Assessment of Potential Bias in Hydroacoustic Estimation of Fraser River Sockeye and Pink Salmon at Mission, B.C.

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Pacific Salmon Commission
Technical Report No. 11

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ABSTRACT

This document is a summary of a four-year (1995-1998) co-operative hydroacoustic study conducted by the Pacific Salmon Commission (PSC) and Canada Department of Fisheries and Oceans (DFO) on the adult sockeye (*Oncorhynchus nerka*) and pink salmon (*Oncorhynchus gorbuscha*) migratory behaviour in the Fraser River at Mission, British Columbia, Canada. The study focused on gathering information for analysis of potential sources of bias in the PSC standard (single-beam) hydroacoustic programme identified in 1994 by the Mission Hydroacoustic Facility Working Group (1994). Preliminary observations from 1995 were published in a previous report (Xie et al, 1997). Studies conducted in subsequent years refined the data-collection and data-analysis methods. As a result of the expansion of this work, a sounder digitizer and a differential GPS (global positioning system) receiver were implemented into the mobile single-beam system in 1996, making the single-beam data available for in-depth analyses and comparisons with the split-beam results. Two software packages were also developed to process and track echo data from both sounder systems with range-dependent tracking algorithms (Xie 2000). The software programs also allow users to examine and edit the resulting tracks produced by the tracker (PSC, 1999, 1999B, 1999C).

This report presents the results of the 1995-1998 split-beam and single-beam work that examined the sources of bias in the single-beam hydroacoustic estimates of migratory salmon abundance past Mission. The study led to the following findings:

- The majority of the salmon migrate upstream past Mission. The downstream portion accounts for approximately 7% of the total migratory abundance. Not all of the downstream portion is salmon.
- The downward-looking single-beam mobile system is capable of sampling a large portion of the river. The system is incapable of sampling a surface layer of 2 m and a layer of 1-1.5 m above the river bottom. To provide insight into the magnitude of this effect, we used an extensively analysed data set from the 2001 season and found that from 5 to 30% of the estimated total upstream fish passage was detected in the 2 m surface layer by the side-looking system. Fish were observed frequently in the bottom layer and infrequently in the top layer, which indicates that the detection problem is even more pronounced for the near bottom layers than for the surface layer.
- Significant fluxes were detected near the shore of the river where the downward-looking single beam system has much reduced detection due to the shallow water. Again from the 2001 data, approximately 70% of the fish travelled upstream within the first 60 m of the left bank shore and approximately 12% travel within the first 60 m of the right bank shore. This represents significant fish passage in the near-shore areas and shows that approximately 18% of the passage was spread out over the remaining 280 m of the middle portion of the river. This pattern is somewhat dynamic but in general these distributional trends remain.
- There is evidence that the vessel affects the spatial distribution of the fish. However, a comparison of the total fish fluxes as estimated by the side-looking split-beam system with those estimated by the survey vessel showed no statistically significant differences. Our tentative conclusion is that the fish do react to the moving survey vessel, but maybe not in a manner that results in a biased estimate of fish flux. Further work is required to confirm or refute this observation, as boat avoidance behaviour has potential to reduce the accuracy of the passage estimates.
- The fish migration speed as measured by the side-looking split-beam system is similar to the speed of the transecting vessel. As the fish speed increases over the season, the bias in the passage estimates will increase, potentially leading to overestimates.

- The single-beam transducer systematically under-estimates duration-in-beam statistics for fish targets at depths greater than 5 m causing an overestimate of mean swimming speed. This source of bias may cause over-estimates of migratory salmon abundance but would need more investigation only if the single-beam system continues to be used.

INTRODUCTION

The Pacific Salmon Commission (PSC) has used a downward-looking single-beam echo sounder (Biosonics Model 105) to estimate the passage of migratory sockeye (*Oncorhynchus nerka*) and pink (*Oncorhynchus gorbuscha*) salmon in the Fraser River at Mission, B.C. since 1977 (Woodey 1987). This programme, hereafter referred to as the *standard hydroacoustic programme*, consists of two components: transect and stationary soundings. These two operational modes are designed to provide data on two aspects of migratory salmon abundance. The transecting vessel collects information on fish density across the river; the stationary sounding acquires statistics on migration speed. The data obtained from the standard programme is processed using a duration-in-beam method (Thorne 1988), which leads to daily estimates of salmon escapement past the survey site over a 24-hour period. The statistical handling of the data has been refined and improved recently (Banneheka et al. 1995). However, the accuracy of the estimates depends on the validity of a number of assumptions. The following are the most important:

- All fish swim upstream along trajectories parallel to the river banks;
- The majority of the fish are distributed in the mid-water portion of the water column with few migrating near the river surface where they would not be insonified, or near the river bottom where target returns would not be discernible from the bottom echo;
- Few fish migrate in the shallow water where the survey vessel is incapable of sampling;
- Fish swimming speed is negligible relative to the transecting speed of the survey vessel;
- Fish behaviour is not altered by the presence of the survey vessel.

The first four assumptions define fish behaviour scenarios that are ideal for a downward-looking acoustic sampling of fish targets; the last is related to a fish-vessel interaction. Violation of these assumptions could result in bias in the daily estimates of abundance, as described in Banneheka et al. (1995). Therefore, it is essential that these assumptions be assessed in the river by independent measurements.

Under a joint agreement between the Pacific Salmon Commission and Fisheries and Oceans Canada (DFO), split-beam hydroacoustic experiments were conducted at Mission during the annual salmon returns from 1995 to 1998 to obtain information on fish behaviour. The primary fish targets were sockeye and pink salmon. The overall objective of the study was to assess the sources of potential bias in the duration-in-beam method as conducted on the Fraser River by the PSC. We used HTI Model 240 and Model 243 split-beam echo sounder systems (HTI 1993, HTI 1998) to examine the distribution, direction of travel and swimming speed of salmon at the standard transect site. The systems were similar to that used at Qualark Creek by DFO from 1993 to 1998 (Enzenhofer and Cronkite 2000). Operating from a location on the riverbank, we monitored migrating salmon without disturbing their migration. The split-beam echo sounder provided data that allowed the tracking of fish as they swam through the acoustic beam. This provided direct measurements of the fish's acoustic size, swimming speed and trajectory through the beam. Narrow beam transducers were used with the split-beam sounder and aiming adjustments were controlled by a mechanical rotator, making it possible to obtain three-dimensional fish distribution.

During the first field season in 1995, effort was devoted to the design of data collection methodologies for the split-beam system. After the 1995 field season, the PSC-DFO research team developed software packages and data processing procedures for the split-beam sonar data in order to determine fish behaviour. Preliminary results based on the 1995 experiment were summarised and presented in a previous report (Xie et al. 1997). Studies conducted in subsequent years refined the data-collection and data-analysis methods developed for the 1995 experiment. As a natural expansion of this work, the PSC implemented an echo sounder digitizer and a differential GPS receiver into the mobile single-beam sounder system of the standard programme in 1996, making the single-beam data available for digital signal processing analyses and comparison with the split-beam results. Two software packages were also developed to process and track echo data from both sounder systems with range-dependent tracking algorithms (Xie 2000). The software also allowed users to visually examine and edit the resulting fish tracks produced by the tracker (PSC 1999, 1999B, 1999C).

The split-beam work provided answers to some questions relating to the bias investigation, but other questions remained unanswered due to the acoustic limitations of the current split-beam system. When we lacked ground-truth information to quantify a source of bias, we compared information acquired independently from the split- and single-beam systems to propose probable causes for the bias. The results demonstrated weaknesses in both acoustic systems. Attempts to overcome these weaknesses are expected to lead to more defensible estimates of salmon flux.

DATA ACQUISITION METHODS

Study Site

The split-beam data were obtained at the PSC acoustic site on the Fraser River near Mission (Figure 1) which is located 80 km upstream from the river mouth. The study site was approximately 2 km upstream from the Mission Railway Bridge, where the river was approximately 450 m wide. The maximum depth varies with discharge from approximately 18 m in June, during the high run-off period, to 12 m in October at low flow. Tidal influence becomes noticeable in late summer and early fall, and the river may occasionally reverse its flow during fall flood tides.

Data Sampling

The data sampling system consisted of the same components that have been discussed in the previous report by Xie, Cronkite and Mulligan (Xie et al.1997). The only additional components were the following:

- ASL 10-kHz Sounder Digitizer;
- CSI Model GBX-8A differential GPS receiver (CSI, 1997);
- 320-kHz GPS correction beacon - signals used are broadcast by the Canadian Coast Guard radio beacon station in Richmond, BC.

Data Sampling and Processing Software

The data sampling and processing software consisted of the same components that have been discussed in the previous report (Xie et al. 1997). In addition, the following software programs were used:

- Pacific Salmon Commission *SplitBeamFishTrack* program developed for split-beam data analyses. The manual editing functions allow the user to remove tracked data from noise events or to remove incorrectly tracked fish data. Refer to PSC (1999) for details;
- Pacific Salmon Commission *SingleBeamFishTrack* program developed for processing the PSC single-beam acoustic data. Refer to PSC (1999B, and 1999C) for details;

ASL Environmental Sciences Inc. developed the PSC_DIG software for the PSC in 1997. This program controls the real-time digitisation process through a laptop computer for the analogue voltage-signal outputs from the Biosonics Model 105 sounder. It synchronised and registered the GPS data with the digital echoes according to ping number (ASL, 1999).

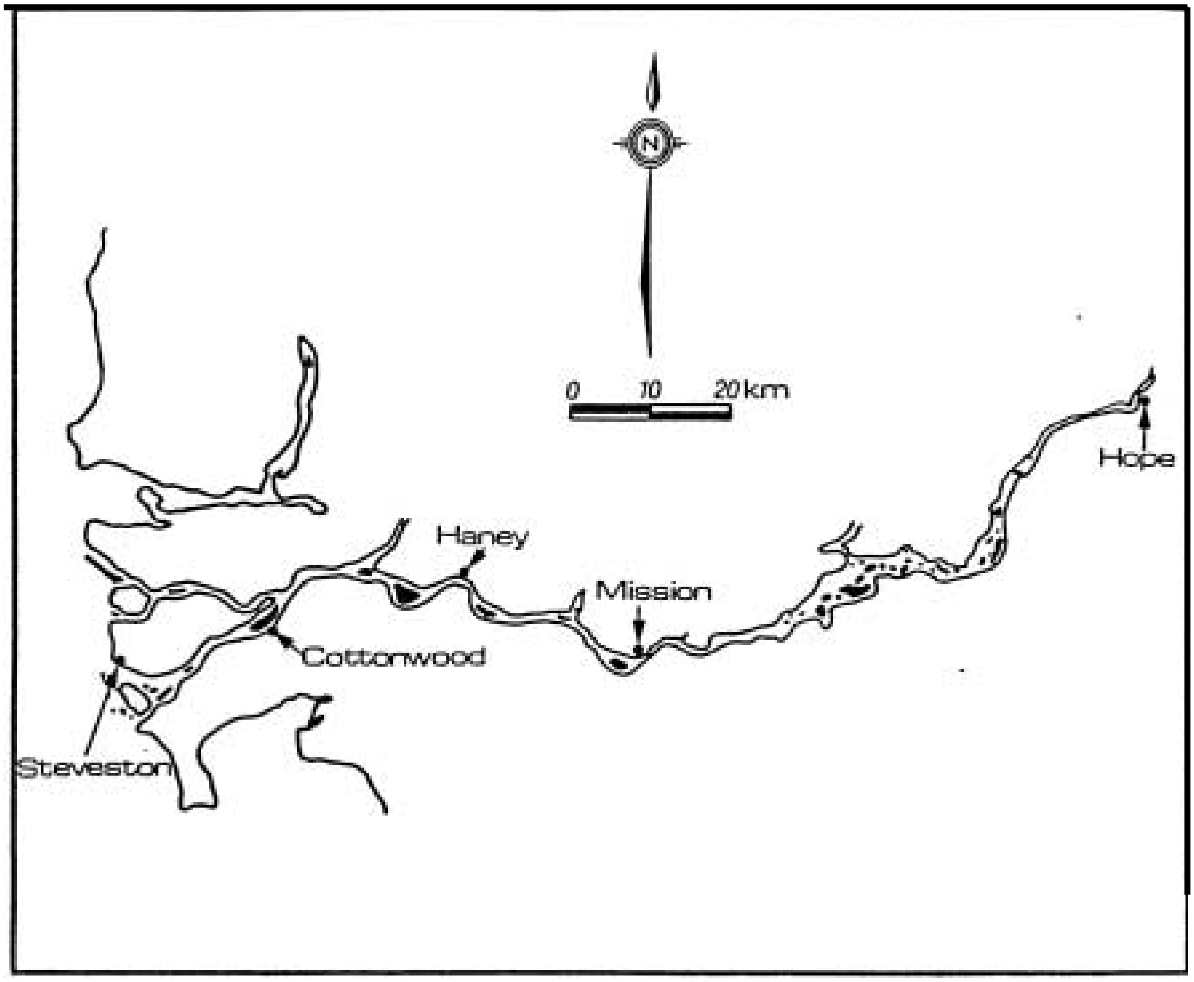

Figure 1. Mission hydroacoustic experimental site.

Instrument Set-up, Sampling Configuration and Data Acquisition Settings for the Split-Beam System

The electronic components, including the split-beam sounder, digital echo processor and rotator controller, were set-up inside the cabin of a landing-craft vessel, which allowed portable operation and therefore the ability to monitor both the north and south banks. A tide gauge attached to a piling in the area permitted monitoring of water level. Using a differential global positioning receiver, the location of the piling was determined to be 49^{o} 08.175'N and 122^{o} 16.466'W. This location was chosen as a reference point for our hydroacoustic studies at Mission.

Acoustic transducers were mounted on a tripod that was deployed on the river substrate from the working vessel. The tripod was positioned as close to the shoreline as possible and was moved progressively offshore as the water level receded. The transducers were linked to the echo sounder via underwater cables. The transducer aims were controlled through a dual-axis rotator controller, and monitored with the underwater position sensor.

The acoustic system was initially set up to monitor fish passage with a horizontal aim that was perpendicular to the shore. The mean migration angle of the salmon passage relative to the shoreline was estimated after the 1995 field season based on trajectory data of individual fish. In 1996, we adjusted the horizontal aim so that the acoustic beam would be perpendicular to the mean swimming direction of the migrating salmon as observed from the south bank. This maximised the detection of salmon targets by the acoustic system.

We used vertical aiming strata to partition the spatial and temporal sampling effort over the entire water column. The sampling plan made use of five vertical aims with the 4°×10° transducer and two aims with the 2°×10° transducer. The 4°×10° was aimed at 8°, 4°, 0°, -4° and -8°, relative to horizontal, and the 2°×10° was aimed at –1° and –3°. A complete cycle of these strata by the two side-looking transducers was made up of the seven vertical aims with each stratum being insonified for 15 minutes. We found that this sampling pattern gave good coverage of the water column, with the acoustic beam at the –8° aim being positioned as close to the bottom as possible. The data collection ranges were limited primarily by boundary interactions (bottom or surface) and reverberation noise levels. Figure 2 is a schematic illustration of a typical sampling pattern covered by the acoustic beams.

