A brief history of Fraser River hydroacoustics

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Estimating the sockeye salmon (*Oncorhynchus nerka*) escapement in the Fraser River with acoustic systems is a two step process: (1) compiling upstream and downstream counts of salmon with acoustic systems to calculate net upstream flux (=escapement), and (2) the allocation of acoustic counts to salmon species based on test fishing or some other representative sample of the species and their relative abundances in the river. Although there are uncertainties in both steps, we focus this paper only on the acoustic component of this process because substantial advancements in methodology have reduced the impact of biases affecting acoustic estimates and the overall uncertainty in the resulting escapement estimates. Estimating species composition remains challenging, particularly during pink salmon years (odd-numbered years) in the Fraser River.

Daily in-season estimates of gross sockeye salmon escapement have been made using hydroacoustic technology at Mission since 1977. The Fraser River is about 400 m wide at Mission, current velocity is relatively low, and tidal effects at the site become more pronounced as discharge drops through the summer. A downward-looking single-beam acoustic system has been used to estimate sockeye salmon and pink salmon (*O. gorbuscha*) escapement in the Fraser River at Mission since 1977 (Woodey 1987). The transducer was mounted in a towed-body attached to a vessel that transects the river from bank-to-bank throughout the migration period to estimate fish density. Nine stationary soundings at random locations across the river are interspersed among transects in each 24-hr period to obtain estimates of fish speed and direction of travel (Banneheka et al. 1995) and the data from the transects and stationary soundings are processed using a modified duration-in-beam technique (Thorne 1988) to estimate the net upstream flux (escapement) of salmon. Approximately 18 h of transecting and 3-h of stationary soundings are conducted in each 24-h period. The methods used to produce escapement estimates from the vessel-based single-beam system are well described by Banneheka et al. (1995).

Because of the large width of the Fraser River at Mission, a single acoustic system cannot cover the entire river cross-section. The single-beam vessel-based echosounder was the sole source of official estimates of salmon passage at Mission from 1977 to 1998. A fixed location side-looking 200 kHz split-beam acoustic system was deployed on the left (south) bank in 1999, sampling approximately 100-150 m of the cross-section on a consistent basis, and data from this system combined with the transecting vessel have been used to produce official estimates of gross escapement at Mission since this time. The implementation of the left-bank split-beam system was the result of extensive development and testing of this approach by DFO at Qualark (see Enzenhofer and Cronkite 2000) and a four-year collaborative program (1995-1998) to assess biases and test the validity of key assumptions of the single-beam system used at Mission (see Xie et al. 1997, 2002). Testing of a down-looking split-beam transducer on the transecting vessel in parallel with the single-beam system began in 2001 and 2002. Official estimates of daily passage from the boat-based system were derived from the split-beam echosounder beginning in 2004. The single-beam data were collected as backup and for compatibility with the historical legacy. The main advantages of a split-beam systems relative to a single-beam system are that the split-beam system can accurately determine the position coordinates (x,y,z) of a target within the beam and can use this information to correct acoustic target size information based on position within the beam. In contrast, a single-beam system is only able to accurately determine the range of a target from the transducer (z coordinate) and so cannot correct target size information for position within the beam. In 2005, as a result of discussions and collaborative research with DFO, the PSC undertook preliminary work to establish a side-looking acoustic system using the DIDSON imaging sonar technology on the right-(north) bank of the Fraser River and in 2008 a permanent facility was constructed. The present configuration of the acoustic systems at Mission consists of a shore-based split-beam system on the left-bank, covering 100-150 m of cross-section, a shore-based DIDSON system on the right-bank covering 75 m of cross-section, and the downward looking vessel-based split-beam system covering the middle portion of the river.

