population (Lotka 1925, Volterra 1926). In the Laurentian Great Lakes, however, predator populations are artificially controlled by hatchery production rather than by density-dependent feedback mechanisms. These artificially controlled piscivore populations support a recreational sport fishery valued in the billions of dollars (Talhelm 1988). In such a system, hatchery production is maximized in response to public demand at the risk of exceeding the ecosystem's capacity to support stocking rates. When stocking rates exceed the carrying capacity of the lake, catastrophic mortality may occur (e.g., chinook in the late 1980s) directly impacting the sports fishery. Recently, management practices have qualitatively considered the status of prey fish populations when making stocking decisions. However, the unknown natural production of salmon in Lake Michigan tributaries may be a significant component of the lake population thus complicating stocking decisions based solely on prey fish supply and potentially disrupting the balance between predator demand and prey supply. The Lake Michigan Fish Community Objectives recognize natural production of Pacific salmon and highlight the necessity of understanding natural salmon recruitment for sustained production and harvest of salmonines, as well as for maintaining a healthy Lake Michigan ecosystem (Eshenroder et al. 1995).

Increases in natural reproduction of anadromous salmonids have resulted from mandated changes in hydropower operations that have improved salmonid nursery habitat below hydropower dams. Further changes in hydropower operations are expected, which should further increase the availability of spawning areas and increase natural production. The increase in natural reproduction, combined with decreases in natural mortality from Bacterial Kidney Disease (BKD), and an increased forage biomass of alewives, has permitted population biomass and harvest rates of Lake Michigan chinook salmon to return to near-peak levels observed during the early 1980s. The present record numbers of adult salmonids, which during the 1980s depleted alewife forage and experienced high disease-related mortality, have spurred managers to reduce hatchery production, and thereby place greater importance on wild recruitment.

Although recruitment of Lake Michigan salmon and trout originally depended entirely on hatchery production, significant natural reproduction of chinook salmon and steelhead now occurs in Lake Michigan tributaries, and may contribute 20-40% of the total adult population (Seelbach 1993; Rand et al. 1993; Hesse 1994). Recently, Rutherford et al. (1999) reported that 76-96% of returning adult chinook in the Manistee and Muskgon Rivers during 1996-1997 were of wild origin. But, annual production of wild smolts (recruits) is variable (Seelbach 1993; Hesse 1994). We currently know little about which river(s) contribute the majority of natural recruitment to the fishery, the magnitude of the adult spawning runs and corresponding recruitment, and the corresponding rates of river exploitation. Sustainable management of the salmonid fisheries requires knowledge of recruitment variability, the relationship between recruitment and spawning stock biomass, as well as estimates of catchability and exploitation. These parameters are currently unknown, but are central to models (yield-per-recruit, spawner-recruit) used by Lake Michigan fisheries managers to determine size and bag-limit regulations, stocking rates, and predict population biomass and harvest.

To improve our understanding of Pacific salmon natural recruitment, we proposed to estimate absolute abundance and behavior of out-migrating smolts (e.g., chinook and steelhead) to later relate back to river habitat. To do this, we modified hydroacoustic techniques commonly used on the west cost of the United States to measure the abundance of adult salmon in rivers and develop the appropriate protocol for measuring salmon smolts.

Our specific objectives were:
i. To quantify smolt behavior during migration.
ii. To estimate abundance of out-migrating smolts.
iii. To evaluate the feasibility of using fixed-location riverine hydroacoustic technology to measure smolt abundance.

GENERAL METHODOLOGY

We focused our efforts on the Muskegon River (**Figure 1**) to complement data collected from past studies and because the Muskegon River is believed to be a major producer of chinook salmon to Lake Michigan. Sampling occurred in the spring and early summer of 2001 and 2002. The following methods are broken down into several categories which include- parr and pre-smolt surveys, biological collection of emigrating chinook smolt, description of hydroacoustic equipment, site selection and deployment of hydroacoustic equipment, hydroacoustics data collection, signal processing and software evaluation, and hydroacoustic estimates of smolt passage.

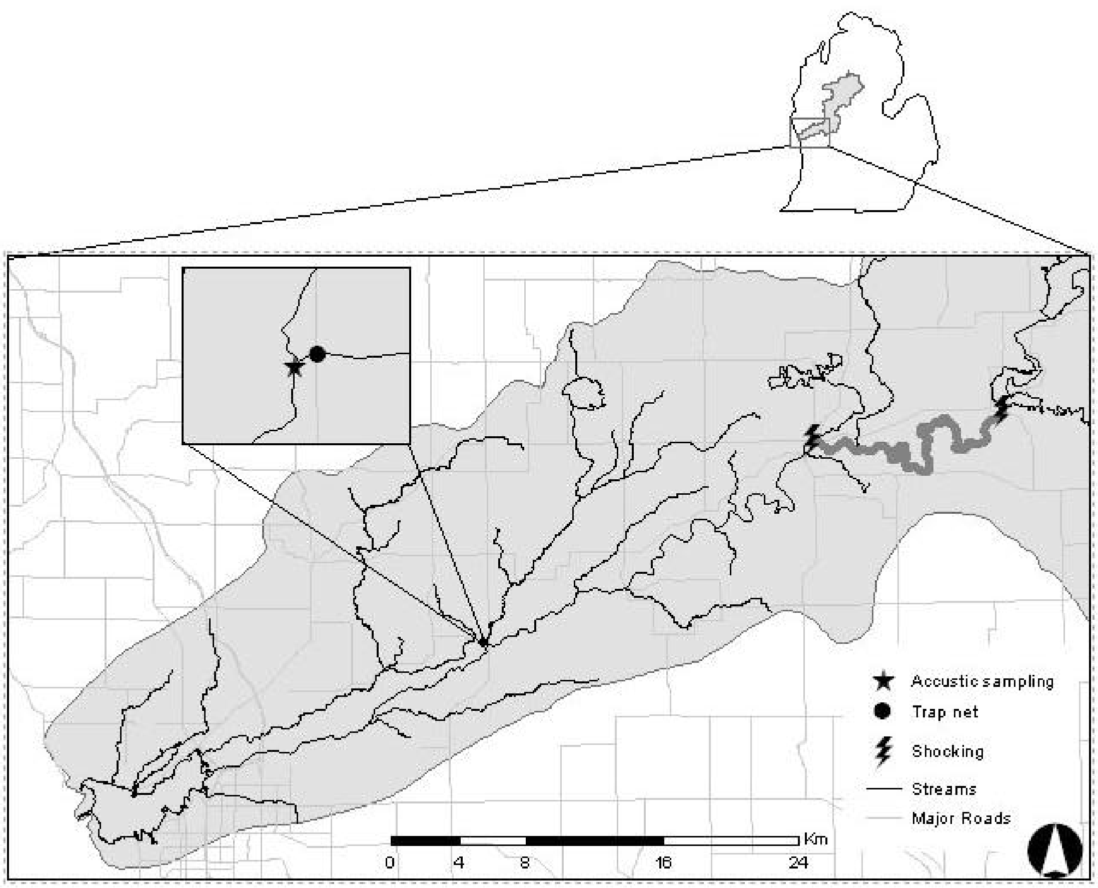


***Figure 1**. Map of the Muskegon River watershed and the location of the hydroacoustics deployment, auger trap deployment and electrofishing survey for parr and pre-smolts.*

Parr and pre-smolt surveys. Chinook salmon parr and pre-smolt abundance was estimated from samples collected by electrofishing along shoreline sites using a boat-mounted DC electrofishing unit (i.e. a stream shocker). The chinook salmon pre-smolt survey was conducted May 7-8 in 2001 and May 11, 12, and 15 in 2002 at 5 historic sites (Figure 1); sites sampled in previous studies by Carl (1982) and O'Neal (1988). Salmonid parr and pre-smolt densities were estimated using a 2 or 3-pass depletion method (Seber and LeCren 1967). Non-salmonid fishes were recorded as present/absent in the chinook pre-smolt survey.

Collection of emigrating smolt. Muskegon River chinook salmon smolt were sampled continuously from May 2 to June 26 in 2001 and May 8 to July 2 in 2002 at the Maple Island Bridge (**Figure 1**) using a 2.4-m diameter rotating auger trap (**Figure 2**). The trap was set in the river thalweg, and sampled the top meter of the water column and approximately 3.4% of the river width. The trap was checked a minimum of once daily and captured smolt were counted and measured (weight g, length cm). Flow rate and water temperature were collected at the trap. Estimates of trap efficiency was obtained by marking migrating chinook smolt that were collected in the trap, releasing them approximately 0.5 km upstream of the trap, and then recapturing; efficiency was estimated by the percentage of recaptures. A second independent estimate of trap efficiency was obtained by counting the number of hatchery chinook caught in the trap that were stocked upstream of the trap. Approximately 50,000 chinook smolt were released upstream at Hennings Park on 14 May 2001. Smolt daily passage was then estimated as number caught in the trap per day divided by trap efficiency. Seasonal smolt abundance was

Figure 2. *A photograph of the 2.4-m diameter rotating auger trap used in this study.*

simply the sum of the daily passage estimates.

Description of hydroacoustics system. Riverine applications of hydroacoustics use stationary transducers aimed at a relatively small volume of water, in contrast to the mobile hydroacoustic surveys in the Great Lakes that synoptically sample a large volume of water on mobile platforms (ships) (e.g., Brandt et al. 1991; Mason et al 2001). Fixed-location hydroacoustic technology has been used since the 1960s to estimate adult salmon escapement in nearly 50 rivers (1-20 m deep, 12-500 m wide) in North America and Europe (Johnston and Steig 1995) and is a reliable and accurate technique for enumerating adult salmon in riverine systems (Enzenhofer et al. 1998).

There are currently three types of hydroacoustics systems used for riverine studies: single beam, dual-beam, and the split-beam echosounders. Split-beam echosounders are superior to single and dual-beam systems in riverine applications (Traynor and Ehrenberg 1990; Ehrenberg and Torkelson 1996). Both split-beam and dual-beam hydroacoustics echosounders remove the effect of the beam pattern factor to provide a direct measure of the reflectivity (or acoustic size) of a fish. However, split-beam technology provides estimates of angular location, which significantly enhances the tracking performance and usefulness of data compared to data collected from single and dual-beam systems. Angular location estimates are used to estimate the three-dimensional coordinates of a fish in the beam and track that fish in three dimensions. Angular location data in conjunction with ping-by-ping target tracking of individual fish provides accurate and precise estimates of size (Burwen et al. 1995, Traynor and Ehrenburg 1990), swimming speed, location in the river (nearshore vs. offshore, surface vs. bottom) and direction of travel. Also, split-beam echosounders are relative insensitive to the effects of additive noise and angular location data can be used to sort out returns from single and multiple targets. Data from split-beam echosounders also permit discrimination of upstream vs. downstream migrating fish and fish from debris, and also provide valuable information on fish behavior for improved estimates of abundance.