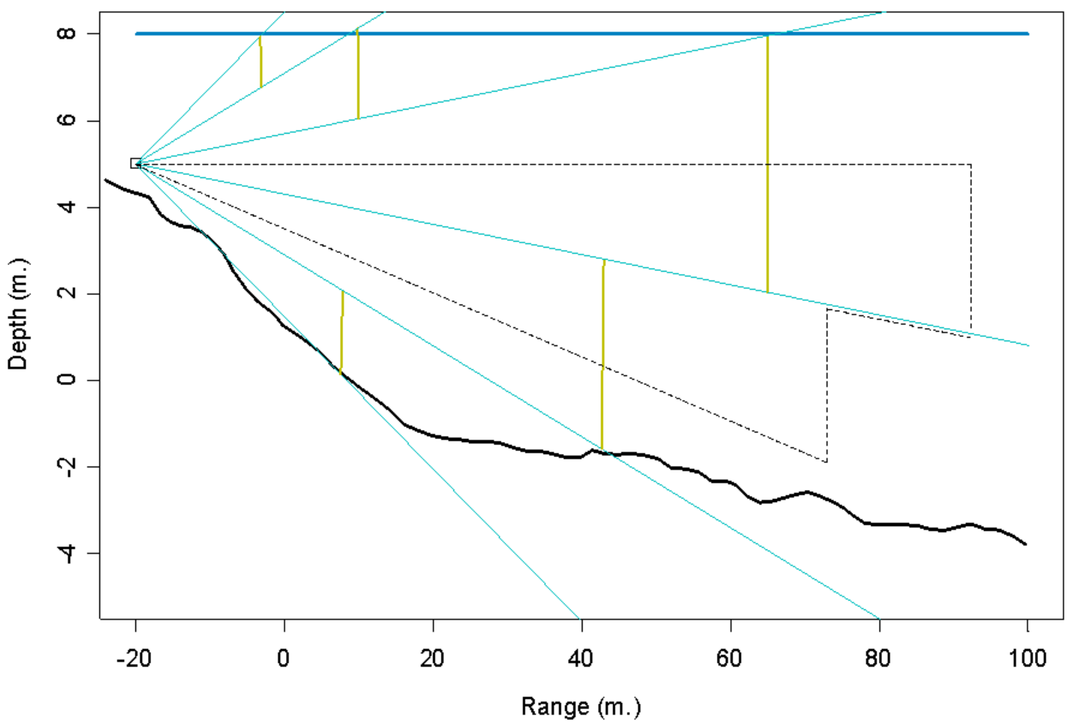

Figure 2. Schematic illustration of the side-looking coverage of the river cross section adjacent to the south bank by the 4°×10° (solid lines) and 2°×10° (dashed lines) split-beam transducers. The heavy black line is the measured river bottom contour, while the blue line represents the mean water level. The vertical yellow lines show the maximum range for data collection that avoided interference with either the bottom or the water surface. The origin of the axes on this plot is located at the base of the reference dolphin. Note: the vertical scale of this plot has been significantly exaggerated relative to the horizontal scale.

A complete cycle of sequential aims took 105 minutes (7 × 15 min = 105 min), and resulted in a duty cycle of 14 percent. Over a 24-hour time period, the 4°×10° transducer would have sampled each of the areas enclosed by the solid lines in Figure 2 for approximately 3.4 hours. The 2°×10° transducer would have sampled each of the areas enclosed by the dashed lines for the same amount of time. The transducers sampled overlapping areas for a portion of the water column.

Each year we examined the bottom profile along the compass bearing corresponding to the transducer's horizontal aim. This allowed us to optimise the aims according to the bottom contour at the site (see Fig. 2). The topography of the river bottom can change significantly from year to year due to the movement of river sediment. However, the topography at the site was found to be stable throughout each operating season.

The typical data acquisition settings for the side-looking split-beam soundings are summarised as follows:

(1) The acoustic pings were 0.2ms long with a central frequency of 200 kHz;
(2) The ping rates were set to 10 pings per second for the 4°×10° transducer, and 5 pings per second for the 2°×10° transducer to allow data collection at longer ranges;

(3) The maximum data acquisition ranges for the 4°×10° transducer varied from approximately 20 m at the 8° aim to 60 m at the 0° aim. The range for the 2°×10° transducer was set to a maximum of 100 m (at the –1° aim);
(4) Voltage thresholds were chosen according to the observed noise level. This is composed of the ambient noise and air bubble content in the water, both of which increase as a result of wind and/or rain. Under normal conditions, voltage thresholds were set so that the sounder would reject echoes from targets with on-axis TS values less than – 42dB;
(5) The width of the received pulse between the –6 dB points relative to the maximum signal must fall within the range of 0.1 to 0.3 ms;
(6) The angular location of a target (relative to the acoustic axis of the sound-beam) must be within the range of ±8º (horizontal) by ±2º (vertical) for the 4°×10° transducer, and ±8º (horizontal) by ±1º (vertical) for the 2°×10° transducer. Echoes outside these limits would not be included in the raw echo database that was used for tracking fish.

The specifics of the Cartesian co-ordinates and the geometry of the insonified volumes are given in detail in Xie et al, 1997.

Active Tracking Split-Beam System

We attempted to test the assumption that fish behaviour was not altered by the presence of an approaching survey vessel with the use of the Biosonics Active Tracking Split-Beam Sonar system (Hedgepeth, et al, 1998). This active tracking system was operated in the 1998 season during the time when sockeye dominated the upstream migration. Measurements of evasive behaviour of individual fish reacting to approaching vessels proved to be very difficult to obtain from a fixed-aim split-beam transducer. Therefore, we hoped that the ability of the active tracking split-beam sonar to follow a moving target over a long distance would allow us to detect and quantify avoidance behaviour. However, the results obtained with the active tracking system were inadequate for quantitative analysis of the vessel-avoidance effect. For a detailed review of the active tracking experiment the reader is referred to Cronkite et al, (2000).

SPLIT-BEAM DATA PROCESSING

Trace Counting

Our data processing protocol is applicable for the low-to-medium fish densities that are routinely observed at Mission. However, there were times when migratory abundance showed extremely high densities (as observed during migration of the 1998 Late-run sockeye), or when fish migrated upriver in clusters (as observed during migration of the 1995 pink salmon run). Such migratory patterns occurred for relatively brief time intervals (several days) for sockeye stocks over the entire migration season. The trace-counting technique is unlikely to succeed in accurately enumerating fish at these high densities. Two possible solutions for estimating fish abundance during extremely high-density migrations would be 1) to use a modified echo-integration technique to obtain biomass estimates or 2) to use a narrower beam transducer to reduce the probability of acquiring multiple targets, so that estimating fish flux by individual tracks remains feasible. The standard echo integration technique currently requires a uniform random distribution of targets in the beam, which generally does not occur for salmon in the riverine environment, especially with side-looking transducers.

The focus of our study was on the examination of migratory behaviour of adult salmon at normal migration rates that allowed the use of trace-counting to estimate fish flux. The 4°×10° transducer sampled sufficiently low numbers of fish in the acoustic beam to permit trace counting for most days. However, a narrower sound-beam was necessary for estimating the highly clustered pink salmon observed in 1995. After 1995, a 2°×10° transducer was purchased. This narrower beam acoustic transducer should help with the enumeration of high-density migrations.

Fish Tracking with a Split-Beam Echo Sounder

A split-beam acoustic system measures the range of a fish target and also its angular location relative to the acoustic axis of the beam, thus providing four-dimensional echo data (3-dimendional location versus time). Using the split-beam system, we were able to measure the target strength, swimming speed and direction of travel of fish passing through the beam. Detailed explanations of the split-beam data and the analysis techniques are presented in Xie et al, (1997). The methods have not changed significantly from those presented in this earlier report.

A Range-Dependent Fish Tracker

In order to track fish at different ranges and densities, a fish tracking algorithm was developed to construct fish tracks from the raw echo data obtained with the split-beam acoustic system. The details of this algorithm are discussed in Xie (2000). This algorithm was then implemented as a component of the *PSC SplitBeamFishTrack* software program. The software performs offline fish tracking for the split-beam data and was chosen for both in- and post-season data processing and analyses due to its ease of use and, most importantly, our understanding of its range-dependent algorithm. For a detailed description of the algorithm, readers are referred to Xie (2000).

RESULTS

The 1995-1998 split-beam hydroacoustic studies on migratory salmon behaviour were focused primarily on Early Summer and Summer-run Fraser River sockeye stocks from late July to early September. However we have included some observations of the migratory behaviour of pink salmon obtained in the 1995 and 1997 seasons, and an unusual migration pattern observed in September 1998 when the Late-summer sockeye migrated past Mission.

Sockeye Salmon

Down-stream Moving Fish

One of the assumptions explicit in the duration-in-beam model used for analysing the data from the standard programme is that all migratory fish move upstream. To validate this assumption, we gathered 4 years of split-beam data from 1995-1998 to examine the ratio, R_D, of daily down-stream estimates, D, over daily total fish estimates, T,

$$R_D = \frac{D}{U+D} = \frac{D}{T} \qquad (1)$$

where U is daily upstream estimate. For the purpose of deriving statistical results from (1), we outline its limiting values expected for low, medium and high migratory abundance.

1) During very low abundance periods, resident fish in the river are the main contributors to the target count. As resident fish are assumed to have equal probabilities of moving up- and down-stream when crossing the sound-beam, they tend to generate equal up- and down-stream estimates, i.e., $U \approx D$. In a limiting case of no migratory fish in the river, one would expect from (1) that $R_D = 0.5$.

2) During periods of low abundance when the migratory abundance is comparable to the resident population, R_D, it can be shown that $R_D \approx 1/3$.

3) During medium to high abundance periods when the migratory abundance is much greater than the resident population, it follows that $U >> D$. As a result, one would expect $R_D << 1$.

As migratory fish increase in relation to the resident fish, R_D will continue to decrease. Figure 3 shows R_D as a function of the observed hourly counts.

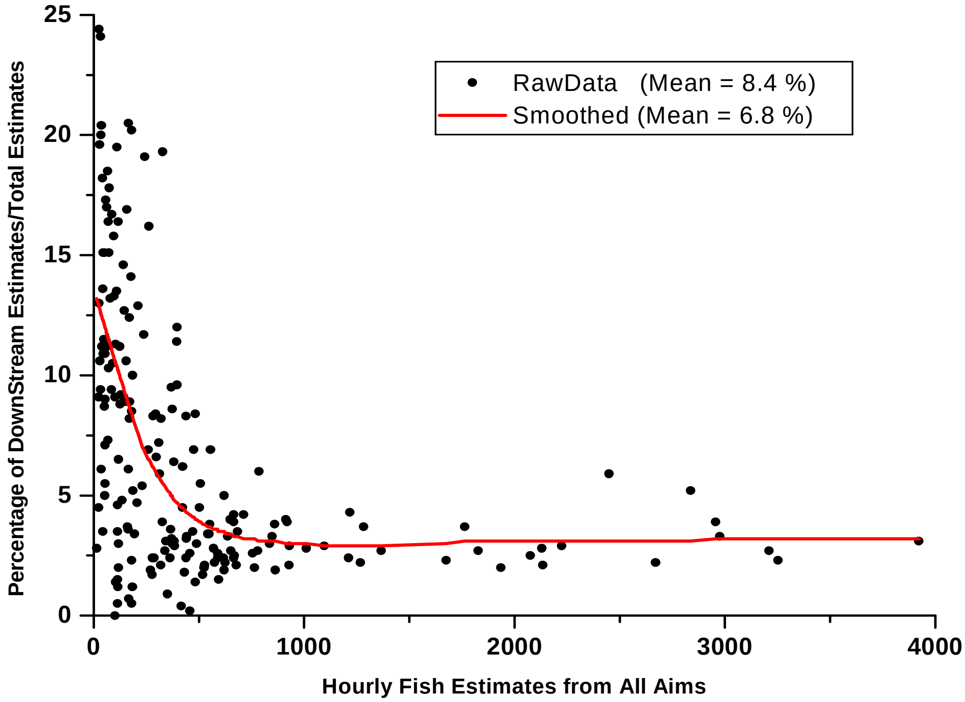

Figure 3. Daily ratio of down-stream over total estimates versus daily average hourly fish estimates. The line is fit to the data using a locally weighted regression smoothing function.

The data show the following features of migrating sockeye:

- The downstream targets typically account for less than 5 percent of total targets for medium to high migration periods when hourly estimates exceeds 1000 fish per hour from all 5 aims by the 4°×10° transducer (Fig. 3).
- The ratio of down-stream over total estimates increases as migratory abundance decreases. This is likely due to resident species at the site.

To estimate the actual number of fish migrating upstream, N, we suggest using

$$N = U - D \qquad (2)$$

This will correct the observed number of upstream targets for any milling activity of the migratory fish and for the detection of resident fish. For the case of single-beam data, where only the total flux is observed, the true estimate is

$$N = T - 2D \qquad (3)$$

If no upstream-downstream information is available, then the total flux will always be biased high. However, if U and D can be obtained from split-beam data, or some other source, then (3) should be used to remove the bias.

The overall ratio of down-stream targets to total targets for 1998 was approximately 8% (see Fig. 3). Our proposed model of Equation (3) can be rewritten as

$$N = (1 - 2 \cdot R_D) \cdot T \tag{4}$$

Using the 1998 split-beam data presented in Fig. 3, we found R_D had an overall average value of 8%. However, during times of medium to high salmon passage, when the hourly passage exceeded 1000 fish per hour, the average R_D decreased to approximately 4%. If we substitute 4% as the estimated R_D into (4), we calculate that the single-beam system would over-estimate the fish flux by 8.7 % due to the milling behaviour of both migratory and resident fish.

To provide a sense of the magnitude of this error as a function of total abundance, we used the hourly total fish data shown in Figure 3 as T, and the smoothed R_D to project the true upstream migration abundance using Equation (4). The resulting estimates for N are shown in Fig. 4 with residuals of T-N shown in Fig. 5.

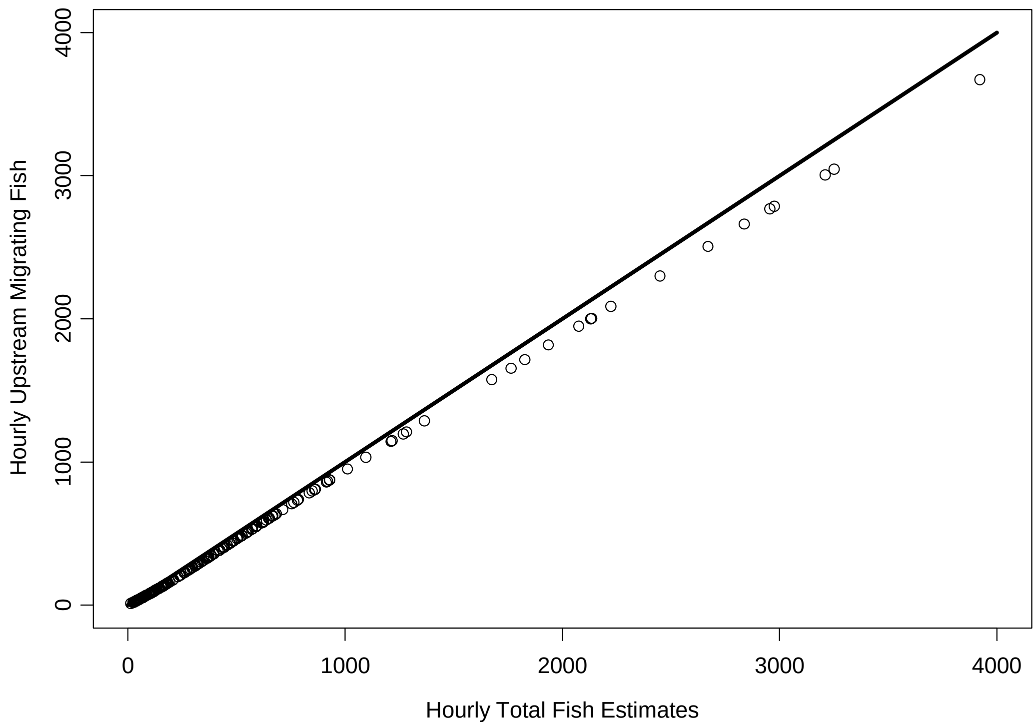

Figure 4. Projected hourly upstream migrating fish, N, based on hourly total fish, T, and smoothed R_D shown in Fig. 3 using Equation (4). Also shown is the 1:1 line.

