Effects of Flow Augmentation on Snake River Fall Chinook

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1. Introduction

Snake River summer flow augmentation has been used in recent years in an attempt to improve the survival of fall chinook from the Snake River basin.[1] A number of studies have been conducted to evaluate and improve the effectiveness of flow augmentation. Studies on the spawning, rearing and migratory requirements of fall chinook salmon were conducted in the Columbia River basin in the early 1990s (Rondorf and Miller, 1993; Rondorf and Miller 1994; Rondorf and Tiffan, 1994). Studies in 1994 and 1995 (Connor et al. 1996 and 1997) characterized the early life history of Snake River fall chinook and their survival to Lower Granite Dam. Using data from 1991-1995, Giorgi and Schlecte (1997) assessed the volume and shape of flow augmentation delivered in the Snake River basin and attempted to evaluate the consequences of the augmentation on ESA-listed salmon stocks in the drainage using the CRiSP 1.5 smolt passage model (Anderson et al. 1996). In 1999, the PATH (Plan for Analyzing and Testing Hypotheses) analysis group developed spawner recruit data for Snake River fall chinook and addressed issues on the impacts of fish transportation and dam removal on fall chinook (Peters, Marmorek and Parnell eds. 1999). In a four-year study (1995-1998), environmental variables were correlated with fall chinook survival in the Snake and Clearwater Rivers (Williams and Bjornn 1997; Williams and Bjornn 1998; Muir et al. 1999). Finally, in a September 1999 draft White Paper, NMFS reviewed recent data analysis on the effects of flow management in the Columbia River and salmon travel time and survival (NMFS 1999). NMFS concluded: “Direct evidence for a survival benefit to fall chinook from flow management is strongly supported by research results” and “thus, with the existing project configuration and outmigration timing, additional flow augmentation to benefit Snake River fall chinook salmon would likely increase survival.”

The objective of this report is to review the existing data with thorough statistical and ecological analysis to quantitatively assess the impacts of flow and flow augmentation and to identify the possible mechanisms by which flow acts on fall chinook survival.

Whereas the NMFS draft White Paper focused on demonstrating correlations between survival and environmental variables, our approach is to address mechanisms as well as correlations. In this manner, we provide a more ecologically-based assessment of the impacts of flow and flow augmentation on fish survival.

In the September 1999 draft White Paper on flow and survival, NMFS justifies flow augmentation for Snake River fall chinook based on four main points:

- In the reaches above dams (life stage 1), travel time is not related to flow but NMFS believes smolts may stop or slow migration as flow decreases and water temperature increases.
- In the reaches above dams (life stage 1), a flow-survival relationship exists within the migration season, and correlations of flow with water clarity and temperature require managers to consider both quality and quantity when managing flows to benefit fall chinook.
- In the hydrosystem (life stage 2), no direct flow survival benefits are detected.
- However, NMFS believes that good flow (spill conditions) since the 1995 BiOP may provide survival benefits downstream as smolts migrate through the estuary and into the near ocean (life stage 3).

However, the recent studies have emphasized that impacts of flow are uncertain because other environmental variables also change at the same time as flow and may affect fish survival. Furthermore, although the studies to date have focused on the correlation between natural seasonal variations in water properties and fish survival, our emphasis is on addressing the impacts of flow augmentation that occurs in addition to the seasonal variations of flow.

2. Approach and Objective

Our objective is to address the impacts of flow augmentation on the outmigration of fall chinook from the Snake River system through ocean entry. We begin by considering

[1]Fall chinook are also known as ocean-type chinook or sub-yearling migrants.

the general life history of these fish. Snake River fall chinook spawn in the Snake River below Hells Canyon Dam. The eggs hatch in early spring. The juveniles rear in the Snake River above Lower Granite Dam in the spring and the smolts slowly migrate out of the Snake River, passing Lower Granite Dam in the summer. The smolt rate of migration increases as they move downstream, beginning at 2 to 5 km per day above Lower Granite Dam and increasing up to 30 km per day as they pass McNary Dam. Smolts reach the estuary in late summer, enter the ocean, and migrate north. The adults spend several years in the ocean where they are caught in fisheries as far north as Alaska. On the return, fall chinook are caught primarily in British Columbia, Oregon, and Washington coastal fisheries, and in the Columbia River. The adults enter the Columbia River in the late summer and pass Lower Granite Dam in September and October.

Our approach is to assess, in a statistical and ecologically mechanistic framework, how flow augmentation affects survival of fall chinook smolts from the beginning of the migration in the Snake and Clearwater Rivers (Figure 1, path 1) through hydrosystem passage (Figure 1, path 2) and into the estuary and ocean (Figure 1, path 3). We consider four sources of data: 1) PIT tag studies, which cover fish survival from the rearing habitat to Lower Granite Dam (Figure 1, path 1) and through the hydrosystem (Figure 1, path 2); 2) spawner-recruit data, which expresses the survival of fish from spawning in the tributaries through freshwater outmigration through the estuary to ocean residence and adult migration back to the spawning grounds (Figure 1, path 4); 3) water quality and flow data from the Snake and Columbia River system; 4) passage timing information of wild fall chinook at Lower Granite Dam.

We first review the studies relating seasonal changes in flow to fish travel time and survival and expand on the analysis conducted by NMFS in their Flow Survival Draft White Paper (NMFS 1999). In the draft White Paper, NMFS concluded that the environmental variables and survival were confounded making it difficult to resolve the impact of flow on fish with its approach. We apply additional statistical methods to clarify the collinearity of the data and show that it is unlikely that flow is the driving factor in the seasonal survival pattern. We next explore the impacts of flow augmentation on environmental variables and fish survival. Taking a mechanistic approach, we find that the seasonal relationships cannot be extrapolated to infer the impacts of flow augmentation on fish. We apply the CRiSP smolt passage model to quantify the likely impacts of Snake and Clearwater augmentation on smolt survival to Lower Granite and Bonneville Dams and find that flow augmentation from Brownlee Reservoir has no discernible effect on survival, but there is a survival benefit from Dworshak Reservoir flow augmentation. Finally, we consider the impacts of flow from a fish life cycle perspective. We find that flow has an insignificant effect on spawner to recruit survival for fish in both the Columbia and Snake River basins. In conclusion, we reconcile the strong seasonal flow/survival relationship discussed by NMFS with the nonexistent year-to-year flow survival relationship and the ineffectiveness of flow augmentation from the Snake River.

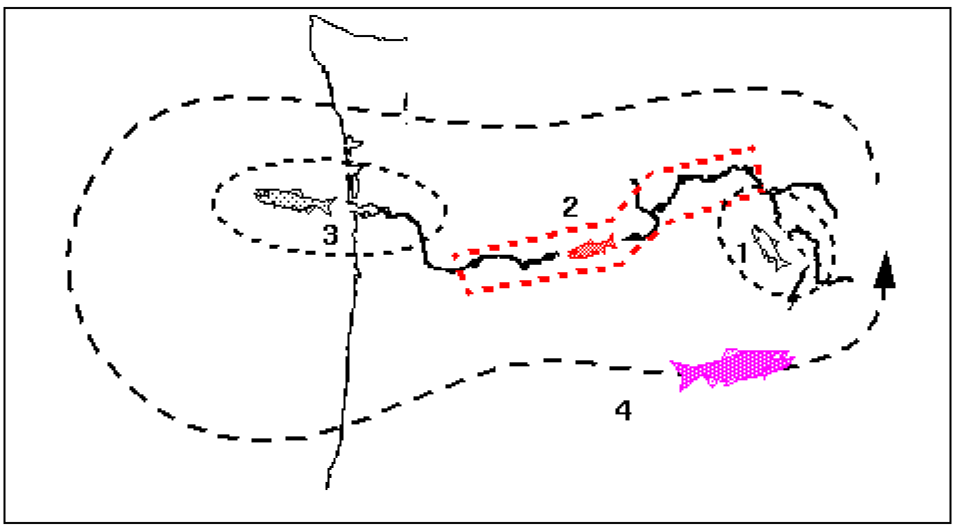

Figure 1. Life cycle stages for which survival data are available.

3. The 1995-1998 Survival Studies

The assessment of the impacts of flow on freshwater juvenile chinook survival are based on the 1995-1998 PIT-tag studies of fish released above Lower Granite Dam. Information on the studies is published in annual reports for 1995 (Williams et al. 1997), for 1996 (Williams et al. 1998), for 1997 (Muir et al. 1999), and for 1998 (Muir in press).

In these studies, PIT-tagged cohorts of fall chinook from Lyons Ferry Hatchery were released at Pittsburg Landing, which is near the upstream end of the fall chinook habitat in the Snake River, at Billy Creek in the Snake River just upstream of the Snake/Clearwater River confluence, and at Big Canyon Creek in the Clearwater River watershed (Figure 2). The fish were detected at Lower Granite Dam. Sixty-two groups of hatchery fish were released over the four years. The reports show fall chinook survival and travel time correlations to indices of flow, temperature, and water clarity.[2] The indices were defined as average values of the environmental variables between the release date and the passage of 5% of the group at Lower Granite Dam. These indices were selected to characterize the conditions experienced by most of the fish after release and before initiation of migration. The general belief is that the fish move quickly to the head of Lower Granite pool where they rear until they reach a size sufficient to begin the downstream migration. The indices based on 5% arrival are intended to characterize the time the fish are in their rearing habitat. The NMFS studies also determined the downstream survival and travel time to Lower Monumental Dam.

The analysis in the reports found that, within a season, fall chinook survival between release location and Lower Granite dam was correlated with flow, temperature and water clarity, but that travel time was not correlated with survival. As the season progresses, flow decreases, while temperature and water clarity increase. The reports also noted that survival decreases markedly with groups released later in the migration season and that the environmental variables (flow, temperature and water clarity) were all significantly correlated with each other, and exhibited seasonal trends. Between Lower Granite Dam and Lower Monumental Dam, survival was not correlated with environmental variables (Muir et al. 1999).

Muir et al. (1999) suggested that river flow, water temperature, and water clarity might affect survival estimates in a number of ways. Hypothesized causes for lower survival of fish migrating later in the season may include disorientation of migrants under lower

[2]Water clarity is the inverse of turbidity that was used in the NMFS reports. Later in this paper, where NMFS data is used in regression analysis, its use of the term “turbidity” or “TURB” has been maintained, but the variable is actually water clarity.

flows, increased risk of predation and disease in the warmer waters, and increased water clarity later in the season, which makes the smolts more visible to predators.

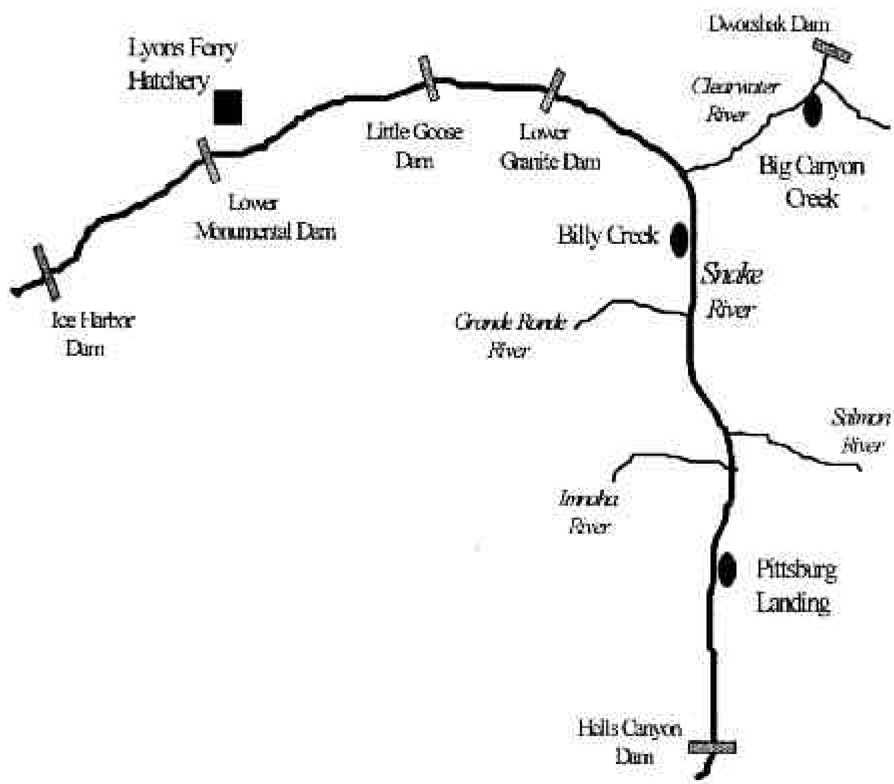

Figure 2. Study area showing location of Lyons Ferry Hatchery and the Pittsburg Landing, Billy Creek, and Big Canyon Creek release sites for the fall chinook survival studies (from Muir et al. 1999).

3.1 Seasonal cycles: flow, water temperature, clarity, survival, and travel time

Between the spring fry emergence and their arrival at Lower Granite Dam in the summer, the chinook are exposed to rapidly changing environmental conditions. During this time, the flows first increase due to the spring freshet and then decrease as the summer progresses. Water clarity follows the flow changes, decreasing as flow increases and then increasing over the summer as flow decreases. Temperature continually increases from winter through summer. Typical examples of the seasonal pattern of flow and temperature are illustrated in Figure 3. As described in a number of studies, all of these processes are related and are coupled to seasonal weather patterns (Rondorf and Miller 1993; Muir et al. 1999).

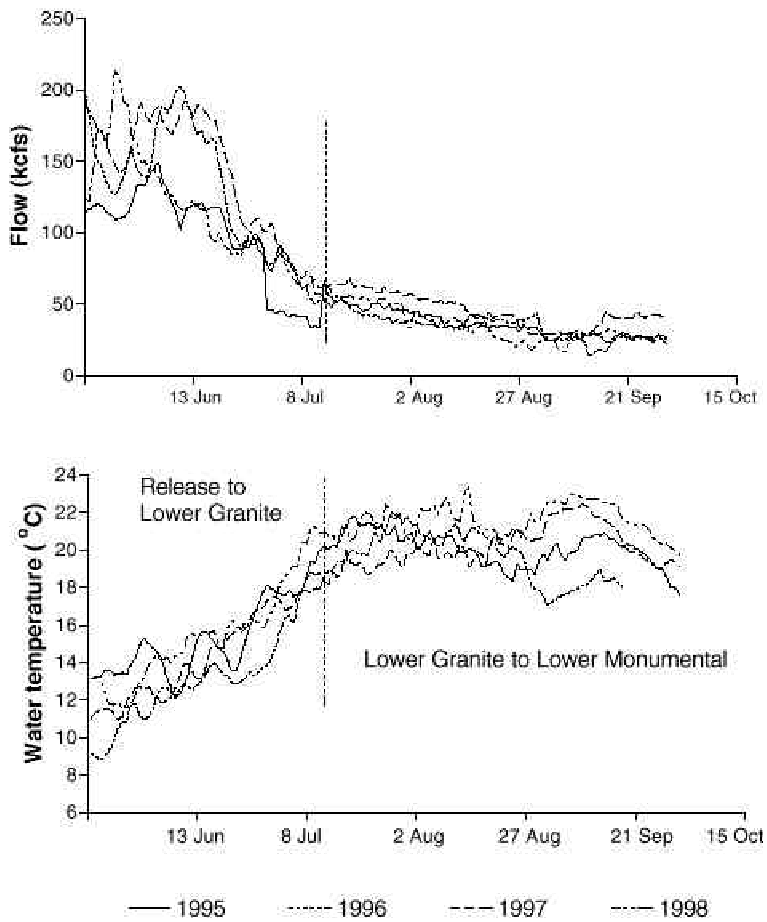

Figure 3. Seasonal patterns of temperature and flow at Lower Granite Dam.

