Latent Mortality Associated with Passage through Snake River Dams: 2009 Tagging Activities and Final Report for the 2006 Juvenile Migration Year

Douglas M. Marsh, Neil N. Paasch, Kenneth W. McIntyre, Benjamin P. Sandford,
William D. Muir, and Gene M. Matthews

Report of research by

Fish Ecology Division
Northwest Fisheries Science Center
National Marine Fisheries Service
National Oceanic and Atmospheric Administration
2725 Montlake Boulevard East
Seattle, Washington 98112-2097

for

U.S. Department of Energy
Bonneville Power Administration
Division of Fish and Wildlife
P.O. Box 3621
Portland, Oregon 97208-3621
Contract No. 32992, Project 2003-041-00
Performance period April 2009 through March 2010

March 2010

EXECUTIVE SUMMARY

During spring 2009, the National Marine Fisheries Service PIT-tagged yearling hatchery Chinook salmon *Oncorhynchus tshawytscha* for the fifth year of a study to evaluate latent mortality associated with passage through Snake River dams. We also monitored adult returns from study fish tagged in 2006, 2007, and 2008. Returns of age-3-ocean adults in 2009 completed adult returns from the 2006 tagging.

For the 2009 tagging season, we continued to mark fish based on a modified study design first used in 2007. In our original (2005-2006) study design, fish detected at McNary Dam were assigned as replicate "releases" to form treatment groups. This design provided a known number of fish in each treatment group. However, efforts to tag the number of fish needed for this design (301,000) were unsuccessful. In addition, concern was expressed about the impact on the run in general of tagging such a large portion of the overall hatchery population.

Because of these concerns, we developed a new study design in 2007 where numbers of fish arriving at McNary Dam tailrace were estimated. Estimated numbers assigned to each study group were based on fish detected at McNary Dam. Using this method, we reduced the number of fish needed for tagging from 301,000 to a minimum of 111,222. Due to recent low smolt-to-adult return rates (SARs), we increased the tagging goal in 2009 to 120,000 fish.

Snake River dam operations during spring 2009 were similar to those during 2007 and 2008 with a delayed start to collection and transport. As in 2008, despite the delay in general collection, we were able to begin tagging as planned due to prior agreement with agency and tribal managers. We began tagging on 24 April and finished on 16 May.

From 24 April to 16 May 2009, we released a total of 120,662 hatchery spring/summer Chinook salmon. Of these fish, 28,882 were transported by truck and released below Ice Harbor Dam, 45,535 were transported by truck and returned to Lower Granite Dam for release into the tailrace, and 46,245 fish were released directly into the Lower Granite Dam tailrace with no transport (trucking effect reference group). For each replicate, all three study groups were released simultaneously.

In 2009, the overall estimated juvenile survival to McNary Dam was 84.3% for fish released at Ice Harbor Dam, 76.7% for fish released at Lower Granite Dam, and 79.3% for reference fish. Based on these survival estimates, we estimated numbers of fish from each group arriving at McNary Dam tailrace at 24,348 from the Ice Harbor group, 34,497 from the Lower Granite group, and 36,225 from the reference group.

Detection rates at McNary Dam based on these estimated numbers of fish arriving at McNary Dam were 42.0, 36.7, and 38.1% for the respective Ice Harbor Dam, Lower Granite Dam, and reference groups.

From releases of tagged juveniles in 2009, adults will return from 2010 (jacks) to 2012 (3-ocean fish). At Bonneville Dam, the principle adult recovery site for the 2009 study, we detected 37 age-3-ocean adults from 2006, 222 age-2-ocean adults from 2007, and 384 jacks from 2008 releases.

Returns of age-3-ocean adults in 2009 completed returns from fish marked as juveniles in 2006. In 2006, since we were only able to mark and release 189,462 of the planned 301,000 hatchery spring/summer Chinook salmon, we analyzed adult return rates for these fish based on the methods developed for the study since 2007.

Based on the estimated numbers of juveniles surviving to McNary Dam tailrace in 2006, total adult returns for all three groups increased from 249 using the original study design (based on fish detected at the dam) to 913 based on the estimated number of fish surviving to the tailrace. Using the estimated numbers, SARs were 0.71 (95% CI 0.61-0.80) for the Ice Harbor group, 0.70 (0.61-0.78) for the Lower Granite group, and 0.65 (0.59-0.72) for the reference group. This produced a weighted geomean SAR ratio of 0.94 (0.65-1.36) for Lower Granite to Ice Harbor Dam groups. Comparison of SARs between the Lower Granite and reference group to determine if a trucking effect exists produced a weighted geomean SARs ratio of 1.06 (0.92-1.22), indicating no trucking effect.

CONTENTS

INTRODUCTION

Populations of Snake River spring/summer Chinook salmon *Oncorhynchus tshawytscha* have declined extensively since completion of the Federal Columbia River Power System (Raymond 1979; Schaller et al. 1999). Declines began in the early 1970s as Lower Granite, Little Goose, Lower Monumental, and John Day Dams were added to the existing hydropower system. Initial decreases in abundance were roughly proportional to direct mortality suffered by smolts during downstream migration through the completed system.

Since the early 1980s, direct mortality of smolts passing dams has been reduced considerably (Williams et al. 2001), coincident with structural and operational changes designed to enhance downstream passage survival (Williams and Matthews 1995). Despite these efforts, and substantial improvements in smolt passage survival, adult return rates of Snake River Chinook salmon have not increased to levels that existed prior to dam construction (Schaller et al. 2007). During the early 2000s, smolt-to-adult return rates (SARs) exceeded 2%, the minimum level necessary for recovery (Scheuerell and Williams 2005); however, these increased SARs were not sustained throughout the decade.

Thus, an important question facing regional managers is whether or not migration through the hydropower system, as currently configured, causes latent mortality to anadromous salmonids. That is, mortality not expressed until after these fish have passed through the Federal Columbia River Power System (Budy et al. 2002). The concept of hydropower-related latent mortality was developed during the multi-agency process known as the *Plan for Analyzing and Testing Hypotheses* (Marmorek et al. 1998). Latent mortality was hypothesized as a possible explanation for the relatively greater loss in productivity postulated for upper river populations (i.e., Snake River) vs. lower river populations (downstream from McNary Dam) of spring/summer Chinook salmon (Schaller et al. 1996, 2007).