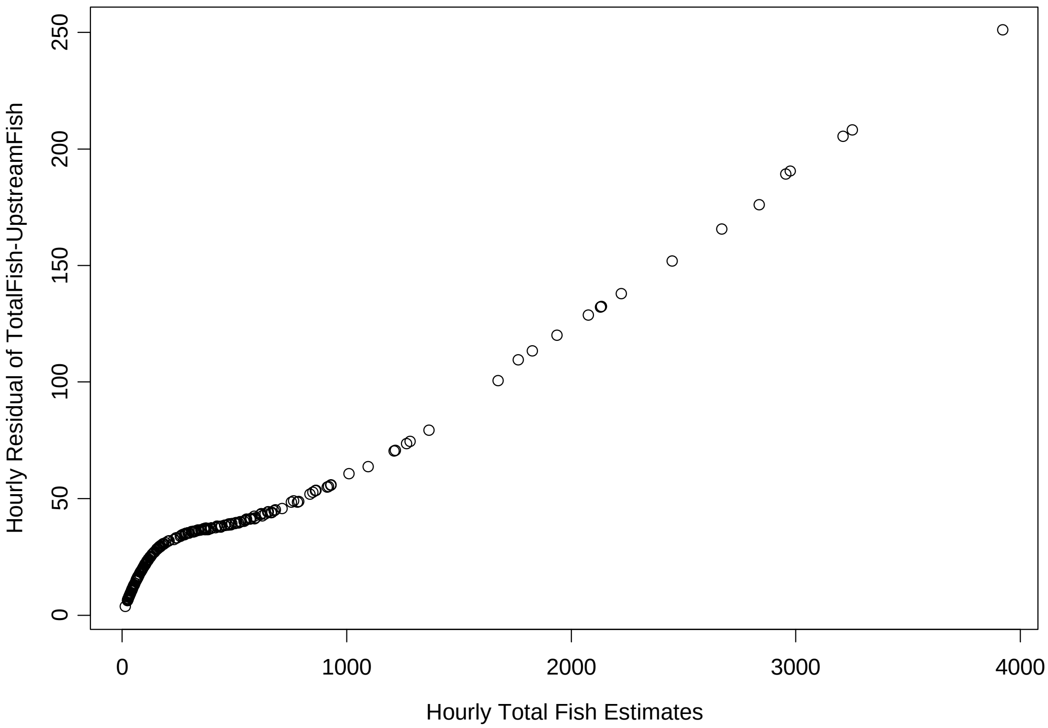

Figure 5. Residuals of *T*-*N* (shown in Fig. 4) as a function of hourly total fish.

The cumulative *T* from our data is 99,100, and the cumulative *N* projected by our model (4) with the smoothed R_D is 91,100, which gives an overall relative difference of 8.8%. This analysis indicates that ignoring milling behaviour results in positively biased estimates of upstream fish flux. The bias has a relatively small effect on high fish fluxes, however, for low fish fluxes, the bias can result in relatively large overestimates.

<u>Spatial Distributions</u>

One of the objectives of the split-beam project was to investigate the vertical and horizontal distribution of fish using the tracked target data. With a 4°×10° transducer, we sampled a cross-section of the river adjacent to the south bank with 5 strata. (Fig. 6). Due to the boundary effect of river surface and the irregular bottom profile, the effective ranges of the side-looking 4ºx10º acoustic beam were limited to a maximum of 65 m at the horizontal aim. This prevented us from obtaining an overall spatial distribution of migratory salmon across the entire river. Nevertheless, we can still study the fish distributions in this limited cross-section. Historically the south bank provides passage for a significant portion of migratory fish flux past Mission.

The top plot in Fig. 6 is a typical 24-hour cumulative Summer-run sockeye flux distribution from split-beam data. It is evident that the migration route for many of the fish was located close to the river bottom and within approximately 60 m of the shoreline. The same feature was observed by the PSC single-beam downward looking mobile sounder that insonified most of the river cross-section (see the bottom density plot in Fig. 6).

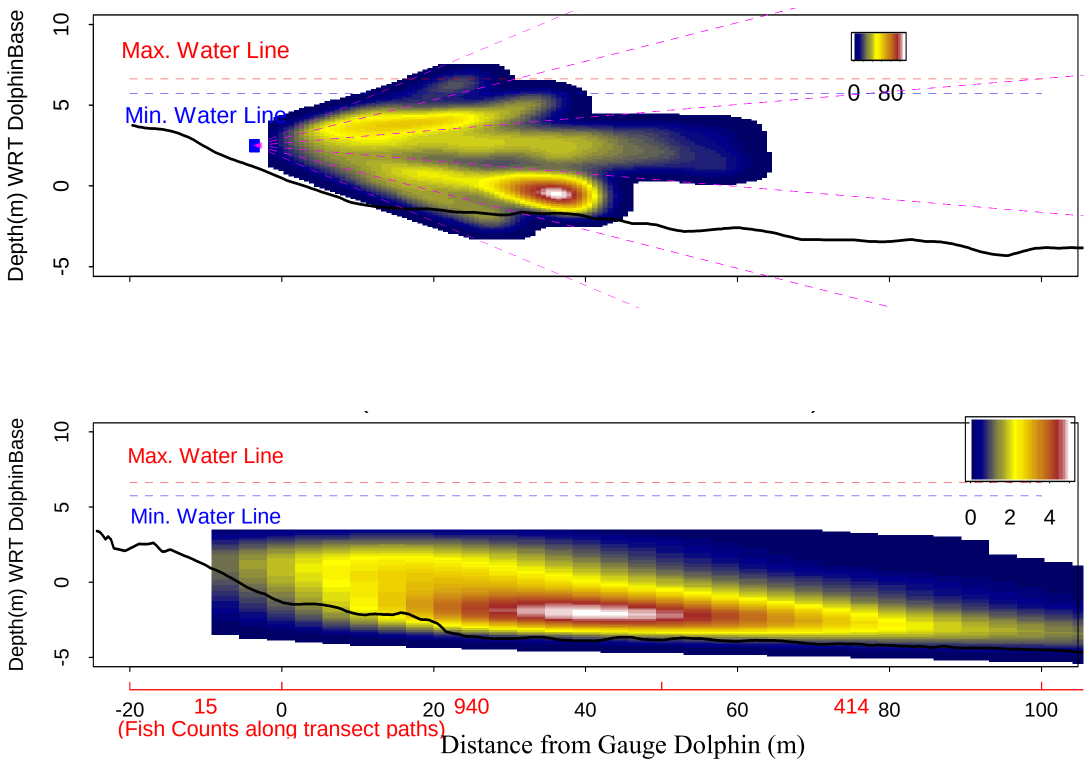

Figure 6. 24-hour cumulative fish flux obtained on August 18, 1998 at Mission, BC. Top plot: fish flux observed by a side-looking split-beam echo-sounder system. The five pairs of radiating dashed lines outline the -3dB sound-beam projected at five aims; Bottom plot: fish density observed by a mobile down-looking single-beam system. The two systems insonified two slightly different cross-sections of the river off the south bank. The apparent presence of fish below the river substrate is due to the smoothing algorithm used to present the data.

Comparisons of Fish Flux Distributions from the Split- and Single-Beam Systems

The sampling of a common area of the river cross section by both the split- and single-beam systems allowed us to compare the spatial distributions of the observed fish flux. Twelve time periods that covered a wide range of flux were selected from the 1998 data (table 1). To obtain the spatial distribution of flux for the survey vessel, we used the duration-in-beam model combined with the GPS data. We compared both the digitised and manually processed single-beam data with the split-beam data. The estimate from digitised single-beam data was based on the method presented by Banneheka et al, 1995, which included the correction for fish speed vs. boat speed. The Pacific Salmon Commission's current standard methodology for producing estimates of passage from manually processed single-beam data is also based on Banneheka et al, 1995 except that the correction for fish speed vs. boat speed recommended by Banneheka is not applied.

Since the sound-beams from the two systems insonified different cross-sections, approximately 10m apart, the bottom profiles where the two transducers were operating were not identical (see the two density plots in Fig. 6). This presented a difficulty in achieving absolute spatial comparisons of fish fluxes obtained from the two systems, especially near the river bottom. To overcome this difficulty we assumed that the fish migrate upstream by maintaining constant distance off the river bottom over this stretch of river. Accordingly, we referenced the position of the fish relative to the river bottom. Hence, the river profile is inverted with the zero height-off-bottom representing the bottom as shown in Fig. 7.

Fish flux was then estimated and displayed on this transformed cross-section for both split-beam and single-beam systems. The estimates were presented as numbers of fish per hour passing through each of the 5m (range) by 1m (depth) cells. The commonly insonified cross-section was confined by the spatial sampling limits of the two systems. As mentioned before, the side-looking acoustic beam was subjected to range limits imposed by the boundary effect of the river, which resulted in a finite sampling area outlined in Fig. 7. On the other hand, the down-looking single-beam had a 2 m blind zone below the river surface. This blind zone was due to the rejection of near-field echoes by the sounder and a finite deployment depth of the transducer relative to the water surface. Therefore, no data were available for the first 2 m of the water column for the single-beam fish density plot in Fig. 6. Figure 7 is the flux difference between the two systems (single-beam flux minus split-beam flux) for one of the twelve time periods.

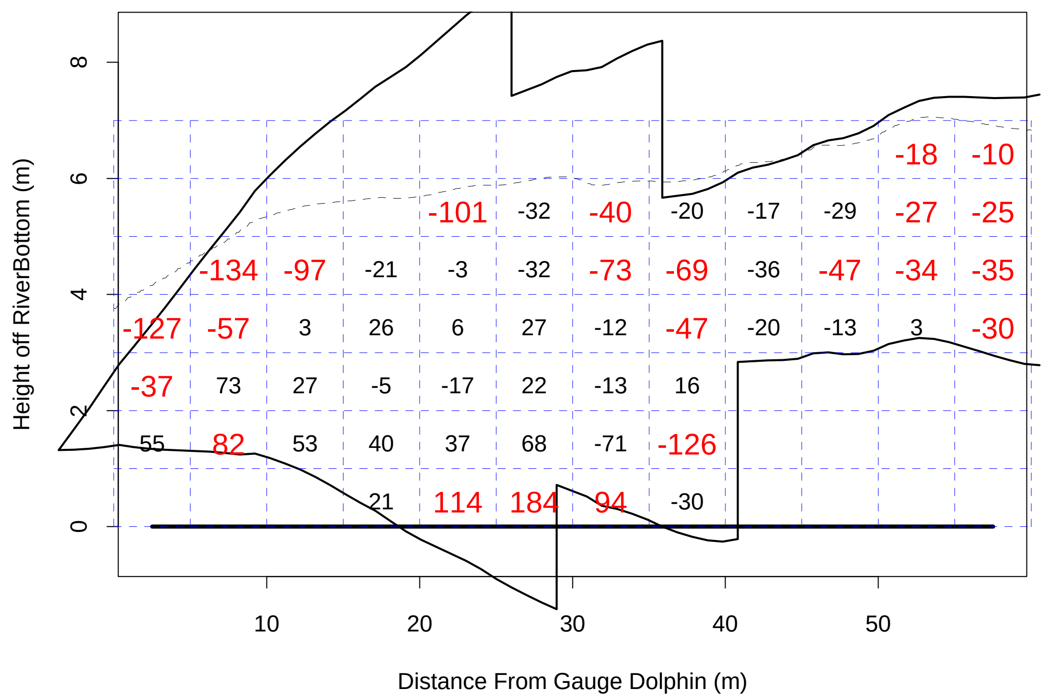

Figure 7. Daily fish flux difference between single-beam and split-beam systems for Aug. 18, 1998. The river cross section has been divided into height-off-bottom and distance-from-gauge cells. Negative values correspond to lower single-beam estimates than the split-beam estimates. The black and red fonts indicate whether the difference values are inside or outside of the 95% confidence intervals (with respect to individual cells) respectively.

The data from Fig. 7 can also be displayed graphically to help identify patterns in the differences of the two spatial distributions (Fig. 8). Here colour is used to indicate the flux differences, with the negative differences (shown in magenta) indicating that the side-looking system observed larger flux than the down-looking system and positive differences (shown in blue) indicating the opposite to be true. If both systems observed the same distribution on average, one would expect that the pattern of coloured squares would be random. Any systematic pattern is evidence for a systematic difference in the two spatial distributions. For example, Figure 8 demonstrates that the side-looking system tended to observe more flux in the upper water column and nearer to the shore than did the down-looking system. On the other hand, the down-looking system tended to observe more flux near the bottom.

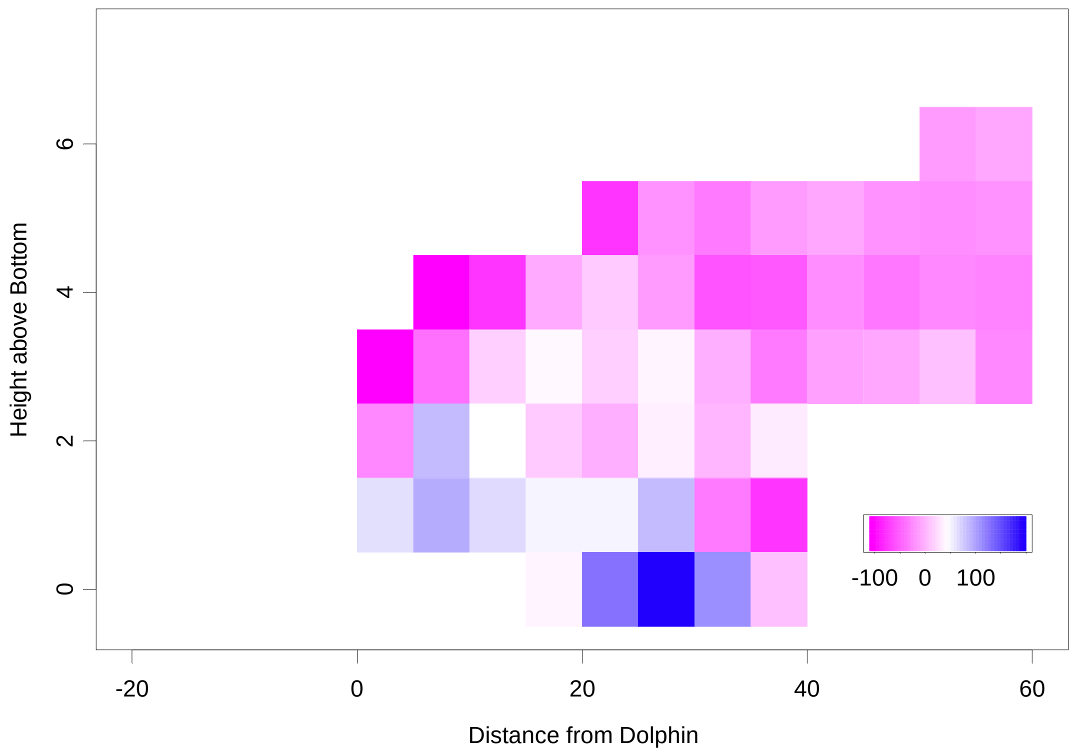

Figure 8. Same as Fig. 7 but using colour to indicate the flux differences.

