The Flow Survival Relationship and Flow Augmentation Policy in the Columbia River Basin

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Flow augmentation and flow targets have been central programs in Columbia River salmon management for more than twenty years. Over this time, water requests have increased from 3.75 MAF in 1983 when the Water Budget was established (NPPC 1983) to between 13 and 16 MAF in the 1995 and 2000 NMFS Biological Opinions (NMFS 1995a; NMFS 2000a). Over the same period, the body of science on the effects of flow grew from a single graph between smolt survival and Snake River flow, to a body of information involving the tagging of a million smolts with survivals measured over the entire salmon life cycle. Whereas the growing body of scientific evidence indicates that variations in flow have no measurable effect on survival of juvenile salmon and steelhead through the mainstem of the Columbia and Snake, the fish managers continue with their policy of augmenting to these flows and have effectively halted further withdrawals of water from the mainstem of the system. In this paper I explore the history of the flow survival research and how political objectives produced a growing disconnect between the research and the water policy.

The development of flow policy

The flow augmentation policy established two decades ago is based on the initial research suggesting small changes in flow are correlated with large changes in fish survival. However, the policy is based on two assumptions 1) a flow survival relationship actually exists and 2) the effect natural flow variations have on survival can be achieved with flow augmentation.

Even prior to the completion of the hydrosystem National Marine Fisheries Service researchers (NMFS) documented the detrimental effect of dams on the survival and travel time of fish during their migration to the ocean. Prior to the construction of the Snake River dams (1964-1974), smolt traveled from the Snake River to the ocean in a matter of days and with the construction of the dams (1974-1994), the travel time extended to several weeks (Figure 1). Concomitant with the increasing travel time the percent of adults returning, designated the smolt-to-adult ration (SAR) declined. While it was clear that fish suffered mortality as they passed the dams, there was also a concern that the extended travel time contributed to the fish mortality. The hypothesis was that extended travel times increased the exposure of fish to predators and disease and delayed their entrance into saltwater, resulting in additional stress and mortality both in the river migration and in the estuary. Researchers studied survival of smolts from the Snake River to John Day Dam over seven years. Based on two low survivals in years with very low flows they hypothesized that more flow produced higher smolt survival (Figure 2). The hypothesis became known as the Sims and Ossiander flow survival relationship after the NMFS scientists that published the finding in an annual research report (Sims and Ossiander 1981).

Associated with the construction of the hydrosystem, the Columbia and Snake River salmon stocks declined and so fish managers sought a number of partial solutions to restore the runs. The two main actions were limiting harvest and increasing the production of hatchery fish to compensate for habitat lost by the dam. In addition, fisheries managers sought to increase survival by bypassing smolts around the turbines and by speeding their seaward migration by flushing additional water through the river during the spring migration. The initial flow augmentation occurred in 1983, and was base on two premises. One was intuitive. Because smolts migrated during the spring flushet and the dams diminished the spring flows, augmentation of the spring flows with water from the storage reservoirs would partially mimic the natural conditions and therefore increase smolt survival. The second premise was quantitative. The Sims and Ossiander flow survival hypothesis suggested great benefits from modest increases in flow. For example, fish managers predicted spring chinook survival would increase 180% with a 47 kcfs increase in flow at Ice Harbor Dam (CBFWA 1990). However, applying the Sims and Ossiander curve to predict the benefits of flow augmentation involved a very important, but unstated, assumption. The Sims and Ossiander curve was derived by plotting yearly averaged flow against yearly average survival and thus represented a relationship between years. Flows between years depend on the amount of rainfall, snow, and the temperature patterns, which together control environmental conditions prior to and during the smolt migration. Thus, a yearly average flow survival relationship involves many factors other than just the flow fish experience migrating through the river. Flow augmentation, however, is produced by shaping the available flow within the season. Thus, by applying the Sims and Ossiander curve to flow augmentation fish managers assumed that the benefits of a wet year could be achieved in a dry year by simply reshaping the timing of the spring runoff.

Two decades ago when the Water Budget began, neither the flow survival hypothesis nor the hypothesis on the equivalence of natural and augmented flows were challenged and in fact they was simply not discussed. However, these assumptions were central to the Water Budget in 1983. Thus, the fish water policies today have a direct lineage to the curve Sims and Ossiander drew through seven data points representing observations of (1973-1979) yearly averaged flows at Ice Harbor Dam against the per project survival of spring chinook and steelhead smolts from the Snake River to John Day Dam.

Testing the hypothesis that survival increases as flow increases

Over the past two decades, flow was hypothesized to affect survival via the effect of flow on travel time, altering the exposure of fish to predators and deleterious river conditions. While studies establish that flow was related to travel time, the Sims and Ossiander flow survival hypothesis could not be reproduced. A weaker relationship between flow measures and SARs was identified but the underlying factors could not clearly be identified prompting a revision of the flow survival mechanism to include other factors such as estuary arrival timing. Even though the research did not support the hypothesis, fish managers strengthen the flow policy based on the hypothesis.

Although the Sims and Ossiander flow survival hypothesis is critical to fish water policy, it has not been precisely formulated and the proposed underlying mechanism has changed over time in response to finding of the flow survival research. In the initial mechanism, flow affected survival via its effect on fish travel time. Increased flow decreased fish travel time, which increased fish survival. Petrosky (1992) demonstrated an inverse correlation between travel time of Snake River water survival and the survival of smolts to adult (SAR) (Figure 1). A paper by Berggren and Filardo (1993) provided support for the travel time mechanism by showing flow and smolt travel time were significantly related for Snake River spring chinook. Hilborn (1993) compared SARs of spring chinook from the Upper and Lower Columbia and concluded the SAR difference between the two reaches was greater for years with lower flows. Cada et al. (1994) reviewed a range of studies and suggested other factors were also of importance, especially temperature. With these reports, NMFS established a flow augmentation policy in the 1995 Biological Opinion (NMFS 1995a, b). The dominant justification was in terms of the flow travel time link. NMFS used travel time as one of the main performance measures in setting the spring and summer flow targets the hydrosystem required to insure safe passage of smolts. The flow target justification also involved temperature: fish arriving at projects later with higher temperatures would encounter more active predators and could have lower bypass efficiency causing more fish to pass through turbines. Thus, the water policy, up through the 1995 Biological Opinion, was based on a handful of studies that supported the Sims and Ossiander assumption that natural increases in flow increase salmon survival. There was no test and little discussion of the second assumption that the benefit assumed from natural year-to-year flow variations could be achieved by reshaping flows within a year.

