The residence time of juvenile Fraser River sockeye salmon (*Oncorhynchus nerka*) in the Strait of Georgia

D.B. Preikshot, R.J Beamish, R.M Sweeting, C.M. Neville and T.D. Beacham

Fisheries and Oceans Canada
Pacific Biological Station
3190 Hammond Bay Road
Nanaimo British Columbia V9T 6N7 CANADA

Abstract

Residence time of juvenile sockeye salmon (*Oncorhynchus nerka*) in the Strait of Georgia was estimated from catches of juveniles in a trawl survey and smolt sampling in the Fraser River. A residence time model indicated that most juvenile sockeye salmon remained in the Strait of Georgia from 27 to 45 days with an average residence time of 35 days. An analysis of Chilko Lake smolts indicated a residence time of 33 to 37 days. Observed growth of sockeye salmon smolts in the Strait of Georgia indicated a residence period of up to 40 days. Using a definition of residence time of the number of days between the day that the last 1% of the smolts entered the Strait of Georgia and the day the last 1% of the juveniles left the strait, we concluded that an average residence time was 35 days.

Introduction

The fishery for sockeye salmon (*Oncorhynchus nerka*) produced in the Fraser River drainage is probably the most important fishery on Canada's Pacific coast. The fishery is shared with the United States as some returning adults move into United States waters before entering the Fraser River. The United States and Canada established an international commission in 1937 (Roos 1991) to ensure that fishing was sustainable and to provide information that could be used to portion the catch between each country. Since 1937, there have been many issues and challenges, culminating in 2009 when the lowest adult return in recorded history surprised everyone. It was apparent that the poor survival occurred in the ocean as the number of smolts produced by the brood year was exceptionally large (Beamish *et al*. 2011a).

Until recently, little attention has been paid to the marine life history of sockeye salmon (Beamish *et al*. 2004). A seminal early work on sockeye salmon (Foerster 1968) devoted only one page out of more than 400 to the early marine life history phase. Even by the early 1990s, a 100-page chapter on sockeye salmon devoted only 1% of the text to the early marine life of sockeye salmon (Burgner 1991). The paucity of attention reflected the belief that processes in fresh water and fishing were the major influences on sockeye salmon production. As a consequence, there was relatively little information about the marine life history of Fraser River sockeye salmon until recently.

Studies in the spring of 2007 in the Strait of Georgia showed that there was exceptionally poor survival or growth or both for Pacific salmon (*Oncorhynchus* spp.) (Thomson *et al*. 2011, Beamish *et al*. 2011a). Maturing Fraser River sockeye salmon that returned to the drainage in 2009 first entered the Strait of Georgia in the spring of 2007. The extremely unfavourable ocean conditions in 2007 likely affected juvenile sockeye salmon. However, because the residence time of the juvenile sockeye salmon in the Strait of Georgia was uncertain, some studies have reported that impacts of marine rearing must have occurred after the juveniles left the strait (Welch *et al.* 2009, 2011). Thus, an estimate of average residence time is an essential part of determining why the marine survival was so poor for the Fraser River sockeye salmon smolts that entered the ocean in 2007.

<u>Definition of Residence Time</u>

Residence time for sockeye salmon in the Strait of Georgia has been reported in other studies (Healey 1980, Groot *et al.* 1985, Peterman *et al.* 1994), but these studies did not define the term and we are not aware of a definition. There is a general acceptance that residence time refers to the time a juvenile Pacific salmon spends in the Strait of Georgia, but for species that migrate out of the strait, there needs to be a clearer understanding of residence time. A number of definitions are possible. Any definition for the Strait of Georgia needs to consider that there are entry dates, exit dates and maximum abundance dates. Ocean entry and exit dates should relate to the movement of a percentage of the population which we consider is between 1% and 99%. Thus, the ocean entry date occurs when 1% of the population is in the strait and the exit date is when 99% have left the strait. We define the maximum abundance date as the day when the largest number of juvenile sockeye salmon is in the Strait of Georgia. We could determine the maximum abundance date in a trawl study that fished transects across the northern Strait of Georgia each day from about mid May to mid July in which the maximum of a standardized daily catch would be the maximum abundance date.

Average residence time could be the number of days between the date when the maximum number of smolts entered the Strait of Georgia and the maximum abundance of juveniles in the strait. However, we considered average residence time to be the number of days between the date that the last 1% of all smolts had entered the Strait of Georgia and the date that the last 1% of the juveniles left the strait. Other scenarios could be defined, such as total residence time which would be the number of days between the date that 1% of the smolts entered the strait and the date that 1% remained. There may also be components of the population that have different behaviours and life history strategies. Thus, larger and older juvenile sockeye salmon may migrate faster out of the Strait of Georgia, resulting in shorter average residence times when compared to most other juveniles. There could be residence times for specific populations or for specific groups of fish as might occur in tagging studies. However, residence times for particular groups should not be considered to be representative of all populations without evidence.

Methods

We estimated the timing of smolt entry into marine waters from timing data derived from a study of pink salmon (*O. gorbuscha*) fry migrations in the Fraser River. Consequently, Strait of Georgia entry data were only available for even-numbered years. Data from Fisheries and Oceans Canada (D. Patterson, pers. comm.) and the Pacific Salmon Commission were used to estimate the proportion of downstream migrating sockeye salmon smolts that passed a counting fence located 90 km upstream from the Fraser River mouth at Mission, British Columbia. These data were converted to a cumulative form using the summed proportion of the population that entered the strait, as indicated by a logistic growth curve for our model as:

$$Sum_d = (k\cdot(P_0\cdot e^{r\cdot d})) / (k+ P_0\cdot e^{r\cdot d})-1)$$

Where

Sum_d = Sum of population past Mission on day n

k = the maximum sum, *i.e.*, carrying capacity in the classic form of the model

r = growth rate

P_0 = starting number, *i.e.*, zero, and

d = time, in days.

The cumulative daily proportion of migrating smolts entering the Strait of Georgia was estimated with Microsoft Excel Solver to minimise the sum of squared differences between observed and predicted daily cumulative abundances by optimising r and P_0, *i.e.*, the ‘growth rate’ and initial population estimate, with k was set to 100, *i.e.*, 100 % of the fish being in the strait. This methodology was used to estimate time span for the smolts to migrate past Mission in a typical year by fitting logistic curves to individual years of available data (1998, 2000, 2002, 2004, 2006, and 2008). We defined the time of entry into marine waters as the date at which 99% of the smolt run had passed the sampling location.

We subsequently used catch per unit effort (CPUE) data from trawl surveys in the Strait of Georgia to estimate the timing of smolt emigration from the strait. A description of the juvenile salmon trawl survey program and sampling protocols was identified by Beamish *et al*. (2000) and Sweeting *et al*. (2003). Daily CPUE data were averaged for all sets in one day and for that day in all surveys. We also examined the declining trend with respect to sampling date of these average daily catches for each year to estimate the average maximum and minimum exit dates. Because we did not know the maximum CPUE, we were not able to estimate when 99% of the population had exited the strait, and thus we used the date when the declining CPUE was estimated to be zero as a proxy for exit date. We know that some juvenile sockeye salmon remained and we considered that the zero CPUE date represented a date when about 1% of the juveniles remained. The difference in time between 99% smolt entry into marine waters and 99% exit from the Strait of Georgia was defined as average residence time in the Strait of Georgia.