In order to estimate the upstream flux of fish from the vessel data, knowledge of the velocity and direction of travel of targets is needed. These parameters cannot be estimated while the vessel is moving so periodically stationary soundings are made to estimate velocity and direction of travel. This procedure was effective for the single-beam system, although the data exhibited considerable noise owing to the method of estimating these parameters, i.e., duration in beam technique. However, even with stationary soundings, velocity and direction of travel cannot be estimated with the downward looking split-beam system on the vessel because the data from this transducer exhibit a positional bias toward the beam axis (i.e., target positions are recorded closer to the centre of the beam than is true) that cannot be corrected during the collection or analysis of these data. As a result, the split-beam system on the vessel overestimates fish velocity and produces unreliable direction of travel data when fish density is high; fish density estimates are not seriously affected by this positional bias. The impact of positional bias on the stationary left-bank system, which uses elliptical 2° x 10° and 4° x 10° transducers, is minimal relative to the vessel-based system and the data from the left-bank system are currently applied to the vessel split-beam data across the middle portion of the Fraser River. The use of the left-bank velocity and direction of travel estimates across the entire cross-section is a potentially serious bias and a concern to both DFO and the PSC, but at present there are no alternative methods if the current configuration of vessel-based and bank-based systems is left unchanged. A combination of site characteristics (wide river, slow currents reducing upstream stimulus to fish, tidal influence), fish behaviour (boat avoidance, milling on high slack tides late in the season), and the allocation of acoustic counts to species from the test fisheries species composition data are ongoing technical challenges that reduce precision and contribute to uncertainty in the Mission estimates of gross escapement.

Substantial discrepancies between the Mission estimates and upstream estimates of total summer-run sockeye salmon escapement in 1992 and 1994 led to public reviews of Fraser River sockeye salmon assessment and management, resulting in the Pearse (1992) and the Fraser River Sockeye Public Review Board (1995) reports. Both inquires concluded that these discrepancies could not be attributed solely to measurement error or natural variability, noting concerns about the accuracy of the Mission estimates based on biases identified in the acoustic methodology, and recommended validating and improving the Mission estimates and analysis using new techniques and technology (Farmer et al. 1994). Larkin and Pearse (1992), in a technical appendix to the main Pearse (1992) report, specifically recommended the establishment of acoustic facilities upstream of Mission to estimate the daily migration of sockeye salmon as an independent check on the accuracy of escapement estimates made by the PSC at Mission. DFOs implementation of the Pearse (1992) review recommendations led to the establishment of the Riverine Acoustics program in early 1993.

In early 1993, DFO surveyed the mainstem of the Fraser River for acoustic sites to develop new techniques for assessing migrating fish populations in riverine environments. This survey went as far upstream as the Big Bar ferry crossing and identified potential sites at Boston Bar and a site about 5 river km below Yale, the Qualark acoustic site. Based on physical (current velocity patterns, cross-sectional profile, bottom substrate), logistical (road and boat access were desirable), and political (cooperation of First Nations, desire be near Sawmill Creek fishing boundary) considerations, the decision was made to develop a site near the confluence of Qualark Creek and the Fraser River (Mulligan 1996). The Qualark acoustic site is approximately 95 km upstream from the Mission Highway Bridge and was operated as an experimental research facility from 1993 to the end of 1998 sockeye salmon run. The primary goal of research at Qualark was to develop the equipment and acoustic methods to produce accurate estimates salmon escapement in riverine environments. A variety of experiments were conducted during this period to address specific sources of error or bias in the methodology as they were identified (Mulligan 1996) and an echo counting model that addresses biases associated with non-uniform density distribution across the beam cross-section (Mulligan and Kieser 1996). Although upstream migration was monitored periodically between 1993 and 1998, Qualark never produced daily estimates of upstream flux operationally for management purposes. One of the more important aspects of the Qualark work is that the accuracy of the methodology was validated by an experiment at Spences Bridge on the Thompson River, which concluded that escapement estimates produced with the new methodology were as accurate as visual counts over the range of fish densities typically observed from migrating sockeye salmon (Enzenhofer et al. 1998). This work also demonstrated that Spences Bridge is a good acoustic site and could probably be used to provide estimates of sockeye salmon gross escapement into the Thompson system. Many of the technological and methodological innovations developed at Qualark were transferred to the PSC and continue to be used by the Mission acoustic facility at present. Enzenhofer and Cronkite (2000) document the specialized equipment and techniques developed and tested at Qualark, along with operational procedures for the site.

