Implementation of Stationary Hydroacoustic Sampling Systems to Estimate Salmon Passage in the Lower Fraser River: *A final project report to the southern boundary restoration and enhancement fund*

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ABSTRACT

Stationary sampling methods were implemented to estimate daily salmon influx in the 2008-2012 field seasons at the Pacific Salmon Commission's Mission hydroacoustic site (Xie et al. 2007, 2008, 2010, 2011, 2012). The research and field work leading to the implementation of the methods were funded by the Southern Boundary Restoration and Enhancement Fund (SEF). The ultimate goal of the project is to develop a hydroacoustic sampling system with multiple stationary sub-sampling components extending from both shores to accurately estimate salmon passages in extended near-shore areas of the river. With the existing left-bank side-looking split-beam sonar, these multiple stationary sub-sampling systems can sample a total of 120-m cross-river range from the shorelines (80m from the left bank and 40m from the right bank). Historically, these near-shore areas accommodate 70% of sockeye and nearly 90% of pink salmon migrations past Mission. This report presents key results and major findings from the field programs in the 2010, 2011 and 2012 seasons through a SEF funded 2-year project. The daily salmon passage produced by the proposed sampling system was compared with daily salmon passage estimated at Department of Fisheries and Oceans hydroacoustic site at Qualark Creek (95km upstream of Mission). The study provides quantitative analyses and results from the data to assess the following 4 aspects of the sampling system:

1. Accuracy of Mission sockeye estimate relative to Qualark sockeye estimate;
2. Accuracy of Mission pink salmon estimates relative to marine test-fishing estimates;
3. Estimation accuracy vs. program costs;
4. Precision of Mission estimates.

This document is a final report to SEF for this 2-year project.

Key words: hydroacoustics, estimation, DIDSON, split-beam, sampling effort, accuracy, precision, mixture model, sockeye, pink salmon, Mission, Qualark, lower Fraser River

INTRODUCTION

Background

The Pacific Salmon Commission (PSC) conducts a hydroacoustic program near Mission B.C. on the Fraser River to estimate the daily influx of adult sockeye and pink salmon to the lower river as the fish head for their spawning tributaries. The near-shore salmon flux off the left bank is estimated from a shore-based, side-looking split-beam sonar system over ranges up to 80m from the left bank. Fish migrating in offshore water and in near-shore area off the right bank of the river are surveyed by a downward looking transducer from a moving vessel that transects the river. The offshore salmon flux is estimated via a density based flux model that assumes (1) uniform fish behaviour across the river (Xie et al. 2005) and, (2) fish do not avoid the mobile survey vessel. Studies in recent years have shown that fish can behave differently across the river due to the inhomogeneous flow field and tidal influence (Xie et al. 2010). Fish were also observed avoiding the survey vessel within a 4-m range from the propeller (Xie et al. 2008). The violation of the two basic assumptions can bias estimates of offshore and right-bank fish flux.

To improve the accuracy and precision of salmon flux estimation in the offshore area, a stationary sub-sampling method was tested during the 2008-2010 field seasons with funding from the Southern Boundary Restoration and Enhancement Fund (SEF). The findings and results from the 2008-2010 sampling seasons concluded that the strong and varying currents in the mid-channel posted severe challenges for vessel-based stationary acoustic sampling (Xie et al 2010, 2011). Upon reviewing the findings from the 2008-2010 sampling seasons, the PSC hydroacoustics group proposed a sampling strategy (Xie et al 2012) that would extend sampling capacity of the shore-based sonar systems from both banks towards offshore water while still leaving the mid-channel fish flux being sampled by the transecting vessel with an upgraded split-beam system of enhanced target recognition. The SEF committee approved the funding for a 2-year project for the 2011 and 2012 seasons to test this sampling strategy.

Project goal and objectives of the 2-year program

The goal of this project is:

Developing and implementing a robust and cost-effective sampling system that provides accurate estimation of total salmon flux with shore-based and bottom-mounted side-looking and side-scanning sonar at the Mission hydroacoustic site.

To achieve this goal, we set out 3 objectives for the 2011 and 2012 field programs:

1. assess the improvement of estimation accuracy of total salmon passage by the proposed sampling system during times when migration is dominated by sockeye or pink salmon;
2. explore the potential use of Qualark estimates (funded by SEF in the 2011 and 2012 seasons) to assess bias in the Mission estimate;
3. assess the cost and benefit of the proposed sampling system for in-season use.

Preliminary findings from the 2011 sampling season are presented in Xie et al (2012). In this final report, we present key findings and analyses from the 2010, 2011 and 2012 data related to the 3 objectives.

MATERIALS AND METHODS

Study site

The PSC Mission hydroacoustic station is located 80 km upstream from the mouth of the Fraser River (Figure 1). The maximum wet-width of the river at the site is approximately 450 metres during freshet in early summer. The maximum water depth varies from approximately 18 m in June during high run-off to 12 m in October at low discharge. The river flow is influenced by tides. During extreme high tides the river may occasionally reverse its flow. The flow field is non-uniform with stronger currents occurring in the deepest channel near the right bank (see Figs. 1 and 4 in Xie, et al. 2010). The turbid water prevents visual detection and counting of fish passage. Figure 2 is a site photo taken from the left bank.
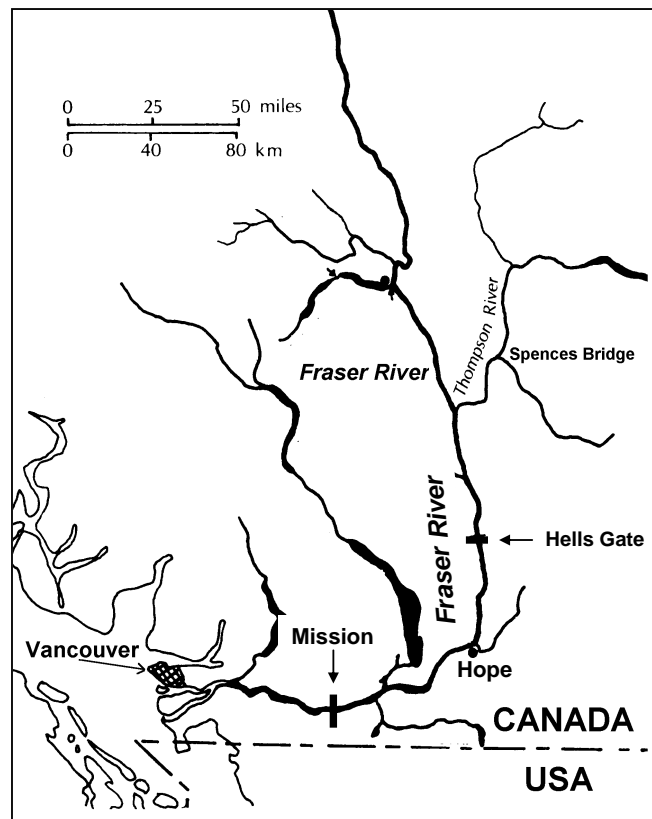
Figure 1. Site map of the PSC Mission hydroacoustic station.

Figure 2. A left-bank view of the PSC Mission hydroacoustic site. The iron dolphin, located at $49^o08.175$'N; $122^o16.466$'W, is the geographic reference for positioning all sampling apparatus for the field program at the site. Also shown are the mobile survey vessel and a fish-deflection weir (approximately 35 metres in length) on the left bank. The weir prevents fish from swimming behind the sonar beams.

Sampling method

In addition to the left-bank HTI split-beam system (http://www.htisonar.com), we deployed 3 to 4 shore-based and bottom-mounted side-looking DIDSON imaging sonar units (http://www.soundmetrics.com/) on both banks to enumerate near-shore fish passages using hourly systematic sampling method. We also installed a DT-X sounder (http://www.biosonicsinc.com) on the transecting vessel to gain better performances on the detection and identification of fish targets in offshore water. The DT-X system provided not only the single-target detection data but also the raw echo data, thus allowing operators to better discern fish targets. Figure 3 is a schematic illustration of deployment locations and sampling geometry of the 2 split-beam systems and the 4 DIDSON imaging sonar units. The 6 sonar systems were implemented in the field programs for the 2011 and 2012 seasons with the exception that D_4 was deployed from the vessel in the 2012 season to collect offshore fish behaviour data during stationary soundings. This sampling design provides a larger

sampling capacity than the current system for the total salmon flux at Mission which show skewed distributions towards near-shore waters (see Appendix 5).
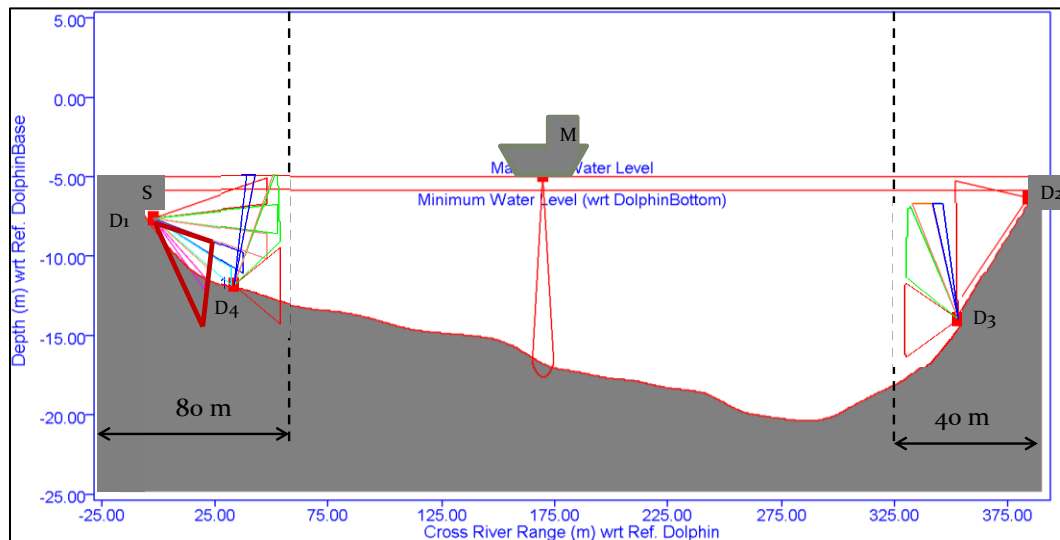
Figure 3. Deployment locations and sampling geometry of left-bank (S) and mobile (M) split-beam systems and 4 DIDSON imaging sonar units (D_1, D_2, D_3, D_4). The 6 sonar units constitute the proposed sampling system. D_4 was deployed from the vessel for stationary sounding of offshore fish behaviour in the 2012 season.

Lists of key equipment and sampling schedules and data acquisition parameters for all sonar systems are given in the Appendix section. Also included in the Appendix is a special sampling method to use a scanning DIDSON system to sample fish passages from the left bank for the high water period in July 2012.

Assessment method of accuracy of Mission sockeye estimates

Lacking independent estimates for in-season comparisons, the Qualark estimate of salmon flux (Enzenhofer et al 2010) is the only data source that allows for qualitative, or under some special scenarios, semi-quantitative time series analyses to assess the accuracy of Mission estimate relative to Qualark estimate. In Xie et al (2012), we reported time series analyses of temporal patterns of total salmon migration profiles estimated at the 2 sites. However, there are biological and fisheries factors that can divert passages of sockeye salmon at the 2 sites. These are:

1. sockeye stocks that pass Mission but spawn below Qualark; most notably are the Harrison, Weaver, Birkenhead, Cultus and Chilliwack stocks,
2. fisheries removals between the 2 sites, and on-route mortality from Mission to Qualark.

In this study, we use Mission-projected Qualark sockeye estimates to assess accuracy of Mission estimates. The projection was done by removing below-Qualark stocks (based on PSC in-river test fishing data) and in-river fisheries catches between Mission and Qualark (based on DFO catch reports) from Mission estimated total

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sockeye. The method also assumes a 2-day travel time for early summer and summer run sockeye to reach Qualark from Mission whereas for late-run sockeye or pink salmon a travel time of 3 days is used. From the estimation data collected in 5 sockeye return seasons from 2008-2012 when the hydroacoustic facilities at both Mission and Qualark were operating simultaneously, we select 3 datasets to assess hydroacoustic biases in the Mission estimator. The 3 datasets reflect 3 unique sockeye return scenarios to the lower river. These are:

1. Lower run size in non-pink years with a moderate portion (<40%) spawning below Qualark (2012),
2. Lower run size in pink return years with a large portion (~50%) spawning below Qualark (2011), and
3. Large run size in non-pink years with a large portion migrating through both sites (2010).

The deviation between the two estimates is gauged by *R*: the 3-day averaged ratio of Qualark estimated sockeye (*Q_Sox*) to Mission-projected Qualark sockeye (*MpQ_Sox*):

$$R = \frac{Q\_Sox}{MpQ\_Sox}. \qquad (1)$$

Assessment method of accuracy of Mission pink salmon estimates

The accuracy of Mission estimates during pink salmon dominated migration periods is gauged by R_{pink}: the seasonal ratio of marine test-fishing based run-size estimate (*TF_Pink*) to Mission-hydroacoustics based run-size estimate (*MH_Pink*):

$$R_{pink} = \frac{TF\_Pink}{MH\_Pink}. \qquad (2)$$

Assessment of accuracy vs. program cost for sockeye salmon

With the parallel datasets from both sites, we can assess accuracy improvements of Mission estimates relative to Qualark estimates as we increase sampling capacities. This assessment is conditioned on the method PSC used to convert hydroacoustically estimated total salmon at Mission to project Qualark total sockeye as described before. We attempt to answer a question:

What is the relationship between improved accuracy in the estimate and the associated program cost for PSC Mission hydroacoustic program?

The basic variables we use to quantify such relationships are the seasonal Mission-projected Qualark sockeye (*Total_MpQ_Sox*) and Qualark estimated sockeye (*Total_Q_Sox*). Using the two variables we define a *percent relative difference* (*PRD*) to gauge the accuracy of Mission estimates:

$$PRD = 100 \times \frac{(Total\_MpQ\_Sox) - (Total\_Q\_Sox)}{(Total\_Q\_Sox)} \qquad (3)$$

We estimate the dependency of *PRD* on the number of deployed sonar systems and the corresponding daily operating and capital costs. The operating cost includes salaries for in-season staff, travel, contractual services and materials and supplies; the daily capital cost is estimated from the total purchase costs of the sonar systems divided by the expected life span of the equipment (in days). Our current budget practice is to project the costs for full replacement amounts in the year that the equipment is due for life cycle replacement. We suggest that setting aside annual amounts for capital replacement is worth consideration in the future. It should also be mentioned that the values used for the daily operating cost are based on both our regular budget as well as funding we have received from the SEF.

Assessment of accuracy vs. program cost for pink salmon

For pink salmon, we use the marine test-fishing based run-size estimate (*TF_Pink*) and Mission-hydroacoustics based run-size estimate (*MH_Pink*) to define a *PRD* to gauge the accuracy of Mission estimates for pink salmon:

$$PRD = 100 \times \frac{(MH\_Pink) - (TF\_Pink)}{(TF\_Pink)} \qquad (4)$$

Precisions of hydroacoustic estimates by the shore-based sonar systems

The precision of estimated daily fish passage by the mobile sampling method is estimated at 4% in terms of coefficient of variance by Banneheka, et al (1995). Since we adopted the left-bank split-beam system in the 2004 season, we only use the vessel-based mobile system to estimate less than 50% of the total salmon flux across the river (see Appendix 5). With the majority of the total flux being estimated by the shore-based counting systems, it is important that we estimate the precision of the shore-based sampling system. For this purpose, we selected left-bank DIDSON fish counts from 5 distinctive daily sockeye migration scenarios in the 2010 season for the evaluation analysis. We also examined the relation between precision and sampling fractions for the hourly systematic sampling as we increase the hourly sampling time from 5 to 10, 15, 20 and 30 minutes, respectively. The detailed analyses and methods are presented in Appendix 6.

Using DIDSON length data to partition salmon and non-salmon species

Apart from migrating salmon, the lower Fraser River hosts many small resident fish. The standard DIDSON operating at 1.8-MHz is able to identify fish as small as 5 cm at 10-m range. Visually discounting small non-salmon sized fish during the counting of individual fish images adds extra workloads and in some cases presents challenges for the readers. Since the size distribution of non-salmon fish targets partially overlaps with that of salmon targets, it is difficult, if not impossible, to reliably classify individual fish based on length only. Our approach is to count all fish targets in the DIDSON files regardless of their sizes and then take a subsample of counted fish to measure their lengths. With the length data we partition the count into salmon and non-salmon targets by using a mixture model on the length data. For confirmation purposes, we implemented under statistical package *R* (http://www.r-project.org/) both a maximum likelihood version and a Bayesian version of the model to interpret the DIDSON length data. Detailed descriptions and applications of the mixture model are presented in Appendix 7.

RESULTS

We present findings and analyses directly related to the 3 objectives for this project.

Comparisons of Mission-projected sockeye and Qualark estimated sockeye

The following results are derived from hydroacoustic estimates of total salmon and biological partitioning of the estimates into individual species and stocks. While the in-season sampling system at Mission for 2010 consisted of only 2 sub-systems of left-bank split-beam and mobile split-beam systems, the sampling system for the 2011 and 2012 seasons included a right-bank near-shore DIDSON system.

Mission projection vs. Qualark estimate for the 2012 season

The 2012 season is a low-return year of the Fraser River sockeye. A total of 1,778,000 salmon were estimated past Mission from July 11 to August 24, and according to PSC test-fishing catch data at Whonnock, 1,600,000 of these fish were assigned as sockeye salmon. Using the catch data and in-river catch reports between Mission and Qualark, PSC produced the Mission-projected Qualark sockeye daily passage time series throughout the season. By the end of the season, PSC projected a total of 983,758 sockeye had passed Qualark while Qualark estimated a total of 952,736 sockeye passed the site. Figure 4 shows the comparison plots of the two time series.

