An analysis of 2005 data from the Lummi smolt trap on the Nooksack Mainstem

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Lummi Biologist, 9/1/2005

Executive Summary

Total production estimates for Chinook fry outmigrating from the Nooksack River in 2005 ranged from **926,466** (ACRM) to 1,345,994 (YCCE) individuals. 764,000 Chinook fry were released into the Nooksack between April 14 and May 26. Wild production estimates ranged from as low as 142,362 (adjusted ACCE/YCCE) to as high as **162,466** (ACRM/Peterson). If hatchery-origin fry suffer mortality before reaching the trap site then these estimates are likely to be slightly too high. The low-level of wild-production in 2005 is consistent with the hypothesis that severe hydrological events that occur in fall have a large adverse effect on wild production.

Residence time modeling for Chinook fry in 2005 supported the hypothesis that early release dates give rise to longer residence times prior to outmigration. Average residence times for an early-released group of marked hatchery-origin smolts was c. 28 days, and for the last group that was released at the end of May the average residence times was c. 16 days.

The total production estimate for Coho smolts was **2,280,573** smolts (ACRM). 1,245,234 smolts were released from hatcheries between May 5 and May 17. The wild production estimate is therefore **1,035,339** smolts, assuming no mortality occurs 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 was confounded by too-high daily production estimates derived using ACCE or YCCE methods. Modeled residence times using adjusted ACCE estimates of daily production ranged from 10 days for the earliest group (Kendall hatchery) to 1 – 3 days for later groups (Skookum hatchery). This compares well to most previous year's data that suggests an average residence time of 2 to 3 days for Coho released in mid to late May, and slightly longer for Coho released in early May.

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 in 2002, 2003, & 2004 (Dolphin, 2002; 2003; 2004).

This year represents the first time since trap operations began in 1994 that100% of hatchery-released age-zero Chinook were marked and could be reliably separated from wild-origin Chinook. However, WDFW estimates that up to 3% of the clips were "bad" (partial or no adipose fin clip applied). Consequently, there could be anywhere up to 17,358 'unmarked' hatchery-origin Chinook smolts that may be mistaken for wild-origin smolts in the smolt trap data. However, screw trap crew may have been able to count some of the partial clips so the true number of 'missing' clips is not known.

In 2005 the screwtrap was operated from December 7, 2004 through to July 20, 2005 and beyond, although sampling intensity was highest from early April through to the end of June (Fig. 1). This report considers data collected from December 2004 through to July 20, 2005 only.

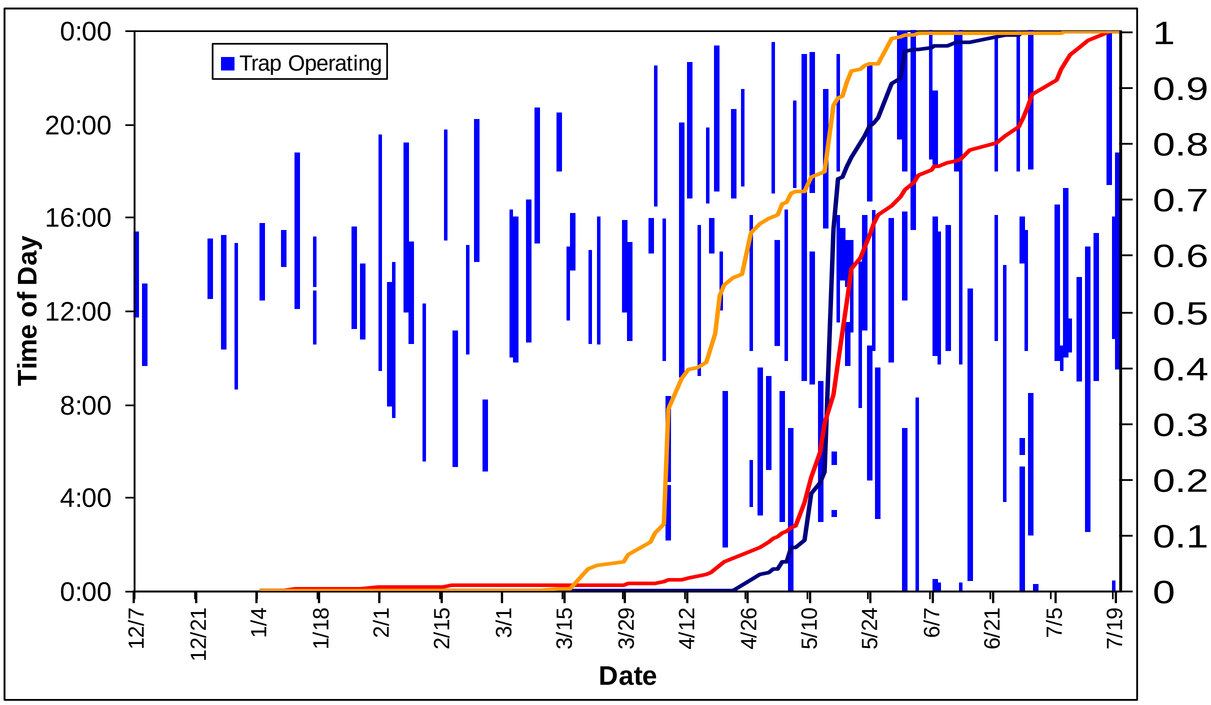

Figure 1. Daily sampling effort on the Lummi smolt trap in 2005.

This report aims to report the results of the sampling program in 2005, summarize the principle 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 or Pink salmon has been made to date.

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. A summary of the field data for each set and subset is provided in Appendix A.

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 2005.

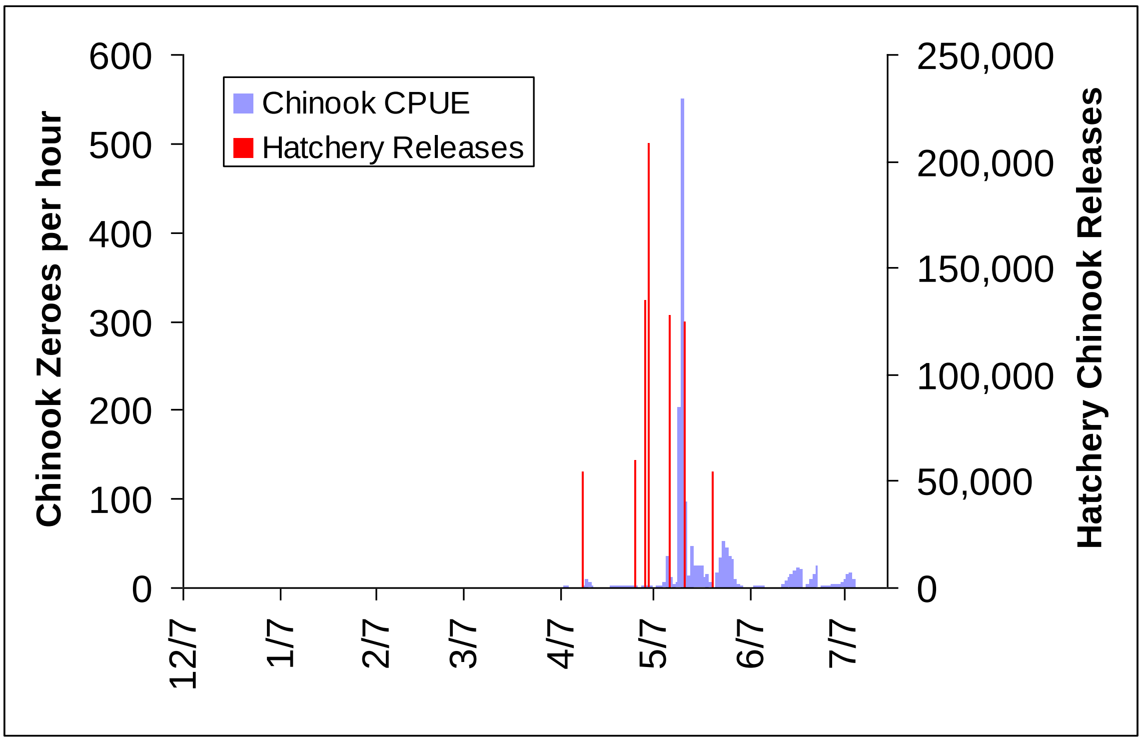

Figure 2. Average daily catch per hour for zero-age Chinook smolts in 2005

Table I. *Details of Hatchery releases of zero-age Chinook Fry in 2005*

Date	Location	Ad. Clip only	Ad. Clip & CWT	CWT only	daily totals
14-Apr	Kendall Creek Hatchery	54,500			54,500
1-May	Kendall Creek Hatchery	59,500			59,500
4-May	North Fork Nooksack near Deadhorse Creek	15,000	59,000	61,000	135,000
5-May	Middle Fork near Clearwater Creek	208,000			208,000
12-May	North Fork Nooksack near Deadhorse Creek	4,000	62,100	61,900	128,000
17-May	North Fork Nooksack near Deadhorse Creek	3,000	59,000	62,500	124,500
26-May	North Fork Nooksack near Deadhorse Creek	54,500			54,500
	Totals	**398,500**	**180,100**	**185,400**	**764,000**

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 2005.

	2005	
Number of marked smolts released	764,000	N_1
Number of marked smolts recaptured	**3,715**	M_2
Marked Smolt Recapture Ratio	0.487% (3dp)	
Total number of smolts caught	**4,505**	N_2
Estimated Total production of Chinook smolts in 2005	**926,466**	N_P
Upper 95% Confidence Limit	938,906	
Lower 95% Confidence Limit	914,025	

The results of using this method suggest that a total of **926,466** smolts migrated downstream past the Screwtrap in 2005. Since we know that 764,000 smolts were released from the hatchery, the difference (**162,466**) 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, overall, 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 14th were 2 fry per hour, then the rate used for daytime on May 12th would be 3 fry per hour.

The rules for interpolation used to analyze the 2005 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 sampe 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*

One of these methods 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 sechi-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 more than 24 hours. Furthermore, the relationship between sechi 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, 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 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 season.

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 versus 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 short time periods 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 sample 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 fish, then the estimate of average trap catch efficiency for marked hatchery fish can be extrapolated to unmarked hatchery fish, and possibly wild-origin smolts 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 six 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, 1999, 2002, 2003, 2004, & 2005 show very similar average catch efficiencies (~2.6 - 3.3%) after extrapolating based on sampling effort, whereas recapture rates were below expectations in 2001 (1.73%) and much higher in 2000 (7.3%). Flows in 2001 were quite low, possibly explaining the reduced catch efficiency, but no such explanation is known for the 2000 data when river flows and secchi depth were moderate but catch efficiencies much higher than expected.

