An analysis of 2008 data from the Lummi smolt trap on the Nooksack Mainstem

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Lummi Biologist, 3/30/2009

Executive Summary

Total production estimates for Chinook fry outmigrating from the Nooksack River in 2008 ranged from 1,676,347 (ACRM/Peterson) to **1,917,047** (adjusted ACCE) individuals. 1,376,480 Chinook fry were released into the Nooksack between April 15 and May 20. Wild production estimates ranged from as low as 299,867 (ACRM/Peterson) to as high as **549,848** (adjusted ACCE). If hatchery-origin fry suffer significant mortality before reaching the trap site then these estimates are likely to be biased high. Wild-production in 2008 is probably amongst the best we have seen in the last 7 years.

Residence time modeling for Chinook fry in 2008 was badly disrupted by the release of half a million smolts at Bertrand Creek, not far upstream of the trap. The Bertrand Creek release distorted residence time modeling because of the very large number of fish, the very close proximity of the release site to the trap, and the very different outmigration behavior of the smolts released at that site compared to other groups released in traditional areas after a reasonable acclimation protocol. However, modeling results for the last four groups of hatchery Chinook (after the Bertrand Creek fish were gone) were consistent with data from previous years.

The total production estimate for Coho smolts was **1,557,140** smolts (ACRM). 1,245,070 smolts were released from hatcheries between May 9 and May 29 of which **1,178,892** were adipose-fin clipped. The wild production estimate is therefore **312,070** Coho yearlings, assuming that no mortality occurred for hatchery-origin smolts prior to reaching the trap site. The effect of post-release mortality would be to inflate production estimates and the magnitude of the error incurred would be roughly proportional to the true mortality rate.

Residence time modeling for Coho smolts indicated that the residence time from release to passing the trap site was 3.5 days, with the first group released on May 9th taking considerably longer to outmigrate past the trap site (8.8 days) compared to Coho released in late May (2.4 – 2.3 days).

Contents

Introduction

Lummi Natural Resources operates a rotary screw smolt trap on the Nooksack River in the lower mainstem, at Hovander Park near Ferndale. The goals of the sampling program are to develop accurate estimates of the annual production of outmigrating wild-origin salmon fry and smolts. The emphasis of the program is to quantify wild Chinook production for the endangered North Fork and South Fork stocks, but secondary objectives include stock assessment for other native salmonids such as Coho. Data analyses of data from the Lummi screwtrap have been previously conducted from 2002 to 2007 (Dolphin, 2002; 2003; 2004; 2005; 2006; 2007).

2008 was only the fourth year since trap operations began in 1994 that virtually 100% of hatchery-released age-zero Chinook were marked and could be reliably separated from wild-origin Chinook. This year WDFW released 1.376,480 zero-age Chinook upstream of the screwtrap, including 499.237 that were released into Bertrand Creek, which is a new release site. Of the smolts released in 2008, it is estimated that approximately 9,278 released Chinook were unmarked by either adipose fin clip or coded wire tag which represents just 0.06% of the total.

In 2008 the screwtrap was operated from December 17, 2007 through to October 7, 2008 and beyond, although sampling intensity was highest from April through July (Fig. 1). This report considers data collected from December 2007 through to October 7, 2008 and aims to report the results of the sampling program in 2008, summarize the main findings, and compare these results to previous data (where available) for Chinook fry (age 0+) and Coho smolts (age 1+). No analysis of the data for Chum, Pink, or Sockeye salmon has been made to date.

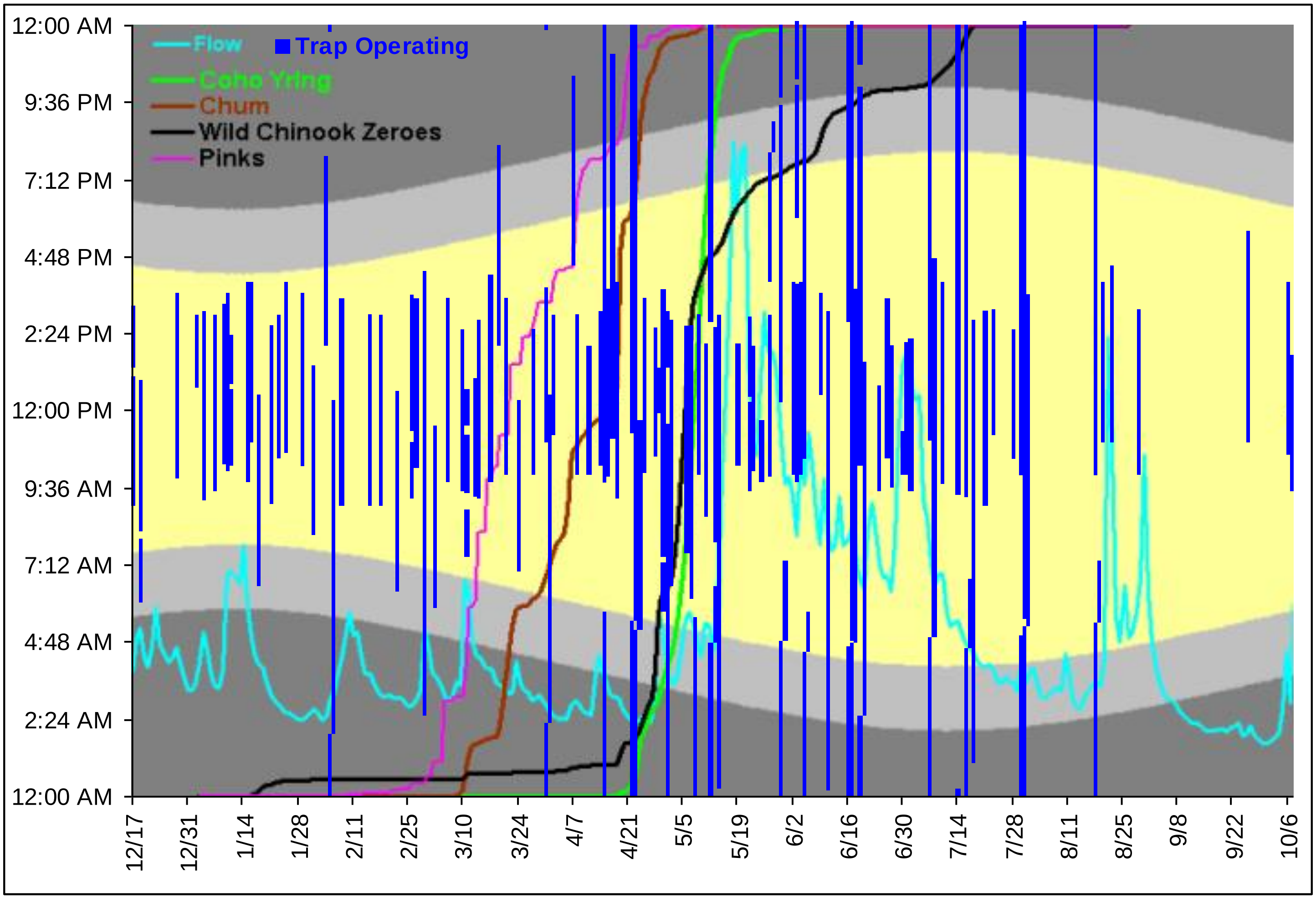

Figure 1. Daily sampling effort (Dark Blue) on the Lummi smolt trap in 2008 superimposed on a background of daylight (yellow), twilight (light gray), and night (dark gray) time periods, relative river flow at Ferndale (light blue), *cumulative production estimates* for unmarked Chinook zero-age smolts (black), and *cumulative catch curves* for Coho Yearling smolts (Green), Chum fry (Brown), and Pink Salmon fry (Pink).

Field Methods

The full methodology for the operation of the smolt trap is not given here but interested readers are referred to Conrad & MacKay (2000) for a full description of the site, sampling apparatus, and field protocols.

Chinook

Results

Figure 2 shows the average daily catch per hour for zero-age Chinook smolts based on trap data and linear interpolation between sample measurements. Table I outlines the timing, magnitude, and details of hatchery releases in 2008.

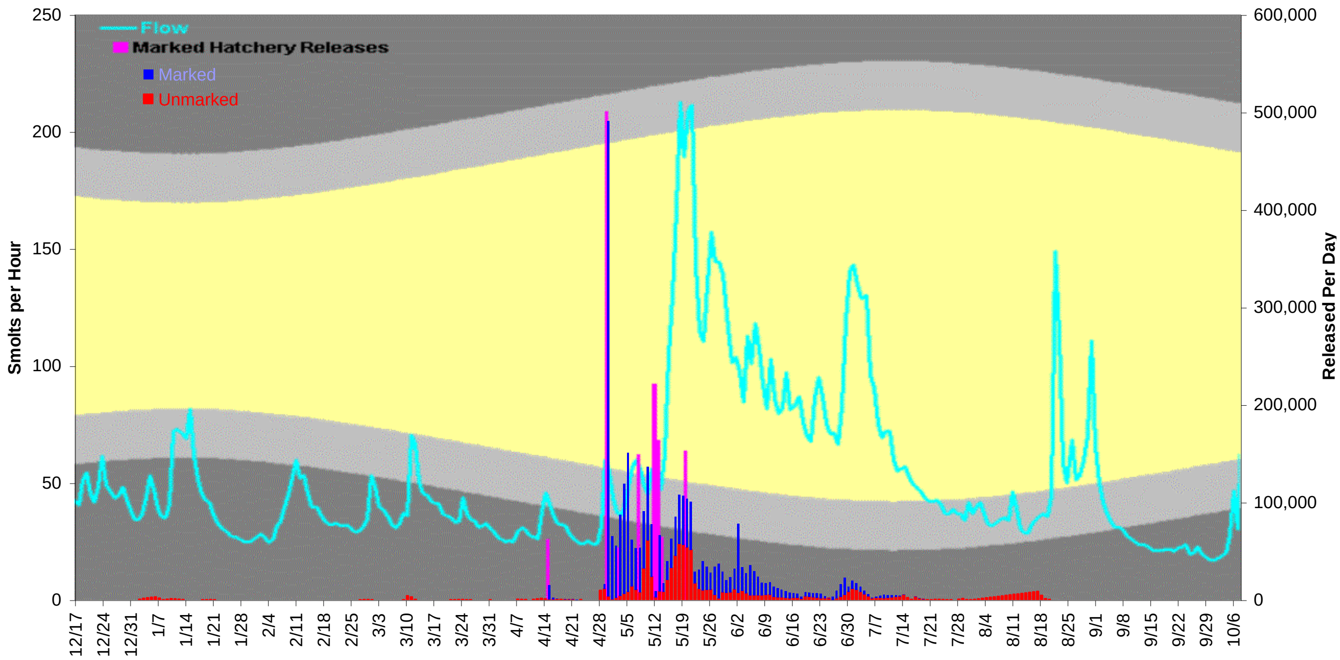

Figure 2. Average daily catch per hour for zero-age Chinook smolts in 2008. Hatchery releases are shown in the background along with relative river-flow at Ferndale, and approximate photoperiod (daylight is yellow, twilight is light gray, and night is dark gray). Marked and Unmarked Chinook bars are vertically stacked.

			Ext. Marked			Unmarked		
Release Date	**Source**	**Release Site**	**Ad-Clip Only**	**Ad-Clip & CWT**	**CWT Only**	**No Clip. No Tag**	**Total Release (All)**	**Total Release (Externally Marked)**
4/15/2008	Kendell Hatchery	Kendall Creek	62,496	0	0	504	63,000	**62,496**
4/30/2008	Samish Hatchery	Bertrand Creek	499,237			5,043	504,280	**499,237**
5/3/2009	Kendell Hatchery	Kendall Creek	54,340	0	0	660	55,000	**54,340**
5/8/2008	Kendell Hatchery	North Fork Nooksack	7,250	67,145	74,322	383	149,100	**148,717**
5/12/2008	Kendell Hatchery	Middle Fork	220,446	0	0	1,554	222,000	**220,446**
5/13/2008	Kendell Hatchery	North Fork Nooksack	4,427	88,146	71,590	337	164,500	**164,163**
5/14/2008	Kendell Hatchery	Kendall Creek	65,172	0	0	328	65,500	**65,172**
5/20/2008	Kendell Hatchery	North Fork Nooksack	17,830	71,285	63,516	469	153,100	**152,631**
Grand Total			**931,198**	**226,576**	**209,428**	**9,278**	**1,376,480**	**1,367,202**

Table I. *Details of Hatchery releases of zero-age Chinook Fry in 2008*

Chinook Production Estimate Methods

Method 1. *Ad-Clipped Hatchery smolts recapture ratio method (ACRM)*

Traditional mark-recapture models use the ratio of marked individuals in the total catch, along with the original number of marked individuals that were released, to provide an estimate of how many individuals are represented by the catch. Several models have been developed for a range of scenarios where multiple releases of marked individuals and multiple catches are made. However, the simple Peterson estimate (single release, single recapture) is most appropriate in this case because outmigrating smolts are assumed to be catchable only once as they move out of the river. Assumptions made when making Peterson mark recapture estimates include the following:

1. The population under study should be both *geographically closed* and *demographically closed*.
2. Each member of the population has the same probability of being captured, and this capture probability does not change over time.
3. Marked and unmarked individuals randomly mix between samples.
4. Marks are permanent and always recognizable.