However, with the development of the PIT-tag marking system, which allowed greater precision in estimating smolt survival, scientists were able to fully test the first hypothesis and partially test the second hypothesis. The first test of the Sims and Ossiander flow survival hypothesis was obtained in Little Goose Reservoir in 1992. It was a low flow year similar to 1973 and NMFS researchers expected survival to be low, but surprisingly, the PIT-tag measured survival was higher than the highest survival obtained in the highest flow year of the Sims and Ossiander study. Results from 1994 also showed very high survival. It is noteworthy that in developing the flow targets for the 1995 Biological Opinion, NMFS rejected the 1993 and 1994 PIT tag studies (NMFS 1995b). However, with each additional year of data, the rejection of the flow-survival hypothesis became stronger: Survival of spring chinook and steelhead through the hydrosystem is not related to variations in flow (NMFS 2000b; Bickford and Skalski 2000, Muir et al. 2001). Researchers reviewed the early studies and found flaws. The strong flow survival relationship in the Sims and Ossiander data (Figure 2) depended entirely on low survivals in the two drought years, 1973 and 1977. A closer look at the historical records revealed these low survivals were likely caused by poor dam passage conditions, not the low flows. Because the dam intakes were not regularly cleaned, larger numbers of tree, branches and other trash, accumulated at the face of the upper most dam on the Snake River (Williams and Matthews 1995). A review of the Petrosky's (1992) travel time and SAR relationship also revealed flaws with the analysis. NMFS used data representative of the current fish passage environment and found a weaker relationship between SAR and water travel time (Figure 2) (NMFS 2000b). For the first time NMFS articulated the previously unquestioned second hypothesis stating, "Correlation does not necessarily imply causation (Sokal and Rohlf 1981), and higher SARs associated with higher flows does not necessarily indicate the SARs can be increased by adding more flow to the river" (NMFS 2000b, 53). Skalski, *et al.* (1996) revaluated the Hilborn *et al.* study (1993) and found that the relationship between SARs and flow depended wholly on the choice of reference sites. Finally, Giorgi *et al.* (1997) found flow and travel time were not correlated for mid-Columbia fish. Thus, the flow travel time relationship Berggren and Filardo (1993) found for Snake River fish could not universally applied.

With a plethora of information seriously challenging the data and the theory on which the 1995 Biological Opinion was based, NMFS sustained its policy notwithstanding the data by concluding "that although a direct flow survival relationship cannot be established by data, it does not preclude benefits of flow augmentation because increased flows may improve survival outside the hydrosystem as a result of earlier arrival to the estuary, improved estuary conditions and reduced delayed mortality (NMFS 2000b, 58)." For the 2000 Biological Opinion NMFS continued to call for flow targets: "These results support management actions to provide flows of at least 85 kcfs in the Snake River and 135 kcfs in the upper (mid-) Columbia River during spring and 200 kcfs in the lower Columbia River during the summer (NMFS 2000b, 57)." Furthermore, NMFS implemented the "no net withdrawal" policy to preclude additional withdrawals of water from Columbia and Snake River Basins.

Newer research shows no flow survival relationship

The newest studies firmly rejected the flow-survival hypothesis. For yearly averaged data, which tests for a relationship between years, both in-river and SAR measures of survival were either independent of flow or exhibited statistically weak increases with flow. However, when comparing weekly or daily averaged data within each year, which tests for a flow survival trend within a season, no relationships were evident whatsoever.

Research published after the 2000 Biological Opinion strengthens the conclusion that flow is not related to survival. NMFS's scientists (Smith *et al.* 2002) wrote, "Correlations between river discharge and survival between Lower Granite Dam and McNary Dam and between travel time and survival were neither strong (within or between years) nor consistent from year to year." However, the paper took particular care to offer alterative theories under which the agency's policy might still make sense: "Thus, survival benefits to the stocks from increased flow in this stretch of the river were at best minimal; any measurable benefits occurred downstream from the Snake River. (Smith et al 2002)". Going further, the publication speculated that flow augmentation during smolt migration might provide survival benefits in other portions of the salmonid life cycle and in free-flowing sections of the river both upstream and downstream from the hydrosystem. They suggested flow augmentation may improve the arrival timing of fish to the estuary citing a paper by Zabel and Williams (2002) that found the date of fish arrival to Lower Granite Dam in 1995 correlated with rate of return of adults. However, the example is not convincing. Zabel and Williams (2002) also found that arrival date only correlated with survival for in-river passing smolts in one year. For smolts transported though the river the opposite trend existed, the later arriving fish survived better and in 1996, no significant difference was found between release date and returning adults for either transport or in-river groups.

The question remains, then, does flow augmentation directed at fish migrating through the hydrosystem improve survival of fish in the tributaries above hydrosystem, in the estuary, or in the Columbia River plume below the hydrosystem? It is noteworthy that to the present time little research has been conducted to test the hypothesis that flow affects fish outside the hydrosystem (Giorgio *et al.* 2002). However, data does exist to address this issue. First, consider the evidence for a flow-survival relationship above the hydrosystem. Six years of NMFS studies (Muir *et al.* 2001) demonstrated that hatchery spring chinook survival from Snake River tributaries to Lower Granite Dam was significantly related to distance traveled, but not travel time. Since fish survival was not related to fish velocity, the data contradicts the flow/travel time survival hypothesis. Moreover, plotting over ten years spring chinook survival traveling the 116 km distance between Dworshak Fish Hatchery on the Clearwater River to Lower Granite Dam clarifies the picture (Figure 4). The flow survival relationship was flat over the very large flow range of 20 to 140 kcfs. Snake River fall chinook is the only stock exhibiting a correlation between flow and survival to Lower Granite Dam. However, the studies also demonstrated that survival was strongly correlated with release date, temperature, and turbidity (Anderson *et al.* 2000; Dreher *et al.* 2000; NMFS 2000b). These analyses all conclude that with the existing data, flow cannot be the identified as the operative variable affecting survival. Furthermore, travel time is not correlated with flow or survival in these data, so if flow were the operative variable it does not act through the previously assumed mechanism involving exposure time. If flow affects survival, it would most likely work indirectly through the effect of temperature on smolts and their predators and through the effect of turbidity on the water clarity of the habitat. However, flow augmentation from the Hells Canyon Reservoir complex warms the Snake River, which would presumably increase predator activity and therefore decrease smolt survival (Anderson 2000b). The NMFS (2000b) report also noted that the relationship of flow and survival was variable and less pronounced below within the hydrosystem between Lower Granite and Lower Monumental dams.