Surveys were conducted earlier than normal in 1997 and 2010, allowing us to use the trawl survey data in these two years to estimate a maximum CPUE. This maximum CPUE date was compared to the dates at which 100% of smolts had passed Mission as a means to infer the first half of residency. In both 1997 and 2010 there were surveys in early May before the juvenile sockeye salmon had moved to the northernmost areas of the Strait of Georgia.

Residence time was also estimated specifically for smolts from Chilko Lake. The estimated transit time from Chilko Lake to the Strait of Georgia was seven days (Crittenden 1994). Because the dates of emigration from the lake are known, we determined the entrance time of the population into the strait by lagging the exit date from Chilko Lake by seven days. DNA stock identification (Beacham *et al.* 2005) was used to identify juvenile Chilko Lake sockeye salmon in the Strait of Georgia. Using the date at which Chilko Lake smolts were sampled in the Strait of Georgia, we identified a minimum and maximum number of days that they had been in the Strait of Georgia in 2008 and 2009. Length data from Chilko Lake sockeye salmon smolt emigration surveys and catches of juvenile Pacific salmon surveys in the Strait of Georgia provided an estimate of minimum growth of juvenile sockeye salmon during their Strait of Georgia residence to infer minimum possible residence times. Length frequency data for growth analysis were obtained for sockeye salmon smolts leaving Chilko Lake in 2010 (T. Cone, DFO, pers. comm.) and from 2010 trawl and purse seine surveys. The mean and median values of length from these data sets were compared to estimate minimum and maximum growth rates. The estimate of minimum growth of juvenile sockeye salmon during their Strait of Georgia residence was compared to the other estimates of residence times.

Results

The standard trawl survey in the Strait of Georgia begins in late June or early July and ends a week or two later (Beamish *et al.* 2011a). Because this period tends to be after the maximum abundance of sockeye salmon, the daily averaged CPUE declined from larger values at the beginning of the survey, with the largest CPUEs found on the earliest dates for which surveys were conducted. The daily average CPUE for all sockeye salmon smolt surveys resulted in a trend which was very similar to a negative logistic curve (Figure 1, R^2 = 0.84). The declining trend indicated an average rate of movement out of the Strait of Georgia that would continue to the exit date. Daily CPUEs for individual years are shown in Table 1. Linear trend analysis of each year predicted a zero CPUE between July 4 and July 22 with a mean date of July 12. Two years, 1998 and 2002, were excluded because the linear trend continued to increase to infinity. In some years high catches at the end of sampling or low catches at the beginning suggested that abundance would increase and these years were not included in the calculation of exit date. These annual and long-term CPUE trends suggest that, on average, after mid-July very few sockeye salmon smolts that went past Mission in April/May are left in the Strait of Georgia.

Observed smolt abundances at Mission in 1998, 2000, 2002, 2004, 2006, and 2008 indicated that it took about 4-5 weeks for smolts to migrate past Mission (Figure 2). Maximum long-term daily abundance occurred on May 2 (Figure 3), which can be estimated as cumulative abundance by a logistic curve, $R^2 = 0.97$ (Figure 4). Logistic relationships were used in the residence time model to calculate the proportion of smolts passing Mission and then entering the Strait of Georgia (Figure 2). Individual yearly variation ranged from a minimum of 19 days for passage in 2000, to a maximum of 48 days for passage in 2004 (Figure 2). Cumulative abundance past Mission closely followed a logistic curve in all years (R^2=0.85, 0.96, 0.98, 0.99, 0.98, and 0.98 for 1998, 2000, 2002, 2004, 2006, and 2008 respectively.) Model results using July 12 as the mean last exit day indicated that maximum abundance of juvenile sockeye salmon occurred between May 30 and June 15 (Figure 5). In these years the first to enter had already exited the strait by the time the last smolts entered. The mean residence time was 35 days (Figure 6).

Parabolas fitted to the CPUE data indicated that peak juvenile abundances occurred on June 14 (1997) and June 18 (2010) (Figure 7). With an average maximum smolt abundance date at Mission of May 2, the average number of days between the two maxima would be 43 days in 1997 and 47 in 2010.

The projections of Chilko Lake sockeye smolt migration into the Strait of Georgia in 2008 and 2009 indicated that the 1st, 50th and 99th percentiles of the population entered the strait on April 27, May 13 and May 26 in 2008 and on May 7, May 13 and May 19 in 2009, respectively (Figure 8). When these early, middle and late entry dates were compared to dates Chilko Lake sockeye salmon smolts were sampled in late surveys, the minimum time the smolts could have been in the Strait of Georgia was calculated to be 34 to 35 days (2008) and 33 to 37 days (2009). This estimate assumed that the juvenile sockeye salmon sampled in the strait came from the 99th percentile to have entered the Strait of Georgia; i.e., how many days would the sampled smolts have been in the strait had they been among the last of the smolts to have entered the strait. Estimates using the 50th and 1st percentiles, i.e., assuming the sampled smolts entered the strait near the peak or the beginning of the migration into the strait, were outlined in Table 2. These latter scenarios suggested that some juvenile Chilko Lake sockeye salmon could have been in the strait for as long as six to eight weeks.

Chilko Lake smolts were approximately 92 mm mean fork length upon leaving Chilko Lake in 2010 around May 3rd, 103 mm in length when caught in the Strait of Georgia on May 19th, 117 mm when caught on June 4th, and approximately 131 mm when caught on June 15th (Figure 9).Growth of juveniles in the Strait of Georgia in 2010 was about 0.9 mm a day, as they grew about 39 mm in length in about 43 days during downstream migration and residency in the strait (Table 3). If the time from Chilko Lake to the Strait of Georgia is seven days, the growth of 39 mm would occur in 36 days under the assumption of no growth during freshwater migration, resulting in a growth of approximately 1.1 mm a day.

Discussion

This study indicated that the time between last (1%) entry of juvenile sockeye salmon into the Strait of Georgia and last exit from the strait was an average of 35 days. This estimate of average residence time was almost identical to estimates for Chilko Lake smolts in 2008 and 2009. Our examination of growth of juvenile Chilko Lake sockeye salmon in 2010 indicated at least a five week residence time. Estimates of the interval between maximum abundances of smolts at Mission and juveniles in the Strait of Georgia averaged 45 days. Considering that it would take one to two days to enter the Strait of Georgia after passing Mission, and that an average maximum abundance date was used at Mission, the time between the two maxima is somewhat longer than the estimated average residence time of 35 days. Thus, there was consistency in the estimate of an average residence time of at least 35 days in the Strait of Georgia. We recognize that individual fish may behave differently, with some, perhaps the larger and older juveniles, having only a short residence time.