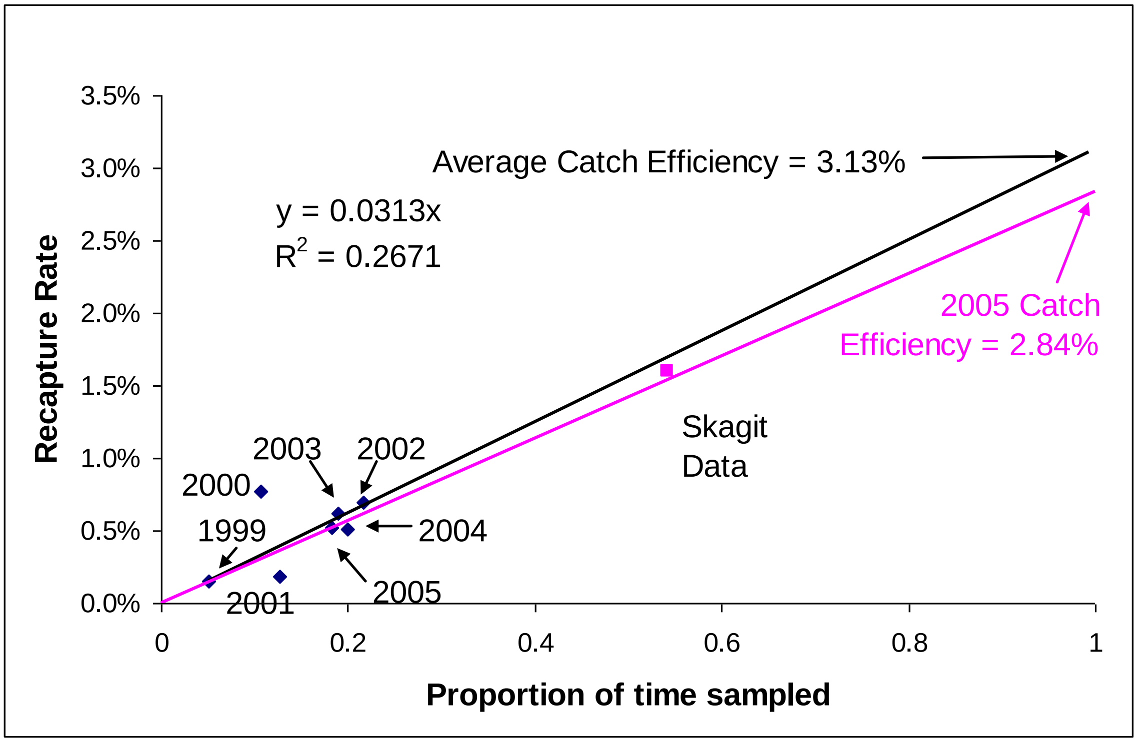

Figure 3. Season wide recapture rates of marked hatchery Chinook smolts versus the proportion of time sampled.

Based on the 2005 season catch efficiency of 2.84%, 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 1,345,994 smolts. Of this estimate, 1,134,579 smolts are theoretically of hatchery origin and the remainder, 211,414 smolts, is wild-origin. However, we know that the actual number of marked smolts released was only 764,000 in 2005 so it is apparent that the YCCE estimate overestimated the true production of hatchery smolts by 32.66% in 2005. If this bias is the same for wild-origin smolts, then the number of wild-origin smolts leaving the river in 2005 would be **142,362** smolts.

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 2 days in early May. If river conditions on those two days meant that the trap was slightly more efficient that the season-wide average on those two days then it could cause an upward bias in the overall production estimate. This problem is inherent when using any constant value to represent trap catch efficiencies 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. Additionally, the actual sampling time during these two days was extremely short because of the logistics of sorting, meansuring etc so many smolts. Consequently, we are basing these very high catch per hour values on very short set durations (20 minutes to half an hour). It is difficult to say if such a high cpue would have held up if sampling had been over a longer time. However, the trap crew reported that the river surface was ‘just jumping with fish’ at the time so it is likely that actual productivity was high for most of the day.

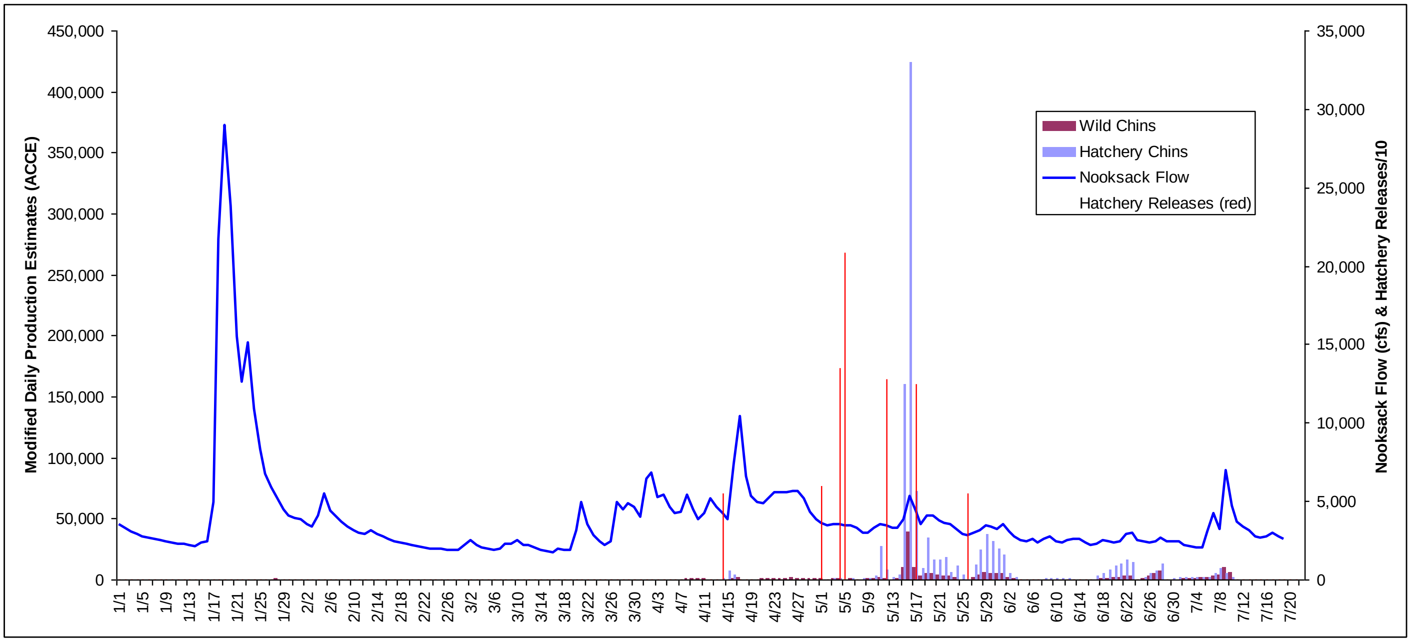

Figure 4. Daily production estimates in 2004 for zero-age Chinook smolts calculated from daily catch per hour and using a constant catch efficiency of 2.84% (YCCE)

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 3.13% based on the past 7-year’s data.

The results of this method for 2005 suggest that the total production of zero-age Chinook smolts was 1,221,285 smolts. Of this number, 1,029,459 smolts are theoretically of hatchery-origin and 191,827 smolts are of wild-origin. As with the YCCE estimate, the number of hatchery smolts passing the trap site predicted by this method exceeds the known number of smolts released. The

ACCE method, however, had a smaller bias (25.79%) compared to the YCCE estimate. By scaling the results to mach the known hatchery release, then the number of wild-origin smolts passing the trap site is once again **142,362** smolts. This number is identical to the adjusted YCCE estimate because scaling the results to match the known hatchery release makes the two methods mathematically identical. The overall pattern of outmigration prior to scaling the results to match the known size of the hatchery release is shown in Figure 5.

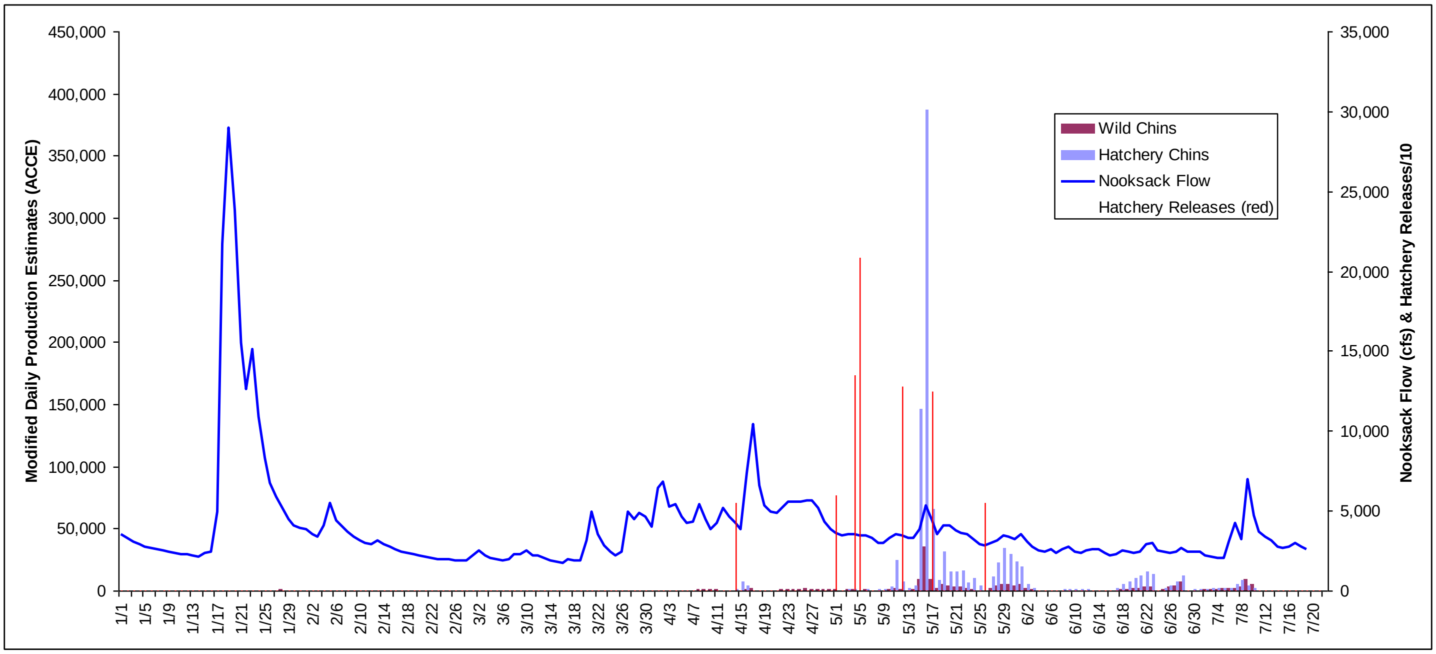

Figure 5. Daily production estimates in 2004 for zero-age Chinook smolts calculated from daily catch per hour and using a constant catch efficiency of 3.13% (ACCE)

Comparison of the three production estimates

Results from 1999 – 2005 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 the 2005 data in Figure 3.