The information available to address the impact of flow augmentation on salmon survival below the hydrosystem is more problematic. For this assessment, several studies have compared the SARs or the log of the ratio of the recruits to spawners (ln(R/S)) with flow measures. However, if such correlations exist flow is not necessarily the causative factor. Changes in the hydrosystem over the years of observation and the natural variability in the ocean conditions that may correlate with the wet and dry years, and therefore, flow make it impossible to establish a clear cause and effect relationship between the natural year-to-year variations in flow and these indicators of survival (NMFS 2000b). Confining the analysis to years representative of the current hydrosystem, several studies show a relationship between SAR or ln(R/S) and a measure of flow during the migratory season. However, as noted factors preclude associating the relationship with in river flows. NMFS (2000b) found over the years 1974-1994 a weak statistical relationship between water travel time and SAR for spring chinook but not for steelhead. Snake River fall chinook survival, expressed as the residuals of the spawner recruit curve, was uncorrelated with the flow during smolt migration (Anderson Hinrichsen and Van Holmes 2000), while for Marsh Creek spring chinook a relationship was found (Petrosky 1991). With selected data, yearly averaged relationships between flow and adult survival measures may or may not be found, but since about 90% of the Snake River smolts were transported, their exposure to the river environment was very limited. In contrast, Mid-Columbia stocks are not transported and they have flow survival correlations. However, over the years of these studies the high flows corresponded to warm ocean conditions, which produce poor salmon survival in the ocean (Mantua and Hare 1997, Anderson 2000). Therefore, survivals that correlate with high flows also correlate with years of better ocean survival. NMFS sums up the SAR flow information up through 2000 as follows, “While it is not possible to establish a clear cause and effect relationship with these [SAR and ln(R/S)] data, it is not possible to rule one out" (NMFS 2000b p 54).

However, the real question is not whether SAR is related to the natural year-to-year variations in flow, but whether SAR is related to flow augmentation. Germane to this question is the recent data on in-season flow and SAR, which was not available when NMFS prepared the white paper (NMFS 2000b). With nearly 700,000 run of the river PIT tagged salmon and steelhead smolts and 5000 adult returns it is now possible to explore if an in-season flow SAR relationship exists for Snake River fish. Figure 5 shows the results for in-river passing wild spring chinook over the years 1995 to 2000. The data represent averages of groups of fish that passed Lower Granite Dam weekly. Regression lines of weekly averaged SAR vs. weekly averaged flow for each year reveal no flow survival pattern within a year or between years for Lower Granite Dam flows ranging between 50 and 200 kcfs.

Models and the flow augmentation hypothesis

Since the flow-survival studies conclusively demonstrate that the effect of flow augmentation on fish survival above, below, or within the hydrosystem is so small, if it exists at all, as to be unmeasurable, models must be used to assess the incremental and cumulative impact of flow augmentation. Since models are simplified, but quantitative, representations of our understanding, as the data improves, the models are updated and revised. The first models developed by NMFS twenty years ago reflected the extremely limited data available and predicted a strong flow-survival relationship. The models now used by NMFS and the Region, which are based on an additional decade of high quality data, contain no flow-survival relationship whatsoever. Analysis also indicate even moderate water withdrawals should have virtually no impact on fish survival.

It is important to realize that the flow augmentation volumes released from upstream reservoirs are extremely small compared to the natural variations in flow, and the irrigation withdrawals at issue in this action are smaller still. Consequentially, since the relationship of survival and flow is inconclusive over the scale of year-to-year variations and flow and survival are uncorrelated over the seasonal scale, it virtually impossible to measure the impacts of flow augmentation on fish survival. Therefore, with present technology the second assumption that varying flow through augmentation produces the same effect as natural variations in flow is untestable. Thus, to extrapolate information derived from natural variations to flow augmentation we must use models. NMFS developed the first model of flow augmentation, which was no more than a fit of a two-parameter equation through seven data points (Figure 2) (Sims and Ossiander 1982). The equation is empirical, it has no basis in fish ecology, but fish managers readily accepted it as a valid description of the impacts of flow on smolt survival through the hydrosystem.

In the 1990s, two juvenile passage models, FLUSH and CRiSP, were developed or revised for use in the PATH process, a regional workgroup changed with evaluating the impacts of dam removal on the recovery of Snake River salmon (Marmorek 1998). The FLUSH model assumed that the fish mortality rate, the percent of the remaining population that dies each day, increases the longer fish are in the hydrosystem. The CRiSP model assumed mortality rate is constant over the migration. The FLUSH model, like the early Sims and Ossiander empirical model, produces a strong flow-survival relationship while the CRiSP model has a relatively weak flow-survival relationship. Because at the time of PATH there were no measurements of fish through the entire extent of hydrosystem, scientists calibrated the two models with the available data, which extended halfway through the hydrosystem. Due to the nature of the models, they produced essentially the same survivals to the midway point, but because the mortality rate in the FLUSH model strongly increases with fish travel time the predicted survival through the entire hydrosystem was less than half the CRiSP model prediction (~ 20% survival for FLUSH and ~40% survival for CRiSP). A panel charged with reviewing the two models believed that smolt mortality should increase strongly with travel time through the hydrosystem and weighted the FLUSH model over the CRiSP model.

After the PATH review, survival estimates over the entire hydrosystem were finally available to test the two models. NMFS estimated juvenile spring chinook survival from the tailrace of Lower Granite Dam to the tailrace of Bonneville Dam was 48% for the 1997 migration. The two model teams then provided their prediction. CRiSP model developers estimated survival was 59% and the FLUSH model developers estimate survival was 24%. In the next two years, NMFS provided additional hydrosystem survivals, which the CRiSP model team compared to their model predictions. For the 1998 smolt passage, the NMFS estimate as 63% and the CRiSP prediction was 49%. For 1999, the NMFS estimate was 56% and the CRiSP prediction was 54% (CBR 2000). The FLUSH modelers did not provide model either year, but by reverse engineering the FLUSH model (the actual model was never released to the scientific community), the estimated survivals for the two years would be below 15%. The results are clear, the FLUSH model and PATH scientific review panel's weightings are not supported by the survival studies.

NMFS was well aware of the failure of the FLUSH model and the difficulties of the PATH process so they develop an alternative model, SIMPAS, which is based on PIT tag survival studies between 1992 and 1999 (NMFS 2000c). Most significant, the SIMPAS model describes survival through the hydrosystem on a per kilometer basis. That is, the model contains no flow survival relationship whatsoever. Furthermore, NMFS used SIMPAS in developing the 2000 Biological Opinion.