We know that some lake-type sockeye salmon remain longer (Beamish *et al.* 2011a), but the general decline in abundance of juveniles identified in this study indicated that virtually all juveniles left the Strait of Georgia by July 12 in an average year. Because our surveys were usually seven to ten days in duration, the annual declines in CPUE were manifested as linear trends whereas a long-term average CPUE as seen in 1997 and 2010 had a logistic shape. We expect that more intensive and longer duration surveys in the Strait of Georgia would show that a logistic-type relationship represents the pattern of abundance as identified by CPUE.

Another factor influencing the model is the assumption that the measured cumulative abundance of sockeye salmon smolts at Mission is an indication of the passage of all Fraser River populations. However, there may be some years in which the behaviour of one or two populations dominates the Mission data set. For instance, in 1998 there was a bimodal distribution of the emigrating smolts which reflected Chilko Lake smolt emigration timing from Chilko Lake a few days earlier (T. Cone, DFO, pers. comm.). Furthermore, the Chilko Lake smolt counts in 1998 showed that emigration continued for several days after counting at Mission was over; thus, 100% cumulative abundance was not achieved. The implication may be that the Mission smolt counts did not capture the end portion of smolt passage.

The average number of smolts passing Mission (Figure 4) indicated that more than one half of the smolts had migrated into the strait by mid May. An extensive purse seine survey in 2010 did not detect any juvenile Fraser River sockeye salmon in the passages exiting the northern Strait of Georgia during May 15-18 (Figure 10). This same survey did find Fraser River sockeye salmon smolts in the Strait of Georgia from May 18-23, 2010. Because large abundances of smolts entered the strait by mid May and few had left as indicated by the purse seine survey, it is possible that large abundances of juvenile sockeye salmon are in the Strait of Georgia in early May. The distribution of juvenile Fraser River sockeye salmon in Queen Charlotte Sound and Hecate Strait in late June (Thomson *et al.* 2011) indicates that the juveniles are leaving the Strait of Georgia north through Johnstone Strait. By early July, juvenile sockeye salmon from the Fraser River are distributed from the Gulf Islands in the Strait of Georgia to Hecate Strait (Thomson *et al.* 2011, Beamish *et al.* 2011a). We are not able to relate the relative abundances of these juveniles to the abundance of all surviving juveniles; however, we know that there is a relationship between the average catches and the total return (Beamish *et al.* 2011a), suggesting that the abundances within the strait are representative of abundances that have left the Strait of Georgia. This would also indicate that in years of small average CPUEs there would be only small abundances outside the Strait of Georgia. It is in mid June when we estimate that the maximum number of juvenile sockeye salmon is in the Strait of Georgia.

The model did not attempt to capture the migration timing and duration of Harrison River sockeye salmon smolts. Many life history characteristics of this population are distinct from other Fraser River sockeye salmon. Most Fraser River sockeye salmon migrate to sea in spring after spending two or three winters in fresh water. Harrison smolts migrate to sea later in the calendar year, after having only spent the winter after their brood year in fresh water (Beamish *et al*. 2010, 2011b). One consequence of this behaviour may be some of the anomalously high catches seen in CPUE data from mid July onwards. One way to exclude Harrison fish from our data set would be through genetic analysis but this was conducted only in 2008 and 2009. Beamish *et al.* (2011a) considered a scenario that excludes catches of smaller fish in order to assess the impact of Harrison sockeye salmon in the data from the trawl survey. They found that a possible impact of Harrison sockeye salmon in the trawl surveys occurred only in 1998 and 2006.

The movement of juvenile Fraser River sockeye salmon through the Strait of Georgia has been interpreted to be relatively rapid and directed. Clemens (1951) reported that “undoubtedly the bulk of Fraser River sockeye salmon smolts migrating through the Strait of Georgia go to the open sea by the southern route through Juan de Fuca Strait.” This conclusion was based on the knowledge that sockeye salmon smolts remain in upper waters which are under tidal influences drawing them towards the Juan de Fuca Strait on the ebb tide and outflow of the Fraser River plume on the surface which tends to leave the Strait of Georgia through Haro Strait. The combination of the two physical processes can result in currents in excess of 5 knots. Thus, the implication was that movement of sockeye smolts through the Strait of Georgia would be both directed southwards and be relatively rapid. However, there was no confirmation of these ideas. Clemens (1951) reported that in beach seine surveys around the San Juan Islands between July 3 and August 8, 1950, no sockeye salmon were observed. He hypothesised that this could be due to the fish already having passed with confirmation of the short residence time or at least a residence time shorter than the pink, chum (*O.* keta) and chinook (*O. tshawytscha*) salmon that were found in the seine nets. He also suggested that the juvenile sockeye salmon may not be vulnerable to capture by beach seines if their larger juvenile size gave them the ability to use deeper offshore water.

Despite relying on only negative evidence, the short residence time, southern migration route hypothesis was accepted by most researchers (Foerster 1968). More intensive surveys summarised in Healey (1980) maintained the suggestion that sockeye salmon smolts exited the Strait of Georgia by Juan de Fuca Strait with an estimated total time for transiting the Strait of Georgia of 20 to 30 days. We note that the upper end of Healey's 1980 estimate was close to the 35 days identified by this study.

The southern route hypothesis was not challenged until the mid 1980s with the results outlined by Groot and Cooke (1987). They tested the hypothesis that the tendency of adult Fraser River sockeye to use either the northern or southern route around Vancouver Island reflected the exit route the juveniles used. After analysing survey data from 1982 to 1984, they reported that almost all juvenile Fraser River sockeye salmon exited the Strait of Georgia by the northern route. This conclusion agrees with observations reported in Beamish *et al*. (2010, 2011b). Genetic evidence from surveys outside the Strait of Georgia also suggested that Fraser River sockeye salmon exited the Strait of Georgia by the northern route with the exception of some Harrison River smolts found on the west coast of Vancouver Island (Tucker *et al*. 2009).

Groot and Cooke (1987) suggested that the juveniles moved through the Strait of Georgia, with a residence time of 30 days, which is similar to our estimate of 35 days. Peterman *et al*. (1994) suggested that the duration of smolt migration through the Strait of Georgia was influenced by physical forcing, mostly by wind. Peterman *et al*. (1994) used a smolt migration model that included effects from wind, tides, and Fraser River flow to estimate a mean residence time of 24 days. They proposed that an index of this type of forcing could be related to subsequent marine survival of Fraser River sockeye salmon populations. Our results were more consistent with a movement model that involves a degree of dispersion of sockeye salmon smolts into the Strait of Georgia, either as a result of innate behaviour or physical forcing in the marine environment or both.

Welch *et al.* (2009) inserted acoustic tags in juvenile sockeye salmon that were leaving Cultus Lake in the Fraser River drainage. The fish they tagged were about 50% larger than the average smolt produced within the drainage. Ricker (1962) reported that these larger smolts would be expected to have a higher ocean survival than the average sized smolt. Thus, it might be expected that the behaviour of these tagged fish was not representative of the average juvenile sockeye salmon. However, Welch *et al.* (2009) reported that the average residence time of the tagged fish in his study was 26 to 34 days, which is only slightly shorter than our estimate for the average residence time of 35 days.