The formula used in the Peterson mark-recapture method is shown in 1 below:

$$\hat{N}_P = \frac{N_2 N_1}{M_2} \qquad (1)$$

…where N_1 = the number of marked smolts released, N_2 is the total number of smolts caught during sampling, M_2 is the number of marked smolts caught at the trap during sampling, and N_P is the estimated size of the total population.

95% confidence intervals for N_P can be calculated using a variety of probability distributions. However, when the percent of marked individuals recaptured is less than 10% of the number released (M_2/N_1), and the number of recaptures, M_2, is greater than or equal to 50, a confidence interval based on the Normal distribution is the most appropriate method. Consequently, confidence intervals for the ACRM method are calculated using equation 2:

$$\mathbf{N_P \pm 1.96 * \sqrt{Var(N)}} \qquad (2)$$

…where N_P is the population estimate, and the variance of N_P is determined using equation 3.

$$Var(N_P) = \frac{(N_1+1)(N_2+1)(N_1-M_2)(N_2-M_2)}{(M_2+1)^2(M_2+2)} \qquad (3)$$

Table II shows the total number of hatchery Chinook that were marked (either through an ad-clip, CWT, or both) and then released, as well as the number of marked smolts that were recaptured, and the total number of Chinook smolts captured in the same sampling program. If any marked hatchery fish die before reaching the trap site, or do not pass the trap site, then the final estimate of total production is likely to be too high because the true recapture rate will be higher than calculated in Table II.

Table II. Chinook clipped adipose fin smolts recapture rate details for 2008.

	2008	
Number of marked smolts released	1,367,202	N_1
Number of marked smolts recaptured	**5,851**	M_2
Marked Smolt Recapture Ratio	0.43% (2dp)	
Total number of smolts caught	**7,174**	N_2
Estimated Total production of Chinook smolts in 2008	**1,676,347**	N_P
Upper 95% Confidence Limit	1,694,749	
Lower 95% Confidence Limit	1,657,946	

The results of using this method suggest that a total of **1,676,347** smolts migrated downstream past the Screwtrap in 2008. Since we know that 1,376,480 smolts were released from the hatchery, the difference (**299,867**) could be interpreted as wild-origin smolts. However, this does not incorporate any loss of hatchery fish due to mortality prior to their arrival at the trap site. The magnitude of any bias caused by wrongly assuming no mortality occurs when using the ACRM method is discussed further in the Coho production estimate results section but, generally, this error would lead to overly optimistic estimates for wild-origin Chinook production.

Time-series based production estimate methods…

Other methods to estimate the annual production of Chinook smolts attempt to create a time series of catch-per-hour measurements for the entire outmigration period, and then convert this time-series into production (the number of fish passing the trap site per day) using a trap-specific catch efficiency estimate. Summing the daily production estimates over the entire outmigration period provides an estimate of total production. All of the methods that use this time series as a basis explicitly make predictions as to the magnitude and timing of outmigration past the trap site.

The time-series of catch-per-hour data for Chinook is created using trap catch rates stratified by dawn, day, dusk and night sampling periods. Measured data are extrapolated to a maximum of 24 hours after each sample based on relationships between cpue and set type for various times of the day. This relationship is derived from a scatter plot of cpue versus set type (dawn, day, dusk, night) with data gathered since 2003. For times beyond 24 hours from the last actual measurement, catch rates are interpolated linearly within sampling strata. As an example, if catch rates during the day on May 10th were 4 fry per hour, and catch rates during the day on May 12th were 2 fry per hour, then the rate used for daytime on May 11th would be 3 fry per hour.

The rules for interpolation used to analyze the 2008 data are summed up as follows:

1. Extrapolate from actual data within a 24 hour period of the last known sample, based on strongest predictive relationship between sample types (dawn, day, dusk, or night)
2. Secondarily, use linear interpolation to obtain values between actual and extrapolated data points
3. Do not linearly interpolate between data values that occur immediately before and after a hatchery release, instead assume that the last sample before the release is true for all subsequent dates prior to release, and that the first sample after the release is true for all previous dates from the time of release.

The third rule was deemed necessary because field staff actively try to catch the leading edge of any released smolts that outmigrate immediately following release. Since the sample timing is therefore non-random with respect to release timing it was necessary to avoid inadvertently overestimating the hatchery releases by linearly interpolating during a period in which hatchery fish that have not yet been released could not possibly be passing the trap site.

Three methods have been used historically to derive estimates for the trap's catch efficiency.

Method 2. *Secchi-Depth – Catch Efficiency Relationship Method*

This method used a secchi-depth reading to estimate the trap's catch efficiency during each sampling period. However, application of this method in previous years has proven to provide very poor results. Moreover, the original secchi-depth-catch efficiency relationship was based on recaptures of newly released Chinook smolts and the behavior of smolts in the 24 hours after release is unlikely to be like that of smolts that have been at liberty for considerably more than 24 hours. Furthermore, the relationship between secchi depth and trap catch efficiency began to break down as more release trials were done. Consequently, *this method has been abandoned* because it was not representative of the behavior of smolts acclimated to riverine conditions and because no dependable relationship could be found. Nonetheless, workers on the trap continue to believe that water clarity is an important factor in the trap's catch efficiency and if some method can be found to measure catch efficiency versus secchi depth for river acclimated smolts then this method may provide a significant improvement in our daily production estimates.

Method 3. ***Summed Daily Production Estimates – Year-Specific Constant Catch Efficiency method (YCCE)***

The percentage of marked smolts recaptured is a function of trap catch efficiencies that may vary from day-to-day and within day, fish migration timing, sample timing, and overall hours fished. To measure catch efficiency it is necessary to isolate catch efficiency from sample timing and amount of effort. Because we cannot measure the actual numbers of fish moving past the trap site we cannot directly measure catch efficiencies on a within day or day-to-day basis, so the most we can do is to estimate ‘average’ catch efficiency for the whole season. One indirect measure of the average instantaneous trap efficiency in a season can be obtained using the percentage of marked hatchery Chinook that were recaptured, along with the proportion of time that was spent sampling during the time when those marked fish were passing the trap site.

For this ‘average’ seasonal value to be useful for converting catch per hour values into production per hour values, it is necessary to assume that trap catch efficiencies are constant throughout the diurnal cycle, and throughout the sampling season. Since we do not see consistent differences in catch per hour between day and night sampling times, it is likely that trap catch efficiency is similar for both time periods. However, catch rates do appear to be slightly higher around dawn and dusk which may indicate either higher catch efficiency during these times, or else higher outmigration rates at these times. Any error created by failing to differentiate sampling efficiencies for these time periods is likely to be reduced by the comparatively short time (4 hrs a day total) involved for these sampling periods.

We know that if the trap were not operated at all (effort = zero hours) then no fish would have been recaptured at all. We also know that we caught a certain percentage of the marked hatchery fish after sampling a known proportion of the total time possible (and the effort was spread throughout the season). Assuming that the number of marked fish recaptured is *linearly* related to hours of effort, then the slope of the line joining these two points is the average trap catch efficiency during that sampling season. Clearly, this extrapolation will be most convincing when the actual sampling effort is a large proportion of the overall time.

If we assume that trap catch efficiencies during the outmigration period of the marked fish are also representative for the remainder of the outmigration season, and are similar for unmarked and wild fish, then the estimate of average trap catch efficiency for marked hatchery fish can be used to estimate production for unmarked hatchery fish, and unmarked wild-origin fish also.

Figure 3 shows the relationship between the recapture rate of marked hatchery smolts, versus the proportion of time sampled during their outmigration period, for the past seven years. An analogous value is also shown based on an identical screwtrap operating in the Skagit River mainstem. Based on the larger volume of water in the Skagit you would expect that the Skagit trap would have a lower catch efficiency rate.

Overall, 2002, 2003, 2004, 2005, and 2006 show very similar average catch efficiencies (~2.3 - 3.3%) after extrapolating based on sampling effort, whereas recapture rates were below expectations in 1999 (1.46%), 2001 (1.73%), 2007 (2.03%), 2008 (2.06%), and much higher in 2000 (7.3%).

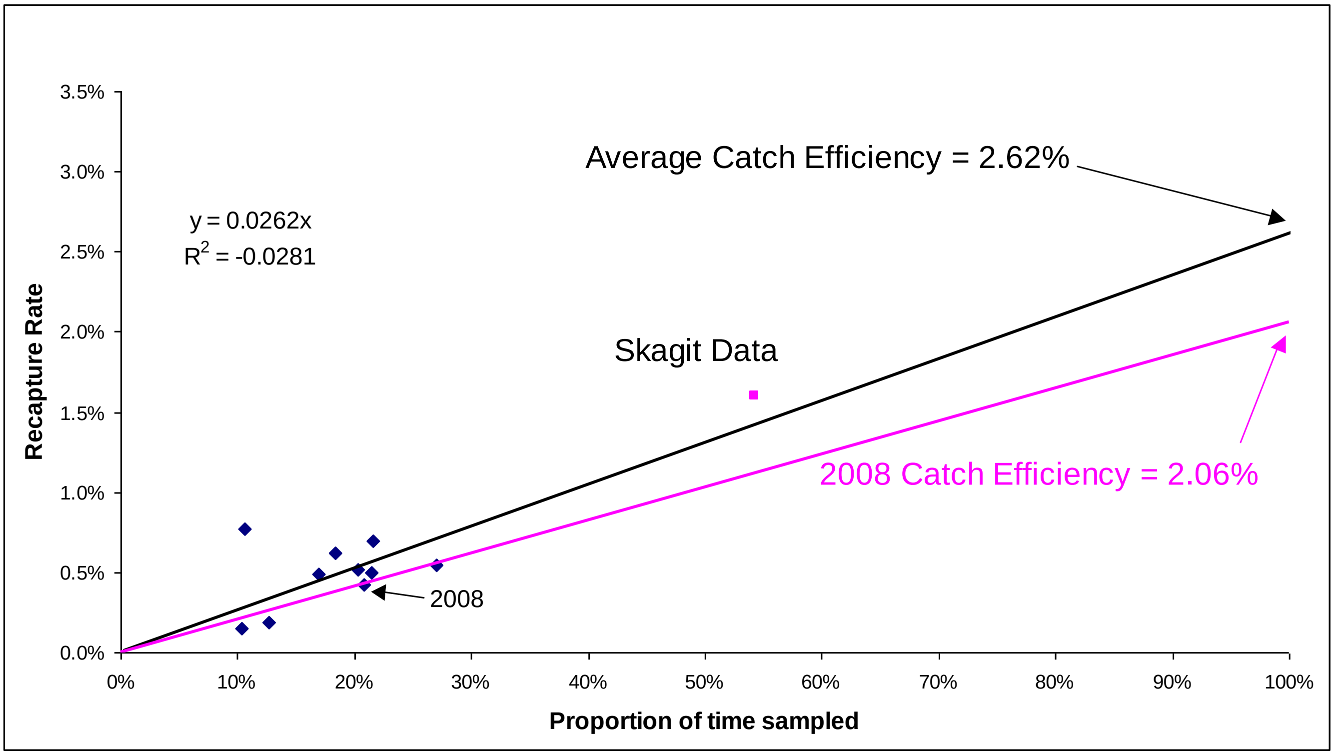

Figure 3. Season wide recapture rates of marked hatchery Chinook smolts versus the proportion of time sampled.

Based on the 2008 season catch efficiency of 2.06%, daily production estimates were derived using the interpolated daily catch-per-hour data shown in Fig. 2. The results of this analysis are shown in Figure 4. The total number of zero-age Chinook smolts outmigrating past the trap-site was estimated to be 1,560,363 smolts. Of this estimate, 1,112,820 smolts are marked and the remainder, 447,450 smolts are unmarked. However, we know that the actual number of marked smolts released was 1,367,202 in 2008 so it is apparent that the YCCE estimate underestimated the true production of marked smolts by 18.6%. Assuming that this bias is the same for unmarked smolts, then the number of unmarked smolts leaving the river in 2008 would be 549,844 smolts.

In addition, we estimate that c. 9,278 unmarked smolts were released from hatcheries in 2008 (Table I). Thus, the final estimate for wild-origin smolt production is **540,566** smolts using the YCCE estimate method and removing known bias.

It should be remembered that this estimate assumes that no mortality occurs between release and recapture for marked smolts. Mortality rates ought to be low, but if wrong then this assumption will tend to artificially reduce the catch efficiencies estimated in Figure 3. Underestimating the true catch efficiency of the trap would cause production estimates to be biased upward. This problem is compounded by the migratory behavior of the smolts where large fraction of the annual outmigration may pass the trap site in a relatively short period of time. The data in Figure 2 shows that large numbers of smolts were passing the trap site on a handful of days in late May and early June. If river conditions on those days meant that the trap was slightly more efficient than the season-wide average then it could cause an upward bias in the overall production estimate (or vice versa). This problem is inherent when using any constant value to represent trap catch efficiencies that are actually variable through time, and highlights the need to get accurate and reliable predictive relationships for actual trap catch efficiencies that are based on objective measurements of riverine conditions. Unfortunately, such an exercise is not logistically possible at the present time.