Based on estimated spawner and recruit data, Schaller et al. (1999, 2007) and Deriso et al. (2001) concluded that productivity declined more for upriver stocks, and that these declines were most affected by hydropower development. This reduction was thought to have occurred primarily after completion of the three final dams on the Snake River. Furthermore, this differential decline was greater than could be explained by differences in direct mortality caused by the additional dams. Schaller et al. argued there was little evidence that factors unrelated to the hydropower system could account for the differences in productivity and survival between upstream and downstream stocks.

This conclusion has been questioned with evidence provided by other researchers that several other factors could be at least partially responsible for differences in productivity between salmon populations from the two areas (Zabel and Williams 2000; Hinrichsen 2001; ISAB 2007). The scientific debate surrounding this issue will continue unresolved in the absence of experimental data.

The goal of this study is to determine whether migration through Snake River dams and reservoirs causes latent mortality in Snake River yearling Chinook salmon smolts. Specifically, the study will evaluate smolt-to-adult return rates (SARs) of yearling Chinook salmon passing McNary Dam. Comparisons of SARs will be made between three study groups; fish transported and released to the tailrace of Ice Harbor Dam, fish transported and released to the tailrace of Lower Granite Dam (which will require the latter to pass three additional dams and reservoirs to reach McNary Dam), and fish released to the tailrace of Lower Granite Dam without transport to serve as a reference to evaluate the effects of trucking.

Here we present final results from study fish released in 2006 and information on tagging of juveniles in 2009.

METHODS

Juvenile Collection and Tagging, 2009

In 2009, we collected and PIT-tagged Snake River hatchery spring/summer Chinook salmon at Lower Granite Dam from 24 April to 16 May. This schedule was intended to coincide with the passage period at the dam of the hatchery spring/summer Chinook salmon population in general. Timing was based on observations from previous studies, which have shown these fish generally begin passing Lower Granite Dam around 20-25 April and end by mid-May.

Collection and handling techniques, including use of a recirculating anesthetic water system, followed the methods of Marsh et al. (1996, 2001). Tagging for each of 10 replicates was conducted in 2-d blocks over 20 total days. On the first day of each 2-d block, reference fish (LN) were tagged and sent to a holding tank for 24-h. On the second day of each block, we tagged two treatment groups; one for Ice Harbor Dam transport (IH), and one for Lower Granite Dam transport (LG). All tagging was concluded by 1600 PDT each day to comply with the limited number of driving hours allowed per day for truck drivers (for safety reasons). This allowed the driver releasing fish at Lower Granite Dam to return to his base of operations within the allotted time.

All fish were released at approximately the same time. Upon arrival at Ice Harbor Dam (approximately 1900 PST), IH treatment fish were released into the juvenile fish facility bypass pipe. A circuitous route was devised for the Lower Granite Dam (LG) release group so that the truck carrying these fish returned to Lower Granite Dam at the same time the other truck was arriving at Ice Harbor Dam. Upon return to Lower Granite Dam, trucked fish were released through a pipe that runs along the top of the juvenile fish facility bypass pipe. Immediately following release of the Lower Granite treatment group, the reference group was released through the same pipe.

Evaluation will be based on annual ratios of SARs, that is, SAR_{LG}/SAR_{IH}, or (LG/IH ratio). Note that as a ratio of SARs from groups "released" at McNary Dam, LG/IH is a measure of differential survival below McNary Dam. As such, it is analogous to the differential mortality parameter, *D*, which has been computed for the comparison of transported to inriver fish below Bonneville Dam. Thus, an LG/IH ratio significantly less than 1.0 would indicate significant latent mortality for fish that passed through the three additional dams in the hydropower system between Lower Granite and McNary Dams.

Sample sizes for each year of this study were designed to provide an 80% probability ($\beta = 0.20$) of detection if the true LG/IH ratio was less than or equal to 0.80 (i.e. survival was at least 20% lower for fish released at Lower Granite Dam) using a one-sided hypothesis test at $\alpha = 0.05$ (i.e. null hypothesis was that the true ratio was 1.00). We also assumed that SAR_{IH} was at least 1.5% (see below).

Required sample sizes were derived by determining the required precision around the estimated LG/IH such that the one-sided confidence interval on the true LG/IH did not contain the value 1.0, or the confidence interval of the true natural-log-transformed LG/IH, ln(LG/IH), did not contain zero. If the confidence interval does not contain 1.0, then we can reject the null hypothesis, that there is no difference between rates of survival to adulthood for LG and IH fish, and that the true value of LG/IH is thus less than 1.0. Therefore, for a desired $\alpha = 0.05$ and $\beta = 0.20$, the number of fish needed was

$$\ln\left(\frac{LG}{IH}\right) - (t_\alpha + t_\beta) \times SE\left[\ln\left(\frac{LG}{IH}\right)\right] \approx 0$$

and

$$SE\left[\ln\left(\frac{LG}{IH}\right)\right] \approx \sqrt{\left(\frac{1}{n} + \frac{1}{n}\right)} = \sqrt{\frac{2}{n}}$$

where n is the number of adult returns per treatment, and $n_{IH} = n_{LG}$ (n for Ice Harbor Dam and Lower Granite Dam tailrace groups set equal for simplicity). The previous two statements imply that the required number of adults is:

$$n \approx \frac{2\,(t_\alpha + t_\beta)^2}{\left[\ln\left(\frac{LG}{IH}\right)\right]^2}$$

If we expect SAR_{IH} to be at least 1.5%, then the number of detections needed at McNary Dam are listed as follows:

True LG/IH	n	N_{IH}	$N_{LG} = N_{IH}/(LG/IH)$	N_{Total}
0.80	333	22,200	27,750	49,950

where N denotes the number of juveniles needed per treatment.

These calculations provided the sample sizes needed for each "release group" at McNary Dam. However, these "release" groups are formed of fish from each treatment group that survived to the McNary Dam tailrace. To determine the total number of fish needed for tagging, we used an assumed probability of survival to McNary Dam for Ice Harbor and Lower Granite release groups. These assumed probabilities of survival were based on survival estimates from our 2006 study year, and accounted for fish removed for transport. For 2009, we estimated the proportion of fish surviving to McNary Dam tailrace was 0.830 for fish released to Ice Harbor Dam tailrace and 0.657 for fish released to Lower Granite Dam tailrace.