The survival of subyearling fall chinook also exhibits a seasonal pattern. In the PIT tag studies, the fish released earlier in the season had the highest survival, while the fish released latest in the season had the lowest survival. This is evident in regressions of survival vs. release (Rls) day for each year (Table 1). The relationships are linear and the slope and intercept are very similar between years giving a good correlation when the data are combined into a single regression (Figure 4). The outlier was 1995, which was the first year of the study with a limited range of release dates. Fish at Pittsburg Landing and Billy Creek were released over a 9-day period in 1995 while in the other years the release dates extended over a month.

Table 1. Regressions of survival vs. release day (Rls), Survival = a + b * Rls.

	1995	**1996**	**1997**	**1998**	**Total**
Intercept (a)	1.8	3.29	2.74	2.37	2.69
Slope (b)	-0.0078	-0.0170	-0.0137	-0.0116	-0.0134
r-squared	0.93	0.92	0.81	0.73	0.79

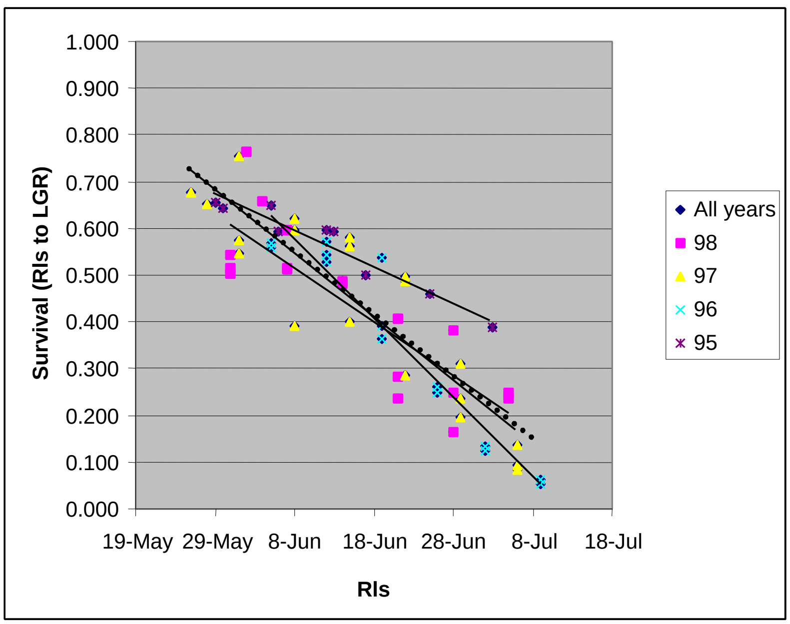

Figure 4. Survival from release to Lower Granite Dam exhibits a linear relationship with release day (Rls). Regression lines depict relationship in each year.

Release day of the fish varied from late May through early July. Over this period of time flow, temperature and water clarity increased in linear fashion (Table 2). The salient point is that survival and all of the environmental variables were strongly correlated with release day.

Table 2. Regressions of environmental variables against smolt release day.

	1995	**1996**	**1997**	**1998**	**Total**
Flow = a + b * Rls					
Intercept (a)	345	451	690	287	473
Slope (b)	-1.57	-2.16	-3.38	-1.20	-2.24
r-squared	0.97	0.93	0.96	0.98	0.62
Temperature = a + b * Rls					
Intercept (a)	-8.93	-8.97	-9.05	-7.11	-6.81
Slope (b)	0.159	0.151	0.151	0.148	0.142
r-squared	0.95	0.93	0.98	0.94	0.82
Clarity = a + b * Rls					
Intercept (a)	-5.2	-11.6	-7.8	-1.8	-6.0
Slope (b)	0.054	0.087	0.058	0.029	0.053
r-squared	0.97	0.96	0.86	0.95	0.45

The strong linearity of survival and environmental variables with release date insures a strong linearity of each of the environmental variables with survival. As discussed below in the multiple regression analysis, the correlation between these variables does not imply that the survival can be attributed simply to changes in flow or any other single variable. The relationships between the environmental variables and survival are not as strong as the relationship between survival and release day. (The relationships with release day exhibit r-squares greater than or equal to the relationships with environmental variables, see Tables 1 and 3). The seasonal relationship between survival and the environmental variables was different for each year, shifting both the slope and the intercept (Figures 5, 6, 7). In contrast, the relationship between release date and survival was remarkably consistent from year-to-year (Figure 4).

Table 3. Regressions of survival against environmental variables.

	1995	**1996**	**1997**	**1998**	**Total**
	Survival = a + b * Flow				
Intercept (a)	0.15	-0.20	-0.03	-0.39	0.08
Slope (b)	0.0047	0.0071	0.0038	0.0095	0.0037
r-squared	0.86	0.81	0.74	0.71	0.48
	Survival = a + b * Temperature				
Intercept (a)	1.34	2.25	1.84	1.76	1.72
Slope (b)	-0.045	-0.110	-0.087	-0.752	-0.076
r-squared	0.84	0.92	0.74	0.72	0.61
	Survival = a + b * Water Clarity				
Intercept (a)	1.06	1.00	0.87	1.56	0.762
Slope (b)	-0.137	-0.18	-0.21	-0.37	-0.11
r-squared	0.86	0.90	0.79	0.65	0.35

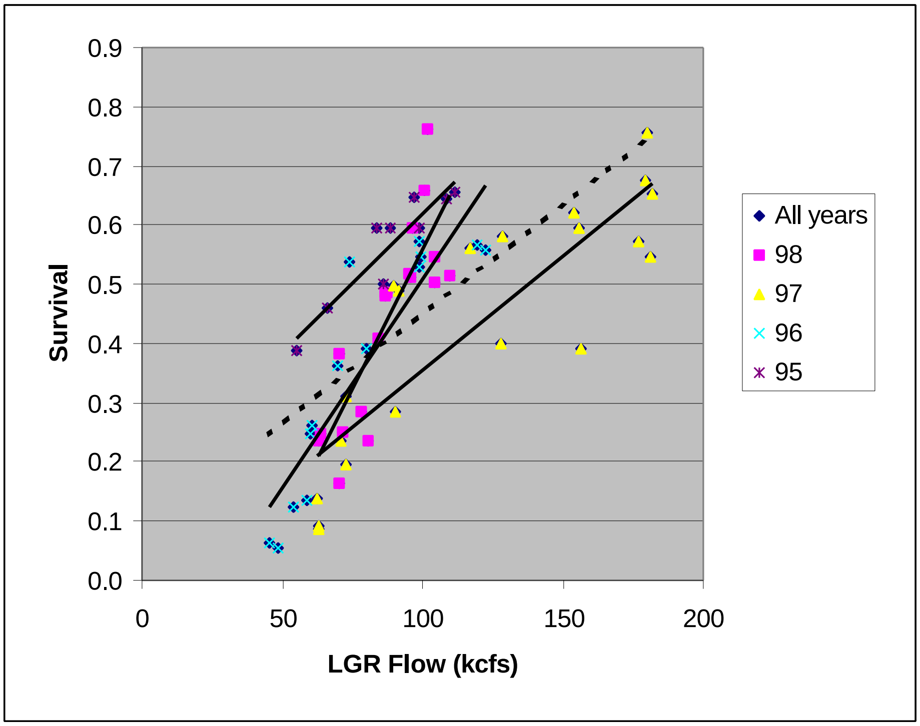

Figure 5. Relationship of survival to Lower Granite Dam and flow. Dashed line is the average regression over all years.

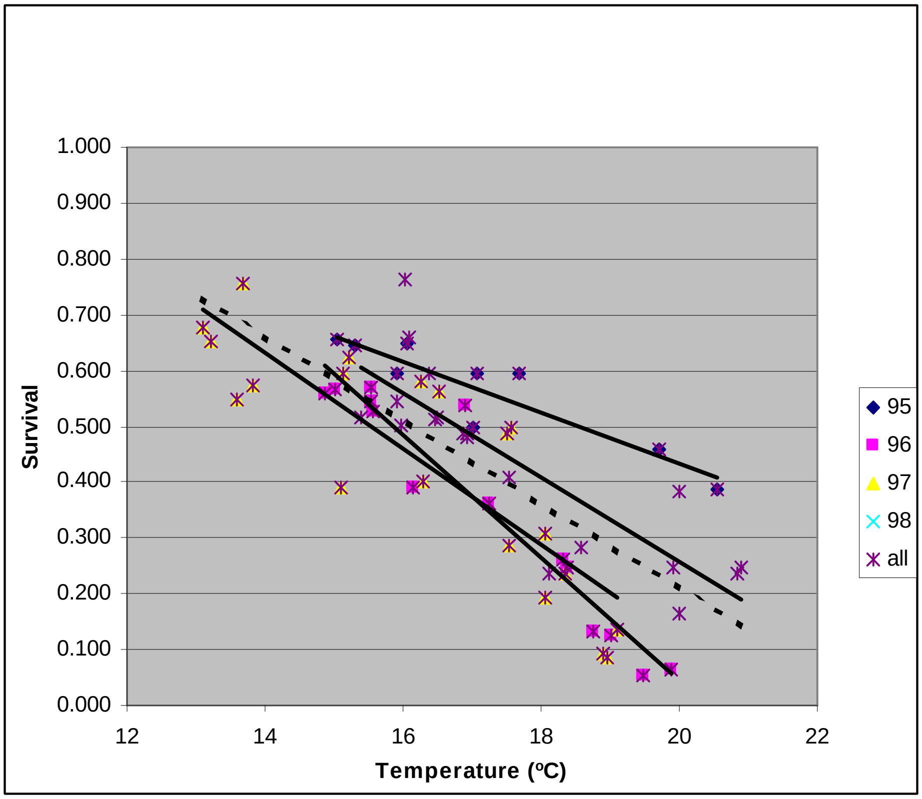

Figure 6. Survival vs. temperature for release to Lower Granite Dam. Dashed line is the average regression for all years.

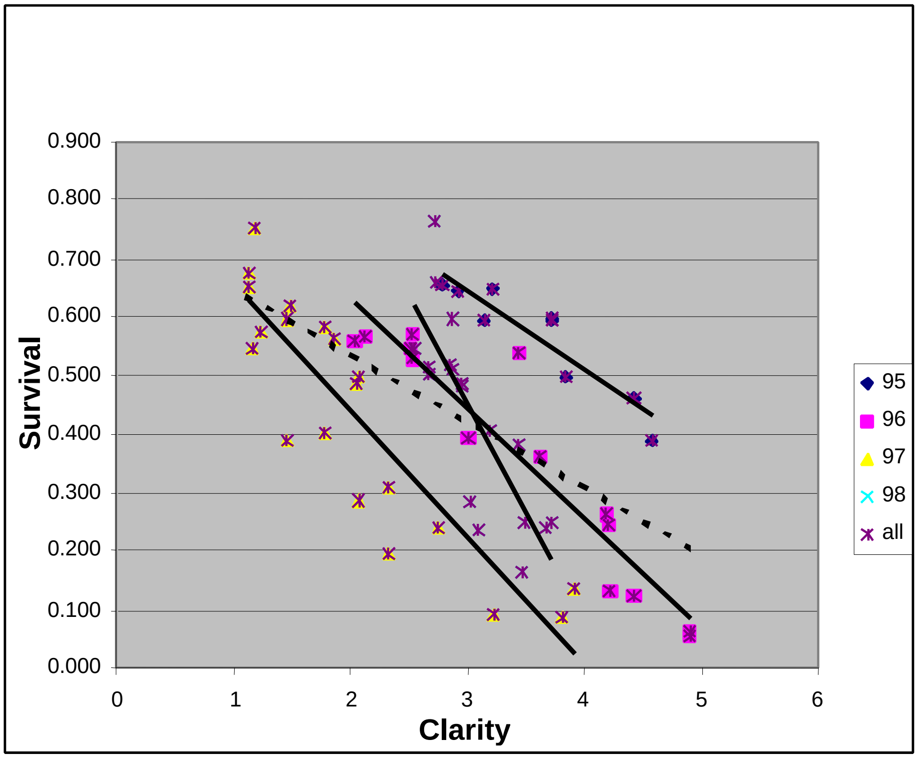

Figure 7. Survival vs. clarity for release to Lower Granite Dam. Dashed line is the average regression for all years.

These regressions suggest that there is no straightforward association between seasonal change in survival and any single environmental variable. Specifically, linear correlations of survival with seasonal flow cannot be directly extrapolated to impacts of flow augmentation on survival. The impacts of seasonally averaged flow are addressed in Section 3.2. The interactions of survival over season with a multiple regression technique are explored in Section 4 where a formal analysis is applied to determine which variables are most statistically significant in explaining survival. However, the statistical evaluation does not consider the mechanisms through which environmental variables act on smolt survival. The mechanistic or ecological processes are considered further in Section 7.

3.2. Hydrosystem survival and environmental factors

The fall chinook release studies from 1995, 1996 and 1997 indicate that survival between Lower Granite Dam and Lower Monumental Dam had no consistent year-to-year relationship with environmental conditions (Muir et al. 1999).

3.3 Migration and environmental factors

In this section, we consider how flow and temperature are related to fish migration properties including the rate of fish migration, travel time from release to Lower Granite Dam and arrival date at Lower Granite Dam. Studies by Connor, Berge and Miller (1993, 1994) considered the rate of migration between release of tagged cohorts and their arrival at Lower Granite Dam. Using a multiple linear regression, they suggested that flow was a dominant factor in determining the migration rate of juvenile fall chinook. However, the PIT-tag studies in 1995-1998 did not support a well-defined relationship between migration rate or travel time and environmental variables. The lack of a relationship is illustrated in Figure 8 and Table 4, which shows the travel time vs. flow for the 1995-1998 studies. The relationship is poor within a year, and the slope and intercept of the flow travel time relationship is highly variable between years. Only in the high flow year of 1997 was there a suggestion that increased flow decreased smolt travel time. In other years, flow exhibits little correlation with travel time; from this we conclude that flow is not related to the travel time of the smolts to Lower Granite Dam. The regressions in Tables 9a and 9b also illustrate that travel time is not correlated with temperature or water clarity.