Figure 4. Mission-projected Qualark sockeye vs. Qualark estimated sockeye for the 2012 season. Also shown is the hydroacoustically estimated total salmon at Mission.

The seasonal comparison appears to support the hypothesis that the Mission estimator performed similarly to the Qualark estimator for the 2012 season even though PSC biological interpretations removed 631,000 fish as below-Qualark stocks from the 1,600,000 Mission sockeye to produce the projection. However, the Mission projection of Qualark sockeye time series derived from simple subtractions of below-Qualark stocks and in-river catches tends to maintain the same phase structure as that of hydroacoustically estimated Mission total salmon (see the red vs. blue line plots in Figure 4). The PSC projection method cannot project the actual phase of sockeye migration profile at Qualark (see the blue vs. pink line plots in Figure 4). As a result, the comparison is not very informative for assessing the in-season performance of either estimators on a daily or even a weekly basis. Figure 5 shows the oscillatory behaviour of R as defined by Formula (1). Due to phase difference between Q_Sox and MpQ_Sox, the 3-day averaged ratio R peaks at troughs of MpQ_Sox. This could create a false impression on a short time scale of say, 3-5 days, that Mission estimator is biased either high or low in comparison to Qualark. On the seasonal basis, however, R shows a mean of 0.99 for the entire season of 2012.
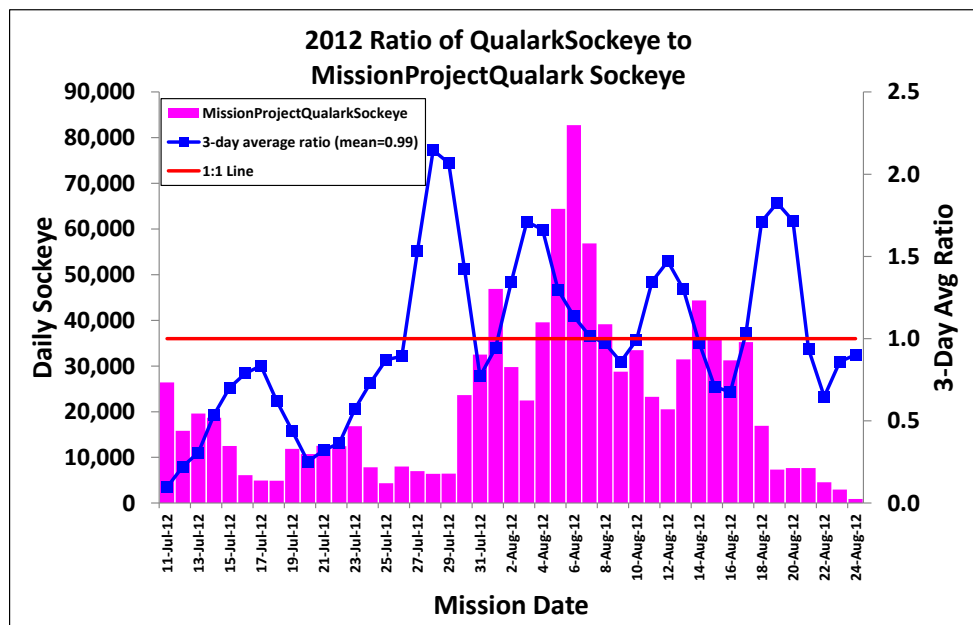
Figure 5. The 3-day ratio R of Qualark estimated sockeye to Mission-project sockeye for the 2012 season. The ratio oscillates as a result of phase difference between the 2 time series.

Mission projection vs. Qualark estimate for the 2011 season

The 2011 season is another low-return year of the Fraser River sockeye followed by a large return of pink salmon in September. To avoid a potentially large impact on sockeye estimates due to species composition error between sockeye and pink salmon, we used the data up to August 25 for the comparison. A total of 2,970,000

salmon were estimated past Mission from July 21 to August 25, and 2,150,000 were assigned as sockeye with the remainders being assigned as Chinook and pink salmon. For this time period, the PSC projected a total of 1,100,000 sockeye had passed Qualark while Qualark estimated a total of 1,333,000 sockeye. Figure 6 shows the comparison plots of the two time series.
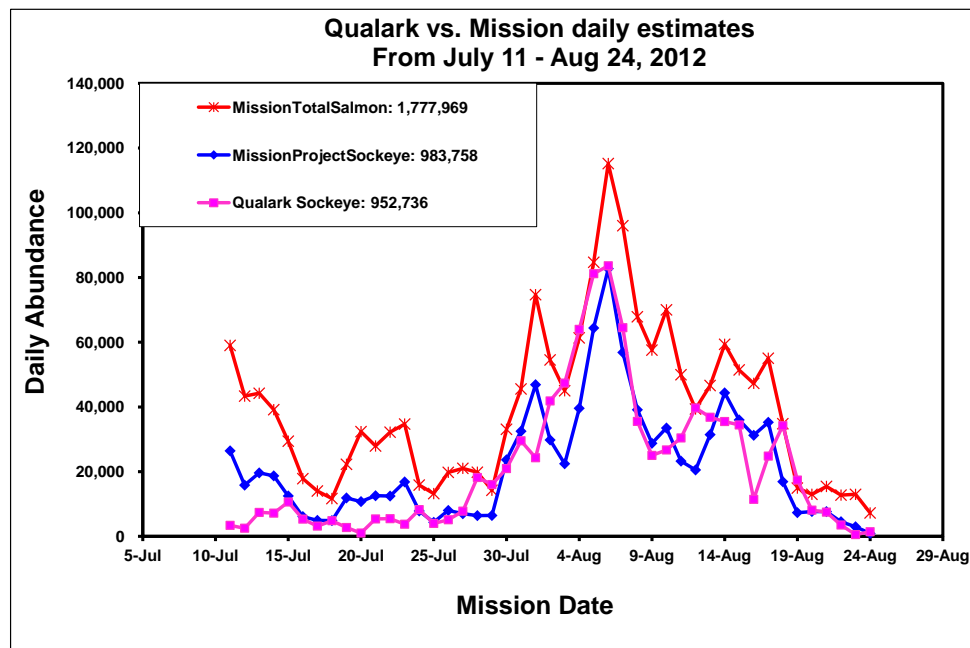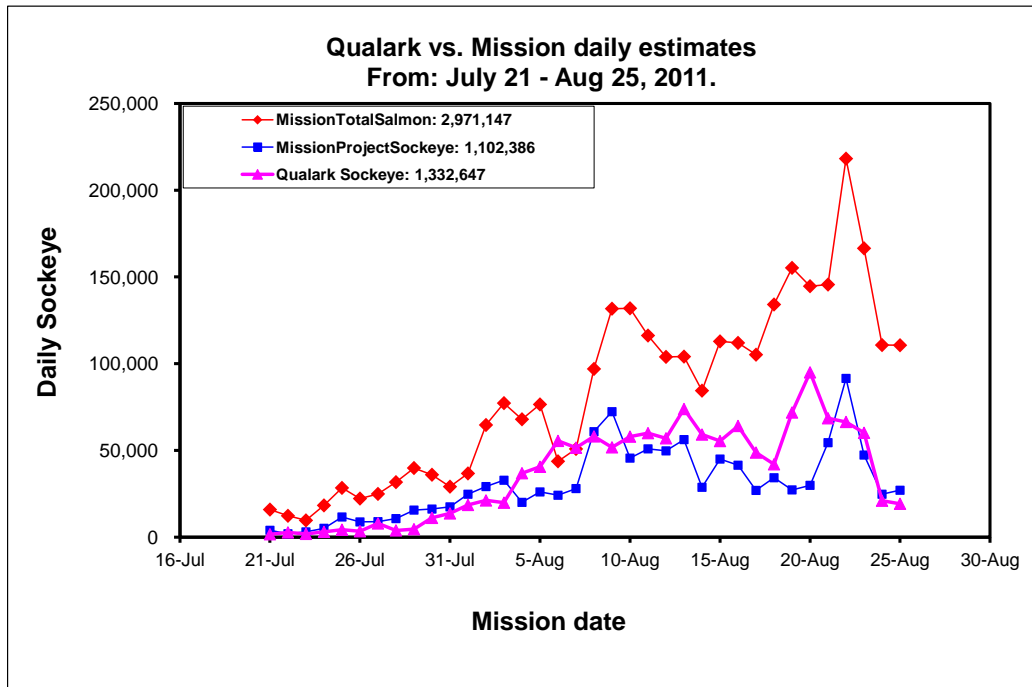

Figure 6. Mission-projected Qualark sockeye vs. Qualark estimated sockeye for 2011 season. Also shown is the hydroacoustically estimated total salmon at Mission.

The seasonal comparison indicated that the Mission estimate was 17% lower than the Qualark estimate. But this difference cannot be attributed solely to the hydroacoustic errors in the Mission estimator as the PSC biological interpretations removed 1,050,000 below-Qualark stocks from the 2,150,000 Mission sockeye to produce the projection. The estimated 1,050,000 below-Qualark stocks account for 50% of the total sockeye past Mission. These stocks mainly comprise of the Harrison, Weaver, Birkenhead, Cultus and Chillwack sockeye with the Harrison stock accounting for a very large component of the sockeye run in the 2011 season. Errors in the estimation of below-Qualark stocks from the test-fishing data could cause a large error in the projection of Qualark sockeye for migration scenarios encountered in the 2011 season when a large portion of the total sockeye return do not reach Qualark. This analysis demonstrates that for migration scenarios similar to the 2011 season, Qualark estimates are not very informative for assessing accuracy of Mission hydroacoustic estimates due to the large portion of below-Qualark stocks.

Mission projection vs. Qualark estimate for the 2010 season

The 2010 season saw a record return of approximately 28 million Fraser River sockeye since 1913. The run was dominated by the late timing group heading for the Adams River with more than 7 million fish arriving at the spawning tributaries. Since the abundant late-run fish migrated past both Mission and Qualark, Qualark estimates are informative for assessing potential biases in Mission hydroacoustic estimates for the 2010 migration scenario. A total of 13.6 million salmon were estimated past Mission from July 18 to October 3, and 12.8 million of these fish were assigned as sockeye. From the 12.8 million estimated sockeye at Mission, PSC projected a total of 11 million sockeye past Qualark while Qualark estimated a total of nearly 14 million sockeye. Figure 7 shows the comparison plots of the two time series.
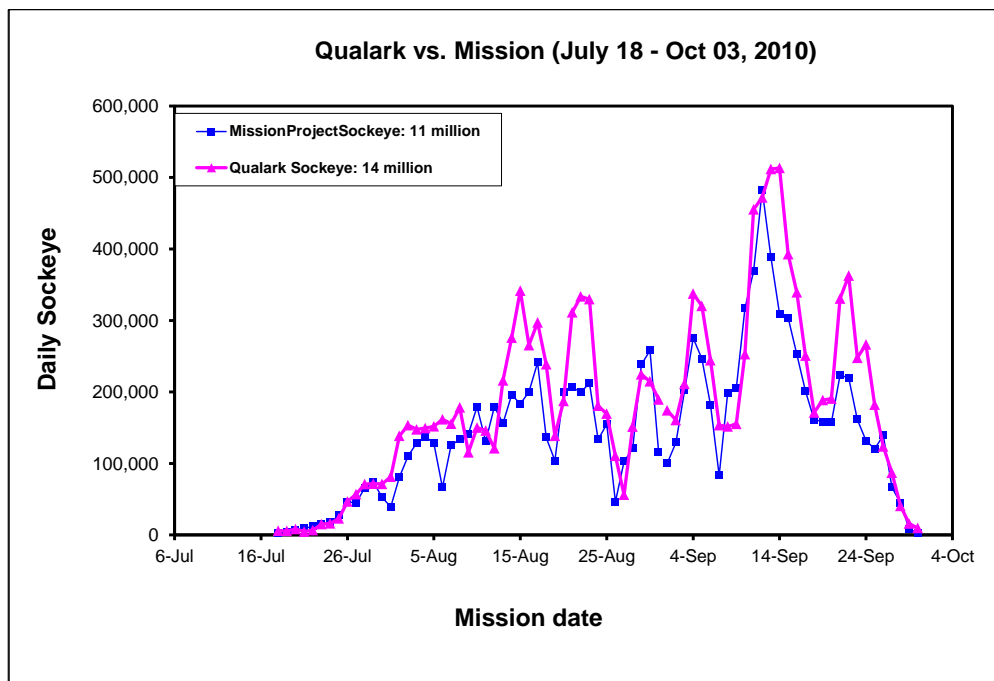
Figure 7. In-season Mission-projected Qualark sockeye vs. Qualark estimated sockeye for the 2010 season.

The seasonal comparison indicated that the Mission in-season estimate was 21% lower than the Qualark estimate for 2010 season. The 3-day averaged ratio of Qualark estimated sockeye to Mission-projected Qualark sockeye also confirms a directional derivation between the 2 estimates (Figure 8). The post-season analysis with the right-bank DIDSON fish counts indicated a portion of the near-shore migration off the right bank was missed by the downward looking mobile split-beam system. With the right-bank DIDSON counts adding to the estimate, Mission would have projected a total of 12.2 million sockeye past Qualark in 2010 season resulting in a relative difference of 13%.
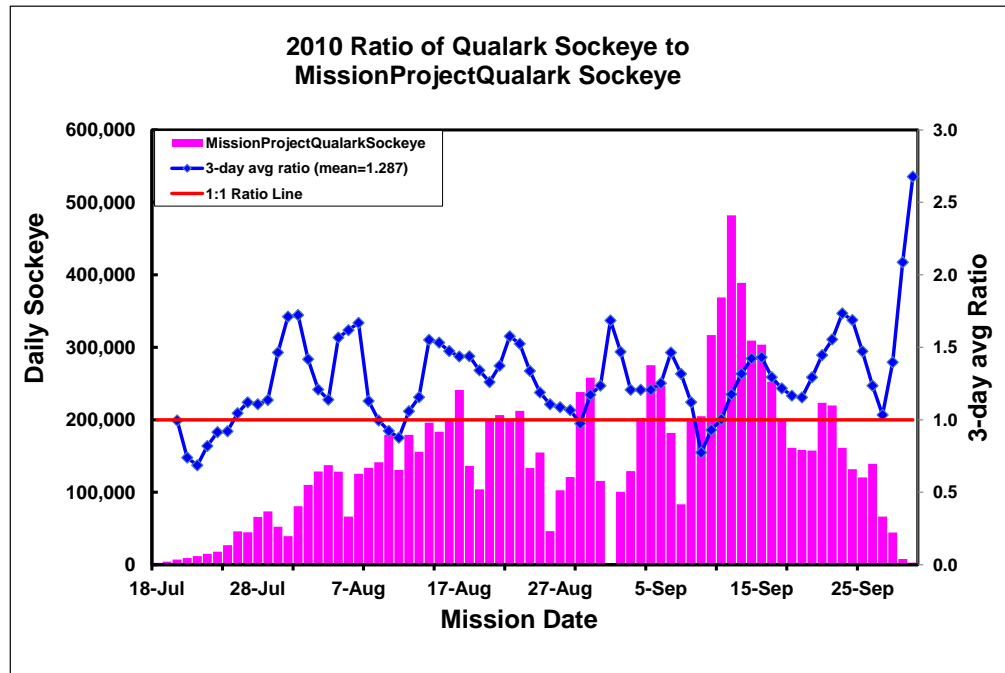
**Figure 8.** The 3-day ratio of Qualark estimated sockeye to Mission-projected sockeye for 2010 season. Mission projection is significantly lower than Qualark estimate. The ratio oscillates as a result of phase difference between the 2 time series.

Accuracy versus program costs for sockeye migration scenarios

Accuracy vs. cost for the 2010 scenario (large runs through both sites)

In the 2010 season, we deployed 2 DIDSON units off the right bank to increase the sampling capacities of salmon migration near the right bank. Since the 2 units were deployed in separate monitoring periods of the season, we present in the following relationship assessments of accuracy vs. program cost conditioned by the availability of the sonar units.

Period 1: August 01-31, 2010

This is the period when the migration was dominated by early-summer and summer run sockeye. Figure 9 shows the relation of cost vs. accuracy (*PRD*) for this period.
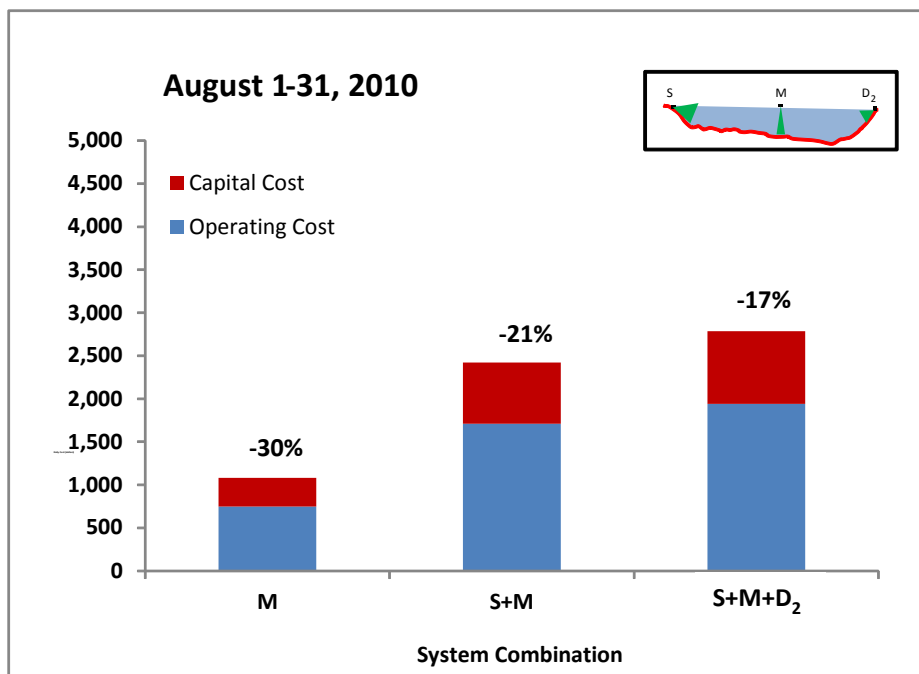
Figure 9. Daily program cost vs. system combinations and corresponding estimation accuracy in *PRD* (numerically labelled on tops of the bar plots) for Aug 01-31, 2010. The inset schematically shows the locations and sampling areas of individual sonar units across the river (*S*: left-bank split-beam; *M*: Mobile split-beam; D_2: right-bank inshore DIDSON).