During the 1996-1998 seasons when the Qualark acoustic systems were operated in fish passage monitoring mode, the pattern and magnitude of changes in fish passage estimates at Qualark tracked those at Mission, especially for summer-run sockeye salmon stocks (Figure 1). The Qualark time-series data are lagged 2-3 days relative to the Mission data to account for the time required by fish to migrate between Mission and Qualark (Mulligan 1996). Although these similarities are impressive considering that primary goal at Qualark was research rather than producing daily passage estimates, there are some discrepancies between estimates of fish passage at these sites in July and late August-September. The early season differences are related to the presence of early Stuart fish, which enter the Fraser during a period when freshets often occur, and respond to the combination of fast currents and high silt loading associated with freshets by travelling closer to the shoreline and nearer the surface than later summer-run stocks. The shoreline and surface orientation of these fish as they travel upstream coupled with their low numbers adversely affect the performance of hydroacoustic enumeration system at Mission, in contrast to Qualark, where fish counting is not strongly affected by these issues. However, by the end of the season, fewer fish were counted at Qualark relative to Mission because of the presence of in-river fisheries between the two sites; neither time-series was corrected for riverine catches or the presence of stocks that pass Mission but not Qualark. The accuracy of the Qualark data is supported by results of the Spences Bridge experiment (Enzenhofer et al. 1998), in contrast to Mission estimates, which have never been formally assessed and probably can't be assessed directly. A disadvantage of using Qualark data for in-season management is that some sockeye salmon stocks for which there are important conservation concerns such as Cultus Lake, Chilliwack River, Weaver Creek, Birkenhead River, upper Pitt River, and the Harrison system, leave the Fraser River before they arrive at Qualark.

The only other site identified on the mainstem of the Fraser River in 1993 as a potential acoustic site was Boston Bar. Boston Bar is 47 km upstream from Qualark and 142 km from the Mission, meaning 4-5 days travel for fish from Mission. Acoustic data collection at Boston Bar would provide passage estimates above