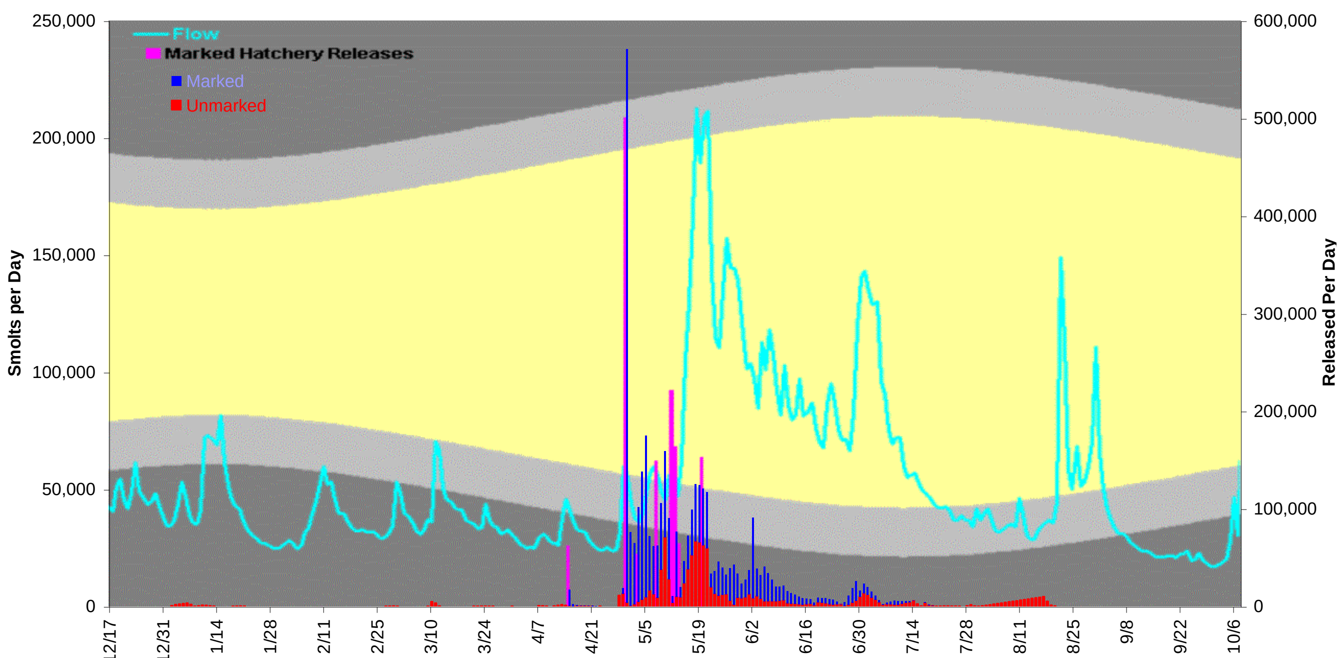

Figure 4. Daily production estimates in 2008 for zero-age Chinook smolts calculated from daily catch per hour and using a constant catch efficiency of 2.06% (YCCE).

Method 4. ***Summed Daily Production Estimates – Average Constant Catch Efficiency method (ACCE)***

This method is identical to the year-specific constant catch efficiency method except that, instead of using different constant catch efficiencies for each outmigration season, the long-term average catch efficiency across all seasons is used. This long-term average catch efficiency is represented as the slope of the trendline shown in Figure 3. Overall, the average catch efficiency for the Lummi screw trap is estimated to be 2.62% based on the past 10-year's data.

The results of this method for 2008 suggest that the total production of zero-age Chinook smolts was 1,228,044 smolts. Of this number, 875,818 smolts are marked and 352,228 smolts are unmarked. As with the YCCE estimate, the number of hatchery smolts passing the trap site predicted by this method differs from the known number of smolts released. The ACCE method, however, had an even larger bias (36%) compared to the YCCE estimate (18.6%). By scaling the results to mach the known hatchery rel ease of marked smolts, then the number of unmarked smolts passing the trap site is 549,848 smolts. Deducting the 9,278 unmarked hatchery-origin smolts released in 2008 gives a wild-origin estimate of **540,570** smolts.

This number is almost identical to the adjusted YCCE estimate because scaling the results to match the known hatchery release makes the two methods mathematically identical (except for rounding differences). The overall pattern of outmigration prior to scaling the results to match the known size of the hatchery release is shown in Figure 5.

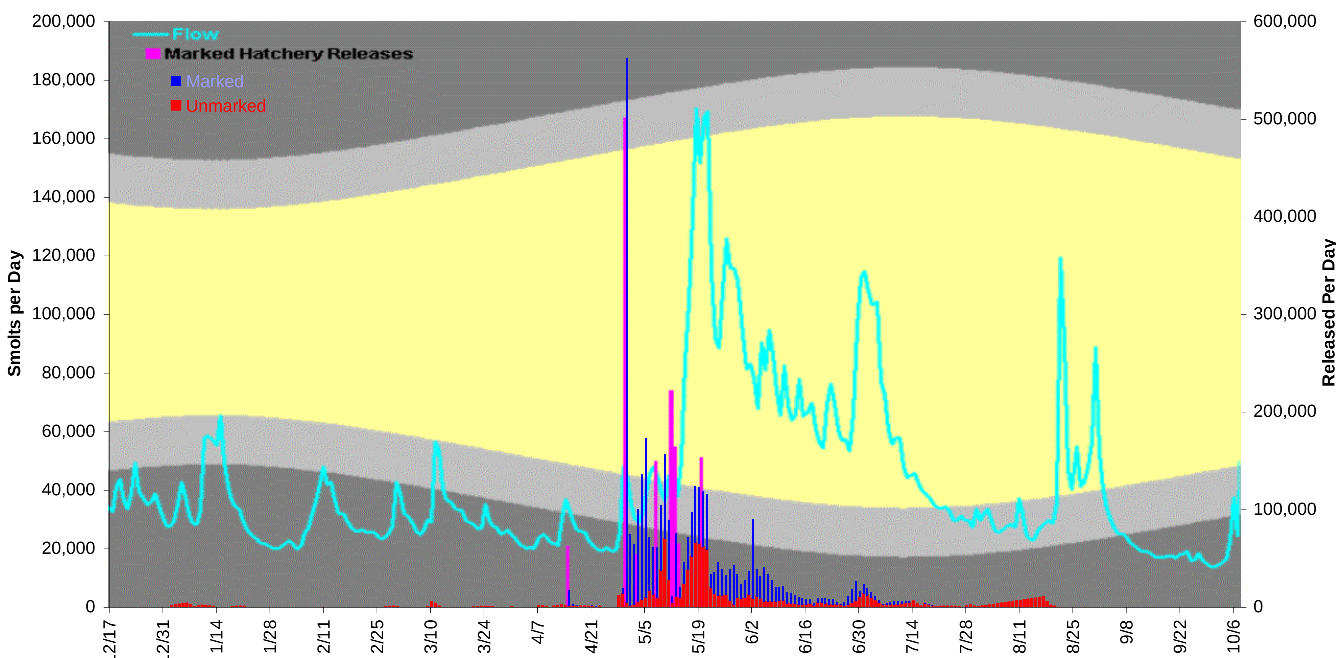

Figure 5. Daily production estimates in 2008 for zero-age Chinook smolts calculated from daily catch per hour and using a constant catch efficiency of 2.62% (ACCE)

Comparison of the three production estimates

Results from 1999 – 2008 that were obtained using the three methods presented here are shown in Figure 6 and compared to the known hatchery releases in each year. Note that the absolute values in this graphic will differ slightly from those presented in earlier reports because the ACCE catch efficiency value has changed slightly with the inclusion of 2008 data in Figure 3.

Although data from the previous three years suggested that the ACCE estimate may have been a less biased predictor of production, in 2008 the ACCE estimate underestimated the known release of marked smolts by nearly twice as much as the YCCE estimate (36% vs 18.6%). However, over the past four years, the average bias of the YCCE method is to overestimate smolt production by ~17.3%, and the ACCE tends to underestimate production by 13.6%. However, the variance in the results so far indicates that this bias is not significantly different than zero at a 95% confidence level for either method.

Relative performance of the ACCE/YCCE estimates and the ACRM estimate is more difficult to evaluate. Comparison of the estimates to known hatchery releases suggests that maybe the ACCE estimate is more 'realistic' in the majority of years, but the ACRM estimate makes more sense in 1999.

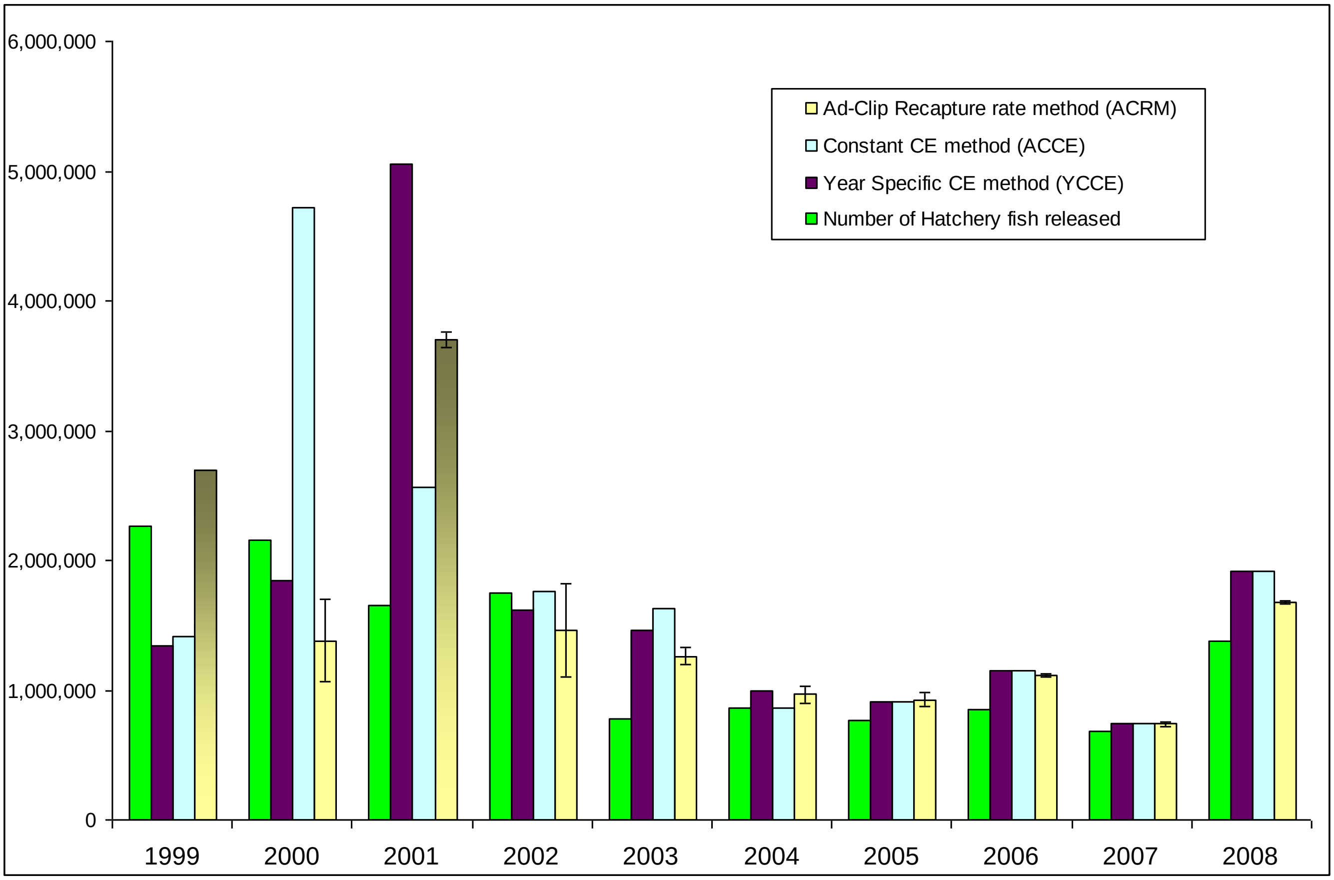

Figure 6. Three alternative production estimates for zero-age Chinook smolts outmigrating from the Nooksack River from 1999 – 2008, compared with the number of hatchery-origin smolts released in each year (green). Shading of the two ACRM bars in 2001 and 1999 indicates that many fewer marked hatchery smolts were caught relative to other years, and the ACRM estimate might be more prone to large error because of the increased scaling factors. This may also result from unusually high mortalities of marked hatchery smolts prior to recapture. ACCE estimates for 2005, 2006, 2007, & 2008 have been adjusted to correct for known bias in estimating marked hatchery releases (assuming zero mortality).