The relation shows a small benefit of adding the right-bank inshore DIDSON (D_2) to the sampling system for this time period. An accuracy gain of 4% was achieved with an increase in daily cost to $2,787 from the cost of $2,422 for the *S+M* estimator.

Period 2: September 01-12, 2010

Period 2 saw the primary migration peak of the late-run sockeye on September 12 with a daily abundance of 509,000 sockeye past Mission. Figure 10 shows the relation of cost vs. accuracy for this period when the migration was dominated by late-run sockeye.

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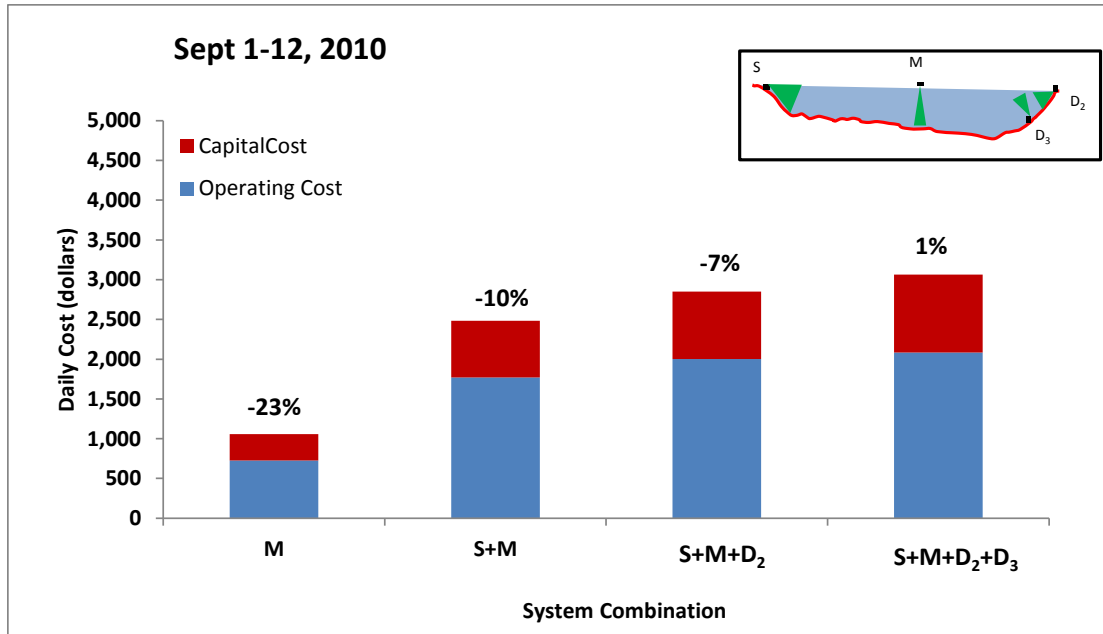
Figure 10. Daily program cost vs. system combinations and corresponding estimation accuracy in *PRD* for September 01-12, 2010. The inset schematically shows the locations and sampling areas of individual sonar units across the river (*S*: left-bank split-beam; *M*: Mobile split-beam; D_2: right-bank inshore DIDSON; D_3: right-bank offshore DIDSON).

The relation shows a large benefit of adding the right-bank offshore DIDSON (D_3) to the sampling system for this time period. A gain of 8% was achieved with a small increase of daily cost to $3,064 from the cost of $2,849 for the $S+M+D_2$ estimator. On the contrary, the inshore DIDSON (D_2) only contributed to a 3% gain with an increase of cost to $2,849 from $2,483 for the $S+M$ estimator. This is likely a result of fewer fish migrating in the near-shore water off the right bank in this time period.

Period 3: September 13 - October 03, 2010

This period saw the last migration peak of the late-run sockeye on September 21 with a daily abundance of 311,000 sockeye past Mission. Figure 11 shows the accuracy vs. cost relation for this period when the migration was dominated by the late-run sockeye.

Figure 11. Daily program cost vs. system combinations and corresponding estimation accuracy in *PRD* for September 13-October 03, 2010. For definitions of all legends, refer to Fig. 10.

The relation shows a large benefit of adding the right-bank offshore DIDSON (D_3) to the sampling system. An accuracy gain of 15% was achieved with an increase in daily cost to $2,926 from the cost of $2,483 for the *S+M* estimator. However, lacking the right-bank inshore DIDSON (D_2) for this period of time may have caused an undercounting of the near-shore migration off the right bank.

Accuracy vs. cost for the 2011 scenario (small runs and large portion of below-Qualark stocks)

Figure 12 shows the accuracy vs. cost relation for August 12-25, 2011 when the migration was dominated by summer-run sockeye.
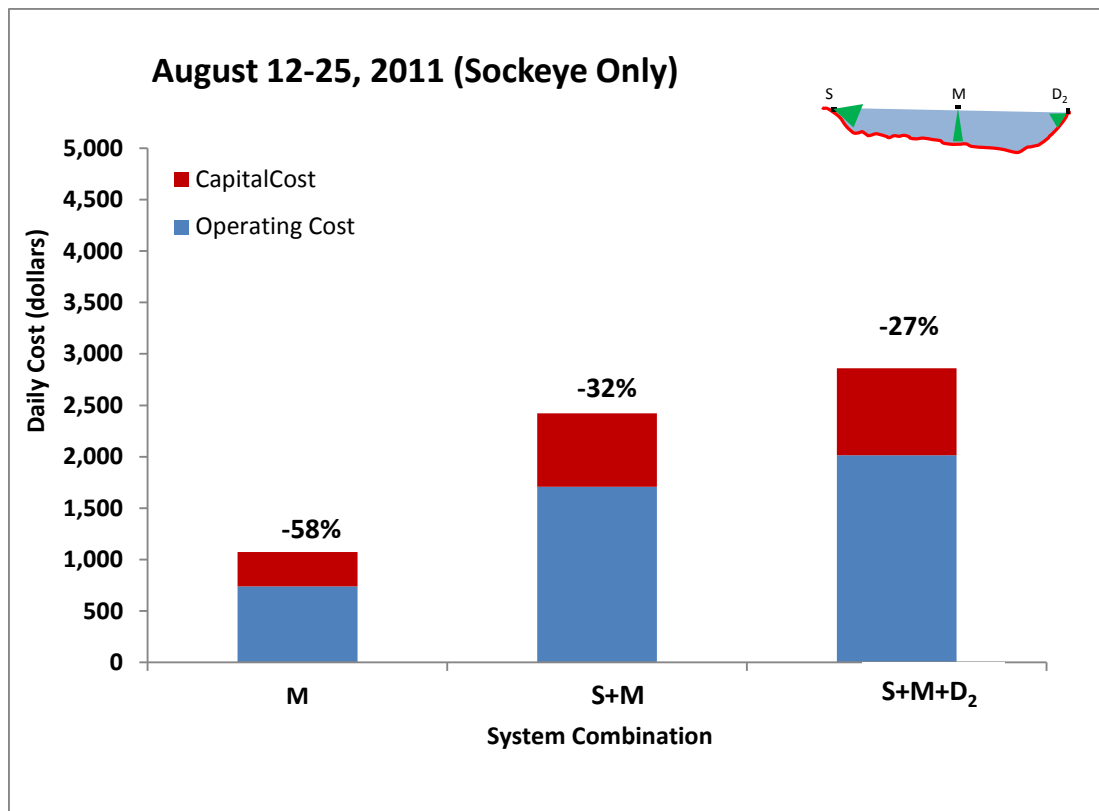
Figure 12. Daily program cost vs. system combinations and corresponding estimation accuracy in *PRD* for August 12-25, 2011. For definitions of all legends, refer to Fig. 10.

The relation shows only a 5% gain in accuracy by adding a right-bank inshore DIDSON (D_2) to the sampling system with an increase of daily cost to \$2,861 from the cost of \$2,421 for the *S+M* estimator. This is likely a result of fewer fish migrating in the near-shore water off the right bank in this time period. Even with the *S+M+D_2* estimator, a large difference of 27% remains between Mission-projected Qualark sockeye and Qualark estimated sockeye. Some of this large difference may have been caused by the species and stock identification errors at Mission. These non-hydroacoustic errors can have a big impact on the total estimation error for a small run size with a large proportion of below-Qualark stocks as encountered in the 2011 season.

Accuracy vs. cost for the 2012 scenario (small runs and small portion of below-Qualark stocks)

Figure 13 shows the relation of accuracy vs. cost for August 08-24, 2012 when the migration was dominated by early summer and summer run sockeye.
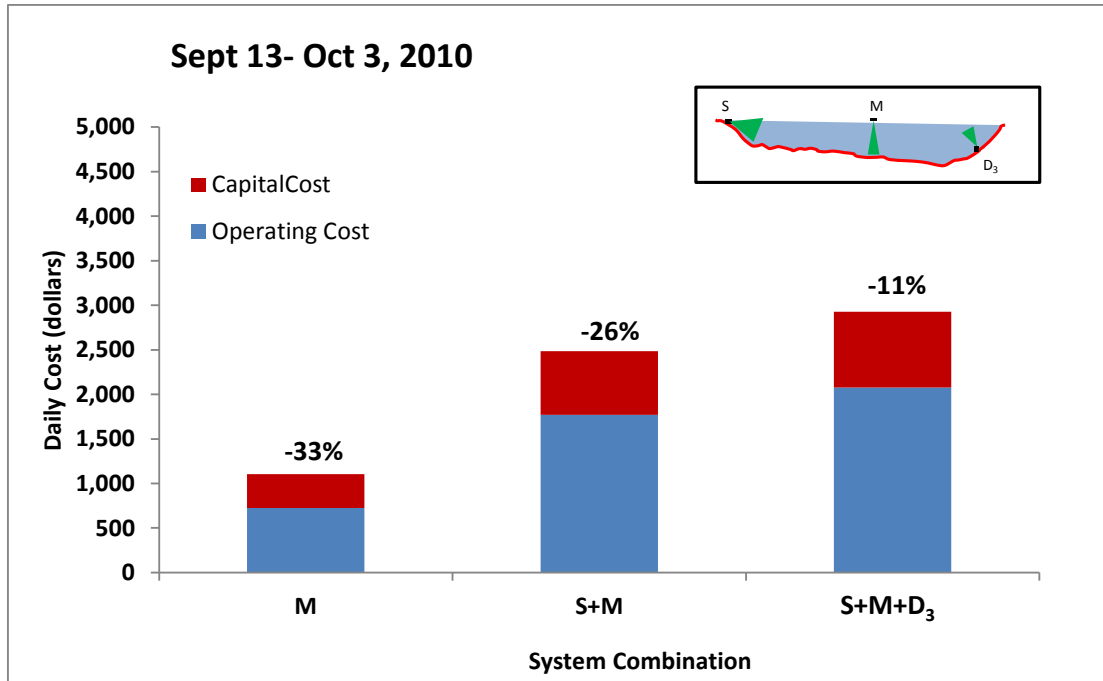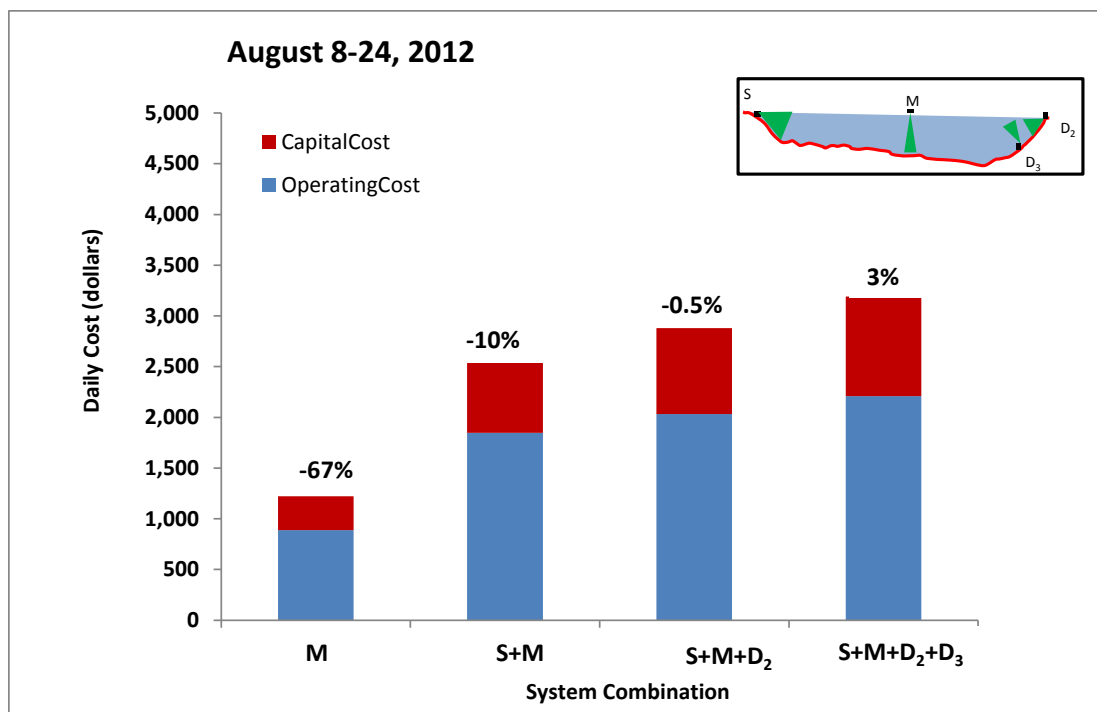
Figure 13. Daily program cost vs. system combinations and corresponding estimation accuracy in *PRD* for August 08-24, 2012. For definitions of all legends, refer to Fig. 10.

The relation shows a large benefit of adding the right-bank inshore DIDSON (D_2) to the sampling system. An accuracy gain of 9.5% was achieved with a small increase of daily cost to $2,880 from the cost of $2,562 for the *S+M* estimator. On the contrary, the offshore DIDSON (D_3) only contributed to a 3.5% gain with an increase in cost to $3192 from $2,880 for the *S+M+D$_2$* estimator. This is likely a result of fewer fish migrating in the offshore water of the right bank during this time period.

The numerical values of accuracy vs. program costs shown in Figures 9-13 are summarized in Table 1.

Table 1. Summary of accuracy vs. program cost relations for 2010, 2011 and 2012 sockeye migration scenarios. Presented are percent relative difference (PRD) (w.r.t Qualark estimated sockeye) and daily operating cost for different system combinations. NA: the specified combination not available.

Year	System Date	Combinations of Systems		M		S+M		S+M+D$_3$		S+M+D$_2$		S+M+D$_3$+D$_2$	
2010	Aug 01-31			-30%	1,081	-21%	2,422	NA	NA	-1%	2,787	NA	NA
	Sept 01-12	*PRD*	Daily Cost ($)	-23%	1,058	-10%	2,483	-3%	2,850	-7%	2,849	1%	3,064
	Sept 13-Oct 03			-33%	1,106	-26%	2,483	-11%	2,925	NA	NA	NA	NA
2011	Aug 12-25			-58%	1,074	-32%	2,421	NA	NA	-27%	2,861	NA	NA
2012	Aug 08-24			-67%	1,221	-10%	2,562	-5%	2,881	-0.5%	2,880	3%	3,192

Accuracy versus program costs for pink salmon in the 2011 season

Using marine test-fishing based pink salmon run size of 18.3 million for the 2011 season, we estimate the dependency of *PRD* on the number of deployed sonar systems and the associated daily operating cost. Figure 14 shows the accuracy of pink salmon estimation vs. program cost for the 2011 season. The migration was dominated by large pink returns in the month of September. Xie and et al. (2012) provide a detailed description of using a combined split-beam and DIDSON sampling system to enumerate pink salmon passages at Mission.
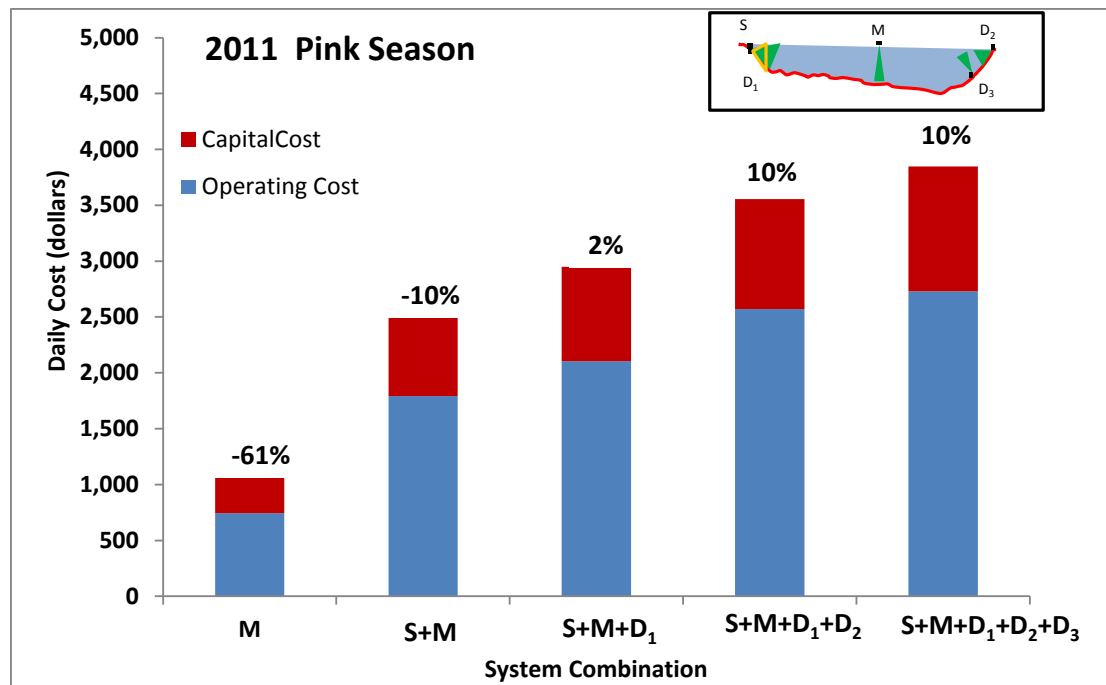
Figure 14. Daily program cost vs. system combinations and corresponding estimation difference in *PRD* of hydroacoustically estimated pink run size relative to the marine test-fishing based run-size estimate for the 2011 season. D_1: left-bank inshore DIDSON. For definitions of all other legends, refer to Fig. 10.