***Figure 3**. Framework for mounting of dual-axis rotators and transducers*

We used a dual frequency (200 KHz and 420 KHz) Biosonics DE6000 split beam system. Transducers (elliptical beam, $3° \times 6°$) where mounted on a dual-axis rotators and the rotators were mounted on a frame (**Figure 3**). The rotator served to aim and hold the transducer in position while data collection occurred. The rotator was mounted on a frame constructed of 1/2 inch galvanized pipe. The frame was located to a position close to the shore in the river approximately 1 m deep. Using the rotator controls, the transducer was pointed towards the center of the river with the acoustic axis perpendicular to the main flow. The vertical aiming of the transducer was tuned to maximize the range of usable data collected.

Site Selection and equipment deployment. Rivers are inherently noisy environments and care must be exercised in selection of a sampling site. The ideal location for deployment of stationary side looking riverine hydroacoustics is in areas with acoustically soft bottoms (silt to small cobble), smooth and gradual gradients gently sloping from the shore (no bottom protrusions or obstructions), and laminar flow with minimal turbulence and entrained air, and site security.

Cross-sectional Profile. The cross-sectional profile of each site was qualitatively measured using a Humminbird® 200kHz fish finder. The most desirable channel characteristics are a narrow channel with gradual gradation of smooth streambed to the thalweg. The streambed must slope down to the thalweg at an angle slightly greater than the angle at which the sound beam opens on the vertical axis, in our case this was 3°. Streambed slopes much 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 and or surface of the water will interfere with the beam reducing the range at which we can collect data. Objects creating relief off the bottom also return an echo. While echoes from bottom relief are easily identified due to their long traces on the echogram, they must be excluded from the analysis.

Current Velocity. The type of flow at the study site is an important factor in the success or failure of a riverine acoustic survey. Problems can be associated with both high and low flow rates. Sedentary behavior of non-target species such as, *Notropis spp*., is likely to occur in areas of low flow and would likely bias smolt estimates high by the inclusion of non-target fish traces. High flow rates are likely to introduce two problems. Objects that differ in density with the water will scatter sound waves (MacLennan and Simmonds 1992). Rapid flow results in turbulence that entrains air bubbles with high acoustic reflectivity. Large numbers of air bubbles will decrease the signal-to-noise and decrease the precision of the angular position estimates for single targets. Keiser et al. (2000) found that low signal-to-noise ratio causes a systematic underestimation of angles off the acoustic axis and, thus, an underestimation of swimming speed and an overestimation of density. The second issue with high flow is target detectability on successive pings. Rapid flow rates can carry objects, including fish, quickly through the ensonified volume. This translates to a reduced probability of multiple target detections for an individual object, making it impossible to determine direction of passage. Given that passage estimates are based on having multiple pings on a single target as the target traverses the beam, high flow rates may bias passage estimates low.

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

In 2001, after carefully evaluating several sites based on our site selection criteria, we selected a site approximately 0.5 miles downstream from the location of the smolt trap. This site seemed to be the best candidate based on the cross-sectional profile of the river, turbulence of the flow, accessibility, and security. After obtaining permission to use the site from the landowner, we acquired the necessary materials to construct a 4'x 7' storage shed to house and protect the hydroacoustic system. Shed construction was completed on May 14. Shortly afterward, a massive rainfall event occurred throughout a large portion of the Muskegon River watershed, which resulted in a dramatic increase in river stage and discharge causing flooding of at our deployment site. This flooding event postponed the complete installation of the equipment and the starting date for data collection.

Due to the problem of flooding in 2001, we reevaluated potential sites for deployment of hydroacoustics gear. Site selection for the 2002 field season took place over a six-day period beginning May 2. Several new sites were evaluated and compared to our site from 2001. After an exhaustive search of approximately 2.5 miles of the river, we selected a site located approximately 0.1 mile downstream of the smolt trap. After acquiring permission from the landowner, we relocated the shed to the property. We also revised our strategy for shed location. To avoid the risk of flooding, we moved the shed into a 16-foot johnboat owned by the Michigan Department of Natural Resources (**Figure 4**). Frame mounted transducers were deployed near shore (**Figure 4**) and re-aimed daily to maximize the signal to noise ratio at maximum ranges throughout the season.

Hydroacoustics data collection. Data were collected at a rate of 7 pings sec^{-1} and with a pulse width of 0.4 ms. A systematic sampling strategy was adopted to limit the volume of data collected. The echosounder was configured to collect data for two minute, rest for four minutes, and reassume data acquisition for two minutes. This rate was maintained 24 hours a day for the duration of the sampling. Skalski et al (1992) found that a systematic sampling strategy could be used to collect more manageable data volumes without sacrificing precision of passage estimates.

***Figure 4**. Revised 2002 deployment showing shed mounted on johnboat. Red markers and flags highlight transducer location.*

In 2001 we collected acoustics data 24 hours a day from June 6 through June 25. The late start date was due to the above-described flooding event that postponed installation and deployment of equipment. In 2002, we initially deployed the equipment on May 15 but data collection was postponed until May 24 due to damage to the hydroacoustic system. Data were collected 24 hours a day from May 24 to June 9. Further equipment problems, believed related to the earlier damage to the echosounder, resulted in cessation of data collection for a seventeen-day period following June 9. Sampling resumed on June 26 and continued until July 2.

General protocol was to check the hydroacoustic system daily in mid- to late-afternoon, at which time data were transferred from the data acquisition laptop to a 120 GB portable hard drive. The deep cycle 12-volt marine battery used to power the system was swapped out for a fully charged replacement. The dual axis rotators were also repositioned to maximize the range of usable data.

Equipment calibration using a standard reference sphere (38.1-mm tungsten carbide sphere) was performed regularly throughout the sampling season. In addition, we mapped the beam geometry as a function of range from transducer to determine the extent and location of acoustical coverage using the tungsten carbide reference (see "Methods for beam mapping" below).

<u>Signal processing and evaluation of software</u>. All data processing was completed using SonarData Echoview® Version 3.0.80. Raw data files were loaded into Echoview®, inspected for noise, and then filtered using the Single Target Detection Algorithm (STDA) in the software. Single targets identified by STDA were then run through the Fish Tracking Algorithm to identify fish tracks (multiple ping-to-ping returns from a single fish). Fish tracks were then visually inspected and summed for every 1-hour interval. The sum of fish tracks per hour interval was then multiplied by 3 (sampled 1/3 of an hour) to estimate the number of fish passing through the acoustic beam per hour.

STDA is a process that identifies echoes that meet a serious of criteria defined for single targets. These criteria include: target strength thresholds (TS), Pulse Length Determination Level (PLDL), minimum/maximum normalized pulse width, maximum beam compensation, and maximum standard deviation of major and minor-axis angles. Echoes passing all criteria are stored in the single target variable for further analysis.

Target strength is the acoustic size (acoustic reflectivity) of a fish and is measured in units of decibels - dB. To determine the target strength thresholds, we need to have estimates of the TS for smolt from the river. Chinook smolt length is available from the smolt trap collections; all that is needed is the equation that converts length in cm to TS. We used the length-target strength relationship developed by Lilja et al. (2000). Lilja et al. (2000) developed a side aspect length-target strength relationship for brown trout *Salmo trutta* and Atlantic salmon *Salmo salar* using a 200 kHz system. The relationship is

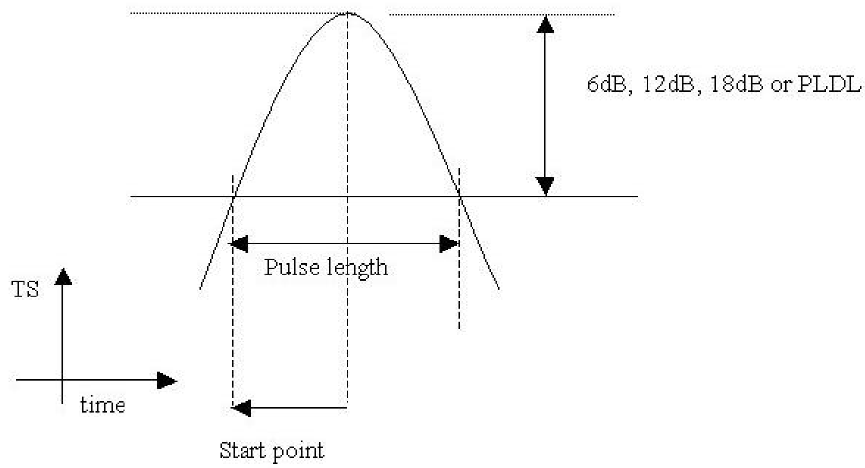
$$TS = 26.2 \times \mathrm{Log}_{10}(L) - 73.8 \qquad (1)$$

where L is fish length in cm.

Pulse Length Determination is simply the distance measured (in dB) down from the peak of the echo trace as measured on an oscilloscope (**Figure 5**). Normalized Pulse Length is then measured at this distance. 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 were background noise might interfere with detection.