The data from all 12 time periods can be compared using the same graphical technique (Fig. 9). These twelve images are arranged in time sequence going from left to right and from top to bottom. Notice that early in the season the water level is higher and the shoreline is further to the left than was observed for the later season. Thus, the cross section used for comparison changed with changing water level. If we examine these images, all but the top left panel tends to show the same type of systematic pattern we described for Fig. 8. Therefore, in general, the vessel observed lower fish flux near shore and near the surface when compared to the shore-based system. Conversely, the vessel observed higher flux near the bottom than the shore-based system.

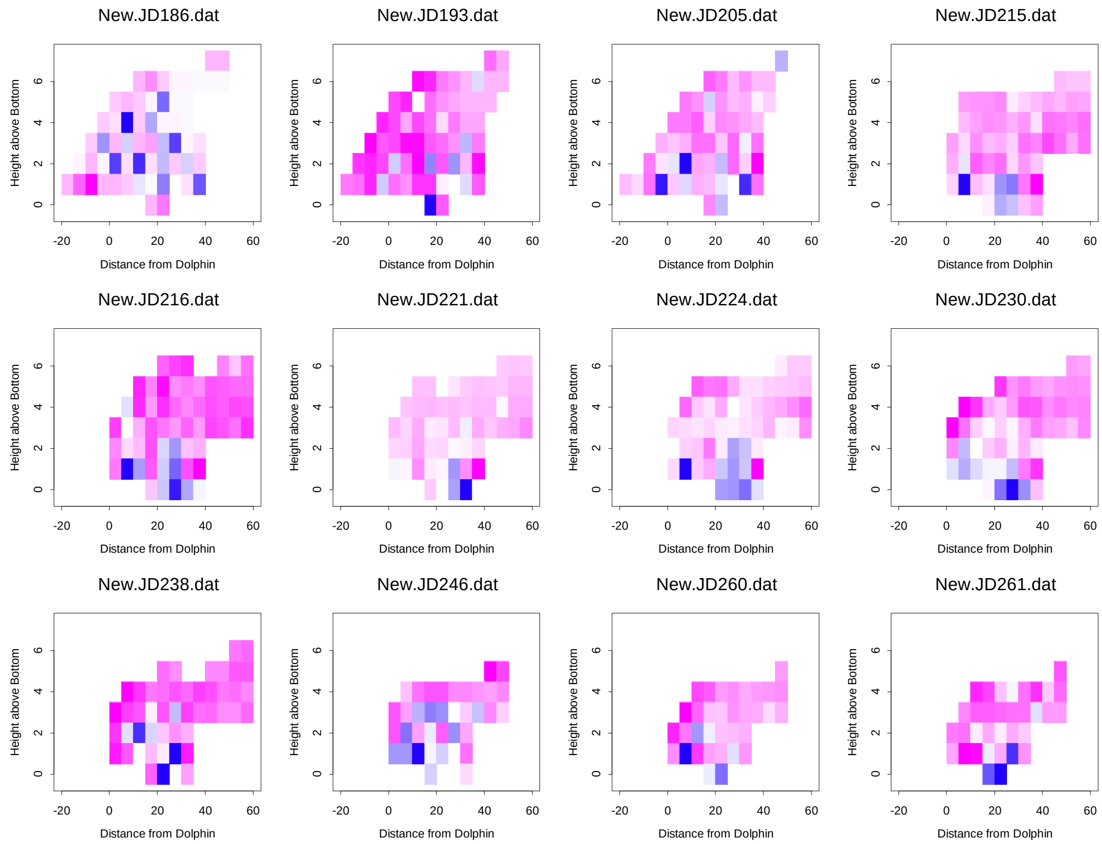

Figure 9. Data from all twelve time periods using colour to indicate the flux differences. Patterns can be noted in the distribution of the colours.

Two potential explanations for the systematic flux differences seem feasible. First, the fish detection probability of the two systems might be different for different parts of the water column. Second, the moving vessel might be affecting the spatial distribution of the fish. In order to help choose between these, we examined the total fish flux within the cross sectional areas that are displayed by the images in Fig. 9 without reference to their spatial properties. When we examine the scatter plot of these 12 total flux estimates from each system, we see that they are scattered symmetrically around the one-to-one line (Fig. 10).

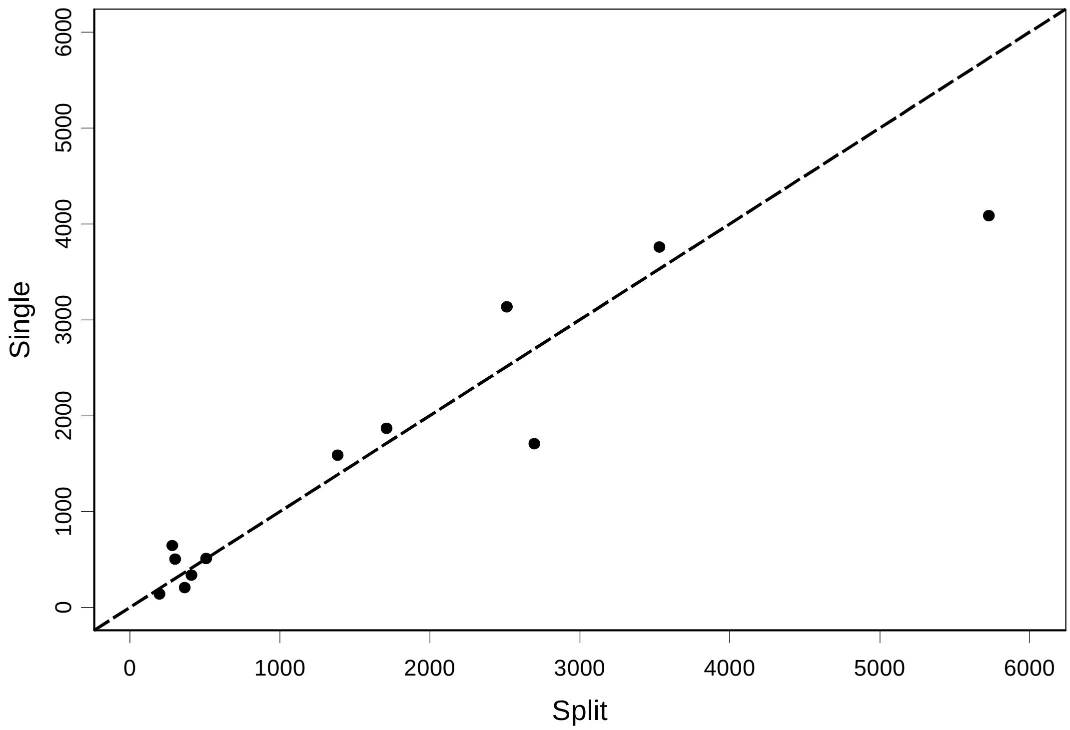

Figure 10. Scatter plot of single-beam (based on digitised data) versus split-beam flux estimates. The dashed line is the one to one line.

If we use linear regression to examine the trend line, we reach the conclusion that the total fish flux as observed by the two systems is not statistically different. This holds true whether we use the digital or the analogue data from the single-beam system for the analyses (Figs 11 and 12). Note that, for the regressions we have used the log-transformed fluxes. This is typical for these types of data, which are more likely to have proportional errors than additive errors. We have also used the two extreme cases for each regression comparison, namely assuming that all the error lies in the split-beam data and then assuming that it all lies in the single-beam data. Since both measurements are made with error, the true regression line lies somewhere between these two extreme cases. However, the extreme cases are almost identical in result and both differ very little from the one-to-one line.

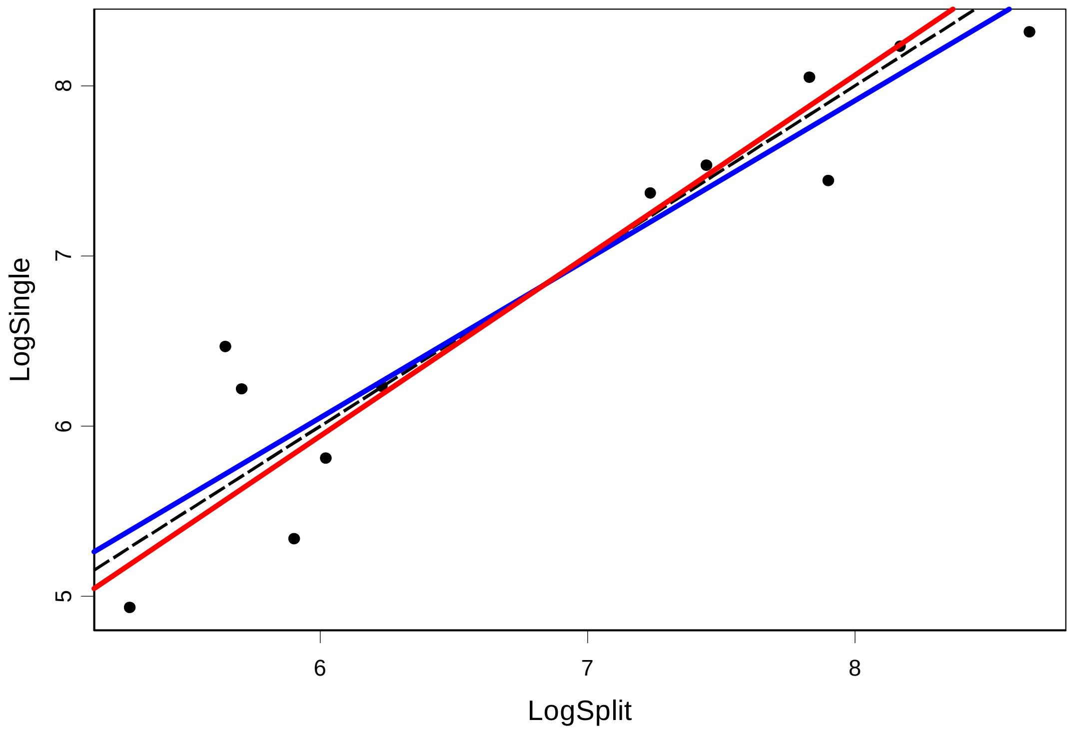

Figure 11. Linear regressions of log transformed fluxes. The blue line represents the regression line for LogSplit vs. LogSingle (derived from digitised data) and the red line represents the same for LogSingle vs. LogSplit. The dashed line is the one to one line.

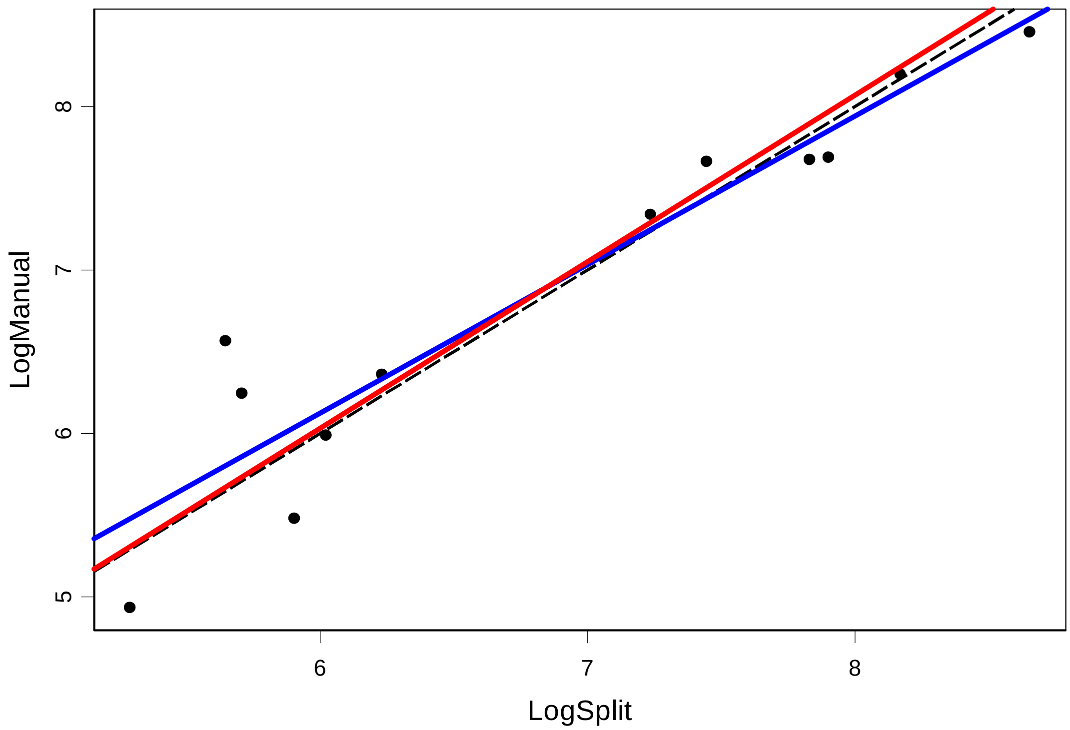

Figure 12. Linear regressions of log transformed fluxes. The blue line represents the regression line for LogSplit vs. LogManual (derived from analogue outputs from the single-beam system) and the red line represents the same for LogManual vs. LogSplit. The dashed line is the one to one line.

<u>Comparisons of Vertical Fish Distributions Observed from Mobile and Stationary Surveys by the Single-Beam Sounder System</u>

This section provides further evidence to help determine the nature of the spatial differences described in the previous section. The duration-in-beam method for daily fish flux estimates uses two types of information from the echo data obtained by the single-beam sounder. They are (1) fish densities and (2) migration speeds. The density data are obtained from the vessel transect data; whereas, the speed is estimated through the duration-in-beam data observed by the same acoustic beam while stationed at random locations across the river. The two scatter plots in Fig. 13 are examples of typical target distributions based on the data obtained from mobile and stationary soundings by the single-beam system.

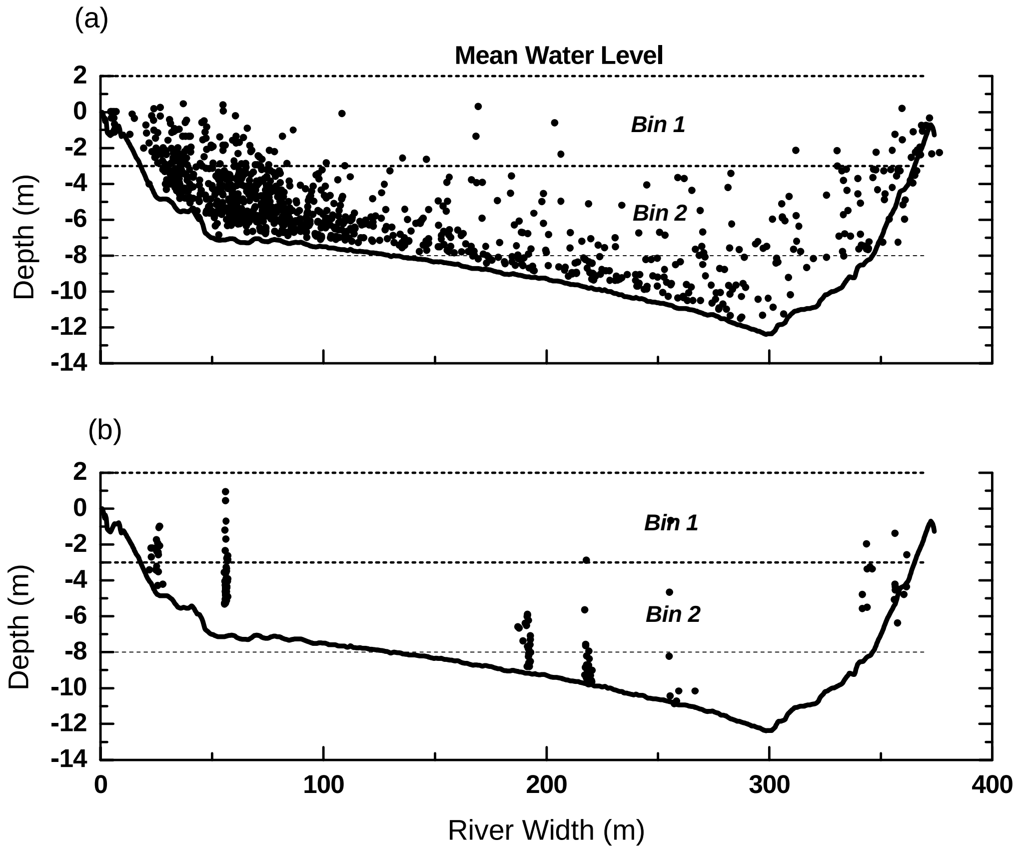

Figure 13. (a) Cumulative cross-river target distribution based on 18 hours of transect sampling on August 12, 1998. Each point represents the mean position of one fish. A total of 1,200 targets were identified as migratory fish; (b) Target distributions on southern, central and northern sections of the river based on 3 hours of stationary sampling on the same day. Each point represents the mean position of one fish. A total of 150 fish targets were identified. The three dashed lines outline the 0-5 m and 5-10 m depth-strata (labelled as Bin1 and Bin2) from the mean river surface.