The numerical values of accuracy vs. program costs shown in Fig. 14 are summarized in Table 2.

Table 2. Summary of accuracy vs. program cost relations for the 2011 pink salmon migration scenario. Presented are percent relative difference (w.r.t marine test-fishing based pink estimate) and daily operating cost for different system combinations.

Time Period	Combinations of Systems		M		S+M		S+M+D_1		S+M+D_1+D_2		S+M+D_1+D_2+D_3	
Aug 8-Sept 27	PRD	Daily Cost ($)	-61%	1,077	-10%	2,506	2%	3,174	10%	3,554	10%	3,848

The relation shows a large benefit of adding the left-bank inshore DIDSON (D_1) to the sampling system for pink salmon. A gain of 12% was achieved with an increase of daily cost to $3,174 from the cost of $2,506 for the *S+M* estimator. Adding the right-bank inshore DIDSON (D_2) further increases the gain by 8% but the right-bank

offshore DIDSON (D_3) detected little passage of the pink salmon. This is a result of the majority (90%) of pink salmon migration taking place in near-shore waters off both banks. The hydroacoustic estimator $S+M+D_1+D_2$ estimated 10% more pink salmon than the marine test-fishing based estimator for the 2011 season (20 million vs. 18.3 million). Coefficient of variance (*CV*) of the hydroacoustic estimate is approximately 6% (see Appendix 6) whereas *CV* of the test-fishing estimate can be as high as 45%.

Precisions of hydroacoustic estimates by the shore-based sonar systems

We selected 5 days of left-bank DIDSON full counts from the 2010 season for the evaluation analysis. We also examined the relation between precision and sampling fractions for the hourly systematic sampling as we increase the hourly sampling time from 5 to 10, 15, 20 and 30 minutes, respectively. The detailed analyses and methods are presented in Appendix 6. Figure 15 shows *precision* versus *sampling fraction* relations for the systematic sampling method derived from the 5 DIDSON full-count data.
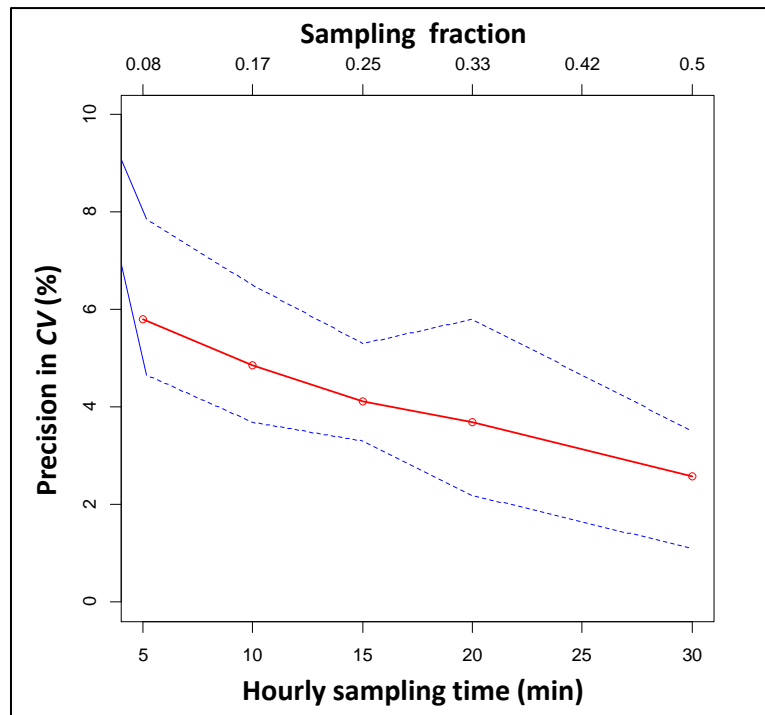
Figure15. Plots of precision vs. sampling fraction for hourly systematic sampling. The relation (in red) is averaged from samplings of the full-count left-bank DIDSON data acquired on August 17, 18, 19, 21 and September 25, 2010. The blue dashed lines are the maximum and minimum lines of the relation observed from the 5 datasets.

Listed in Table 3 are the numerical values of the precision (in *CV*) vs. sampling fraction relations shown in Figure 15.

Table 3. Precision (in *CV*) vs. sampling fraction for hourly stratified systematic sampling derived from the 5 full-count datasets. The underlined values show scenarios where precision of systematic sampling does not improve with increasing sampling effort.

Date \ HourlySampleMin	5	10	15	20	30
17-Aug-10	4.9	4.5	<u>3.3</u>	<u>3.7</u>	1.1
18-Aug-10	4.7	3.7	3.8	3.4	3.5
19-Aug-10	6.5	5.7	4.5	2.2	3.0
21-Aug-10	7.9	6.5	<u>5.3</u>	<u>5.8</u>	2.8
25-Sep-10	5.0	3.9	3.7	3.4	2.5
Mean *CV* (%)	**5.8**	**4.9**	**4.1**	**3.7**	**2.6**
Max *CV* (%)	7.9	6.5	5.3	5.8	3.5
Min *CV* (%)	4.7	3.7	3.3	2.2	1.1

These results show that the hourly sampling time of 5 minutes (or a sampling fraction of 8.3%) achieves a high precision of 5.8% (in terms of *CV*) for the migration scenarios at Mission.

Using DIDSON length data to partition salmon and non-salmon species

With the DIDSON length data we partition the count into salmon and non-salmon targets by using a mixture model on the length data. Detailed descriptions and applications of the mixture model are presented in Appendix 7.   Figures 16 and 17 show the estimated 2-group (salmon vs. non-salmon) distribution for the 394 DIDSON length data acquired from August 17-19, 2011 using a maximum likelihood and a Bayesian versions of the mixture model. During this time period, the migration was dominated by sockeye salmon.
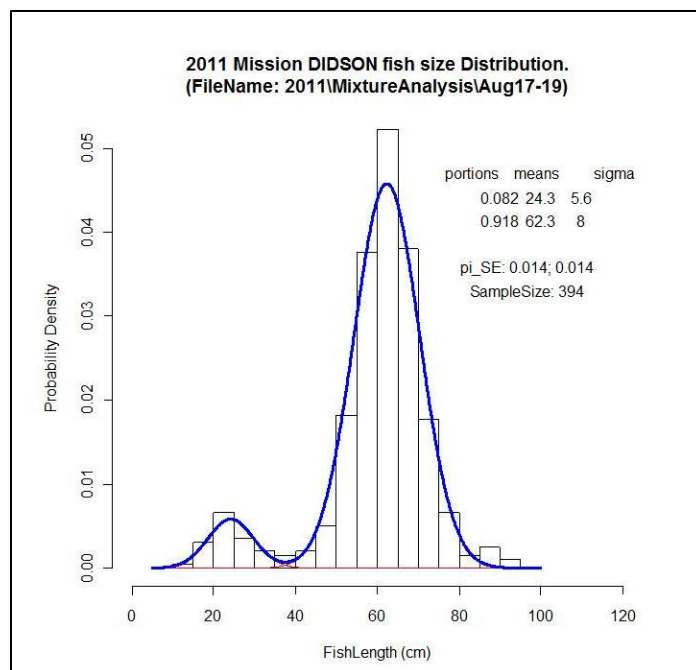
Figure 16. Histogram of the 394 DIDSON length data and estimated 2-group distribution (the blue line) using a maximum likelihood version of a 2-group normal mixture model for the data. The model estimates 8.2% of the observed fish are non-salmon species.
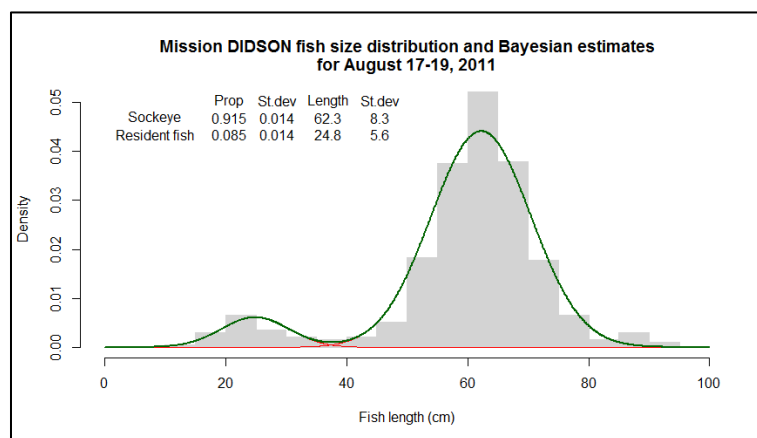
Figure 17. Histogram of the 394 DIDSON length data and estimated 2-group distribution (the green line) using the Bayesian version of a 2-group normal mixture model for the data. The model estimates 8.5% of the observed fish as non-salmon species.

For this dataset, both versions of the model produce very similar estimates for non-salmon proportion: 8.2% vs. 8.5%. As the season progressed, an increased number of pink salmon started entering the lower river and co-migrating with sockeye salmon. The 2-group model was upgraded to a 3-group model to better interpret the observed length data. Figures 18 and 19 show the estimated 3-group (pink salmon, sockeye

salmon and non-salmon) distributions for the 327 DIDSON length data acquired from August 25-26, 2011 using the 2 versions of the mixture model.
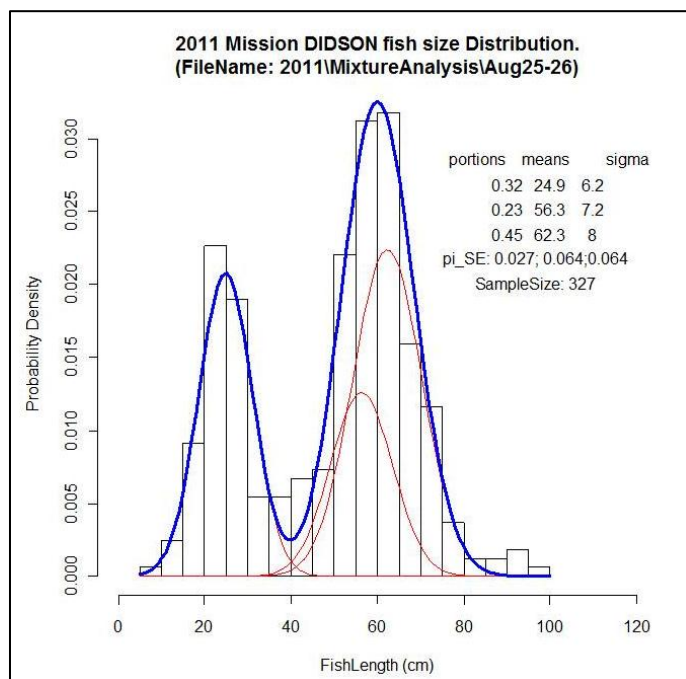
Figure 18. Histogram of the 327 DIDSON length data taken from Aug 25-26, 2011 and estimated 3-group distribution (the blue line) using a maximum likelihood version of the 3-group normal mixture model for the data. The red lines depict the 3 estimated distributions of individual groups that compose the mixture.
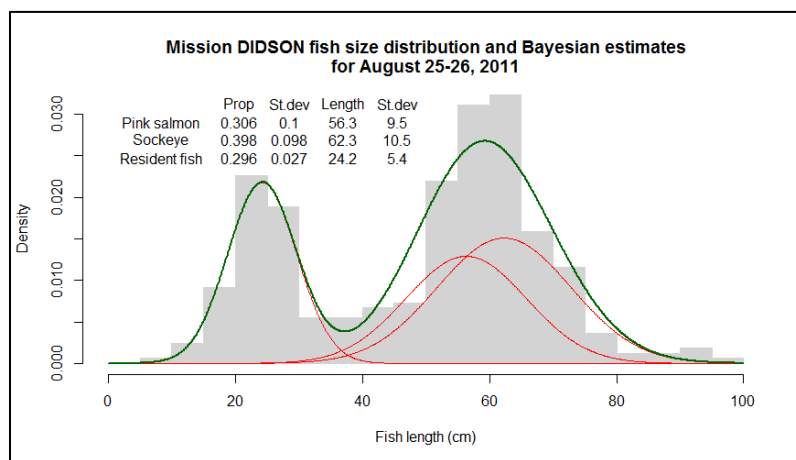
Figure 19. Histogram of the 327 DIDSON length data taken from Aug 25-26, 2011 and estimated 3-group distribution (the green line) using a Bayesian version of the 3-group normal mixture model for the data. The red lines depict the 3 estimated distributions of individual groups that compose the mixture.

Again, both versions of the mixture model produce very similar estimates for non-salmon proportion: 32% vs. 30%. However, the 2 modeling approaches produce noticeably different proportions of pink and sockeye salmon for this dataset. The estimated proportions and associated uncertainties are summarized in Table 4.

Table 4. Estimated species proportions and associated uncertainties from the DIDSON length data by the 2 versions of mixture models. All values are listed for the maximum likelihood estimates followed by the Bayesian estimates.

Data source:	394 DIDSON length data from Aug 17-19, 2011		
Species	Resident fish	Sockeye salmon	Pink salmon
Proportion (%)	8.2; 8.5	91.8; 91.5	NA; NA
Standard error (%)	1.4; 1.4	1.4; 1.4	NA; NA
Data source:	327 DIDSON length data from Aug 25-26, 2011		
Species	Resident fish	Sockeye salmon	Pink salmon
Proportion (%)	32; 30	45; 40	23; 30
Standard error (%)	2.7; 2.7	6.4; 10	6.4; 10

CONCLUSIONS

The following are the key findings and results from the studies under this project.

1. The shore-based DIDSON systems are far more effective than the current sampling system for the enumeration of near-shore salmon passages. When the migration is dominated by near-shore migrants such as pink salmon or late-run sockeye salmon, the proposed sampling system captures a large portion of the abundance migrating near both banks which would have been missed by the mobile sounding system (Figures 9 and 14).

2. Since more than 75% of the salmon migration occurs in the near-shore water, the proposed sampling system significantly increases the overall accuracy of Mission estimate (Tables 1 and 2). This has yielded the best gain for the SEF fund investments for the Mission hydroacoustic program improvement since 2008.

3. From the cost-benefit analysis, it is evident that migration behaviour and cross-river distribution of fish play a key role in estimation accuracy that a given sampling system can achieve. To account for various migration scenarios in the lower river, the sampling system must maintain an adequate sampling capacity for a number of contrasting scenarios encountered so far at Mission (Figures 9-14; Tables 1 and 2).

4. When the abundance of below-Qualark stocks is relatively small compared to the total run size (e.g. the late-run sockeye migration in 2010), Qualark estimates can be used to gauge Mission estimates on a probably weekly basis through a comparison analysis of estimates from the 2 sites by the current PSC method. However, such comparisons become increasingly uncertain and unreliable with increased below-Qualark stocks. Robust and reliable models must be established to extract common migration signals from the 2 time series so that estimates from Qualark can be used as a robust feedback for Mission for all migration scenarios.

5. The current comparison method by the PSC does not address temporal changes of migration profiles as fish move towards Qualark from Mission. This prevents accuracy assessments on a daily scale of Mission estimate by using Qualark estimate.

6. The sampling fraction of fish passage at Mission by the shore-based system is 8% (or 5 minutes per hour). The precision with this sampling rate is estimated at a *CV* level around 6% (Figure 15 and Table 3). Increasing the hourly sampling time from 5 to 10 minutes only leads to a very small gain with the *CV* decreasing to 5% (see Table 3). Our data analyses conclude that the Mission hydroacoustic station produces precise estimates of daily salmon passage at the site.

7. The proposed sampling system produced sensible estimates of pink salmon escapement at Mission (Figure 14). Combined with the Qualark pink salmon estimate, not only the total run size can be derived from the Mission estimate but also the distributions of pink salmon populations above and below Qualark (see Table 9 in Xie et al 2012).

8. At this time there is still no practical solution to the replacement of the mobile sampling system, but the proposed sampling method increases the accuracy of estimation for up to 75% of the total salmon flux in the lower river.

Based on these analyses and findings, we conclude that the proposed sampling system (Figure 3) is more robust than the current system and we recommend the implementation of the proposed sampling system for the PSC Mission hydroacoustic program.

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REFERENCES

Banneheka, S.G., R.D. Routledge, I.C. Guthrie and J.C. Woodey. 1995. *Estimation of in-river fish passage using a combination of transect and stationary hydroacoustic sampling*. Can. J. Fish. Aquat. Sci. 52: 335-343.

Cochran, W. G. 1977. *Sampling techniques*. John Wiley & Sons, Inc.

Enzenhofer, H.J., Cronkite, G.M.W., and Holmes, J.A. 2010. *Application of DIDSON imaging sonar at Qualark Creek on the Fraser River for enumeration of adult pacific salmon: An operational manual.* Can. Tech. Rep. Fish. Aquat. Sci. 2869: iv + 37 p.