Thus, over two decades of modeling the impacts of the hydrosystem on juvenile salmon migration NMFS has progressed from a model with a very strong flow-survival relationship to a model with no flow-survival relationship. This surprising result may seem at first counterintuitive. NMFS in 1980, and the PATH review panel in 1997, both believed that fish mortality through the hydrosystem depends on how long it takes smolts to migrate through the system. In addition, both groups of researchers believed that the rate of mortality strongly increased over time so that the majority of the fish must die at the bottom of the hydrosystem. How then can survival be independent of the migration time? Anderson and Zabel (in review) developed a mathematically rigorous and intuitive explanation. Simply put, they showed that smolt survival is independent of travel time if the predators are essentially stationary. In this case, the smolts must pass a gantlet of predators and the total mortality does not depend on how fast the smolts migrate but on how many predators they encounter while passing through the hydrosystem gauntlet. (It should be noted that predator densities are in fact higher below the dams than within the hydrosystem; migrating salmon experience a gauntlet nearly everywhere they go.)

Against the gauntlet description, flow proponents have suggested that fish mortality increases with passage time as a result of cumulative stress experienced by the migrating fish (Budy et al. 2002). Although questions on the significance of stress are yet to be resolved we can summarily disregard the contribution of flow augmentation and water withdrawals to the fish stress levels since these actions only change the total travel time of the fish by minutes over a total migration of weeks.

Over the last few years, the CRiSP model has been used to estimate the impacts of flow augmentation and water withdrawals on smolt survival and in each case, the impacts are insignificant (Anderson 1999). For example, a 147 cfs withdrawal from the mid-Columbia was estimated to reduce adult returns by less than 9 fish out of a population of a half million and the travel time would be increased by minutes.

The new data and model trim even these estimates. From our recent studies, smolt mortality depends more on distance traveled than travel time, and the predicted impacts of flow augmentation in the updated model will be about 75% less than the impacts predicted in the previous model. Thus, where the CRiSP 1.6 model predicted a 9 fish loss the updated model, CRiSP 1.7, will predict about a two fish loss. However, even this miniscule loss is high. In previous evaluations of the impact of flow augmentation, we assumed that water withdrawn for municipal or agricultural uses is lost to the system. In fact, the majority of water pumped from the mainstem of the Columbia River system returns to the system, either as treated water or as ground water recharge. Thus, the impact need to be lowered in proportion to water actually lost relative to the amount withdrawn. In the above example, the predicted impact of a 147 cfs withdrawal is expected to be less than one adult salmon. Alternatively, using the SIMPAS model the impact is zero fish lost.

Is the addition or loss of one or even a hundred adult salmon out of a population of a half million significant to the salmon populations? On an intuitive level, the answer is clearly no. Using models, NMFS concluded that recovery of Snake River salmon was not dependent on further improvements in hydrosystem survival (Kareiva *et al*. 2000). Moreover, NMFS has also concluded that even large reductions in adult returns are not significant to recovery, as evidenced by the fact NMFS allows the in-river harvest of thousands of salmon in the mainstem of the Columbia River that would otherwise reach their final destination in a few weeks.

The disconnect between policy and science

While the cumulative body of scientific information all points to flow not affecting survival in any meaningful context, the policy of reducing water withdrawals and augmenting river flow has continued to expand. Furthermore, fish and water managers have consistently acted to discredit or ignore the information against their policies

The hypothesis that flow will improve fish survival was first proposed in 1981which led to the establishment of the Water Budget in 1983. Over the next two decades, only five additional studies and reports provided any indirect support for the hypothesis while more than twenty studies have directly refuted the hypothesis (Table 1). The evidence is now overwhelming to reject the hypothesis and the contention that flow augmentation and water withdrawals in the mainstem of the river system have any impact on salmon. However, over this same period the fish and water managers have increased the flow augmentation and implemented stringent regulations stopping water withdrawals (Table 1). Furthermore, as the research has serially addressed and rejected the hypothesis on which the water policy was based the managers have reformulated the hypothesis into more nebulous forms.

In 1983 the justification for the water budget was to speed fish down the river to increase survival. When this was shown false, the justification was switched to an impact of adult returns (SARs). When it became clear that the benefits of water policy could not be demonstrated in terms of adults returns the managers shifted justification saying that the research could not rule out benefits {"While it is not possible to establish a clear cause and effect relationship with these [SAR and ln(R/S)] data, it is not possible to rule one out" (NMFS 2000b p 54)}. When models demonstrated that the benefits of water policy were insignificant managers rejected the model (in the case of CRiSP) [Barwin transcript] or simply ignored the model (in the case of SIMPAS). When models predicted miniscule impacts managers challenged the conclusions applying a *reduction ad absurdum* proof, noting that a miniscule impact is significant if the entire river is withdrawn. In the face of the accumulating evidence *against* the benefits of flow, managers continue to rely on non-deductive logic, statements of belief, and qualitative extrapolations: “Additional water withdrawals have the probable affect of exacerbating the situation thus delayed or prevent recovery of listed fish [Barwin transcript]. Frequently and consistently, when new information emerges against the flow-survival hypothesis the fish managers mount attack on the data and its analysis.

References

Anderson, J.J. 1998. Weight of evidence for passage, transport, extra mortality, and aggregate hypothesis submission 14 in PATH weight of Evidence Report.

Anderson, J.J. 1999. Analysis of biological impacts of water withdrawal application No. S4-30976. In Regional water supply plan for cities of Kennewick, Pasco, richland and West Richland. Prepared by Economic and Engineering Services.

Anderson, J. J. 2000a. Decadal climate cycles and declining Columbia River salmon. In “Proceedings of the Sustainable Fisheries Conference, Victoria, B.C," ed. E. Knudsen. American Fisheries Society Special publication no. 2x. Bethesda, MD.

Anderson, J. J. 2000b. Heat Budget of Water Flowing through Hells Canyon and the Effect of Flow Augmentation on Snake River Water Temperature. http://www.cbr.washington.edu/papers/jim/SRheatbudget.html.

Anderson, J. J., R. H. Hinrichsen, and C. Van Holmes. 2000. Effects of flow augmentation on Snake River Fall Chinook. 64 pages. Report to the Committee of Nine and the Idaho Water Users Association D.

Anderson, J.J. and R.W. Zabel (in review). Travel time and distance dependent smolt survival: model, observations and implications. Ecology in Review.

Berggren, T.J., and Filardo, M.J. 1993. An analysis of variables influencing the migration of juvenile salmonids in the Columbia River basin. N. Amer. J. Fish. Manag. 13: 48-63.

Budy, P, G.P. Thiede, N.Bouwes, C.E. Petrosky and H. Schaller. 2002. Devidence linking delayed mortality of the Snake River salmone to their earlier hydrosystem experience. North American Journal of Fisheries Management 22(2) 35-51.