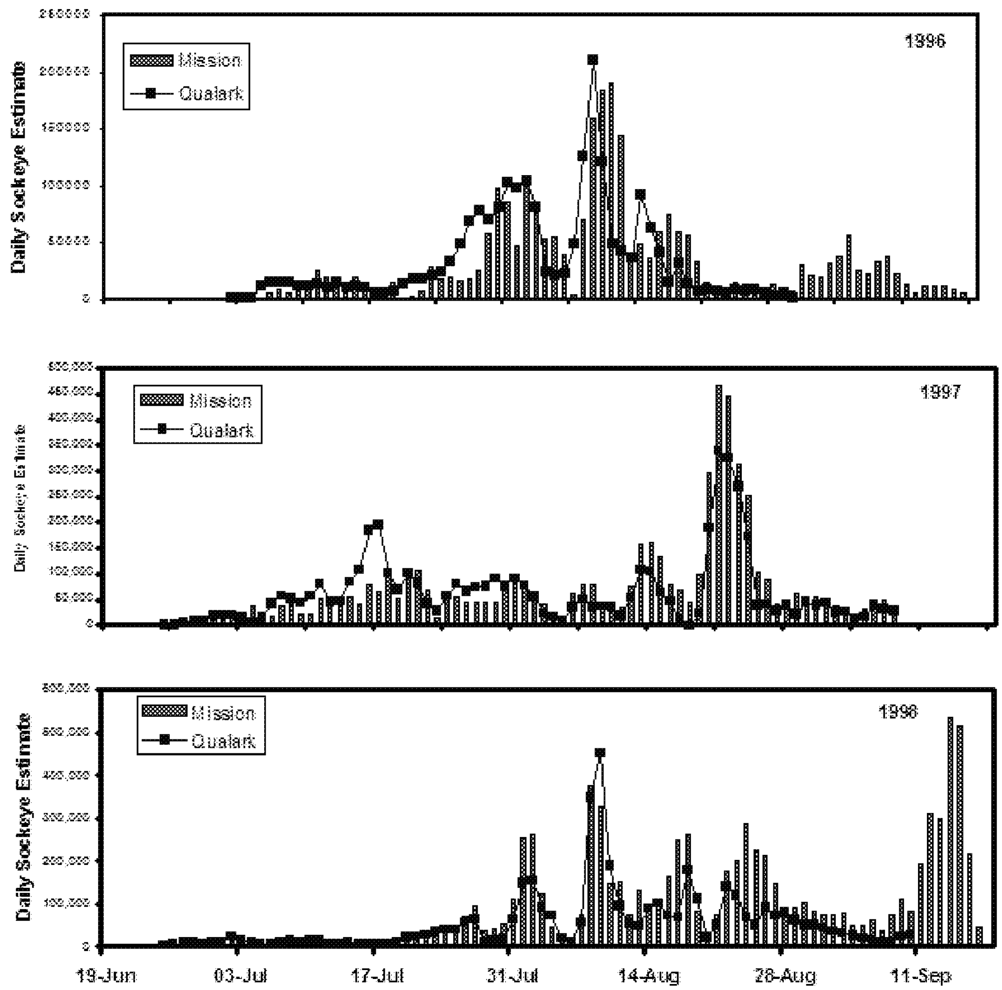

Figure 1. Time series plots of Mission and Qualark daily sockeye salmon escapement estimates (lagged 2 days) for 1996 (top), 1997 (middle) and 1998 (bottom). Note: Qualark estimates after August 15 in 1998 are incomplete due to low water at the site.

Hell's Gate (as recommended by Larkin and Pearse 1992) so that mortality in the canyon could be assessed but it seems unlikely that data collected at Boston Bar could be used for in-season management, owing to its location far up the watershed. Two sites, one above the North Bend bridge (<100 m) and one below the bridge were examined by DFO on 07 Oct 1993 with a split-beam system to assess acoustic background noise levels. Based on this work, it was concluded that both locations were workable, with the upstream site being more favourable for hydroacoustics due to a lower current flow, but Boston Bar was not developed further owing to logistical and political considerations. As part of joint DFO/PSC Hydroacoustic Working Group (HaWG) discussions, both locations were re-visited on 04 Feb 2003, for further assessment when the low river discharge exposed more of the bottom. The PSC conducted a short study in September 2005 with a DIDSON imaging system at the location below the North Bend Bridge and concluded that migrating salmon could be detected at this site (Pacific Salmon Commission 2007). Follow-up work including verification of the river profile, extended testing, testing fish detection on the left bank, confirming river height fluctuation and developing a sampling plan was not performed nor was a benefit-cost analysis completed. DFO/PSC discussions concluded that 3-5 years of development work would be needed to assess the reliability of the fish passage estimates made at Boston Bar and implement these data into operational in-season management of Fraser River sockeye salmon. If this site was developed, careful consideration would need to be given to identifying the lead agency (DFO, PSC, other) responsible for the operation of this site.