Enzenhofer, H.J., Cronkite, G.M.W. 2003. *Towed bodies for echo sounding from boats*. Can. Tech. Rep. Fish. Aquat. Sci. 2467: 12p.

Fleischman, S. J., and D. L. Burwen. 2003. *Mixture models for the species apportionment of hydroacoustic data, with echo-envelope length as the discriminatory variable*. ICES J. Mar. Sci., 60: 592-598.

Fraley, C., and A. E. Raftery. 1998. *How many clusters? Which clustering method? Answers via model-based cluster analysis*. Computer J. 41: 578-588.

Gelman, A., J.B. Carlin, H.S. Stern, and D.B. Rubin. 1995. *Bayesian data analysis*. Chapman & Hall, New York.

Gilk, W.R., Thomas, A. and D.J. Spiegelhalter 1994. *A language and program for complex Bayesian modeling*. The Statistician: 43, 169-177.

Harley, S.J. and R.A. Myers. 2001. *Hierarchical Bayesian models of length-specific catchability of research trawl surveys*. Canadian Journal of Fisheries and Aquatic Sciences: 58, 1569-1584.

Levy, D. A. and A. D. Cadenhead. 1995. *Selective tidal stream transport of adult sockeye salmon (oncorhynchus-nerka) in the Fraser River Estuary*. Can. J. Fish. and Aquat. Sci. 52: 1-12.

Lilja, J., T. Ridley, G.M.W. Cronkite, H. J. Enzenhofer, J. A. Holmes. 2008. *Optimizing sampling effort within a systematic design for estimating abundant escapement of sockeye salmon (Oncorhynchus nerka)*. Fish. Res. 90: 118-127.

McLachlan, G.J., and K. E. Basford. 1988. *Mixture models*. Marcel Dekker, Inc., New York, New York.

Meyer, R. and R. B. Millar. 1999. *BUGS in Bayesian stock assessments*. Canadian Journal of Fisheries and Aquatic Sciences: 56, 1078-1086.

Millar, R.B. and R. Meyer. 2000. *Non-linear state space modeling of fisheries biomass dynamics by using metropolis-Hastings within-Gibbs sampling*. Applied Statistics: 49(3), 327-342.

Skalski, J. R. and A. Hoffmann. 1993. *Fix-location hydroacoustic monitoring designs for estimating fish passage using stratified random and systematic sampling*. Can. J. Fish. Aquat. Sci. 50: 1208-1221.

Xie, Y., F. J. Martens, and J. L. Nelitz. 2012. *Implementation of stationary sub-sampling systems to estimate salmon passage in the Lower Fraser River: Year 1 of 2011 and 2012 project report to Southern boundary restoration and enhancement fund*. Pacific Salmon Commission, Vancouver, British Columbia. May, 2012.

Xie, Y., F. J. Martens, Andrew P. Gray and Jacqueline L. Nelitz. 2011. *A feasibility study on using stationary hydroacoustic sub-sampling methods to estimate offshore fish flux in the lower Fraser River: A year-3 project report to Southern Boundary Restoration and Enhancement Fund*. Pacific Salmon Commission, Vancouver, British Columbia. April, 2011.

Xie, Y., F. J. Martens and Andrew P. Gray. 2010. *A feasibility study on using a stationary hydroacoustic sub-sampling method to estimate offshore fish flux in the lower Fraser River: A project report to Southern Boundary Restoration and Enhancement Fund*. Pacific Salmon Commission, Vancouver, British Columbia. February, 2010.

Xie, Y., C. G. J. Michielsens, A. P. Gray, F. J. Martens, and J. L. Boffey. 2008. *Observations of avoidance reactions of migrating salmon to a mobile survey vessel in a riverine environment*. Can. J. Fish. Aquat. Sci. 65: 2178-2190.

Xie, Y, A. P. Gray, F.J. Martens, J.L. Boffey, and J.D. Cave. 2007. *Development of a Shore-based Hydroacoustics System on the Right Bank of the Lower Fraser River to Monitor Salmon Passages: A project report to Southern boundary restoration and enhancement fund*. Pacific Salmon Commission, Vancouver, British Columbia. April, 2007.

Xie, Y, A. P. Gray, F.J. Martens, J.L. Boffey, and J.D. Cave. 2005. *Use of dual-frequency identification sonar to verify split-beam estimates of salmon flux and to examine fish behaviour in the Fraser River*. PSC Tech. Rep. No. 16.

APPENDICES

I. List of key equipment

The following sonar equipment was used in this study:

- Three standard DIDSON units, two of which were equipped with SMC interfaced rotators (X2 rotators hereafter) that can be programmed within the DIDSON software to perform scheduled aim changes;
- One long-range DIDSON unit;
- One Biosonics DT-X split-beam echo-sounder with a 5.7^o transducer;
- One HTI Model 243 split-beam echo-sounder with a $2^o \times 10^o$ and $4^o \times 10^o$ elliptical-beam transducers;

II. Sampling schemes and data acquisition parameters for fix-mounted sonar systems

Hourly systematic sampling schemes were implemented for all the fix‑mounted sonar systems and detailed below. The sampling geometry of each of the fix‑mounted systems is illustrated in Figure 1.

Left-bank split-beam system (S)

Tables A1 and A2 show the details of the sampling scheme and data collection parameters used in the 2011 and 2012 season.

Table A1. Summary of hourly sampling scheme of left-bank split-beam system for 2011 and 2012 season

(a).2011 Settings

Sampling time (min)	Vertical aim (deg)	4×10 transducer status	2×10 transducer status	Sounding range (m)		Ping rate (pps)	
				07/12 – 08/22	08/22 – 09/27	07/12 – 08/22	08/22 – 09/27
0-6	-8	active	silent	30	25	10	20
6-12	-4	active	silent	45	30	10	20
12-18	0	active	silent	50	30	10	20
18-24	0	silent	active	55	50	5	10
24-30	-2	silent	active	55	55	5	10
30-36	-4	silent	active	60	50	5	10
36-42	-6	silent	active	50	40	5	10
42-48	-8	silent	active	40	35	5	10
48-54	-10	silent	active	35	25	5	10
54-60	-12	silent	active	30	24	5	10

(b).2012 Settings (represents average settings for 2012 season)

Sampling time (min)	Vertical aim (deg)	4×10 transducer status	2×10 transducer status	Sounding Range(m) 07/11-08/26	Ping rate (pps) 07/11-08/26
0-6	-8	active	silent	40	10
6-12	-4	active	silent	45	10
12-18	0	active	silent	25	10
18-24	0	silent	active	20	5
24-30	-2	silent	active	60	5
30-36	-4	silent	active	60	5
36-42	-6	silent	active	55	5
42-48	-8	silent	active	50	5
48-54	-10	silent	active	35	5
54-60	-12	silent	active	15	5

Table A2. Summary of left-bank split-beam data acquisition parameters for the 2011 and 2012 seasons.

Transducer Sn	Beam-width (deg)	Source level (dB re uPa@1m)	Pulse-width (millisecond)	Transmit Power Level (dBW)	Receiver Gain (dB)	Voltage (V)	Data threshold (dB)*
926448	4x10	219.83	0.2	25	-18	0.264	-45
925038	2x10	221.08	0.2	25	-18	0.27	-45

* See calibration manual for HTI Model 243 system (March 2010).

Left-bank inshore DIDSON (D₁)

In the 2011 season, this system was deployed on July 12th, and in 2012 it was deployed on July 27th. Tables A3 and A4 show the details of the sampling scheme for 2011 and 2012, respectively.

Table A3. Summary of the hourly sampling scheme of left-bank inshore DIDSON for the 2011 season.

Sampling time (min)	Vertical aim (deg)		Bearing (deg)	Sonar Status*	Operating frequency (MHz)	Range window (m)	Frame rate (frames per second)
	07/12-08/31	09/01-09/28					
0-25	-8	-12	340	TR	1.8	2-12	8
25-30				TNR	-	-	-
30-55	-8	-12	340	TR	1.8	12-22	4
55-60				TNR	-	-	-

  *TR = Transmitting and Recording; TNR = Transmitting but Not Recording

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Table A4. Summary of the hourly sampling scheme of left-bank inshore DIDSON for the 2012season

Sampling time (min)	Vertical Aim (deg)		Bearing (deg)	Sonar Status*	Operating frequency (MHz)	Range window (m)	Frame rate (frames per second)
	07/27-08/01	08/02-08/26					
0-25	-11	-14	340	TR	1.8	0.83-10.83	8
25-30	-	-	-	TNR	-	-	-
30-55	-11	-14	340	TR	1.1	10.83-20.83	8
55-60	-	-	-	TNR	-	-	-

Left-bank offshore DIDSON (D₄)

This system was deployed from September 6 - 22, 2011. Table A5 shows the details of the sampling scheme.

Table A5. Summary of the hourly sampling scheme of the left-bank offshore DIDSON for the 2011 season.

Sampling time (min)	Vertical aim (deg)	Bearing (deg)	Sonar Status*	Operating frequency (MHz)	Sounding range window (m)	Frame rate (frames per second)
0-12	2.6	344	TR	1.1	1.67-21.67	8
12-14	-	-	TNR	-	-	-
14-26	8.2	347	TR	1.1	1.67-21.67	8
26-28	-	-	TNR	-	-	-
28-40	19	351	TR	1.1	1.67-21.67	8
40-42	-	-	TNR	-	-	-
42-54	37	0	TR	1.1	1.67-21.67	8
54-60	-	-	TNR	-	-	-

This system was deployed from the vessel in the 2012 season for stationary soundings.

Vessel-based DIDSON (D₄)

This system was deployed from July 11 - August 15, 2012 on the port side and from August 16 to August 26 on the starboard side of the vessel. The system was operated

during stationary soundings on the left and right bank; three hours a day for each bank. Table A6 shows the details of the sampling scheme.

Table A6. Summary of the sampling scheme for the vessel-based DIDSON in the 2012 season.

Sampling time (min)	Sampling Location	Vertical Aim (deg)	Bearing (deg)	Sonar Status*	Operating frequency (MHz)	Range window (m)	Frame rate (frames per second)
0-60	Left-bank	-20	130	TR	1.8	2-12	8
0-60	Right-bank	-10	328	TR	1.8	2-12	8

Right-bank inshore DIDSON (D$_2$)

This long-range unit was deployed from August 11 – September 28, 2011, and August 6-26, 2012. Tables A7 and A8 show the details of the sampling scheme for 2011 and 2012, respectively.

Table A7. Summary of the hourly sampling scheme of the right-bank inshore long-range DIDSON for the 2011 season.

Sampling time (min)	Vertical aim (deg)		Bearing (deg)	Sonar Status*	Operating frequency (MHz)	Sounding range bins (m)	Frame rate (frames per second)
	08/11-09/03	09/03-09/28					
0-15	0	-8	134	TR	1.2	Bin1: 1.67-11.67	10
15-20				TNR	-	-	-
20-35	0	-8	134	TR	0.7	Bin2: 12.5-32.5	5
35-40				TNR	-	-	-
40-55	0	-8	134	TR	0.7	Bin3: 10-50	4
55-60				TNR	-	-	-

Table A8. Summary of the hourly sampling scheme of the right-bank inshore long-range DIDSON for the 2012 season.

Sampling time (min)	Vertical Aim (deg)		Bearing (deg)	Sonar Status*	Operating frequency (MHz)	Sounding range bins (m)	Frame rate (frames per second)
	08/06-08/20	08/21-08/26					
0-25	-6	-9	130	TR	1.2	Bin 1: 0.83-10.83	10
25-30	-	-	-	TNR	-	-	-
30-55	-6	-9	130	TR	0.7	Bin 2: 10.83-20.83	8
55-60	-	-	-	TNR	-	-	-

Right-bank offshore DIDSON (D$_3$)

This system was deployed from August 15 – September 28, 2011 and August 8 to August 26, 2012. Tables A9 and A10 show the details of the sampling scheme for 2011 and 2012, respectively.

Table A9. Summary of the hourly sampling scheme of the right-bank offshore DIDSON for the 2011 season.

Sampling time (min)	Vertical aim (deg)	Compass Bearing (deg)	Sonar Status*	Operating frequency (MHz)	Sounding range window (m)	Frame rate (frames per second)
0-12	-4	130	TR	1.1	1.67-21.67	8
12-14			TNR	-	-	-
14-26	11	130	TR	1.1	1.67-21.67	8
26-28			TNR	-	-	-
28-40	26	130	TR	1.1	1.67-21.67	8
40-42			TNR	-	-	-
42-54	41	130	TR	1.1	1.67-21.67	10
54-60			TNR	-	-	-

Table A10. Summary of the hourly sampling scheme of the right-bank offshore DIDSON for the 2012 season.

Sampling time (min)	Vertical Aim (deg)	Bearing (deg)	Sonar Status*	Operating frequency (MHz)	Range window (m)	Frame rate (frames per second)
0-6	-10	135	TR	1.1	1.67-21.67	8
6-7	-	-	TNR	-	-	-
7-13	12	125	TR	1.1	1.67-21.67	8
13-14	-	-	TNR	-	-	-
14-20	35	125	TR	1.1	1.67-21.67	8
20-21	-	-	TNR	-	-	-
21-27	56	135	TR	1.8	1.67-11.67	7
27-28	-	-	TNR	-	-	-
28-34	0	320	TR	1.8	1.67-11.67	7
34-35	-	-	TNR	-	-	-
35-41	23	328	TR	1.8	1.67-11.67	7
41-42	-	-	TNR	-	-	-
42-48	45	328	TR	1.8	1.67-11.67	7
48-49	-	-	TNR	-	-	-
49-55	69	318	TR	1.8	1.67-11.67	7
55-60	-	-	TNR	-	-	-

III. Sampling schemes and data acquisition parameters for the mobile sampling systems

Fish migrating beyond the sounding ranges of shore-based sonar systems were sampled by a transecting vessel, with 2 downward looking split-beam transducers. Deployed on July 12, 2011 from the port-side was a 200-kHz, 15° circular beam HTI transducer. Deployed on September 9-26, 2011 and from July 11 to August 20, 2012 from the starboard side and from August 21-26, 2012 the port side was a 210-kHz, 5.7^{o} Biosonics transducer mounted on a tow-body designed by Hermann Enzenhofer of DFO for a similar transducer (see Fig. 1 in Enzenhofer et al 2003). Both systems recorded GPS trajectory data of the vessel. Table A11 summarizes key data acquisition parameters of the 2 systems.

Table A11. Summary of key data acquisition parameters of the 2 mobile split-beam systems.

Sounder system	Transducer sn	Beam-width (deg)	Sounding range (m)	Source level (dB re uPa@1m)	Pulse-width (millisecond)	Ping rate (pps)	Data threshold (dB)	Source level Reduction (dB)
HTI	1425506	15	22	213.4	0.2	20	-45*	-
DT-X	DT206144	5.7	17	222.2	0.2	20	-130**	0

* This is the threshold used for single-target filtering based on the transmitting power level of 20 dB-Watts and receiver gain of -18 dB. Please see calibration manual for Model 241 system (April 2007).
** This is the threshold used for the collection of raw echo data (unfiltered).

IV. DIDSON estimation of left-bank near-shore fish flux under the high-water condition in July 2012

At the beginning of the 2012 field season, the water level of the Fraser River was abnormally high with daily discharges above 10,000 cubic metres per second from July 1–14 (http://www.wateroffice.ec.gc.ca/). During the high water period from July 11-25, it was not possible to deploy the split-beam transducers with the fish deflection fence on the left bank. The high discharge also brought to the lower river a large amount of debris from upstream. In order to acquire reliable fish counts (primarily for the small run size of Early Stuart sockeye) under this very noisy condition, a standard DIDSON mounted on an X2 rotator was deployed on a tripod on the bottom of the left bank to sample near-shore fish flux from the 8 non-overlapping angular sectors as shown in Figure A1. The flux through the entire 180° angular section was estimated by expanding counts observed by the 14° vertical beam-sector at the 8 aims which accounted for a total angular space of approximately 120°. Fish behaviour from the DIDSON data was also used in conjunction with the vessel-based split-beam density data to derive the offshore flux for this period. Tables A12 and A13 enlist data acquisition parameters of this DIDSON system over 2 time periods in July with the settings for the 1st time period for the initial trial of the system.

Table A12. Summary of the hourly sampling scheme of the left-bank inshore DIDSON during the July11-16, 2012 high water period.

Sampling time (min)	Vertical Aim (deg)	Bearing (deg)	Sonar Status*	Operating frequency (MHz)	Range window (m)	Frame rate (frames per second)
0-12	24	145	TR	1.8	0.83-10.83	8
12-15	-	-	TNR	-	-	-
15-27	9	320	TR	1.8	0.83-10.83	8
27-30	-	-	TNR	-	-	-
30-42	24	320	TR	1.1	0.83-20.83	8
42-45	-	-	TNR	-	-	-
45-57	39	320	TR	1.8	0.83-10.83	8
57-60	-	-	TNR	-	-	-

Table A13. Summary of the hourly sampling scheme of the left-bank inshore DIDSON during the July16-25, 2012 high water period.