Table 4. Regressions of travel time vs. flow. Travel time = a + b * Flow.

	1995	**1996**	**1997**	**1998**	**Total**
Intercept (a)	67	48	56	37	55
Slope (b)	-0.116	0.010	-0.136	0.009	-0.118
r-squared	0.25	0.004	0.59	0.003	0.21

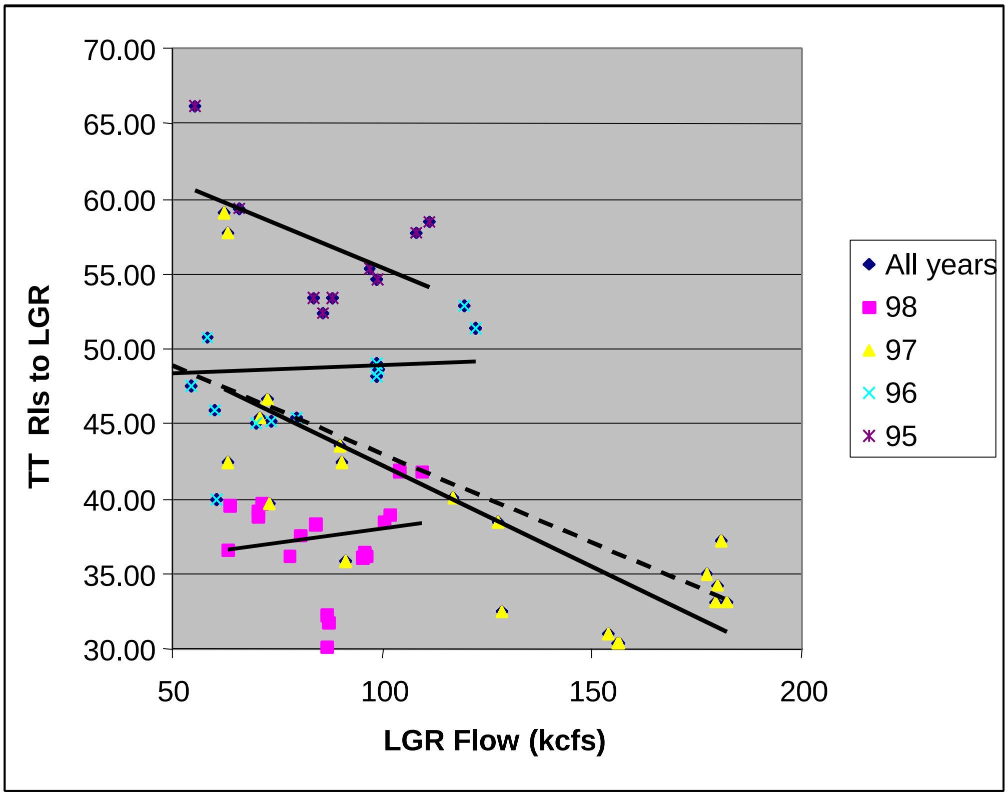

Figure 8. Regressions of flow to travel time of smolts to Lower Granite Dam for each year and for all years (dashed line).

A second measure of smolt migration is the arrival time at Lower Granite Dam. This is a different measure from travel time or migration rate because it involves the date of release in addition to the rate of migration. The arrival time of wild fall chinook smolts to Lower Granite Dam is related to temperature (Peters et al. 1999), the belief being that fish do not begin active migration until they have reached a certain size and they reach the size faster at higher temperatures. Zabel (1999) determined that the arrival time at Lower Granite Dam is linearly related to mean temperature in the first 180 days of the year. The choice of dates over which temperature was averaged was not sensitive to characterizing the temperature- arrival time relationship (Figure 9).

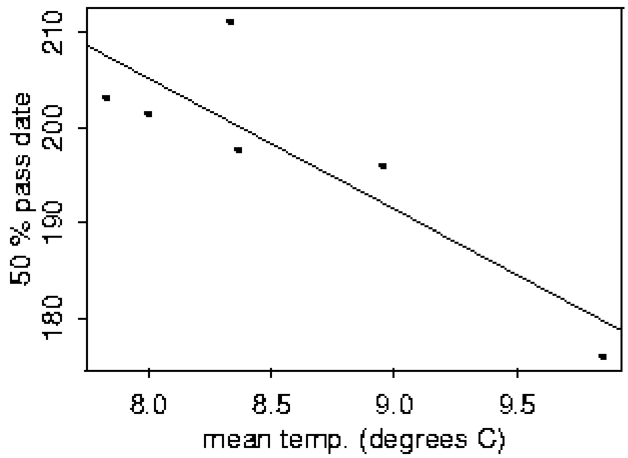

Figure 9. Median passage day of year vs. mean temperature for the years 1992-1997 (from Zabel 1999).

To identify if flow relates to fall chinook arrival timing at Lower Granite Dam, the arrival distribution of Snake River fall chinook was regressed against the average flow in June and July at Lower Granite Dam. Arrival distributions of wild fall chinook were obtained from the Columbia Basin Research — In Season Forecasts webpage at www.cbr.washington.edu/crisprt/index.html. This was supplemented with information from Townsend, Skalski and Yasuda (1996). Flows were obtained from DART www.cbr.washington.edu/dart. The data are given in Table 5 and a regression of arrival date against average flow is shown in Figure 10. The r-squared value is 0.01 and the slope of flow to arrival date is essentially flat. Thus, the results are not sensitive to the selection of dates over which the average flow is defined. This analysis indicates that there is no relationship between average seasonal flow and arrival date.

Table 5. Wild Subyearling Chinook -- Snake River outmigration timing characteristics and flows (kcfs) at Lower Granite Dam.

	----------- Passage Dates ----------					LGR flow
Year	**5%**	**10%**	**50%**	**90%**	**95%**	
1985			07/04			49
1986			06/29			71
1991			07/17			55
1992			06/24			27
1993	06/26	07/01	07/27	09/02	10/25	76
1994	06/23	06/30	07/17	09/03	11/01	39
1995	06/20	06/22	07/23	09/18	10/26	88
1996	06/01	06/06	07/12	08/21	10/31	98
1997	06/09	06/13	07/07	08/14	10/13	118
1998	06/09	06/21	07/09	08/10	10/19	92
1999	06/08	06/11	06/29	08/20	10/16	98

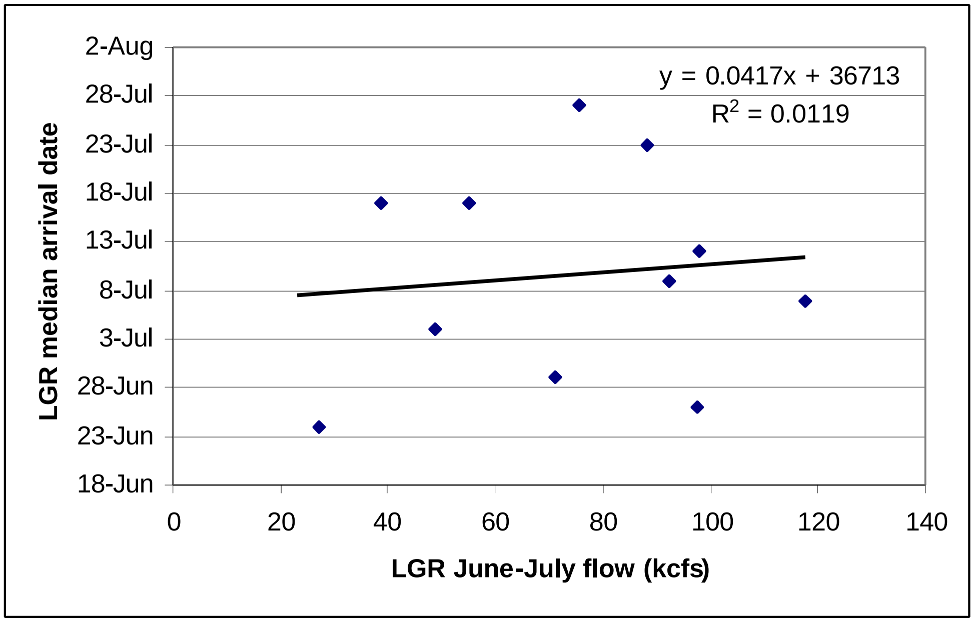

Figure 10. Relationship between Lower Granite Dam June-July average flow and wild fall chinook Lower Granite Dam arrival date.

3.4 Yearly averaged flow survival relationship

Although seasonal variations in survival are evident, a strong seasonal survival relationship with environmental variables does not imply that year-to-year differences in total flow over the outmigration equate to strong year-to-year differences in the survival of the outmigrating population. To explore this, we characterize the yearly average flow survival of juvenile fall chinook in two ways. First, a simple unweighted average of survivals and flows for each year in the 1995-1998 studies was calculated. Second, the individual releases in each year were weighted by the fraction of the total fall chinook outmigration passing Lower Granite Dam at the same time as the average arrival time for each release group. With the available data, we can only define a yearly flow survival relationship based on four data points (Table 6). In particular, in the high flow year 1997, the average survival was no greater than the average survival from the normal flow years of 1995, 1996 and 1998 (Figure 11). This result stands in contrast to the NMFS draft White Paper claim that flow augmentation benefits fish even at high flows: NMFS states, “Benefits of additional flow continue at flows well above those recently observed during a wetter than average hydrologic condition which included the use of stored water to augment flows (NMFS 1999)." The yearly flow survival relationship is not only statistically insignificant, the data indicates that the effect is minuscule. Using the regression in Table 6, a 10 kcfs increase to an 80 kcfs flow would increase survival to Lower Granite Dam from 50% to 50.4%. Our analysis also indicates that yearly average temperature and water clarity exhibits no relationship with yearly average fall chinook survival.

Table 6. Flow survival regression S = a + b * Flow for seasonal data average by unweighted and weighted by smolt passage index. $\Delta S = (S_{80}-S_{70})/S_{80}$ is a relative increase in survival with a 10 kcfs increase in flow where S_{80} and S_{70} are survivals at 80 and 70 kcfs Lower Granite Dam flows.

Type	a	b	R^2	DS
Unweighted	0.39	0.0006	0.014	0.013
Weighted	0.45	0.005	0.048	0.010

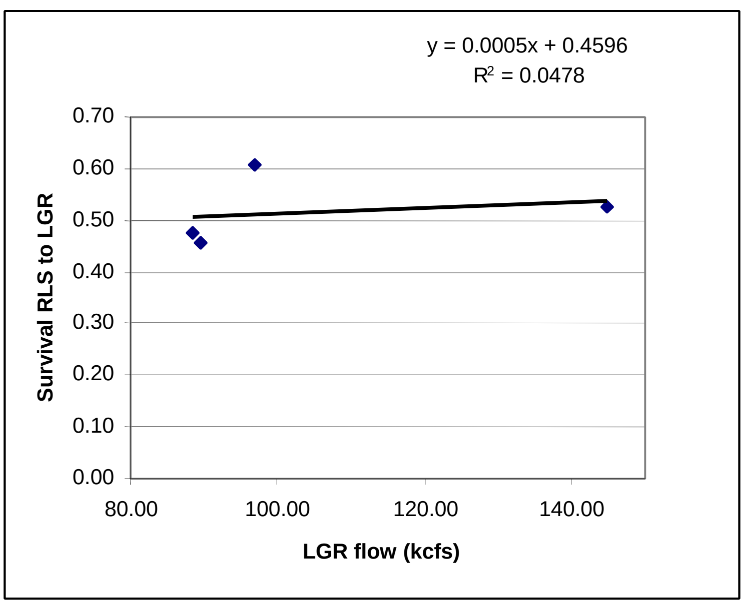

Figure 11. Lower Granite Dam yearly average flow against survival. 1997 flow is at145 kcfs.

3.5 Conclusions from the fall chinook survival studies

Smolt survival to Lower Granite Dam, water temperature, water clarity, and flow exhibit statistically significant linear correlations with smolt release date. Statistically significant correlations between survival and the environmental variables were also found but those relationships were not as significant as the correlation between survival and release date.

Smolt survival and travel time from Lower Granite Dam to Lower Monumental Dam exhibited no consistent year-to-year relationship with flow or other environmental parameters.

Arrival timing of smolts at Lower Granite Dam was related to temperature. Arrival timing had no relationship with flow.

While flow and survival to Lower Granite Dam were related within the year, no relationship exists between years for average flow and survival.

4. Multiple Regressions with PIT-tag Data

4.1 Separating environmental effects

Statistically determining how passage survival relates to environmental variables is essentially impossible because the environmental variables (migration timing, temperature, water clarity, flow, and smolt travel time) are highly correlated with one another. The usual method of determining the statistical effect of each of the environmental variables is to place them in a linear regression as predictor variables (predictors), using survival as the response variable. In the best case, the predictors will not be related to one another, so that each supplies a statistically unique contribution to the regression; this yields useful information about the statistical effect of each predictor on survival. Frequently, however, when analyzing environmental data, the predictors are related in such a way that multiple linear regression results are nonsensical. This is the curse of *collinearity* that often plagues nonexperimental data analysis (Belsley 1991). Collinearity occurs because, *statistically*, the set of predictors contains redundant information. As a result, the model is unable to separate out the unique contribution of each predictor to changes in survival. In other words, the effects are confounded. In a laboratory setting, investigators solve the problem of confounded variables by manipulating the different predictors; usually by varying one predictor while holding the others constant. However, with respect to Snake River flows, it is not feasible to manipulate the temperature, flow, or water clarity regimes in such a way that they are unrelated over time. Flow naturally decreases through the summer coincident with increasing temperatures and increasing water clarity. These natural relationships are difficult (perhaps impossible) to substantially alter by manipulation of the hydrosystem.