The duration-in-beam method assumes that fish distributions are not altered by the presence of the survey vessel. Therefore, the relative target density observed from the mobile survey should be similar to that from the stationary survey for the same time periods. To test this assumption, we gathered 10 days of digitised single-beam data and calculated relative densities of fish abundance in two vertical strata labelled as Bin 1 and Bin 2 in Fig. 13. Bin 1 refers to the top 5 m layer of water measured from the mean water surface, which includes 2 m of surface blind zone. Bin 2 refers to the 5 m layer of water beneath Bin 1. This binning procedure is used by the PSC as part of its standard procedure for estimating the daily passage at Mission (Banneheka, 1995). We calculated the ratios of the mobile and stationary target counts for these two layers. The results are shown in Fig. 14.

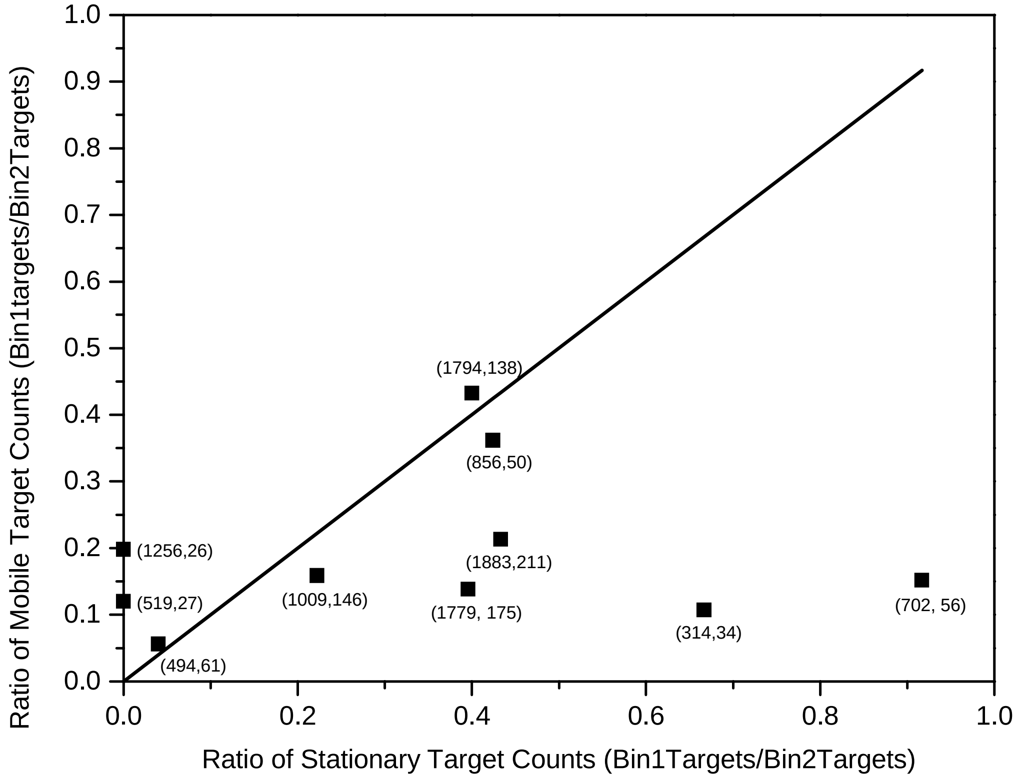

Figure 14. Comparisons of relative fish counts observed by the mobile and stationary soundings with a down-looking single-beam transducer for the 10 days. The 2 numbers by each point are the total sample sizes from the mobile and stationary surveys, respectively. The 1:1 line is also plotted.

The two null values for the stationary data in Fig. 14 may have resulted from the small sample sizes (27 and 26 fish targets) detected by the stationary sounding. During the stationary soundings, the engine of the vessel was turned off. Therefore, estimates of fish densities from the stationary data were less likely to be affected by the presence of a "silent" stationary vessel. As the majority of the data points are below the 1:1 line, the plot in Fig. 14 reveals a systematic difference between these two types of observations. Since we are examining the ratio, we cannot say whether one or both bin densities are different between these data sets. Ignoring the two null values, we performed a Welch modified two-sample *t*-test for these data. The test yielded a *p-value* of 0.024, which led to a rejection of the null hypothesis at the 0.05 level in favour of the alternative hypothesis that higher percentages of fish targets were detected in the upper water column during stationary surveys than during mobile surveys. This is consistent with the findings from the flux-difference of fish targets in the upper water column observed by the split- and single-beam systems discussed above. The combined statistical analyses on estimates of fish distributions from the split-beam and single-beam systems, and from the two independent survey modes by the single-beam system, indicate that the moving vessel does modify salmon distribution in the water column; however, the total flux estimates appear to be equal as presented in the previous section .

Qualitative Evidence of Boat Avoidance in the Vicinity of the Survey Vessel

Qualitative evidence of boat avoidance was noted during the 1998 Adams River run. At a time of very high-density fish passage, we saw what appears to be fish reacting to the survey vessel. Fig. 15 shows a standard echogram of range vs. time for this time period. The echogram was obtained with a horizontally aimed 4^o x 10^o split-beam transducer deployed off the south bank. The grey line shows the distance from the transducer to the transecting vessel. The fish appear to be moving aside as the vessel passes but the timing differs by about 50 seconds. There is a possibility that the time recorded by the south bank split-beam system could have been in error, as the time for this system was manually set and the clock was observed to be slow as compared to the GPS time. A differential GPS receiver was used in the vessel to measure the range between the vessel and the deployment site of the 4º x 10º split-beam transducer. When the timing is adjusted by the 50 second apparent offset, the grey line falls directly in the middle of the path through the fish density. Due to this time uncertainty, this echogram proves to be somewhat inconclusive but we present it to show that in the area adjacent to the transecting vessel, there appears to be a reaction by the fish. These fish are travelling in the shallower near-shore areas of the south bank of the river. Several fish (shown in grey) on the left side of the break in the density are travelling downstream (Fig. 16). It is unusual to see a concentration of downstream moving fish like this, especially when such high densities are moving up the river.

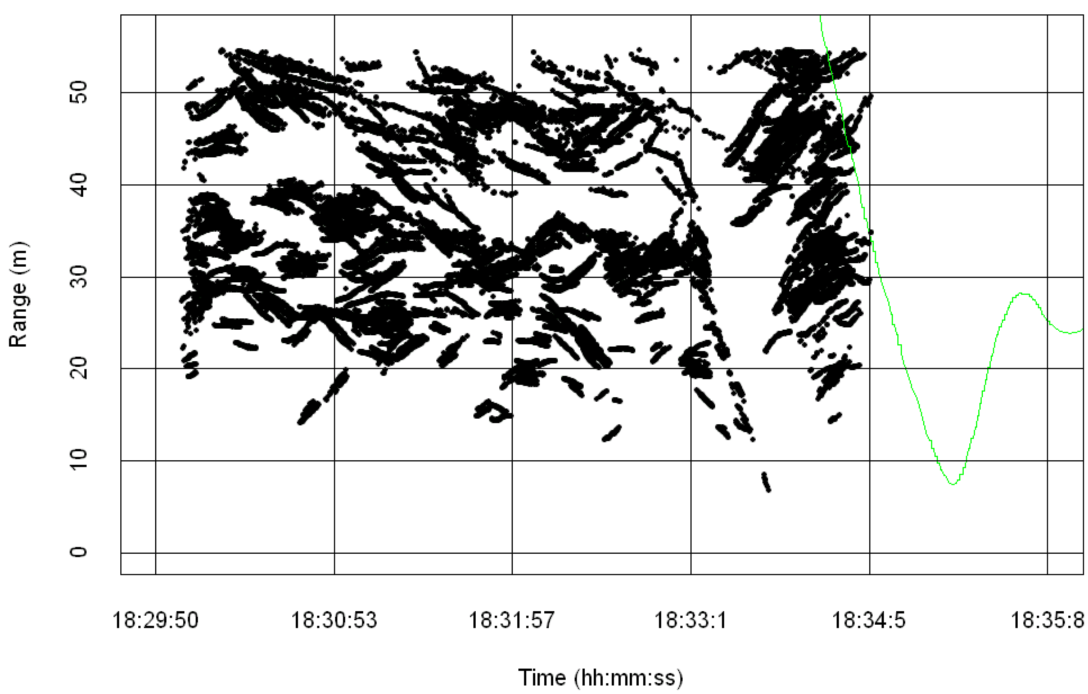

Figure 15. Echogram shows possible fish reaction to the transecting vessel, observed on Sept. 15, 1998. The grey line shows the distance from the vessel to the transducer at a particular time. If a time adjustment of 50 seconds is applied then the vessel distance from the transducer line falls directly in the path through the fish. Fish tracks are not present in the right-hand portion of the echogram, as the system had stopped processing to move to the next sampling strata. The echogram has been expanded to show the position of the survey vessel.

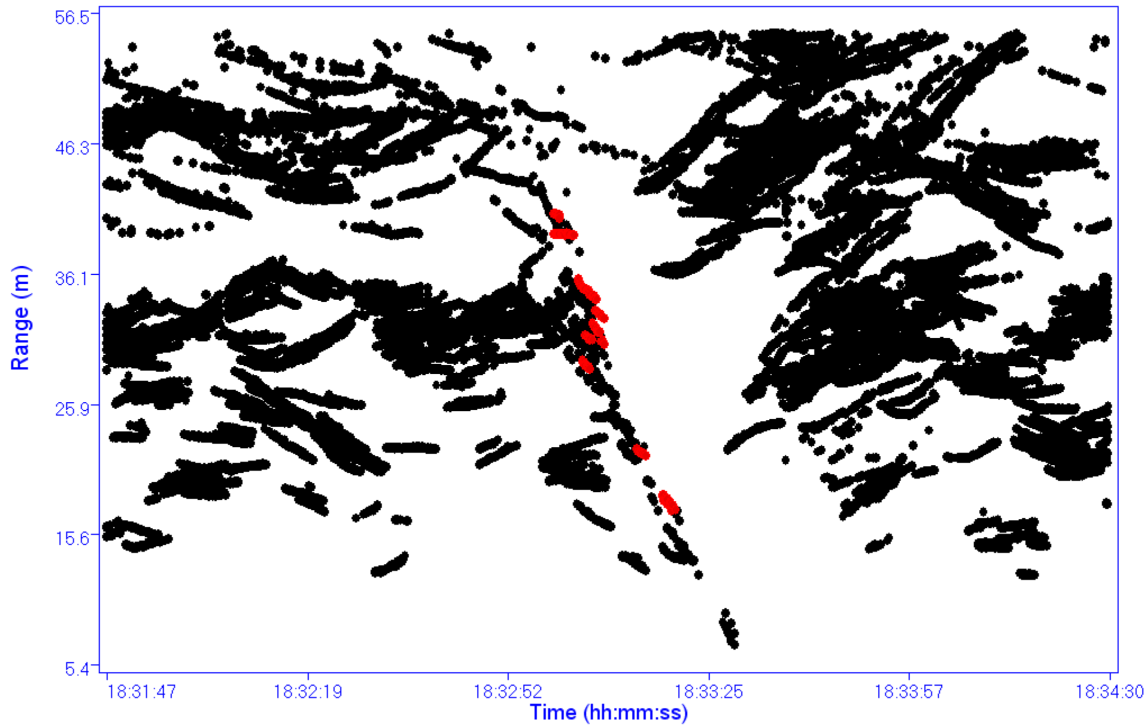

Figure 16. The coloured tracks are travelling downstream and occur along the boundary of the disturbance.

This type of fish behaviour relative to the transecting vessel may seem inconsistent with the observations of total flux being equal from the side- and down-looking systems presented in the previous section. However, the presented fish flux comparisons were carried out in the commonly insonified areas of both the split- and single-beam systems, which excludes the near-surface water due to the blind-zone effects (Fig. 6). Fig. 15 presents 5 minutes of data from September 15 to 16, 1998, at which time over one million late-run sockeye passed Mission. The densest fish passage was observed in the top 1-2 m layer of water during the slack tides (Fig. 17). Such surface-oriented distributions placed the majority of the sockeye in the blind zone of the downward-looking single-beam system. The effect of under-sampling the fish at times of surface oriented migration could result in severe under-estimation of migratory abundance.

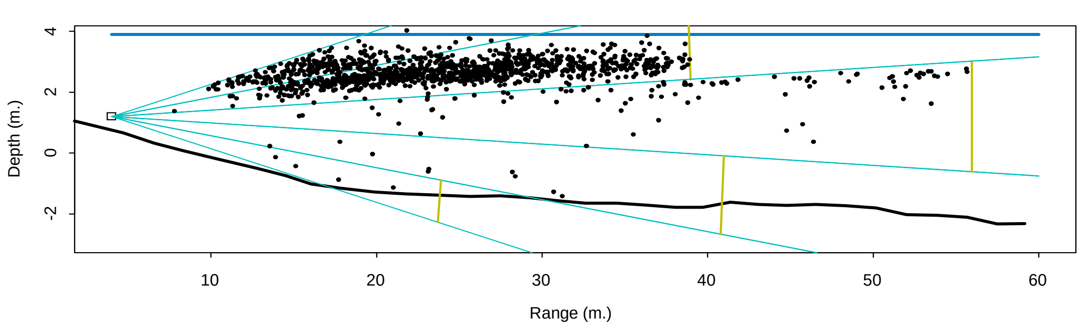

Figure 17. Side-view density plot showing the surface-orientated concentration of the migrating Late-run sockeye during September 1998 at Mission, BC.