Sampling time (min)	Vertical Aim (deg)	Bearing (deg)	Sonar Status*	Operating frequency (MHz)	Range window (m)	Frame rate (frames per second)
0-6	0	132	TR	1.8	0.83-10.83	8
6-7	-	-	TNR	-	-	-
7-13	23	132	TR	1.8	0.83-10.83	8
13-14	-	-	TNR	-	-	-
14-20	45	132	TR	1.8	1.25-11.25	8
20-21	-	-	TNR	-	-	-
21-27	67	132	TR	1.8	0.83-10.83	8
27-28	-	-	TNR	-	-	-
28-34	-6	328	TR	1.8	0.83-10.83	8
34-35	-	-	TNR	-	-	-
35-41	17	328	TR	1.8	1.25-11.25	8
41-42	-	-	TNR	-	-	-
42-48	40	328	TR	1.8	1.25-11.25	8
48-49	-	-	TNR	-	-	-
49-55	63	328	TR	1.8	1.25-11.25	8
55-60	-	-	TNR	-	-	-
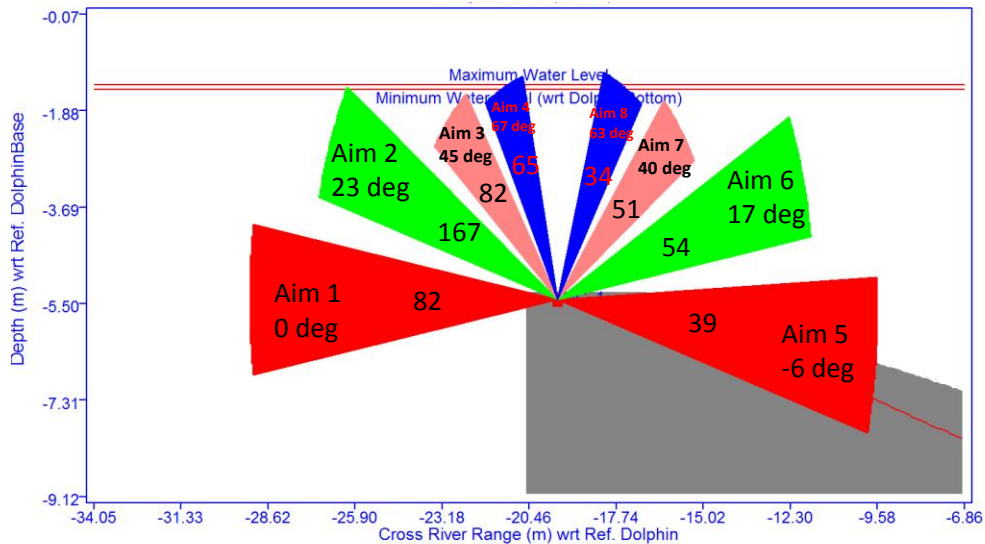
Figure A1. Hourly sampling scheme of the left-bank inshore DIDSON at 8 aims during the high-water period from July 16-25, 2012 (see Table A13 for details). Numbers shown in the plot are upstream fish counts acquired on July 17, 2012 by this system.

V. Cross river fish distributions for sockeye and pink dominated migrations at Mission

Due to strong offshore currents at the site, salmon tend to migrate in near-shore waters (Xie et al 2005). The migration flux is also unevenly distributed across the river skewing towards the left-bank, especially during pink salmon migrations. Figures A2, A3, and A4 show the cross-river distributions over the 3 areas for sockeye dominated migrations in 2010, 2011 and 2012 using post-season estimates. Figure A5 shows the distribution for the 2011 pink salmon migration.
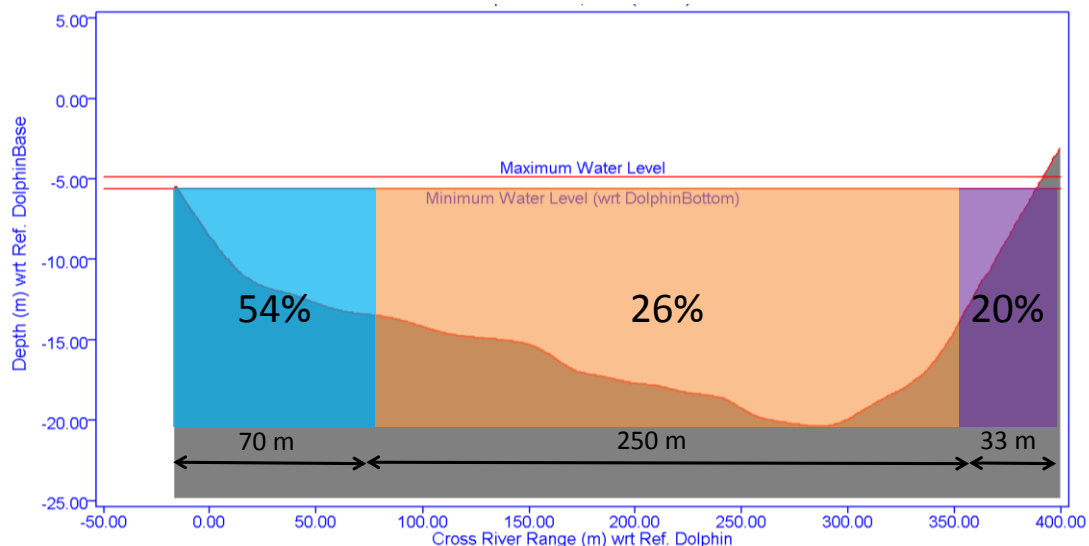
Figure A2. Cross-river fish flux distribution for September 01 - October 03, 2010 (late-run sockeye dominated migrations).
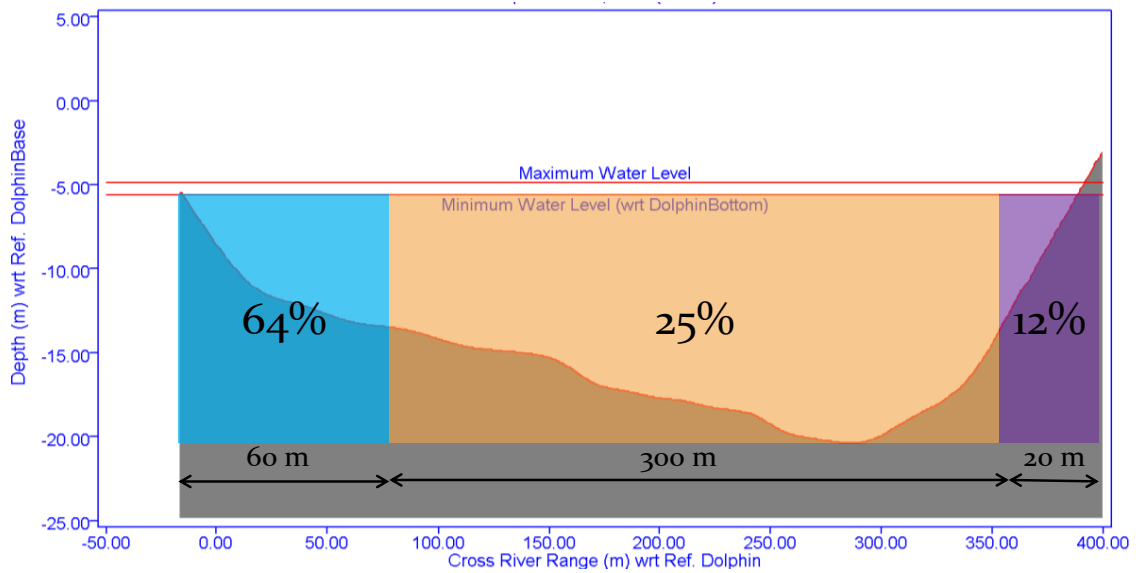
Figure A3. Cross-river fish flux distribution for August 12-31, 2011 (sockeye dominated migrations).
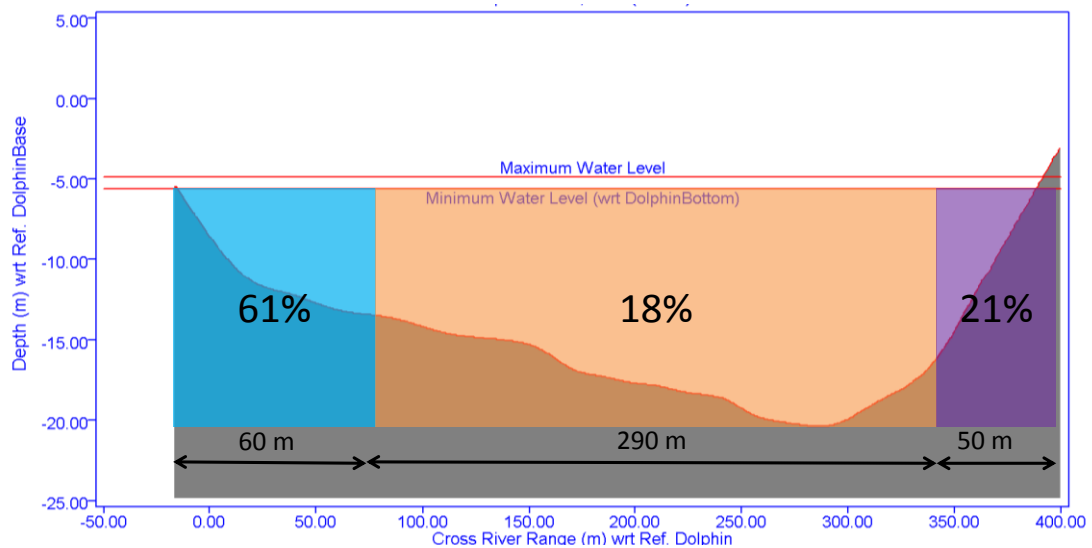
Figure A4. Cross-river fish flux distribution for August 08-26, 2012 (sockeye salmon dominated migrations).
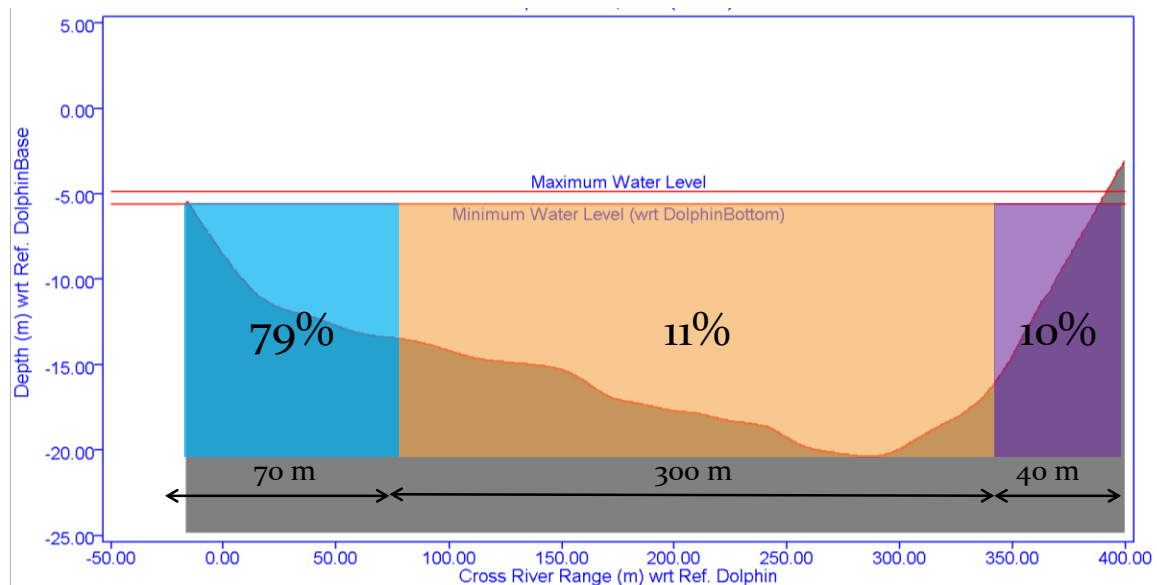
Figure A5. Cross-river fish flux distribution for September 2011 (pink salmon dominated migrations).

All 4 plots show skewed distributions towards the left-bank. During sockeye migration periods, the flux sampled by the 2 near-shore systems accounted for > 70% of the total flux while the offshore area (sampled by the mobile system) accounted for less than 30% of the flux. This skewness is even more pronounced for pink dominated migration (Figure A5) with nearly 80% of the total migration occurring near the left-bank, 10% near the right bank, and only 11% in offshore water.

VI. Precision versus sampling effort for shore-based estimates

To evaluate precision of DIDSON estimated fish passage near the left bank, we select 5 daily full count datasets from 5 distinctive sockeye migration scenarios in the 2010 season for the analysis. These scenarios encompass small to heavy daily migrations as well as migrations impacted by in-river fisheries. For comparison purposes, we present the evaluated precision of hourly systematic sampling method which we implemented for the field program together with that of hourly random sampling, and simple random sampling methods.

Analysis approaches

The essence of the analysis is summarized here.
1. Record data continuously for 55 minutes on an hourly basis with a 5-min recording pause between adjacent hours to allow DIDSON to close and open hourly files;

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2. Manually count the fish passage on a 5-minute interval to produce 5-min counts as the basic sample units for the analysis. The total number of sample units for each hour is 12 with the 12th unit being the average between the 11th unit of the hour and 1st unit of the following hour. Thus, we form a finite population of $Y = [y_1, y_2, ..., y_N]^T$ with $N=288$ units over a 24-hour daily period. The 5-min count data series can be readily converted to 10-, 15-, 20- or 30-min full-count series.
3. Estimate the *CVs* (coefficient of variance) of hourly mean estimates by taking sub-samples of n units from the N units via hourly stratified systematic sampling. If each unit is formed by a 5-min count and we take one unit per hour for each sampling, the sampling fraction for the finite population Y is $\dfrac{n}{N} = \dfrac{24}{288} = 8.3\%$;
4. Increase sampling fraction n/N and examine the response of *CV*.

To perform hourly stratified sampling (abbreviated as *systematic sampling* hereafter) of the full-count data, we express Y as a matrix $Y = [y_{ij}]$ where y_{ij} is the ith unit located in j^{th} hour. Indices $i = \{1, 2, ..., k\}$ denotes i^{th} sample and $j = \{1, 2, ..., n\}$ denotes j^{th} hour. If y_{ij} is a 5-min count unit, $k=12$, $n=24$ and $n \times k = N = 288$.

The systematic sampling produces an unbiased estimate of population mean (Cochran 1977) i.e., $E(\bar{y}) = \bar{Y}$ meaning the sample mean $\bar{y}$ converges statistically to the population mean $\bar{Y}$. However, the variance of the estimate by this sampling method is influenced by the correlation of cross-hour phase structures. Because of this unique feature, the variance of estimates from systematic sampling is less predictable than that from other sampling methods (Skalski et al 1993). The variance of estimate from systematic sampling is (see eqn. (8.11) in Cochran 1977):

$$V(\bar{y}) = \frac{S^2_{wst}}{n} \times (1-f) \times \left[1 + (n-1) \times \rho_{wst}\right] \qquad \text{(A1)}$$

Where

$$S^2_{wst} = \frac{\sum\limits_{j=1}^{n}\sum\limits_{i=1}^{k}(y_{ij} - \bar{y}_{\cdot j})^2}{n \times (k-1)} \quad \text{is within-hour variance of } y_{ij} ;$$

$$\rho_{wst} = \frac{2}{n(n-1)(k-1)}\sum\limits_{i=1}^{k}\sum\limits_{j<u}\frac{(y_{ij} - \bar{y}_{\cdot j})(y_{iu} - \bar{y}_{\cdot u})}{S^2_{wst}} \quad \text{is cross-hour correlation coefficient}$$

among units. Note: ρ_{wst} is greater than $1/(1-n)$ and can be negative.

The metric to gauge precision of estimated hourly mean $k \times \bar{y}$ is:

$$CV = \frac{\sqrt{V(k \times \bar{y})}}{E(k \times \bar{y})} = \frac{k \times \sqrt{V(\bar{y})}}{k \times E(\bar{y})} = \frac{\sqrt{V(\bar{y})}}{\bar{Y}} \qquad \text{(A2)}$$

Therefore, the evaluation of precision by *CV* of estimated hourly mean is equivalent to that of sample mean. In some literature, percent of 95% confidence limits (*PCL$_{95}$*) is chosen to gauge the precision. Assuming error term $\bar{y} - \bar{Y}$ is normally distributed with zero-mean, it can be shown that $PCL_{95} \approx \pm 2 \times CV$. We use *CV* as a formal metric to gauge precision in this study.

Full-count data for the analysis

The 24-hour full-count datasets selected for this analysis were acquired in the 2010 season by DIDSON sonar from the left bank of the Mission site. Table A14 is a summary of the key acquisition parameters of the data. Figure A6 shows the time series plots of the full-count data.

Table A14. Summary of key data collection parameters for the 5 24-hour full-count DIDSON datasets collected in the 2010 season from the left bank of PSC Mission site.

Date	Aug-17	Aug-18	Aug-19	Aug-21	Sept-25
Sonar type	Standard	Standard	Standard	Standard	Long-range
Start range (m)	3.33	3.33	3.33	3.33	12.5
End range (m)	23.33	23.33	23.33	23.33	32.5
Verical aim(deg)	-8	-8	-8	-8	-8
Bearing (deg)	340	340	340	340	340
Freq. (MHz)	1.8	1.8	1.8	1.8	1.2
24-hour total	135,244	115,568	14,526	61,497	169,990
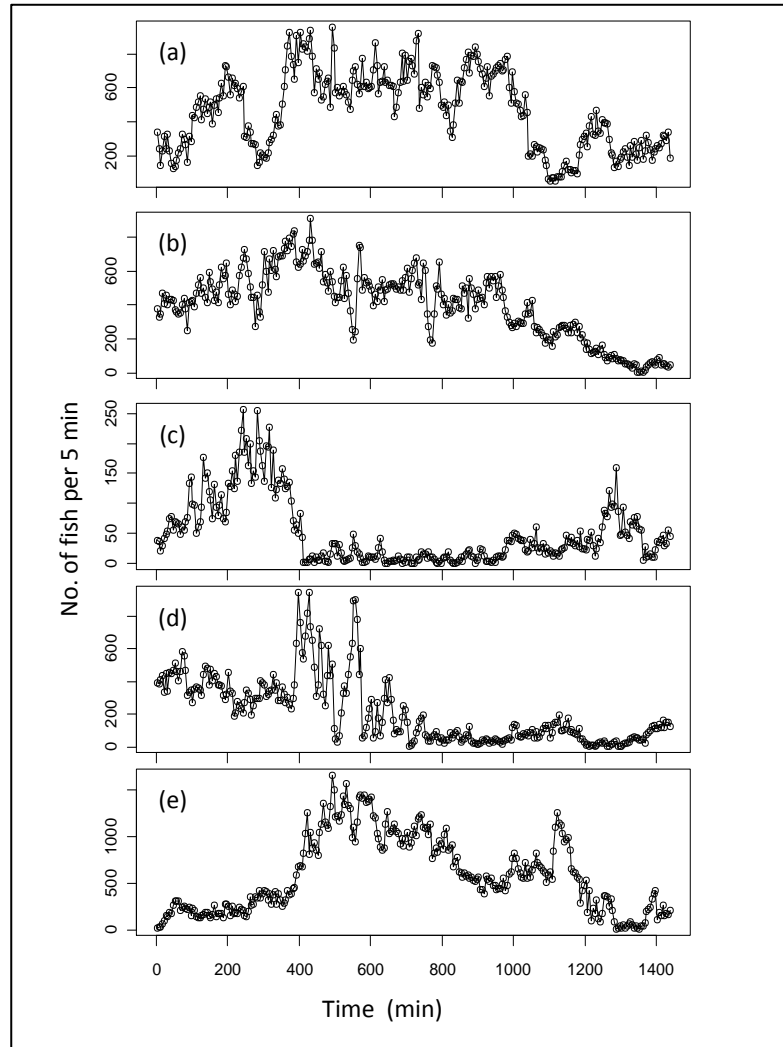
Figure A6. Time series plots of 24-hour DIDSON full-count data acquired from the left bank at Mission in the 2010 season on (a) Aug 17, (b) Aug 18, (c) Aug 19, (d) Aug 21, and (e) Sept 25. Each data point represents a 5-minute fish count.