4.2 Collinearity

Can collinearity really be detected in multiple regressions of passage survival against the predictors migration timing, temperature, water clarity, flow, and smolt travel time? Absolutely. The telltale signs of collinearity are: high standard errors of the regression coefficients (poor precision) and nonsensical or overly sensitive parameter estimates. To illustrate this, consider the regression of passage survival against flow:

$$survival_i = B0_{year} + B1_{year} * Flow_i + \varepsilon_i$$

where $B0_{year}$ and $B1_{year}$ are year-specific regression coefficients, allowing a different intercept and slope for each individual year (1995-1998), and ε_i is a normal error term to account for the unexplained variations in survival and the real errors in measurements of survival and flow. In Table 7, a single regression, the estimates of the slopes of the flow-survival relationship are precise (much smaller than the estimated effect of flow on survival) and the slope for each year is statistically significant at the 0.05 level (denoted by *). However, when temperature is added to the regression, the flow coefficients become nonsignificant and their standard errors are large (Table 8). This classic case of collinearity occurs because flow and temperature are highly correlated in each year of study (Tables 9a and 9b). The *least* correspondence between flow and temperature is seen in 1996 when the correlation is r = -0.965, close to the perfect (negative) correspondence (r = -1). In each year of study, decreases in flow over the season coincide with increases in temperature. (This does not mean that increasing flow through augmentation, however, will decrease temperature. The effects of augmentation on temperature are discussed below.) Tables 9a and 9b demonstrate that, due to the high correspondence between all of the predictors, collinearity will be a problem regardless of what subset of predictors is chosen. The effects of how migration timing, temperature, water clarity, flow, and smolt travel time relate to survival are impossible to ascertain through multiple regressions. In particular, multiple linear regressions cannot be used to infer the impacts of flow over the migration season.

Table 7. Regressions of passage survival against predictor variables. * indicates significance at the $\alpha = 0.05$ level.

Flow (S =Year + Year×Flow + epsilon)

Parameter	Value	Std. Error	t value	
YEAR95	0.15	0.158	0.93	
YEAR96	-0.20	0.081	-2.47	*
YEAR97	-0.03	0.058	-0.48	
YEAR98	-0.39	0.132	-2.93	*
YEAR95Flow	0.00	0.002	2.69	*
YEAR96Flow	0.01	0.001	7.15	*
YEAR97Flow	0.00	0.000	8.44	*
YEAR98Flow	0.01	0.001	6.31	*

Temperature (S = Year + Year×Temp + epsilon)

	Value	Std. Error	t value	
YEAR95	1.34	0.273	4.90	*
YEAR96	2.25	0.232	9.69	*
YEAR97	1.85	0.156	11.81	*
YEAR98	1.76	0.195	9.02	*
YEAR95Temp	-0.05	0.016	-2.85	*
YEAR96Temp	-0.11	0.013	-8.20	*
YEAR97Temp	-0.09	0.010	-9.10	*
YEAR98Temp	-0.08	0.011	-6.82	*

Table 7 continued on next page

Turbidity (S = Year + Year×Turb + epsilon)

	Value	Std. Error	t value	
YEAR95	1.06	0.175	6.04	*
YEAR96	1.01	0.085	11.87	*
YEAR97	0.87	0.051	17.16	*
YEAR98	1.56	0.175	8.90	*
YEAR95Turb	-0.14	0.048	-2.86	*
YEAR96Turb	-0.19	0.024	-8.01	*
YEAR97Turb	-0.22	0.023	-9.27	*
YEAR98Turb	-0.37	0.057	-6.46	*

Travel time (S = Year + Year×TT + epsilon)

	Value	Std. Error	t value	
YEAR95	1.26	0.749	1.68	
YEAR96	0.84	0.490	1.72	
YEAR97	1.20	0.179	6.68	*
YEAR98	0.53	0.426	1.24	
YEAR95TT	-0.01	0.013	-0.93	
YEAR96TT	-0.01	0.010	-1.00	
YEAR97TT	-0.02	0.004	-4.35	*
YEAR98TT	0.00	0.011	-0.22	

Release Day (S = Year + Year×Rls + epsilon)

	Value	Std. Error	t value	
YEAR95	1.84	0.390	4.71	*
YEAR96	3.29	0.329	10.02	*
YEAR97	2.74	0.224	12.24	*
YEAR98	2.37	0.258	9.19	*

Table 8. Regressions of passage survival against two predictor variables. * indicates significance at the α = 0.05 level.

Flow and Temperature (S =Year + Year×Flow + Year×Temp + epsilon)

Parameter	Value	Std. Error	t value	
YEAR95	-0.4582	3.632	-0.13	
YEAR96	3.1624	1.167	2.71	*
YEAR97	1.0539	1.566	0.67	
YEAR98	0.8888	1.373	0.65	
YEAR95Flow	0.0071	0.014	0.50	
YEAR96Flow	-0.0029	0.004	-0.80	
YEAR97Flow	0.0016	0.003	0.51	
YEAR98Flow	0.0039	0.006	0.64	
YEAR95Temp	0.0231	0.139	0.17	
YEAR96Temp	-0.1504	0.052	-2.89	*
YEAR97Temp	-0.0501	0.072	-0.69	
YEAR98Temp	-0.0450	0.048	-0.93	

Flow and Turbidity (S =Year + Year×Flow + Year×Turb + epsilon)

Parameter	Value	Std. Error	t value	
YEAR95	0.4886	1.868	0.26	
YEAR96	1.8588	0.736	2.53	*
YEAR97	0.5286	0.199	2.65	*
YEAR98	-0.4991	1.064	-0.47	
YEAR95Flow	0.0030	0.010	0.31	
YEAR96Flow	-0.0052	0.004	-1.16	
YEAR97Flow	0.0016	0.001	1.75	
YEAR98Flow	0.0100	0.005	1.96	*
YEAR95Turb	-0.0519	0.283	-0.18	
YEAR96Turb	-0.3171	0.113	-2.81	*
YEAR97Turb	-0.1404	0.048	-2.90	*
YEAR98Turb	0.0221	0.207	0.11	

Table 8 continued on next page

Table 8 (continued)

Flow and Travel Time (S =Year + Year×Flow + Year×TT + epsilon)

Parameter	Value	Std. Error	t value	
YEAR95	0.3233	0.577	0.56	
YEAR96	0.4046	0.273	1.48	
YEAR97	0.3272	0.220	1.49	
YEAR98	-0.0500	0.248	-0.20	
YEAR95Flow	0.0044	0.002	2.30	*
YEAR96Flow	0.0072	0.001	7.71	*
YEAR97Flow	0.0030	0.001	4.41	*
YEAR98Flow	0.0098	0.001	6.86	*
YEAR95TT	-0.0026	0.008	-0.32	
YEAR96TT	-0.0127	0.005	-2.30	*
YEAR97TT	-0.0064	0.004	-1.67	
YEAR98TT	-0.0099	0.006	-1.57	

Flow and Rls (S =Year + Year×Flow + Year×Rls + epsilon)

Parameter	Value	Std. Error	t value	
YEAR95	3.5582	3.439	1.03	
YEAR96	4.4928	1.462	3.07	*
YEAR97	4.9981	1.561	3.20	*
YEAR98	3.7902	3.033	1.25	
YEAR95Flow	-0.0050	0.010	-0.50	
YEAR96Flow	-0.0027	0.003	-0.84	
YEAR97Flow	-0.0033	0.002	-1.46	
YEAR98Flow	-0.0049	0.011	-0.47	
YEAR95Rls	-0.0156	0.016	-0.99	
YEAR96Rls	-0.0227	0.007	-3.21	*
YEAR97Rls	-0.0248	0.008	-3.22	*
YEAR98Rls	-0.0175	0.013	-1.38	

Table 9a. Correlations between predictors.

1995

	S	TT	Rls	Flow	Temp	Turb
S	1.000	-0.556	-0.963	0.929	-0.916	-0.926
TT	-0.556	1.000	0.480	-0.503	0.559	0.408
Rls	-0.963	0.480	1.000	-0.988	0.972	0.987
Flow	0.929	-0.503	-0.988	1.000	-0.993	-0.987
Temp	-0.916	0.559	0.972	-0.993	1.000	0.976
Turb	-0.926	0.408	0.987	-0.987	0.976	1.000

1996

	S	TT	Rls	Flow	Temp	Turb
S	1.000	-0.219	-0.961	0.901	-0.960	-0.947
TT	-0.219	1.000	0.170	0.061	0.114	0.060
Rls	-0.961	0.170	1.000	-0.963	0.981	0.980
Flow	0.901	0.061	-0.963	1.000	-0.965	-0.980
Temp	-0.960	0.114	0.981	-0.965	1.000	0.995
Turb	-0.947	0.060	0.980	-0.980	0.995	1.000

1997

	S	TT	Rls	Flow	Temp	Turb
S	1.000	-0.767	-0.898	0.862	-0.863	-0.888
TT	-0.767	1.000	0.791	-0.771	0.755	0.825
Rls	-0.898	0.791	1.000	-0.985	0.991	0.928
Flow	0.862	-0.771	-0.985	1.000	-0.991	-0.887
Temp	-0.863	0.755	0.991	-0.991	1.000	0.898
Turb	-0.888	0.825	0.928	-0.887	0.898	1.000

1998

	S	TT	Rls	Flow	Temp	Turb
S	1.000	-0.050	-0.855	0.842	-0.847	-0.809
TT	-0.050	1.000	-0.123	0.172	0.040	-0.034
Rls	-0.855	-0.123	1.000	-0.993	0.971	0.977
Flow	0.842	0.172	-0.993	1.000	-0.972	-0.964
Temp	-0.847	0.040	0.971	-0.972	1.000	0.971
Turb	-0.809	-0.034	0.977	-0.964	0.971	1.000

Table 9b. R-squared of correlation between predictors.

1995

	S	TT	Rls	Flow	Temp	Turb
S	1.000	0.309	0.927	0.863	0.839	0.857
TT	0.309	1.000	0.231	0.253	0.313	0.166
Rls	0.927	0.231	1.000	0.977	0.946	0.975
Flow	0.863	0.253	0.977	1.000	0.986	0.973
Temp	0.839	0.313	0.946	0.986	1.000	0.953
Turb	0.857	0.166	0.975	0.973	0.953	1.000

1996

	S	TT	Rls	Flow	Temp	Turb
S	1.000	0.048	0.923	0.812	0.922	0.896
TT	0.048	1.000	0.029	0.004	0.013	0.004
Rls	0.923	0.029	1.000	0.927	0.962	0.960
Flow	0.812	0.004	0.927	1.000	0.930	0.960
Temp	0.922	0.013	0.962	0.930	1.000	0.991
Turb	0.896	0.004	0.960	0.960	0.991	1.000

1997

	S	TT	Rls	Flow	Temp	Turb
S	1.000	0.588	0.806	0.743	0.745	0.788
TT	0.588	1.000	0.626	0.595	0.570	0.681
Rls	0.806	0.626	1.000	0.970	0.983	0.862
Flow	0.743	0.595	0.970	1.000	0.982	0.787
Temp	0.745	0.570	0.983	0.982	1.000	0.806
Turb	0.788	0.681	0.862	0.787	0.806	1.000

1998

	S	TT	Rls	Flow	Temp	Turb
S	1.000	0.003	0.732	0.710	0.717	0.654
TT	0.003	1.000	0.015	0.030	0.002	0.001
Rls	0.732	0.015	1.000	0.985	0.942	0.954
Flow	0.710	0.030	0.985	1.000	0.945	0.929
Temp	0.717	0.002	0.942	0.945	1.000	0.943
Turb	0.654	0.001	0.954	0.929	0.943	1.000

4.3 Model selection

Despite the difficulties of collinearity in the multiple regression analysis, we can determine what single predictor or group of predictors provides the best fit to the passage survival data. We examined models defined by all possible combinations of five predictor variables: single predictors (5 models), two predictors (10 models), three predictors (10 models), four predictors (5 models), all five predictors (1 model) and no predictors (1 model), for a total of 32 different models. For fit criteria, we used the standard AIC and BIC goodness-of-fit criteria which weigh the better fit provided by an additional predictor variable against a penalty for its inclusion. The AIC and BIC scores provide measures for selecting a "best" model; that is, a model that best explains the variance in survival (a good fit with the response variable), without over-parameterizing (Akaike 1973, Schwarz 1978).

Mathematically, these criteria are described by

$$AIC = -2 * \log(Likelihood) + 2 * p$$

$$BIC = -2 * \log(Likelihood) + \log(n) * p$$

where Likelihood is the likelihood function (evaluated at the maximum likelihood estimates), n is the number of observations, and p is the number of parameters. For both of these criteria, lower numbers imply better fit. The BIC penalizes the addition of parameters more heavily than the AIC criteria, as evidenced by the BIC's penalty term $\log(n) * p$ which is larger than the AIC's penalty term of $2 * p$ when $n>8$.

Based on the AIC criteria, the best of the 32 models examined contains migration timing, as quantified by day of release (Rls), and water temperature (Temp). No other predictor variables, including flow, were needed to explain the survival (Table 10a). This model however, shows minuscule improvement in AIC over the model that contains migration timing (Rls) alone. The best model in terms of BIC contains only migration timing (Rls) (Table 10b). The parameter estimates and r^2 values for these two models are contained in Tables 11a and 11b. The model that contains both migration timing and temperature (the best based on AIC) is plagued by collinearity because these predictors are highly correlated (r>0.97 for each year, Table 9). For this model, therefore, the estimated effects of temperature (Temp) and migration timing (Rls) are generally imprecise and at times nonsensical (Table 11). Most of the slope coefficients are not significant. For this reason, on a statistical basis, the regression model that contains migration timing alone (the one selected by the BIC) is preferable because it has a good fit to the data (the best based on BIC), its parameters are estimated with high precision, and the parameter estimates are all statistically significant.

Notice that migration timing (Rls), temperature (Temp), and turbidity (Turb = water clarity) are each superior to flow (Flow) as predictor variables. Only travel time (TT) is a worse predictor than flow. Based on these results, flow would not be selected as a predictor in the multiple regressions because using migration timing alone, or a combination of migration timing and temperature, provides a superior fit to the survival data.

Table 10a. Models ordered by AIC, with larger negative AIC indicating better fit.