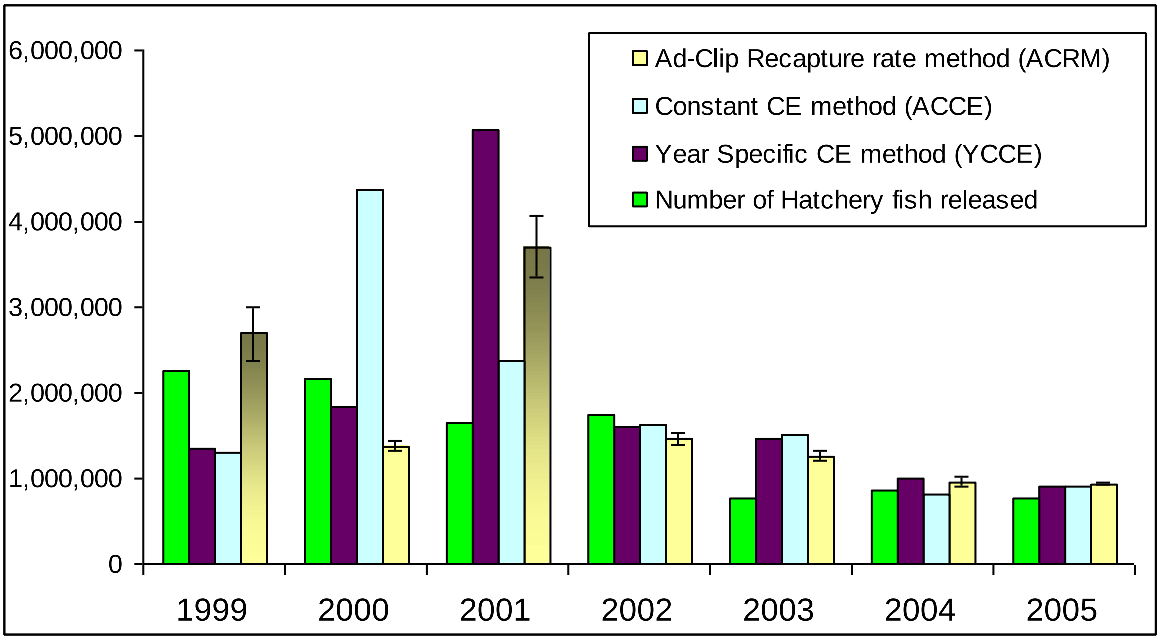

Figure 6. Three alternative production estimates for zero-age Chinook smolts outmigrating from the Nooksack River from 1999 – 2005, compared with the number of hatchery-origin smolts released in each year (green). Shading of the two ACRM bars in 2001 and 1999 indicates that many fewer marked hatchery 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.

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 small proportion 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. In theory, 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 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 2005

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, but it is the case in 2005.

In 2005 several groups of ad-clipped Chinook smolts from Kendall Hatchery were released into the Nooksack River (Table I). The first group (54,500 smolts) was released on April 14. The last group (also 54,500 smolts) was released on May 26.

The first marked smolts (n=50) were caught at the screw trap during the day on April 15 (see Appendix A). No sampling was done on April 16, but no further marked smolts were caught during sampling over 5 consecutive days of sampling from April 17th to 21st. Only one other marked smolt was caught prior to the second release of 59,500 smolts on May 1st. In the week following the second release, only 19 smolts were caught despite a daily sampling regimen. Clearly, only a small fraction of the fish released in the early two groups left the river very soon after their liberty.

The last marked smolt (n=1) was caught at the trap site on July 13th which was 49 days after the last release of hatchery smolts Assuming that this smolt represents the last outmigrating hatchery fish, this suggests that the maximum residence time observed may be as high as 49 - 91 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 2005 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. 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 ACCE daily production estimates for each calendar date (rows).

The first column for each group of smolts simply 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 of all marked fish in the river above the trap site, at the beginning of each day, that group of fish represents.

The sum of each group's outmigrant column 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.

A summary of the table showing the final model for marked hatchery smolts in 2005 is presented in Appendix B. The results for 2005 are shown in Figure 7.

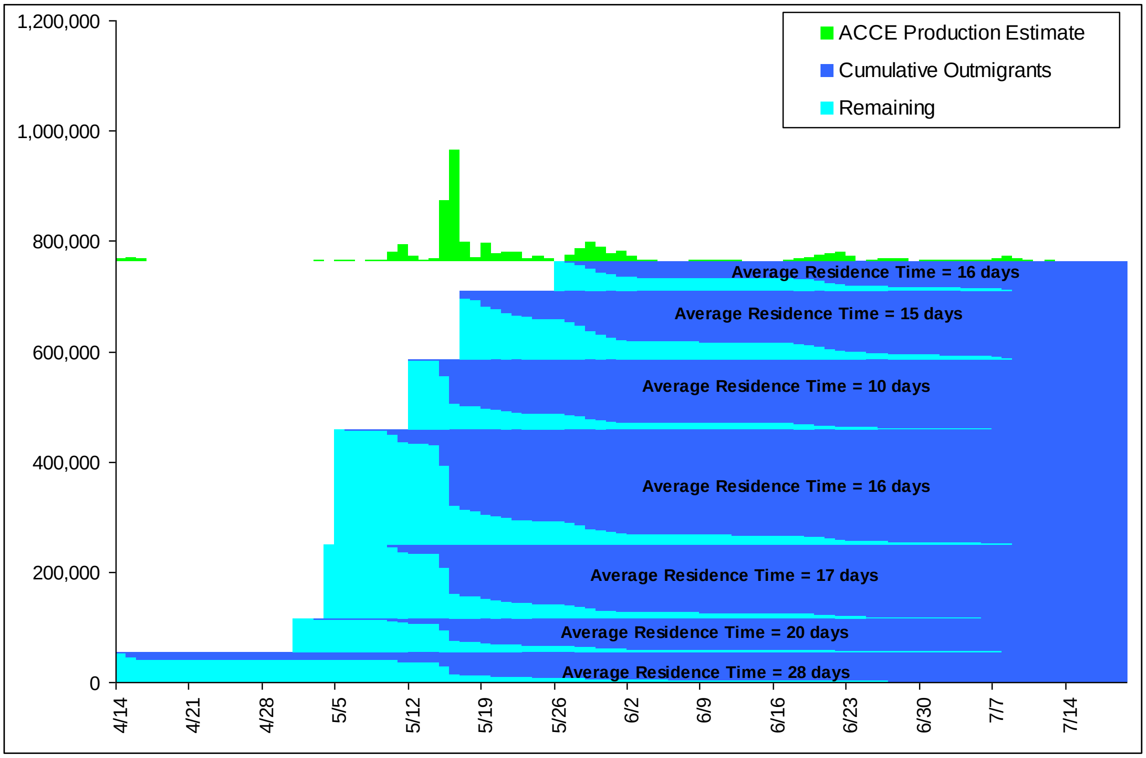

Figure 7. Model output showing cumulative outmigration, mortality, and adjusted-ACCE daily production estimates for two groups of ad-clipped hatchery-origin Chinook smolts in 2005.

Similar modeling was also conducted using historical data for 2004, 2003, 2002, 2001, and 1999. Modeling could not be conducted for 2000 data because ACCE production estimates for marked fish in 2000 was nearly double that of the number of marked fish that were released. The reason for this large discrepancy is not known at this time, but one potential explanation could be that hatchery records may be erroneous for that year. Alternatively, low sampling effort combined with poor survival of marked hatchery fish may have strongly affected the measured recapture rate for ad-clipped fish in 2000. The results of the model for 1999 differ markedly from those of 2001 – 2003 but this may be a result of the poor sampling effort in 1999, which is discussed further in the section comparing the three methods of determining production estimates.

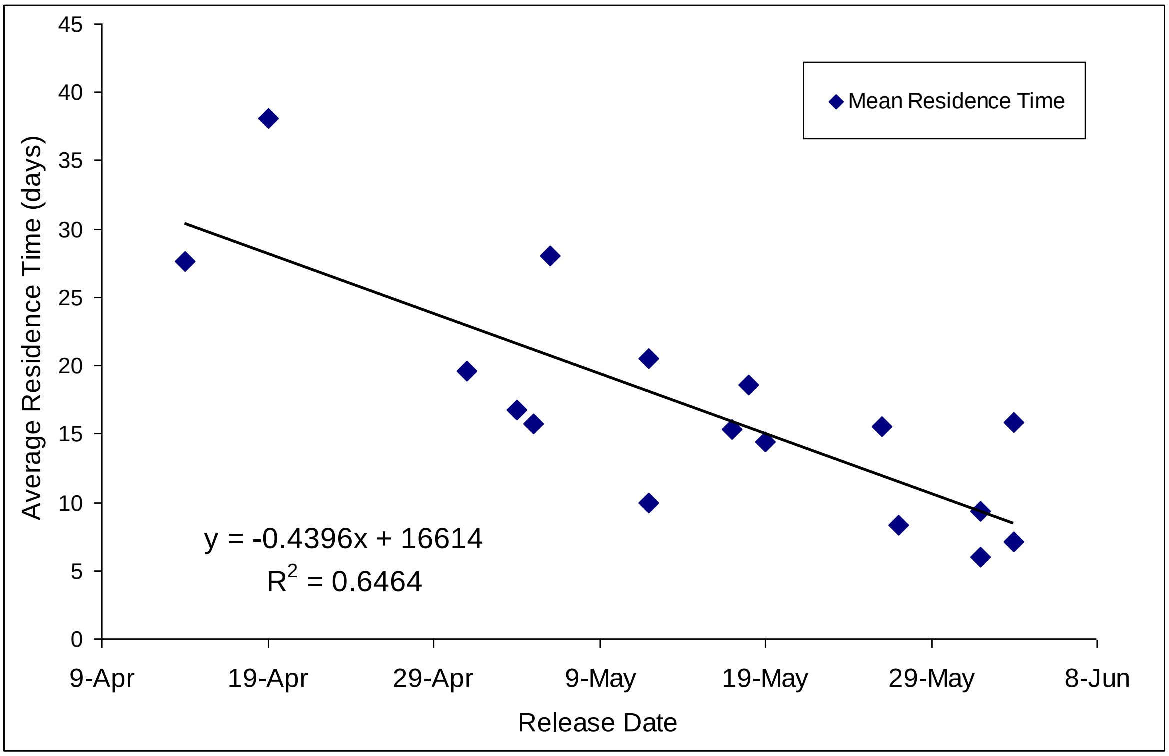

Figure 8. Modeled average residence time versus group release date for groups of marked hatchery Chinook smolts released in 1999, 2001, 2002, 2003, 2004, & 2005.