Thus, to obtain the necessary number of study-fish detections at McNary Dam required releases of approximately 26,747 fish (22,200/0.83) to Ice Harbor Dam tailrace and 42,237 fish (27,750/0.657) to Lower Granite Dam tailrace. An additional 42,237 non-transported fish were released directly into Lower Granite Dam tailrace to serve as reference fish in evaluation of potential transport effects. Therefore, the total tagging requirement was 111,222 fish. Because of the low SARs experienced over the past several years, we increased the release number to 120,000 fish. These release numbers were then divided into 10 sets of releases through time in order to replicate the study over fish differences, varying river operations (at dams), and environmental fluctuations.

Juvenile Collection and Tagging, 2006

Juvenile collection and tagging methods used in 2006 were the same as those described above for tagging and release in 2009. However, as previously discussed, we based the original sample size needed presuming we would use actual detections of tagged fish at McNary Dam rather than an estimated number passing the dam (Marsh et al. 2006a). From multiple years of reach-survival studies, survival was estimated at 0.929 from Ice Harbor to McNary Dam and 0.723 from Lower Granite to McNary Dam. A detection probability of 0.25 was estimated at McNary Dam in 2000. With release numbers being based on these estimates, our original study design in 2006 required the release of approximately 71,475 fish (16,600/0.929/0.250) into Ice Harbor Dam tailrace, 114,799 fish (20,750/0.723/0.250) into Lower Granite Dam tailrace, and 114,799 non-transported fish released directly into Lower Granite Dam tailrace to control for potential transport effects. This brought the total tagging requirement to 301,073 fish. This target was not reached in 2006 for reasons discussed previously.

Adult Recovery and Data Analyses

Bonneville Dam serves as the principal adult recovery site for this study. Using this site for adult recovery provides for the maximum study SARs by avoiding potential losses from upstream passage mortality and mainstem fisheries above the dam. Data acquired from other areas will be considered ancillary. For the 2009 marking year, we will analyze results in 2012 when adult returns for the 2009 study releases are complete. We will evaluate LG/IH ratios based on estimates of juvenile fish passing McNary Dam. Confidence intervals for LG/IH ratios were calculated using the ratios of these estimates and their associated variances (Burnham et al. 1987).

For returns to date, we assumed that the true distribution of LG/IH ratios was approximately log-normal, and therefore calculated confidence intervals on the natural log scale and then transformed the endpoints back to the original scale. For the mean using the time-replicate ratios, this process was the same as calculating a geometric mean. Additionally, we used a weighted geometric mean where the weights were the estimated inverse relative variances (coefficient of variation squared) of the time-replicate ratios (Smith et al. 2006). Note we had to adjust estimates of variance used in these intervals to account for variation in the estimation process, the method *posteriori* that we used to estimate the number of juveniles that survived and were detected in the tailrace of McNary Dam. Methods used for these estimates and for calculating their variances are provided in Appendix B.

RESULTS

Juvenile Collection and Tagging, 2009

The 2009 marking year was the fifth study year of juvenile tagging. Juvenile tagging in 2009 was fully successful, with tagging goals met for all three groups of fish.

With expectations that hatchery spring/summer Chinook salmon would reach Lower Granite Dam in large numbers between 20 and 25 April, we began tagging on 24 April and ended on 16 May. However, as in 2008, hatchery Chinook salmon did not begin to arrive in large numbers until 29 April, the day we were collecting for the first day of our third 2-d replicate block. Due to the late run-timing, the tagging effort was initially between 2,500 and 3,700 fish behind what should have been tagged for each treatment group. However, once fish began arriving in large numbers, we attempted to catch up by surpassing daily tagging goals by as many fish as possible over the remainder of the tagging season. Because reference fish were the only group tagged on the first day of the 2-d replicate block (i.e., all personnel tagged the same group), the deficit in this group was easily eliminated. In fact, over the last three replicates, we had to slow tagging efforts because we had turned the deficit into an excess of over 2,700 fish.

We tagged Ice Harbor and Lower Granite truck treatment groups on the same day by splitting tagging personnel between two groups, but this made it more difficult to make up the deficit in each of these groups. However, by the end of the tagging period, we had eliminated the deficit and had to reduce our tagging on the last day to avoid tagging too many fish. Overall, we exceeded our total tagging goal of 120,000 by 1,200 fish.

From 24 April to 16 May, we tagged 121,232 hatchery yearling spring/summer Chinook salmon and released a total of 120,642 (Table 1). Fish were divided into three groups, with 28,882 released below Ice Harbor Dam (IH), 45,527 released into Lower Granite Dam tailrace after being transported by truck for an equal amount of time (LG), and 46,233 released as reference fish into Lower Granite Dam tailrace with no transport (LN).

Table 1. Dates of collection, PIT-tagging, and release of hatchery yearling spring/summer Chinook salmon for the latent mortality study at Lower Granite Dam in 2009. Numbers of fish released are also shown.

Collection date	Tag date	Release date	Number of fish released	Release number per 2-d block
23 April	24 April	25 April	1,852	
24 April	25 April	25 April	1,719	3,751
26 April	27 April	28 April	3,919	
27 April	28 April	28 April	6,852	10,771
28 April	29 April	30 April	7,306	
29 April	30 April	30 April	10,790	18,096
30 April	1 May	2 May	5,045	
1 May	2 May	2 May	9,313	14,358
3 May	4 May	5 May	6,211	
4 May	5 May	5 May	8,787	14,998
5 May	6 May	7 May	5,248	
6 May	7 May	7 May	8,934	14,182
7 May	8 May	9 May	4,825	
8 May	9 May	9 May	7,014	11,839
10 May	11 May	12 May	4,271	
11 May	12 May	12 May	5,063	9,334
12 May	13 May	14 May	3,936	
13 May	14 May	14 May	9,808	13,744
14 May	15 May	16 May	3,620	
15 May	16 May	16 May	6,129	9,749

Post-tagging mortality was determined using the reference group (LN), which was held for 24-h prior to release. Average post-tagging mortality for the entire tagging period was 0.53%, with daily values ranging from 0.03 to 1.59%. This rate was lower than observed in past tagging efforts using hatchery spring/summer Chinook salmon at Lower Granite Dam.

Mortalities were examined for any obvious injury that would indicate problems with tagging technique (e.g., punctured kidney or other organ damage). We observed that 14.6% of mortalities had been described as descaled at the time of tagging, while only 4.6% of the entire tagging population was so described. Body injury also contributed to mortality, as 18.6% of mortalities had been recorded as having some form of body injury at tagging, while only 6.2% of all tagged fish had records of body injury at tagging. While this effect of descaling and body injury on post-tagging mortality was similar to that found in previous studies of hatchery spring/summer Chinook salmon at Lower Granite Dam, the levels of descaling and body injury can not be compared to previous years. In 2009, we emphasized the recording of fish condition during tagging, a practice that had fallen off in recent years.