Marked Hatchery Chinook Residence Time Modeling

One of the concerns associated with a hatchery program releasing smolts into the upper watershed of a river system is whether the presence of hatchery fish might have adverse impacts on wild-origin Chinook smolts. Such impacts could, hypothetically, come about through predation (i.e., large hatchery smolts eating small wild-origin smolts), competition for food (e.g., aquatic stages of stream insects, drift of aerial insects, etc), competition for space (e.g., prime holding habitat, flood refugia, etc), and possibly transmission of diseases from hatchery-origin smolts to wild smolts. To evaluate the likelihood of predatory and competitive interactions, as well as the potential for disease transmission, it is necessary to understand the behavior of hatchery smolts after their release. Logically, there is less opportunity for competitive/predatory interactions if hatchery smolts head downstream until they reach the estuary immediately upon release. Conversely, if hatchery-origin smolts prefer to spend long periods of time in the upper watershed they will have to eat suitable food and spend time in suitable micro-habitats that afford predator protection, foraging opportunities, and refuge from flood water velocities. Obviously this strategy increases the potential for interaction between hatchery and wild-origin smolts.

It is not possible to directly observe the behavior of individual hatchery smolts after release because radio/acoustic tagging is not presently possible with Chinook smolts in the size range released. However, a large proportion (~99.4%) of the hatchery smolts are marked in one of two ways. Some hatchery smolts have a coded wire tag (CWT) inserted into their snout, some have their adipose fin clipped (this fin does not re-grow), and some have both CWT and the adipose clip. We know when and where the marked smolts are released, and we can identify marked smolts amongst the smolts caught in the trap. Essentially, we ought to be able to measure the average length of time taken for the marked fish to leave their release site and reach the trap (i.e., the residence time). This information should provide an indication of hatchery fish residence times in general (if you assume that marked hatchery fish behave in the same way as unmarked hatchery fish).

Unfortunately, this is not as simple in practice as in theory; and there are several reasons for this difficulty.

Firstly, we are not intercepting all marked fish that are going down the river but instead are catching an unknown (and potentially variable) proportion on a daily basis. This problem can be resolved somewhat by making assumptions about the catch efficiency of the trap from day-to-day (that is, we can assume it is constant) but this itself can lead to inaccuracies if the trap's catch efficiency is not constant.

Secondly, the timing of hatchery smolt release is sometimes complicated by an extended volitional release strategy. This is where the smolts are kept in a holding pond and an opening is made between the pond and the river itself, and the smolts allowed to emerge from the pond at their leisure. At some point, the last smolts are eventually driven from the pond. Sometimes this 'volitional release' period may last for as long as a week. This issue could be remedied for by counting smolts as they leave the pond but, unfortunately, no such counts are made for Chinook smolts. As a result, it becomes necessary to make some further assumptions regarding the rate of smolt departure from the holding ponds when volitional release is practiced. Fortunately, no volitional releases were made for Chinook smolts in 2007

A third problem arises when more than one group of marked smolts is released into the river at different times/locations. This is especially problematic when marked smolts from one group are still arriving at the screw trap when another marked group is released somewhere upstream. Once you have two groups of identically marked smolts in the river above the trap, it is impossible to know whether a marked fish arriving at the trap has been in the river for a short time (second release group) or a long time (first release group). Consequently, it becomes necessary to make assumptions about the proportion of marked fish arriving in the trap that belong to each of the two (or more) groups of marked smolts that may be present in the river upstream.

A fourth problem arises when the summed daily production estimates for marked hatchery smolts do not tally with the number of marked smolts released. In some case, these discrepancies suggest that fewer marked fish are moving downstream past the trap site than were originally released. This problem can be overcome by assuming that a number of marked hatchery fish die (or else decide to outmigrate as yearlings the following year). Skalski (1998) suggested that survival of marked hatchery smolts in the Snake River remained relatively constant throughout the outmigration period. Consequently, a constant daily survival rate may be a reasonable solution, although it is likely that survival would also depend on fluctuations in the environmental conditions experienced by the smolts. However, if the summed daily production estimates exceed the known size of the release group then we are left with a major headache. The only solution to this problem is to scale all the daily estimates down so that their sum matches the size of the known hatchery release. This problem does not arise every year, and it is not the case in 2007. However, the advent of nearly 100% marking allows us to adjust for bias in either direction and avoid the issue altogether.

In 2007 several groups of ad-clipped Chinook smolts from Kendall Hatchery were released into the Nooksack River (Table I). The first group (52,911 smolts) was released on April 16. The last group (61,318 smolts) was released on May 31.

The first marked smolts (n=33) were caught at the screw trap just after noon on April 17. Figures 4 and 5 show that only a small fraction of the fish released in the early group left the river very soon after their liberty.

The last marked smolt (n=1) was caught at the trap site on July 24th which was 55 days after the last release of hatchery smolts and 100 days after the first release. Assuming that this smolt represents the last outmigrating hatchery fish, this suggests that the maximum residence time observed may be as high as 55 - 100 days (depending on which group this fish originally came from).

To estimate the average residence time for hatchery fish it is necessary to model each group of released fish individually, and make some assumptions regarding their actual release times, daily mortality rate, and what proportion of the fish from mixed groups arriving at the trap belong to each group.

Critical assumptions used in residence time models

1. If volitional releases are practiced, all smolts leave the holding pens on the first day of their volitional release period. This may result in overestimating the actual residence times if smolts entered the river at a later date. Unfortunately, no end dates for volitional release were reported by the hatcheries in some years. This assumption is not necessary for 2006 data.

2. Daily survival/mortality is fixed and constant throughout the season. If summed daily production estimates are lower than the known hatchery release then this variable can be manipulated until model output matches daily production estimates for marked hatchery smolts. If summed daily production estimate exceed known hatchery releases mortality is set to zero and daily production estimates are uniformly scaled so that the sum of these estimate equals the size of the known hatchery releases.

3. The number of fish from one group that is caught in the screw trap catch is assumed to be directly proportional to the percentage of the total marked fish population made up by that group at the start of the day. That is, if 30% of all marked fish upstream from the trap belong to 'Group 1', then 30% of the fish caught in the trap that day are assumed to be from 'Group 1'. If this number exceeds the total number of smolts remaining in that group, then the actual number remaining is used and the remainders of the captured smolts are split proportionally amongst any remaining groups.

4. Adjusted ACCE daily production estimates for marked smolts are a good indicator of relative daily production (outmigration) rates.

In essence, the residence time model works by establishing 6 columns for each group of marked hatchery fish that was released, with a separate column containing the adjusted ACCE daily production estimates for each calendar date (rows).

The first column for each group of smolts records the number of days since that group was released. For example, The first group of marked smolts that were released were considered to be caught 0 days after release if they were caught on April 14, 1 day after release if they were caught on April 15, and so on.

The second column records the numbers of fish in that group that are alive and still upstream from the trap site at the beginning of the day. This value corresponds exactly to the number remaining alive in the river at the end of the previous day, except for day 0 when this is the number of smolts released (another column elsewhere in the spreadsheet).

The third column indicates how many of those smolts will die that day. This is simply the number of smolts alive at the start of the day, multiplied by a constant mortality rate (if applicable).

The fourth column is the estimated number of marked smolts *from that group* that outmigrate past the trap site during that day. This is a function of the total daily production estimate for that day, multiplied by the proportion of all marked fish, that are alive and upstream of the trap, that belong to that group at the start of that day (calculated in column 6).

The fifth column is the number of fish remaining alive and upstream from the trap site at the end of the day (= number alive at start of day, minus the number dying, minus the number outmigrating.)

The last column calculates what proportion that a group of fish represents of all marked fish in the river above the trap site, at the beginning of each day.

The sum of all group's daily outmigrant columns must equal the ACCE daily production estimate for marked smolts. The only variable that can be altered is the daily mortality rate (a constant). If necessary, an iterative process varies the mortality rate until the model output exactly matches the ACCE daily production estimate and all remaining fish are accounted for by mortality.

Now we have an approximation of the daily outmigration and mortalities for each group of marked fish. The average residence time is calculated by multiplying the combined mortalities and outmigrants for each day, by the number of days that have passed since release (the first column for each group). These values are summed for each group and then divided by the number of smolts in that group that were originally released.

Overall group survival (to the trap site) can also be estimated by summing the total number of modeled outmigrants for that group and dividing this by the number of smolts that were originally released.

The results for 2008 are shown in Figure 7.

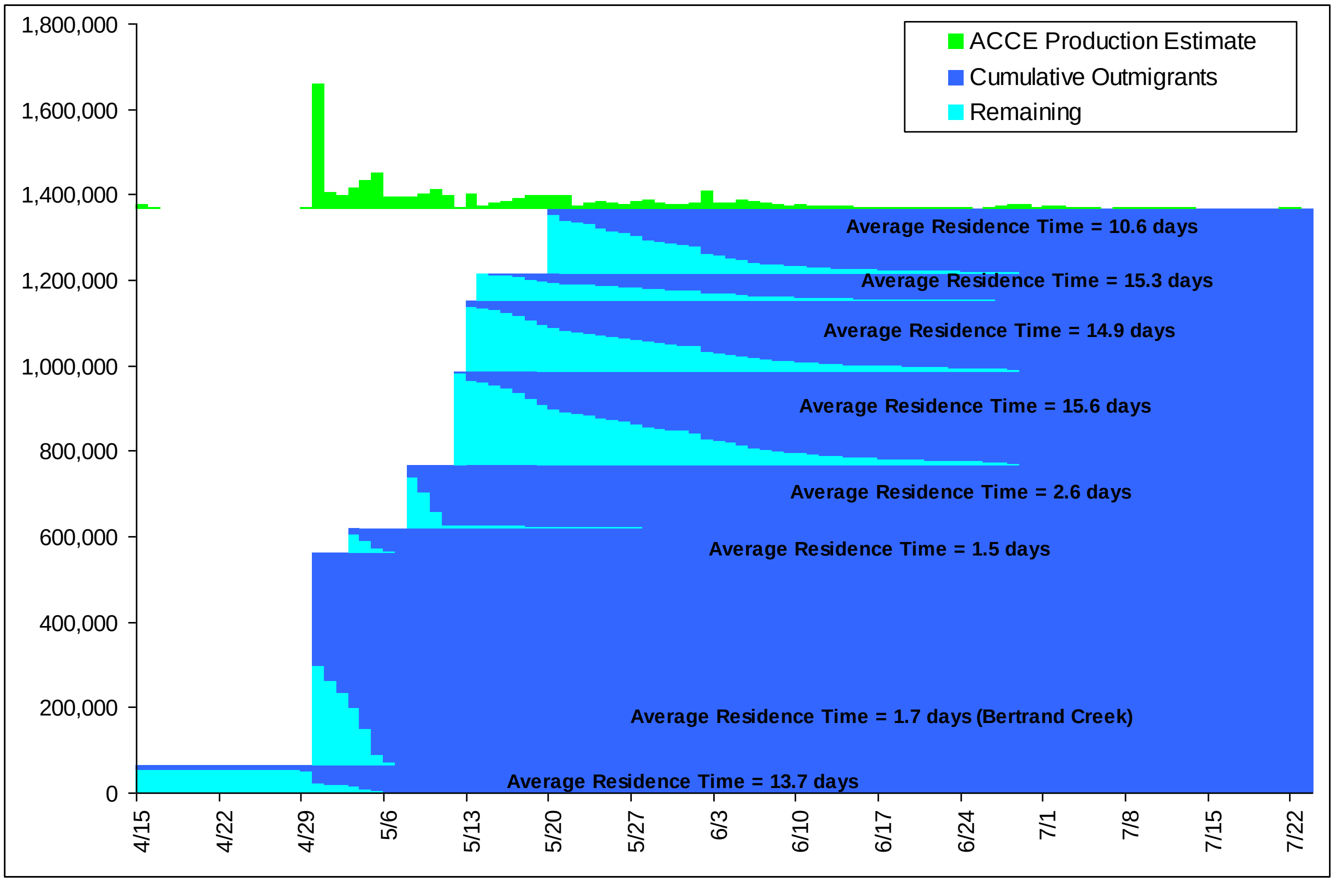

Figure 7. Model output showing cumulative outmigration, mortality, and adjusted-ACCE daily production estimates for eight groups of ad-clipped hatchery-origin Chinook smolts in 2008.

Previous modeling work has shown a general trend for smolts to have a longer upstream residence time if they are released earlier in the spring (Figure 8). However, this year the pattern of residency was upset by the introduction of half a million smolts in Bertrand Creek (only a few miles above the trap site), in addition to the usual releases of smolts in the upper river.

Unfortunately, there is no objective way to identify exactly which group of smolts an individual smolt belongs to when it is captured at the trap site. Accordingly, the residence time model assumes that the group composition of fish arriving at the trap is the same as the group composition in the river upstream as a whole. The residence time model makes no adjustment for release site proximity and implicitly assumes that the outmigration behavior of smolts released at different sites is the same everywhere.

In this case, the Bertrand Creek smolts clearly outmigrated almost immediately upon release (average residence time 1.7 days), which is a completely different behavior than we have seen for smolts released in the upper watershed in other years, and also this year (after the Bertrand fish had cleared out). As a result, the model breaks down as soon as the Bertrand Creek group remains at large in the river and distorts residence times for other groups of fish that are released before, during, and shortly after the Bertrand Creek group was released.

This means that the residence time of the Bertrand creek fish is artificially increased a little, while the residence times of the other (smaller) groups are artificially decreased by a significant amount. In this case, the impact of the Bertrand Creek smolts on the model was notable for Chinook released prior to May 12, and negligible from May 12 onwards.