Normalized pulse length is the length of the received echo pulse divided by the transmitted pulse length (**Figure 5**). This value is used to ensure the echo received is from a single target. Echoes with pulse widths shorter than the propagated signal are considered noise. This is because the likelihood of a sound pulse shortening in length is very low. Echoes with pulse widths substantially larger than the propagated signal are likely to be from multiple targets at similar ranges and are not included in the analysis. We used echoes with a Normalized Pulse Length

Figure 5*. Echo trace showing the Pulse Length Determination Level (PLDL, distance from top of echo trace measured in dB) and Normalized pulse length (width of echo trace). Figure taken from Echoview help file.*



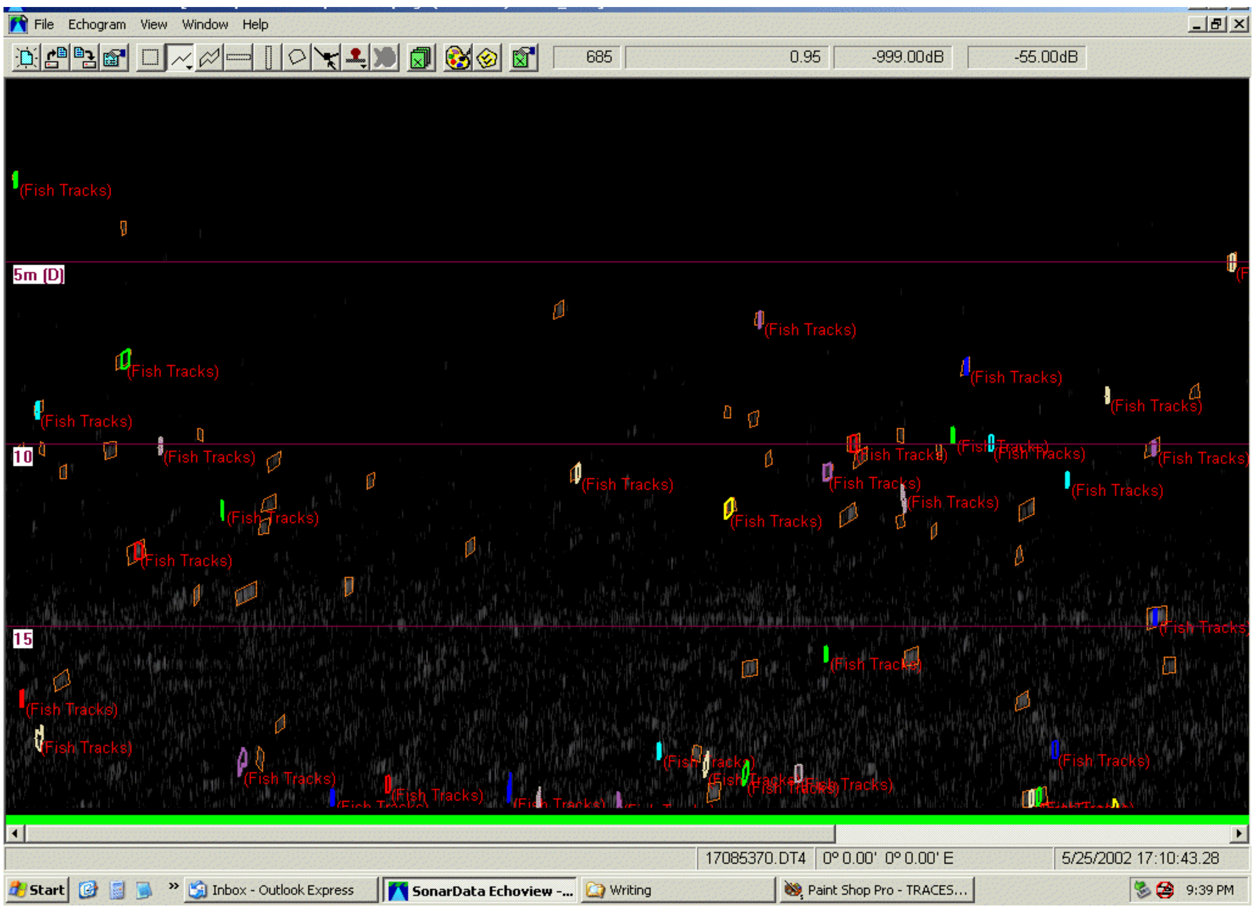
between 0.8 (minimum) and 1.5 (maximum).

Beam Compensation corrects for targets off the acoustic axis. As targets move away from the acoustic axis the amount of energy in the beam decreases and thus the echo intensity of the fish also decreases. Split-beam systems account for this loss through beam compensation. By limiting the beam compensation, low quality targets from beyond the nominal beam angles can be excluded from the analysis. Difficulties in detecting single targets led to slight loosening on this criterion. This value was set at 6 dB.

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, called the *standard deviation of major and minor-axis angles*. The precision of these estimates is sensitive to background noise in the data. Therefore, in the noisy environment of a river, the standard deviations of the angular position estimates will be relatively high. We used a value of 1.5 for each angular dimension of the beam (horizontal and vertical). This value was the lowest value at which adequate numbers of single targets could be detected for fish tracking analysis.

Echoview's Fish Tracking Algorithm (FTA) is then applied to the single targets identified from the STDA to determine tracks of individual fish. This is necessary as only the fish tracks are counted for estimates of smolt passage. The FTA analyzes the single targets by a process called candidature. When the algorithm encounters a single target, a fish track is opened. The algorithm then searches for echoes that are likely to be associated with the opening (first identified) target. An ellipsoid is created to predict the 3-dimensional location of the target on the next ping. If a target falls within that ellipsoid, it is added to the track, and 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" or "range-gating" parameter is exceeded. Ping gap allows for a missed ping during the tracking of a fish and is defined over a sequence of consecutive pings. A fish may be missed during a ping if it swims out of the ensonified region and then quickly returns for the next ping. Range gating is the distance measure of the target between consecutive pings. When the distance exceeds a threshold value, the individual target is considered another fish. When the maximum ping gap and/or range gating has been reached, the track is closed. This procedure is done on all raw data (**Figure 6**). TS and spatial data for each track are then exported for further analysis.

***Figure 6**. Screen shot of Echoview® signal processing software (Sonar Data Ptd) showing identified fish tracks. The top of the image is the transducer facing in a horizontal direction across the river. The red horizontal lines mark distance from the transducer in 5 m intervals. Each fish track is outlined in a polygon and labeled as a fish track. Gray in the background is river noise.*



<u>Analysis of software performance</u>[1]

The purpose of the performance analysis was to assist in the parameterization of the single target detection and fish tracking algorithms, to evaluate the performance of the software, and to

[1] This process of software evaluation helped identified serious bugs in the software for target tracking. Based on this information and information from others, Sonar Data Ptd. was made aware of the problem and the software problems fixed. However, due to the existence of the serious bug, all of the data had to be reprocessed setting the project behind schedule.

provide baseline results that could be applied to the estimated total chinook smolt passage. The process involved a number of steps:

1.) Trace definition
2.) Data processing
3.) Evaluation of processing results
4.) Adjustment of algorithm parameters

Trace Definition. Thirty raw data echograms were randomly selected from the data collected from May to July of 2002. Each echogram was displayed using Echoview and visually inspected for traces. The visual inspection process focused on the data at two connected levels- the single target or echo, and trace levels. 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, both levels of the data must be evaluated concurrently. In the trace definition process, qualitative judgments were made to identify potential fish traces based on several traits. Decisions regarding the relationships of a sequence of echoes were guided by observations of echo characteristics and trace morphology.

Echo Characteristics. In the trace definition process, we evaluated the characteristics of echoes that were visible on the TS echogram (e.g., **Figure 6**). This included two primary observations, pulse width and TS. Pulse width was qualitatively evaluated in a manner similar to that portion of the STDA. For this analysis, we set the minimum TS threshold to –55 dB. This equates to a chinook smolt 52.2 mm in length (equation 1). Echoes with TS values falling below this threshold are not visible on the echograms. Thus, they are not identified in the trace definition process. Echoes meeting the visual inspection requirements were considered for trace definition.

Trace Morphology. TS is also a consideration at the trace level. The TS of most echoes in a trace should be similar in magnitude after beam directivity compensation has been applied. However on a raw signal echogram (i.e. the echogram used in trace identification), the first and final echoes of a trace will generally exhibit the weakest target strength. Echo TS gradually increases to a maximum value somewhere within the trace and then decreases in a similar pattern to the value of the final echo. The raw data was compared to this model to ensure that the majority of echoes within a trace were actually associated.

The two main uses of spatial data in the trace definition process both deal specifically with range. Complexities associated with integrating three-dimensional data into the trace definition process on a large scale prevent filtering of traces by direction of travel. Thus, no consideration was given to angular data in the trace definition process.

The first range consideration is the maximum change in echo range on sequential pings. Generally speaking, out-migrating chinook are expected to be traveling downstream with minimal lateral (relative to the direction of flow) movement. In the trace definition process, echoes showing a high degree of lateral movement relative to each other were only defined as traces if they also 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 the 3-dimensional displacement to be calculated from which swimming speed and direction of travel are derived. At close range, actively swimming targets are unlikely to be detected on numerous pings due to the narrow width of the beam. As range increases the beam width increases in a linear fashion. Thus, the probability of numerous detections increases. For this analysis, the minimum number of echoes required to constitute a trace at short ranges (= 10 meters) is two. However, at extended ranges (> 10 meters), difficulties in distinguishing background noise from short fish tracks prevent all short tracks from being identified, especially when the single targets from the track are similar to the background noise level.

In addition to the minimum number of targets required, there are 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.

Sequences of echoes that met the aforementioned guidelines were outlined using a polygon (**Figure 6**). This polygon served as a marker region for spatio-temporal comparisons 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 were visually inspected to evaluate the performance of software algorithms relative to the expectations defined during the trace definition process. Codes were assigned to each user-defined polygon indicating a potential trace. Codes were 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. The list of result codes include:

- 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.

Figure 7 illustrates the code assignment process in a flow diagram.

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 divided into three broader groups to simplify performance evaluation. These categories were: Good (codes 0 & 6- correctly identified fish tracks), Bad (codes 4, 5, 7, & 9- identified fish tracks but the analysis was compromised or identified tracks were none existed), and Omitted (codes 1, 2, & 8- completely failed to identify fish tracks). 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 occurred as a function of range. Thus, the data were binned into four 5-meter increments. Names of these increments correspond to their maximum range (i.e. 10 to 15 meter interval corresponds to the interval 10-15m from the transducer and is referred to as 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. The results showed significant differences ($P<0.05$). Thus, proportions for result codes and categories by file began were calculated treating each bin separately.

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. The starting value for this parameter 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 to maximize the proportion of good results while minimizing the proportion of bad and omitted.