CBFWA. 1990. Integrated system plan for salmon and steelhead production in the Columbia River Basin. Prepared by the Agencies and Indian Tribes of the Columbia Basin fish and Wildlife Authority. 90-12.

Cada, G.F., M.D. Deacon, S.V. Mitz, and M.S. Bevelhimer. 1994. Review of information pertaining to the effect of water velocity of the survival of juvenile salmon and steelhead in the Columbia River basin. Prepared for Chip McConnaha, Northwest Power Planning Council, Portland, Oregon.

CBR (Columbia Basin Research) 2000. Columbia River Salmon Passage Model CRiSP 1.6 Theory and Calibration. CBR at University of Washington. www.cbr.washington.edu/crisp/models/crisp1manual/theory16/

Dreher, K.J., C.R. Petrich, K.W. Neely, E.C. Bowles, and A. Byrne. 2000. Review of survival, flow, temperature, and migration data for hatchery-raised, subyearling fall chinook salmon above Lower Granite Dam, 1995-1998. Idaho Department of Water Resources, Boise.

Giorgi, A. E., D. R. Miller, and B. P. Sanford. 1994. Migratory characteristics of juvenile ocean-type salmon, *Oncorhynchus tshawytscha,* in the John Day Reservoir on the Columbia River. Fishery Bulletin 92: 872-879.

Giorgi, A. E., T. W. Hillman, J. R. Stevenson, S. G. Hays, and C. M. Pevin. 1997. Factors that influence the downstream migration rate through the hydroelectric system in the Mid-Columbia River basin. North American Journal of Fisheries Management 17: 268-282.

Giorgi, A. E., M. Miller, J. R. Stevenson. 2002. Mainstem passage strategies in the Columbia River system: transportation, spill and flow augmentation. BioAnalysts, Inc. prepared for Northwest Power Planning Council.

Hilborn, R., R. Donnelly, M. Pascual, and C. Coronado-Hernandez. 1993b. The relationship between river flow and survival for Columbia River chinook salmon. Draft Report to U.S. DOE, Bonneville Power Administration, Portland, Oregon.

ISAB (Independent Scientific Advisory Board). 2001. Review of Lower Snake River Flow Augmentation Studies ISAB 2001-4.

Kareiva, P. M. Marvier and M/ McClure 2000. Recovery and management options for spring/summer chinook in the Columbia Riber basin. Science 290:977-979.

Mantua, N.J., S.R. Hare, Y. Zhang, J.M. Wallace and R.C. Francis. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. Bulletin of the American Meteorological Society 78:1069-1079.

Marmorek, D. R. and C. N. Peters. editors. 1998. Plan for analyzing and testing hypotheses (PATH): Preliminary decision analysis report on Snake River spring/summer chinook. Prepared by ESSA Technologies, Ltd. Vancouver, British Columbia.

Marsh, D. M. and S. Achord. 1992. A comparison of PIT-tagged spring and summer chinook salmon detections rates with Snake River flows at Lower Granite Dam. National Marine Fisheries Service. Northwest Fisheries Science Center, 2725 Montlake Blvd. E., Seattle Washington, 98112-2097. 5 p.

Muir, W.D., Smith, S.G., J.G. Williams Hockersmith, and Skalski, 2001. Survival Estimates for Migrant Yearling Chinook Salmon and Steelhead Tagged with Passive Integrated Transponders in the Lower Snake and Lower Columbia Rivers, 1993–1998. North American Journal of Fisheries Management 21(2) 269-282.

NMFS (National Marine Fisheries Service). 1995a. Endangered species Act- Section 7 consultation Biological Opinion; Reinitiation of Consultation on 1994-1998 operation of the Federal Columbia River Federal Power System and juvenile transportation program in 1995 and future years. NMFS (National Marine Fisheries Service).

NMFS (National Marine Fisheries Service) 1995b. Basis for flow objectives for operation of the Federal Columbia River Power System (February 1995). National Marine Fisheries Service and the National Oceanic and Atmospheric Organization.

NMFS (National Marine Fisheries Service). 2000a. Endangered species Act- Section 7 consultation Biological Opinion; Reinitiation of Consultation on 1994-1998 operation of the Federal Columbia River Federal Power System, including the juvenile transportation program and 19 Bureau of reclamation Projects in the Columbia Basin. National Marine Fisheries Service and the National Oceanic and Atmospheric Organization.

NMFS 2000b. White paper: Salmonid travel time and survival related to flow in the Columbia River Basin. Northwest Fisheries Science Center, National Marine Fisheries Service, 2725 Montlake Boulevard East, Seattle, Washington 98112

NMFS (National Marine Fisheries Service). 2000c. Appendix D Biological effects analysis and SIMPAS model documentation. For Endangered species Act- Section 7 consultation Biological Opinion; Reinitiation of Consultation on 1994-1998 operation of the Federal Columbia River Federal Power System, including the juvenile transportation program and 19 Bureau of reclamation Projects in the Columbia Basin. National Marine Fisheries Service and the National Oceanic and Atmospheric Organization.

Northwest Power Planning Council. 1983. Columbia River Basins fish and wildlife program. Portland Oregon.

Olsen, D. and J. Richards. 1994. Inter-basin comparison study, Snake River chinook production compared to other West Coast production areas, phase II report. Pacific Northwest Project, Kennewick, Washington.

Olsen, D., J. Anderson, R. Zabel, J. Pizzimenti and K. Malone. 1998. The Columbia-Snake river flow targets/augmentation program: A white paper review with recommendations for decision makers. Pacific Northwest Project, Kennewick, Washington.

Petrosky, C. E. 1991. Influence of smolt migration flows on recruitment and return rates of Idaho spring chinook salmon. Idaho Dept. of Fish and Game, Boise, Idaho. 23 p. + Figures.

Petrosky, C. E. 1992. Analysis of flow and velocity effects: smolt survival and adult returns of wild spring and summer chinook salmon. Chinook Smolt Workshop Draft Summary. Idaho Dept. of Fish and Game, Boise, Idaho.

Petrosky, C. E., and H. Schaller. 1998. Smolt-to-adult return rate estimates of Snake River aggregate wild spring and summer chinook. Submission 10 In: Marmorek and Peters, eds. PATH Weight of Evidence Report. 6 p. + tables and figures

Raymond, H. L. 1979. Effects of dams and impoundments on migrations of juvenile chinook salmon and steelhead from the Snake River, 1966 to 1975. Transactions of the American Fisheries Society 108:505–529.