Figure 8 shows the group residence times versus the release date based on historical trap data. Clearly there appears to be a relationship between the timing of release and the modeled length of time that hatchery-origin smolts take to reach the trap site after release. Unfortunately, multiple groups being released into the river at different times confound the data from 2002, 2003, 2004, & 2005.

If you were to assume that all fish caught in the trap were from the first group released, regardless of other groups being introduced before the first group had cleared the system, then the average residence time for the first group would be shortened, but the average residence time for subsequent groups would increase commensurately. However, this would be an unlikely scenario because fish from the second or third groups would probably not delay their outmigration solely because of the lingering presence of some fish from the first group.

Hatchery-origin smolt outmigration timing versus wild-origin outmigration timing.

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 these, as they were indistinguishable from wild-origin Fall Chinook or unmarked hatchery-origin Chinook caught in screw trap operations. 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. For the first time, however, almost 100% of the hatchery-origin smolts were marked before release enabling us to directly separate hatchery smolts caught in the trap from wild-origin smolts (Figure 5). This is a vast improvement over previous years.

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). With the advent of comprehensive marking of hatchery smolts we can now sample wild-origin smolts exclusively, thereby reducing the cost of DNA testing. Unfortunately, this kind of analysis is still prohibitively expensive. Nonetheless, DNA samples from a large percentage of wild-origin smolts has been collected from the 2005 season in hopes that funding may become 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. In 2005, 2004, 2003, 2002, and 2000 the confidence intervals were remarkably tight (<5%) around the estimate. The estimates for 1999 and 2001 had worse confidence intervals, but they remained relatively 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 could not mix with fish that were 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. That is, not all fish may have had an equal chance of being sampled. Consequently, I would treat the ACRM estimate and the associated confidence intervals with due 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, and an unknown number of wild-origin fish presumably also outmigrate 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. We also believe that, historically, the number of wild-origin smolts wouldn't be all that high in relation to the hatchery-production since we believe that wild-origin adults have typically been a small proportion of the total adult return. For the first time, this assumption can be validated empirically by our trap data because almost 100% of the hatchery smolts were marked in 2005, and over 83% of all smolts caught in the trap were marked.

Figure 6 shows the production estimates for the last 6 years that were derived by 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, 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 in 2002, 2003, 2004, & 2005. The ACRM, YCCE, and ACCE methods all agree fairly closely for 2002, 2003, 2004, & 2005. By contrast, the three methods provide far less consistency during the 2000 and 2001 seasons. Both the ACRM and YCCE methods produced estimates that are reasonably similar in magnitude, but the ACCE method differs strongly in both years. Why does the ACCE method diverge 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, both the ACRM and YCCE methods estimated that the total production of Chinook fry from the river exceeded the number of hatchery-origin fry that were released. 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 these 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 these assumptions, 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 know 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 now have 100% marking, we are more accurately able to measure the bias in the ACCE and YCCE models. In 2005 the ACCE model overestimated the hatchery production by c. 27.53% while the YCCE method overestimated by c. 32.5%. Based on this it seems that the ACCE estimate may perform a little better than the YCCE estimate. Given that we know that both the ACCE and YCCE methods are slightly too high in 2005, the ACRM result is probably pretty close to reality. In fact, if you adjust the ACCE and YCCE estimates to eliminate the known bias they fall within the confidence limits of the ACRM estimate. Whether or not this pattern holds true in the future is difficult to say, but for now I think the ACRM is the best estimator for seasonal production of Chinook smolts, and that the current ACCE and YCCE methods provide some ball-park information on in-season patterns but at a cost of reduced numerical accuracy unless the bias can be quantified and removed as was done in 2005. Nonetheless, a bias of ~30% doesn't seem too bad considering the number of assumptions made and the expansion factors involved at various levels of the analysis.

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 validates the change in sampling protocols since 2002 that has increased the overall effort, begun to stratify sampling by dawn, day, dusk, and night, and to minimize the length of the gaps in the sampling effort to avoid missing pulses of fish moving downstream. It seems that these methods do produce results that are in the right ball park.

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 and our estimates of production may be slightly biased too high as a consequence.

Another possible bias could 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 yearling Chinook smolts have ever been caught in the screw trap (except when clipped 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, and happened to be caught as they passed the Nooksack estuary. 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 us problems is the constant trap catch efficiency assumption. We strongly suspect that trap catch efficiency will change somewhat depending on environmental conditions (turbidity, noise due to fast rotations etc). When salmon move in short pulses, the catch efficiency during that short time could be reasonably different than the average for the whole season leading to an erroneous production estimate for that short time frame. Unfortunately, our only attempt to get around this problem (secchi depth – catch efficiency trials) proved to be far too unreliable even for the specific groups of fish being used.

We also assume that wild fish behave like river-acclimated hatchery fish, and that catch efficiencies prior to hatchery releases is similar to afterwards. For the first time we can see that the bulk of wild smolts do have a similar outmigration pattern to hatchery fish, and that relatively few wild smolts outmigrate before hatchery releases begin. Consequently, this assumption appears to be reasonably well supported. However, we were unable to fish in mid January due to high flows. Data from the previous two years suggests that a small group of zero-age Chinook may outmigrate during this time period. If this is true, then we may be excluding this distinctive group of wild-origin Chinook in our final production estimate.

Hatchery Chinook Residence Times

In 2005 the shortest residence time was 1 day, and the longest residence time observed may have been as long as 49 - 91 days. Modeling results suggest that the average residence time for the first group was around 28 days, and the last group averaged somewhere around 16 days. These results are consistent with trends from earlier modeling data where 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), so the modeling results for zero-age Chinook are within the realm of possibility. If the model findings are true, then there are obviously implications for the scheduling of hatchery releases. Delaying hatchery releases until the end of May/start of June should minimize the duration of whatever interactions exist between hatchery-origin and wild-origin smolts.

Residence time modeling has provided a consistent pattern of residence times versus release date over several years of data. Better release rate information for extended volitional releases (in earlier years) would probably result in only minor adjustments to the model results. Significant changes to the model output will probably only arise if day-by-day trap catch efficiency information becomes available so that changes in environmental conditions are ***reliably*** taken into account (e.g., secchi depth, flow patterns, etc) each day.

Modeled daily survival rates of zero-age Chinook smolts in 2001, 2002, 2003, and 2004 were 99.21%, 99.66%, 99.43% and 99.17% respectively. These survival rates are all better than those for outmigrating zero-age Chinook smolts in the Snake River (98.16% surviving per day; Muir *et al*., 1999). This is likely because zero-age Chinook outmigrating from the Nooksack River do not have to contend with predator-filled impoundments or additional mortality associated with hydroelectric schemes present on the Snake River (e.g., turbine damage, oxygen-super-saturation, spillway turbulence, etc). However, these results should be taken with a grain of salt as we now know that both ACCE and YCCE methods can be wrong by up to 33% and calculating survival in years where the estimate for hatchery smolts is lower than the known release size is likely to be more influenced by the problems with the analysis method than by the sampling results.

Wild-origin Chinook Production Patterns

The wild-origin production estimate for 2005 varies from 160,021 (ACRM method) to 209,261 (unadjusted YCCE method). However, when the known bias for hatchery fish is removed from the ACCE and YCCE methods then the wild-origin estimate produced by both methods is 141,241 smolts. Consequently, I believe that the true wild-origin production of Chinook smolts for 2005 is in the range **141,000 – 160,000**.

The low level of wild production in 2005 (Figure 9) is consistent with low egg survival in the fall and winter of 2004. The low survival was probably due to the timing and magnitude of large-scale flood events in the Nooksack during November, December, & January of 2004/2005 when most of the eggs would have been at their most vulnerable and severe scouring would have occurred. Similarly bad flow regimes have occurred every year since 1998 except for the fall-winters of 2000 and 2002 that produced relatively strong production of wild-origin smolts in 2001 and 2003 (Table III). The comparatively strong wild production estimate in 1999 probably reflects more on the low sampling effort and consequently low-quality analysis than actual trends in wild production. Similarly, other data prior to the 2002 season is more at risk of error than from 2002 onwards.

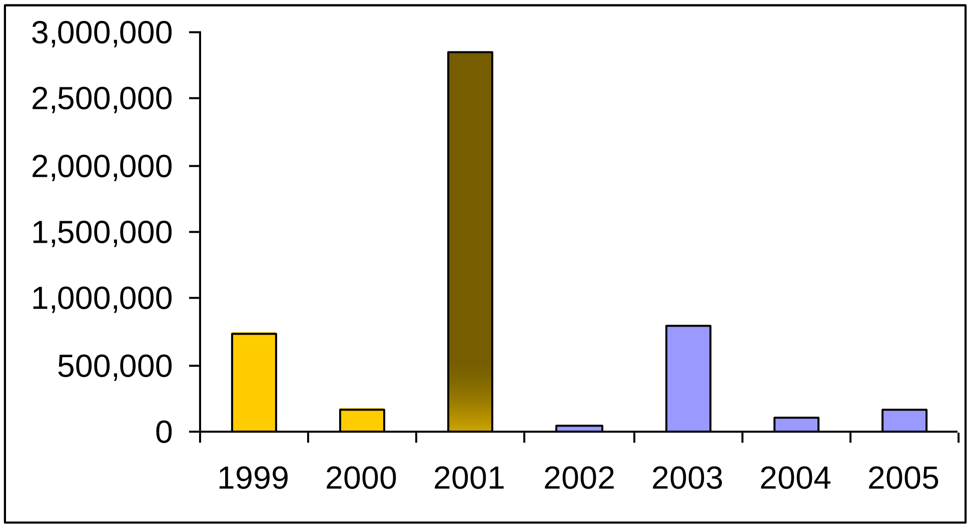

Figure 9. Wild-Origin Production Estimates from 1999 to 2005. Blue bars indicate estimates are probably reliable. Shaded-orange bars indicate data quality is not as good.