Covariates Included	**n**	**p**	**ss**	**aic**	**bic**	**r^2**	**Rank**
Temp+Rls	62	12	0.29	-132.8	-107.3	0.98	1
Rls	62	8	0.33	-132.6	-115.6	0.98	2
Temp+Turb+Rls	62	16	0.26	-130.5	-96.5	0.98	3
Turb+Rls	62	12	0.30	-129.8	-104.3	0.98	4
TT+Rls	62	12	0.31	-128.7	-103.2	0.98	5
Flow+Rls	62	12	0.31	-128.6	-103.1	0.98	6
Temp+TT+Rls	62	16	0.27	-128.5	-94.4	0.98	7
Turb+TT+Rls	62	16	0.27	-128.1	-94.0	0.98	8
Flow+Temp+Rls	62	16	0.27	-128.1	-94.0	0.98	9
Temp+Turb+TT+Rls	62	17	0.27	-126.5	-90.3	0.98	10
Flow+Turb+Rls	62	16	0.28	-125.9	-91.8	0.98	11
Flow+Temp+Turb+Rls	62	17	0.28	-125.0	-88.9	0.98	12
Flow+TT+Rls	62	16	0.29	-124.3	-90.3	0.98	13
Temp+Turb	62	12	0.33	-124.1	-98.6	0.98	14
Flow+Turb+TT+Rls	62	17	0.29	-123.1	-87.0	0.98	15
Flow+Temp+TT+Rls	62	17	0.29	-122.5	-86.3	0.98	16
Flow+Temp+Turb+TT+Rls	62	21	0.26	-122.2	-77.5	0.98	17
Flow+Turb	62	12	0.34	-122.1	-96.6	0.98	18
Temp	62	8	0.39	-121.7	-104.7	0.97	19
Flow+Turb+TT	62	16	0.31	-120.9	-86.9	0.98	20
Turb	62	8	0.40	-120.6	-103.5	0.97	21
Flow+Temp+Turb+TT	62	17	0.31	-119.2	-83.0	0.98	22
Temp+TT	62	12	0.36	-118.9	-93.4	0.97	23
Flow+Temp+Turb	62	16	0.32	-118.0	-84.0	0.98	24
Temp+Turb+TT	62	16	0.32	-117.9	-83.9	0.98	25
Flow+TT	62	12	0.38	-116.6	-91.1	0.97	26
Turb+TT	62	12	0.38	-116.2	-90.6	0.97	27
Flow+Temp+TT	62	16	0.33	-116.0	-81.9	0.98	28
Flow+Temp	62	12	0.38	-115.6	-90.1	0.97	29
Flow	62	8	0.46	-112.6	-95.6	0.97	30
TT	62	8	1.36	-44.8	-27.8	0.90	31
Year Effect Only	62	4	1.89	-32.6	-24.0	0.86	32

Table 10b. Models ordered by BIC, with larger negative BIC indicating better fit.

Covariates Included	n	p	ss	aic	bic	r^2	Rank
Rls	62	8	0.33	-132.6	-115.6	0.98	1
Temp+Rls	62	12	0.29	-132.8	-107.3	0.98	2
Temp	62	8	0.39	-121.7	-104.7	0.97	3
Turb+Rls	62	12	0.30	-129.8	-104.3	0.98	4
Turb	62	8	0.40	-120.6	-103.5	0.97	5
TT+Rls	62	12	0.31	-128.7	-103.2	0.98	6
Flow+Rls	62	12	0.31	-128.6	-103.1	0.98	7
Temp+Turb	62	12	0.33	-124.1	-98.6	0.98	8
Flow+Turb	62	12	0.34	-122.1	-96.6	0.98	9
Temp+Turb+Rls	62	16	0.26	-130.5	-96.5	0.98	10
Flow	62	8	0.46	-112.6	-95.6	0.97	11
Temp+TT+Rls	62	16	0.27	-128.5	-94.4	0.98	12
Turb+TT+Rls	62	16	0.27	-128.1	-94.0	0.98	13
Flow+Temp+Rls	62	16	0.27	-128.1	-94.0	0.98	14
Temp+TT	62	12	0.36	-118.9	-93.4	0.97	15
Flow+Turb+Rls	62	16	0.28	-125.9	-91.8	0.98	16
Flow+TT	62	12	0.38	-116.6	-91.1	0.97	17
Turb+TT	62	12	0.38	-116.2	-90.6	0.97	18
Temp+Turb+TT+Rls	62	17	0.27	-126.5	-90.3	0.98	19
Flow+TT+Rls	62	16	0.29	-124.3	-90.3	0.98	20
Flow+Temp	62	12	0.38	-115.6	-90.1	0.97	21
Flow+Temp+Turb+Rls	62	17	0.28	-125.0	-88.9	0.98	22
Flow+Turb+TT+Rls	62	17	0.29	-123.1	-87.0	0.98	23
Flow+Turb+TT	62	16	0.31	-120.9	-86.9	0.98	24
Flow+Temp+TT+Rls	62	17	0.29	-122.5	-86.3	0.98	25
Flow+Temp+Turb	62	16	0.32	-118.0	-84.0	0.98	26
Temp+Turb+TT	62	16	0.32	-117.9	-83.9	0.98	27
Flow+Temp+Turb+TT	62	17	0.31	-119.2	-83.0	0.98	28
Flow+Temp+TT	62	16	0.33	-116.0	-81.9	0.98	29
Flow+Temp+Turb+TT+Rls	62	21	0.26	-122.2	-77.5	0.98	30
TT	62	8	1.36	-44.8	-27.8	0.90	31
Year Effect Only	62	4	1.89	-32.6	-24.0	0.86	32

Table 11a. Survival dependent on migration timing only.

Parameter	Value	Std. Error	t value	
YEAR95	1.839	0.390	4.71	*
YEAR96	3.293	0.329	10.02	*
YEAR97	2.737	0.224	12.24	*
YEAR98	2.373	0.258	9.19	*
YEAR95Rls	-0.008	0.002	-3.27	*
YEAR96Rls	-0.017	0.002	-8.96	*
YEAR97Rls	-0.014	0.001	-10.33	*
YEAR98Rls	-0.012	0.002	-7.53	*

R^2=0.976
** Indicates significance at the 0.05 level*

Table 11b. Survival model including Rls and temperature.

Parameter	Value	Std. Error	t value	
YEAR95	2.002	0.660	3.03	*
YEAR96	2.817	0.638	4.41	*
YEAR97	4.161	0.625	6.66	*
YEAR98	2.193	0.384	5.72	*
YEAR95Rls	-0.011	0.010	-1.08	
YEAR96Rls	-0.009	0.009	-0.94	
YEAR97Rls	-0.037	0.010	-3.80	*
YEAR98Rls	-0.008	0.006	-1.26	
YEAR95Temp	0.018	0.060	0.30	
YEAR96Temp	-0.053	0.062	-0.86	
YEAR97Temp	0.157	0.065	2.43	*
YEAR98Temp	-0.025	0.041	-0.62	

R^2=0.979
** Indicates significance at the 0.05 level*

4.4 Conclusions of multiple regression analysis

1) Due to high correlations between variables, it is impossible to statistically separate the effects of migration timing, temperature, water clarity, flow, and travel time on passage survival using the fall chinook PIT-tag survival data (1995-1998). Thus, the actual effect of flow on survival cannot be estimated reliably.

2) The models providing the best fit to the survival data are (1) the model containing migration timing alone and (2) the model containing migration timing and temperature. However, model (2) is plagued by collinearity and the estimated effects of migration timing and temperature are imprecisely estimated. As predictors of survival, migration timing, temperature, and water clarity are superior to flow. This conclusion is based on examining 32 possible models, defined by all possible combinations of the predictor variables.

3) The multiple regression analysis indicates that statistical correlations of survival with seasonal flow are insufficient to infer the impacts of flow on survival. Furthermore, inferences on the impacts of flow *augmentation* on survival are even more problematic. Therefore, to evaluate the impacts of flow augmentation we must take a mechanistic approach that includes the ecological principles on how flow augmentation may affect smolt survival.

5. Effects of Flow Augmentation

To evaluate the impacts of flow augmentation, we need to consider the nature of the source of the flow and its impacts on environmental parameters. It is not enough to infer that seasonal relationships between flow and survival, with or without collinearity, can be simply extrapolated to the effects of flow augmentation. The impact of flow augmentation on river conditions depends on the source of the augmentation and the time of the year. The Snake River system has two augmentation sources, Dworshak Reservoir on the Clearwater River and Brownlee Reservoir Dam on the Snake River. Giorgi et al. (1997) evaluated the impacts of augmentation in the period 1991 through

1995 and concluded that augmentation for fall chinook occurred in July and August from both Dworshak and Hells Canyon. Seasonal water released from the storage reservoirs in the Snake basin increased from 1.35 million-acre-feet (maf) in 1992 to a high of 2.65 maf in 1994. In the Upper Snake River, the 427 kaf target for augmentation was satisfied in all years if augmentation in September is included.

To disentangle the relationship between flow augmentation and fall chinook survival, we need to consider the direct and indirect impacts of seasonal and augmented flows on chinook survival (Figure 12). In particular, we need to consider the impacts of augmentation on the juvenile fall chinook prior to their arrival at Lower Granite Dam. Survival of smolts in the reaches above Lower Granite Dam primarily depends on the amount of predation by smallmouth bass, walleye and northern pikeminnows (Zimmerman 1999). This predator-prey interaction depends on the travel time (TT) of the smolts out of the habitat, the predator reaction distance (RD), which is the distance at which a predator can see and attack a smolt, and the metabolism of the predator (M). In turn, the travel time may depend on the water velocity and the behavior of the fish to the velocity, which changes as fish grow (G). Reaction distance depends on visibility as characterized by water clarity, and the frequency of predation attacks depends on the predator metabolism, which increases with water temperature. The only direct effect of seasonal and augmentation flows is through water velocity, which may affect smolt travel time. The effects of seasonal and augmented flows on water temperature and visibility may indirectly affect smolt survival. Each of the direct and indirect effects of seasonal and augmented flows must be considered. It is not sufficient to simply infer the effects of seasonal flow from correlations while ignoring the ecological mechanisms.

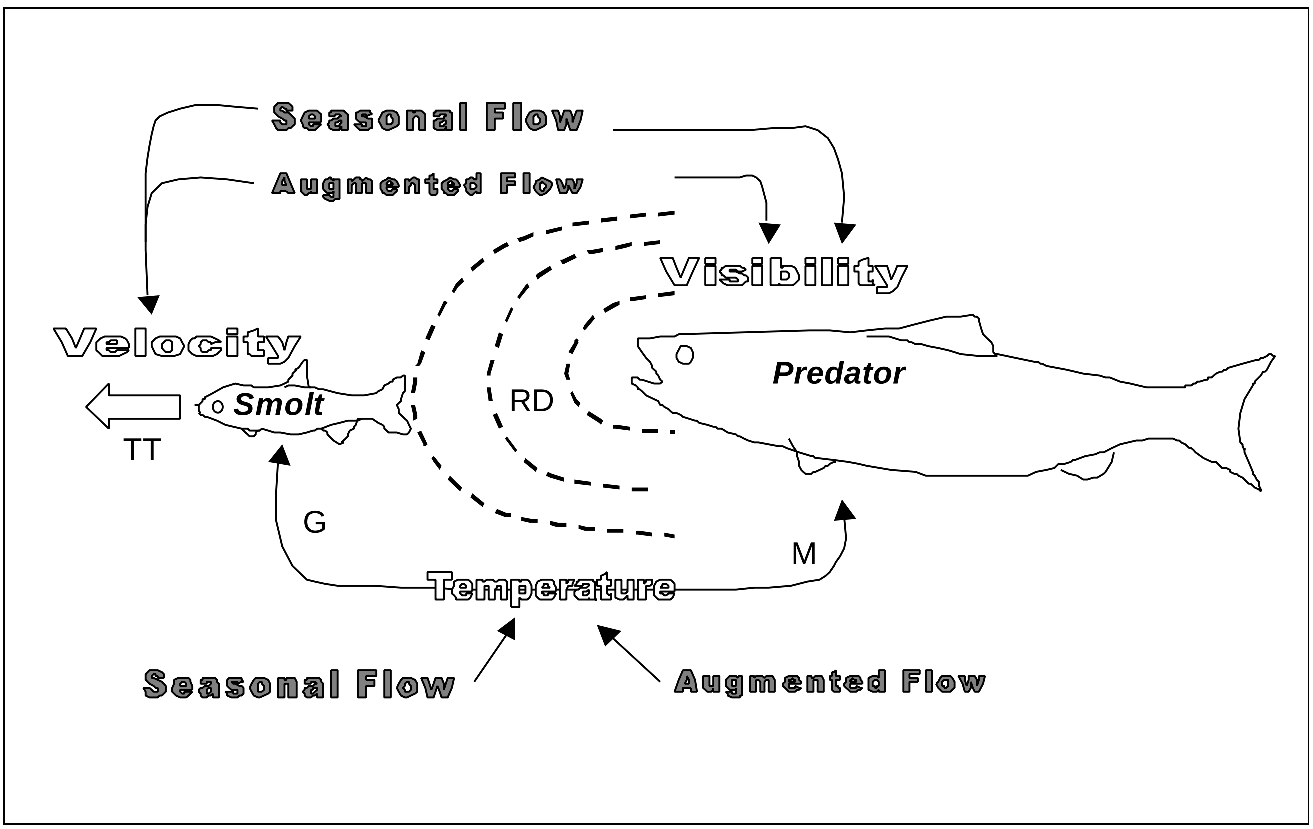
Seasonal Flow
Augmented Flow
Visibility
Velocity
Smolt
RD
Predator
TT
G
M
Temperature
Seasonal Flow
Augmented Flow

Figure 12. Conceptual diagram illustrating direct and indirect effects of seasonal and augmentation flows on smolt survival.

Figure 12 also characterizes the movement and survival of smolts through the hydrosystem including specific mortality effects of the dams. For subyearling migration in the summer, the main impact of the dams is direct mortality in dam passage. Since total dissolved gas levels are low in the summer, the effects of gas supersaturation from planned or forced spill do not need to be considered.

5.1 Flow augmentation and temperature

A number of studies have demonstrated that augmentation from Hells Canyon does not have an appreciable effect on downstream temperatures, while augmentation from Dworshak does (Bennett, Karr and Madsen 1994; Giorgi et al.,1997; Connor, Garcia, Burge and Taylor 1993;Connor, Bjornn, Burge, Garcia and Rondorf. 1997). To evaluate the impacts on temperature from augmentation, Giorgi et al. (1997) correlated temperature data with augmentation flows at Anatone gage on the Snake River, 76 km downstream of Hells Canyon Dam, at Peck gage 23 km downstream of the Dworshak Dam, and at the Lower Granite Dam. Temperatures during a base line period between 1981-1990 were compared to the temperatures during the augmentation period 1991-1995. The impacts of augmentation on temperature were determined by comparing the difference in the baseline and augmentation temperatures to the augmentation flows. Two regression approaches demonstrated that Dworshak Reservoir augmentation affected temperatures, while the Hells Canyon augmentation had little or no effect on temperature in the Snake River.

This difference in the effect of augmentation in the Clearwater and Snake systems reflects the difference in the storage water temperatures relative to the unregulated stream temperatures. Flow in the Snake River comes from Brownlee Reservoir through the Hells Canyon complex, which represents about 50 to 70% of the water flowing through the lower Snake River above the confluence of the Clearwater (Connor et al. 1993). The remaining contributions come from the Salmon, the Imnaha and the Grande Ronde Rivers. The temperatures of these rivers are similar to each other and the mainstem; thus, flow augmentation from Hells Canyon affects flow but not temperature. The temperature in Hells Canyon is influenced by the air temperature 14 to 30 days prior to flow release from the reservoirs (Connor et al. 1993). In contrast, augmentation from Dworshak Reservoir is with reservoir water that is about 10^{o}C, while the other branches of the Clearwater are on the order of 5 to 10^{o} C warmer. Therefore, augmentation from Dworshak Reservoir has an impact on the Clearwater at the confluence of the Snake and Clearwater Rivers and is evident down to Lower Granite Dam. The characteristic summer temperature distribution in the Snake River system above Lower Granite Dam is illustrated in Figure 13.