Our analysis of growth data in the Strait of Georgia indicated that juvenile Chilko Lake sockeye salmon grew about 0.9 mm a day while resident in the Strait of Georgia. We recognize that the increases in size may be a combination of growth and size selective mortalities. This increase in size or growth indicated that some juvenile Chilko Lake sockeye salmon sampled in our surveys remained and fed in the Strait of Georgia. The rate of growth is consistent with rates reported for juvenile Pacific salmon (Groot and Margolis 1991).

An average residence time of 35 days indicates that most juvenile sockeye would be affected by conditions in the Strait of Georgia. In 2007, juvenile Pacific herring and juvenile Pacific salmon experienced very poor growth and survival (Beamish *et al.* 2011a, Thomson *et al.* 2011). The adult production from this year class resulted in an historic low abundance for Pacific herring and sockeye salmon (Beamish *et al.* 2011a, Thomson *et al.* 2011). Very poor survival also occurred for coho and chum salmon (Beamish *et al.* 2011a). The very poor early marine survival probably was due to low food levels arising from unfavourable wind and river discharge condition around the Strait of Georgia in the spring of 2007 (Thomson *et al.* 2011). Juvenile sockeye salmon that experienced poor growth and survival resulting from the unfavourable conditions were also confronted with poor ocean conditions in areas north of the Strait of Georgia (Thomson *et al.* 2011). However, it is the residence period in the Strait of Georgia in 2007 that Beamish *et al.* (2011a) consider was the main reason for the record low return of sockeye salmon to the Fraser River in 2009.

Future research could be increased to sample the migrating juveniles as they enter and exit the Strait of Georgia. Frequent sampling of the north end of the Strait of Georgia from mid May to mid July would help to identify when maximum abundances occurred. An increased effort would improve estimates of the timing and duration of juvenile sockeye salmon migration through the strait as well as provide estimates of abundances and of juvenile mortality. After about 100 years of research, it would be most helpful if we were able to understand the mechanisms that affect the survival of juvenile sockeye salmon in the early marine period in the Strait of Georgia.

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References

Beacham, T.D., J.R. Candy, B. McIntosh, C. MacConnachie, A. Tabata, K. Kaukinen, L. Deng, K.M. Miller, R.E. Withler, and N.V. Varnavskaya. 2005. Estimation of stock composition and individual identification of sockeye salmon on a Pacific Rim basis using microsatellite and major histocompatibility complex variation. Transactions of the American Fisheries Society 134:1124–1146.

Beamish, R.J., C. Neville and R.Sweeting. 2011a. Evidence of a synchronous failure in juvenile Pacific salmon and herring production in the Strait of Georgia in the spring of 2007. (included in this submission to the Cohen Commission May 20, 2011)

Beamish, R.J., R.M. Sweeting, C.M. Neville, D. Preikshot, K.L. Lange and T.D. Beacham. 2011b. A late ocean entry life history type has improved survival for sockeye and chinook salmon in recent years in the Strait of Georgia. (included in this submission to the Cohen Commission May 20, 2011)

Beamish, R.J., K.L. Lange, C.M. Neville, R.M. Sweeting, T.D. Beacham and D. Preikshot. 2010. Late ocean entry of sea type sockeye salmon from the Harrison River in the Fraser River drainage results in improved productivity. North Pacific Anadromous Fisheries Commission Document 1283. 30 pp.

Beamish, R.J., J.T. Schnute, A.J. Cass, C.M. Neville, and R.M. Sweeting. 2004. The Influence of climate on the stock and recruitment of pink and sockeye salmon from the Fraser River British Columbia, Canada. Transactions of the American Fisheries Society 133:1396–1412.

Beamish, R.J., D. McCaughran, J.R. King, R.M. Sweeting, and G.A. McFarlane. 2000. Estimating the abundance of juvenile coho salmon in the Strait of Georgia by means of surface trawls. North American Journal of Fisheries Management 20:369-375.

Burgner, R.L. 1991. Life history of sockeye salmon (*Oncorhynchus nerka*). Pages 1-118 in C. Groot and L. Margolis (editors), Pacific Salmon Life Histories. University of British Columbia Press, Vancouver.

Clemens, W.A. 1951. The migration of Pacific salmon (*Oncorhynchus*). Transactions of the Royal Society of Canada Section V, Series 3, 45:9-17.

Cone, T. Personal communication. Data Manager, Fisheries and Oceans Canada, Sockeye & Pink Analytical Program. 100 Annacis Parkway, Unit 3 Delta, British Columbia V3M 6A2 Canada. Telephone : 604-666-7269.

Crittenden, R.N. 1994. A diffusion model for the downstream migration of sockeye salmon smolts. Ecological Modelling 71:69-84.

Foerster, R.E. 1968. The Sockeye Salmon *Oncorhynchus nerka*. Fisheries Research Bulletin Canada Bulletin 162, 422 p.

Groot, C., and K. Cooke. 1987. Are the migrations of juvenile and adult Fraser River sockeye salmon (*Oncorhynchus nerka*) in near-shore waters related? Pages 53-60 in H.D. Smith, L. Margolis, and C.C. Wood (editors), Sockeye Salmon (Oncorhynchus nerka) Population Biology and Future Management. Canadian Special Publication of Fisheries and Aquatic Sciences 96.

Groot, C., and L. Margolis (editors). 1991. Pacific Salmon Life Histories. University of British Columbia Press, Vancouver.

Groot, C., K. Cooke, G. Ellis, and R. Bailey. 1985. Data record of juvenile sockeye salmon and other fish species captured by purse seine and trawl in the Strait of Georgia and Johnstone and Queen Charlotte straits in 1982, 1983, 1984, and 1985. Canadian Data Report of Fisheries and Aquatic Sciences 561, 147 p.

Healey, M.C. 1980. The ecology of juvenile salmon in Georgia Strait, British Columbia. Pages 203-229 in W.J. McNeil and D.C. Himsworth (editors), Salmonid Ecosystems of the North Pacific. Oregon State University Press and Oregon State University Sea Grant College Program, Corvallis.

Patterson, D. Personal Communication. Research Biologist, Freshwater Ecosystems Section, Fisheries & Oceans Canada, Co-operative Resource Management Institute c/o REM, Simon Fraser University. 8888 University Drive, Burnaby B.C. V5A 1S6 Canada. Phone: 604-666-5671

Peterman, R.M., S.G. Marinone, K.A. Thomson, I.D. Jardine, R. Crittenden, P.H. LeBlond, and C.J. Walters. 1994. Simulation of juvenile sockeye salmon (*Oncorhynchus nerka*) migrations in the Strait of Georgia, British Columbia. Fisheries Oceanography, 3:221–235. doi: 10.1111/j.1365-2419.1994.tb00100.x

Roos, J.F. 1991. Restoring Fraser River salmon: A history of the International Pacific Salmon Fisheries Commission 1937-1985. The Pacific Salmon Commission, Vancouver, B.C, 438 p.