After acquiring a DIDSON imaging sonar system in 2004, DFO surveyed the upper Fraser River and Shuswap Lake area to identify potential deployment sites for the DIDSON system and to determine the in-river equipment (e.g., weirs) needed to enhance the performance of the DIDSON system as a tool for counting salmon (Holmes et al. 2005). The focus of these surveys was on tributaries in which mark-recapture programs are currently used to estimate sockeye escapement. Site selection is key to successful implementation of hydroacoustic systems in riverine environments. Ideal conditions include a single channel, laminar flow, planar bottom configuration, fish actively migrating through the site with no milling or holding behaviour, a location below known spawning areas and a site that is easily accessible from nearby roads. Based on a combination of in-stream testing and site visits, Holmes et al. (2005) concluded that the DIDSON system could be used to effectively estimate escapement of sockeye salmon in Scotch Creek, Chilko, Horsefly, Mitchell and Seymour Rivers, and probably the upper Adams River as well. The Lower Shuswap, Lower Stuart, and Tachie Rivers were not considered suitable for deployment of the DIDSON system due to its range limitations and the widespread distribution of migrating fish across each river. Acoustic counting of migrating fish in the Lower Stuart River, particularly Chinook salmon, could be accomplished with shore-based side-looking split-beam systems, but at least one season of testing would be required to confirm this hypothesis. Neither the Lower Shuswap nor the Tachie were amenable to acoustic counting because of the high probability of unusual fish behaviour and poor site characteristics, respectively. Appropriate acoustic sites in the Fraser River watershed can be grouped into two categories: wide, high velocity sites (e.g., mainstem Fraser at Qualark Creek, Chilko, Adams) and narrower, lower velocity sites at which fish passage can be constricted by weirs (e.g., Horsefly, Mitchell, Seymour). Holmes et al. (2006) completed validation studies in 2004 to assess the accuracy and precision of data produced with a DIDSON system and concluded that the DIDSON data were as accurate as the visual counts of salmon through an enumeration fence (the most accurate method in clear-water streams in BC) provided that the acoustic beams were ensonifying the area through which fish are swimming, i.e., there are no blind zones near the surface or bottom through which fish can swim undetected and fish cannot swim upstream behind the acoustic system.

A DIDSON system was successfully deployed on the Horsefly River in 2005 to estimate sockeye salmon escapement and to begin the transfer of this technology into operational sockeye salmon assessment programs in British Columbia (Cronkite et al. 2006). This project also developed, tested and documented appropriate sampling protocols, length measurement protocols, data quality assurance procedures, and accessory equipment. Research was also conducted during the Horsefly River project to assess whether systematic hourly sampling (e.g., 10- and 20-min h^{-1}) was adequately representative of the stock of salmon migrating upstream when temporal variation in migration patterns is not known (Lilja et al. 2008), as this kind of sampling strategy is the most practical protocol for operational implementation. Lilja et al. (2008) concluded that the systematic sampling/counting scheme used to estimate sockeye salmon escapement on the Horsefly River was not biased by high-frequency temporal variation and that this design provided a representative sampling of the sockeye salmon stock in 2005 and based on simulations of sampling rate and precision attainable, recommended sampling a minimum of 10-min and a maximum of 20-min per hour to estimate salmon escapement, assuming that there are no other causes of variation in the data.

Surveys for potential DIDSON deployment sites in tributaries of the lower Fraser River were conducted in 2005. The lower Pitt River, the Harrison River above the confluence with the Fraser, and the Chilliwack/Vedder River were examined. Sweltzer Creek (the outlet of Cultus Lake) was not examined because there is a permanent enumeration fence on this system. Based on site visits and on-site testing, DFO concluded that there were no viable DIDSON deployment sites on the Lower Pitt or Harrison Rivers, but a potential site was identified on the Chilliwack River at the outlet of Chilliwack Lake and could be used if an alternative method of estimating escapement into Chilliwack Lake was necessary.