Table III. *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.*

	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
Max Jan	23,200	10,300	14,300	4,890	7,640	24,100	13,900	11,700	29,000	?
Max Feb	8,470	5,680	9,500	5,160	2,900	27,500	8,210	6,700	5,480	?
Max Mar	33,700	8,160	7,180	5,860	5,810	5,760	16,200	6,970	6,400	?
Max Apr	10,100	5,730	5,730	13,800	5,100	15,700	7,740	4,040	10,400	?
May May	17,700	6,500	10,000	8,390	7,140	9,860	6,150	6,580	5,290	?
Max Jun	12,400	4,420	10,600	13,300	7,150	13,100	5,270	5,740	3,070	?
Max Jul	15,300	5,300	8,450	4,720	3,190	5,729	2,990	2,970	6,970	?
Max Aug	3,230	2,230	6,090	3,600	9,860	2,280	1,940	9,920	1,840	?
Max Sep	7,470	1,340	3,350	4,950	2,690	2,490	1,640	9,580	?	?
Max Oct	13,000	3,560	16,600	9,990	8,790	1,880	32,300	6,340	?	?
Max Nov	7,700	16,600	19,800	3,290	17,700	13,700	25,400	31,100	?	?
Max Dec	12,600	21,100	19,100	4,260	19,300	11,100	6,620	22,400	?	?
Wild Production Estimate (0+ Chinook)			737,765	170,877	2,852,540	50,819	797,733	108,726	172,436	?
Wild Catch / Hundred Hours (Yearling Chinook)				16.2	5.6	15.4	2.0	7	4	?

Wild Chinook Outmigration Timing

The bulk of the wild outmigration in 2005 began very slowly in early April about a week before the first release of hatchery smolts. The wild outmigrants trickled downriver until mid June, when both wild and hatchery smolts appear to have responded to a small peak in river flows, and over half the run outmigrated during the following 2 week period.

The next two weeks saw reduced river flows and no significant outmigration of either wild or hatchery origin smolts.

The remainder of the smolts left during another 2 week period that began around the longest day of the year and mostly finished by July 10th or thereabouts. A very small rise in river flows coincided with the main part of the first group of outmigrating smolts following the longest day, but the rise in outmigration preceded the slightly increased flows by a couple of days.

It would be tempting to speculate that the two main 'pulses' of smolts might belong to different stocks (i.e., springs vs. falls) but there is another small pulse of fish that could also be of interest. In 2003 and 2004 we noted a small pulse of wild-origin smolts that outmigrated past the trap site in mid January. Although we attempted to sample during this period in 2005, a severe flood event coincided with the week of interest and prevented sampling for the whole week. The last set before the big flow event caught the first Chinook of the year, and the first sampling period after the big flow event caught 2 Chinook. No more Chinook were caught thereafter until the end of March. Consequently, it seems likely that there was a group of mid-January Chinook outmigrants again in 2005 but we were unable to sample them. The magnitude of this group of outmigrants in 2003 and 2004 was quite small: probably no more than 20,000 – 40,000 smolts) but it is hard to be sure because we encountered the peak of this group on the first set of the year in 2004 and so we cannot determine when the group started outmigrating. If this group is actually a real phenomenon, and not just a few unlucky smolts that accidentally get flushed out or are forced to leave during winter, then the stock composition of this group would be interesting to compare with that of the main May/June outmigrants.

To some degree there is evidence to support the notion of follow the leader behavior in Chinook smolts since small pulses of hatchery fish arriving immediately after release are accompanied by small pulses of wild smolts. However, it is also possible that both groups of smolts are deciding to outmigrate based on environmental cues such as photoperiod and river flow/water clarity etc. For example, hatchery personnel deliberately release their smolts when river conditions are more turbid to improve smolt survival. Wild-origin smolts are already beginning to trickle downstream by early to mid April without hatchery smolts to take their cues from. Consequently, it seems likely that wild-origin smolts are cueing off photoperiod (lengthening days) to determine when to think about outmigrating, and that once the photoperiod is long enough, sudden rises in river flow (and/or increasing turbidity) may provide the actual trigger to move. River temperatures are likely to get warmest following the longest day, so a declining photoperiod might also trigger smolts to leave even if flows/turbidities are not ideal. Exactly how these factors influence the fish is wide open to debate. It may be temperature itself rather than photoperiod that triggers outmigration. It should also be noted that summer flows in 2005 were atypically low compared to long term average flows and this may have caused outmigration timing to be similarly atypical. However, we will not be able to asses this until we have more than one year of data for comparison.

Coho

2005 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 2005*

	Ad. Clip only	Ad. Clip - CWT	CWT only	Source
5/5	203,100	47,100	47,800	**Kendall Hatchery**
5/13	226,979	12,639		**Skookum Hatchery**
5/14	369,561	20,578		**Skookum Hatchery**
5/15	153,455	8,545		**Skookum Hatchery**
5/16	121,756	6,780		**Skookum Hatchery**
5/17	26,183	1,458		**Skookum Hatchery**
Total	1,101,034	97,100	47,800	

Coho Production Estimate Methods

There are four potential methods for quantifying Coho production based on smolt trap data.

Adipose-fin Clipped Recapture Method (ACRM)

The first method is to use the percentage of marked (adipose fin-clipped) hatchery smolts that were captured in the trap after being released upstream, to convert the number of all smolts that were caught in the trap to an estimated total production assuming that the recapture rate is the same for marked and unmarked smolts. The calculations and assumptions underlying this method have been previously described in the Chinook methodology section. Using this method allows you to calculate a total production estimate but does not provide any information on the timing of migration during the season.

Time-series based production estimate methods…

The remaining three methods attempt to create a time series of catch-per-hour measurements for the entire outmigration period, and then convert this time-series into production (all fish passing the trap site) per hour using a trap-specific catch efficiency estimate that is derived in different ways. Summing the hourly 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 Coho is created using trap catch rates stratified by day versus night sampling periods. Intervals between sampling periods are assumed to be related primarily to catch rates during other portions of the same 24-hour period. That is, if night time sampling data is available for a particular 24-hour period, then the day time value is assumed to be a function of the night time sample. This relationship is derived from a regression of a scatter plot of day versus night catch rates. For days in which no sampling data is available at all, catch rates are interpolated linearly within sampling strata between known days for which data is available. As an example, if catch rates during the day on May 12th were 4 smolts per hour, and catch rates during the day on May 14th were 2 smolts per hour, then the rate used for daytime on May 13th would be 3 smolts per hour.

Secchi Depth-Catch Efficiency Relationship Method (SDCE)

Trap catch efficiencies can be derived using any number of methods. Historically, it was thought that trap catch efficiencies were a function of smolt size and visibility through the water (i.e., unlit secchi depth readings). To determine the relationship between secchi depth and catch efficiency for yearling smolts, marked hatchery smolts have been released about a mile above the trap site and the number of smolts that were recaptured after 24 hours was measured. However, catch efficiencies measured using this methodology for highly stressed smolts that were recaptured in the first 24 hours after release are unlikely to closely resemble those of wild fish, or even hatchery fish that have become acclimated to riverine conditions over time. Furthermore, as more trials were conducted it became apparent that no reliable relationship could be observed for any species. Finally, day time versus night time catch efficiencies are likely to exist for Coho due to the diurnal migratory behavior they exhibit. Consequently, the catch efficiencies measured in the small scale trials are also likely to be a function of both trap catch efficiency and diurnal timing of movement past the trap site. Because trap catch efficiencies based on the trials are extremely low (<0.5%), and likely to be unrealistic for fish accustomed to riverine conditions, the very large scaling factors will potentially magnify error up to 200 times! Unless you can really hang-your-hat on the secchi depth-catch efficiency relationship this is a recipe for disaster. Consequently, this approach to determining trap catch efficiencies has been abandoned for all species: including Coho.

Year-Specific Constant Catch Efficiency Method (YCCE)

Marked fish that are caught in the trap either have their adipose-fin clipped, or they have a coded wire tag implanted, or both, and are released from hatcheries in the upper watershed. The number of these released, marked fish are known and reported by the hatchery. Consequently, it is possible to determine what percentages of the released fish are recaptured at the trap over the period of the outmigration season. However, because the fish do not all go past the trap en-masse this value is unlikely to represent the true catch efficiency of the trap. Moreover, the trap does not operate 24-7 during the entire outmigration period and, consequently, many individuals that would have been caught if the trap were operating are never captured at all. Obviously, the actual recapture rate results from a combination of instantaneous trap catch efficiencies, the timing of outmigration, and the duration and timing of the trap sampling activities during the outmigration period. However, we do know exactly when the trap was operating and it is therefore possible to estimate the *average* instantaneous catch efficiency of the trap during the outmigration season.

- We know that if we did no sampling at all while the fish were outmigrating then we would have caught no fish.

- We know that we sampled a certain percentage of the possible time during the period when the marked smolts were outmigrating past the trap site (this period defined as beginning on the day that the first marked smolt is caught and ending on the day that the last marked smolt is caught).

- We also know what percentage of the marked fish was recaptured during the outmigration period.

- Generally we assume that the timing of sampling within the outmigration period is not important but it would be better to sample evenly throughout the outmigration period for this number to be realistic.

By assuming that the number of fish captured is a linear function of how much time is spent sampling during the outmigration period, we can plot a line on a chart showing recapture rate versus the proportion of the outmigration period that was sampled. One end of the line would be at the origin (0% recaptured, 0 time sampled) and the other end of the line would be the actual recapture rate at the known proportion of time sampled. The slope of the line represents the average instantaneous catch efficiency of the trap for that year's outmigration period.

This value is calculated separately for each year's results, and then used to transform catch per hour data into production-per-day data separately for each year.