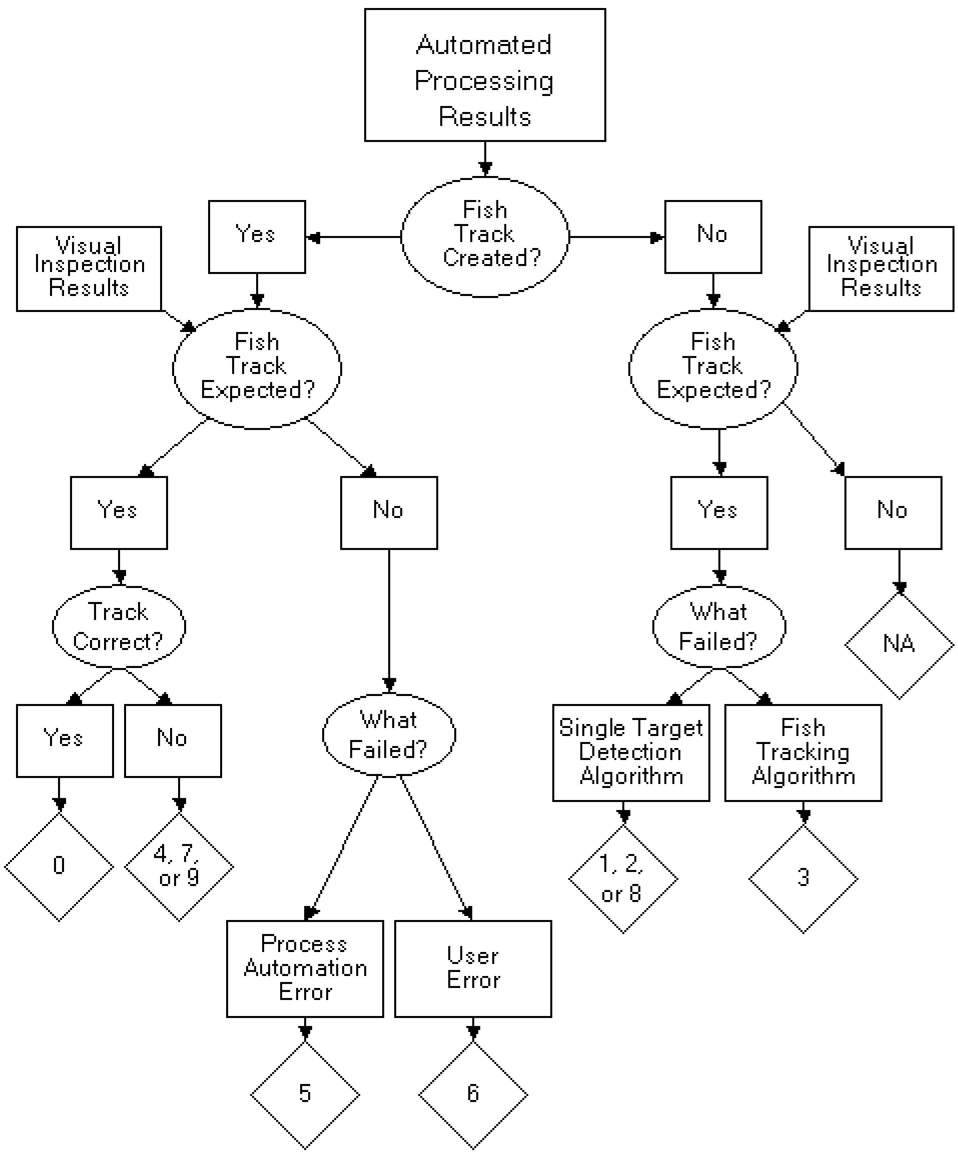
Methods for beam mapping

Following standard data processing procedures, single target data of the standard reference sphere was exported from Echoview and analyzed. The two-dimensional (range and vertical) location of 63 targets was plotted in relation to the transducer and beam axis. The range of these targets from the transducer varied from 10.7 to 19.7 meters. Least squares regression was applied to the data to determine the location of the line marking the intersection of the 3-foot plane and the vertical plane of the beam axis. The regression parameters were subject to the constraint:

$$b(\mathrm{Cos}(\mathrm{Tan}^{-1}(m))) = -0.4644 \text{ meters} \qquad (2)$$

where m = slope and b = intercept in meters. This constraint ensured that when rectified, the position of the transducer was accurate relative to the 3-foot plane that the reference sphere was

***Figure 7**. Flow chart used to analyze performance of the fish tracking algorithm in the digital signal processing software (Echoview). Numbers at terminal nodes (diamonds) reflect code assignment. See text for definition of codes.*



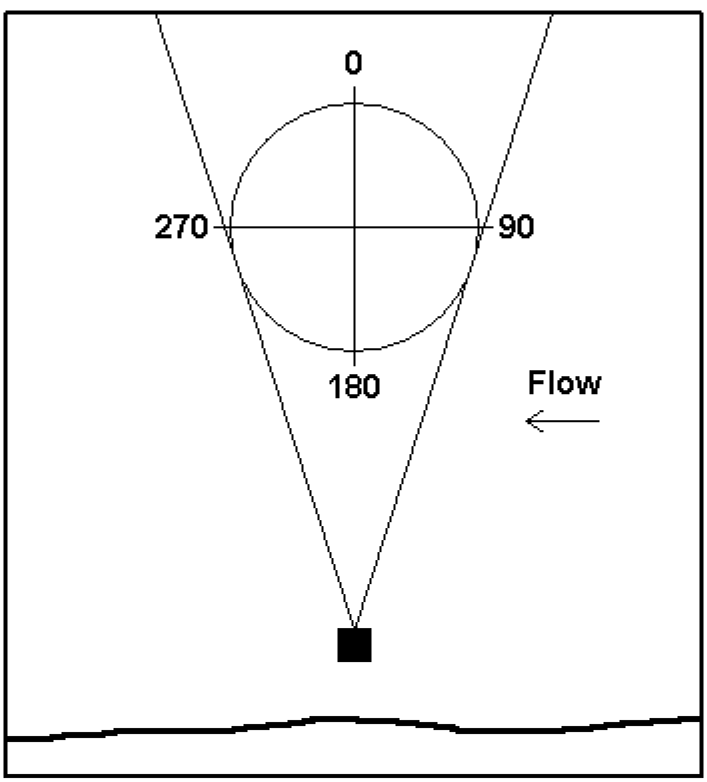
passed through. The beam axis was then geometrically rectified relative to the surface of the water. The upper and lower boundaries of the beam (±1.5°) were then plotted to provide information regarding the coverage of the top 1-meter of the river. The proportion of the cross sections coverage was calculated for four 5-meter increments totaling 20 meters from the location of the transducer.

Smolt passage

We estimated daily smolt passage 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 available for export includes but is not limited to the following: date, time, mean TS, max TS, mean target range, swimming speeds, horizontal direction of travel, time in beam, and tortuosity. These variables were used in the track filtering process to isolate and identify chinook smolt from other fishes and debris.

Known behavior of out-migrating smolt provided guidance on selecting filtering criteria. Both 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. This presents an added degree of difficulty to threshold selection process. Fängstam (1993) also found that actively swimming smolt exhibited swimming speeds of approximately 2.2 body-lengths/second. This translates to approximately 0.11 to 0.23 meter/second for smolt of the size produced in the Muskegon River. Given the level of precision of the angle estimates in the collected data, it is unlikely that this difference could be detected on a consistent basis. As a result, swimming speed was not used in the filtering process.

Figure 8. *Geometry and Heading definitions for the split beam echosounder.*



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. **Figure 8** shows the geometry of the horizontal direction measurements. In this configuration, objects moving from upstream (right) to downstream (left) while looking across the river from the transducers position exhibit a horizontal direction of 270°. 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 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, and is a measure of the "curviness" of the swimming direction. Tracks with only two targets in them have a tortuosity of 1, i.e., a straight line. 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 for tracked fish. The side-aspect length/TS relationship (equation 1) 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. The minimum and maximum length of chinook from the previous and subsequent days were used to estimate minimum and maximum TS.

Fish traces that passed the above criteria were exported for and used to estimate fish passage. Total numbers of fish tracks passing the criteria per hour were summed and multiplied by 3 (20 minutes out of every hour) for each distance interval. Results for each 5-meter increment were then multiplied by a range dependent scaling factor to estimate the total number of tracks that would be detected if the top meter of the water column were completely covered for that range. Daily track totals were then calculated (sum of 1 hour intervals over 24 hours) for the following ranges: 0 to 5 m, 0 to 10 m, 0 to 15 m, and 0 to 20 m. An estimate for the entire river cross-section was also calculated by mirroring the 0 to 15 m results as an estimate of passage beyond the range of usable data (**Figure 9**). These daily totals were then correlated to daily passage rates as estimated from the auger trap.

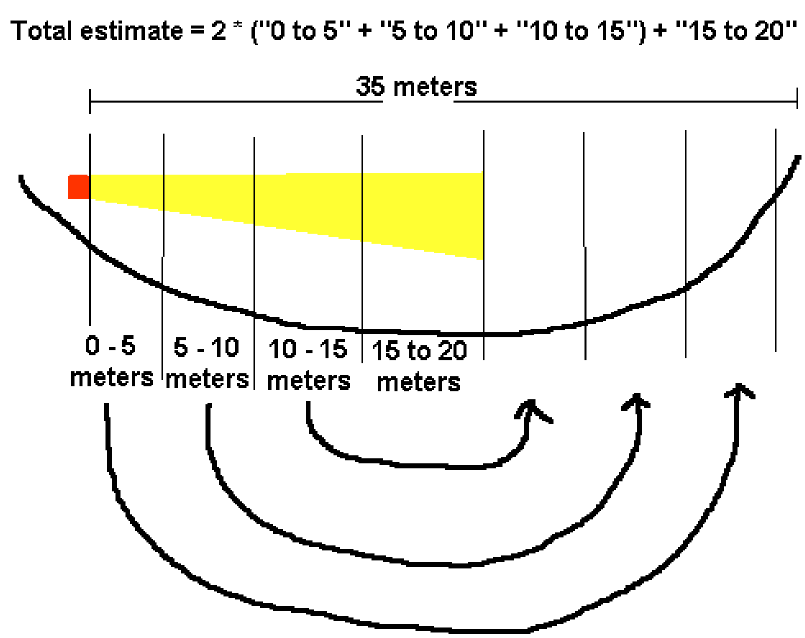


***Figure 9**. Diagram illustrating the calculation of total daily fish passage from the hydroacoustics data.*

RESULTS AND DISCUSSION

Pre-smolt and smolt abundance from electrofishing and smolt trap

2000. Pre-smolt surveys and smolt trapping indicated natural recruitment of chinook salmon in 2000 was low compared to historic estimates. The pre-smolt abundance estimates indicated 100,000 wild pre-smolts were available to leave the Muskegon River by early May. This estimate compares to 350,000 estimated by Carl (1982) in 1979, and an estimated 284,000 pre-smolt estimated by O'Neal (1988) in 1988. Smolt estimated from catches in the auger trap from late 27 April – 30 June indicated a total of 70,000 smolt left the river. The peak of the chinook smolt migration occurred during the late May to early June (**Figure 10**). Majority of the smolts began out-migrating when water temperatures ranged between 13° and 20°C (**Figure 11A**). Efficiency of the smolt trap was estimated at 2.8%.