Sims, C., and F. Ossiander. 1981. Migrations of juvenile chinook salmon and steelhead in the Snake River, from 1973-1979, a research summary. Report to the U.S. Army Corps of Engineers, Contract DACW68-78-0038.

Skalski, J.R., R.L. Townsend, R.F. Donnelly, and R.W. Hilborn. 1996. Final Report: The relationship between survival of Columbia River fall chinook salmon and in-river environmental factors. Analysis of historic data for juvenile and adult salmonid production: Phase II. Bonneville Power Administration, Public Information Center, Portland, Oregon.

Smith, S. G., W. D. Muir, E. E. Hockersmith, S. Achord, M. B. Eppard, T. E. Ruehle, and J. G. Williams. 1997a. Draft: Survival estimates for the passage of juvenile salmonids through Snake River dams and reservoirs. Annual Report, 1996. US Dept. of Energy, Bonneville Power Administration, Contract Number DE-AI79-93BP10891.

Smith, S. G., W. D. Muir, E. E. Hockersmith, M. B. Eppard, and W. P. Connor. 1997b. Passage survival of natural and hatchery subyearling fall chinook salmon to Lower Granite, Little Goose, and Lower Monumental Dams. In: Williams, J.G., and T.C. Bjornn. 1995. Annual Report: Fall chinook salmon survival and supplementation studies in the Snake River reservoirs, 1995. Bonneville Power Administration, Public Information Center, Portland, Oregon.

Smith, S. G., W. D. Muir, E. E. J.G. Williams. 2002. Factor associated with travel time and survival of migrant yearling chnook salmon and steelhead in the Lower Snake River. North American Journal of Fisheries Management 22:385-4-5.

Williams, J. G., Smith, S.G., and Muir, W.D. 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(2) 310-317.

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 93:732–740.

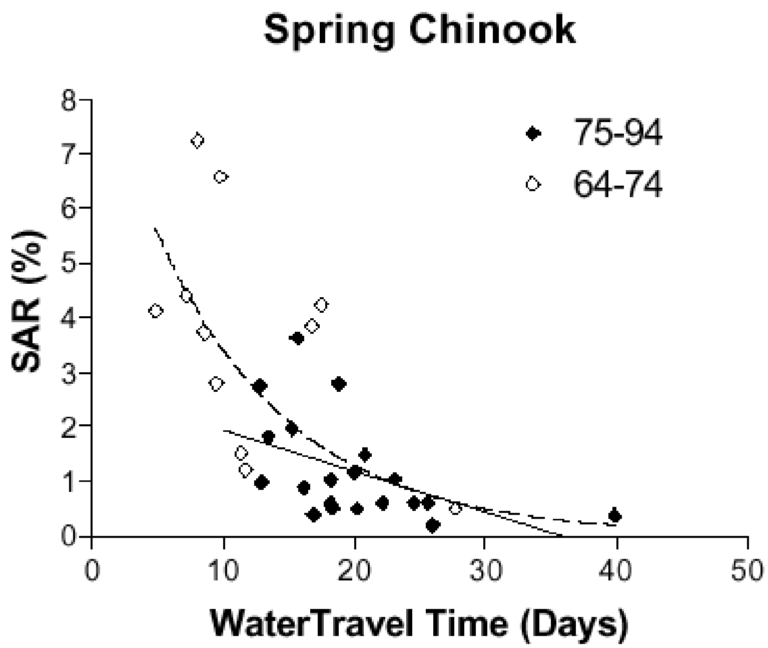

Figure 1. Regressions of smolt-to-adult returns versus water travel time for Snake River spring/summer chinook salmon for the 1964-1994 smolt migration (after Petrosky and Schaller 1998). The dashed line represents the regression line for the entire period; the solid line is for the years 1975-1994. From NMFS (2000b).

Table 1. History of Flow-Survival Relationship Key Studies and Program/Plans

Year	Evidence for flow-survival hypothesis and policy	Evidence against flow survival hypothesis and policy
1981	**Sims and Ossiander 1981** (73-79 Spring Chinook Studies)	
1983	**NPPC 1983** Fish & Wildlife Program* (**Policy**)	
1990	**CBFWA 1990** Integrated System Plan	
1992	**Petrosky 1992** (Adult Returns Rates Correlated with water Travel Time in Snake River)	**Marsh and Achord 1992** (First PIT-tag Study Shows High Survival with Low Flow)
1993	**Hilborn et al. 1993 ;** (Fall Chinook Flow-Travel Time Relationship) **Berggren and Filardo 1993** Snake River spring chinook travel time decreases with flow	
1994	**Cada et al. 1994** (Review from Several Systems Conclude Flow and Other Factors Affect Survival)	**Giorgi et al. 1994** (No Flow-Travel Time Relationship in mid-Columbia) **Olsen and Richards 1994** (Ocean Conditions affect West Coast Chinook)
1995	**NMFS 1995** BiOp* (Proposed Flow Targets) (**Policy**)	**Williams and Matthews 1995** (1970s, Low survival from Trash at Dams) **Skalski et al. 1996** (Fall Chinook Survival Depends on Comparison Stock)
1997		**Smith et al. 1997a** (1993-1997 Data Shows No Within-Year Flow Survival Relationship for Spring Chinook) **Giorgi et al. 1997 ; Smith et al. 1997b** (No Within-Year Flow Survival Relationship in Fall Chinook) **Mantua et al. 1997** (Ocean Regime Shifts Alter Salmon Production is an Alternative Reason for Stock Decline)
1998	**Marmorek et al. 1988** (FLUSH Passage Model Predicts Strong Flow Survival Relationship)	**Marmorek et al. 1988** (CRiSP Passage Model Predicts Weak Flow Survival Relationship) **Olsen et al. 1998** (Comprehensive Review of the Flow Program Questioning Policy, Hydrology, Biology, and Economics)
1999		**NMFS** obtains first estimate of smolt survival through the entire hydrosystem and requests FLUSH and CRiSP project survivals for model tests. FLUSH error is 3 times grater than CRiSP error.
2000	**NMFS 2000a** BiOp* (Continues with Flow Targets and Flow Augmentation Proposed in 1995 BiOP plus established a no net withdrawal policy) (**Policy**)	**NMFS 2000b** (No Flow Survival Relationship for Snake River Spring Migrants for 1995-1999) **NMFS 2000a** (NMFS Adapts SIMPAS Model in which Smolt Survival Depends on Distance, Not Travel Time) **Anderson et al. 2000; NMFS 2000b** (Snake River Fall Chinook Survival to LGR Dam Not Related to Travel Time, Survival has Highest Correlation with Release Date and Water Quality Parameters, which covary)
2001		**Muir et al. 2001** (Hatchery Chinook Survival Varied Inversely with Distance to LGR Dam. Hydrosystem Survivals in 1990S Equal Survivals in the1960s and Little Mortality Occurs in Reservoirs) **Williams et al. 2001** (Survival Increases from 1970s to 1990s not Accompanied by Change in Flow)

2002	Fisheries Agencies challenge the Giorgi 2002 report	**Giorgi. 2002** (Review of Data determined that little evidence for supporting flow survival relationship across water years 1993-2002 for yearling chinook and steelhead) **Smith et al. 2002** (Between Lower Granite and McNary Dam flow survival relationship with the in season or between years) **Anderson and Zabel *in review*** (Smolts passi a gauntlet of predators making survival dependent on distance not travel time)

* Fish migration and recovery programs.