Estimated juvenile survival to McNary Dam in 2009 was 84.3% for the Ice Harbor transport treatment (IH), 76.7% for the Lower Granite transport treatment (LG), and 79.3% for the Lower Granite Dam reference group (LN; Table 2). Based on these survival estimates, we estimated numbers of tagged fish reaching McNary Dam tailrace at 24,348 Ice Harbor treatment fish, 34,497 Lower Granite treatment fish, and 36,225 reference fish. When adult returns are complete, these juvenile numbers will be used to determine SARs for comparisons among the three groups.

Table 2. Number of PIT-tagged hatchery yearling spring/summer Chinook salmon released by treatment group for evaluation of latent mortality, 2009. Estimated survival from release to McNary Dam and estimated numbers of fish arriving in the tailrace of McNary Dam by treatment are also shown.

Release group	Number released	Survival to McNary Dam (%)	Estimated number at McNary Dam tailrace
Lower Granite trucked	45,527	76.7	34,497
Reference	46,233	79.3	36,225
Ice Harbor trucked	28,882	84.3	24,348

While survival rates for the 2009 Ice Harbor Dam (IH) release group were the third highest of the five tagging years, survival rates for 2009 Lower Granite Dam trucked (LG) and non-transport (LN) release groups were the highest of the five tagging years. As in past years, the similarity in survival rates between the LG and LN groups indicated that transporting fish in a truck had little or no effect on juvenile survival through the hydropower system. We await adult returns to determine if there are any impacts of trucking on SARs. Adults from 2009 releases will begin returning in 2010 (jacks), with complete adult returns expected in 2012.

Juvenile Collection and Tagging, 2006

Details of juvenile collection and tagging in 2006 were reported by Marsh et al. (2006a), and numbers of fish released for all treatments in 2006 are shown in Table 3. Total tagging and release numbers by treatment are shown in Appendix Table A1.

Table 3. Dates of collection, PIT-tagging, and release of hatchery yearling spring/summer Chinook salmon for the latent mortality study at Lower Granite Dam in 2006. Numbers of fish released are also shown.

Collection date	Tag date	Release date	Number of fish released	Release number per 2-d block
20 April	21 April	22 April	3,879	
21 April	22 April	22 April	3,438	7,317
23 April	24 April	25 April	6,414	
24 April	25 April	25 April	9,496	15,910
25 April	26 April	27 April	3,390	
26 April	27 April	27 April	8,318	11,708
27 April	28 April	29 April	12,498	
28 April	29 April	29 April	12,580	25,078
30 April	1 May	2 May	10,390	
1 May	2 May	2 May	9,241	19,631
2 May	3 May	4 May	11,881	
3 May	4 May	4 May	7,608	19,489
4 May	5 May	6 May	9,576	
5 May	6 May	6 May	9,665	19,241
7 May	8 May	9 May	11,742	
8 May	9 May	9 May	10,994	22,736
9 May	10 May	11 May	12,873	
10 May	11 May	11 May	11,418	24,291
11 May	12 May	13 May	11,412	
12 May	13 May	13 May	12,649	24,061

Our original study design was based on comparisons of fish detected at McNary Dam, so juvenile fish were monitored as they migrated downstream after release (Table 4 and Appendix Table A2). The purpose of the non-transported group released at Lower Granite Dam (LN group) was to provide a reference for potential effects of transport (trucking). Based on juvenile detections of the 2006 releases, trucking did not appear to affect the juvenile stage, as the trucked (LG) and reference (LN) groups released at Lower Granite were detected at McNary Dam in nearly the same proportions (Table 4).

Table 4. Numbers of PIT-tagged hatchery yearling spring/summer Chinook salmon released by treatment for evaluation of extra mortality in 2006. The number and percent detected at McNary Dam by treatment group is also shown.

Release group	Number released	Number detected at McNary Dam	Percent detected at McNary Dam
Lower Granite trucked (LG)	56,939	11,261	19.78
Reference (LN)	94,055	18,949	20.15
Ice Harbor trucked (IH)	38,468	13,090	34.03

Adult Recovery and Data Analysis

We began recovering jacks in 2007 from study fish released at Lower Granite Dam in 2006. In August 2009, we completed recoveries from the 2006 release year with the collection of age-3-ocean adults. Using the modified study design the estimated number of juveniles that reached the McNary Dam tailrace ranged from approximately 32 thousand to 64 thousand fish (Table 5 and Appendix Table A3). We estimated 913 adults returned from these groups.

Table 5. The number of PIT-tagged hatchery yearling spring/summer Chinook salmon released at Lower Granite Dam after trucking (LG), released at Lower Granite Dam without trucking (LN), and released at Ice Harbor Dam (IH) for evaluation of latent mortality in 2006. Survival from release to McNary Dam, the number of fish transported from a collector dam, and the estimated number of fish arriving in the tailrace of McNary Dam are also shown.

Treatment group	Number released	Estimated survival to McNary Dam (%)	Transported	Estimated survival to McNary Dam (n)
Lower Granite (LG)	56,939	0.697	2,148	37,902
Reference (LN)	94,055	0.717	3,833	64,268
Ice Harbor (IH)	38,468	0.840	0	32,305

Smolt-to-Adult Return Ratios—Using the fish estimated to have arrived in McNary Dam tailrace as juveniles, SARs were 0.71 for Ice Harbor fish, 0.70 for Lower Granite fish, and 0.65 for reference fish (Table 6). These SARs were based on the 228, 265, and 420 adults returning from each respective treatment. Based on these SARs, the weighted geomean LG/IH ratio was 0.94 (95% CI, 0.65-1.36), indicating there was no latent mortality caused by migration through the three lower Snake River dams. When we compared the Lower Granite and reference treatments, the weighted geomean LG/LN ratio was 1.06 (95% CI, 0.92-1.22), indicating there was no trucking effect.

Table 6. Number of juveniles, adults, and the SARs and weighted geomean SAR ratios for PIT-tagged hatchery yearling spring/summer Chinook salmon estimated to have arrived in McNary Dam tailrace from fish released at Lower Granite Dam after trucking (LG), released at Lower Granite Dam without trucking (LN), and released at Ice Harbor Dam (IH) for evaluation of latent mortality in 2006.

