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and the Columbia River Basin Indian Tribes
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Review of Flow Augmentation: Update and Clarification

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February 10, 2003
ISAB 2003-1

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Executive Summary

Background

At its November 14, 2002 meeting, the Northwest Power Planning Council asked the ISAB to update and clarify its review of flow augmentation by the end of January 2003. The Council and the Columbia River Inter-Tribal Fish Commission (CRITFC) submitted questions on the subject to the ISAB. The issue is timely for the Council as it proposes amendments to the mainstem portion of the Fish and Wildlife Program. The issue is important in a broader context, because flow commitments are part of the legal agreements under ESA for some listed stocks. The relationship between river flows and salmon production has been reviewed before by the ISAB, but many questions remain. Uncertainties about the relationship have been reiterated in presentations to Council by interested parties, in public comments on the Council's proposed mainstem amendments, and in questions to the ISAB from Council members and the tribes. The issues are complex and have troubled the region for decades. Many specific questions arise from the broader issues. The ISAB considered the Council's questions and deadline, and suggested (by memo of December 19) that it could make a short response to the questions within that timeframe, and, if requested, follow this response with more detailed information. This report contains our initial response.

Stimulated by the specific questions posed by Council and others, the ISAB has taken a fresh look at the whole matter of river flow and fish survival with special emphasis on the Lower Snake River reaches. There have been improvements in study designs over the years, particularly in the PIT-tag and radiotelemetry studies. Also, the quantity and quality of accumulated data have improved, and the range of factors potentially related to survival of anadromous fish has been extended. This has allowed more patterns to be resolved in analyses. To focus only on the specifics of the questions posed to the ISAB would be to miss the point: the whole issue of flow and fish survival requires reevaluation. Management alternatives for improving survival of migrating juvenile anadromous fish include many dimensions beyond the current procedures for "flow augmentation." The ISAB answered the specific questions in the text of this report, but considers them to be a subset of the broader issue.

The executive summary provides our conclusions related to the needed reevaluation of flow issues, focusing on the Lower Snake River, and the text of the report contains the scientific justification for those conclusions and answers to the specific Council and CRITFC questions. The text provides, in sequence, a brief background for the flow augmentation issue, an overall conclusion of the ISAB regarding the present status of scientific knowledge bearing on flow augmentation, the specific questions asked of us and our answers, and a summary of the implications of our review for the Council's draft mainstem amendments. A set of appendices provides more detailed evidence for our conclusions and answers, which we were not able to fully integrate with the text in the time available. The evidence is organized by specific findings about current scientific information. Hypotheses are presented that may explain the information and offer guides for managing the hydrosystem to benefit fish. As indicated, our report was prepared with limited time to refine the analysis in order to provide the Council with the thrust of our review by the stipulated deadline. The review could be further refined and enlarged with additional work.

Development and operation of the hydroelectric system in the Columbia River Basin led to changes in the normal pattern of flow. Dams on U.S. and Canadian tributaries regulate flow in the mainstem. These reservoirs are lowered seasonally to allow storage capacity that will reduce the frequency and intensity of flooding, primarily during the spring freshet, and then refilled to provide sources of water for later power production and other uses. As a result, the magnitude and variability of the spring freshet through the lower Columbia River basin has been greatly reduced and the timing is partially controlled. These changes have many ecological consequences that might affect salmon production. In fact, flooding was almost certainly good for salmon production, but flooding is no longer considered a viable management option. Accordingly, attention has centered on less dramatic, incremental adjustments of the present flow regime, in the hope of identifying flow changes that confer benefit to salmon production.

There was early concern that juvenile salmonids migrating downstream at the time of the spring freshet might experience in-river mortalities that are higher than normal because of the diminished flows. Therefore, the Council's first (1982) Fish and Wildlife Program specified a modest volume of water, identified as the "Water Budget," relative to a base amount for hydropower and flood control, to be used in the spring months for the purpose of improving survival of migrating juvenile salmonids. Subsequently, specified flows have also been added to benefit summer migrants. "Flow augmentation," as this programmed increment to some of the seasonally managed flows is called, does not in any way restore original natural flow. It has been a subject of contention from the time of its initiation, both because of competing uses and values for the stored water (e.g., hydropower, irrigation, recreation on fully filled reservoirs, and biological productivity in reservoirs or downstream rivers), and because the benefit to salmon of these incremental adjustments has not been well quantified.