Average Constant Catch Efficiency Method (ACCE)

One of the problems of the YCCE method is that the timing of Coho outmigration appears to be typically rapid for the majority of the hatchery production (2 - 6 days) with a few stragglers outmigrating in low numbers for the remainder of the outmigration period. If environmental conditions during that short period of high-intensity outmigration are unusual, or if the trap operating hours within that time period are greatly different than for the remainder of the outmigration period, then it is possible that the catch efficiency determined by the YCCE method could be unrealistic, and thus greatly distort the production estimate for that year.

One way to avoid year-specific problems with the timing and magnitude of sampling effort within the outmigration period would be to standardize effort at the highest level for the entire outmigration period. Unfortunately, that is logistically beyond our means. One alternative approach would be to step back from year-specific predictions of catch efficiency and use the average catch efficiency calculated from data collected over several years (YCCE method catch efficiencies). This can be done by plotting several years observed recapture percentage versus the proportion of the outmigration period sampled in each year. Since we also know that no effort equals no fish, we regress the data points using a line that passes through the origin. This time, the slope of the regression is the estimated average constant catch efficiency (ACCE) of the trap over a period of years.

This single catch efficiency value can then be used to transform catch per hour data for all years into production per hour data, and therefore total production estimates also. Obviously, with each new year's data, the average value will change and the production estimates for each year will then need to be recalculated.

The risk to this approach is that if actual trap catch efficiencies are non-average during the peak outmigration period then using an average catch efficiency calculated across several years could strongly bias the resulting production estimates. The only way to remove this risk, and to simultaneously avoid the risk of differential sampling effort within the outmigration period, would be to use the YCCE method, but maintain consistent relative effort throughout the entire outmigration period. Of necessity, the amount of effort should be as high as possible.

Another serious issue with both the ACCE and YCCE methodologies is that Coho smolts are known to migrate primarily at night, and move closer to the surface at night which ought to mean that the trap should have a higher catch efficiency for Coho at night than it does during the day. Unfortunately, there is presently no way to reliably separate out the trap catch efficiencies for day vs night sampling for Coho because we have no way to independently and accurately measure the number of fish moving past the trap site in each time period. Any attempt to use the trap catch rates to estimate the numbers of Coho passing the trap at night versus day is hopeless because the trap catch rate is a function of both the number of fish moving downstream and the instantaneous catch efficiency of the trap. You cannot measure one factor without knowing the other. Moreover, yearling smolts are more competent at evading capture than zero-age smolts/fry and, consequently, the catch efficiency for yearling smolts will be much lower than for zero-age fish. This, in turn, means that expansion factors will be larger and any error is likely to be magnified by a similar degree.

Nonetheless, when we plot separate scatterplots of actual recapture percentage versus the proportion of the outmigration period that was actually sampled at night and at dawn/day/dusk time strata we find that night sampling is a better predictor of Coho catch rates and results in higher estimates of trap catch efficiency (YCCE 1.16%; ACCE 1.345%, R^2=0.61) than day sampling rates (YCCE 0.68%; ACCE 0.838%, R^2=0.29). This is consistent with the hypothesis that Coho smolts are more likely to be caught by the trap at night. However, because we cannot separate the actual recapture rate for day and night sampling, the scatterplots are likely to underestimate Coho catch efficiencies at night and over estimate catch efficiencies during the day. Since Coho are known to move downstream primarily at night, this problem is most likely to result in an overestimate of the Coho production rate.

Coho Production Estimate Results

Adipose-fin Clipped Recapture Method (ACRM)

Table V *Results obtained using the ACRM method for smolt trap data from 1999 to 2005.*

Year	2005	2004	2003	2002	2001	2000	1999
Total Production Estimate (N_P)	2,280,573	2,693,075	1,988,042	2,077,633	2,162,813	2,260,919	4,640,808
Known Hatchery Releases (H)	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)	1,035,339	1,452,070	584,942	772,802	932,066	831,719	1,971,071
Ad-Clips Released (N_1)	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)	3,489	2,898	4,056	5,997	3,946	2,937	782
Ad Clips Recaptured (M_2)	1,833	1,284	2,761	3,536	2,136	1,774	54
Observed Recapture Rate (M_2/N_1)	0.15%	0.11%	0.20%	0.29%	0.18%	0.13%	0.02%
Variance (N_P)	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	71,805	109,721	41,834	43,785	62,014	66,100	1,152,101

Table V shows the parameters and results obtained using the ACRM/Peterson's Mark-Recapture method for smolt trap data in 2005 and earlier seasons. The production estimates are also presented graphically in Figure 10.

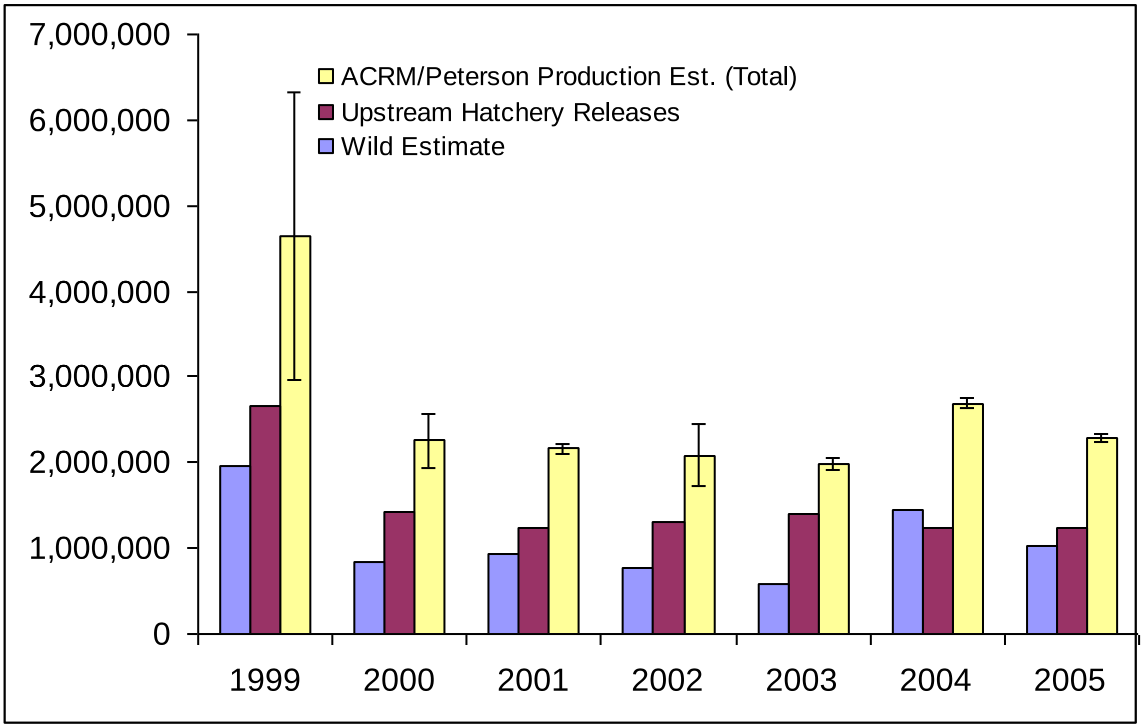

Figure 10. ACRM / Peterson Mark-Recapture Production Estimates for Coho Yearling smolts outmigrating from the Nooksack River (+/- 95% CL).

Based on the data in Table V it appears that c.2.3 millions coho smolts outmigrated in 2005. We know that 1.25 million smolts were released from hatcheries above the trap-site, and this suggests that the difference is comprised of wild-origin smolts (~1 million). 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 measured recapture rate is probably biased slightly lower than the true recapture rate. 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 instead possible to model different scenarios to determine how sensitive the estimate is to varying levels of mortality. Accordingly, I have constructed a theoretical plot (Figure 11) showing 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).

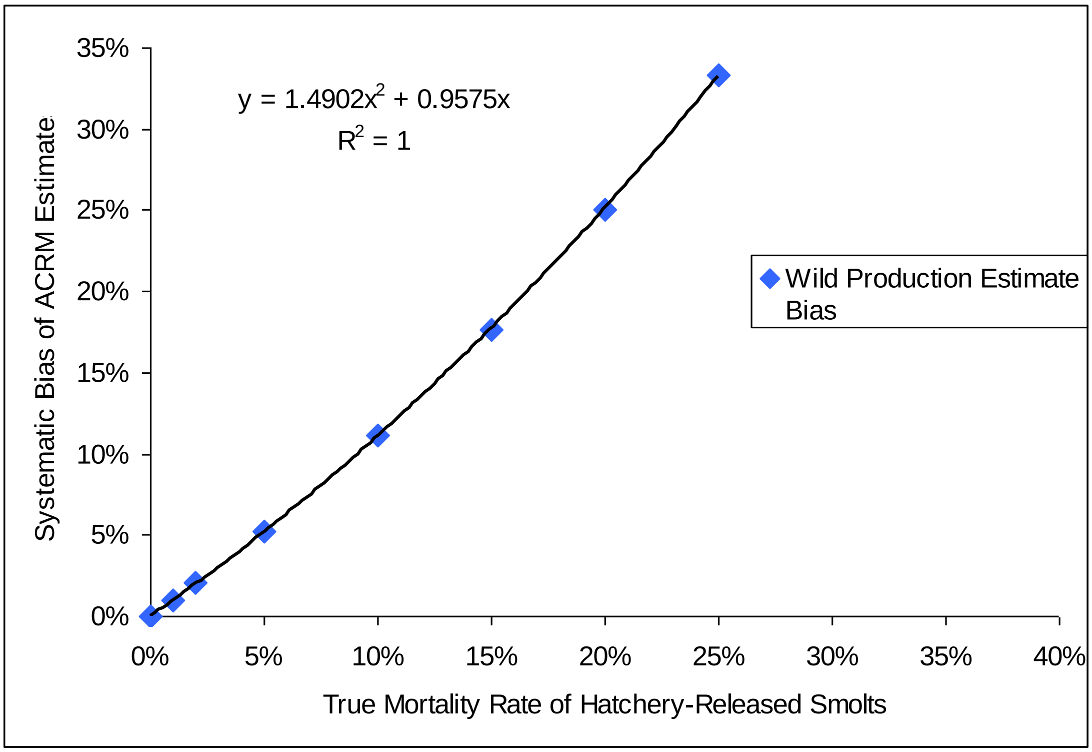

Figure 11. Plot of modeled ACRM bias magnitude compared to theoretical group mortality rates for hatchery-origin smolts prior to reaching the trap site.