	Returns by age-class				Weighted geomean
Juvenile numbers	Jack	2-ocean	3-ocean	SAR (95% CI)	SAR ratio: LG/IH or LG/LN (95% CI)
Ice Harbor trucked (IH)					
32,447	53	168	7	0.71 (0.61-0.80)	
Lower Granite trucked (LG)					
38,097	56	199	10	0.70 (0.61-0.78)	0.94 (0.65-1.36)
Reference (LN)					
64,598	67	333	20	0.65 (0.59-0.72)	1.06 (0.92-1.22)

Length at Tagging—Using fish detected at McNary Dam as juveniles, returning age-2-ocean and age-3-ocean adults from the reference group were larger at tagging than returning adults from either the Ice Harbor or Lower Granite treatment groups, while the jacks from the reference group were the smallest (Table 7). Unlike the juveniles marked in 2005, which produced age-3-ocean adults that were larger at tagging than age-2-ocean adults (Marsh et al. 2006b), in 2006 age-3-ocean adults came from the smallest juveniles tagged (as has been observed in previous years with wild fish).

Also unlike 2005, in 2006 adults that returned from all three treatment groups were larger at tagging than fish that did not return, with the exception of the few age-3-ocean adults, which were smaller. In previous observations of wild fish, returning adults have typically been larger at tagging, on average, than fish that did not return.

When we looked at the returning adults from study fish estimated to have arrived in McNary Dam tailrace as juveniles, we found adults from the reference group had been smallest at tagging (jacks were in the middle). Because we do not know the average tag length of fish estimated to have arrived in the McNary Dam tailrace, we can not compare tag lengths of returning adults and those fish that did not return.

Table 7. Average length at tagging of adult hatchery spring/summer Chinook salmon PIT-tagged as juveniles at Lower Granite Dam and detected at McNary Dam in 2006.

Age class	Treatment group	Average length at tagging for all fish (mm)*	Number of returning adults	Average length at tagging for returning adults (mm)
	Detected juveniles at McNary Dam			
Jacks	Ice Harbor (IH)	135.0	17	142.9
	Lower Granite (LG)	134.8	8	147.1
	Reference (LN)	135.3	23	140.9
Age-2-ocean	Ice Harbor (IH)	135.0	66	135.5
	Lower Granite (LG)	134.8	39	135.1
	Reference (LN)	135.3	81	138.3
Age-3-ocean	Ice Harbor (IH)	135.0	1	122.0
	Lower Granite (LG)	134.8	1	117.0
	Reference (LN)	135.3	3	134.0
	Estimated juveniles at McNary Dam			
Jacks	Ice Harbor (IH)	Unknown	53	141.5
	Lower Granite (LG)	Unknown	55	144.9
	Reference (LN)	Unknown	67	142.5
Age-2-ocean	Ice Harbor (IH)	Unknown	167	137.1
	Lower Granite (LG)	Unknown	194	137.5
	Reference (LN)	Unknown	318	136.7
Age-3-ocean	Ice Harbor (IH)	Unknown	7	132.4
	Lower Granite (LG)	Unknown	10	135.2
	Reference (LN)	Unknown	19	130.9

* This column is the average of all fish that fit the categories; i.e., all juveniles that were detected at McNary Dam as juveniles. Because we do not know which of the individual tagged fish actually reached McNary Dam, there was no way to determine their average length at tagging. Of the returning adults from fish estimated to have reached McNary Dam, 23 did not have a juvenile tagging length recorded.

DISCUSSION

In 2006 we began juvenile tagging at Lower Granite Dam on 21 April and finished on 13 May. Although we released 189,462 hatchery yearling spring/summer Chinook salmon, we fell far short of our goal of 301,000. We were unable to tag the necessary number of fish in part due to the unusually large numbers of hatchery steelhead arriving at the dam during our tagging period. These large numbers required us to process many more steelhead than expected, and the additional time required to process these fish was considerable. Tagging numbers were also curtailed by the necessity of having to shorten tagging days to avoid forcing the truck drivers to work beyond their permitted number of hours on the road per day. These factors, along with concerns about having to handle such a large portion of the run, led us to change our study design the following year.

In 2006, juvenile survival from release at Lower Granite Dam to the McNary Dam tailrace was similar to annual survival estimates made in this stretch in previous years (Faulkner et al. 2009). River flow in April and May of 2006 was above the 10-year average (1996-2005), with spill occurring from 3 April through the end of August. Ocean conditions were poor to moderately favorable for juvenile salmonids entering the ocean in spring 2006.

We did not use the initial study design to evaluate adult returns. After evaluating the original design with one that estimated total numbers of fish to the tailrace of McNary Dam we found a temporal pattern to virtually all aspects of salmon migration. When we examined the detection probability at McNary Dam, we found that it was highest early in the juvenile migration season, decreased through mid-season, and was quite low at the end. After determining median passage date at McNary Dam for the three groups, we found the median passage date for each of the ten releases was 4 to 6 days earlier for the Ice Harbor released fish. This resulted in the median passage date for fish from the first release at Lower Granite Dam coinciding with the same date as for fish from the fourth release at Ice Harbor Dam. Combining the temporal pattern in detection probability with the differences in median passage dates, we determined the composition of fish forming the detected group from Ice Harbor was different from the composition of fish forming the two Lower Granite groups (Table 8).

Table 8. Composition of 2006 study groups by release date under the two methods of analysis.

Release date	Ice Harbor: Fish detected at McNary Dam	Ice Harbor: Fish estimated in McNary Dam tailrace	Lower Granite: Fish detected at McNary Dam	Lower Granite: Fish estimated in McNary Dam tailrace	Reference: Fish detected at McNary Dam	Reference: Fish estimated in McNary Dam tailrace
4/22/06	0.0391	0.0352	0.0535	0.0397	0.0572	0.0452
4/25/06	0.1196	0.1007	0.1340	0.1029	0.0930	0.0716
4/27/06	0.0917	0.0769	0.1217	0.0885	0.0510	0.0367
4/29/06	0.1325	0.1273	0.1947	0.1541	0.1874	0.1382
5/2/06	0.0978	0.0868	0.1235	0.1007	0.1449	0.1093
5/4/06	0.0899	0.0877	0.0780	0.0771	0.1377	0.1269
5/6/06	0.1139	0.1016	0.1086	0.1043	0.1069	0.1202
5/9/06	0.1025	0.1050	0.0956	0.1052	0.1109	0.1095
5/11/06	0.0832	0.1337	0.0536	0.1051	0.0724	0.1360
5/13/06	0.1297	0.1450	0.0368	0.1224	0.0387	0.1064

For instance, the last Ice Harbor release formed 13.0% of the group, while the last release from the two Lower Granite groups comprised only 3.7% (LG) and 3.9% (LN) of each group. Knowing that different hatcheries dominate the collection at different times during the outmigration, we believe the LG/IH comparison based on fish detected at McNary Dam was biased by the fact that the two groups were comprised of different fish.