Review by the ISAB

In the time available, the ISAB gathered the latest scientific information on the relationships between smolt survival and flow, and the operational features of the hydrosystem that might affect them. We did this through briefings, review of the latest reports and publications, and independent data analyses. Because of interest in ESA-listed species, more information is available for the lower Snake River; little information was available for the mid-Columbia River.

A different perspective emerged from this latest review. We realize that the prevailing rationale for flow augmentation is inadequate. It is neither complete nor comprehensive.

There is room for alternative explanations of available data that have both scientific justification and practical value for managing the hydrosystem for multiple uses including salmon recovery.

The prevailing flow-augmentation paradigm, which asserts that in-river smolt survival will be proportionally enhanced by any amount of added water, is no longer supportable. It does not agree with information now available.

First, for the lower Snake River studied between 1996 and 2001, there is a range of lower flows over which survival of PIT-tagged smolts increases with increasing flow and a range of high flows in which fish survival appears to be independent of incremental changes in flow. There is an apparent breakpoint in the relationship between survival and flow (i.e., a rather sharp change in the slope of models fitted to the data or a sharp corner on a "broken-stick" model) near 100 kcfs for yearling chinook salmon and steelhead and an appearance of a break near 50 kcfs for underyearling fall chinook salmon. The pattern is evident despite a large amount of scatter in the data. Whether these apparent breakpoints represent two distinctly different mechanisms at different flows or one continuous mechanism with a general curve is a subject we discuss. Survival data within years do not consistently show a pattern because the range of flows within a given year is relatively small.

Second, radiotelemetry of yearling chinook salmon and steelhead smolts in Lower Granite Reservoir (1996-2001) also showed an apparent breakpoint in the relationship of smolt behavior and flow near 100 kcfs. Above that level, smolts moved through the reservoir at decreasing velocities as flow decreased and the dam was approached, but passage was generally not hindered. At flows below 100 kcfs, smolt migrations were slowed markedly at the dam, often to zero, and they began extensive upstream movements. These upstream wanderings often exceeded the length of Lower Granite pool and took many days, potentially exposing smolts to more predators, excessive use of stored energy, or other factors affecting survival. Similar results were seen for underyearling fall chinook salmon in Little Goose Reservoir 1995-1997.

Third, the current view of the effects of flow on smolts is also not consistent with a number of physical and biological mechanisms in reservoirs and at dams that clearly do not operate in a way that is strictly proportional to flow. The text and appendices describe some of these mechanisms.

Superficially, the patterns for reach survival and telemetry suggest a survival benefit from increasing flow when flow is low, but no indications of added benefit at higher flows, within the range of flows that have occurred in the past few years. At a deeper level, however, many questions remain. These questions concern the possible mechanisms for the different effects at different flows (and whether they might be managed more effectively than flow alone). They also concern how travel time and survival of smolts in discrete river reaches relates to timing and success of passing down river, through the estuary, and into the ocean. This latter set of concerns is beyond the scope of this report, but is worthy of additional analysis.

Snake River: A Different Rationale and Implications for Management

These results indicated to the ISAB that the prevailing rationale for decreased survival at lower flows (reduction in average river velocity, which slows migration and, for example, fosters predation) deserves reexamination. That is, why should there be a break in the flow-survival relationship? What causes it? Does the radiotelemetry study point to details of fish behavior that could provide some answers? Does reach survival change with flow simply as a result of changed exposure time to the same sources and rates of mortality? Is there an effect of flow on the mortality rate itself, such as smolts being exposed to a different suite of predators as they wander back upstream? Are the flow effects confined to the lower range of flow rates, or are we simply obscuring the effect at high flows by measuring reach survival over too short a distance? Would clarifying the causes for the observed data offer opportunities for hydrosystem management other than simply adding more water to the river?