Sweeting, R.M., R.J. Beamish, D.J. Noakes, and C.M. Neville. 2003. Replacement of wild coho salmon by hatchery-reared coho salmon in the Strait of Georgia over the past three decades. North American Journal of Fisheries Management 23:492-502.

Thomson, R.E., R.J. Beamish, T.D. Beacham, M. Trudel, P.H. Whitfield, and R.A.S. Hourston. 2011. Anomalous ocean conditions may explain extreme variability in Fraser River sockeye salmon production. (included in this submission to the Cohen Commission May 20, 2011)

Tucker, S., M. Trudel, D.W. Welch, J.R. Candy, J.F.T. Morris, M.E. Thiess, C. Wallace, D.J. Teel, W. Crawford, E.V. Farley Jr., and T.D. Beacham. 2009. Seasonal stock-specific migrations of juvenile sockeye salmon along the west coast of North America: implications for growth. Transactions of the American Fisheries Society 138:1458–1480.

Welch, D.W., M.C. Melnychuk, E.R. Rechisky, A.D. Porter, M.C. Jacobs, A. Ladouceur, R.S. McKinley, and G.D. Jackson. 2009. Freshwater and marine migration and survival of endangered Cultus Lake sockeye salmon (*Oncorhynchus nerka*) smolts using POST, a large-scale acoustic telemetry array. Canadian Journal of Fisheries and Aquatic Sciences 66:736-750.

Welch, D.W., M.C. Melnychuk, J.C. Payne, E.L. Rechisky, A.D. Porter, G.D. Jackson, B.R. Ward, S. P. Vincent, C.C. Wood, and J. Semmens. 2011. In situ measurement of coastal ocean movements and survival of juvenile Pacific salmon. Proceedings of the National Academy of Sciences (in press).

Table 1: Daily average hourly CPUE, by year, for juvenile sockeye salmon in the trawl surveys in the Strait of Georgia, 1997-2010. Average daily CPUE is the shown in the column on the right.

	Average hourly CPUE														
	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	Average
27-June												150.4	22.0		137.6
28-June												76.0	135.3		105.6
29-June												97.0			97.0
30-June		25.8	2.0									33.8	183.0		59.0
01-July		14.0	121.4									0.5	62.6		51.8
02-July		28.0	49.3			11.0						33.1	41.1		35.7
03-July		67.5	12.9			4.6						9.1	16.9	9.3	16.0
04-July		6.5	0.6			5.0		574.6				0.6	5.7	6.0	90.7
05-July		6.7	0.3			19.3		4.6					6.7	1.4	6.7
06-July	1.3	0.3	1.1			3.3		20.5				2.4	4.0	7.7	5.9
07-July	2.0	0.0	12.3		99.0			17.3					1.0	4.4	28.9
08-July	8.0	0.0	1.4		16.9	3.8		16.0			3.6			2.0	6.8
09-July	3.7	92.0			58.3	10.0		8.8		4.0	3.7			0.6	19.0
10-July				0.0	9.3	2.3		13.0			2.2			8.8	6.4
11-July					12.0	0.3		0.5		0.3	6.9			13.0	4.2
12-July					3.1			4.5		9.7	3.7			2.7	4.8
13-July				11.7	21.7			2.0		0.3	0.3				7.5
14-July				11.4	25.5				9.1	9.7	0.6				9.9
15-July				10.8	36.0				1.8	0.0	0.0			4.0	12.3
16-July				1.7					20.0	19.5					15.1
17-July				2.7					10.6						7.4
18-July				24.7					6.9						15.8
19-July				0.0					15.4	0.3					5.8
20-July				1.0					11.7	0.0					5.5
21-July									0.9						0.9

Table 2: Estimated residence time for juvenile Chilko Lake sockeye salmon in the Strait of Georgia as part of the 1st, 50th and 99th percentiles when sampled in late June and early July 2008 and 2009.

		27-Jun-2008	28-Jun-2008	
1%	4-May-2008	54	55	
50%	10-May-2008	48	49	
99%	24-May-2008	34	35	
		28-Jun-2009	1-Jul-2009	2-Jul-2009
1%	27-Apr-2009	62	65	66
50%	13-May-2009	46	49	50
99%	26-May-2009	33	36	37

Table 3: Mean lengths of Chilko sockeye salmon smolts and mean day of sampling at Chilko Lake (03 May 2010), and for juveniles in the Strait of Georgia (19 May 2010, 04 June 2010 and 15 June 2010). Mean growth per day is calculated as the difference of the mean lengths when sampled divided by the total number of days between the sampling dates. Growth estimates include an estimated 7 days for migrate out of the Fraser River. If no growth occurred during this time, the estimated daily growth rates would be larger.

Date	Mean Length (mm)	Mean growth (mm / day)
03-May-10	91.9	
19-May-10	103.0	0.7
04-Jun-10	117.0	0.9
15-Jun-10	130.7	1.3

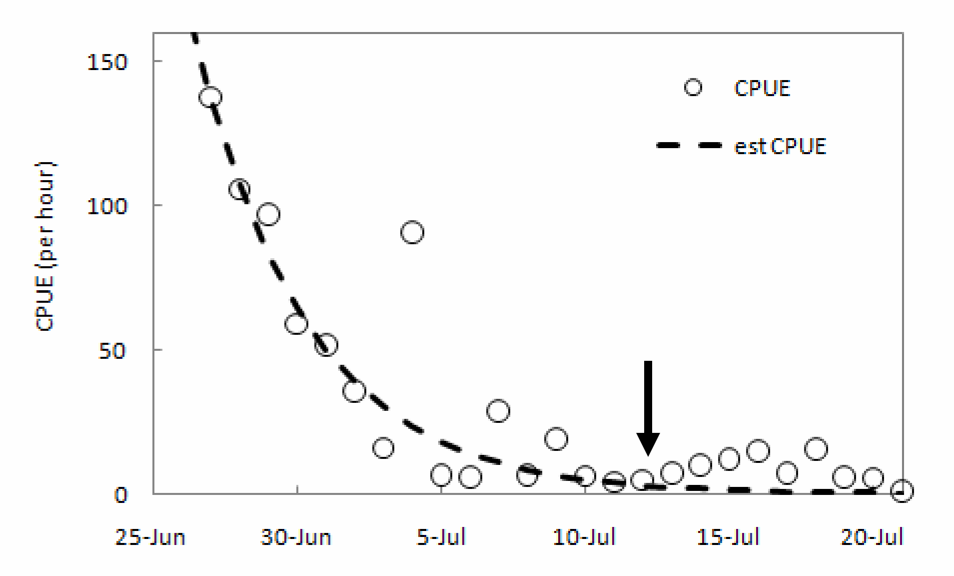

Figure 1: CPUE of average juvenile sockeye salmon for each day, averaged over twelve years of trawl survey data in the Strait of Georgia. The dotted line shows the fit of the logistic model estimation to the data, R^2=0.84. Arrow identifies the average exit date of July 12.