However, when we estimated the number of fish arriving at McNary Dam, the last release comprised 14.5, 12.2, and 10.6% of the total Ice Harbor, Lower Granite, and reference groups, respectively. Additionally, this method increased the number of adults we could analyze from 249 to 913. For these reasons, we believe using the estimated number of juveniles, which resulted in more similar composition among the study groups, was the best way to compare the Ice Harbor (IH) and Lower Granite (LG) groups in 2006.

Based on the modified study design using the estimated number of juveniles arriving in the McNary Dam tailrace, we did not observe significant latent mortality during the 2006 outmigration. Further, it did not appear that trucking significantly affected smolt-to-adult-return rates.

ACKNOWLEDGMENTS

We thank the U.S. Army Corps of Engineers (USACE) for their cooperation with this study. In particular, we thank Mike Halter and his staff at Lower Granite Dam, and John Bailey for his help in obtaining the use of USACE fish transport tankers. We also thank Scott Davidson of our Pasco shop for his help in preparing the tankers for our use, for coordinating the trucking contract, and for conducting the release operations at Ice Harbor Dam.

REFERENCES

Budy, P., G. P. Thiede, N. Bouwes, C. E. Petrosky, and H. Schaller. 2002. Evidence linking delayed mortality of Snake River salmon to their earlier hydrosystem experience. North American Journal of Fisheries Management 22:35-51.

Burnham, K. P., D. R. Anderson, G. C. White, C. Brownie, and K. H. Pollock. 1987. Design and analysis methods for fish survival experiments based on release-recapture. American Fisheries Society Monograph 5:1-437.

Dersio, R. B., D. R. Marmorek, and I. J. Parnell. 2001. Retrospective patterns of differential mortality and common year effects experienced by spring and summer Chinook salmon (*Oncorhynchus tshawytscha*) of the Columbia River. Canadian Journal of Fisheries and Aquatic Sciences 58:2419-2430.

Faulkner, J. R., S. G. Smith, W. D. Muir, D. M. Marsh, and J. G. Williams. 2009. Survival Estimates for the Passage of Spring-Migrating Juvenile Salmonids through Snake and Columbia River Dams and Reservoirs, 2008**.** Report of Research by Fish Ecology Division, Northwest Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration to Bonneville Power Administration, Portland, OR, Project No. 1993-02900, 117 p. (Available online at http://pisces.bpa.gov/release/documents/ documentviewer.aspx?doc=P112186)

Hinrichsen, R. A. 2001. The importance of influence diagnostics: examples from Snake River Chinook salmon spawner-recruit models. Canadian Journal of Fisheries and Aquatic Sciences 58:551-559.

ISAB (Independent Scientific Advisory Board). 2007. Latent Mortality Report. Review of hypothesis and causative factors contributing to Latent Mortality and their likely relevance to the “below Bonneville” component of the Compass Model. ISAB 2007-1. Northwest Power and Conservation Council, Portland, OR. Available on line at Http://www.council.org.

Marmorek, D. R., C. N. Peters, J. Anderson, L. Barnthouse, L. Bostsford, N. Bouwes, P. Budy, T. Conney, R. Dersio, J. Gieselman, A. Giorgi, J. Hayes, R. Hinrichsen, M. Jones, L. Krasnow, O. Langness, D. Lee, C. McConnaha, C. M. Paulsen, R. Peterman, C. E. Petrosky, C. Pinney, H. Schaller, S. Smith, C. Toole, E. Weber, J. Williams, P. Wilson, and R. Zabel. 1998. Plan for analyzing and testing hypotheses (PATH): weight of evidence report. Report prepared by ESSA Technologies LTD. for the Bonneville Power Administration, Portland, OR.

Marsh, D. M., J. R. Harmon, , K. W. McIntyre, K. L. Thomas, N. N. Paasch, B. P. Sandford, D. J. Kamikawa, and G. M. Matthews. 1996. Research related to transportation of juvenile salmonids on the Columbia and Snake Rivers, 1995. Report of the National Marine Fisheries Service to the U.S. Army Corps of Engineers, Walla, Walla, Washington.

Marsh, D. M., J. R. Harmon, N. N. Paasch, K. L. Thomas, K. W. McIntyre, B. P. Sandford, and G. M. Matthews. 2001. Research related to transportation of juvenile salmonids on the Columbia and Snake Rivers, 2000. Report of the National Marine Fisheries Service to the U.S. Army Corps of Engineers, Walla, Walla, Washington.

Marsh, D. M., J. R. Harmon, N. N. Paasch, K. L. Thomas, K. W. McIntyre, B. P. Sandford, W. D. Muir, and G. M. Matthews. 2006a. A study to evaluate latent mortality associated with passage through Snake River Dams, 2006. Report of the National Marine Fisheries Service to the Bonneville Power Administration. Available at www.efw.bpa.gov/searchpublications (April 2009)

Marsh, D. M., J. R. Harmon, N. N. Paasch, K. L. Thomas, K. W. McIntyre, B. P. Sandford, W. D. Muir, and G. M. Matthews. 2006b. A study to evaluate latent mortality associated with passage through Snake River Dams, 2005. Report of the National Marine Fisheries Service to the Bonneville Power Administration. Available at www.efw.bpa.gov/searchpublications (April 2009)

Marsh, D. M., J. R. Harmon, N. N. Paasch, K. L. Thomas, K. W. McIntyre, B. P. Sandford, W. D. Muir, and G. M. Matthews. 2007. A study to evaluate latent mortality associated with passage through Snake River Dams, 2006. Report of the National Marine Fisheries Service to the Bonneville Power Administration. Available at www.efw.bpa.gov/searchpublications (April 2009)

Mood, A. M., Graybill, F. A. and Boes, D. C. 1974. *Introduction to the theory of statistics*, 3rd ed. McGraw-Hill, New York.