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

Figures 11 and 12 show scatterplots of the season-wide recapture rate of hactehry Coho smolts plotted against the proportion of the nighttime hatchery outmigration period that was sampled, and against the proportion of the dawn/day/dusk outmigration period that was sampled respectively.

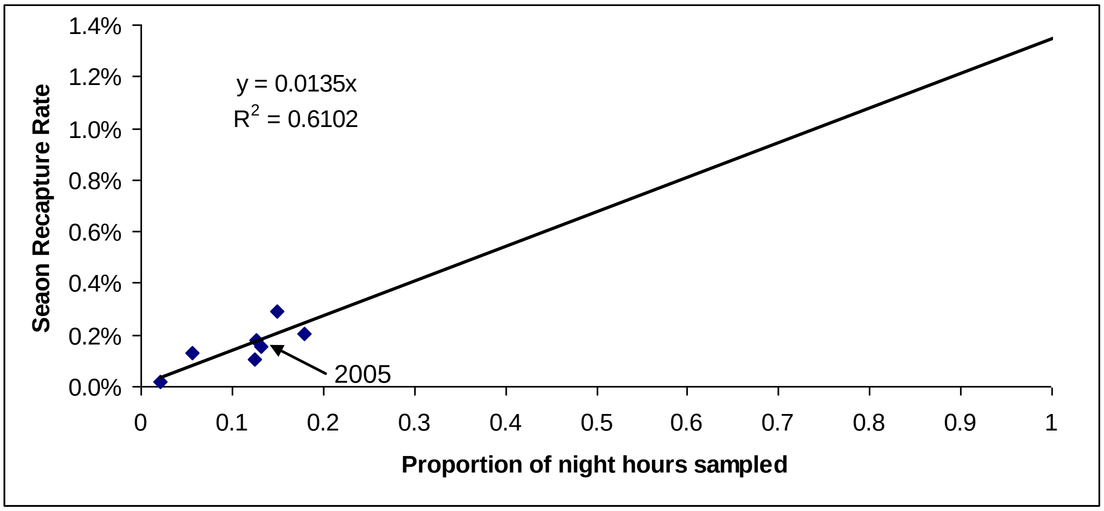

Figure 11. Coho recapture rate versus proportion of nightime sampled during the outmigration period

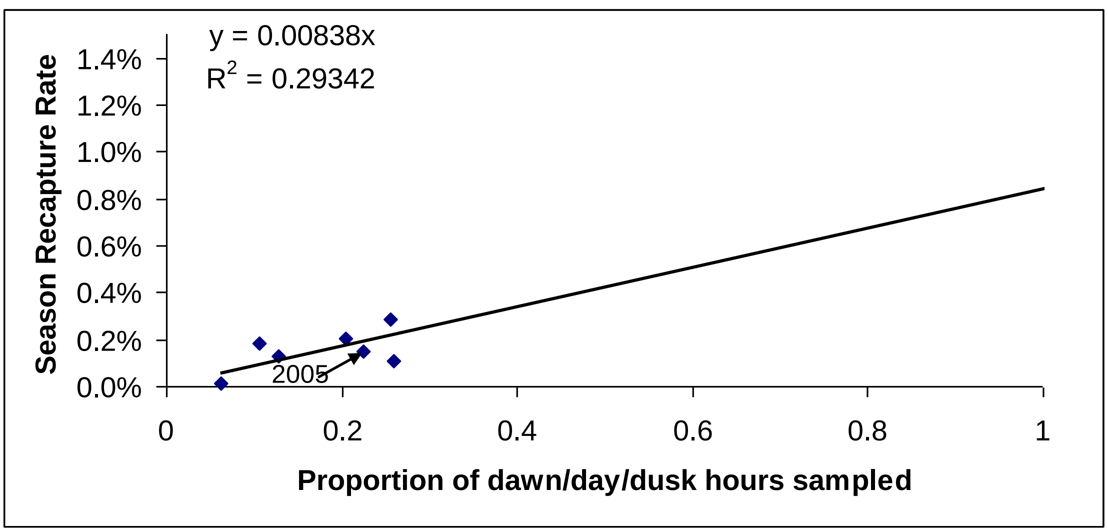

Figure 12. Coho recapture rate versus proportion of the hatchery outmigration period sampled at dawn, day, and dusk times

The YCCE estimate for nighttime catch efficiency was 1.16% and for the daytime was 0.68%. The ACCE estimate for nighttime catch efficiency was 1.35% and for the daytime was 0.838%. However, we strongly suspect that these numbers are likely to be too low for the nighttime and too high for the daytime.

Both methods use the interpolated trap catch per day data (summarized in Figure 13) to extrapolate catch data based on constant catch efficiencies but stratified by sampling time (i.e., night vs. day).

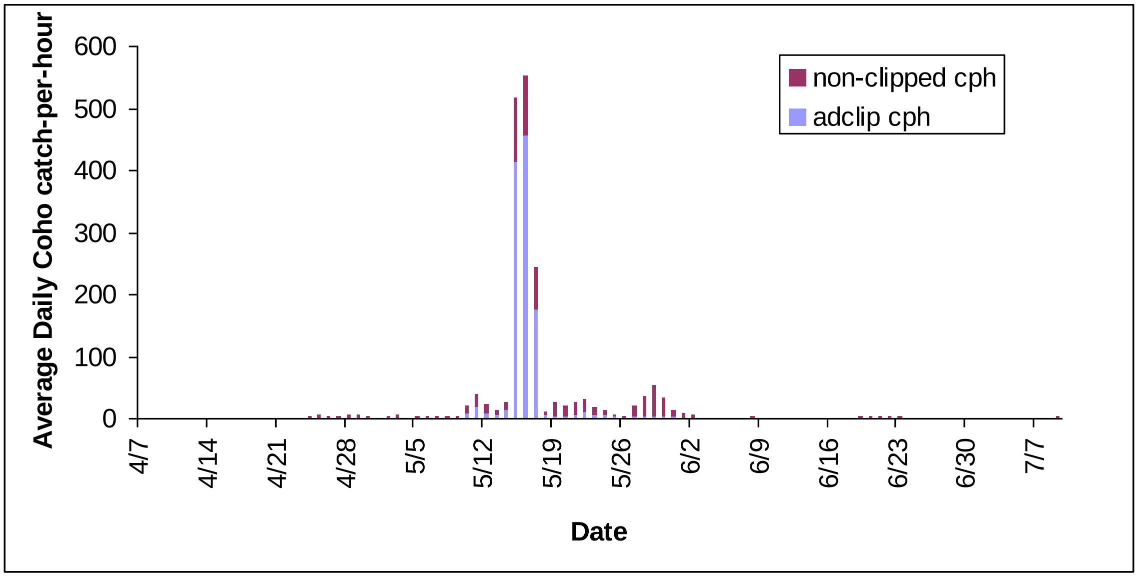

Figure 13. Average daily catch rates for adipose fin-clipped and non clipped Coho yearlings in 2005.

As we have seen previously, hatchery fin-clipped Coho smolts outmigrate over a relatively short time span, en-masse. Un-clipped (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 stocks are still likely to be affected by an underestimation of night time catch efficiencies though.

Using the ACCE catch efficiencies the total production of ad-clipped Coho yearlings for 2005 is 2,597,694 smolts and the total production of un-clipped smolts is 1,514,901 smolts. Using the YCCE catch efficiencies, the clipped production would be even higher, 3,117,403 clipped smolts and 1,818,214 unclipped smolts. However, we know that only 1,198,134 clipped smolts were released in 2005 making the ACCE estimate over as high as it should be for clipped hatchery smolts, and the YCCE estimate 2.6 times too high. Consequently, neither model is really convincing enough to make estimates of wild Chinook abundance.

This large over-estimation for Coho yearlings suggests that actual trap catch efficiencies on the two-three days when most of the Coho were passing the trap site were higher than our season-wide estimates. The extremely short residence times of Coho contrast with much longer residence times for Chinook fry and make estimating the production without daily catch efficiency data even more fraught with peril. The only way to resolve this problem is to be able to derive daily, or even hourly, estimates of trap catch efficiencies. Although it is not possible to do this at the present time, it is worth considering how this might be achieved in the future given suitable resources.

The basic information needed to calculate daily or hourly catch efficiencies is a reliable count of the fish of interest that are passing the trap site during the time period of interest. In the past we have tried to release groups of a thousand Chinook fry about a mile upstream from the trap and making assumptions that all pass by the trap site within 24 hours and that these highly stressed, newly released fry will exhibit similar behavior and catchability to fry that were released in the upper watershed and that have become acclimated to river conditions over time, and to wild origin fry. Unfortunately, catch efficiencies for these fish were not reliably predicted by environmental parameters such as secchi depth. We also suspect that their catchability may be different to fry that have become acclimated to riverine life. Any future effort to determine true trap catch efficiency must use fry that behave the same as river acclimated fry.

Two methods suggest themselves. One is to use some form of radio transmitter on thousands of smolts so that enough are caught in the trap (minimum of 20 per day) and the rest passing the trap site can be counted by a radio signal counter of some kind. Given that we suspect ‘average’ catch efficiencies for Coho yearling range between 0.8% in the day and 1.3% at night, we would need to have around 1500 radio transmitter tagged smolts passing the trap site during the night, and around 2500 tagged smolts passing the trap site during the day in order to get an accurate and reasonably precise measurement of catch efficiency for each time period. Such a method is not technically possible for Chinook fry at the present time because of their smaller size. If radio transmitters are used, it would be necessary to assume that the catchability and behavior of tagged smolts is the same as non-tagged smolts.

The other method is to count all ‘untagged’ smolts passing the trap site using some other method than the existing smolt trap. One method might be to use a large net, immediately below the trap site, across the entire width of the river to physically catch everything passing the trap site. However, this would be logistically very taxing and impossible in some flow situations where large woody debris etc is being swept downstream. Another method would be to use new sonar methods (e.g., DIDSON) that may be able to both count and identify species (separating age-zero Chinook from Coho yearlings by size for example). I think that the DIDSON method offers the most realistic chance of being able to measure trap catch efficiencies accurately and under the widest range of conditions.

Residence Time Modeling for Coho

Although the ACCE estimates are not particularly convincing, if the results are first scaled to match the known release of hatchery smolts (Fig 14) then it is still possible to model upstream residence times (Figure 15).