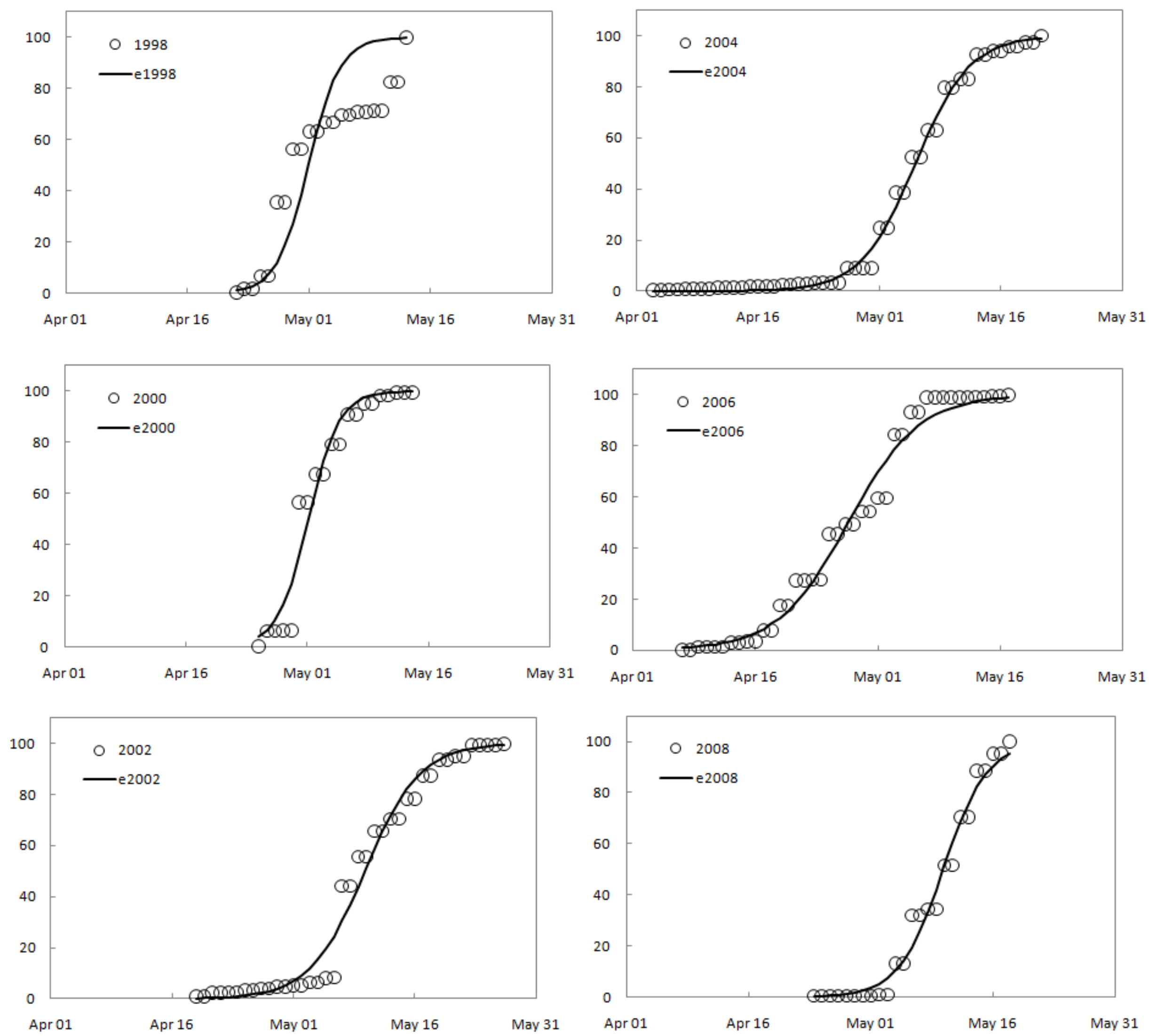

Figure 2: Estimates of downstream migrating sockeye salmon smolts in 1998, 2000, 2002, 2004, 2006, and 2008, fitted to a logistic curve.

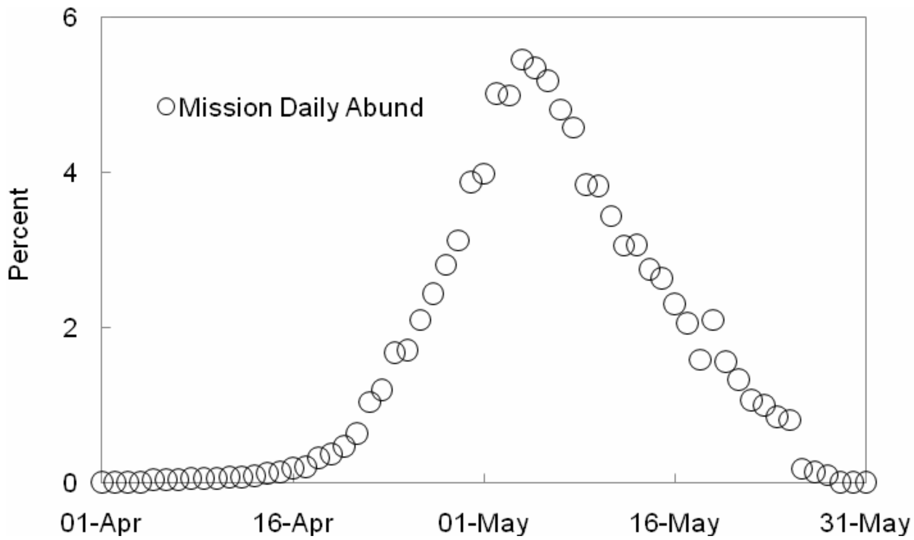

Figure 3: Average daily percent (open circles) of downstream migrating sockeye salmon smolts moving past Mission. Data are calculated for the period from 1976 to 2008 and provided by David Patterson (pers. comm.).

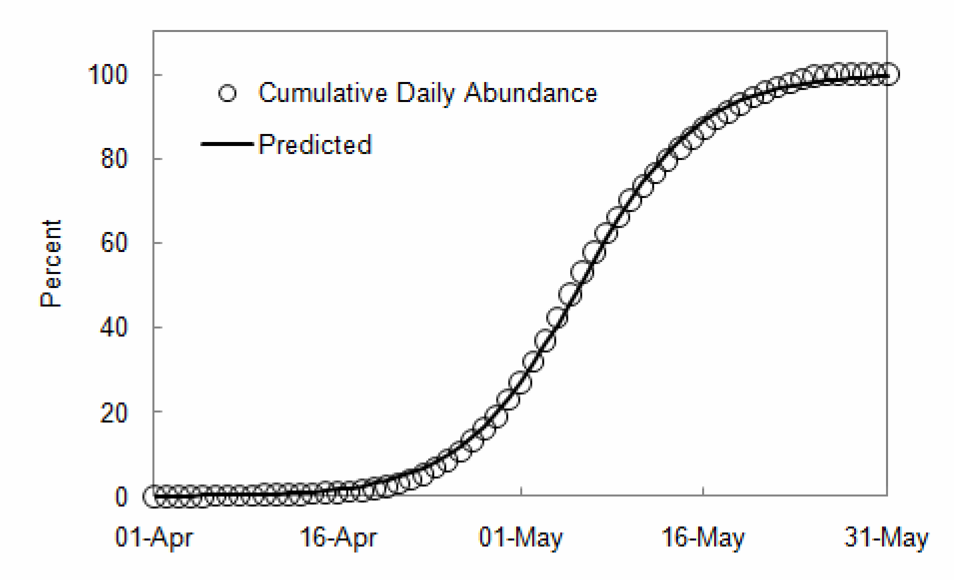

Figure 4: Average cumulative daily abundance of sockeye salmon smolts moving past Mission with a logistic approximation.