2001. Pre-smolt surveys and smolt trapping indicated natural recruitment of chinook salmon in 2001 was high and comparable to historic estimates. The pre-smolt early May abundance estimates (electrofishing survey) indicated 857,840 wild pre-smolt were available to leave the Muskegon River. This estimate compares to 350,000 estimated by Carl (1982) in 1979, and an estimated 284,000 pre-smolts estimated by O'Neal in 1988. Smolt estimated from catches in the auger trap from 2 May - 26 June indicated 384,000 smolt left the river; approximately 45% of the estimated number of pre-smolts. The peak of the chinook smolt migration occurred during May 10^{th} compared to early June in 2000 (**Figure 10**). Majority of the smolt began out-migrating when water temperatures ranged between 13 and 18°C (**Figure 11B**). Efficiency of the auger trap was estimated at 1.85 %, which was lower than the estimate for 2000 and previous efficiency estimates of 3-5% made using this trap in the Au Sable River in 1999 and Manistee

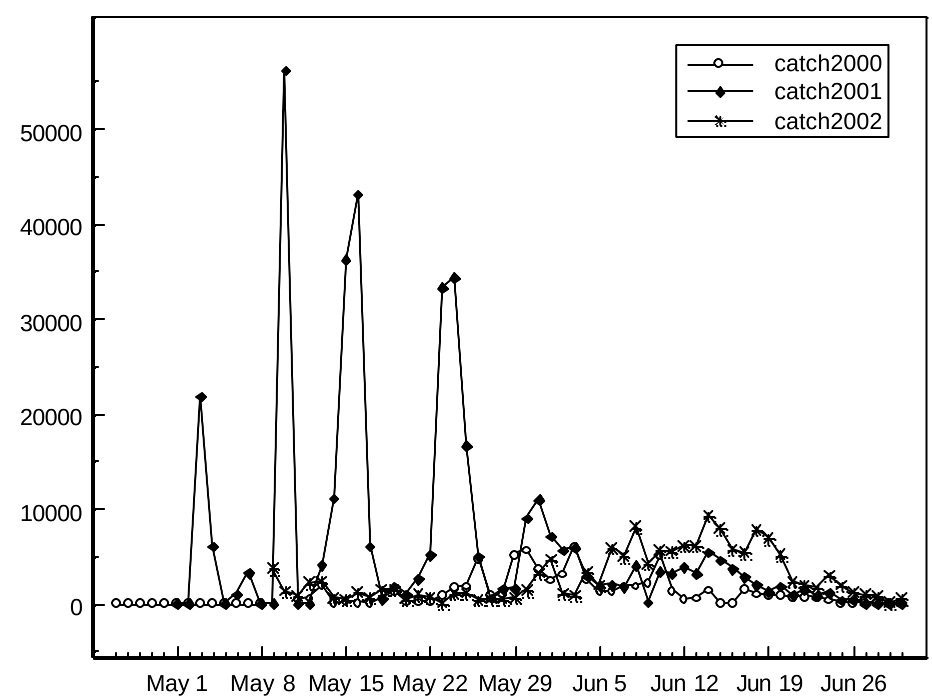


Figure 10. *Daily estimates of wild chinook smolt passage for years 2000-2002.*

River in 1998. The lower efficiency in 2001 was likely a result of extremely high river discharge

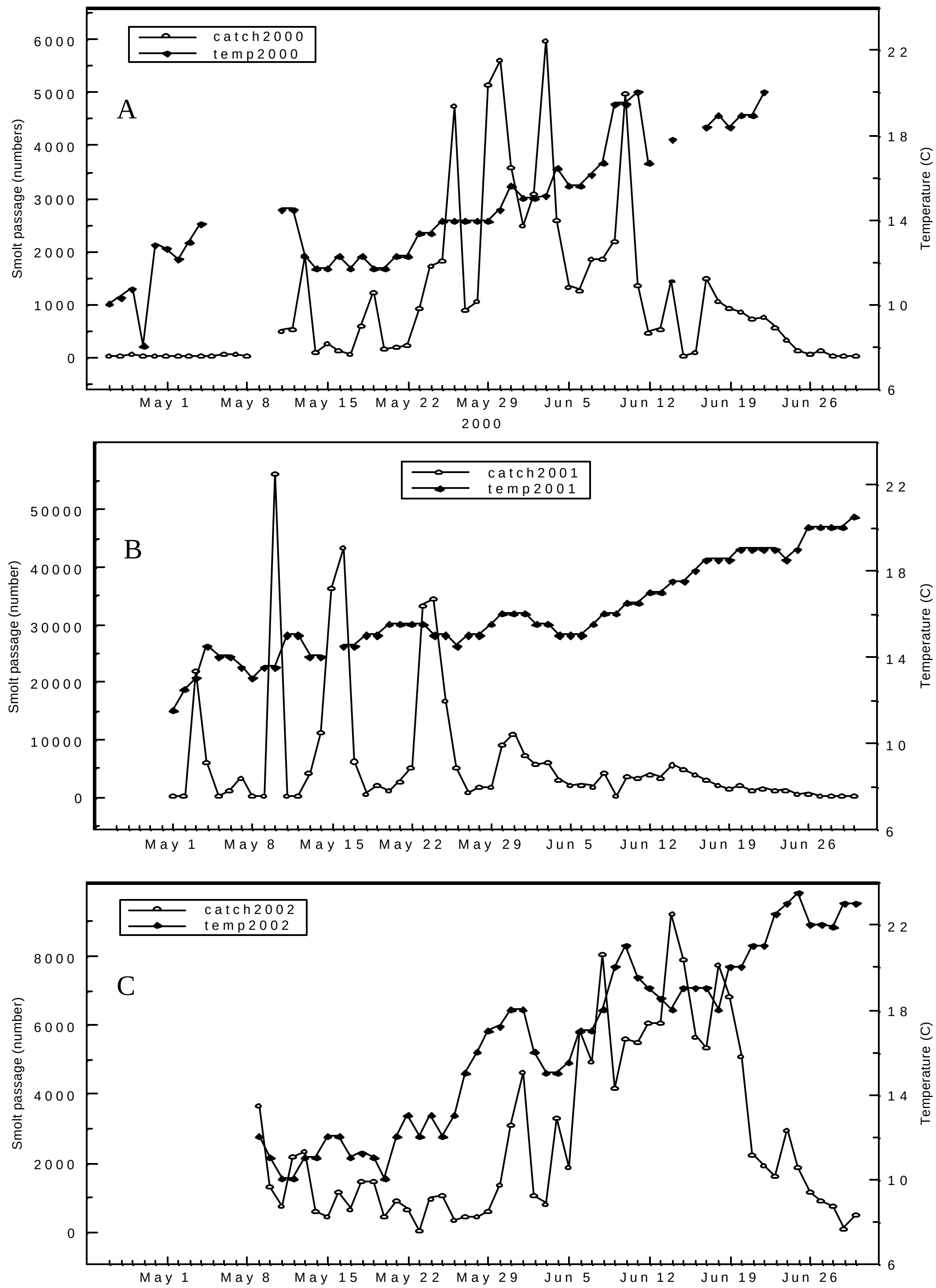


***Figure 11**. Daily chinook smolt passage and water temperature for years 2000 (A), 2001 (B), and 2002 (C).*

2002. Chinook salmon passage over the course of the 2002 field study was estimated to be 137,150 identified wild chinook smolt. Our 2002 estimate of wild fish is approximately twice that estimated in 2000 (70,000 smolt) and less than half of that estimated for 2001 (384,000 smolt). The peak of the migration occurred on June 14 (9,205 out-migrants). This is the latest peak observed in this study, with the 2000 and 2001 peaks occurring in June 3 and May 10 respectively (**Figure 10**). Majority of smolt out-migrated when water temperature ranged between 13 and 20°C, similar to the 2 previous years (**Figure 11C**). We estimated trap efficiency at 1.26% in 2002.

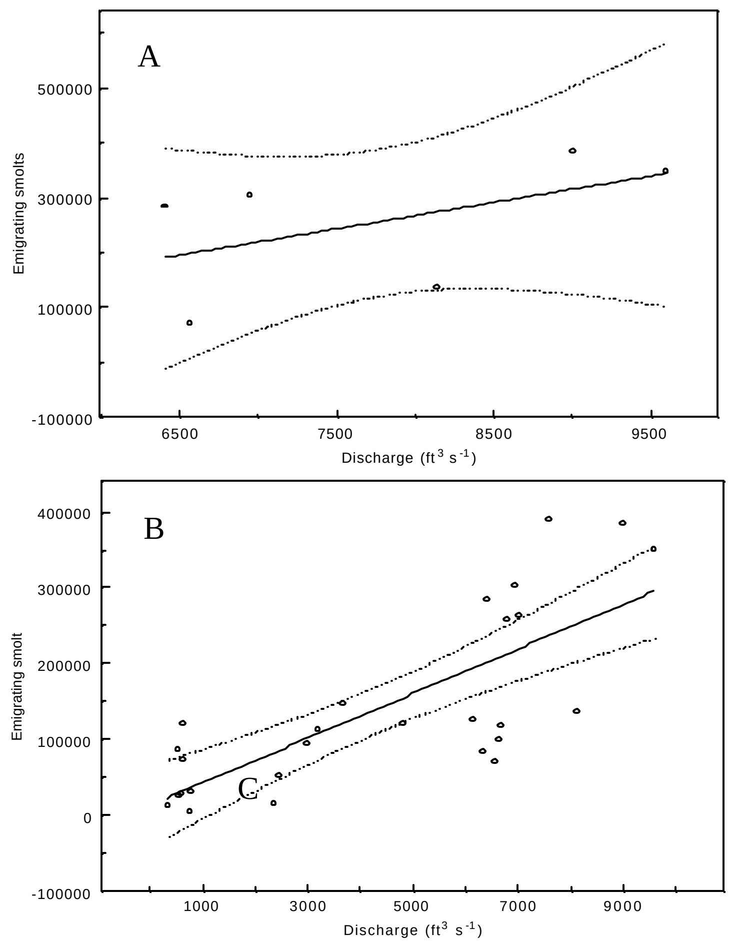


Figure 12. *Discharge – chinook smolt abundance relationship with 95% confidence limits for Muskegon River (A) and for a composite of 5 Lake Michigan tributaries (B). At the scale of the Muskegon River, river discharge is a poor predictor of wild fish abundance (R^2 = 0.27; P<0.29). However, at the scale of several watersheds, river discharge is a relatively good predictor of chinook abundance (P<0.001, R^2 = 0.59).*

Differences between historic and present survey estimates of chinook smolt abundance may be explained by annual variability in river discharge. Chinook recruitment has been positively correlated with river discharge in the Pere Marquette River (Zafft 1992) and in west coast populations. Muskegon River discharge from mid-March to June was extremely high (8,994 ft^3 s^{-1}) compared to discharge of 9,590 ft^3 s^{-1} estimated during 1979, a year of high recruitment. Discharge was near a period-of-record low (6,557 ft^3 s^{-1}) in 2000 when we observed a low recruitment. Regression analysis of observed chinook recruitments in the Muskegon River indicated a positive but non-significant relationship (P<0.29, R^2 = 0.27) between recruitment and discharge (**Figure 12A**). However, when Muskegon River data were compared with recruitment data for other Lake Michigan tributaries, there is a significant positive relationship (P<0.001, R^2 = 0.59) between chinook recruitment and discharge (**Figure 12B**).