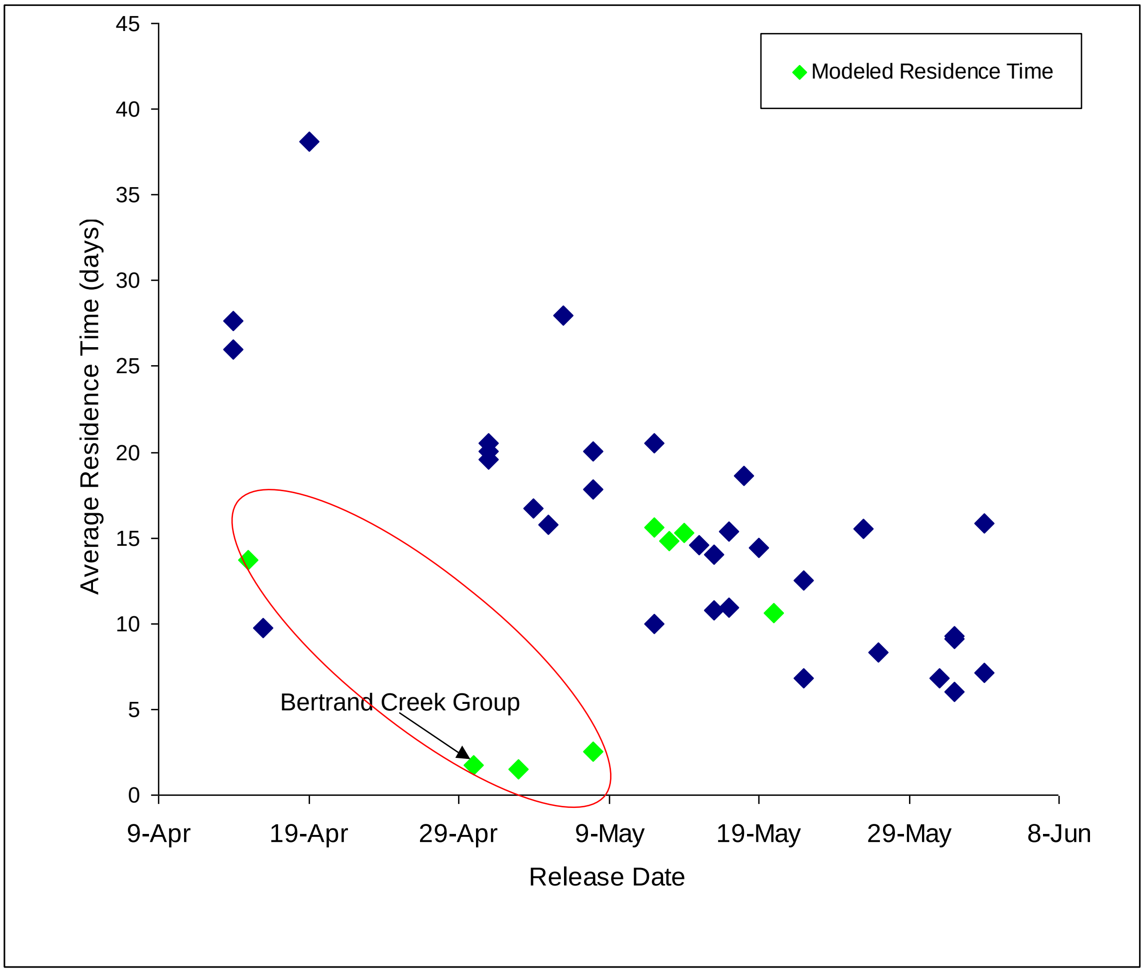

Figure 8. Modeled average residence time versus group release date for individually-modeled groups of marked hatchery Chinook smolts released in 1999, 2001, 2002, 2003, 2004, 2005, 2006, 2007(navy) & 2008 (green). Red circle indicates 2008 results that are dubious because of model assumptions violated by the Bertrand Creek release.

Wild-Origin Stock Composition

Ultimately we are interested in estimating what the annual production of Spring Chinook smolts is from the Nooksack River. Unfortunately, in previous years we have had no direct means of counting this stock, as they are indistinguishable from wild-origin Fall Chinook, or from unmarked hatchery-origin Chinook. Consequently, we previously needed to devise some means of indirectly separating wild-origin from hatchery-origin smolts, and then further subdividing the wild-origin component into the Spring and Fall stocks. However, beginning in 2005, almost 100% of the hatchery-origin smolts have been marked before release enabling us to directly separate hatchery smolts caught in the trap from wild-origin smolts (Figure 5).

Unfortunately, there is still no way to separate wild-origin Spring smolts and wild-origin Fall smolts from each other, save by comprehensive DNA analysis (to ascertain stock of each wild-origin smolt caught). With the advent of comprehensive marking of hatchery smolts we can now sample wild-origin smolts almost exclusively, thereby reducing the number (and therefore the cost) of DNA testing. Despite this improvement, comprehensive DNA analysis is still prohibitively expensive. Nonetheless, DNA samples from a large percentage of wild-origin smolts have been collected from the 2005 - 2008 seasons in hopes that funding eventually becomes available to allow the samples to be analyzed.

Chinook Discussion

Comparison of Production Estimate Methods over Time

It is difficult to assess the relative merits of each of the three estimation methods without knowing the true number of smolts outmigrating in any given year, or knowing the width of confidence intervals around each estimate.

The only confidence interval available for any of the estimates is the ACRM (= Peterson mark-recapture) method. From 2002 – 2002, and in 2000, the confidence intervals were remarkably tight (<5%) around the estimate. The estimates for 1999 and 2001 had worse confidence intervals, but they remained fairly narrow (11% and 10% respectively). However, it should be remembered that this method makes some critical assumptions that could easily be violated in this application. For example, marked fish do not mix with other fish that are caught prior to their release. Also, marked fish may not behave identically to unmarked hatchery fish, and hatchery fish overall may not behave like wild-origin fish, leading to differences in trap catch efficiency for each stock. Even worse, in 2008 the behavior of fish released at Bertrand Creek was clearly quite different than fish released higher in the system. The upshot of all this is that not all fish would have had an equal chance of being sampled. Consequently, the ACRM estimate and the associated confidence intervals should be considered with appropriate caution.

The only reference value that we know with reasonable certainty is the number of hatchery fish that were released into the river. An unknown (but probably large) proportion of the hatchery-origin fish survive to reach the trap site, along with an unknown number of wild-origin fish that are also outmigrating past the trap site. Consequently, we would expect that a good production estimation method would not result in values markedly below the known release of hatchery smolts. Historically, we had also assumed that the number of wild-origin smolts wouldn't be very high relative to the number of hatchery-produced smolts because we have observed that returning wild-origin adults have typically been only a small proportion of the returning adult population. From 2005 onwards, this assumption has been validated directly as a result of the 100% marking policy adopted by the hatcheries. This has allowed us to empirically quantify the origin of smolts caught at the trap site: 83%, 76%, 91%, and 81% of all smolts caught in the trap were definitely hatchery-origin in 2005, 2006, 2007, & 2008 respectively.

Figure 6 shows the production estimates for the last 10 years that were derived using each of the three methods detailed above, as well as the number of hatchery-origin smolts released each year.

Sampling effort in 1999 was much lower than other years, and featured very few nighttime samples. Inadequate nighttime sampling might considerably under-estimate the total number of fish if smolts are more likely to outmigrate, and/or be caught by the trap, at night. Consequently, it is likely that the most useful production estimate for the 1999 season will the Ad-Clip Recapture Ratio method. Supporting this contention, both the YCCE and ACCE methods estimate a number that is approximately one half of the known hatchery release in 1999. Unless the hatchery releases were subject to drastic mortality (disease perhaps?), these numbers are unlikely to be realistic.

Since 1999, the proportion of sampling effort conducted at night has increased considerably, particularly from 2002 – 2008. The ACRM, YCCE, and ACCE methods all agree closely for 2004, 2005, 2006, & 2007, and slightly less closely for 2002, 2003, and 2008. However, the three methods provide far less consistency prior to 2002, when the ACRM and YCCE methods produced estimates that were reasonably similar in magnitude but the ACCE method differed strongly. Why does the ACCE method diverge radically from the other two methods during 2000 and 2001?

River flows during the outmigration in 2001 were considerably lower than usual which could explain why the catch efficiency of the trap differed from 'normal' conditions during that season. Since there is an environmental explanation for unusual trap catch efficiency in 2001, it is likely that the ACRM and YCCE estimates are probably more reliable than the estimate based on long-term trap catch efficiencies (because long term averages are most useful in 'typical' circumstances). However, river flows in 2000 were not unusually low, and secchi-depth readings didn't deviate from the normal range either. There doesn't appear to be an environmental explanation for the extremely high recapture rate of marked hatchery-origin smolts (nearly double what was expected given the amount of sampling effort). One possible explanation could be erroneous records of how many marked, hatchery-origin fish were released in 2000. Given that there is no readily apparent environmental explanation, it may be that the long-term catch efficiency estimate (ACCE) may be more realistic for the 2000 season. Also, although the sampling effort in 2000 was higher than 1999, it was still short of the effort expended in the following seasons. Consequently, large gaps in the sampling record may have resulted in pulses of fish being missed altogether as they migrated downstream.

In 1999 (ACRM only), 2001, 2003, 2004 (barely), 2005, 2006, 2007, & 2008 both the ACRM and YCCE methods estimated that the total production of Chinook fry outmigrating past the trap exceeded the number of hatchery-origin fry that were released upstream. However, in 2000 and 2002 both of these methods estimated that the total production of fry from the river was *lower* than the number of hatchery-origin fry that were released. If true, then the production estimates for 2000 and 2002 are surprising, since we had assumed that hatchery-origin fry would have a fairly short stay in the river and experience only minimal mortality. Also, there ought to be at least *some* wild-origin fry outmigrating as well. This raises some serious questions about the assumptions used, or about the accuracy of the production estimates.

Obviously, the first question is whether these estimates are even in the right ballpark. Until now, we have attempted to answer this question by looking for consistency in the results in comparison to known hatchery releases. However, such an analysis is confounded when you are extrapolating from a small fraction of marked fish to estimate the seasonal hatchery production. Because we have had 100% marking for four years, we are now able to measure the bias in the ACCE and YCCE models (Table III).

Table III. *Measured bias in ACCE and YCCE estimates of marked Chinook smolts production estimates (assumes zero mortality between release and recapture)*

Year	YCCE	ACCE
2008	-18.60%	-36%
2007	16%	-12.30%
2006	40.80%	12.60%
2005	31%	-18.50%
Average Bias	17.30%	-13.55%
Stdev	0.260156	0.201154
Std. Error	13.01%	10.06%
95% Confidence Interval	25.50%	19.71%

Based on the data in Table III, it appears that typically the unadjusted YCCE production estimate overestimates the number of outmigrants, whereas the ACCE estimate typically underestimates the number. However, the large variance in the observed bias from year to year means that we cannot yet determine if the bias is significantly different from 0 for either method (t-test, $p>0.05$).

The relatively close agreement between the ACRM and the ACCE & YCCE methods from 2002 onwards contrasts strongly with the wildly differing estimates that the three methods produced from 1999 – 2001. This observation validates the changes that were made to the screwtrap protocols beginning in 2002. Generally the changes made were: to increase overall effort; begin to stratify sampling by dawn, day, dusk, and night periods; and aim to minimize the length of the gaps in the sampling time-series to avoid missing pulses of fish moving downstream. It seems likely that these methods are producing results that are at least in the right ballpark.

Leaving aside the question as to the accuracy of the production estimates, is it possible that some of the assumptions made regarding residence times, mortality, or wild production are erroneous? Unfortunately, most of these assumptions are difficult to test directly.

Muir *et al.* (1999) showed that that daily survival rates for marked hatchery-origin Chinook fry (c. 80mm FL) released into the Snake River was c.

98.2% per day. Although conditions in the Nooksack are probably less hostile than the highly regulated (i.e., dammed) Snake River, it is still reasonable to assume that *some* mortality occurs between release sites and the Lummi screw trap. Mortality of Chinook released into the Nooksack River might be due to handling stress, disease (perhaps exacerbated by stress), starvation, predation, or stranding in off-channel habitat when river waters drop suddenly after high-flow conditions. None of the methods used in this analysis explicitly allow for smolt mortality.

Actual recapture rates of marked hatchery smolts will be slightly higher than we report because we are assuming that no smolts die before reaching the trap site. Consequently, our estimates of production may be slightly biased too high for hatchery smolts. At an average residence time of 16 days with a daily mortality rate of 0.9% (half of that calculated by Muir *et al.*, 1999) you would expect around 13.5% of the marked hatchery smolts would perish before passing the trap site. This would mean that our recapture rate for 2008 was actually 0.49% instead of 0.43%; the YCCE instantaneous catch efficiency would change from 2.06% to 2.39%; and the ACCE instantaneous catch efficiency would increase to 2.65%. In turn, this would change the bias of the YCCE and ACCE methods to –19.9% and –27.8% respectively. Such a change would reduce ACRM estimate of wild-production to 259,391 smolts in 2008 (instead of 299,867) and likewise reduce the ACCE and YCCE production estimates (to 475,618 and 475,610 respectively). However, since we have no mortality data for hatchery fish released into the Nooksack River, and especially with the introduction of a large group of rapidly outmigrating smolts at nearby Bertrand Creek confounding expectations for residence times, it is now almost impossible to come up with a defensible estimate of mortality that could be used to realistically adjust the results.