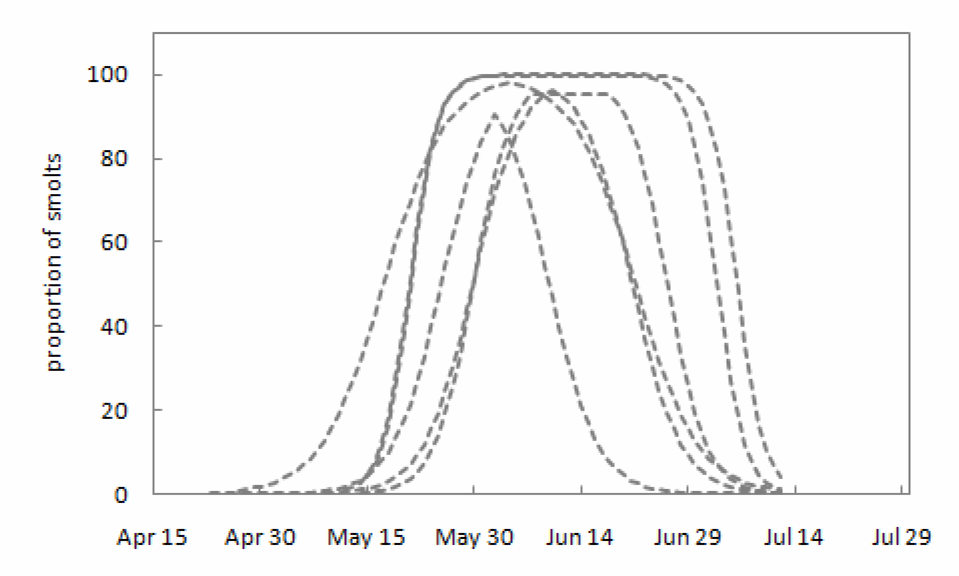

Figure 5: Simulations of the daily proportion of juvenile sockeye salmon in the Strait of Georgia using annual data from Mission (grey dotted lines). Each curve is used to calculate the date, rate of entry and rate of exit, fixed by the July 12 mean last exit date as estimated from trawl survey data.

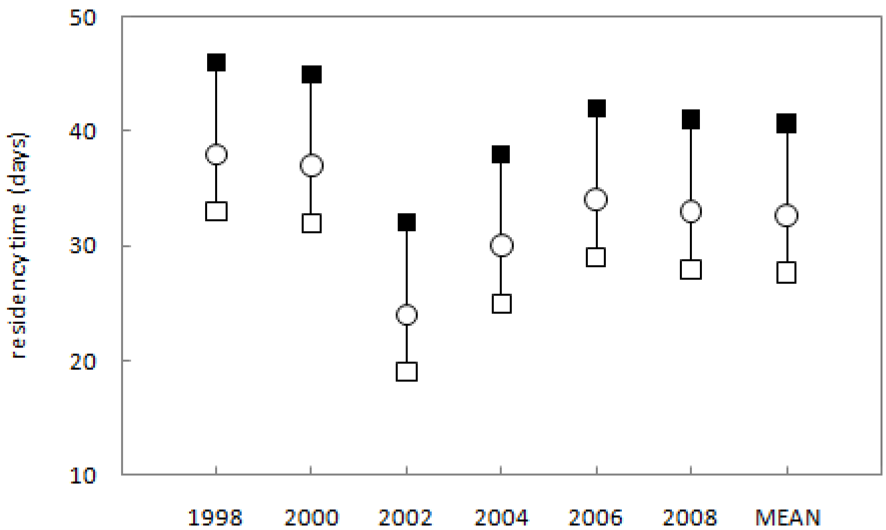

Figure 6: Estimated sockeye smolt residence time in the Strait of Georgia using data from 1998, 2000, 2002, 2004, 2006, and 2008 under scenarios of mean (open circles), early (open square), and late (solid square) exit days. The mean values of these estimates over all years are: early - 27 days, mean - 35 days, late - 45 days (on x-axis after 2008).

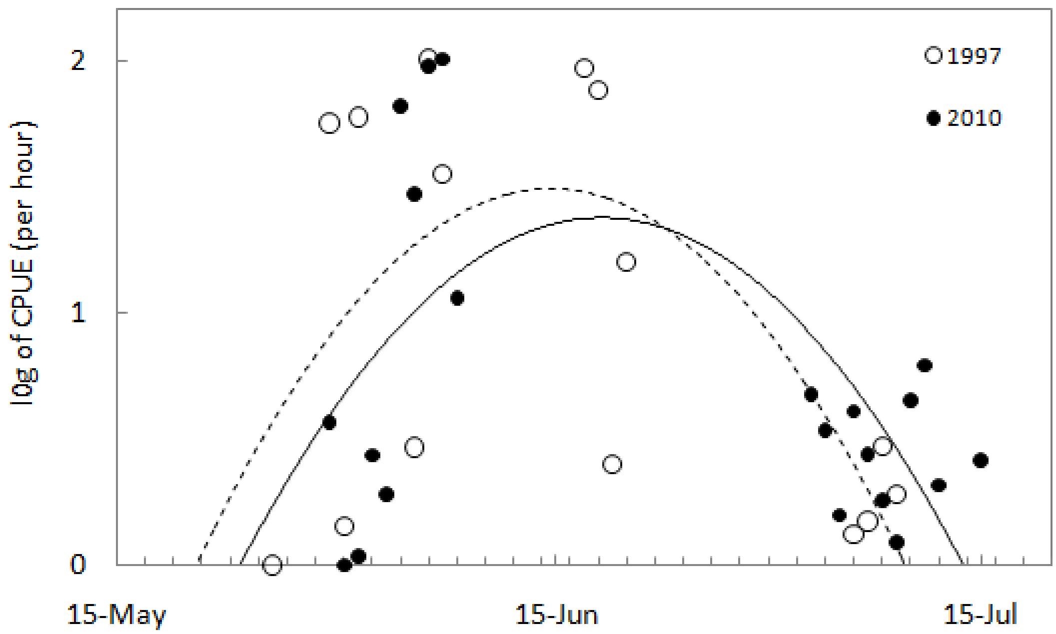

Figure 7: Average CPUE of juvenile sockeye salmon in the 1997 and 2010 surveys fitted using parabolas for 1997 (open circle, dotted line) and 2010 (solid circle, solid line).