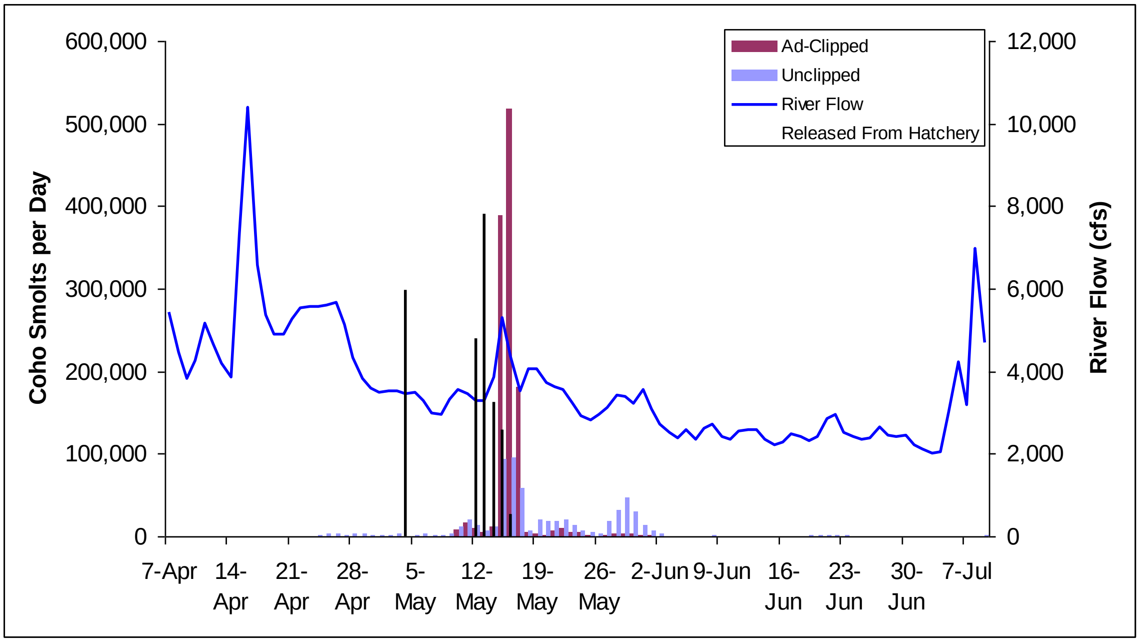

Figure 14. Adjusted ACCE estimates for Clipped and unclipped Coho compared to water flow at Ferndale and hatchery releases.

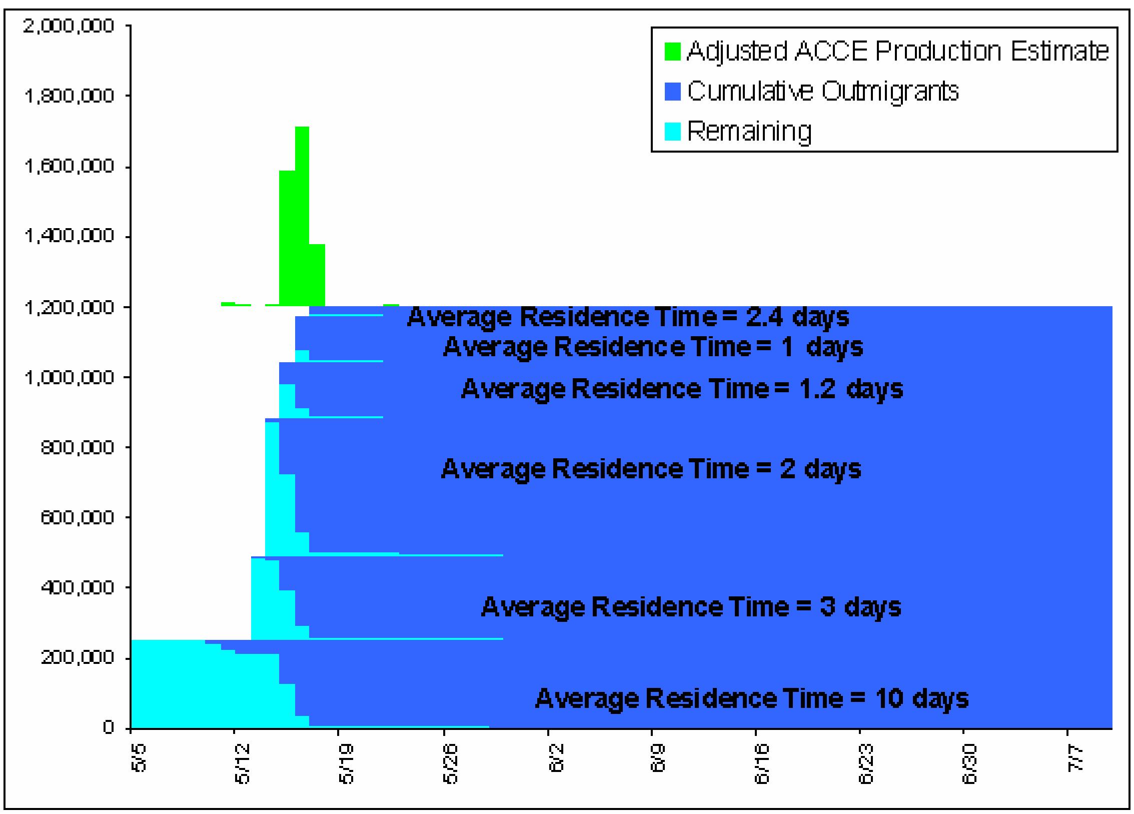

Figure 15. Average residence time modeling output based on adjusted 2005 ACCE daily production estimates.

The data in Figure 15 shows that the May 5 release group from Kendall Hatchery spent an average of 10 days upstream from the trap. By contrast, later releases of Coho yearlings from Skookum hatchery had an average residence time of 1 – 3 days. Data from previous years indicates that Coho smolts released in mid-late May typically have an average residence time of just 2 to 3 days. However, one other Coho release group has also had an average estimated residence time around 11 days (Fig. 16). This group was also released in early May (May 3 – May 7, 2004).

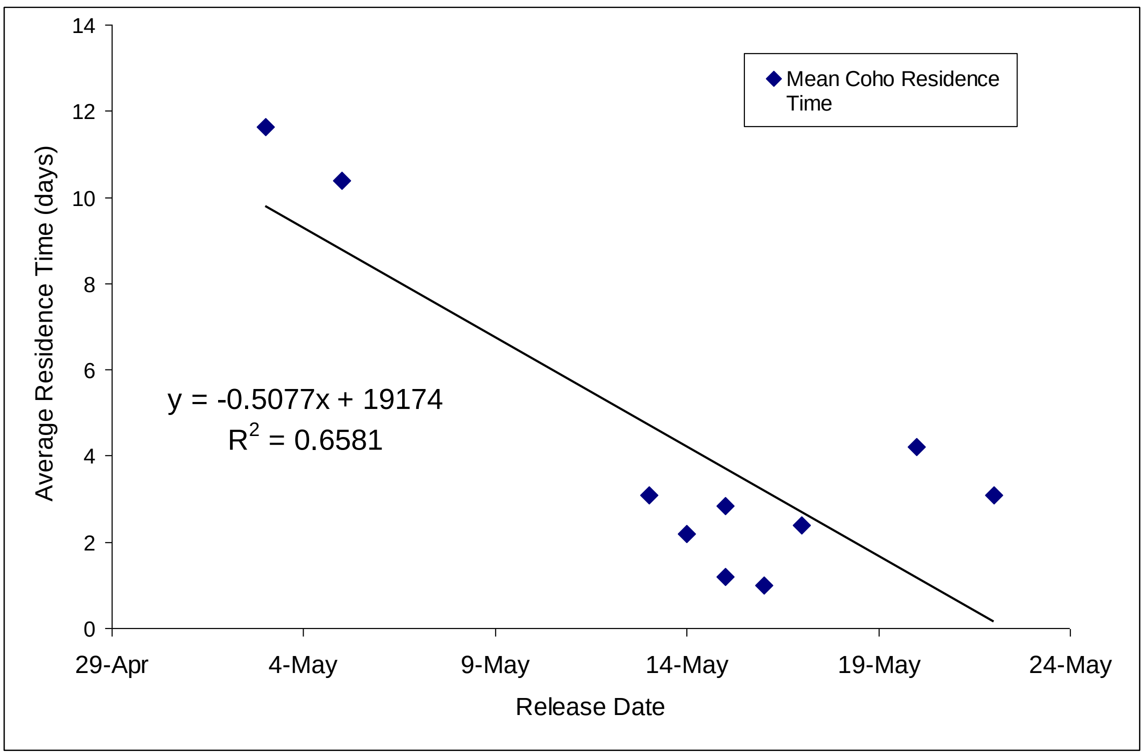

Figure 16. Average Residence times modeled for groups of Coho yearlings released in the Nooksack River.

References

Conrad R.H. & MacKay, M.T. 2000 *Use of a rotary Screwtrap to monitor the outmigration of Chinook salmon smolts from the Nooksack River: 1994-1998*. Northwest Fishery Resource Bulletin, Project Report Series No. 10. Northwest Indian Fisheries Commission, Olympia, WA. 120p

Dolphin, 2002. *A review of data analysis from the 2002 smolt trap program on the Nooksack River at Ferndale*. Lummi Natural Resources. Internal Report.

Dolphin, 2003. *An analysis of 2003 smolt trap data from the Hovander smolt trap*. Lummi Natural Resources. Internal Report.

Dolphin, 2004. *An analysis of 2003 smolt trap data from the Hovander smolt trap*. Lummi Natural Resources. Internal Report.

Muir, W.D.; Smith, S.G.; Hockersmith, E.E.; Eppard, M.B.; Connor, W.P.; Andersen, T.; Arnsberg, B.D. 1999 *Fall Chinook Salmon Survival And Supplementation Studies In The Snake River And Lower Snake River Reservoirs, 1997.* U.S.Dept.Energy Annual Report. Accessed at http://www.efw.bpa.gov/Environment/EW/EWP/DOCS/REPORTS/ DOWNSTRM/ D10891-8.pdf on October 27, 2003.

Skalski, J.R. 1998 *Estimating season-wide survival rates of outmigrating salmon smolt in the Snake River, Washington*. Can. J. Fish. Aquat. Sci. 55: 761-769.

Smith, S.G.; Muir,W.D.; Williams, J.G.; & Skalski, J.R. 2002 *Factors associated with Travel Time and Survival of Migrant Yearling Chinook Salmon and Steelhead in the Lower Snake River*. N.Am.J.Fish.Man. **22**:385-405.