We identified several alternative explanations (hypotheses) for the correspondence of observed flow-survival data and radio-telemetry data, which are not necessarily mutually exclusive. These alternatives do, indeed, lead logically to management opportunities that extend beyond flow augmentation as presently defined. This report outlines several of them. We assembled enough information about them to suggest that they need serious further study and evaluation.

Some of our explanations arose from asking, "What river operations, other than average flow rate, change in the vicinity of the breakpoints?" Such operations might be changed to benefit fish.

One such operation is the fluctuation of dam discharges in ways that are more prominent at lower flows. We find that we have rediscovered a concern that was at the forefront of research in the Columbia River by NOAA Fisheries in the 1970s. We determined, through flow records obtained from DART and other databases, that discharges from the lower Snake River dams fluctuate hourly on a daily cycle (as is well known in the mid-Columbia). The cycle generally follows electricity demand—low at night and highest at the beginning and end of the workday. These fluctuating discharges produce pulses of flow in downstream reservoirs and dam forebays that are not described by the average annual, weekly, or daily flows that to-date have been used in fish-survival studies. Such fluctuations occur at flows that are less than the hydraulic capacities of the powerhouses in the Snake River and the fluctuations are much greater relative to the daily average flow the further these flows decline. The frequency and duration of fluctuations are greater at low flows than at higher flows. During flows typical when underyearling chinook migrate, in July and August the difference between daily maximum and minimum flow rates can exceed 150% of the daily average flow. At the lowest flows, typified by those in January 2003, we determined that the pulses of high and low discharge induce an oscillation (seiche) in the reservoirs, similar to water sloshing in a bath tub, that can induce reverse flow. There would be progressively greater disruptions of river-reservoir hydraulics as flows decline and fluctuations become more prominent. These altered hydraulic patterns likely affect fish orientation and migration, with increased exposure to predators and increased energy consumption at lower flows. This fits the previously observed flow/survival relationship, including the apparent breakpoints in the flow-survival relationships, and it suggests a possible management solution. We believe stabilization of flows could be more effective in improving survival of juvenile salmonids than simply adding a volume of flow, as in flow augmentation, where water can be released intermittently. Instituting stable flows might be undertaken as an experiment. The effects on survival of juvenile salmonids should be measurable immediately.

Other explanations for the correspondence of the apparent breakpoints and hydropower operations arose from considering the biological aspects of smolt migration in reservoirs that may be affected by differences in flow, either stable or fluctuating. Such aspects may be more difficult but not impossible to manage for the benefit of fish.

When smolts migrate downstream using various behavioral cues to distinguish direction, as is generally believed, the cues may diminish or disappear as flows are progressively more impounded near dams. The riverine turbulence and velocity cues may diminish to the point where the fish loses its orientation, stops migration, swims back upstream in an attempt to relocate the flow, or follows the reverse flow induced by a seiche. This is the migration pattern observed in telemetry studies of yearling chinook and steelhead and underyearling chinook, although the mechanism is not established. Further study of reservoir hydraulics at different flows and fish migration mechanisms are needed.

Management approaches to providing more migration cues in reservoirs without augmenting flows might include artificial induction of turbulence and/or velocity and drawing reservoirs to lower levels to extend the riverine reaches closer to the dam. It is clear that different species and life stages of migrants behave somewhat differently and will require somewhat different solutions. Detailed travel time and survival relationships differed among yearling chinook salmon and steelhead, and underyearling chinook salmon. It is possible that the relationships also will be different for other stages of the life cycle and other anadromous species such as coho, sockeye, and lamprey.

Some of the benefits of flow augmentation in the lower Snake River are actually intended for temperature control rather than to enhance the volume of water. The fact that summer temperatures are lowered by selective release of cold water from Dworshak Dam should be a stimulus to consider temperature management in its own right for summer and fall migrants, instead of as a component of aggregate flow changes. This consideration should include the time-dependent trade-off for using water sources differing in temperature (e.g., a warm Snake River from Hells Canyon Dam versus a cold Clearwater River entering Lower Granite pool) to produce combined effects on smolt physiology, migration, and survival.