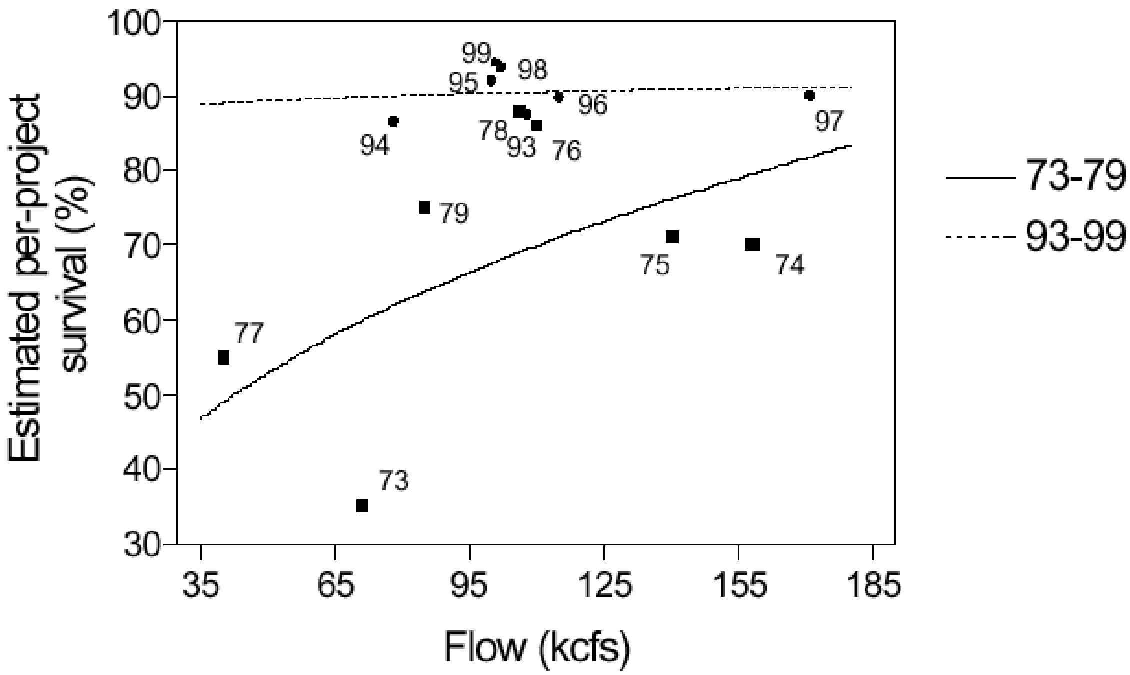

Figure 2. Historical and recent estimates of per-project survival (%) for yearling chinook salmon vs. index of Snake River flow (kcfs). Curves depict fitted nonlinear regression equations describing relationship between flow and survival in the two time-periods. Early period data from Raymond (1979) and Sims and Ossiander (1981). Graph from NMFS (2000b).