The DIDSON imaging sonar uses high frequency sound from multiple beams focused with a lens system to produce video images of objects and is produced in long-range and standard versions. The standard version uses 48 beams and has a maximum working range of 66 m for low frequency (1.1 MHz) and 96 beams and 15 m range for high frequency (1.8 MHz). The beams are usually oriented at a slight grazing angle to provide shape information about a target, but the point of view of the resulting image appears to be from directly above and looking straight down. The DIDSON system cannot collect biological information other than length or detect external tags on fish nor can it automatically count fish or reliably identify different salmon species in a mixed group. Automated counting and species identification are active areas of research at present. During the first phase of the DIDSON program, specialized equipment to support the deployment of the DIDSON system in tributaries of various sizes and accessibility was designed and tested by DFO (Enzenhofer and Cronkite 2005; Enzenhofer et al. 2005; Enzenhofer et al. 2007) and continues to be used at present.

One of the major advantages of adopting the DIDSON technology is that sonar expertise is not required to either operate or interpret the images (data). In contrast, the operation of a hydroacoustic site using split-beam technology requires a high level of acoustic expertise and knowledge of complex analytical protocols (Xie, 2000; Enzenhofer and Cronkite, 2000), which has hampered the transfer of split-beam technology to operational stock assessment staff. The intuitive nature of the DIDSON system means that reliable and timely escapement estimates are produced with a simplicity of operation that substantially reduces the training required for new staff unfamiliar with acoustic systems. The fish-count data produced with a DIDSON imaging sonar are as accurate as visual counts of fish migrating through an enumeration fence in a clear water river as long as the system is aimed so that the beams ensonify the area through which fish are migrating and there are no blind zones near the surface or bottom (Holmes et al., 2006). The simplicity of operation and ease of data interpretation have been important factors in the rapid transfer of this technology to field staff conducting terminal area assessments of sockeye salmon in the Fraser River watershed.

DFO also evaluated the performance of the Blueview ProViewer 900 kHz imaging system as a tool for salmon escapement estimation in 2007 (Cronkite et al. 2008) because the acquisition cost of this technology is about one third the cost of a DIDSON system (76K USD). Cronkite et al. (2008) found that the count data produced by the ProViewer system were systematically biased relative to concurrent visual counts and that variability between observers counting the upstream passage from the ProViewer data files was high at 25.7%. The bias in the count data resulted from the non-detection of fish passing through the ProViewer beams by observers conducting the screen counts and the low precision among observers was related to the level of image resolution and idiosyncrasies of the ProViewer software. Although improvements to the software could increase the usefulness of the ProViewer for counting migrating salmon in rivers, the manufacturer, Blueview Technologies Inc., does not view fisheries applications as the prime market for this technology and has been unresponsive. This lack of interest in fisheries applications is in marked contrast to Sound Metrics, which manufactures the DIDSON system. At present, DFO does not recommended that the Blueview ProViewer be considered for salmon escapement estimation applications.

Discrepancies between Mission estimates of gross escapement and upstream estimates of total summer-run sockeye salmon escapement in 2004 led to further public review of Fraser River sockeye salmon assessment and management. Both the Williams Inquiry (Williams 2005) and a report from the Senate Committee on Fisheries and Oceans (Wappel 2005), which resulted from separate processes, recommended that DFO consider the benefits to management of estimating salmon abundance at sites upstream of Mission and lower river fisheries but before high-stress passage areas in the Fraser Canyon, specifically referring to Qualark. Obtaining reliable estimates of sockeye losses ultimately depends on minimizing the signal-to-noise ratio (i.e. estimation errors) relative to the abundance of the fish. The benefits are therefore conditional on understanding the limits to estimation error relative to differences in fish abundance. During experimental work at Qualark in the 1990s, the split-beam methodology performed well over the range of fish densities typically observed for migrating salmon (Mulligan 1996) and the accuracy of the methodology and resulting estimates was verified experimentally at an independent site on the Thompson River (Enzenhofer et al. 1998).