The effects of water clarity, gas supersaturation, and other factors in the lower Snake River may influence both migration and survival, as several studies have suggested. They probably contribute to the wide scatter among data points seen in flow-survival plots. These factors are often correlated with flow and temperature, and it is unlikely that their effects can be separated clearly by passive monitoring in the absence of deliberately designed experimental manipulations. In general, regression and correlation studies of the relationships of fish survival to flow, water clarity, temperature and other factors are consistent with our findings. However, we do not believe that further refinement of multiple regression estimates will by themselves resolve the relative influences of these factors. Controlled experiments are needed. The experiments are feasible, but may be regarded as excessively disruptive or have the potential to kill significant numbers of fish.

The paradigm that faster movement of smolts to the estuary and ocean is always favorable for survival needs to be evaluated. Most of the reach survival studies we reviewed make this assumption. Increased migration rate and survival in the studied reaches (primarily the lower Snake River) does not ensure survival in lower reaches. The fish have to spend their time somewhere and could experience increased survival rates, the same survival rates, or decreased survival rates. We see a need for more specific analysis of the relationship between survival rates in the upper reaches of the rivers, survival rates in the lower reaches, date of arrival of smolts at the estuary, timing of ocean entry, and their subsequent ocean survival. We see the need for continuing analyses of the effect of annual flow during the outmigration period by separating measurement of in-river survival and ocean survival, with special attention to the more detailed mechanisms having to do with temperature, smolt condition, date of arrival in the estuary and ocean, and measures of ocean conditions.

We recognize another factor that affects reach survival estimates and could produce curves resembling a "broken stick" model. The flow augmentation paradigm is ambiguous, because it fails to distinguish between effects of travel time in a reach and effects of the instantaneous mortality rate (from whatever cause) in that reach, and because it fails to place reach survival in the context of life cycle production. Total elapsed time affects the estimate of total mortality in a reach, due to expected effects of the life table for the fish. The analyses to date have not determined whether the pattern observed has a component due to changes in instantaneous mortality rate. Until that point has been resolved, we cannot know whether the observed pattern of better survival at higher flows is simply a result of shortening the exposure time in the measured reach, with no change in instantaneous mortality rate. Unfortunately practically nothing is known about favorable times for arrival to the estuary and ocean. The region is operating on the established fact that development and operation of the hydroelectric system has resulted in a shift in timing of outmigration of juvenile salmonids toward later times of arrival. On that basis, it has been reasonable to proceed with measures to speed their movement, regardless of whether instantaneous mortality is variable or constant.

The Council's proposed mainstem amendments, as interpreted to us by Council staff in terms of average flows, will likely not have major effects on the migration and reach survival of yearling chinook salmon and steelhead migrating in the river during peak flows of spring (generally over 100 kcfs in the lower Snake River). In contrast, the reduced flows in comparison to BiOp of July-August (near or below 50 kcfs) have the potential of significantly reducing the reach survival of underyearling chinook salmon. Transportation of smolts by barge or truck will lessen some of this effect, although our review has concentrated on in-river migrants. We encourage evaluation of factors other than just gross flow and flow augmentation as presently defined in the management plans (e.g., evaluation of the effects of fluctuating dam discharges and other mechanisms). Based on life cycle considerations, touched on only lightly here, we recommend that future analyses, wherever possible, consider survival to the estuary and survival from the estuary to adult return as important indicators of the effect of a flow regime.

Finally, the ISAB believes that, with improved knowledge and subsequent management actions, it may be possible to achieve improved survival of juvenile salmonids through the lower Snake River reaches and their dams, even at lower flows. With an expanded perspective, this might occur at lower costs for operation of the hydrosystem and more effective use of stored water for other purposes than is possible with the prevailing flow-augmentation paradigm.

Mid-Columbia and Lower Columbia Reaches

Flow appears to be the most influential factor affecting migration speed of steelhead and sockeye; for yearling chinook no effect of flow on migration speed has been found (only level of smoltification affected migration speed); for subyearling chinook no environmental variable was found to affect migration speed in the mid-Columbia. Since 1998, PIT tag and radiotelemetry studies have produced limited data on the survival of yearling chinook. Data on other species is even more limited. The studies-to-date do not indicate any statistically significant effect of flow on survival of juvenile salmonids in the mid-Columbia Reach, other than in the Hanford Reach, where stable flows are the issue.