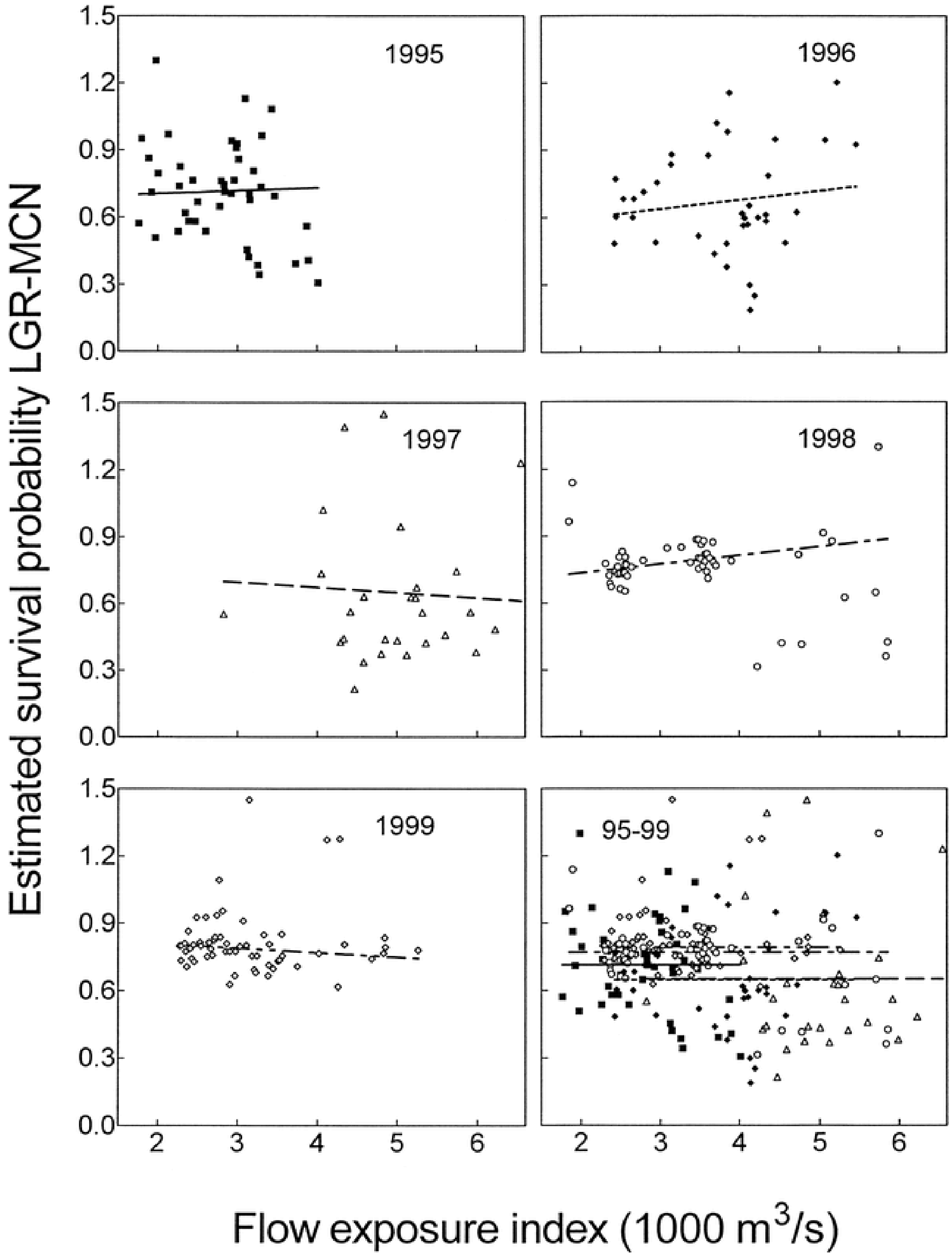

Figure 3. Relation between estimated survival from Lower Granite (LGR) Dam to McNary (MCN) Dam (d) and flow exposure index measured at Lower Monumental Dam for yearling chinook salmon, 1995–1999. Lines in the lower right panel depict the linear regression model identified in the model selection sequence. Regression lines are from weighted analysis (Figure from Smith et al 2002)

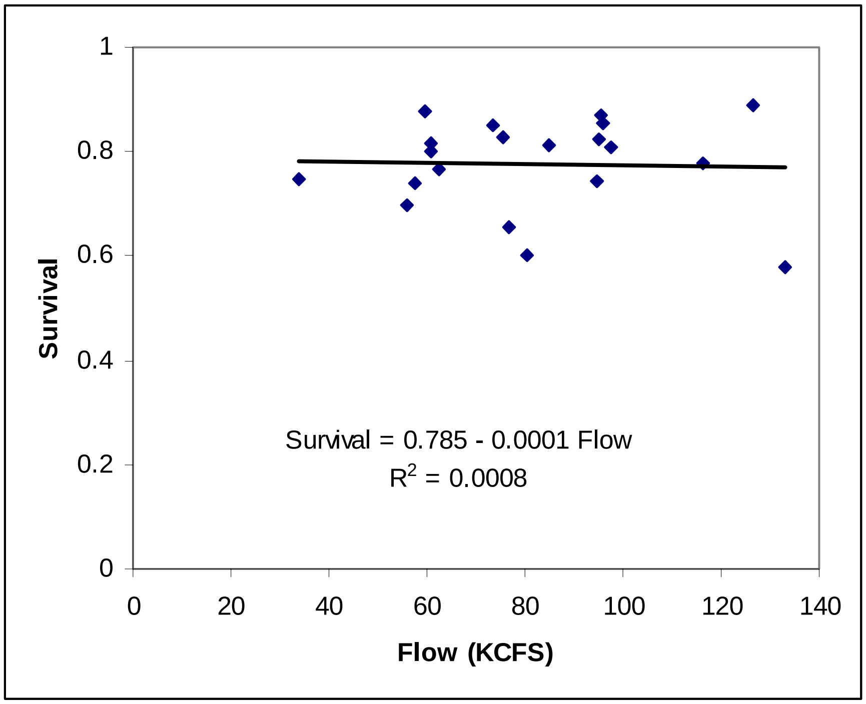

Figure 4. Relationship of flow to spring chinook smolt survival from Dworshak Hatchery to Lower Granite Dam for 10 years of PIT tag data from 1990-2001.

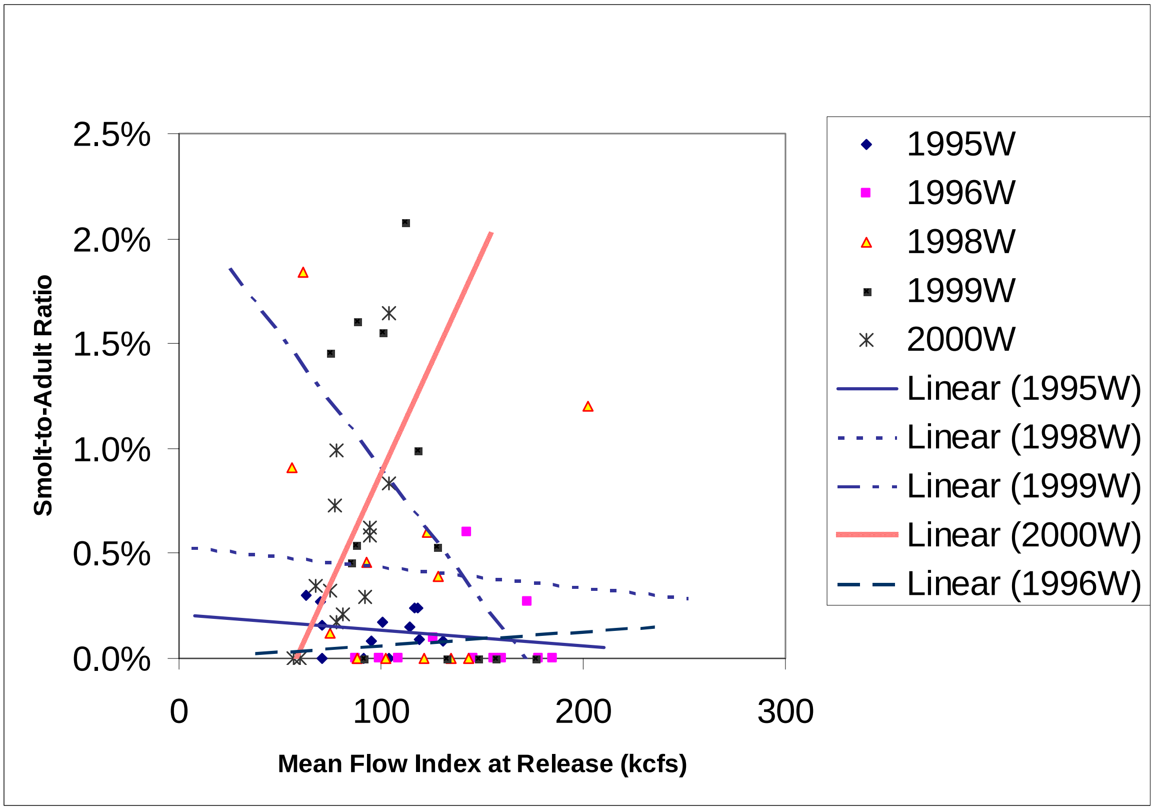

Figure 5. SAR vs. LGR flow index for PIT tagged spring chinook salmon tagged at Lower Granite Dam for between 1995 and 2000.