Reliable estimates of sockeye salmon escapement in the Fraser River are a prerequisite for achieving spawning escapement goals and harvest allocation among stocks. Although the hydroacoustic estimation system at Mission has been improved continuously over the past 30 years, additional gains in reliability owing to operational improvements at this site are unlikely either because the costs will be high relative to the incremental increase achievable or because such improvements are not technically feasible at present. Future options for gross escapement estimation include accepting existing limitations and continue at Mission or finding an alternate site at which the reliability (i.e., accuracy and precision) of escapement estimates is higher than is achievable at Mission. The Qualark acoustic site was identified as a site meeting the latter criterion in the mid 1990s in response to recommendations from the Pearse (1992) report, the first inquiry into "missing fish" in the Fraser River.

DFO operated Qualark in 2008 and 2009 to assess whether Qualark fits into the broader sockeye salmon assessment framework as a system-wide abundance indicator and for verification of the hydroacoustic systems at Mission. This work was part of a broader view on how best to estimate run sizes for fisheries management and to assess both the direct and cumulative fishery and environmental mortality impacts on conservation and resource-use objectives as recommended by Williams (2005) and Wappel (2005). All five Pacific salmon species return to spawn in the Fraser River and pass the Qualark site. Sockeye salmon is the dominant species in even numbered years (e.g., 2008) while in odd numbered years (e.g., 2009), pink salmon are usually more abundant than sockeye salmon. The upstream migration of pink salmon during odd years presents additional technical challenges to the hydroacoustic system at Mission.

Daily estimates of net upstream escapement at Mission and Qualark are strongly correlated in both 2008 and 2009 (Figure 2). The Qualark estimates were produced using DIDSON systems on each bank while the Mission data were produced by the system described earlier. We have a high degree of confidence in the Qualark data, since the accuracy of the DIDSON methodology has been independently validated (Holmes et al. 2006). The Mission data are lagged 3 days relative to the Qualark data in order to account for the time required by fish to swim between the two sites and the 2009 data are scaled an order of magnitude higher than the 2008 data because of the presence of pink salmon in the river from mid-August through to the end of September. By the end of the 2008 run, fewer sockeye were counted at Qualark relative to Mission. A change in the migratory behaviour of sockeye salmon was observed during in-river fishery openings below Qualark in 2008, resulting in an offshore shift by up to 30% of the fish which did not persist beyond the fishery openings (Enzenhofer et al. 2010). Similar behaviour was also observed during the experimental phase of the Qualark site in the 1993-1998 period (Macdonald et al. 2000). The 2009 data shown in Figure 2 represent total salmon counts and again show strong consistency between the two sites. The Mission data have been adjusted to account for fish that pass Mission but not Qualark. Although the high fish densities associated with the migration of pink salmon in 2009 required some adjustments to counting procedures, the average error among counts was 4-5% (Enzenhofer et al. 2010), which was consistent with precision observed at other DIDSON sites with lower fish passage rates (e.g., Cronkite el. 2006; Holmes et al. 2006; Lilja et al. 2008). Further work to compare the 2008 and 2009 data from Mission and Qualark to characterize the similarities and serial dependence in these time series and to assess coherence between these datasets based on common cyclical behaviours, in the time and frequency domains, respectively, is currently planned.

A driftnet test fishery was operated at the Qualark site in both years to determine salmon species composition, to collect biological data for stock identification, and to test for presence/absence of fish passage in offshore waters. This fishery began on July 18 of both years after early Stuart fish had passed the site due to conservation concerns associated with sampling these fish. Test fishing and acoustics from the mid-1990s (Mulligan 1996) and 2008 and 2009 confirm that migrating fish are within 15 m of the shore, regardless of discharge and water levels. In 2009, two offshore drifts were conducted on a weekly basis to determine presence/absence in these waters in case migratory behaviour had changed. These offshore drifts did not capture any fish, nor did hourly offshore data collection with the left-bank DIDSON reveal any fish in these offshore waters. The application of test fishing results to acoustic counts is an active area of interest at Qualark and especially Mission.