Raymond, H. R. 1979. Effects of dams and impoundments on migrations of Chinook salmon and steelhead from the Snake River, 1966-1975. Transactions of the American Fisheries Society 90:58-72.

Schaller, H. A., C. E. Petrosky, and O. P. Langness. 1996. Contrasts in stock recruitment patterns of Snake and Columbia River spring and summer Chinook. In Plan for analyzing and testing hypotheses (PATH): final report of retrospective analysis for fiscal year 1996. Compiled and edited by D. R. Marmorek and 21 coauthors. ESSA Technologies, Ltd., Vancouver, B.C.

Schaller, H. A., C. E. Petrosky, and O. P. Langness. 1999. Contrasting patterns of productivity and survival rates for stream-type Chinook salmon (*Oncorhynchus tshawytscha*) populations of the Snake and Columbia rivers. Canadian Journal of Fisheries and Aquatic Sciences 56:1031-1045.

Schaller, H. A., and C. E. Petrosky. 2007. Assessing hydrosystem influence on delayed mortality of Snake River stream-type Chinook salmon. North American Journal of Fisheries Management 27:810-824.

Scheuerell, M. D. and J. G. Williams. 2005. Forecasting climate-induced changes in the survival of Snake River spring/summer Chinook salmon. Fisheries Oceanography 14:448-457.

Smith, S. G., W. D. Muir, D. M. Marsh, J. G. Williams, and J. R. Skalski. 2006. Survival eestimates for the passage of spring-migrating juvenile salmonids through Snake and Columbia River dams and reservoirs, 2005. Report of Research by Fish Ecology Division, Northwest Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration to the Bonneville Power Administration, Project No. 1993-02900, 125 electronic pages (Available online at http://pisces.bpa.gov/release/documents/documentviewer.aspx?doc=00004922-7)

Williams, J. G. and G. M. Matthews. 1995. A review of flow and survival relationships for spring and summer Chinook salmon, *Oncorhynchus tshawytscha*, from the Snake River basin. Fishery Bulletin, U.S. 93:732-740.

Williams, J. G., S. G. Smith, and W. D. Muir. 2001. Survival estimates for downstream migrant yearling juvenile salmonids through the Snake and Columbia Rivers Hydropower System, 1966-1980 and 1993-1999. North American Journal of Fisheries Management 21:310-317.

Zabel, R. W., and J. G. Williams. 2000. Comments on “contrasting patterns of productivity and survival rates for stream-type Chinook salmon (*Oncorhynchus tshawytscha*) populations of the Columbia and Snake rivers” by Schaller et al. (1999). Canadian Journal of Fisheries and Aquatic Sciences 57:1739-1741.

APPENDIX A:

Tagging and Release Data for Hatchery Spring/Summer Chinook Salmon in 2006

Appendix Table A1. Totals by treatment of hatchery spring/summer Chinook salmon tagged at Lower Granite Dam in spring 2006. After tagging, reference fish were held 24-h prior to release in the tailrace, Lower Granite trucked fish were transported half-way to Ice Harbor Dam and back prior to release in the tailrace, and Ice Harbor fish were transported and released to Ice Harbor Dam tailrace.

	Reference		Lower Granite trucked		Ice Harbor trucked	
Release Date	Tagged	Released	Tagged	Released	Tagged	Released
4/22/06	3,927	3,879	2,035	2,025	1,420	1,413
4/25/06	6,517	6,414	5,578	5,505	4,014	3,991
4/27/06	3,475	3,390	5,234	5,139	3,208	3,179
4/29/06	12,821	12,498	7,667	7,660	4,935	4,920
5/2/06	10,571	10,390	5,985	5,928	3,356	3,313
5/4/06	12,103	11,881	4,191	4,170	3,459	3,438
5/6/06	9,715	9,576	5,651	5,626	4,063	4,039
5/9/06	11,856	11,742	6,938	6,916	4,102	4,078
5/11/06	13,037	12,873	6,631	6,612	4,827	4,806
5/13/06	11,467	11,412	7,369	7,358	5,298	5,291

Appendix Table A2. Total hatchery spring/summer Chinook salmon released at Lower Granite Dam and detected at McNary Dam in spring 2006. After tagging, reference fish were held 24-h prior to release in the tailrace, Lower Granite trucked fish were transported half-way to Ice Harbor Dam and back prior to release in the tailrace, and Ice Harbor fish were transported and released to Ice Harbor Dam tailrace.

	Reference		Lower Granite Trucked		Ice Harbor trucked	
Release Date	Released	Detected	Released	Detected	Released	Detected
4/22/06	3,879	1,083	2,025	603	1,413	512
4/25/06	6,414	1,762	5,505	1,509	3,991	1566
4/27/06	3,390	966	5,139	1,370	3,179	1200
4/29/06	12,498	3,551	7,660	2,192	4,920	1735
5/2/06	10,390	2,745	5,928	1,391	3,313	1280
5/4/06	11,881	2,610	4,170	878	3,438	1177
5/6/06	9,576	2,026	5,626	1,223	4,039	1491
5/9/06	11,742	2,102	6,916	1,077	4,078	1342
5/11/06	12,873	1,371	6,612	604	4,806	1089
5/13/06	11,412	733	7,358	414	5,291	1698

Appendix Table A3. Estimated numbers of hatchery spring/summer Chinook salmon arriving in McNary Dam tailrace in spring 2006 after release at Lower Granite and Ice Harbor Dam. After tagging, reference fish were held 24-h prior to release in the tailrace, Lower Granite trucked fish were transported half-way to Ice Harbor Dam and back prior to release in the tailrace, and Ice Harbor fish were transported and released to Ice Harbor Dam tailrace.