Performance Analysis of Software

Analysis of Variance uncovered a statistically significant effect of range increment on numbers of Good ($p < 0.0001$), Bad ($p < 0.0001$), and Omitted ($p < 0.0001$) tracks per 1000 m^3. **Figure 13** shows the means for each category by range increment. 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.

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 14**). 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. **Figures 15** and **16** show the ratios of Bad to Good results and Omitted to Good Results as a function of range bin and range gating parameter value. As range increased, the range gating parameter had an increasingly positive effect on the ratio Bad to Good results. Little effect of the perturbation was observed on Omitted to Good results across the range bins.

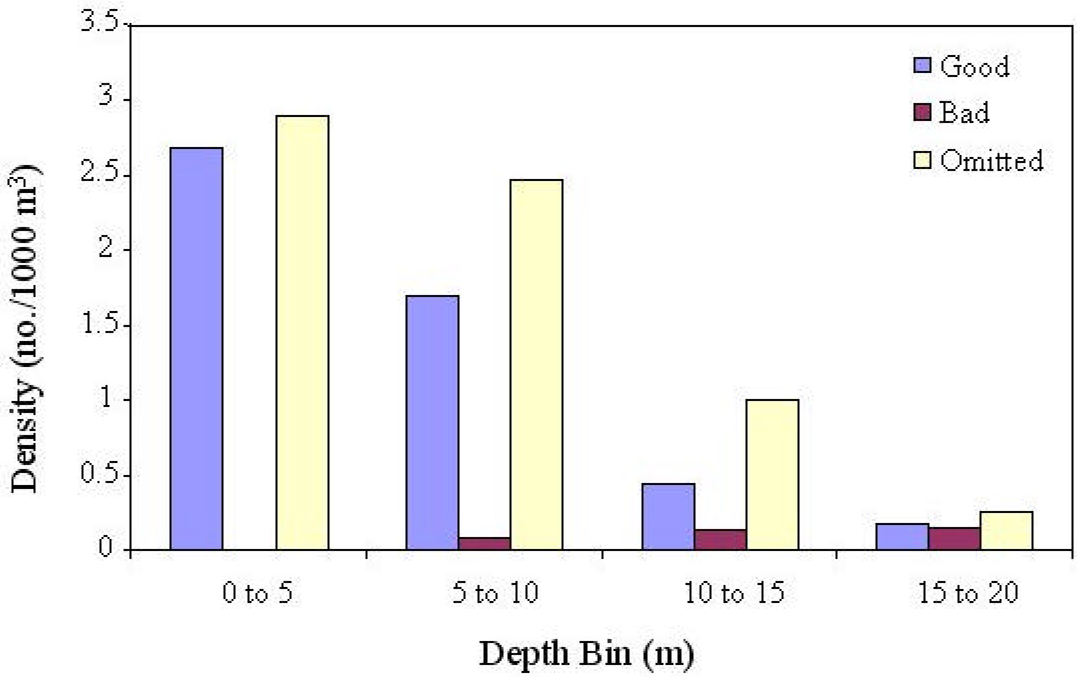


***Figure 13**. Density of tracks per sample volume of " Good" (correctly identified fish tracks), "Bad" (identified fish tracks but the analysis was compromised), and "Omitted" (completely failed to identify fish tracks. See text for complete definitions.*

Table 1 shows the proportions of each result code by depth increment for the optimized parameterization. Result codes 0 and 6 indicate good performance of both algorithms. In general, codes number 0 and 6 decrease with increasing range. Codes 1 and 2 indicate perceived failures in the STDA due to a lack of target detection. Loosening of STDA criteria can reduce these percentages. These codes increased in percentage 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 were 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.

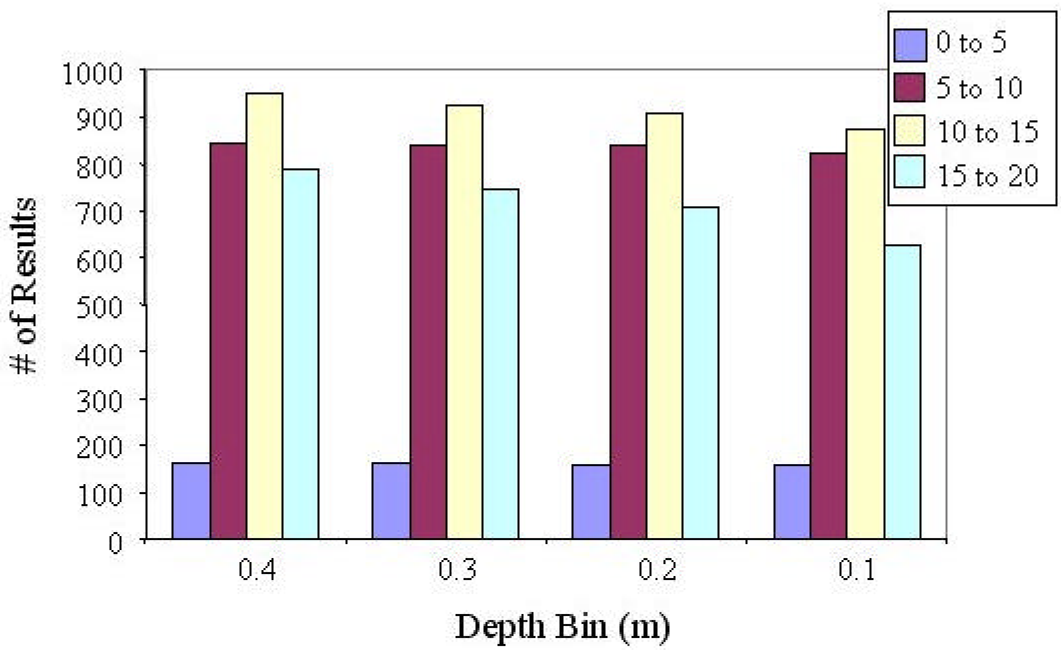


Figure 14. *Number of results (number of tracks) observed as a function of the range gating parameter and distance from transducer. See text for details.*

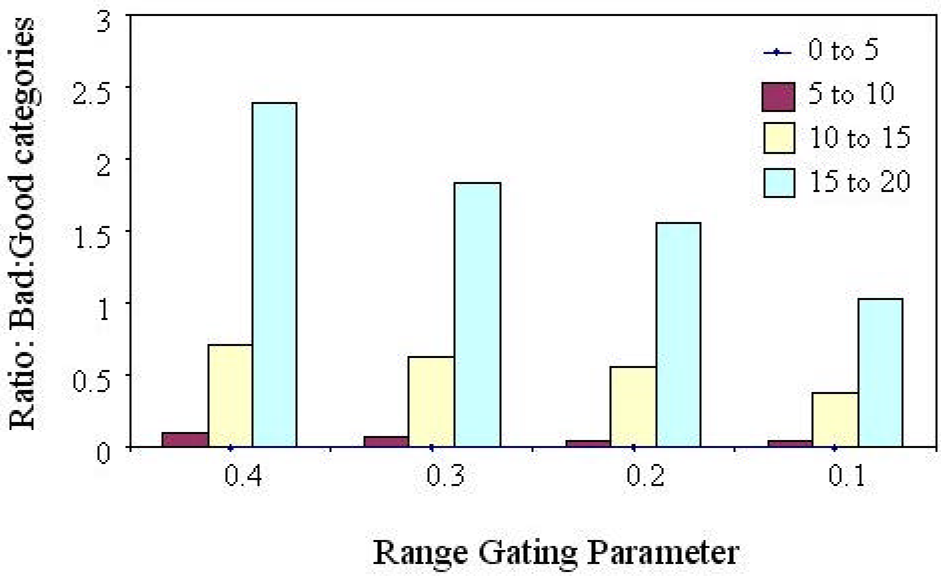


***Figure 15**. Ration of Bad:Good categories as a function of the range gating parameter and distance from transducer.*

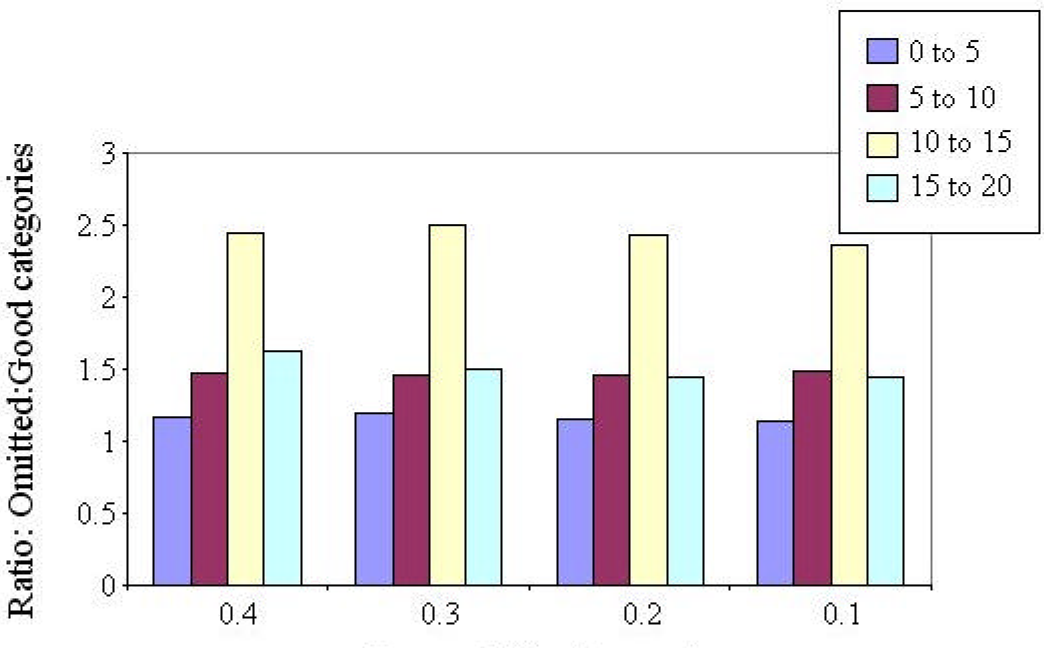


***Figure 16**. Ratio of Omitted:Good categories as a function of the range gating parameter and distance from transducer.*

Table 1 indicates that, as parameterized, the ability of the STDA to detect targets may be limiting the number of expected fish traces that are properly identified. As previously mentioned, relaxation STDA criteria can reduce the occurrence of this code. However, this comes at the cost of data quality control. The parameters that are most likely to increase the number of targets detected are the "standard deviation of minor and major axis angles".