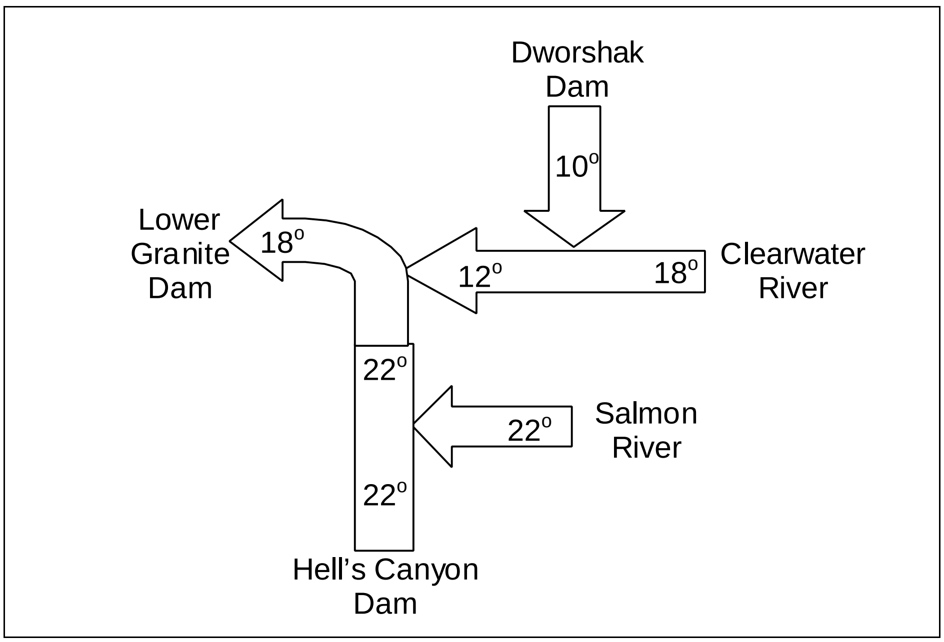

Figure 13. Summer temperatures of normal flows of the Snake River system.

5.2 Flow augmentation and water clarity

The impact of flow augmentation on water visibility has not been evaluated but the mechanisms again depend on the water clarity of the storage reservoirs relative to the clarity of the unregulated streams. Water transparency, or clarity, is measured by the Secchi depth. (Note this measure has been misnamed in the NMFS reports as Turbidity, which moves inversely to water clarity, so that turbidity is higher when water clarity is lower.) A regression of the Secchi depth against seasonal flow has a linear relationship, with visibility decreasing as flow increases. Secchi depth is related to the predator-prey reaction distance. The larger the Secchi reading, the further away the predator can detect a smolt. The Secchi depth and the predator-prey reaction distance both decrease as the concentration of suspended material in the water increases. In turn, the suspended material depends on water velocity and flow, giving a mechanistic basis for the observed seasonal relationship between clarity and flow. The effect of Hells Canyon flow augmentation on water clarity depends on the difference in the clarity of the storage reservoir augmentation flow relative to the clarity of the unregulated stream flows, including the Imnaha, Salmon and Grande Ronde Rivers. If the clarity of water from the storage reservoirs is greater than unregulated streams, because suspended material has settled in the reservoirs, then the augmentation would be expected to increase water clarity, which could increase the rate of predation on smolt.

5.3 Flow augmentation and water velocity

Flow augmentation has been typically applied in the spring and summer to address migration of the yearling and the subyearling chinook. In the 1991-1995 period, spring augmentation increased velocities through Lower Granite Pool an average of 3 to 13% (Giorgi et al. 1997). During the summer, augmentation from Dworshak and Brownlee combined contributed between 5 and 38% of the velocity at Lower Granite Dam. Of this total, the Brownlee can contribute only about one quarter of the flow.

5.4 Flow augmentation and fish travel time

The direct impact of flow on fish survival could be through its impact on travel time of fish from release to Lower Granite Dam. In turn, the seasonal relationship between flow and travel time could be representative of the impacts of flow augmentation. However, flow has no discernable impact on fish travel time (Figure 8). Therefore, flow augmentation would have no impact on fish travel time.

5.5 Conclusions on the effects of flow augmentation

Flow augmentation may affect smolt survival directly through the change in water velocity and indirectly through the changes in temperature and water clarity.

Upper Snake River flow augmentation does not appreciably affect water temperature through the Hells Canyon reach or in Lower Granite Pool. Augmentation from Dworshak lowers the temperature in Lower Granite Pool.

The impact of flow augmentation on water clarity has not been resolved. However, augmentation could increase water clarity, which would increase smolt predation.

Flow augmentation has no discernable impact on fish travel time to Lower Granite Dam or through the hydrosystem.

6. Model Analysis of Flow Augmentation

To further explore the complex effects of flow augmentation in the presence of seasonally changing flows and temperatures we have used the CRiSP smolt passage model. This model simulates the daily movement and survival of fish through the Columbia River system and is based on ecological relationships describing smolt migration and survival. The model describes survival in terms of temperature and travel time of smolt and can characterize the direct and indirect effects of flow on survival. The calibrated model can be used to simulate the individual impact of flow augmentation from the Hells Canyon (Brownlee) and Dworshak storage reservoirs.

6.1 CRiSP description

CRiSP follows the mortality dynamics illustrated in Figure 12, where the activity of predators depends on temperature while the exposure of smolts to predators depends on the smolt travel time (Anderson et al. 1996; Anderson et al. 2000). The model characterizes flow temperature relationships in terms of releases from storage reservoirs and unregulated streams as is illustrated in Figure 13. Flow acts directly on fish travel time using the migration model developed by Zabel and Anderson (1997) and

Zabel et al. (1998). Flow acts indirectly on fish via the relationship of flow and temperature from storage reservoirs and the unregulated streams. The model does not consider water clarity. For fall chinook the equation describing smolt survival, S, takes the form

$$S = \exp\left(g(\mathrm{Temp}) * TT(\mathrm{flow, release\ date}) \right)$$

where g is a function of the daily temperature (Temp), TT is fish travel time and is a function of daily flow and the release date of the fish. Note also that temperature is related to flow and day of year.

Travel time between release and arrival at Lower Granite Dam in CRiSP was calibrated with the fall chinook PIT-tag studies discussed in Section (3). For survival of fall chinook through the hydrosystem, CRiSP was calibrated as part of the PATH analysis (Peters, Marmorek and Parnell eds. 1999). In the calibration (Anderson et al. 2000), a nonlinear calibration technique is used in an iterative fashion; first calibrating travel time using flow and smolt date of release and an approximate survival rate. Next, the survival is calibrated using calibrated travel time parameters and temperature. In the second round, the calibrated survival is used in place of the approximated survival and travel time is recalibrated. This in turn is used to recalibrate survival. The calibration between travel time and survival is repeated until the results converge. This iterative process is required because the arrival time distribution of smolts at Lower Granite Dam can be skewed by the mortality rate and the mortality rate, in turn, depends on travel time.

Since the CRiSP model was calibrated with the same data used in the multiple correlation analysis of Section 4, it suffers from problems of collinearity among environmental variables. The model equations explicitly make temperature a primary factor affecting survival and make flow a secondary factor, similar to that found with the multiple linear regression analysis. The CRiSP model provides information about fall chinook and flow augmentation that cannot be obtained from the multiple linear regressions. First, the basic equation above is a better representation of the underlying ecological processes than the multiple linear descriptions of survival against environmental variables. Second, because CRiSP represents the river geometry and the daily variations of flow and temperature, it can be used to evaluate the individual contributions of flow augmentation from the Dworshak and Hells Canyon (Brownlee) storage reservoirs as the hydrosystem operations change.

6.2 Flow augmentation estimates

To explore the impacts of flow augmentation from each storage reservoir and the combination of reservoirs, a matrix of impacts was evaluated in which augmentation was removed, doubled or left unchanged for each reservoir (Table 12). For each scenario, the CRiSP model was run under the calibration conditions for 1995 through 1998 using the actual release locations and dates of the PIT-tag fish discussed in Section 3. In each run, survival for each PIT tag release was determined to Lower Granite Dam and from Lower Granite Dam to Bonneville Dam. In addition, the average Lower Granite Dam flow and temperature during the migration were simulated in each augmentation scenario.

Table 12. Flow augmentation scenarios run with CRiSP. 1 = existing flow augmentation, 0 = no flow augmentation, 2 = doubling flow augmentation.

Scenario	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Brownlee	1	0	0	0	1	2	2
Dworshak	1	0	1	2	0	0	2

The scenarios with existing flow augmentations used the observed daily flows and temperatures from the Dworshak and Hells Canyon (Brownlee) Reservoirs. To represent zero augmentation from the Dworshak Reservoir, flows during the fall outmigration were removed (Compare Figure 14 with Dworshak flow augmentation to Figure 15, which is Dworshak flow without augmentation). For the doubling scenarios, the observed Dworshak flows were increased by a factor of two. For Hells Canyon

(Brownlee) augmentation scenarios, the estimated augmentation obtained from the Idaho Department of Water Resources, were subtracted from observed Hells Canyon Dam flows to represent the no flow augmentation scenarios and the estimated augmentations were added to the observed dam flows to represent the flow doubling scenarios. Note that the zero and double augmentation scenarios are not necessarily hydraulically possible. They were used in this analysis to explore the sensitivity of fish survival to the individual flow augmentation scenarios. The total yearly estimated flow augmentation volumes provided by the Idaho Department of Water Resources are given in Table 13.

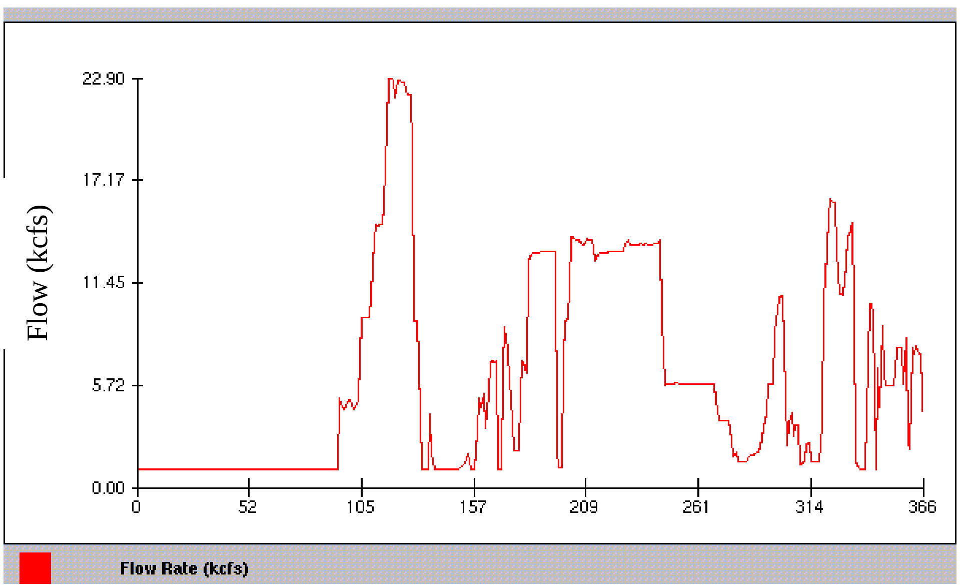

Figure 14. 1995 Dworshak flow vs. day of year with augmentation.

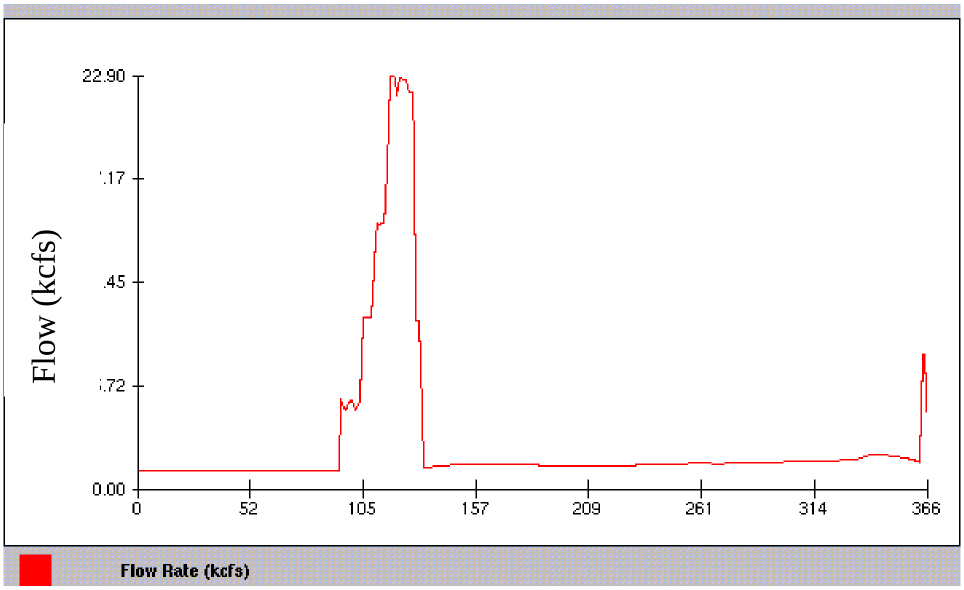

Figure 15. 1995 Dworshak flow vs. day of year without augmentation.

Table 13. Yearly flow augmentation estimate (maf). Data source: Idaho Department of Water Resources.

Reservoir	1995	1996	1997	1998
Hells Canyon (Brownlee)	0.52	0.68	0.65	0.77
Dworshak	1.40	1.87	1.64	1.25

6.3 Augmentation effects on survival and environmental variables

To explore the individual contribution of augmentation from each reservoir, the percent change in survival to Lower Granite and Bonneville Dams was defined relative to the base conditions with the actual flows in the years 1995-1998. The relative measure of survival change is defined

$$\Delta S = 100 * (S_1 - S_i)/S_1$$

where S_1 is survival from release to arrival at a dam from a particular release site under existing conditions (Scenario 1), and S_i is survival with an addition or deletion of flow augmentation from a particular reservoir or combinations of reservoirs (Scenario I).

The relative effects of augmentation on survival to Lower Granite and Bonneville Dams are given in Tables 14 and 15 for flow augmentation scenarios 1-7. Relative survival, ΔS, and absolute survival, S, are given for each release site averaged over the four years. A comparison of Scenario 1 to 3 in Table 14 illustrates that removing augmentation from Hells Canyon (Brownlee) increases survival. This is because the Brownlee augmentation increases water temperature, which is a major factor in determining survival in the CRiSP model.