	Reference		Lower Granite trucked		Ice Harbor trucked	
Release Date	Released	Arrived in tailrace	Released	Arrived in tailrace	Released	Arrived in tailrace
4/22/06	3,879	3,079	2,025	1,593	1,413	1,165
4/25/06	6,414	4,874	5,505	4,128	3,991	3,327
4/27/06	3,390	2,496	5,139	3,552	3,179	2,541
4/29/06	12,498	9,407	7,660	6,183	4,920	4,206
5/2/06	10,390	7,440	5,928	4,038	3,313	2,866
5/4/06	11,881	8,641	4,170	3,091	3,438	2,899
5/6/06	9,576	8,179	5,626	4,185	4,039	3,358
5/9/06	11,742	7,456	6,916	4,220	4,078	3,469
5/11/06	12,873	9,259	6,612	4,217	4,806	4,419
5/13/06	11,412	7,245	7,358	4,908	5,291	4,792

APPENDIX B

Estimated Variance of Smolt-to-Adult Return Ratios

In this study, ratios of the proportion of smolts that returned as adults (SARs) were estimated between paired treatment groups. The estimated variance of SARs ratios has been calculated for NMFS transport studies over many years using Equation 2. This method is widely used to estimate variance in ratios, for example, in relative survival estimates. In most studies, release numbers of smolts are known, and thus assumed to be "fixed," with no variation. However, in this study, release numbers were estimated. Therefore, variance of the estimation process must be incorporated into the variance of the proportions (SARs) and ratios, to reflect the added uncertainty resulting from "non-fixed" release numbers. The derivation shown below in Equations 1 and 2 can be applied to any general pair of treatment groups.

From Mood, Graybill, and Boes (1974, p. 181), using the Delta Method for independent x and y,

$$V\left(\frac{x}{y}\right) \approx \left(\frac{\mu_x}{\mu_y}\right)^2 \left(\frac{V(x)}{\mu_x^{\,2}} + \frac{V(y)}{\mu_y^{\,2}}\right) \tag{1}$$

For $R = SAR_1/SAR_2$, assuming the SARs are binomially-distributed, and using estimated values, this becomes:

$$\hat{V}(\hat{R}) \approx \hat{R}^2 \left(\frac{1}{n_1} - \frac{1}{N_1} + \frac{1}{n_2} - \frac{1}{N_2}\right) \tag{2}$$

since,

$$\frac{\hat{V}(S\hat{A}R_1)}{S\hat{A}R_1^{\,2}} = \frac{S\hat{A}R_1(1 - S\hat{A}R_1)}{N_1 S\hat{A}R_1^{\,2}} = \frac{1 - S\hat{A}R_1}{N_1 S\hat{A}R_1} = \frac{1}{n_1} - \frac{1}{N_1} \tag{3}$$

and similarly for SAR_2.

If, however, N_1 and N_2 are calculated from R_1S_1 and R_2S_2, where the R is the release number and S is survival from release to some location, then from (1):

$$\hat{V}(\hat{R}) \approx \hat{R}^2 \left(\frac{\hat{V}(S\hat{A}R_1)}{S\hat{A}R_1^{\,2}} + \frac{\hat{V}(S\hat{A}R_2)}{S\hat{A}R_2^{\,2}}\right) \tag{4}$$

Now, $$\hat{V}(S\hat{A}R_1) = \hat{V}\left(\frac{n_1}{N_1}\right) = \hat{V}\left(\frac{n_1}{R_1\hat{S}_1}\right) = \left(\frac{1}{R^2}\right)\hat{V}\left(\frac{n_1}{\hat{S}_1}\right)$$

$$= \left(\frac{1}{R^2}\right)\left(\frac{n_1}{\hat{S}_1}\right)^2\left(\frac{\hat{V}(n_1)}{n_1^{\,2}} + \frac{\hat{V}(\hat{S}_1)}{\hat{S}_1^{\,2}}\right) \tag{5}$$

by (1) and, $$S\hat{A}R_1^{\,2} = \left(\frac{n_1}{N_1}\right)^2 = \left(\frac{1}{R^2}\right)\left(\frac{n_1}{\hat{S}_1}\right)^2 \tag{6}$$

So from (5) and (6), and assuming the SARs are binomially distributed,

$$\frac{\hat{V}(S\hat{A}R_1)}{S\hat{A}R_1^{\,2}} = \frac{\hat{V}(n_1)}{n_1^{\,2}} + \frac{\hat{V}(\hat{S}_1)}{\hat{S}_1^{\,2}} = \frac{N_1 S\hat{A}R_1(1 - S\hat{A}R_1)}{n_1^{\,2}} + \frac{\hat{V}(\hat{S}_1)}{\hat{S}_1^{\,2}}$$
$$= \frac{n_1\left(\frac{N_1 - n_1}{N_1}\right)}{n_1^{\,2}} + \frac{\hat{V}(\hat{S}_1)}{\hat{S}_1^{\,2}} = \frac{N_1 - n_1}{n_1 N_1} + \frac{\hat{V}(\hat{S}_1)}{\hat{S}_1^{\,2}} = \frac{1}{n_1} - \frac{1}{N_1} + \frac{\hat{V}(\hat{S}_1)}{\hat{S}_1^{\,2}} \tag{7}$$

Then from (4) and (7) and substituting the estimators for N_1 and N_2,

$$\hat{V}(\hat{R}) \approx \hat{R}^2\left(\frac{1}{n_1} - \frac{1}{R_1\hat{S}_1} + \frac{1}{n_2} - \frac{1}{R_2\hat{S}_2} + \frac{\hat{V}(\hat{S}_1)}{\hat{S}_1^{\,2}} + \frac{\hat{V}(\hat{S}_2)}{\hat{S}_2^{\,2}}\right) \tag{8}$$

For this study, R is the ratio of Treatment 1 SAR to Treatment 2 SAR from McNary Dam (MCN) as juveniles to Bonneville Dam as adults, R_1 and R_2 are the release numbers for the two treatments, N_1 and N_2 are the numbers of the two treatments estimated alive in the MCN tailrace, n_1 and n_2 are the adult return numbers, and S is the survival from release to MCN. The hat notation means that the quantities/parameters are estimated using Cormack/Jolly Seber (CJS) methods.

Data that were ratios of binomial proportions were assumed to be log-normally distributed. Therefore, confidence intervals for this study were calculated as ±2 SEs (for $\alpha = 0.05$, the multiplier is approximately 2) around the natural log-transformed ratio. These endpoints were back-transformed to the original scale. The standard error of the ratio on the log-scale is:

$$\hat{V}(\ln(\hat{R})) \approx \hat{R}^2\hat{V}(\hat{R}) \approx \left(\frac{1}{n_1} - \frac{1}{R_1\hat{S}_1} + \frac{1}{n_2} - \frac{1}{R_2\hat{S}_2} + \frac{\hat{V}(\hat{S}_1)}{\hat{S}_1^{\,2}} + \frac{\hat{V}(\hat{S}_2)}{\hat{S}_2^{\,2}}\right) \tag{9}$$