Fish Fluxes observed by Two Split-beam Transducers

The lack of ground-truth data prevented us from verifying fish flux estimates obtained with the two sonar systems. A visual counting approach would have been an ideal choice for collecting the ground-truth fish flux data as conducted for the Thompson river salmon stocks at Spences Bridge, B.C. in 1995 (Enzenhofer, et al. 1998). However, the highly turbid water of the Fraser River makes it impossible to visually count migratory fish at Mission. So far, only relative comparisons have been carried out for acoustic estimates of fish flux past Mission. These relative comparisons included flux estimate differences between the single- and split-beam systems as described in the previous subsection and comparisons of fish flux estimates obtained with independent split-beam transducers presented in this section. To examine fish behaviour at longer ranges, we projected a narrower sound-beam with a 2°×10° split-beam transducer at –1° and –3° aims, respectively, to insonify fish targets further offshore than is possible with the 4°×10° transducer. Figure 18 illustrates the two insonified cross-sections for the two transducers. It is evident that the cross-section covered by the narrower beam overlapped significantly with that covered by the wider beam at the 0° and –4° aims over a 60-metre range. This allowed us to compare fish flux estimates obtained from the two independent transducers over this commonly insonified area of the river.

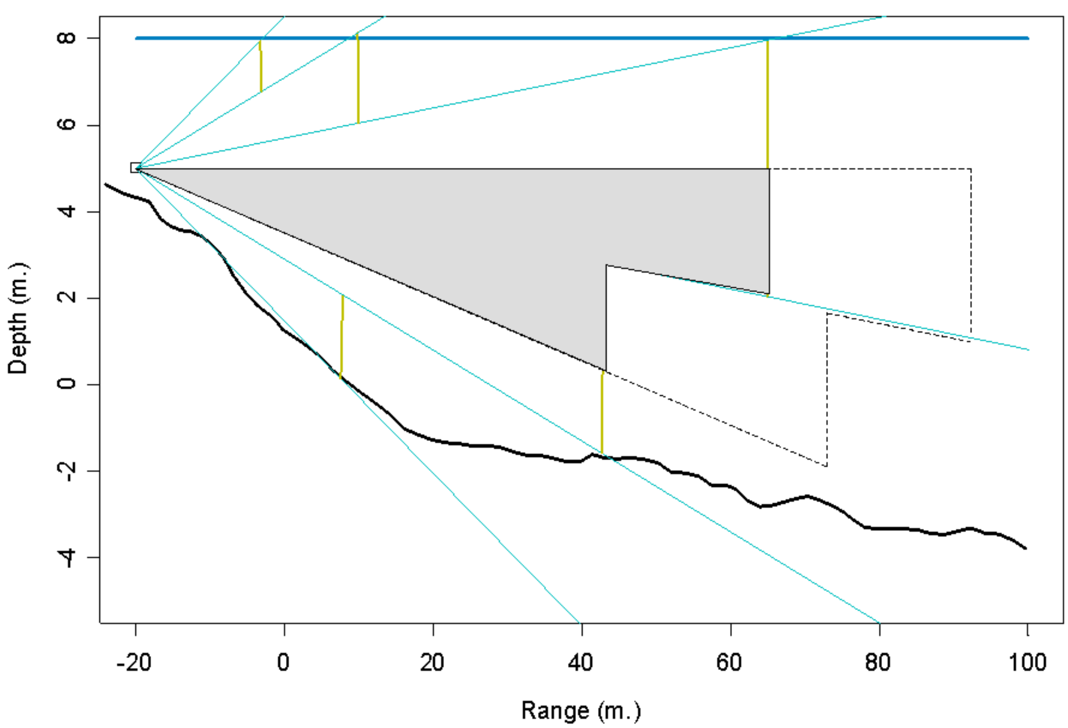

Figure 18. Schematic illustration of the areas insonified by the $4^o \times 10^o$ (solid lines) and

$2^o \times 10^o$ (dashed lines) transducers. The grey filled area was chosen for the comparison of fish flux estimates by the two transducers. Note: the vertical scale of the plot has been greatly exaggerated.

The common area, coloured grey in Fig. 18, was sampled for an equal amount of time by the two transducers (15 minutes per complete cycle of sampling sequence of 105 minutes). Therefore, we were able to make direct comparisons of fish flux in the overlapping areas. Based on approximately three weeks of split-beam data collected by the two transducers between late July and early August in 1998, we calculated the daily average fish fluxes observed by the two transducers for the common area. Figure 19 shows comparisons of the two estimates over a wide range of migratory abundance.

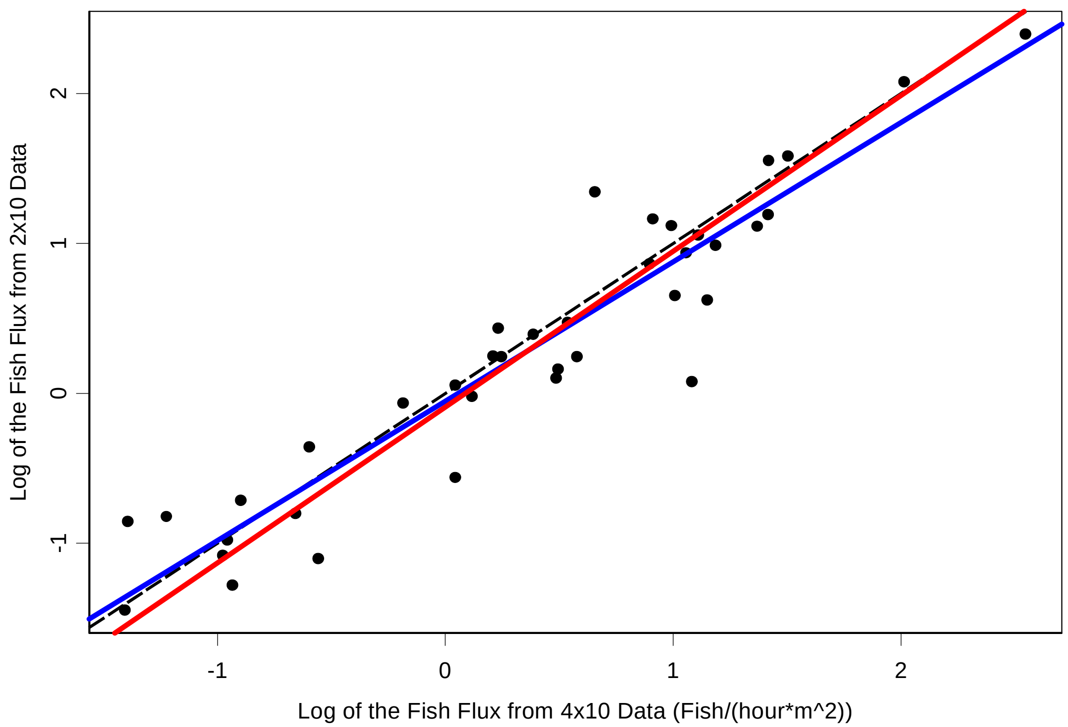

Figure 19. Comparison of daily fish flux estimates by two split-beam transducers of different vertical -3 dB beam-widths. The area of comparison is shown in Fig. 18. The blue line represents the regression line for Log(4x10 flux-estimate) vs. Log(2x10 flux-estimate) and the red line represents the same for Log(2x10 flux-estimate) vs. Log(4x10 flux-estimate). The dashed line is the one-to-one line. The estimates from the two transducers are not statistically different.

It appears that the two independent observations yielded consistent estimates of fish flux. The two-sample *t*-test on the flux data favours the null hypothesis with a significant *P*-value of 0.777. The overall difference of the two estimates is well inside the 95% confidence interval. This analysis, though far from ground-truthing the sonar estimates of migratory abundance, indicates that similar flux distributions are measured even when using different split-beam transducers.

Migration Speed

We were able to determine the direction of travel and swimming speed of individual targets based on the split-beam data. We found that the daily average upstream swimming speeds of Summer-run sockeye were negatively correlated with the river discharge. This implies that strong downstream flows impede the upstream migration of the sockeye salmon. These stocks migrate up the river from mid-July to the end of August and experience large variations in river discharge.

Swimming speed increased steadily over the course of the season as the river discharge decreased. Upstream swimming speed data were plotted in Fig. 20 against the daily river discharge measured at Hope, B.C. between July and early September for the 1995 to 1998 seasons. The data were regressed against the discharge for the period from August 1 to August 31 when summer-run stocks dominated the migration. The resulting regression line was also displayed in the same plot in Fig. 20.

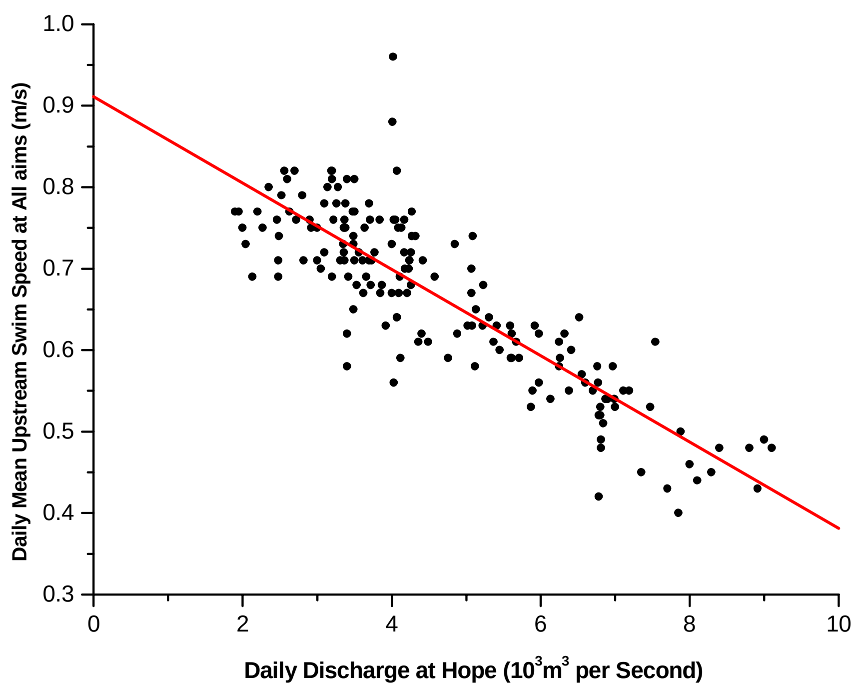

Figure 20. Daily average upstream swimming speed versus river discharge measured at Hope, B.C. (July-September of 1995-1998). The sonar measured the swimming speed using five aims to cover the river cross-section off the south bank. The negatively sloped straight line is the regressed relation.

In these relationships, the estimated swimming speeds were the ground speeds (speed relative to a fixed point) of migratory fish as they passed through the sound-beam. The data show the following features of migrating sockeye:

- During the high discharge periods of early July, upstream swimming speed is relatively low with an average value of 0.5 m/s. The ground speed increases as the discharge decreases. By late August, the average speed increases to 0.8 m/s.
- The regression model for all five aims predicts a swimming speed of 0.91 m/s in still water, which is approximately 1.5 body-lengths per second for Summer-run sockeye (See Fig. 20).
- The resulting regression of daily averaged fish speed from all five aims is:

$$USpeed = -5.3\times10^{-5}\times DG + 0.91 \quad \text{(m/sec)} \qquad (5)$$

where *USpeed* is the daily average upstream swimming speed from the split-beam data for all five aims; *DG* is the daily river discharge in cubic metres per second. The model yields an R^2 of 0.73.

Schooling Patterns Observed during High Density Sockeye Migration

Schooling behaviour is not typical for Summer-run sockeye salmon, although the Late-run sockeye may occasionally adopt this behaviour. For instance, in September 1998, Late-run Adams, Lower Shuswap and Weaver sockeye appeared to be schooling during times of very high density (Figs. 21 and 22). At times, the sockeye migrated near the river surface in a very dense and narrow band (Fig. 17). This high-density migration occurred during flood tides when the downstream flow velocity reached its minimum.

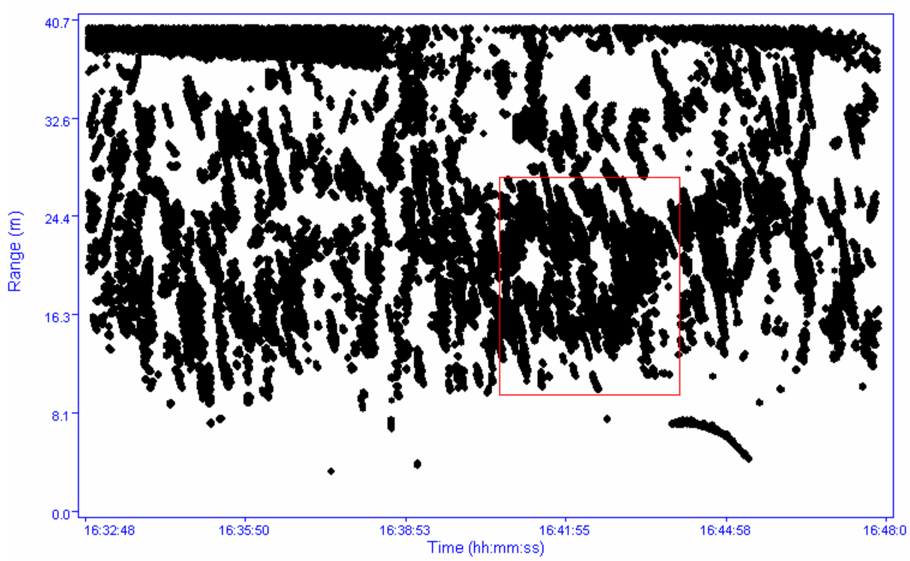

Figure 21. Echogram (range vs. time) of high density Late-run sockeye observed on September 16, 1998 showing the schooling behaviour. The outlined data are magnified in Fig. 22.

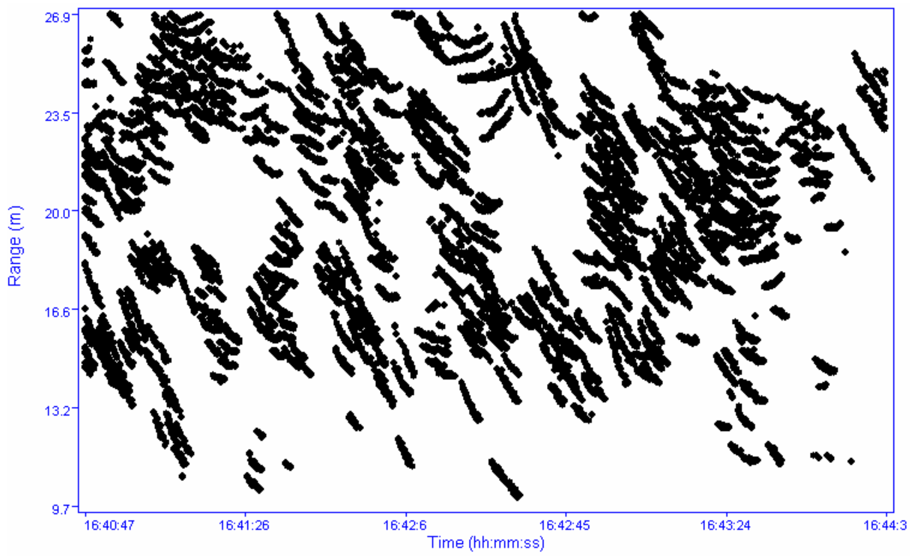

Figure 22. Magnified echogram of the Late-run sockeye shown in Fig. 21. This echogram shows similar schooling behaviour to that of pink salmon in 1995.

We believe that it is feasible to conduct trace counting of individual salmon migrating in schools such as these during most seasons with the side-looking split-beam systems. At times of extremely high density it may be necessary to use the $2^o \times 10^o$ transducer to reduce the number of salmon in the beam at any one time and therefore allow a count to be made.

Migration Patterns of Pink Salmon

The 1995 pink salmon run migrated in dense schools past the Mission acoustic site. This pattern persisted even when the overall fish flux was low. This schooling behaviour was an important occurrence as it provided an opportunity to evaluate and optimise the performance of the split-beam system on congregated targets.