Another possible bias may arise if some of the hatchery-origin fish had not moved downstream past the trap site by the end of sampling. In other words, some hatchery fish might over-winter in the river and outmigrate as yearlings the following year. Arguing against this hypothesis is the fact that no ad-clipped or tagged yearling Chinook smolts have ever been caught in the screw trap (except when clipped/tagged yearlings were also released upstream that same year). However, the number of yearling Chinook caught in the trap is typically very small (10-30 fish per year) so the chances of catching a marked yearling would be very low even if they were present in the river. Interestingly, two adipose-clipped yearling Chinook were caught in beach seines in the Nooksack Estuary in 2003. If these fish were released into the Nooksack as zero-age Chinook then we may have an indication that some hatchery fish may over-winter either in the river or in the estuary. However, the possibility also exists that these yearling Chinook could have been released elsewhere and were simply migrating along the shore from their release site. No further information is available to evaluate the likelihood or proportion of hatchery fish that could be accounted for in this way.

The main assumption that seems to be causing problems during data analysis is the constant catch efficiency assumption. We strongly suspect that trap catch efficiency varies depending on environmental conditions (turbidity, noise due to fast rotation of the cone, etc). When salmon move in short-duration pulses, the catch efficiency during that short time could be quite different than the estimated average for the whole season leading to an erroneous production estimate for that time frame. Unfortunately, our attempt to resolve this problem (secchi depth – catch efficiency trials) proved to be far too unreliable: even for the specific groups of hatchery-origin fish being used.

We also assume that wild fish behave like river-acclimated hatchery fish, and that catch efficiencies prior to hatchery releases are similar to those after hatchery releases. With the advent of ~100% marking in 2005, we can now see that the majority of wild smolts do have a similar outmigration pattern to hatchery fish, and that relatively few wild smolts outmigrate before hatchery releases begin. Consequently, even if this assumption is faulty, it should have relatively little impact on the wild production estimates unless the difference in catch efficiency is very large.

Hatchery Chinook Residence Times

In 2008 the shortest residence time was a few hours, and the longest possible residence time observed may have been as long as 76 days.

For half of the groups of smolts released in 2008, the estimated residence times are consistent with the relationship generated from data obtained in previous years. Generally, this established relationship suggests that early-release groups tend to stay in the upper watershed for a longer time than those released later in the season. This behavioral difference has also been noted in the Snake River, albeit for yearling Chinook smolts (Smith *et al.*, 2002.

However, the residence time results for the first four groups released in 2008 were dramatically different than has been observed previously. In large part, this difference is the result of the introduction of a new release site (Bertrand Creek), which is very close to the screwtrap location (all other sites are much higher in the watershed). The residence time model assumes that groups of fish releases upstream are well mixed by the time that they arrive at the trap site. Generally this assumption has worked well in the past because the smolts generally take at least a couple of weeks to work their way down to the trap site and intermingle as they move downstream. Unfortunately, the behavior of the Bertrand Creek smolts was quite different because most of the fish moved out past the trap site almost as soon as they were released. When combined with the relatively close proximity of Bertrand Creek to the trap site, this meant that there was almost certainly no chance for these fish to mix with other Chinook smolts released elsewhere in the system. Worse still, the magnitude of the Bertrand Creek release was almost an order of magnitude larger than other groups of Chinook released before or soon after the Bertrand Creek group. Accordingly, the model incorrectly assumed that large numbers of smolts outmigrating past the trap site in the days after the Bertrand Release were from some of the smaller, more distant groups released much higher in the watershed. This had the effect of slightly increasing the estimated residence time of the very large Bertrand Creek group, but making a large reduction in the estimate residence time of the much smaller groups of smolts released higher in the watershed that coincided with the Bertrand Creek group. The impact of this group on the model results appears to have been removed by the time the May 12th group was released.

It is likely that the close proximity of the release site will continue to plague any attempts at residence time modeling in future years even if release protocols in future years manage to avoid the rapid outmigration behavior in smolts released at Bertrand Creek.

Wild-origin Chinook Production Patterns

The wild-origin production estimate for 2008 varies from **299,867** (ACRM method) to **549,838** (adjusted ACCE method) smolts. Of these estimates, I tend to favor the larger estimate because the ACRM estimate was disproportionately impacted by a higher than average trap sampling effort during the 2 or 3 days following the massive Bertrand Creek release (well over 40% of the time). This meant that a larger than expected number of marked Bertrand Creek smolts would have been recaptured at the trap than would ordinarily be expected based on the lower sampling effort realized over the entire ‘hatchery fish’ time window (around 20%). Because the ACRM estimate assumes proper mixing of marked and unmarked fish, and there were no ‘under-sampled’ releases of equivalent magnitude, proximity, and duration, this will likely mean that the ACRM estimate of total production will be biased too low.

Depending on which estimate you select, the level of wild production in 2008 (Figure 9) is possibly the best in the last seven years but it could also be about the same as that of 2006 (Brood Year 2005). Regardless, the production of wild-origin Chinook in 2008 was clearly pretty good in the context of the last seven years, and will hopefully result in somewhat better adult returns in due course. Hopefully, early-returns from this stronger year class will spill over into the terrible year class of zeroes that outmigrated in 2007.

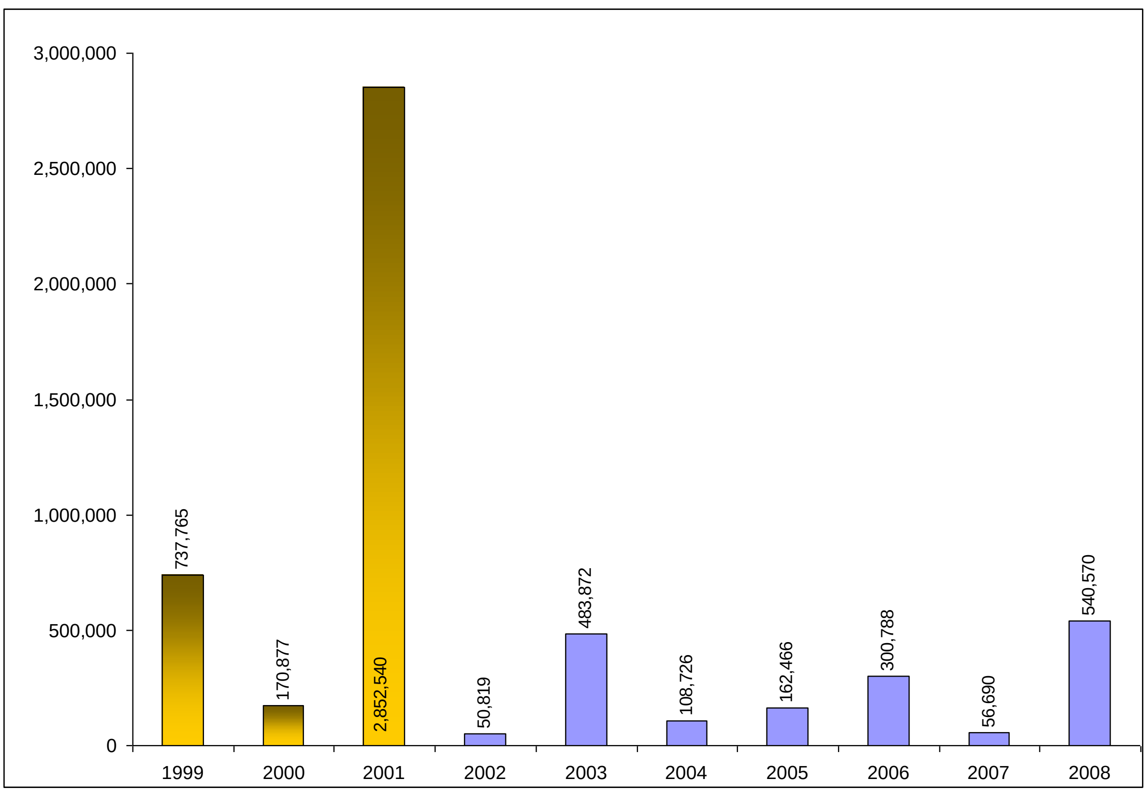

Figure 9. Wild-Origin Production Estimates from 1999 to 2008. Blue bars indicate estimates are probably reliable. Shaded-orange bars indicate data quality is not as good.

Table IV indicates that river flows in fall 2007 exhibited a moderate flow event (19,700 cfs at Ferndale) in early December during the egg incubation period, but no really large flows occurred during October/November before the eggs had an opportunity to harden. Also, no other major flood events occurred during the remainder of the egg incubation period or during the early fry stage. The high production estimates of zero age Chinook in 2008 following the relative benign 2007 fall incubation period, continues to suggest that catastrophic flow events are a primary causative factor in smolt production rates.

Table IV. *Maximum monthly flows (cfs) in the Nooksack River at the Ferndale Gage Station. Red cells indicate severe flows that are most likely to cause scouring. Pink cells indicate years with spawning Pink Salmon. White cells indicate no pink salmon spawning occurred.*

Minimum Summer Flow	1,620	834	1,130	1,090	719	575	943	1,570	685	661	750	1,210	1,640
	1997	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**
Max Jan	23,200	10,300	14,300	4,890	7,640	24,100	13,900	11,700	29,000	16,000	17,700	5,860	47,500
Max Feb	8,470	5,680	9,500	5,160	2,900	27,500	8,210	6,700	5,480	9,510	8,710	4,320	2,840
Max Mar	33,700	8,160	7,180	5,860	5,810	5,760	16,200	6,970	6,400	2,850	23,700	5,090	
Max Apr	10,100	5,730	5,730	13,800	5,100	15,700	7,740	4,040	10,400	5,340	11,800	4,320	
May May	17,700	6,500	10,000	8,390	7,140	9,860	6,150	6,580	5,290	8,850	5,860	15,300	
Max Jun	12,400	4,420	10,600	13,300	7,150	13,100	5,270	5,740	3,070	8,550	7,980	10,100	
Max Jul	15,300	5,300	8,450	4,720	3,190	5,729	2,990	2,970	6,970	4,010	6,570	10,300	
Max Aug	3,230	2,230	6,090	3,600	9,860	2,280	1,940	9,920	1,840	1,730	1,990	10,700	
Max Sep	7,470	1,340	3,350	4,950	2,690	2,490	1,640	9,580	10,600	1,600	2,020	3,600	
Max Oct	13,000	3,560	16,600	9,990	8,790	1,880	32,300	6,340	11,900	2,020	9,610	4,960	
Max Nov	7,700	16,600	19,800	3,290	17,700	13,700	25,400	31,100	7,350	31,800	8,810	17,100	
Max Dec	12,600	21,100	19,100	4,260	19,300	11,100	6,620	22,400	15,900	12,300	19,700	7,080	
		Brood Year											
Wild Production Estimate (0+ Chinook Numbers)			737,765	170,877	2,852,540	50,819	483,872	108,726	162,466	300,788	56,690	540,570	
Wild Catch / Hundred Hours (Yearling Chinook CPUE) Between 1/5 and 6/11 for yearlings			Zero-Age Migrants	16.3 Yearling Migrants	5.84	17.13	1.99	9.25	4.2	4.6	3.2	0.38	

Wild Chinook Outmigration Timing

The bulk of the wild outmigration in 2008 began with a moderate number of smolts detected during the descending limb of the hydrograph during some significant flow events in May. The largest pulse of smolts outmigrated in the middle part of May, followed by a moderate to low trickle of smolts petering out in mid July. However, another bump of smolts was observed unexpectedly coincident with a moderate flow event in mid August, which rapidly died out. However, no sampling occurred for 17 days prior to that observation which resulted in a prolonged period of interpolation that may have overestimated the true number of smolts outmigrating during that interval.

There did not seem to be any evidence of wild-origin Chinook outmigrating immediately following the first hatchery release at Kendell Creek, nor being triggered by the Bertrand Creek release (unsurprisingly since the Bertrand Creek smolts were unlikely to encounter many wild-origin smolts in the mainstem.

There were also a couple of relatively minor ‘bumps’ of outmigrating zero-age Chinook observed very early on in January, and again in March. Generally these coincided with flow events and probably represent fry being swept downstream accidentally rather than deliberate outmigration behavior.

Coho

2008 Hatchery Releases

Table IV shows the data of release, hatchery, and numbers of hatchery-origin Coho yearling smolts released in the Nooksack River upstream from the screw trap location.