While the August 17 and 18 data show a somewhat similar temporal pattern, the August 19 data displays a distinctively different pattern due to the effect of in-river fisheries removal. The pattern of the August 21 data is not a common pattern of daily migration. The pattern of the September 25 data is commonly observed for the daily migration of late-run sockeye salmon; the migration appears to synchronize with the semi-diurnal tides.

Precision comparisons of estimated hourly means among the 3 sampling methods

We apply systematic sampling to the 5-min full-count data series, and calculate the precision of estimated mean from Eqn. (A1). For comparison purposes, we also present the calculated precisions for the simple random and hourly stratified random

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sampling methods using the same data. Figure A7 shows distributions of the estimated hourly means by the 3 sampling methods.
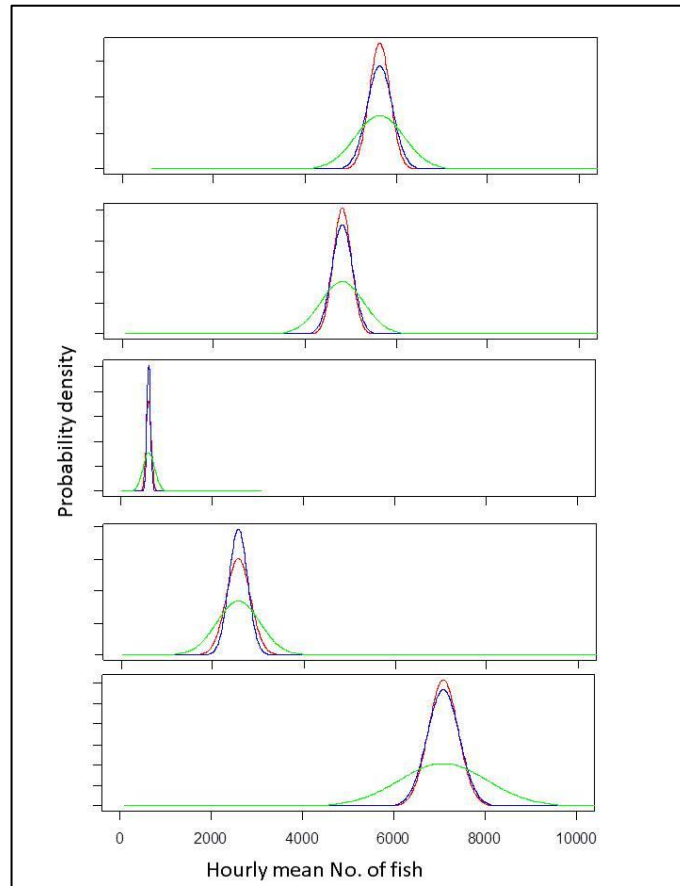
Figure A7. Plots of distributions of hourly mean estimates $k \times \bar{y}$ from the 5-min DIDSON full-count datasets by the 3 sampling methods assuming $k \times \bar{y}$ is normally distributed and centered at the true means. The green lines represent the results for simple random sampling, the red for hourly random sampling, and the blue for hourly systematic sampling.

Table A15 lists the key statistics of hourly mean estimates and precision by the 3 sampling methods for the 5-min full count datasets.

Table A15. Comparison table of precision of hourly mean estimates from the 5-min full-count data by the 3 sampling methods.

Date	Aug-17	Aug-18	Aug-19	Aug-21	Sept-25
Hourly mean (fish per hour)	5635	4815	605	2562	7082
CV_SimpleRandom (%)	9.5	9.8	21.2	18.5	13.6
CV_HourlyRandom (%)	4.0	4.1	9.1	10.3	4.6
CV_HourlySystematic (%)	4.9	4.7	6.5	7.9	5.0
ρ_{wst} (cross-hour coeff.)	0.0216	0.0141	-0.0213	-0.018	0.0077

By comparing achieved precisions among the 3 sampling methods, we conclude that

1. Simple random sampling is the least desirable method among the 3 sampling methods. The uncertainty of estimates by this method is significantly larger than the other 2 methods;
2. Systematic sampling yields slightly higher but very similar precisions to that of hourly random sampling for normal migration scenarios as exhibited in the full-count data of August 17, 18 and September 25. The cross-hour correlation coefficients ρ_{wst} for the 3 data series indicate slightly positive correlations among hourly counts;
3. Systematic sampling yields higher precisions for abnormal migration patterns as exhibited in the August 19 and 21 full-count data. In both cases, ρ_{wst} indicates negative correlations among hourly counts;
4. Being a readily implementable sampling method, systematic sampling is logistically a favourable sampling method for the field program in the lower river. For the migration scenarios exhibited by the 5 representative data examples at the Mission site, this method produces daily estimates of salmon flux with precisions very similar to the theoretically most favourable method of hourly random sampling (Skalski and Hoffmann 1993).

Precision vs. sampling fraction for systematic sampling method

We now examine the relation between precision and sampling fractions for the systematic sampling as we increase the hourly sampling time from 5 to 10, 15, 20 and 30 minutes, respectively. Figure 15 shows the *precision* versus *sampling fraction* relations for the systematic sampling method derived from the 5 full-count datasets. All numerical values are listed in Table 3. From the wide range of migration scenarios revealed by the full-count data, we derived the empirical relations between *precision* and *sampling fraction* for the systematic sampling method that has been implemented for the Mission hydroacoustic programs. We believe this empirical relation is representative and can be used to assess precisions of daily estimates of salmon passage in the lower river. Several key features are worth noting about the relation:

1. While increasing sampling effort likely improves precision with systematic sampling, the improvement is at its most moderate from hourly sampling time of 5 minutes to 10 or 20 minutes. This confirms that the hourly sampling time of 5 minutes (or a sampling fraction of 8.3%) is already quite high to achieve a mean *CV* of 5.8% for the typical migration scenarios at Mission.

2. Contradicting to Fig. 5 of Lilja et al (2008), our data analysis shows that precision of systematic sampling does not improve monotonically with increasing sampling effort as demonstrated by the August 17 and 21 data scenarios where increasing the sampling time from 15 to 20 minutes causes

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the precision to decrease (see the underlined values in Table 3). This counter-intuitive outcome results from the behaviour of cross-hour correlation coefficient ρ_{wst} which cannot be accurately estimated from sub-sampled data.

3. Doubling the hourly sampling time from 10 to 20 minutes leads to a decrease of *CV* from 4.9% to 3.7% (or a decrease of *PCL₉₅* from 9.8% to 7.4%). Therefore, doubling the sampling effort merely improves the precision by 25% with the systematic sampling method. This improvement is only half of that predicted by Lilja et al (2008).

VII. Partition of salmon and non-salmon species through a mixture model

The mixture modeling approach has been widely used to interpret fisheries acoustics data (Fleischman and Burwen 2003). For a general description of the method, readers are referred to McLachlan and Basford (1987).

Maximum likelihood version of the mixture model

The essence of the mixture model when applied to the DIDSON data can be summarized as follows.

Let $\boldsymbol{x} = [x_1, x_2, \ldots, x_N]^T$ represent length data taken from N image samples, and assume the length data are sampled from a 2-group length distribution defined by the following probability density function (*pdf*):

$$f(x_i) = \alpha \times f_1(x_i) + (1-\alpha) \times f_2(x_i) \qquad (A3)$$

where f_1 and f_2 are 2 normal distribution functions with means and variances of (μ_1, σ_1^2) and (μ_2, σ_2^2), respectively; α is the proportion of resident fish. In this representation f_1 represents the size distribution of non-salmon species and f_2 the salmon species. The probability of finding a fish of length within a finite size bin from $[x_i - \Delta/2]$ to $[x_i + \Delta/2]$ is: $\Delta \times f(x_i)$. Since all the N length samples are taken independently, the joint probability of observing $[x_1, x_2, \ldots, x_N]^T$, ignoring the finite bin size Δ, is:

$$f(x_1, x_2, \ldots, x_N; \mu_1, \mu_2, \sigma_1, \sigma_2, \alpha) = \prod_{i=1}^{N} \left[\alpha \times f_1(x_i) + (1-\alpha) f_2(x_i) \right] \qquad (A4)$$

This joint probability density is a function of 5 parameters ($\mu_1, \mu_2, \sigma_1, \sigma_2, \alpha$), and can also be expressed as a product of a conditional and a marginal *pdf*:

$$f(x_1, x_2, \ldots, x_N; \mu_1, \mu_2, \sigma_1, \sigma_2, \alpha) = f(x_1, x_2, \ldots, x_N \mid \mu_1, \mu_2, \sigma_1, \sigma_2, \alpha) \times f(\mu_1, \mu_2, \sigma_1, \sigma_2, \alpha)$$
(A5)

Expressions (A4) and (A5) represent the same joint probability density function except that (A5) is a Bayesian form of the mixture model which treats $\mu_1, \mu_2, \sigma_1, \sigma_2$ and α as 5 random variables.

Log-transforming (A4), we arrive at a likelihood function L:

$$L(x_1, x_2, ..., x_N; \mu_1, \mu_2, \sigma_1, \sigma_2, \alpha) = \sum_{i=1}^{N} \log[\alpha \times f_1(x_i) + (1-\alpha) \times f_2(x_i)] \qquad (A6)$$

L is a function of parameters of the 2 normal distribution functions (μ_1, σ_1^2), (μ_2, σ_2^2) and the proportion of non-salmon species α. Eqns. (A4) and (A6) can be extended readily to more than 2 groups. Since the event of $[x_1, x_2, ..., x_N]^T$ is observed from a single sampling, the likelihood of this event must be very high. The values of the parameters that maximize the likelihood as defined by (A6) are called the maximum likelihood ML estimates. Because the likelihood L is dependent upon multiple parameters, solving for the ML from (A6) usually involves tedious and complex numerical approaches using Newtonian expectation-maximization (EM) algorithms (Fraley and Raftery, 1998) to search for the roots of a set of the following equations:

$$\frac{\partial L}{\partial \mu_1} = 0, \frac{\partial L}{\partial \sigma_1} = 0, \ \frac{\partial L}{\partial \mu_2} = 0, \frac{\partial L}{\partial \sigma_2} = 0 \text{ and } \frac{\partial L}{\partial \alpha} = 0.$$

A Newtonian EM algorithm is implemented in the statistical package under R (http://www.r-project.org/) to solve this type of ML problems. Regardless of the statistical software package used, in many practical cases, limits have to be imposed to the range of possible values for these parameters when searching the ML estimates. In the following, we outline 3 cases where we either fix some of the parameters of the length distributions of the salmon and non-salmon populations based on prior knowledge or treat these parameters as random variables to estimate the proportion of non-salmon species from Eqn. (A6).

i. Estimation of the non-salmon proportion with fixed $\mu_1, \mu_2, \sigma_1, \sigma_2$

In this case, we assume the length distributions for salmon and non-salmon species are known. We search for ML by finding the value of α, denoted as α_{ML} that maximizes L. Since all other parameters are fixed during the search, the resulting α_{ML} is conditioned by the priors of these parameters. The mean and variance of the length distribution for the salmon group were estimated by comparing fork length data from the PSC Whonnock test-fishing samples with the DIDSON image data taken in the same time period when the river is dominated by the migration of single-species salmon. Figure A8 shows the length data based on 206 sockeye samples taken from August 17-20, 2011 at Whonnock by gill-net samplings and 394 length data observed at Mission by the left-bank DIDSON.
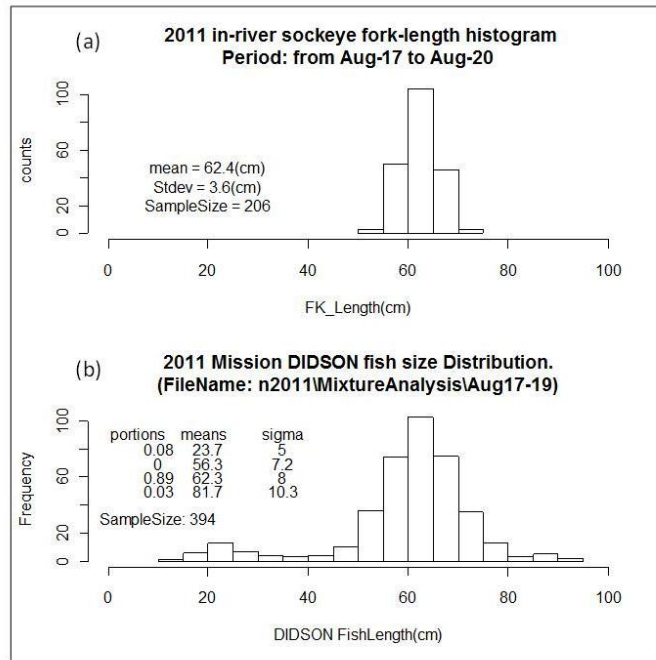
Figure A8. Length data from Whonnock and Mission, Aug 17-20, 2011. (a) histogram of fork-length from 206 sockeye salmon caught at Whonnock. (b) histogram of lateral length from 394 fish images acquired by DIDSON at Mission.

From the acoustic length data, it is evident that there were primarily 2 groups of fish in the river during this time period: sockeye salmon and small resident fish. The mean length of the sockeye group coincided with that of the sockeye fork-length at 62 cm. This agreement is important as it verifies that the DIDSON is an unbiased length estimator. However, the standard deviation of DIDSON fish-length of salmon sized targets is at least 2 times of that of the biological length: 8cm vs. 3.6cm. For the resident fish group, we estimated from the DIDSON data a mean length of 23.7cm and a standard deviation of 3.0cm. With these priors, we have: $\mu_1 = 23.7$cm; $\sigma_1 = 3.0$ cm; $\mu_2 = 62.3$cm, $\sigma_2 = 8$cm. Substituting these priors into (A6), we obtain a conditional likelihood function as a function of α. Figure A9 shows the likelihood function for the 394 length data derived from Eqn (A6).
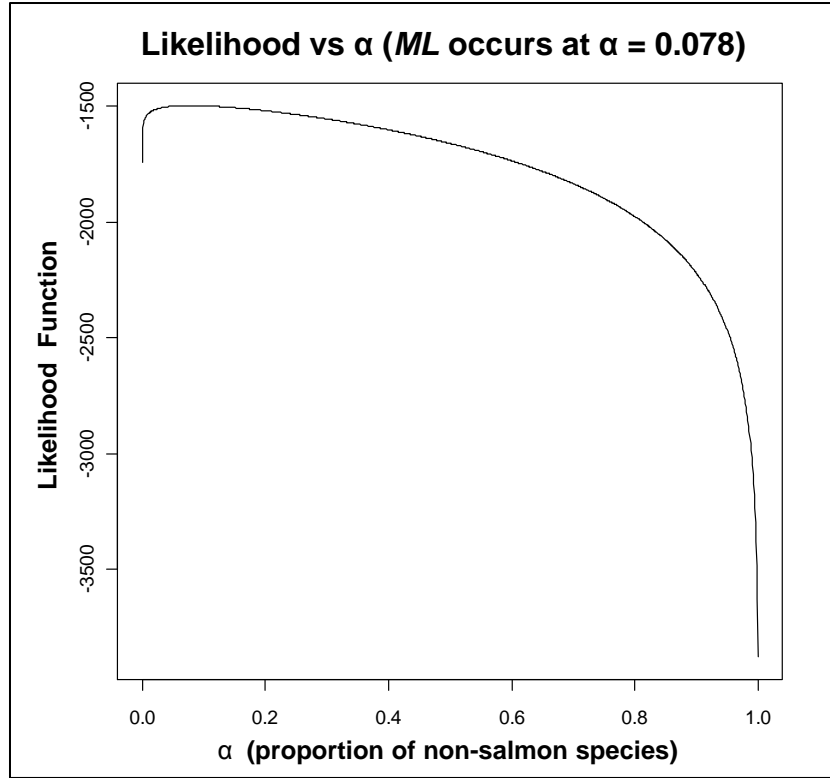
Figure A9. Likelihood function of the 394 DIDSON length data (Figure A8(b)) acquired at Mission from Aug 17-19, 2011. The maximum likelihood occurs at $\alpha = \alpha_{ML} = 0.078$.

With α_{ML} solved, we arrive at an estimated distribution for the observed data as:

$$\hat{f}(x) = \alpha_{ML} \times f_1(x) + (1 - \alpha_{ML}) \times f_2(x) \qquad \text{(A7)}$$

This distribution is conditioned by the 4 fixed priors for the 2 normal distributions. Figure A10 shows the histogram of the data and the estimated distribution for the 394 length data.