Table 15a shows the models predictions of average changes in flow and temperature at Lower Granite Dam over the fall chinook migration season with the seven flow augmentation scenarios. Table 15b shows the difference in flow, temperature and maf for each Scenario relative to the base condition, Scenario 1. Removing the Hells Canyon (Brownlee) augmentation decreases the flow by about 5 kcfs and lowers the temperature about 0.1 ^{o}C.

Table 14. Relative change in average Snake River fall chinook survival to Lower Granite and Bonneville Dams, ΔS (%), and average in-river survival, S (%), under different flow augmentation scenarios. Averages are over years 1995-1998.

Scenario	1	2	3	4	5	6	7
Aug. Brownlee	1	0	0	0	1	2	2
Aug. Dworshak	1	0	1	2	0	0	2
	Fall Chinook Survival Rls thru LGR Dam						
Average Survival	38	33	39	52	33	33	46
ΔS	0	-11	3	37	-13	-12	22
	Survival from LGR thru Bon Dam						
Average Survival	38	35	37	39	35	36	39
ΔS	0	-8	-4	1	-8	-6	2
	Survival from Rls thru Bon Dam						
Average Survival	14	12	14	20	12	12	18
ΔS	0	-19	-1	38	-20	-17	24

Table 15a. Scenario average flows (kcfs) and temperatures (centigrade) plus flow augmentation (maf) between day 160 and 220. Results for Lower Granite Dam over years 1995-1998 and 1998 at Bonneville Dam.

Scenario			1995 LGR			1996 LGR			1997 LGR			1998 LGR			1998 BON		
#	BRN	DWK	flow	temp	maf	flow	temp	maf	flow	temp	maf	flow	temp	maf	flow	temp	maf
1	1	1	67.9	18.2	1.3	84.4	17.1	1.1	97.7	17.5	1.9	73.8	18.9	1.6	225.4	20.6	19.6
2	0	0	57.0	18.8	0.0	74.8	17.3	0.0	82.0	18.3	0.0	60.3	19.3	0.0	212.0	20.5	18.0
3	0	1	65.2	18.0	1.0	83.8	17.1	1.1	95.3	17.3	1.6	69.3	18.7	1.1	221.0	20.5	19.1
4	0	2	73.8	17.0	2.0	86.9	15.9	1.4	104.5	16.5	2.7	78.6	17.2	2.2	230.3	20.0	20.2
5	1	0	59.8	18.9	0.3	78.7	17.4	0.5	84.4	18.4	0.3	64.7	19.5	0.5	216.4	20.6	18.5
6	2	0	62.5	18.9	0.6	82.6	17.5	0.9	86.8	18.5	0.6	69.2	19.6	1.1	220.8	20.7	19.1
7	2	2	79.2	17.4	2.6	94.6	16.4	2.4	109.3	16.8	3.2	87.5	17.9	3.2	239.2	20.2	21.2

Table 15b. Difference between Scenarios 2-7 and Scenario 1 for average flows (kcfs), temperatures (centigrade), and flow augmentation (maf) between day 160 and 220. Predictions for Lower Granite Dam for years 1995-1998 and 1998 at Bonneville Dam.

	1995 LGR			1996 LGR			1997 LGR			1998 LGR			1998 BON		
#	flow	temp	maf	flow	temp	maf	flow	temp	maf	flow	temp	maf	flow	temp	maf
2 - 1	-10.9	0.6	-1.3	-9.6	0.1	-1.1	-15.7	0.9	-1.9	-13.5	0.4	-1.6	-13.5	0.0	-1.6
3 - 1	-2.7	-0.2	-0.3	-0.7	0.0	-0.1	-2.4	-0.2	-0.3	-4.4	-0.2	-0.5	-4.4	-0.1	-0.5
4 - 1	5.8	-1.2	0.7	2.4	-1.2	0.3	6.9	-1.0	0.8	4.9	-1.6	0.6	4.9	-0.5	0.6
5 - 1	-8.2	0.7	-1.0	-5.8	0.3	-0.7	-13.3	1.0	-1.6	-9.1	0.6	-1.1	-9.1	0.1	-1.1
6 - 1	-5.5	0.7	-0.6	-1.9	0.4	-0.2	-10.9	1.0	-1.3	-4.6	0.7	-0.5	-4.6	0.2	-0.5
7 - 1	11.2	-0.8	1.3	10.2	-0.7	1.2	11.7	-0.7	1.4	13.7	-1.0	1.6	13.7	-0.3	1.6

6.4 Conclusions on passage model analysis

The CRiSP passage model simulates smolt survival in terms of travel time, which is flow related, and temperature, which is related to the flows of the unregulated streams and the flows from the storage reservoirs. The model can evaluate the individual impacts of augmentation from Dworshak and Brownlee storage reservoirs.

The model was used to determine the survival impacts of Scenarios that removed or doubled flow augmentation from Hells Canyon (Brownlee) and Dworshak individually and together. Survival was simulated from the Snake River fall chinook habitat to Lower Granite and Bonneville Dams. The model predicts that removing Hells Canyon (Brownlee) flow augmentation decreases flow, decreases water temperature and increases fish survival.

7. Analysis of Fall Chinook Spawner-Recruit (SR) Data

To consider the effects of flow on the returns of progeny adults, we use the conceptual spawner recruit model illustrated in Figure 16. Mature adults return in the autumn to lay their eggs. The eggs hatch and fry emerge in the spring. In the summer, the young fish move down river and enter the estuary and ocean in the late summer. The adults spend several years in the ocean and then return to the Snake River to spawn. Seasonal flows may affect the eggs and juveniles prior to their migration, and juveniles during their migration to the sea. The information on Snake River spawners and recruits (adult progeny) is on a (brood) yearly basis, so that there is only one pair of spawner and recruit numbers for each brood year. Thus, analysis of SR data reflects between-year variation in survival, not within-year variation. To compare the effects of flows on SR relationships the flows must be seasonally averaged.

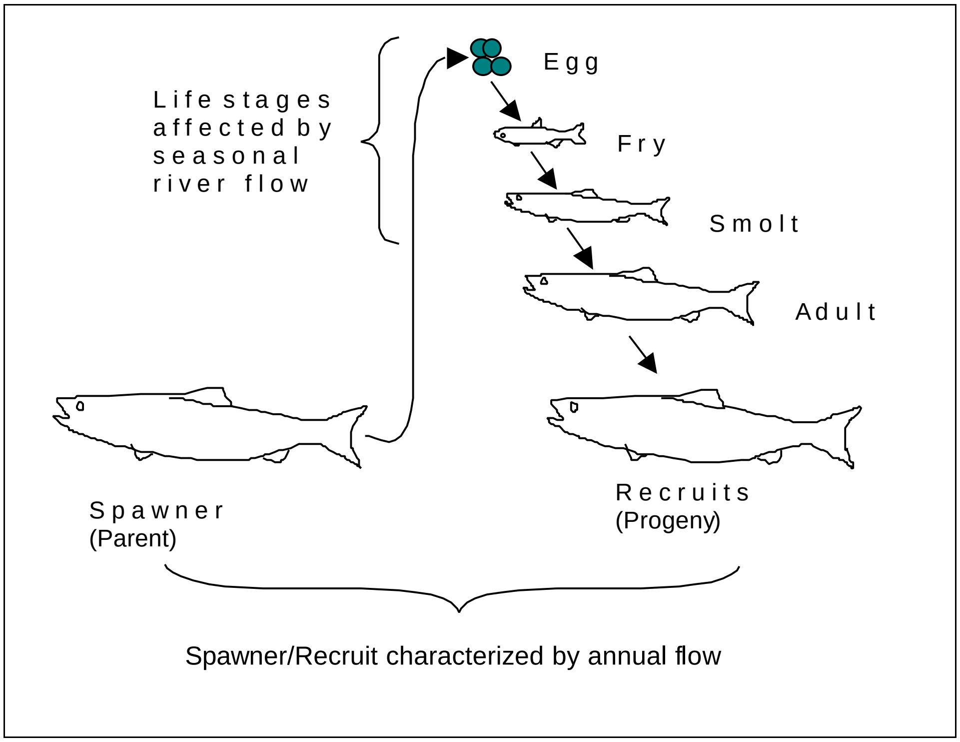

Figure 16. Life cycle framework with early life stage related to seasonal flows and spawner-recruit relationships related to annual flows.

The relationship between spawners and recruits is revealed by plotting the total recruits produced by each spawning cohort (Figure 17). Because the freshwater habitat is limited, the rate of mortality increases with increasing population size. This “density dependent” mortality makes the relationship between the number of spawners and the number of recruits domed shaped. At equilibrium, the number of recruits exactly replaces the spawning population, S*. Below S* there is a surplus recruit production, and above S* the recruit production is not sufficient to replace the spawners. In our analysis we apply the classical Ricker spawner recruit equation to characterize these life cycle relationships. The equation can be expressed

$$R = S \exp(a - b S)$$

where R is the number of recruits returning to the river from the spawning population of size S, a is the average productivity rate over the years of data, and b is the density dependent factor expressing the decrease in stock productivity as the carrying capacity of the habitat S* is approached.

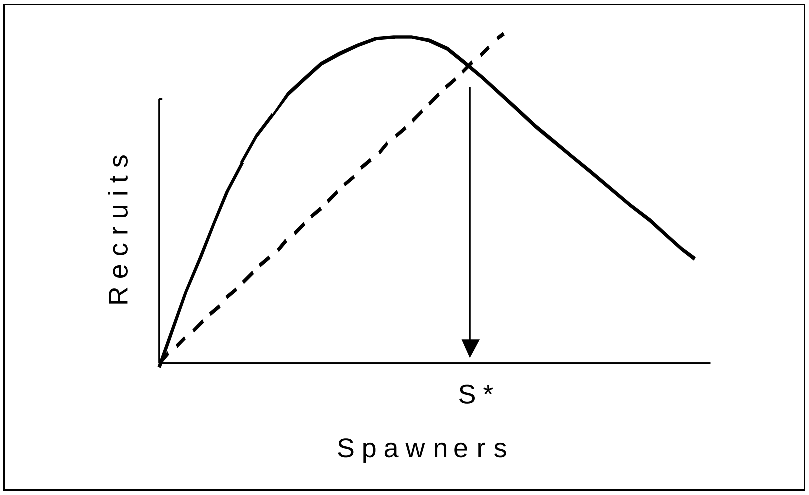

Figure 17. Ricker spawner recruit relationship showing equilibrium point S*.

7.1 Approach

In this analysis, we examine whether there is a statistically significant relationship between flow and life-cycle survival for three different Columbia River fall chinook stocks, the Hells Canyon stocks in the Snake River, the Hanford Reach stocks in the mid-Columbia, and Deschutes River stock in the Lower Columbia. The approach is to determine whether there is a significant effect of flow that can be detected in the spawner recruit (SR) data that extends back to the 1960s (for the Snake and Hanford stocks) and to Brood Year (BY) 1977 for the Deschutes stock. There are many assumptions behind the SR data used for this analysis (Peters et al. 1999), but these data remain the best available indicator of life-cycle survival over a long time record.

The index populations used for this report are the Snake River Bright, the Hanford Reach Upriver Bright, and the Deschutes River Upriver Bright. The characteristics of these populations are listed in Table 16. For each of these populations, spawners (S) and recruits (R) are estimated for each year. The spawners represent the total adults (age 3-6) that spawn, including both natural and hatchery origin fish, and are indexed by the year of spawning. The recruits represent the progeny of a spawner group and are indexed by the year the group spawns. For BY1991, for example, the recruits represent the number of offspring produced by the adults that spawned in year 1991. The recruits (offspring) are counted as adults returning to the mouth of the Columbia, adjusted to represent offspring that would have returned to the Columbia's mouth had harvest not occurred. This allows an estimate of the year-to-year fluctuations in recruitment not due to harvest, but perhaps due to environmental influences. Because these data are derived from many expansions and assumptions (Peters et al. 1999), it is best to view them as representing an index of spawners and recruits, with the understanding that they probably contain large, unknown, measurement errors and biases. Table 17 contains the SR data for the three index stocks.

Daily average flow records were available at Bonneville Dam and Ice Harbor Dam for the entire record of SR data. To characterize the relationship of flow and survival, two places and periods were used for estimating average flow: 1) average Bonneville Dam flows between July 15 and September 15 were used to characterize the flows that affect survival while smolts passed through the estuary; 2) average Ice Harbor flows in June and July were used to characterize the flows that affect survival prior to arrival in the hydrosystem.

Since the flows are correlated between Bonneville and Lower Granite Dams, characterizing the flow survival using the flow from either region should be similar. However, since the Lower Columbia flows are two to three times larger than the Snake River flows, the inferred effects of augmentation using the Lower Granite Dam flows would be two to three times larger than using the Bonneville Dam flows. Thus, establishing a correlation between flow and spawner recruit data does not tell us where the effect occurs. If it occurs in the estuary, then using the Lower Granite flows for the correlation could overestimate the impact of flow augmentation by two to three times. Our approach is to correlate SR based survival to flows when the fish are in the tributaries (June-July) and when they are in the estuary (July 15 to September 15). The flows are indexed by brood year, so that the average daily flow during June-July 1991, for example, is indexed by BY1990. The BY1990 flow thus represents the flow experienced by the progeny of spawners in 1990 during their out migration in 1991. Table 18 contains the daily average flow data used in the analysis.

Table 16. Wild fall chinook index populations in Columbia and Snake River basins.

Stock	Years of S-R Data	# Dams Passed	Distance From Ocean (km)
Snake River above Lower Granite	1964-1991	8	720
Columbia River at Hanford Reach	1964-1991	4	79
Deschutes River	1977-1991	2	167

Table 17. Fall chinook spawner-recruit data. D = Deschutes, H = Hanford Reach, S = Snake R.

Brood Year	Stock	S	R	Stock	S	R	Stock	S	R
1964				H	22703	100043	S	7648	35240
1965				H	26668	239681	S	6339	62471
1966				H	29724	193231	S	8623	34329
1967				H	24638	307471	S	10414	71436
1968				H	24035	263670	S	17556	48681
1969				H	28937	286328	S	4649	35129
1970				H	20511	590130	S	4353	43363
1971				H	26393	471622	S	4091	22699
1972				H	19327	361190	S	1371	17390
1973				H	36343	398212	S	2194	15716
1974				H	28940	333580	S	668	12910
1975				H	34628	268136	S	1387	10619
1976				H	39987	108581	S	691	7019
1977	D	6414	17641	H	40745	107827	S	1011	9259
1978	D	4099	16172	H	21644	56563	S	841	4946
1979	D	3728	15831	H	24840	164027	S	802	11657
1980	D	2788	15490	H	21224	304686	S	515	7817
1981	D	4704	17145	H	14213	265436	S	878	4746
1982	D	5176	15725	H	22598	458905	S	1209	7500
1983	D	4160	16090	H	37038	647038	S	842	8723
1984	D	2690	56348	H	48149	956878	S	552	9721
1985	D	6333	11974	H	71732	274308	S	885	4821
1986	D	6045	11576	H	100626	239529	S	1067	4971
1987	D	6278	4125	H	105347	101086	S	462	2171
1988	D	7903	8804	H	96329	96391	S	495	3748
1989	D	3927	10043	H	72022	151284	S	418	2031
1990	D	2320	14416	H	47856	131271	S	63	975
1991	D	3684	5765	H	37580	38067	S	509	717

Table 18. Average daily flows (kcfs).