Limited data are available for lower Columbia Reach. Low flows are likely to lead to residualization of steelhead.

Life History Survival

Survival throughout the life history of the fish is the element of concern. Reduced or increased travel time may be disadvantageous if it results in arrival in the estuary and/or ocean at times when conditions are not favorable for survival. Further research is needed on relationships of travel time and survival and favorable times for arrival of fish in the estuary and ocean.

Resident Fishes

It is a well-established fact that storage reservoir drawdowns result in adverse effects on resident fish populations and their associated fisheries. In earlier reports we recommended that an effort be made to balance the needs of resident fishes upstream against those of juvenile salmon downstream. We identified the Rule Curves developed in Montana as being reasonable approaches to resolving difficult policy issues with biological implications. The subject of tradeoffs of benefits to salmon versus detriments to resident fishes is one of the subjects deserving high priority action by the Council.

Review of Flow Augmentation: Update and Clarification

I. Assignment, Background, and Procedure

Assignment:
At its November 14, 2002 meeting, the Council approved a request for the ISAB to update and clarify its review of flow augmentation, and submitted a list of questions to the ISAB. On December 12, 2002, CRITFC added a set of questions related to the Council's request. We received additional questions from the Council, and were forwarded (for background) several questions posed in comments on the Council's draft mainstem amendments. On December 19, 2002, the ISAB specified the questions that the ISAB felt it could address by January 31, 2003 and proposed a timeline to address questions it could not adequately address by January 31. The January 31 deadline was extended one week at the ISAB's request.

The Council asked the ISAB two different sets of questions related to the flow-fish survival relationship and of the role of flow augmentation from storage reservoirs. Because similar questions are raised by the Council's draft mainstem amendments, the Council thought it would be useful to obtain an ISAB review in time to contribute to the Council's final decisions on mainstem program amendments.

This report answers Council and CRITFC questions that the ISAB could address by about the January 31 deadline. The report also provides a more general synthesis of new information and the ISAB's views of flow augmentation. If requested, the ISAB can continue its review and provide more information on questions or issues it did not have adequate time to address.

The questions arose, in part, from issues not resolved in the ISAB's recent reviews of flow augmentation and flow-survival relationships (ISAB's review of the Giorgi et al. 2002 summary report [ISAB 2002-1] and ISAB's Review of Lower Snake River Flow Augmentation Studies [ISAB 2001-5]). These questions concern the relevance of conclusions about year-to-year differences in survival at prevailing flows for determining the effects of within-year flow augmentation. Another set of questions concerns the proper statistical methods for evaluating information on flow/survival relationships. There was an expressed desire for scientific peer review of recent analyses by other regional groups related to flow and juvenile salmonid survival that were not examined in the previous ISAB reviews. These analyses include but are not limited to those of the Fish Passage Center (FPC), NMFS, USFWS, and the Idaho Department of Water Resources.

We are pleased that during the hearing on December 11, 2001, Council and staff quoted several statements from previous ISAB reports. However, we stress that the report presented here represents results of our study of much information that was not previously available. Therefore, any conflict that might be discovered is to be resolved in favor of statements in the report presented here.

This report provides, in sequence, a brief background of the flow augmentation issue, an overall ISAB conclusion regarding the present status of scientific knowledge bearing on flow augmentation that is based on our review (regardless of the specific questions), the specific questions and our answers, an appendix that provides evidence supporting our conclusions and answers, an appendix that provides alternative hypotheses for the observed data, and an appendix that mathematically describes a null hypothesis for survival estimation. The evidence section is organized by specific points. Our report was prepared with limited time to refine the presentation in order to provide the Council with the thrust of our review in a timely manner, and could be further refined and enlarged with additional work.