2011 Mission DIDSON fish size Distribution.
(FileName: 2011\MixtureAnalysis\Aug17-19)

portions means sigma
0.078 23.7   3
0.922 62.3   8
SampleSize: 394
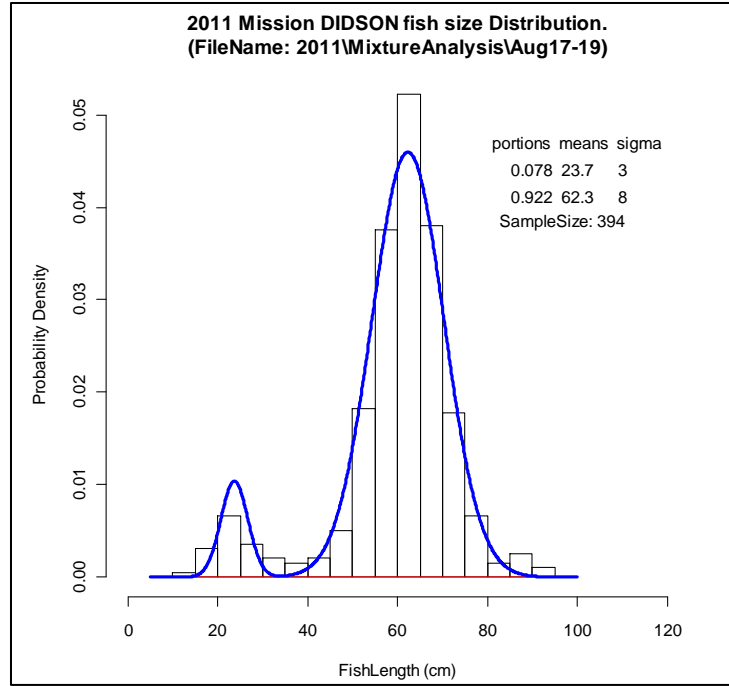
Figure A10. Histogram of the 394 DIDSON length data and estimated 2-group distribution (the blue line) for the data using the maximum likelihood version of a 2-group normal mixture model for the data. This single-parameter model estimates 7.8% of observed fish as non-salmon species.

ii. Estimation of the non-salmon proportion with non-fixed μ_1 and σ_1

Since the size distribution of non-salmon species is unknown due to the lack of biological samplings of these species in the lower river, we do not have verifiable priors for their length distribution as we do for the salmon species. Therefore, it is necessary to use non-fixed priors for μ_1 and σ_1 in (A6) when estimating the proportion of non-salmon species. By treating μ_1 and σ_1 as variables while still keeping μ_2 and σ_2 fixed for salmon species, the likelihood function *L* becomes a function of 3 variables: μ_1, σ_1 and α. Solving for *ML* estimates requires finding solutions to the 3 variables that maximize *L*. This involves the use of numerical approaches to solving a set of 3 equations:

$$\frac{\partial L}{\partial \mu_1} = 0, \frac{\partial L}{\partial \sigma_1} = 0 \text{ and } \frac{\partial L}{\partial \alpha} = 0$$

With the same 394 length data, we use the Newtonian-EM algorithm in *R* to solve for the *ML* estimates by providing the following initial values for the numerical search of the estimates: $\mu_1 = 23.7$ cm and $\sigma_1 = 3.0$ cm. With this approach, we estimated the 2-group distribution and the non-salmon proportion as shown in Figure 16 for the data.

The Newtonian-EM method estimates $\mu_1 = 24.3$cm and $\sigma_1 = 5.6$cm as *ML* solutions which are noticeably different than the priors of 23.7cm and 3.0cm. The distribution

appears to fit the data well and the method estimates 8.2% of the observed fish are non-salmon species. This proportion is slightly higher than 7.8% estimated by the single-parameter model of (A6). The method also provides an estimate of the uncertainty of the estimate for α_{ML} which for this dataset is 1.4%.

iii. Estimation of proportions of multiple groups

The length data presented in the previous 2 sections comprise lengths from primarily small resident fish and adult sockeye salmon. When multiple salmon species in addition to resident fish are present in the river, the 2-group mixture model (A3) becomes inadequate to characterize the data. Instead the modeling of multi-group (>2) mixtures are required. We present here a 3-group mixture model for length data taken from August 25-26 in 2011 when sockeye and pink salmon co-migrated into the lower river. The formulation of the model is straightforward by adding a term to the 2-group model (A3):

$$f(x_i) = \alpha_1 \times f_1(x_i) + \alpha_2 \times f_2(x_i) + \alpha_3 \times f_3(x_i) \qquad \text{(A8)}$$

where subscripts 1, 2, 3 represent the non-salmon, pink and sockeye salmon groups, respectively. We treat μ_1 and σ_1 as variables while using fixed values for $\mu_2, \sigma_2, \mu_3,$ and σ_3 for the 2 salmon species. Since $\alpha_1 + \alpha_2 + \alpha_3 = 1$, there are a total of 4 parameters in (A8) that need to be estimated. The initial values for parameters of the length distribution for non-salmon species are the same as before, i.e., $\mu_1 = 23.7$cm and $\sigma_1 = 3.0$ cm. The fixed values for the means of the pink and sockeye DIDSON length distributions are estimated from the biological samples taken from Whonnock test-fishing catches: the mean pink length (μ_2) is 56.3cm and the mean sockeye length (μ_3) is 62.3cm. The standard deviation of the DIDSON sockeye length distribution is estimated to be twice that of sockeye fork-length distribution from the test-fishing samples (Figure A8(a)). The standard deviation for the DIDSON pink salmon length is obtained by assuming that the coefficient of variance (CV) of the pink salmon length is the same as the CV for the sockeye salmon. The fixed values for the standard deviations of the pink and sockeye salmon length distributions are therefore 7.2cm (σ_2) and 8cm (σ_3) respectively. Using these fixed parameter values for the pink and sockeye salmon groups, the resulting estimated length distributions for all three groups are provided in Figure 18.

Bayesian version of the mixture model

Although estimates from the *ML* version of the mixture model can be bootstrapped to provide approximate standard errors, a Bayesian version of the mixture model is also implemented to interpret the DIDSON length data for comparison purposes. Bayesian methods are particularly well suited for assessing uncertainty in complex or unconventional estimators and provide a formal way to incorporate auxiliary information on the parameters of the model. The Bayesian mixture model was implemented in WinBUGS (Bayes Using Gibbs Sampler (BUGS); Gilks et al., 1994),

available free from http://www.mrc-su.cam.ac.uk/bugs/Welcome.html. For examples of fisheries applications of WinBUGS, see Meyer and Millar (1999), Millar and Meyer (2000), and Harley and Myers (2001).

By applying a Bayesian version of the mixture model, additional information on the parameters of the DIDSON length distributions as well as the proportion estimates can be incorporated. This is done through the application of Bayes' theorem (Gelman et al. 1995) to Eqn. (A5) which in the case of the 2-group mixture model results in the following equation

$$f(\mu_1,\mu_2,\sigma_1,\sigma_2,\alpha \mid x_1,x_2,...,x_N) = \frac{f(x_1,x_2,...,x_N \mid \mu_1,\mu_2,\sigma_1,\sigma_2,\alpha) \cdot f(\mu_1,\mu_2,\sigma_1,\sigma_2,\alpha)}{f(x_1,x_2,...,x_N)}$$

(A9)

whereby $f(\mu_1, \mu_2, \sigma_1, \sigma_2, \alpha \mid x_1, x_2, ..., x_N)$ is the posterior joint probability density function, $f(x_1, x_2, ..., x_N \mid \mu_1, \mu_2, \sigma_1, \sigma_2, \alpha)$ is the likelihood function and $f(\mu_1, \mu_2, \sigma_1, \sigma_2, \alpha)$ is the prior joint probability function of the model parameters $\mu_1, \mu_2, \sigma_1, \sigma_2$ and α. The denominator $f(x_1, x_2, ..., x_N)$ is the marginal probability of the data or normalising constant. Ignoring this normalizing constant in the equation, Bayes' theorem can be expressed as

$$f(\mu_1,\mu_2,\sigma_1,\sigma_2,\alpha \mid x_1,x_2,...,x_N) \propto f(x_1,x_2,...,x_N \mid \mu_1,\mu_2,\sigma_1,\sigma_2,\alpha) \cdot f(\mu_1,\mu_2,\sigma_1,\sigma_2,\alpha)$$
(A10)

Our objective is to estimate the distribution functions of $\mu_1, \mu_2, \sigma_1, \sigma_2, \alpha$ from observed data $x_1, x_2, ..., x_N$ using the posterior joint probability density function $f(\mu_1, \mu_2, \sigma_1, \sigma_2, \alpha \mid x_1, x_2, ..., x_N)$. Assuming the 5 parameters are independent from each other, the posterior function can be expressed as products of 5 marginal posterior probability density functions (pdf):

$$f(\mu_1,\mu_2,\sigma_1,\sigma_2,\alpha \mid x_1,x_2,...,x_N)$$
$$= f(\mu_1 \mid x_1,x_2,...,x_N) \cdot f(\mu_2 \mid x_1,x_2,...,x_N) \cdot f(\sigma_1 \mid x_1,x_2,...,x_N) \cdot f(\sigma_2 \mid x_1,x_2,...,x_N) \cdot f(\alpha \mid x_1,x_2,...,x_N)$$
(A11)

The 5 marginal posterior pdf(s) are obtained from the following integral equations:

$$f(\alpha \mid x_1,x_2,...,x_N) = \int\int\int\int f(\mu_1,\mu_2,\sigma_1,\sigma_2,\alpha \mid x_1,x_2,...,x_N) d\mu_1 \cdot d\mu_2 \cdot d\sigma_1 \cdot d\sigma_2$$

$$f(\mu_1 \mid x_1,x_2,...,x_N) = \int\int\int\int f(\mu_1,\mu_2,\sigma_1,\sigma_2,\alpha \mid x_1,x_2,...,x_N) d\mu_2 \cdot d\sigma_1 \cdot d\sigma_2 \cdot d\alpha$$

$$f(\sigma_1 \mid x_1,x_2,...,x_N) = \int\int\int\int f(\mu_1,\mu_2,\sigma_1,\sigma_2,\alpha \mid x_1,x_2,...,x_N) d\mu_1 \cdot d\mu_2 \cdot d\sigma_2 \cdot d\alpha$$

$$f(\mu_2 \mid x_1,x_2,...,x_N) = \int\int\int\int f(\mu_1,\mu_2,\sigma_1,\sigma_2,\alpha \mid x_1,x_2,...,x_N) d\mu_1 \cdot d\sigma_1 \cdot d\sigma_2 \cdot d\alpha$$

$$f(\sigma_2 \mid x_1,x_2,...,x_N) = \int\int\int\int f(\mu_1,\mu_2,\sigma_1,\sigma_2,\alpha \mid x_1,x_2,...,x_N) d\mu_1 \cdot d\sigma_1 \cdot d\mu_2 \cdot d\alpha$$

In this report, we summarize the marginal pdfs by reporting the median and standard deviation of the pdf for each of the 5 parameters.

For the Bayesian model presented here, prior probability distributions have been used for (1) the mean DIDSON length of small non-salmon species, (2) the *CV*s for the length distributions and (3) the proportions of sockeye salmon and small resident fish and for the observation uncertainty. Fixed values have been assumed for the mean DIDSON length for sockeye and pink salmon based on test fishing samples. The *CV*s of the length distributions for sockeye and pink salmon are assumed equal. This model has been applied to the datasets used for Figures 17 and 19 and results are presented in Table 4.

Differences between the Bayesian results versus the Maximum Likelihood results are limited when the individual distributions are as pronounced within the mixture as on August 17-19, 2011 (Fig.16 vs. Fig.17). When two different length distributions overlap substantially as is the case on August 25-26, 2011 (Figure 19) as sockeye and pink salmon co-migrated in the river, the results of the Bayesian model may differ substantially from the Maximum likelihood results. This is due to the fact that the Bayesian model takes into account the observation uncertainty which will be a function of sample size. As the number of samples used in the analysis increases, the observation uncertainty will decrease and the results from the Bayesian analysis will converge with the maximum likelihood estimate.

FINANCIAL STATEMENT

Project Budget Form

Name of Project: Implementation of an offshore sub-sampling system with side-scan sonar for in-season use
at the PSC Mission Hydroacoustics site

ELIGIBLE COSTS

Labour
Wages & Salaries

Position	# of crew	# of work days	hrs per day	rate per hour	Total (PSC + In-kind + cash)	In-Kind & Cash	PSC Amount	Actual PSC Exp.	Variance from PSC Amt	% Var
Technician(EG-5)	1	25	4	34.9	3,490	3,490				
Technician (EG-3)	1	25	3	30	2,250	2,250				
Biologist (BI-2)	1	25	3	38.2	2,865	2,865				
Scientist (RES-3)	1	25	3	52.6	3,945	3,945				
Support Staff	3	21	8	21.26	10,715		10,715.04	7,487.63	3,227.41	30%
Post-Season Processing	2	45	8	21.26	15,307		15,307.20	12,191.67	3,115.53	20%
							-			
Person Days (# of crew x work days)		1,494	**sub total**		$ 38,572.24	$ 12,550.00	26,022.24	19,679.30	6,342.94	24%

Labour - Employer Costs (percent of wages subtotal amount)

	rate	12%	Seasonal				3,122.67	1,416.59	1,706.08	55%
		25.00%	FullTime			3,138				
			sub total		$ 6,260.17	$ 3,137.50	3,122.67	1,416.59	1,706.08	55%

Subcontractors & Consultants

	# of crew	# of work days	hrs per day	rate per hour						
Software Support	1	19	7.5	70	9,975		9,975.00	4,560.00	5,415.00	54%
Vessel contracting					-					
					-					
					-					
Insurance if applicable	rate	0%								
			sub total		$ 9,975.00	$ -	9,975.00	4,560.00	5,415.00	54%

Volunteer Labour

	# of crew	# of work days	hrs per day							
Skilled					-					
Un-skilled					-					
Insurance if applicable	rate	0%								
			sub total		-					

Total Labour Costs	$ 54,807.41	$ 15,687.50	39,119.91	25,655.89	13,464.02	34%

Site / Project Costs
Provide details in the space below (use an additional page if needed)

		Total (PSC + In-kind + cash)	In-Kind & Cash	PSC Amount	Actual PSC Exp.	Variance from PSC Amt	% Var
Travel (do not include to & from work)		-		-			
Small Tools & Equipment		500	500				
Site Supplies & Materials		2,000		2,000.00	152.29	1,847.71	92%
Equipment Rental	(DIDSON, Cables, Rotator Lease for 1 month + Shipping)	15,128		15,128.00	15,466.47	(338.47)	-2%
Work & Safety Gear		500	500				
Repairs & Maintenace		2,000		2,000.00			100%
Permits		-					
Other site costs	Generator Fuel, anchors, oil, misc	500		500.00			100%
Technical Monitoring		-					

Total Site / Project Costs	$ 20,628.00	$ 1,000.00	19,628.00	15,618.76	1,509.24	20%

ELIGIBLE COSTS

Training (e.g Swiftwater, bear aware, electrofishing, etc.)

Name of course	# of crew	# of days		Total (PSC + In-kind + cash)	In-Kind & Cash	PSC Amount			
				-					
				-					
				-					
				-					
			Total Training Costs	$ -	$ -	-	-		

Administrative Costs

		Total (PSC + In-kind + cash)	In-Kind & Cash	PSC Amount	Actual PSC Exp.		
Office space; including utilities, etc.		1,600	1,600				
Office supplies		600	600				
Telephone & Long Distance		1,000	1,000				
Photocopies & printing		60	60				
Insurance		100	100				
Indirect/overhead costs		2,938		2,938.00	2,938.00		0%
(If the PSC contribution to Indirect costs exceeds 20% of the total PSC grant you will be required to submit back-up documentation justifying the expense).		-					
Other overhead costs (PSC Office Support)		-					
Total Administrative Costs		6,298	$ 3,360.00	2,938.00	2,938.00	-	

Capital Costs / Assets
Provide details in the space below (use an additional page if needed)

Assets are things of value that have an initial cost of $250 CAN or more and which can be readily misappropriated for personal use or gain or which are not, or will not be, fully consumed during the term of the project.

		Total (PSC + In-kind + cash)	In-Kind & Cash	PSC Amount	Actual PSC Exp.		
		-		-			
DIDSON		-		-			
Percent of Existing Acoustic Equipment (DIDSON, Sensors, CPU, Software, Cables, ADCP)		60,000	60,000				
Support Vessel		10,000	10,000				
		-					
Total Capital Costs		70,000	$ 70,000.00	-	-	-	

Project Total Costs	$ 151,733.41	$ 90,047.50	61,685.91	44,212.65	14,973.26	28%

Pacific Salmon Commission

Implementation of an Offshore Sub-Sampling System with Side-Scan Sonar   SF-2012-I-3

Statement of Receipts and Expenditures

As at: March 31, 2013

	ACTUAL	BUDGET	Variance
Receipts			
Project Grant	$ 55,517.00	$ 61,686.00	$ 6,169.00
Total receipts	$ 55,517.00	$ 61,686.00	$ 6,169.00
Expenditures			
Total Labour Costs	$ 25,655.89	$ 39,120.00	$ 13,464.11
Total Site/ Project Costs	$ 15,618.76	$ 19,628.00	$ 4,009.24
Administration	2,938.00	2,938.00	-
Capital Costs			-
Total Expenditures	44,212.65	61,686.00	17,473.35
Balance	$ 11,304.35	$ -	$ (11,304.35)

I certify the information given above is, to the best of my knowledge, correct and complete

Date: May 1, 2013   Signature:

Bonnie Dalziel

Position: Accountant