Table IV. *Coho Yearling Smolts released in 2008. Gray columns indicate 'marked' Coho for the purposes of this report. Note that, unlike Chinook zeroes, Coho yearlings are not scanned for CWT's by the screwtrap field crew.*

Coho Yearlings			Ext. Marked		Unmarked			
Release Date	Source	Release Site	Ad-Clip Only	Ad-Clip & CWT	CWT Only	No Clip. No Tag	Total Release (All)	Total Release (Externally Marked)
5/9/2008	Kendell Hatchery	Kendall Creek	171,494	49,328	49,823	763	271,408	**220,822**
5/22/2008	Skookum Hatchery	Skookum Creek	287,289	15,461	257	4,671	307,678	**302,750**
5/23/2008	Skookum Hatchery	Skookum Creek	232,890	12,533	208	3,786	249,417	**245,423**
5/24/2008	Skookum Hatchery	Skookum Creek	158,089	8,508	141	2,571	169,309	**166,597**
5/25/2008	Skookum Hatchery	Skookum Creek	68,622	3,693	61	1,116	73,492	**72,315**
5/26/2008	Skookum Hatchery	Skookum Creek	75,640	4,070	68	1,229	81,007	**79,710**
5/27/2008	Skookum Hatchery	Skookum Creek	45,862	2,468	41	746	49,117	**48,330**
5/28/2008	Skookum Hatchery	Skookum Creek	26,810	1,443	24	435	28,712	**28,253**
5/29/2008	Skookum Hatchery	Skookum Creek	13,941	751	12	226	14,930	**14,692**
Grand Total			**1,080,637**	**98,255**	**50,635**	**15,543**	**1,245,070**	**1,178,892**

Coho Production Estimate Methods

There are four potential methods for quantifying Coho production based on smolt trap data, which are identical to those discussed previously for Chinook salmon. They are the ACRM method (otherwise known as a Peterson Mark-Recapture estimate), the Average Constant Catch Efficiency (ACCE) method, the Year-Specific Constant Catch Efficiency (YCCE) method, and the Secchi-Depth – Catch Efficiency Relationship Method. We do not use the Secchi-Depth relationship method to predict catch efficiency for either species.

Coho Production Estimate Results

Adipose-fin Clipped Recapture Method (ACRM)

Table V shows the parameters and results obtained using the ACRM/Peterson's Mark-Recapture method for smolt trap data in 2008 and earlier seasons.

Table V *Results obtained using the ACRM method for smolt trap data from 1999 to 2008.*

Year	2008	2007	2006	2005	2004	2003	2002	2001	2000	1999
Total Production Estimate (N_P)	**1,557,140**	**1,939,050**	**2,082,277**	**2,280,573**	**2,693,075**	**1,988,042**	**2,077,633**	**2,162,813**	**2,260,919**	**4,640,808**
Total Hatchery Releases	**1,245,070**	**1,417,895**	**1,316,788**	**1,245,234**	**1,241,005**	**1,403,100**	**1,304,831**	**1,230,747**	**1,429,200**	**2,669,737**
Marked Hatchery Releases (H)	**1,178,892**	**1,417,895**	**1,316,788**	**1,245,234**	**1,241,005**	**1,403,100**	**1,304,831**	**1,230,747**	**1,429,200**	**2,669,737**
Wild Production (N_P-H)	**312,070**	**521,155**	**765,489**	**1,035,339**	**1,452,070**	**584,942**	**772,802**	**932,066**	**831,719**	**1,971,071**
Ad-Clips Released (N_1)	1,178,892	1,283,414	1,170,806	1,198,134	1,193,205	1,353,300	1,225,031	1,170,747	1,365,635	320,465
Total Coho Caught (N_2)	2,857	2,993	4,384	3,489	2,898	4,056	5,997	3,946	2,937	782
Ad Clips Recaptured (M_2)	2,163	1,981	2,465	1,833	1,284	2,761	3,536	2,136	1,774	54
Observed Recapture Rate (M_2/N_1)	0.18%	0.15%	0.21%	0.15%	0.11%	0.20%	0.29%	0.18%	0.13%	0.02%
Variance (N_P)	271,393,928	639,683,736	767,262,913	1,342,138,235	3,133,772,188	455,562,613	499,032,987	1,001,065,168	1,137,357,243	345,516,755,075
95% Confidence Interval Width	32,289	49,572	54,291	71,805	109,721	41,834	43,785	62,014	66,100	1,152,101

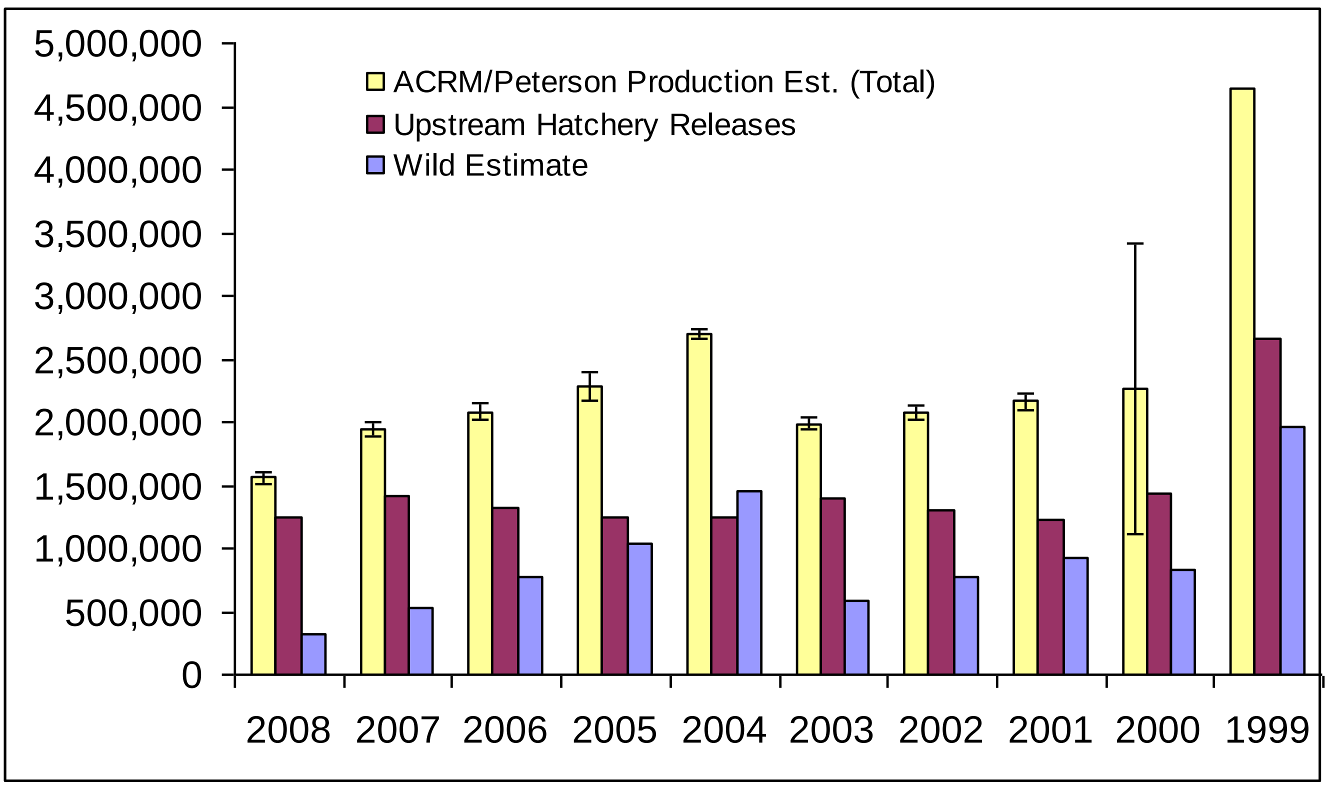

Figure 10. ACRM / Peterson Mark-Recapture Production Estimates for Coho Yearling smolts outmigrating from the Nooksack River (+/- 95% CL).

Based on the data in Table V we estimate that c.1.56 million Coho smolts outmigrated past the screwtrap in 2008. We know that c. 1.245 million smolts were released from hatcheries above the trap-site, and this suggests that the difference (**312,070**) is comprised of wild-origin smolts. However, it is important to remember that one of the primary assumptions in this estimate is that the population is demographically closed: that is, no mortality occurs between release and recapture of the marked fish. Unfortunately we have no means to measure post-release mortality of marked hatchery fish in the river.

In other river systems daily mortality rates of hatchery-released smolts are very low in unobstructed stretches of river. If this is true for the Nooksack River also, then it is likely that overall mortality of the fish is also low…especially since we are confident that their residence time is only a few days. However, it is likely that the calculate rate of recapture is probably biased slightly lower than the true rate of recapture (because we are overestimating the number of released fish moving past the trap). This will have the effect of artificially biasing the final production estimate slightly too high which will artificially inflate the wild production estimate by an unknown amount. On the other hand, when we subtract the total hatchery release from the (presumably slightly too high) ACRM production estimate we do not factor in this mortality of hatchery-released smolts either. This would have the effect of artificially reducing the wild-production estimate by an amount directly related to the actual mortality of hatchery-released smolts. So, on one hand the faulty assumption of nil mortality would increase the wild-production estimate, and simultaneously it would decrease it by a different amount. To quantify which 'bias' would dominate requires a good understanding of daily mortality rates for hatchery-origin smolts as well as a thorough knowledge of residence times. Lacking specific knowledge of true mortality rates, it is possible to model different scenarios to determine how sensitive the estimate is to varying levels of mortality. Accordingly, Figure 11 shows a theoretical plot (Figure 11) modeling the overall effect on the ACRM estimate when mortality ranges from 0% (no mortality) to 25% (25% of all hatchery-released smolts die before reaching the trap site).

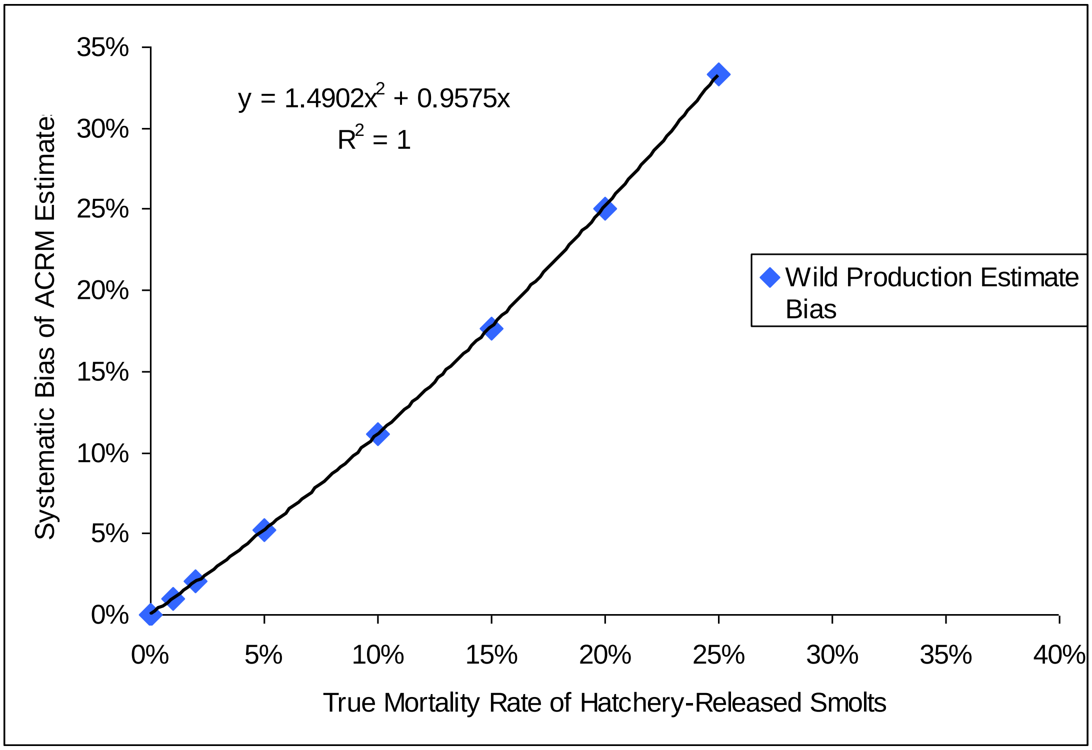

Figure 11. Plot of modeled ACRM bias magnitude compared to theoretical group mortality rates for hatchery-origin smolts prior to reaching the trap site.

Based on the modeling of hatchery-origin smolt group mortality rates, it appears that the ACRM estimate tends to over-estimate the true outmigration by a percentage that can be described by the equation $y = 1.49{*}M^2 + 0.96{*}M$; where y is the percentage bias, and M is the group mortality (%) of hatchery-origin smolts. This relationship also describes the bias of ACRM estimates for total Coho, hatchery Coho, and Chinook fry estimates as well. Consequently, if 5% of all hatchery smolts that are released were to die before reaching the trap (or else become resident upstream until after sampling ceases), then the overall ACRM production estimates for hatchery and wild-origin smolts would both be

$$\begin{aligned} \text{Bias} &= 1.49 * 0.05^2 + 0.96 * 0.05 \\ &= 0.052 \text{ (3dp)} \\ &= 5.2\% \end{aligned}$$

YCCE/ACCE Method Results

Figure 12 shows a scatter plot of the season-wide recapture rate of hatchery Coho smolts plotted against the proportion of the hatchery outmigration period that was sampled.