Table 1. *Percentage of targets for each of the analysis codes (see Figure 7 and code definitions on page 13). Range bin refers to range interval from side looking transducer. For example, range bin 5 is a bin defined for the 5 to 10 m interval, distance from transducer.*

	Percentages of Result Code Occurrences									
Range Bin	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
5	32.5	50.0	0.0	0.0	0.0	0.0	17.5	0.0	0.0	0.0
10	22.7	55.9	0.7	0.2	0.1	1.7	18.4	0.0	0.0	0.1
15	15.4	61.8	1.8	0.0	0.0	8.3	12.3	0.0	0.1	0.1
20	14.5	39.6	2.9	0.0	1.1	25.5	16.2	0.0	0.0	0.2

Loosening of these criteria will reduce the software's ability to determine the direction of travel, an ability that is absolutely crucial to this study. Reduced precision of angle measurements can also lead to biases in TS, swimming speed, and fish density (Kieser et al. 2000). Thus, the parameterization of the STDA should not be loosened from its current status.
Results indicate that the FTA parameterization may also be too lax. However, only low percentages of the results point to shortcomings of the FTA only. The most substantial percentage of discrepancy codes involving the FTA parameterization (code 5) can also be contributed to the STDA performance. Interactions between these algorithms and the parameters within them make prediction of the effects of most perturbations difficult at best. A more extensive parameter perturbation study may provide insight into these interactions. However, design limitations of the Echoview software make such an effort a formidable task.

Beam mapping. **Figure 17** shows the final result of the beam mapping procedure. When aimed to maximize the range of usable data, the beam was pointed slightly downward at approximately 1.97 degrees. Accounting for the vertical beam angles, the beam sampled 13.03% of the top meter in the 5 meters closest to the transducer. The beam covered 38.61%, 44.62%, and 40.46% of the top meter for the remaining distance categories out to 20m. **Figure 17** shows the lower portion of the beam leaving the top meter of the water column resulting in the reduced coverage.

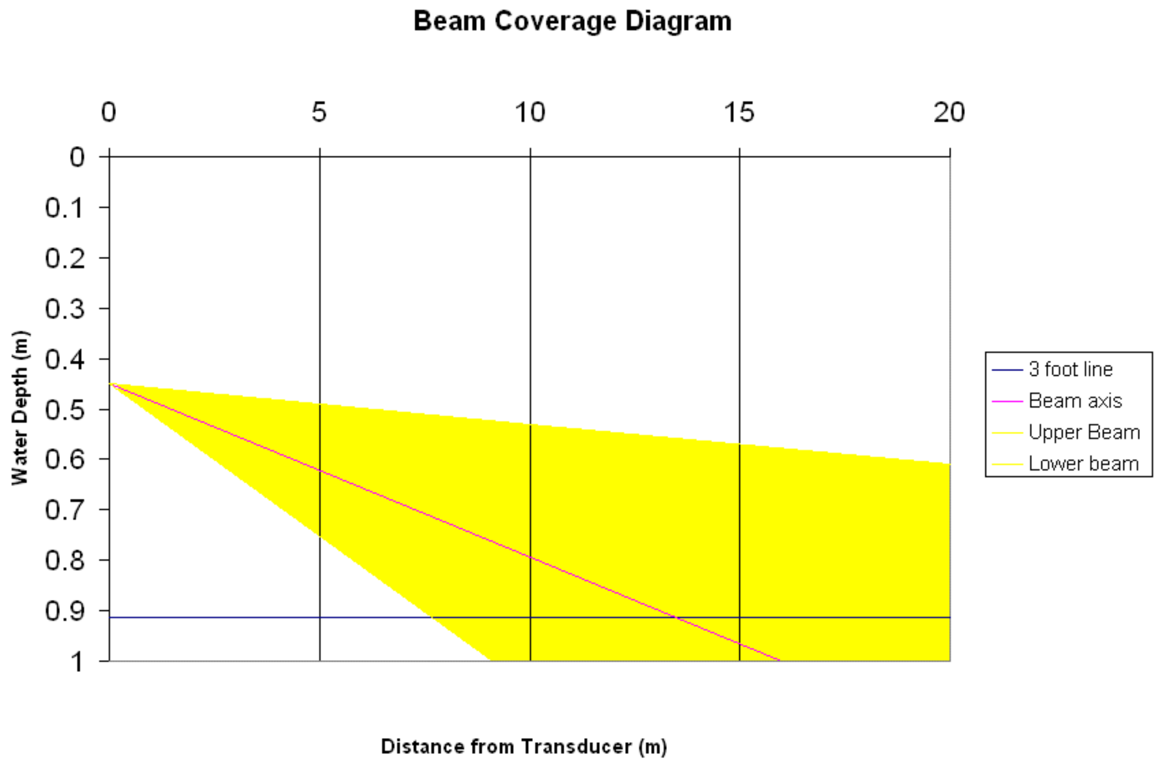


Figure 17*. Mapped acoustic beam. Horizontal axis is distance from transducer and the vertical axis is depth from the surface. The line at 3' deep (~0.9m) was the depth of the reference sphere for mapping the beam.*

Hydroacoustic estimates of fish passage

Table 2 shows the daily passage rate by range, and the auger trap estimates for the same dates. Daily estimates differed between the auger smolt trap and the hydroacoustics. In 2001, the hydroacoustic estimates where generally higher by a factor 3-12 times. However in 2002, estimates where in the same general range, but at times differed on specific dates. Despite differences in absolute passage rages, the relative changes in daily passage rates where similar (**Figure 18**). In 2001, fish passage estimates peaked for both gears within a couple days of one another (June 13 and 14) and declined there after. In 2002, peak densities for both gears occurred on June 7, but the acoustics measured a potentially earlier peak in out-migration not observed in from the smolt trap.

Table 2. Hydroacoustic and trap-based chinook smolt passage rates (number of smolt per day) for specific dates in 2001 and 2002. Distance measures for hydroacoustic estimates represent estimates from 0-5m from the transducer, 0-10m from transducer, etc.

Date	Trap Estimates	Hydroacoustics estimates by range (m)				
		0-5	0-10	0-15	0-20	Entire River
2001						
6/8	4,000	2,087	2,792	5,311	6,888	12,199
6/10	3,351	1,166	2,399	4,683	5,296	9,979
6/11	3,135	1,980	5,847	9,531	10,322	19,854
6/12	3,838	2,947	7,272	15,968	16,917	32,886
6/13	3,189	2,916	6,568	12,440	12,920	25,360
6/14	5,459	1,872	3,657	7,395	8,021	15,416
6/19	1,243	1,128	3,482	4,213	4,319	8,532
6/20	1,838	1,473	4,566	5,476	5,787	11,263
6/21	919	660	2,196	2,949	3,122	6,071
6/22	1,405	1,328	2,664	2,689	2,736	5,424
6/23	865	3,645	5,401	5,455	5,551	11,006
2002						
5/26	317	246	805	1,099	1,346	2,444
5/29	556	752	1,614	2,168	2,544	4,712
5/30	1,349	706	1,330	1,738	1,923	3,662
5/31	3,095	760	1,283	1,424	1,540	2,964
6/5	1,825	576	1,601	1,913	2,105	4,018
6/6	5,793	591	1,373	1,756	2,063	3,819
6/7	4,920	990	1,946	2,522	3,194	5,715