The 1997 pink salmon run never reached the high densities observed in 1995. The pink salmon still showed the characteristic schooling behaviour when their densities were higher, but in general the pinks were more dispersed both vertically and horizontally. During this season it would have been feasible to conduct trace counting of the pink salmon as their density levels could be handled by our software routines. See Xie et al, (1997) for a more detailed discussion on the pink salmon.

The side-looking split-beam system is at this time the most likely system to obtain reliable counts of pink salmon. The reason for this is that the downward-looking system is unlikely to effectively sample regions of high density near the surface and bottom of the river (Fig. 23). The pink salmon migrate in the shallower near shore areas, often close to the substrate, where the current is slower.

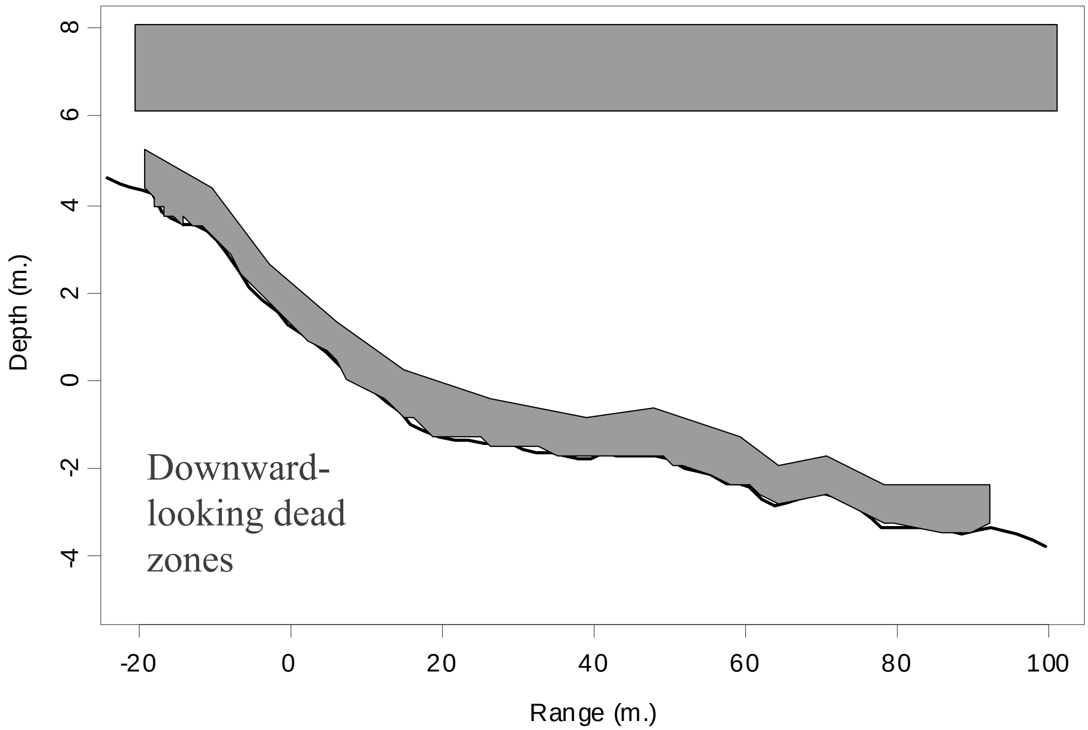

Figure 23. Side-view plot showing the potential down-looking sonar blind-zones. The blind-zones are shown in grey. (Depth "0" is the bottom of the gauge dolphin).

SUMMARY OF THE SOURCES OF BIAS IN THE SAMPLING OF MIGRATORY SALMON BY THE SINGLE- AND SPLIT-BEAM ACOUSTIC SYSTEMS

Split-beam hydroacoustic data provide a means of assessing various sources of potential relative bias between the split- and single-beam systems. The estimation of migratory abundance can be derived from statistical models that use the acoustically obtained fish data as inputs. The accuracy of hydroacoustic estimation of fish abundance partly depends on unbiased sampling of fish targets by these acoustic systems. However, our studies and data analyses show that both the split-beam and single-beam acoustic systems provide biased data on the abundance of salmon targets across the entire river. These biases need to be accounted for where possible, to obtain accurate estimates of abundance.

Sources of bias can be attributed to (1) limitations of acoustic technologies implemented in the two systems in a given riverine environment, and (2) methodologies adopted in the data collection procedures. In this section, we simply list various biases for the two systems. We emphasise that these are the biases that we have been able to identify from our studies. This does not constitute a quantitative evaluation of their combined effect on abundance estimation.

Sources of Sampling and Measurement Bias of the Split-Beam System

The split-beam sounder system utilises not only the strength of the echo signal but also the echo arrival times at four ceramic elements of the transducer to measure the characteristics of a target (Carlson and Jackson, 1980; Ehrenberg, 1981). These characteristics include the target strength and the target's three-dimensional location relative to the acoustic axis of the sound-beam. These features have advanced our understanding of various aspects of fish behaviour and their spatial distributions in rivers and at sea. In order to estimate the three-dimensional location of individual targets, the split-beam sounder uses the single-target-selection criterion to condition the received echo pulses (Ehrenberg and Torkelson, 1996; Soule, et al, 1996). This means that the echo signals received by the split-beam sounder are subsequently filtered, allowing the processor to record only the echoes from well-separated targets. This leads to two sources of potential negative bias in the estimation of fish abundance:

1) Fish targets will be excluded from the fish-track database if their return pulses overlap in time with reflected signals from river boundaries (river bottom or surface). This boundary effect creates blind-zones for the split-beam system such as that illustrated in Fig. 24, as the maximum ranges for data collection have to be reduced to avoid interference from the boundaries;
2) Not all of the echoes from the insonified fish will be registered in the database if multiple, closely spaced, fish targets appear concurrently in the sound-beam causing significant overlapping of echo pulses.

We feel confident that we can measure and correct for these two biases. The bias from the blind zones can be taken into account when estimating the total flux. The maximum ranges can be set to collect data from the blind zones and the data may possibly be used to give flux estimates. More work is required to develop this method. At the very least, the flux can be estimated for the blind zones from the measured fluxes in the bordering areas.

The second source of bias occurs during high-density migrations of sockeye or pink salmon. The bias occurs due to unrecorded echoes causing the tracker to fail to recognise the corresponding fish. This source of bias has been shown to be negative in other studies (Enzenhofer et al. 1998).

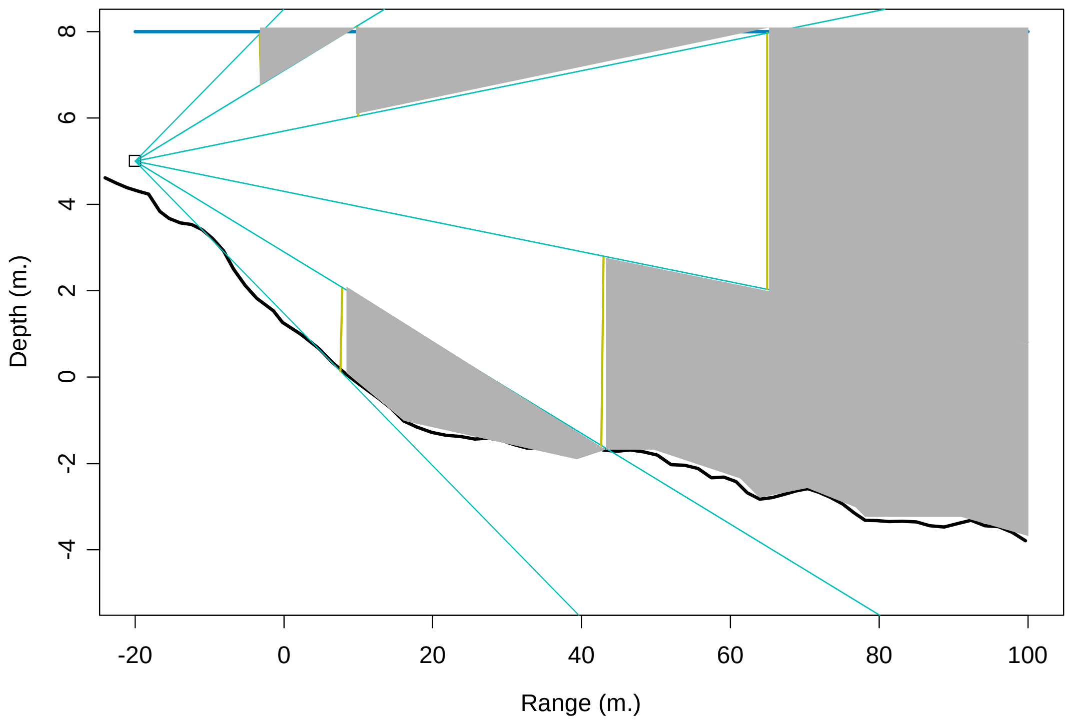

Figure 24. Side-view split-beam fan plot showing the blind zones (grey) for a 4°x10° transducer aiming at five angles from a regular deployment site at Mission, B.C. The lowest aim is likely to result in biased fish counts for the grey shaded area as the lower portion of the beam intersects the substrate before the top portion. The data from beyond this substrate intersection are currently not used.

Sampling Bias of the Single-Beam System due to Boundary Blind Zones

The duration-in-beam method used at Mission requires samples from the cross-section of the river with the single-beam transducer. However, due to the acoustic blind-zones at the surface and along the river bottom, the mobile sound-beam cannot cover the entire water column. The blind-zones are presented in Fig. 23 for the river cross-section near the south bank.

The surface blind-zone resulted from a transducer deployment depth of 0.5 m and the rejection of near-field echoes by the sounder for targets within 1.5 m of the transducer. The blind-zone along the river bottom profile resulted from: 1) a geometric mismatch between the uneven bottom profile and the spherical wave front of the arriving sound pulse, and 2) a finite range resolution determined by the transmitted pulse width (Mission Hydroacoustic Facility Working Group, 1994). These blind-zones prevented the downward looking single-beam transducer from effectively sampling fish targets near the river boundaries. The duration-in-beam model calculates the mean fish density from the total number of fish targets detected by the downward-looking transducer. Therefore, the under-sampling of targets at the river boundaries should cause a low bias in density estimates for migratory salmon, especially if the majority of the salmon are bottom or surface oriented. This bias could be corrected for when estimating salmon flux.

Sampling Bias of the Single-Beam System due to Avoidance of the Survey Vessel

Sonar work at Mission has demonstrated that it is very difficult if not impossible, to obtain acoustic observations of reactions of individual fish to an approaching survey vessel. Our approach to this potential source of bias was twofold: (1) we estimated the difference in fish flux estimates obtained with the split-beam and single-beam systems in an overlapping region near the south shore, and (2) we examined the discrepancies in the vertical fish distributions in the single-beam mobile and stationary data sets. Statistical outcomes of comparisons among these data presented in the *Results* section support the argument that the distribution of fish as seen from the mobile single-beam system are different from those seen by both the stationary single-beam and by the shore-based split-beam systems. However, when we compared the estimates for the total fish flux for the data from the split- and single-beam systems, we concluded that they were not significantly different. This leads us to hypothesise the following: Fish react to the presence of the transecting vessel, but their reaction may be to dive down towards the substrate and they are therefore still being detected as they remain in the acoustic beam. Thus, the spatial distribution between the two data sets differs, while the overall estimates agree. It seems counterintuitive to observe systematic spatial differences, yet no overall difference in the flux measurement. Therefore, we are proposing to study this process further to verify if the hypothesis can be substantiated.

We hope to measure the avoidance behaviour quantitatively, with a multi-beam sonar system looking sideways from the survey vessel. Measuring this bias has been the most difficult task during the course of this study. This may also prove to be the most difficult bias to compensate for. It is important to try to address this bias as it affects both the measurements of density distribution and the estimates of abundance no matter what type of acoustic system is being used. More work is required to address this problem.

Bias in the Estimates of Fish Speed due to Measurement Errors in the Duration-in-Beam Statistics from the Single-Beam System

The *standard hydroacoustic programme* using a single-beam system, relies on the duration-in-beam model to obtain daily fish fluxes past Mission. The model assumes that there are no biases in the acoustic measurements of fish density and swimming speed by the sounder. In reality this is not the case. The effect of under-sampling in blind-zones along the river bottom has been identified as a source of bias in the estimation of fish density. In this subsection, we focus our analyses on another source of bias that arises solely from measurement errors by the acoustic system. Such measurement errors and their effect on the fish flux estimation were not identified in the 1994 Mission Hydroacoustic Programme Review Report (Mission Hydroacoustic Facility Working Group, 1994). Subsequent data analyses and the implementation of a 12-bit digitizer for the single-beam echo sounder in 1997 allowed us to identify these errors. The most significant error was found in the measurement of duration-in-beam statistics by the stationary single-beam transducer for fish targets at depths greater than 5 m. Figure 25 presents time series of daily mean fish swimming speeds observed by the split-beam and single-beam systems. The split-beam speed data were obtained from direct measurements of fish targets through the sound beam. The speed estimations from the single-beam system were calculated using the duration-in-beam technique proposed by Banneheka et al, 1995. This technique uses the measured widths of fish traces on the paper echogram from the stationary soundings to estimate the speed.

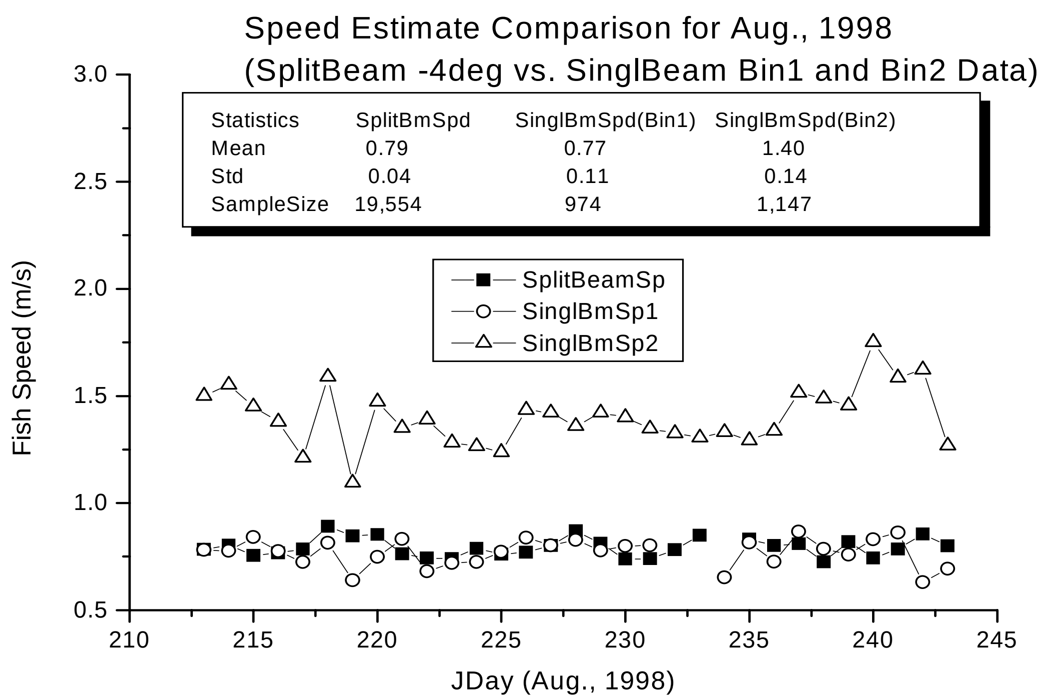

Figure 25. Time series of daily mean fish swimming speeds observed at Mission, B.C. in August of 1998. Solid squares are speed data measured by the 4°x10° split-beam transducer at a side-looking aim of -4 degrees. Open circles are speed data estimated from the duration-in-beam statistics measured with a circular-beam transducer with a beam width of 32° for targets present in a depth stratum of 2-5m (Bin 1) below the transducer. Open triangles are for targets present in a depth stratum of 5-10 m (Bin 2) below the single-beam transducer.