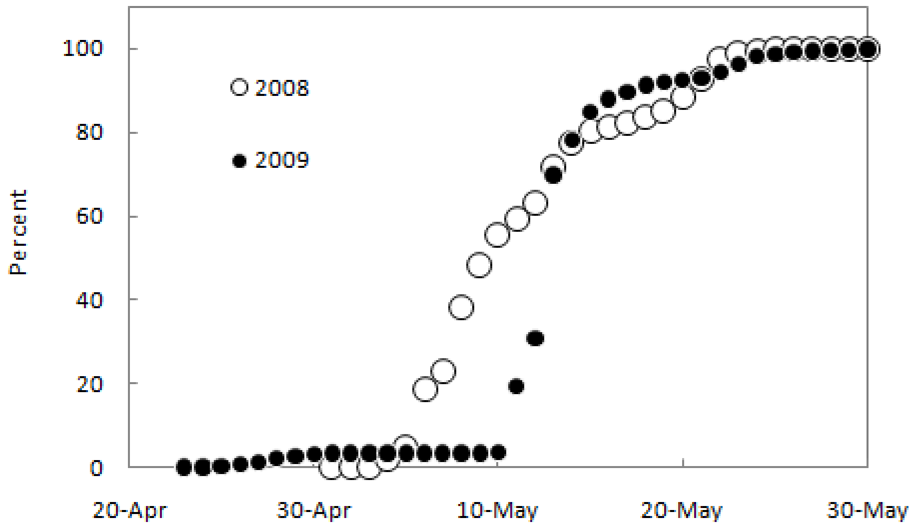

Figure 8: Cumulative percentage of sockeye salmon smolts entering the Strait of Georgia in 2008 and 2009.

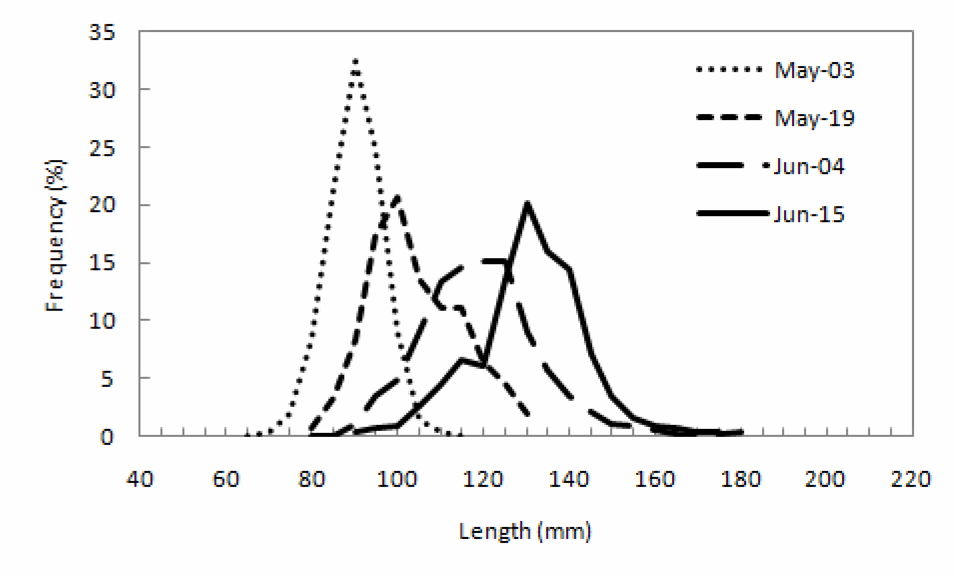

Figure 9: Length frequency distribution of sockeye salmon smolts sampled at Chilko lake (mean date of sample was May 3) and in three separate surveys in the Strait of Georgia (mean dates of surveys were May 19, June 04 and June 15) for the 2010 year to sea.

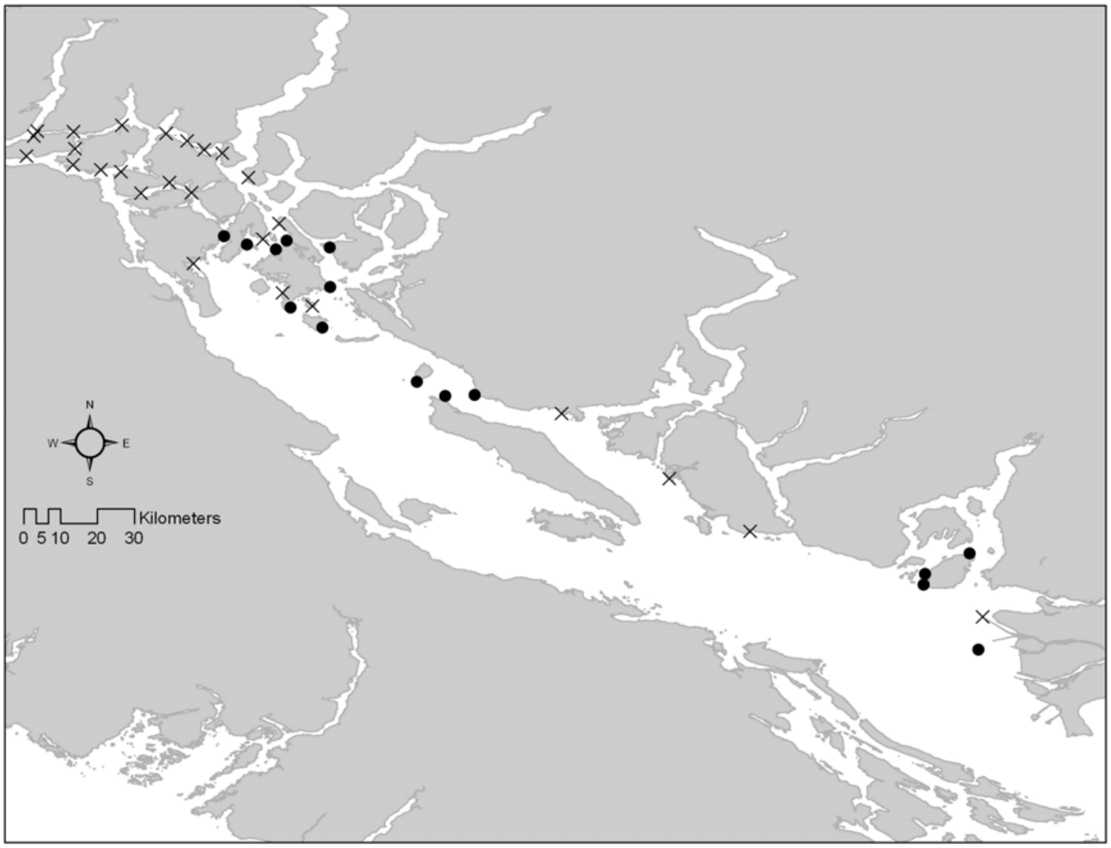

Figure 10: Location of sets during a purse seine survey in the Strait of Georgia from May 15-23, 2010. X indicates that no juvenile sockeye salmon were caught during the dates May 15-18, although other species of juvenile Pacific salmon were caught. Solid dots indicate that juvenile sockeye salmon were caught.