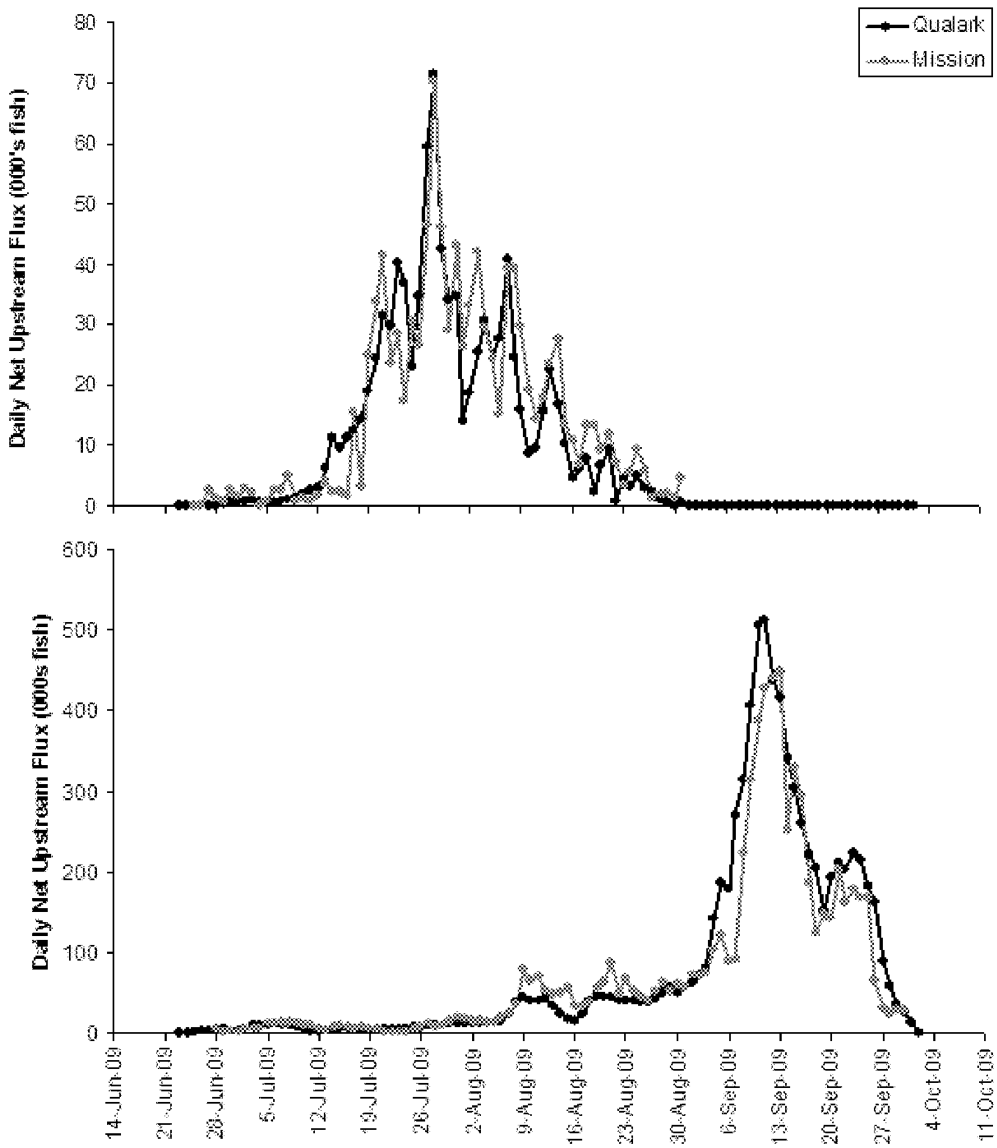

Figure 2. Daily net upstream flux estimates of all sockeye salmon at Qualark and Mission in 2008 (top) and all Pacific salmon 2009 (bottom). Mission estimates are lagged three days in both years to account for travel time between Mission and Qualark. Note difference in scales on the y-axis between years.

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