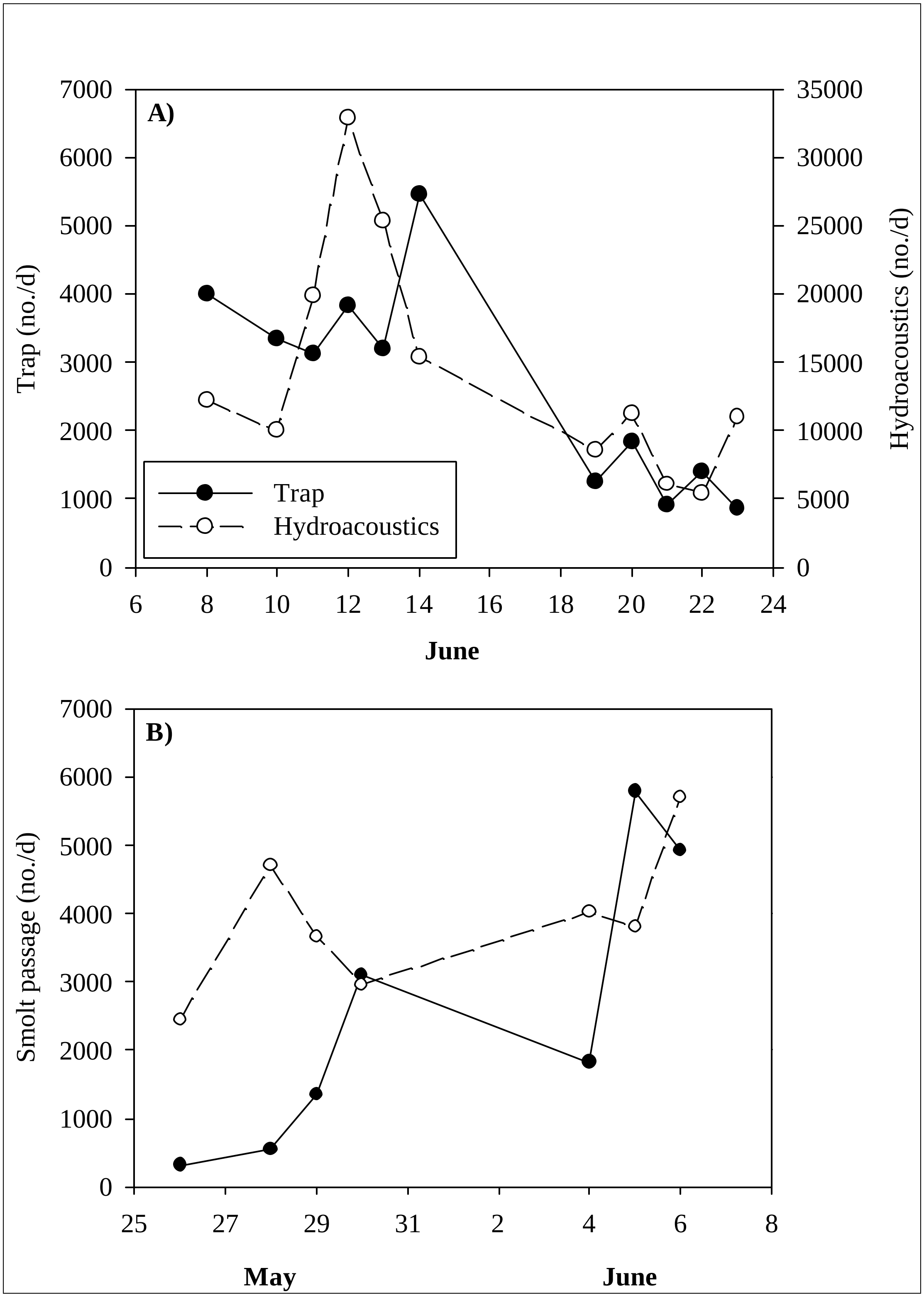


***Figure 18**. Comparision between smolt trap and acoustics for estimating smolt passage for 2001 (A) and 2002 (B).*

Comparison between gear types

Estimates of smolt passage from smolt trap and hydroacoustics were significantly positively correlated within years and when years were combined (**Figure 19**). In general, the hydroacoustics estimated a greater number of smolts out-migrating than the auger smolt trap.

CONCLUSIONS

The application of side-looking fixed river acoustics holds promise for quantifying out-migration of salmon smolts in the Great Lakes. Despite difficulties in deploying the acoustic system, mechanical issues, and river flooding we were able to provide some hydroacoustic estimates of smolt passage. However, further development of the methods used herein will be necessary before accurate estimates of smolt production can be attained using hydroacoustics. Improvements must be made in the quality and volumes of usable data collected for analysis. Improved data quality should result in enhanced STDA performance and increased detection probabilities at extended ranges. Larger numbers of daily estimates will translate to enhanced analytical abilities and clearer explanations of the results obtained. Although hydroacoustics can never completely replace other sampling methods due to the need for ground-truthing data, the method still is worthy of further investigation and development for use enumerating out-migrant salmonids smolt.

Data deficiencies in this study were primarily due to technical issues. System malfunctions resulted in the loss of 27 days of acoustic data. As is often the case with high-tech equipment, system repair, testing, and recalibration take significant quantities of time and cannot be completed on site. Thus, the system must be broken down and shipped to a service center for repair.

Some data losses were due to failure of the dual axis-rotators used to aim the acoustic beam. Fixation of the rotators is a highly desirable quality that was not available on those used in this study. As a result, the weight of the transducer in combination with flow and perturbation by boat traffic sometimes resulted in mechanical failures that drastically changed the orientation of the beam.

Track filtering results were likely biased low due to side-aspect target strength variability. The maximum side-aspect target strength is observed for most species when the fish has a perpendicular orientation relative to the acoustic axis. In this study, the direction of flow was always less than 270^{o} indicating that targets swimming with the current were likely to be detected at less than full side aspect and, thus, exhibit a TS less than those calculated from Length/TS relationship used (Love 1977; Lilja et al. 2000). As a result, smolt on the low end of the length distribution passing that day were likely to be excluded on the basis of low mean TS.

An additional source of process error results from daily variation in the number tracks created by drifting debris/non-target species. The quality control aspects of the software algorithms and post-software filtering remove many of these non-target echoes and traces from the results. However, some meet the criteria and are included. Accounting for additional variables such as these is impossible without increasing the number of degrees of freedom available for the analysis. More days upon which to regress might allow for enhanced statistical abilities such as the use of multivariate regression techniques. These analyses could result in increased correlation between trap and hydroacoustic estimates.

Yet another source of error stems from passage of smolts through areas not adequately covered by the acoustic beam. Low signal-to-noise ratio substantially limited our ability to detect smolt at extended ranges. Therefore in the center of the river channel (an area likely to pass a large portion of migratory smolt) the probability of detecting a given smolt was low. Again, a low bias of total passage is the expected result. Passage occurring shoreward of (behind) the transducer or in the near-field portion of the beam can contribute to a low bias as well. However, these areas are unlikely to pass large numbers of out-migrating smolt due to low flow rates.

One-sided coverage of the stream has the potential to bias estimates high or low depending on flow conditions on the side without coverage. In this study, slightly higher flow rates were observed on the side of the stream opposite the transducer and beyond the range of quality data. Migratory smolt are likely to be aggregated in the swifter parts of the river cross section, thus we would assume that our estimates in this study were again biased low.

The final source of error results from incomplete temporal coverage. Generally, the power source used to operate the system was depleted after approximately 20 hours. The 4 hours of missing date occurred in the late morning to early afternoon. Studies show varying results as to the diel migration rates of migratory salmon (Groot 1972; Fängstam 1993). While the direction of this bias is undoubtedly low, its magnitude remains in question.

The general trend in the direction of bias from the sources of error discussed above is consistent with the findings of the correlation analyses described above. Underestimation of total smolt passage for each of the days is very likely to have occurred. Speculative corrections to these biases could potentially be as erroneous as they would be arbitrary.

One solution that could provide relief from several of these sources of error is an alternative configuration. Deployment of a stationary, up-looking transducer in the deepest portion of the river would increase coverage in the middle of the stream, reduce the need to analyze side-aspect data from extended ranges, and eliminate aspect/orientation issues in the volume covered.

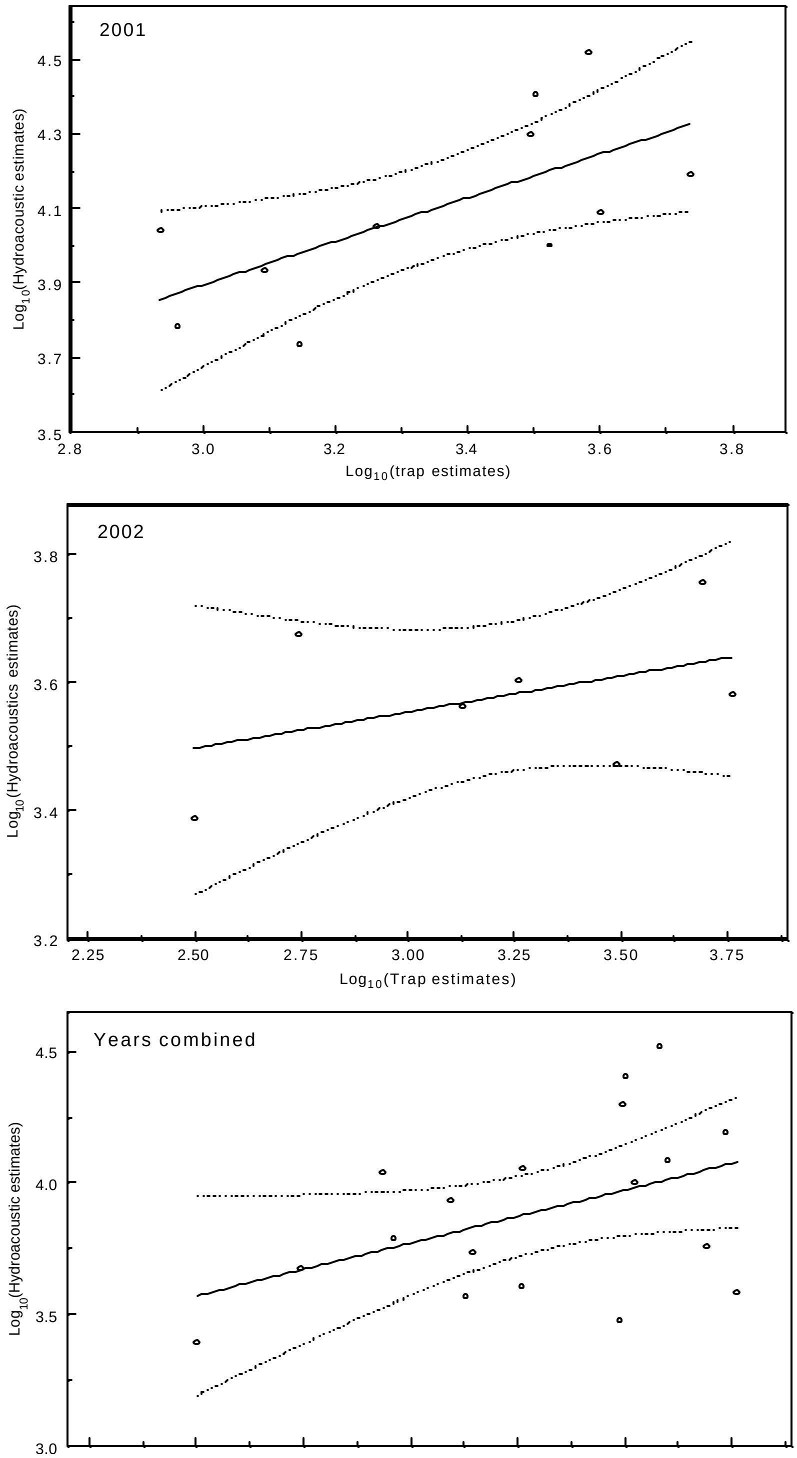


***Figure 19**. Regression (with 95% confidence intervals) between Log_{10} transformed smolt passage estimates from smolt trap and hydroacoustics. 2001- P=0.024, R^2= 0.44; 2002-P=0.08, R^2=0.30; Years combined- P=0.067, R^2=0.19.*

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