Actual Year	Brood Year	Bonneville Flow (July15-Sept15)	Ice Harbor (June July)
1965	1964	182	102
1966	1965	158	41
1967	1966	173	93
1968	1967	162	63
1969	1968	134	59
1970	1969	129	98
1971	1970	169	118
1972	1971	192	105
1973	1972	121	37
1974	1973	182	136
1975	1974	142	115
1976	1975	225	83
1977	1976	100	28
1978	1977	149	79
1979	1978	114	50
1980	1979	125	75
1981	1980	164	77
1982	1981	176	116
1983	1982	173	96
1984	1983	147	126
1985	1984	100	49
1986	1985	134	71
1987	1986	108	23
1988	1987	107	33
1989	1988	99	50
1990	1989	130	50
1991	1990	150	55
1992	1991	113	27

7.2 Correlation analysis

For each of these stocks, we fit Ricker-type models to the SR data (Ricker 1975). For the correlation analysis, we fit Ricker models of the form:

$$\log(R_i/S_i) = a - bS_i + \varepsilon_i$$

for each of the three index stocks. The resulting series of residuals, ε_i , then contains the deviations of the actual log(R/S) from that estimated by the line a - bS_i. During years of higher-than-predicted log(R/S), the corresponding residual is positive; during years of lower-than-predicted log(R/S), it is negative. Thus, the time series of residuals represents a trace of how life-cycle survival, measured by log(R/S), has changed over time. This series can then be matched against the flow time series in an attempt to detect a relationship between flow and life-cycle survival (Figure 16). A correlation table quickly reveals little correspondence between flow and life-cycle survival for any of the three index stocks. We examined the correlation over two periods: 1) BY1964-1991 and, 2) BY1977-1991 and for two flow averages: 1) June and July for Ice Harbor flow to represent the possible of effects of tributary flows on survival in the western reaches of the Lower Snake River basin and, 2) July 15 to September 15 for Bonneville Dam flows to represent the possible effects of flows in the estuary on life cycle survival. We included the BY1977-1991 correlations because one could argue that only after the Snake dams were in place did a relationship form between flow and survival. The low correlations, however, do not support a flow-survival relationship (Table 19 and Figure 18).

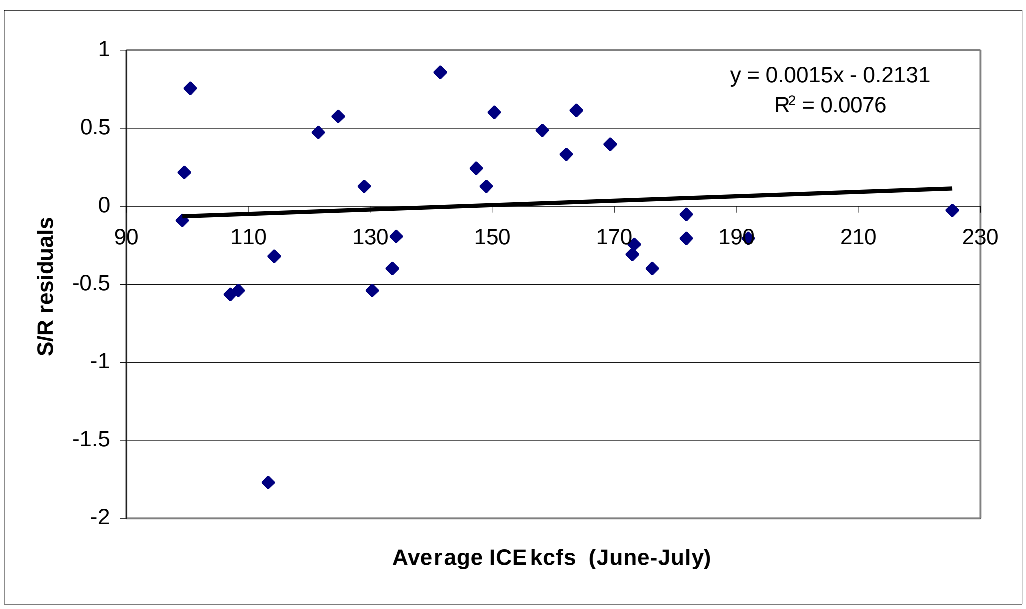

Figure 18. SR/ Residuals against average Ice Harbor Dam flows in June-and July.

Table 19. Correlations of brood year to flows.

Correlations (BY1964-1991)	Snake Residuals	Hanford Residuals	Bon Flow (Jul15-Sep15)	Ice Harbor (June July)
Snake Residuals	1.00			
Hanford Residuals	0.44	1.00		
Bon Flow(Jul15-Sep15)	0.09	0.22	1.00	
Ice Harbor (June-July)	0.23	0.38	0.68	1.00

Correlations (BY1977-1991)	Snake Residuals	Hanford Residuals	Deschutes Residuals	Bon Flow (Jul15-Sep15)	Ice Harbor (June-July)
Snake Residuals	1.00				
Hanford Residuals	0.47	1.00			
Deschutes Residuals	0.64	0.54	1.00		
Bon Flow(Jul15-Sep15)	0.21	0.19	0.09	1.00	
Ice Harbor (June-July)	0.37	0.39	0.34	0.78	1.00

7.3 Regression analysis

We also fit Ricker models of the form

$$\log(R_i/S_i) = a - b\,S_i + c\,Flow_i + \varepsilon_i$$

where the flow during migration enters directly into the Ricker equation. The goal is to formally test whether there is a correspondence between log(R/S) and migration flow (Flow) by fitting the model using least squares, then testing whether the estimate of the regression coefficient for migration flow, c, is significant. None of the regressions, for any of the stocks, or any of the periods (BY1964-1991 and BY1977-1991), indicated a significant ($\alpha = 0.05$) relationship between flow and log(R/S) (Tables 20 and 21). In other words, it is impossible to detect statistically an effect of flow on life-cycle survival. Each of the regressions did, however, indicate a slightly positive relationship, although not statistically significant relationship.

The possible benefits to life-cycle survival predicted by these estimates, however, are small. For the Snake River fall chinook, an increase in flow of 1 maf for 60 days, results in an estimated relative increase in life-cycle survival of 3.2% (based on BY1964-1991 regression) or 9.3% (based on the BY1977-1991 regression) (Tables 22 and 23). That is, if 1% of the smolts return as adults (SAR = 1%) then with a 1 maf augmentation from the Snake River basin the SAR becomes 1.03 to 1.09%. Therefore, not only are these effects not statistically significant, they are not biologically significant.

Table 20. Regression of log(R/S) against flow and S using July 15 to September 15 flows at Bonneville Dam.

Snake fall chinook (BY1964-1991)

Variable	coefficient	Value	Std. Error	t value	
(Intercept)	A	1.9180882	0.50137809	3.83	*
SPAWNERS	B	-5.554E-05	2.7877E-05	-1.99	
FLOW	c	0.0015612	0.00346965	0.45	
r^2=0.137					

Hanford fall chinook (BY1964-1991)

		Value	Std. Error	t value	
(Intercept)	a	1.8271988	9.15E-01	2.00	
SPAWNERS	b	-2.315E-05	6.48E-06	-3.57	*
FLOW	c	0.0066258	5.13E-03	1.29	
r^2=0.508					

Deschutes fall chinook (BY1977-1991)

		Value	Std. Error	t value	
(Intercept)	a	2.5415769	1.02669269	2.48	*
SPAWNERS	b	-0.0003643	9.7553E-05	-3.73	*
FLOW	c	0.0020087	0.00609241	0.33	
r^2=0.562					

Snake fall chinook (BY1977-1991)

		Value	Std. Error	t value
(Intercept)	a	1.4323303	0.9603595	1.49
SPAWNERS	b	-0.0004671	0.00062039	-0.75
FLOW	c	0.0065357	0.00721824	0.91
r^2=0.084				

Hanford fall chinook (BY1977-1991)

		Value	Std. Error	t value
(Intercept)	a	0.3169835	1.94E+00	0.16
SPAWNERS	b	-1.611E-05	9.92E-06	-1.62
FLOW	c	0.0149292	1.18E-02	1.26
r^2=0.487				

* indicates a significant parameter estimate

Table 21. Regression of log(R/S) data against S and Ice Harbor Dam flow June and July.

Snake fall chinook (BY1964-1991)

	Value	Std. Error	t value
(Intercept)	1.868856	0.263755	7.085585
SPAWNERS	-5.5E-05	2.66E-05	-2.083796
FLOW	0.00375	0.003233	1.159974

R^2=0.174

Snake fall chinook (BY1977-1991)

	Value	Std. Error	t value
(Intercept)	1.80039	0.473824	3.799702
SPAWNERS	-0.00075	0.000599	-1.246733
FLOW	0.010698	0.005966	1.793193

r^2=0.228

Note Ice Harbor Dam flow is significant at the 0.10 level but not the 0.05 level.

Table 22. Estimated survival change with augmentation based on Bonneville flow (August 15 to September 15).

MAF	**KCFS**	**% Change In Survival**
	Hanford (BY1964-1991)	
-1.5	-12.45	-1.92
-1	-8.3	-1.29
-0.5	-4.15	-0.65
0	0	0.00
0.5	4.15	0.65
1	8.3	1.30
1.5	12.45	1.96
	Hanford (BY1964-1991)	
-1.5	-12.45	-7.92
-1	-8.3	-5.35
-0.5	-4.15	-2.71
0	0	0.00
0.5	4.15	2.79
1	8.3	5.65
1.5	12.45	8.60

Table 22 continued on next page

Deschutes (BY1977-1991)		
-1.5	-12.45	-2.47
-1	-8.3	-1.65
-0.5	-4.15	-0.83
0	0	0.00
0.5	4.15	0.84
1	8.3	1.68
1.5	12.45	2.53

Snake (BY1977-1991)		
-1.5	-12.45	-7.81
-1	-8.3	-5.28
-0.5	-4.15	-2.68
0	0	0.00
0.5	4.15	2.75
1	8.3	5.57
1.5	12.45	8.48

Hanford (BY1977-1991)		
-1.5	-12.45	-16.96
-1	-8.3	-11.65
-0.5	-4.15	-6.01
0	0	0.00
0.5	4.15	6.39
1	8.3	13.19
1.5	12.45	20.43

Table 23. Estimated survival change for Snake River augmentations in June and July.

Snake Fall Chinook (BY1964-1991)

MAF	KCFS	% Change in Survival
-1.5	-12.45	-4.56
-1	-8.3	-3.06
-0.5	-4.15	-1.54
0	0	0.00
0.5	4.15	1.57
1	8.3	3.16
1.5	12.45	4.78

Snake Fall Chinook (BY1977-1991)

MAF	KCFS	% Change in Survival
-1.5	-12.45	-12.47
-1	-8.3	-8.50
-0.5	-4.15	-4.34
0	0	0.00
0.5	4.15	4.54
1	8.3	9.29
1.5	12.45	14.25

7.4 Conclusions of the SR analysis

There was no statistically discernable relationship (using $\alpha = 0.05$) between recruits per spawner (a measure of life-cycle survival) and flow during juvenile out migration for any of the three fall chinook index stocks studied.

The estimates of the effect of flow on life-cycle survival indicated only a 5 to 14% increase in survival for an increase in flow of 1.5 maf over 60 days. Thus, if SAR is 1%, the flow increase results in a SAR of 1.05 to 1.14%.

The models estimated a small change in survival for a decrease in flow of 1.5 maf over 60 days (survival decrease of 5 to 12%).

8. Discussion and Conclusion

In the NMFS draft White Paper on the effects of flow management on salmonid travel time and survival, NMFS concludes that direct evidence for a survival benefit to fall chinook from flow management is strongly supported by research results (NMFS 1999). Our evaluation of the data and mechanisms relating flow to fall chinook survival do not support the draft White Paper conclusion. We evaluated fall chinook survival, spawner recruit data, and environmental variable data from the NMFS and PATH studies. Our findings are in agreement with the basic elements of the NMFS and PATH analyses. However, when we consider in detail the difference between seasonal flow variation and flow augmentation, we conclude there is no evidence that Snake River flow augmentation has any measurable or ecologically significant impact on Snake River fall chinook.

We evaluated NMFS data and found a significant relationship between survival to Lower Granite Dam and the environmental variables. Using linear regression and multiple linear regression methods, as well as standard goodness-of-fit criteria, we found that the best predictors of seasonal changes in survival were release day and temperature, while flow was the poorest predictor of survival. We also evaluated the environmental factors that affect the arrival date of wild fall chinook to Lower Granite

Dam and found that while fish arrived earlier in the season if the temperature was warmer, flow was not a predictor of arrival time to the dam.

Although temperature plays a large role in fish behavior, temperature cannot be separated from the other environmental variables statistically. In order to understand the impacts of each variable, we considered the ecological principles affecting fish migration and survival. In terms of predator-prey interactions, flow might have a secondary impact on temperature. However, from reviewing studies on the impacts of flow augmentation on temperature, we found that flow augmentation from Brownlee Reservoir did not significantly affect the downstream temperature in Hells Canyon or in Lower Granite Reservoir. Therefore, the only direct effect of Snake River flow augmentation could be on fish travel time. However, we conclude there are no impacts because flow is unrelated to fall chinook travel time. In fact, there is evidence suggesting that Snake River flow augmentation will increase summer water temperature and water clarity, which would tend to increase the predation rate on smolt.

To quantify the impacts of flow augmentation, we used CRiSP 1.6, the newest version of the smolt passage model, as calibrated for the fall chinook analysis in PATH. This model was determined in PATH to be the best fitting available model for evaluating fall chinook smolt passage. We considered three augmentation regimes, the existing levels of flow augmentation in the years 1995-1998, doubling the augmentation over those years, and removing flow augmentation over those years. Contrary to the conclusions of the NMFS draft White Paper our analysis predicts that flow augmentation from Brownlee Reservoir model is detrimental to fall chinook. The highest Snake River fall chinook survivals were predicted with no Brownlee Reservoir flow augmentation.

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