The split-beam system provides direct measurements of fish speed based on large samples, therefore its speed estimates are expected to be more accurate with less variance than that inferred from the duration-in-beam statistics obtained with the single-beam transducer. It is evident from Fig. 25 that for fish targets in the surface layer (Bin1 data), the speed estimates from single-beam system agree well with that observed by the split-beam system. However, for fish targets in the deeper layer (Bin 2 data), the inferred speeds from the duration-in-beam measurements are nearly double the Bin 1 speed estimates: 1.40 ms^{-1} vs. 0.77 ms^{-1}. Such a dramatic increase in fish speed with depth at the south bank of Mission site is unrealistic as the speed estimates by the split-beam sonar data showed a spatial variation in fish speed of 0.2 ms^{-1} for this site.

Figure 26 is a 24-hour cumulative fish speed distribution on a cross-section off the south bank at Mission as measured by the side-looking split-beam system. The pattern of the speed distribution clearly indicates that there are variations in average fish speed as a function of target-depth and range from the shore, with fish generally travelling faster near the shore and the bottom, where the current speeds are slower. The spatially averaged speed for this typical migration day was 0.74 ms^{-1} with a standard deviation of 0.2 ms^{-1}.

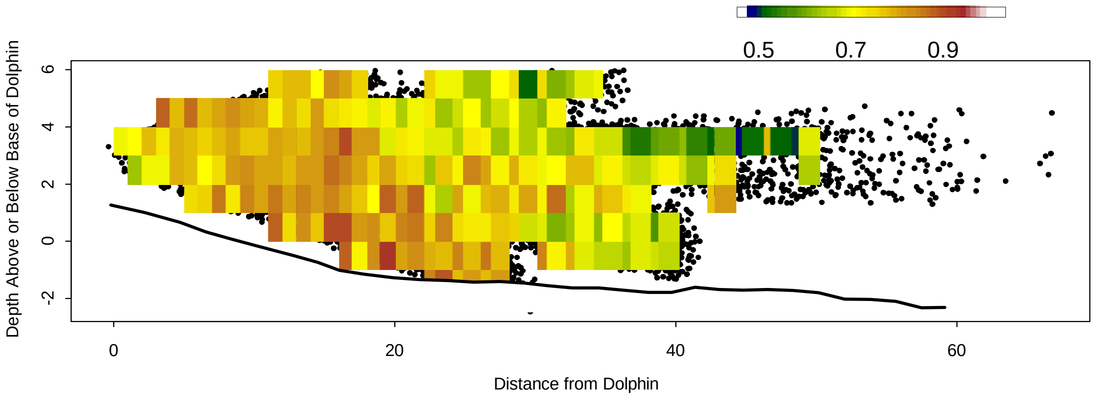

Figure 26. Upstream swimming speed distribution observed by the side-looking split-beam transducer on a cross-river section off the south bank at Mission, B.C., on August 19, 1998. Colours represent the various average speeds for each 2-D grid. The size of the grid is 1m by 1m, and grids with less than 10 observations are not coloured. The black dots show the average position of individual fish as they passed through the beam. The colours have been added over the top of the plot showing the individual fish positions.

The duration-in-beam error in speed estimates for fish in the deeper water layers may possibly be attributed to the acoustic scattering characteristics of fish targets. As demonstrated by Ding (1997) through a laboratory study on both forward and backward scattering patterns by a fish at 38 kHz, the amplitude of back-scattering functions from a fish target is highly sensitive to the incident angle of a sound-beam. The backward scattering function is characterised by multiple lobes of comparable power, in an angular range of ± 30 degrees from the normal incident direction. This may cause fish to appear and disappear momentarily from the echogram as its multiple scattering lobes move across the beam edge. Therefore, we would expect large fluctuations in the signal strength of echoes as the fish enters and exits the sound-beam. When the fish is well inside the sound-beam, we expect the signal strength to be more stable. The fluctuating echo strength from fish at the beam edge would make the evaluation of times of entrance and exit of the sound-beam (the duration-in-beam estimates) ambiguous. The bias effect on duration-in-beam estimates is small for fish targets near the surface but becomes pronounced for fish in the middle and deeper water column as the time when the fish is not detected is expected to increase with range. The consequence of this signal fluctuation would result in the breaking up of the leading and trailing edges of a coherent trace. Therefore, if this theory proves true, the single-beam transducer would tend to underestimate the duration-in-beam for fish targets in the middle and deeper water column. This effect was observed for almost every fish trace, especially for the targets in deeper water. The fact that the error in speed measurement was only apparent for fish observed in Bin 2 may explain why the comparisons between the single- and split-beam systems agree for the portion of the river cross-section seen by both systems, as outlined in Fig.7. The data used for comparison had very few targets observed in Bin 2, so that the effect would be small. However, we believe that the potential is present for serious bias, which would need to be addressed if the single-beam system continues to be used.

We are hoping that we can address the inherent problems with the duration-in-beam technique by switching to a downward-looking split-beam acoustic system. The split-beam system's ability to directly measure fish position and speed should circumvent some of the problems inherent with the duration-in-beam technique. We plan to operate the split-beam system alongside the single-beam system in the future, and eventually switch over to this newer technology if it proves feasible.

Bias in the Estimates of Fish Speed due to the Relative Speed of the Fish and the Survey Vessel when using the Duration-in-Beam Technique

There is an inherent bias that comes about due to the moving survey vessel and the moving fish (Banneheka et al, 1995). This bias can be compensated for if the fish speed and direction of travel are well known. If we assume that the fish and the vessel are travelling perpendicular to each other, the effective beam shape changes due to this relative motion. If this effect is not taken into account, it will create a positive bias. The faster the fish move relative to the vessel, the larger the overestimation of density. This effect can increase over the season as the fish speed increases due to the decreasing current velocities. This bias is also present when using down-looking split-beam sonar, but the split-beam system should provide the needed information on fish speed and direction of travel to allow the corrections to be made. According to the bias estimation model proposed by Banneheka et al 1995 (formula [28]), the relative bias in fish density estimation $\mathrm{RB}(\hat{R})$ due to this over-sampling effect is bounded by the following inequality:

$$\sqrt{1+\frac{\overline{u}_f^2}{u_b^2}}-1 \le \mathrm{RB}(\hat{R}) \le \sqrt{1+\frac{\overline{u}_f^2+\mathrm{var}(u_f)}{u_b^2}}-1 \qquad (6)$$

where u_f is the upstream migrating fish speed (its expectation is indicated with an over-bar), and u_b is the vessel speed, which is treated as a non-random variable in the model. Note, in Banneheka et al's model, the relative bias in fish flux estimates due to the speed effect is equivalent to the relative bias in fish density estimates as fish speed and density statistics are assumed to be independent. The differential GPS recorder on-board the vessel indicated an average transecting speed of approximately 1.38 ms^{-1} for the month of August of 1998. The split-beam data for the same period of time indicated an average upstream fish speed of 0.66 ms^{-1} with a standard deviation of 0.11 ms^{-1}. Substituting these estimates into the above formula, we arrive at a positive bias of between 10.8 and 11.1 %.

Bias in the Estimates of Fish Speed due to the Inaccurate Representation of the Target Width by the Paper Chart Recorder

The duration-in-beam statistics have been made by manual measurements of target widths on the paper echogram printed by an analogue chart recorder for the PSC standard programme. It was found that the digitised target widths were longer than those registered on the paper chart recorder due to the resolution of the chart recorder. This is a subtle machine error that was first noticed in 1995, when the PSC doubled the paper speed of the chart recorder for the echogram outputs from the single-beam system. This error was shown from the PSC 1995 post-season analysis to have caused an overestimation bias of fish flux, as it caused an overestimation of the speed. We have not tried to quantify this overestimation bias, as the best way to remove it is to use the digitised data to obtain the duration-in-beam statistics, or we may be able to switch to the split-beam system and remove the problem altogether.

CONCLUSIONS

Objectives of the 1995-1998 split-beam and single-beam hydroacoustic experiments at Mission, B.C. were focused on the investigation of potential biases in the estimation of migratory salmon abundance based on the acoustic sampling by the downward looking single-beam sounder system. As the work progressed, it became evident that, in addition to those biases that resulted directly from the sampling limitations of the single-beam transducer, there existed another type of bias caused by the signal characteristics of fish echoes. This second type of bias can cause significant errors in duration-in-beam measurements. The digitisation of the single-beam echo data and subsequent processing of these data allowed us to examine characteristics of echo signals in great detail. The simultaneous monitoring of salmon targets by a split-beam sounder over the same section of the river provided opportunities to compare fish behaviour from the two systems. This report addresses the main concerns raised by the 1994 Fraser River Sockeye Public Review Board regarding fish behaviour (Report of the Fraser River Sockeye Public Review Board, 1995) and also examines the assumptions adopted in abundance estimations using the duration-in-beam
method. In addition, our work also identified measurement errors caused by characteristics of echo signals from fish. The findings have increased our understanding of hydroacoustic technologies in terms of estimating salmon abundance in a riverine environment. Yet, there are still many unknowns we need to investigate and understand. The study presented in this report by no means concludes our investigation, but it elevates our viewpoint for future studies. The following is a summary of the major findings that are most relevant to the original objectives.

1. The majority of targets observed during the migration move upstream. Downstream targets typically constitute less than 8% of the total daily estimate. Using formula (4) we estimated that a single-beam system might overestimate the upstream flux by about 9%.

2. There is evidence that the fish reacted to the survey vessel by altering their spatial distribution; however, there appears to be no effect on the number of targets seen by the vessel. The fixed-location side-looking system typically observes the same fish flux as the mobile downward-looking system for that portion of the river cross section monitored by both systems. Thus, at this time, we are led to the conclusion that the fish are diving towards the bottom as the survey vessel approaches, but they are not avoiding detection by the down-looking acoustic system. This conclusion may only hold for our experimental configurations where both the downward and side-looking systems insonified a near-shore area that was frequently (approximately once every 10 minutes) intruded by the survey vessel. The uncertainty of reaction of the near-shore fish to the survey vessel can be removed if shore-based, side-looking split-beam systems are implemented to sample these fish.

3. The down-looking acoustic system has reduced probability of fish detection in the near-shore area, when compared to the side-looking system.

4. There is some discrepancy in fish speeds between those obtained from the split-beam and those from the stationary vessel using the duration-in-beam method. If the survey vessel uses a split-beam system, this discrepancy is expected to be eliminated.

5. Swimming speed of fish (relative to the shore) varies between 0.5 ms^{-1} in early June during high discharge to 0.8 ms^{-1} in late August during lower discharge. Using the formula from

Banneheka et al. (1995) this is expected to result in a bias of from +5% to +13% for the fish density as observed from the survey vessel.

6. Switching to a combination of shore-based split-beam systems and a downward-looking mobile split-beam system should remove many of the biases currently associated with the standard hydroacoustic programme but will be complex to perform. This will require a higher level of personnel training and understanding to operate the field programme and analyse the data. Further development work is required if this plan is to be implemented.

REMAINING ISSUES AND FUTURE WORK

Down-Looking System Blind Zone Measurements

We need to measure the inherent acoustic blind zones for the down-looking acoustic systems. Figure 23 shows the geometrical boundaries of the blind zones associated with the downward-looking system. We can see that if fish are located very close to the bottom or surface then they will be invisible to the acoustic system. In general, the surface blind zone or 'near field effect' is known from calibration experiments but this may be somewhat different when the system operates in the acoustically noisy river environment. The bottom blind zone can vary according to the type of substrate, the size of the sound-beam and the angle at which the beam intersects the bottom. For these reasons, the blind zones need to be measured in the environment where the system is being used and then the amount of fish travelling in these blind zones needs to be determined. This is one reason why the side-looking split-beam system compliments the down-looking system as the side-looking system can cover the areas close to boundaries such as the bottom and surface.

Target experiments are planned to determine the blind zones for both the split-beam and single-beam systems used in the down-looking mode at this site. Targets will be positioned at various distances off the bottom and the transecting vessel will repeatedly pass over them while taking data with both systems simultaneously. By varying the target's distance off the bottom, we can determine how close to the bottom targets can be effectively detected with these systems.

Side-Looking Target near Bottom with Bottom Signal Interference

Side-looking acoustic systems also have zones of reduced detection that need to be measured. Figure 24 shows the reduced detection zones that can affect the side-looking acoustic count. We know that we are able to detect fish travelling through these zones as we see targets beyond the point at which the beam intersects the substrate. We do not know how reliably we can track fish through these zones. It may be that we cannot reliably track the fish in three dimensions in these zones but that we may be able to derive a count of the detected fish. Target experiments are planned to try and gain insight into this problem.

Ground Truth Experiments

Acoustic systems need to be tested for accuracy and precision. With our side-looking split-beam systems at Mission we need to perform tests to ground truth the acoustic system. In some instances this can be done in a clear water system with characteristics similar to the river of interest (Enzenhofer et al. 1998). The acoustic estimates can then be compared with another form of enumeration such as visual estimates so that the accuracy of the acoustic estimates can be evaluated. The problem with the Mission site is that the river is turbid, preventing any form of visual counting using visible light. The river is about 400 m wide and many fish are spread out across the width. The current is relatively slow and therefore fish are not forced to travel close to shore to conserve energy. It has proven impossible so far, to find a clear water river where we can enumerate large numbers of fish at long ranges to test the acoustic system.

There are other options available. One option is to install acoustic tags or ‘pingers’ into the fish and track them with both hydrophones and the acoustic system as they pass the site. By comparing the data from the two independent methods we can determine the accuracy of the acoustic system. Unfortunately, this method is cost prohibitive at this time.

Another method of determining the accuracy is to pass a known number of targets through the acoustic beam and then look at the acoustic count of those targets and compare the results with the known target passage. This type of experiment is possible and multiple target arrays can be made to simulate multiple fish passing through the acoustic beam. We can also adjust the distance between the targets in the array and determine the limits of acoustic detection for fish travelling close together.

Combining Side-Looking and Down-Looking Sampling Configurations to Estimate Fish Abundance

The blind zones identified by our work for both the downward-looking single-beam and the side-looking split-beam configurations indicate a need to combine these two sampling configurations to effectively cover the entire river width. While the downward-looking configuration provides better coverage of fish passage in the middle section of the river, the side-looking configuration is better for monitoring fish migrating in the near-shore areas. We emphasise that both configurations deteriorate in their fish detection performance at the river boundaries. It is anticipated that fish abundance will be estimated by a combination of acoustic systems operating from both shores and from a transecting vessel. The choice of the technologies for each of the acoustic monitoring components remains to be made and will be based on experiments and data analyses yet to be conducted. One important experiment to be performed is the operation of the down-looking split-beam system alongside of the single-beam system to see if the split-beam technology will address some of the currently identified biases.

TABLES

Table 1. 1998 data sets used for flux comparisons.

Date	Split-beam Estimate	Single-beam Estimate	Manual Estimate
July 05	198	139	139
July 12	366	208	240
July 24	412	334	399
August 03	5728	4084	4701
August 04	1387	1585	1540
August 09	1711	1866	2131
August 12	2699	1707	2184
August 18	3531	3758	3634
August 26	508	510	579
September 03	283	644	711
September 17	2515	3133	2154
September 18	301	502	516
Total	19,639	18,470	18,928

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