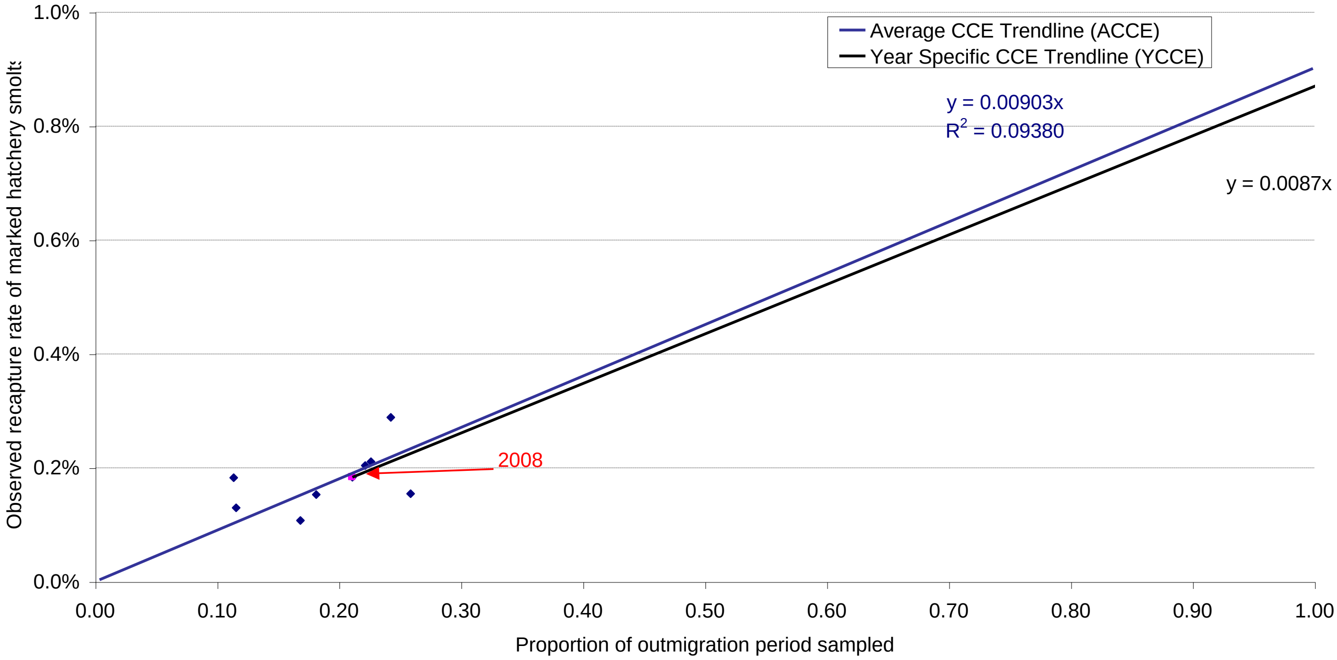

Figure 12. Adipose fin-clipped Coho recapture rate versus proportion of total time sampled during the outmigration period of adipose fin-clipped Coho smolts.

The YCCE estimate for catch efficiency was 0.87%. The ACCE estimate for catch efficiency was 0.903%.

Both methods use the interpolated catch-per-day data (summarized in Figure 13) to extrapolate catch data based on constant catch efficiencies.

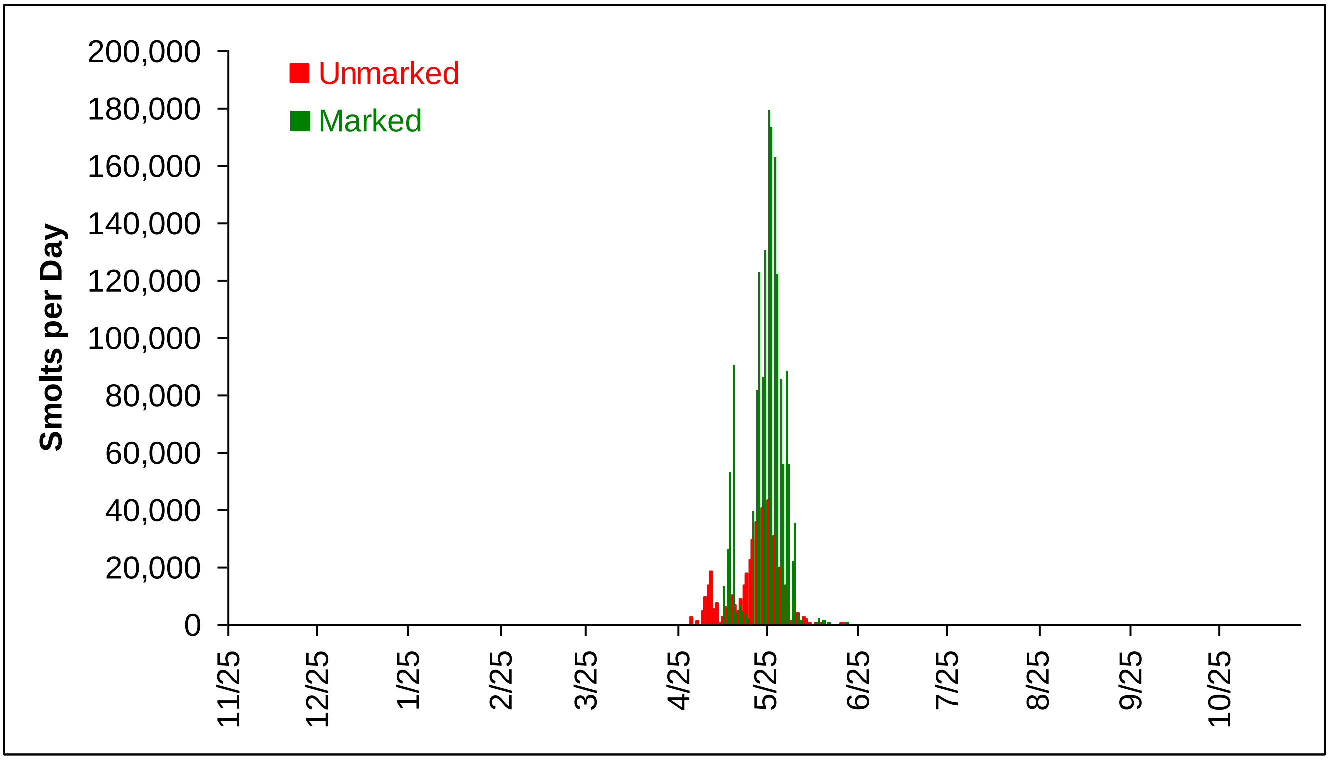

Figure 13. Average daily catch rates for adipose fin-clipped and non-clipped Coho yearlings in 2008.

As we have seen previously, hatchery fin-clipped Coho smolts outmigrate over a relatively short time span, en-masse. Un-clipped/tagged (presumably wild) Coho yearlings tend to outmigrate over a longer time period. This probably indicates that ACCE and YCCE production estimates for hatchery smolts are likely to be more adversely affected by an erroneous assumption of constant trap catch efficiencies than wild Coho. Both groups are still likely to be affected by an underestimation of nighttime catch efficiencies though since wild and hatchery origin smolts swim closer to the surface at night and the true number of marked smolts passing the trap site during the night and during daylight is unknown.

Using the overall ACCE catch efficiencies the total production of ad-clipped Coho yearlings for 2008 is 1,463,017 smolts and the total production of un-clipped smolts is 533,472 smolts. Using the YCCE catch efficiencies, the clipped production would be 1,518,511 clipped smolts and 553,710 unclipped smolts. However, we know that 1,178,892 clipped smolts were released in 2008 making the ACCE estimate 24% too high for clipped hatchery smolts, and the YCCE estimate 28.8% too high.

Adjusting the ACCE and YCCE estimates for unclipped Coho to account for this bias would result in an estimate of ~ 429,869 unmarked Coho smolts passing the trap site in 2008. Of these, we know that around 66,178 were unclipped hatchery-origin smolts. Thus, a wild production estimate for 2008 derived using the ACCE or YCCE estimation methods would be **363,691** wild-origin smolts.

Residence Time Modeling for Coho

Average residence times for hatchery Coho could be modeled in 2008 because there was no noticeable leakage of yearling Coho from the hatcheries prior to release. Figure 14 shows the model results for 2008 Coho releases

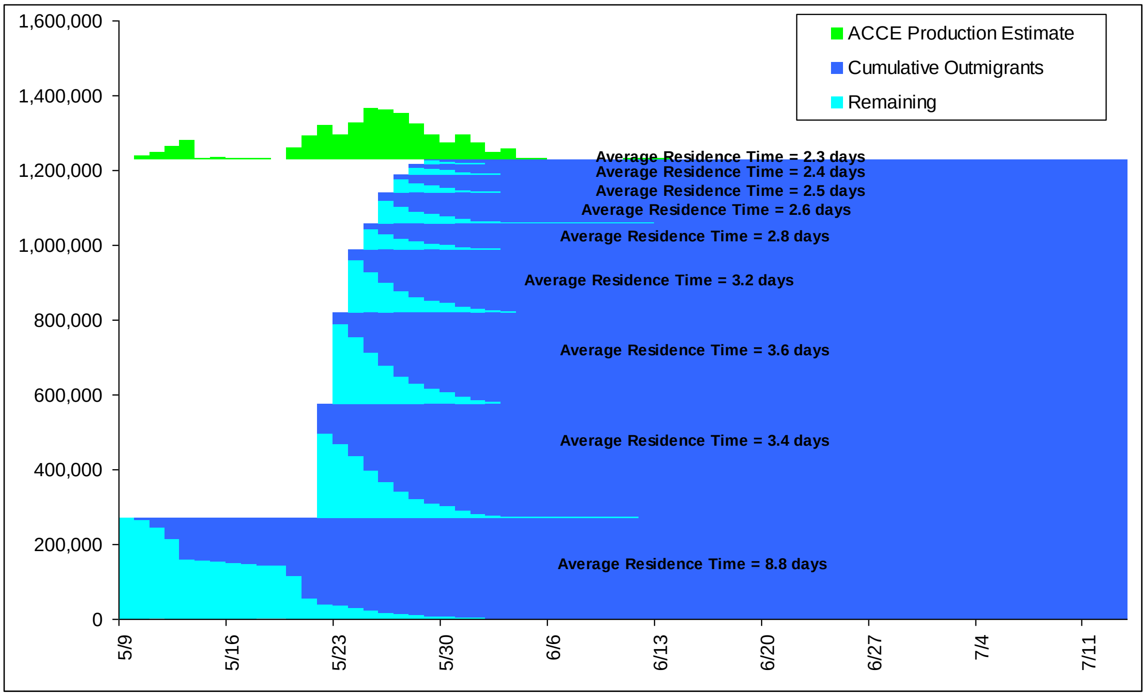

Figure 14. Model results for residence times for hatchery-released Coho Yearlings in 2008. Green bars indicate the total number of Coho smolts passing the trap on each date. The model assumes that the catch composition reflects complete mixing of all groups present upstream on that date.

As with model results from pervious years, the group released earliest in the year tends to exhibit a longer residence time than groups released later in the year, and overall residence times are fairly short (c. 3 days) compared to hatchery-origin age zero Chinook released in the upper watershed (typically c. 10 - 25 days).

Screwtrap Sampling Mortality Results

Table VI shows the total number of individuals handled during screwtrap operations in 2008 grouped into species, life-stage, and presumptive origin based on mark status, and split into those individuals that were released alive and those that were not released alive (morts). The causes of mortality were generally related to inundation of the trap by debris, but also include individuals that were thought to be dead on arrival or deliberately sacrificed for DNA analysis/gut content analysis.

***Table VI**. Summary of Individuals Released Alive vs. Mortalies during Screwtrap operations in 2008 by Species, Lifestage, and Mark Status.*

Species	Lifestage	PresumptiveOrigin	Accidental Death	Dead on Arrival	Sacrificed Intentionally	Total Handled	Mortality Rate
Chinook	**Yearling**	**Wild**	**0**	**0**	**0**	**2**	**0%**
Chinook	Zero-Age	Hatchery	16	1	0	5851	0.3%
Chinook	**Zero-Age**	**Wild**	**12**	**0**	**0**	**1323**	**0.9%**
Chum	Zero-Age	Wild	2	0	0	22576	0%
Coho	Mature Adult	Hatchery	0	0	0	1	0%
Coho	Yearling	Hatchery	34	0	0	2163	1.6%
Coho	**Yearling**	**Wild**	**4**	**0**	**0**	**694**	**0.6%**
Coho	Zero-Age	Wild	0	0	0	18	0%
Cutthroat	Not Recorded	Wild	0	0	0	5	0%
Lamprey (eyes)	Not Recorded	Wild	0	0	0	107	0%
Lamprey (no eyes)	Not Recorded	Wild	0	0	0	35	0%
Pink	Zero-Age	Wild	8	0	0	10084	0.1%
Pumpkin Seed	Not Recorded	Wild	0	0	0	2	0%
Sculpin	Not Recorded	Wild	0	0	2	4	50%
Sockeye	Zero-Age	Wild	0	0	0	1	0%
Steelhead	Not Recorded	Hatchery	0	0	0	182	0%
Steelhead	Not Recorded	Wild	1	0	0	169	0.6%
Stickleback	Not Recorded	Wild	0	0	0	165	0%
Trout - Indeterminate	Zero-Age	Wild	0	0	0	3	0%

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