We acknowledge others who have contributed greatly to the evolution of thinking about flow and smolt survival. The region has a large contingent of capable experts in fishery biology and statistical analysis, and they have placed considerable emphasis on efforts to address this issue. We will not attempt to name them all because it is such a long list we are certain to inadvertently leave some out, but in preparing this report, we acknowledge especially the capable assistance of biologists and statisticians from NOAA Fisheries, the Fish Passage Center, the University of Washington, the U.S. Fish and Wildlife Service, and the Idaho Department of Fish and Game. The Fish Passage Center and the University of Washington, by means of DART, were particularly helpful in providing data and analyses at our request. We appreciate the review provided by Malcom W. Karr of our description of likely hydropower operations in the Snake River as affected by hydraulic capacities of the powerhouses. We take responsibility for any errors.

Our review has benefited by the fact that, at the request of the Council, the ISAB or its predecessor, the Independent Scientific Group (ISG), have participated in several related reviews in the past. These include review of the Hungry Horse/Libby situation (ISG 95-3; ISAB 97-3), a review of the Fish and Wildlife Program (ISG 1996; ISG 2000), review of the report by Dreher et al. (2000) (ISAB 2001-5) and review of Giorgi et al. (2001) (ISAB 2002-1).

Background:

Development and operation of the hydroelectric system in the Columbia River Basin led to changes in the normal pattern of flow (NWPPC 1982; NRC 1996; ISG 2000). In addition to storage dams on U.S. tributaries (e.g., Hungry Horse, Libby, Dworshak, and Brownlee) and dams on the mainstem, which for the most part were run-of-the-river projects with little storage capacity in their reservoirs, a 1961 treaty between the United States and Canada provided for construction of dams for substantial storage of water in the Canadian portion of the Columbia Basin, and of dams in the U.S. that would back water into Canada. In addition to the treaty, an agreement between BPA and B. C. Hydro, known as the "Non-Treaty Storage Agreement." provides for additional storage behind Mica Dam in Canada (Resource Writers, Inc. 1991). These, and to some extent, Grand Coulee Dam, are the primary regulators of flow in the mainstem, as their reservoirs are lowered seasonally to allow for capacity that will alleviate flooding during the spring freshet, and refilled as sources of water to be stored for later power production and other uses. Similarly, Brownlee reservoir and other upstream reservoirs on the Snake River provide the storage capacity for flood control, irrigation and power production, and other uses on the Snake River. Dams below Brownlee on the Snake River are primarily run-of-the-river projects with little storage capacity (Resource Writers, Inc., 1991). As a result, the magnitude of the spring freshet has been reduced[1], and this reduction has many ecological consequences that might affect salmon production. One particular hypothesized relationship has attracted considerable attention, i.e., the concern that juvenile salmonids migrating downstream at the time of the spring freshet might experience in-river mortalities that are higher than normal because of the diminished flows. Therefore, the first Fish and Wildlife Program in 1982 specified a modest volume of water, identified as the "Water Budget" to be used in the spring months for the purpose of improving survival of juvenile salmonids as they make their way downstream (NWPPC, 1982; NRC, 1996; ISG, 1996, 2000)[2]. Subsequently, specified flows have been added to benefit summer migrants. Flow augmentation has been the subject of contention from the beginning.

Water volumes, identified in the NOAA Fisheries Biological Opinion and/or the Council's Fish and Wildlife Program for flow augmentation, are released by the Corps of Engineers and BPA both from upriver Columbia River storage reservoirs and from upper Snake River reservoirs. In the Snake River, flow augmentation for the purpose of temperature reduction also takes place from the Corps' Dworshak Dam on the Clearwater River, just above its confluence with the Snake River (Figure 1).

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[1] In addition to reducing the magnitude of the spring freshet, the effect of drawing upon water from the depths of Lake Roosevelt above Grand Coulee Dam has led to delay of the timing of peak summer water temperatures downstream since 1941, an effect that may reach as far downstream as Bonneville Dam (Ebel, et al., 1989). On the other hand, water at Brownlee Dam is drawn from the surface of the reservoir and is warmer than the incoming Snake River, and warmer than tributaries that enter below the dam, resulting in warmer temperatures in the river below (Anderson, Hinrichsen, and Van Holmes, 2000; Connor et al, in press).

[2] The water budget and flow augmentation are specified in two parts, one as a volume of water to be provided from upper mainstem reservoirs, and the other from Snake River sources.

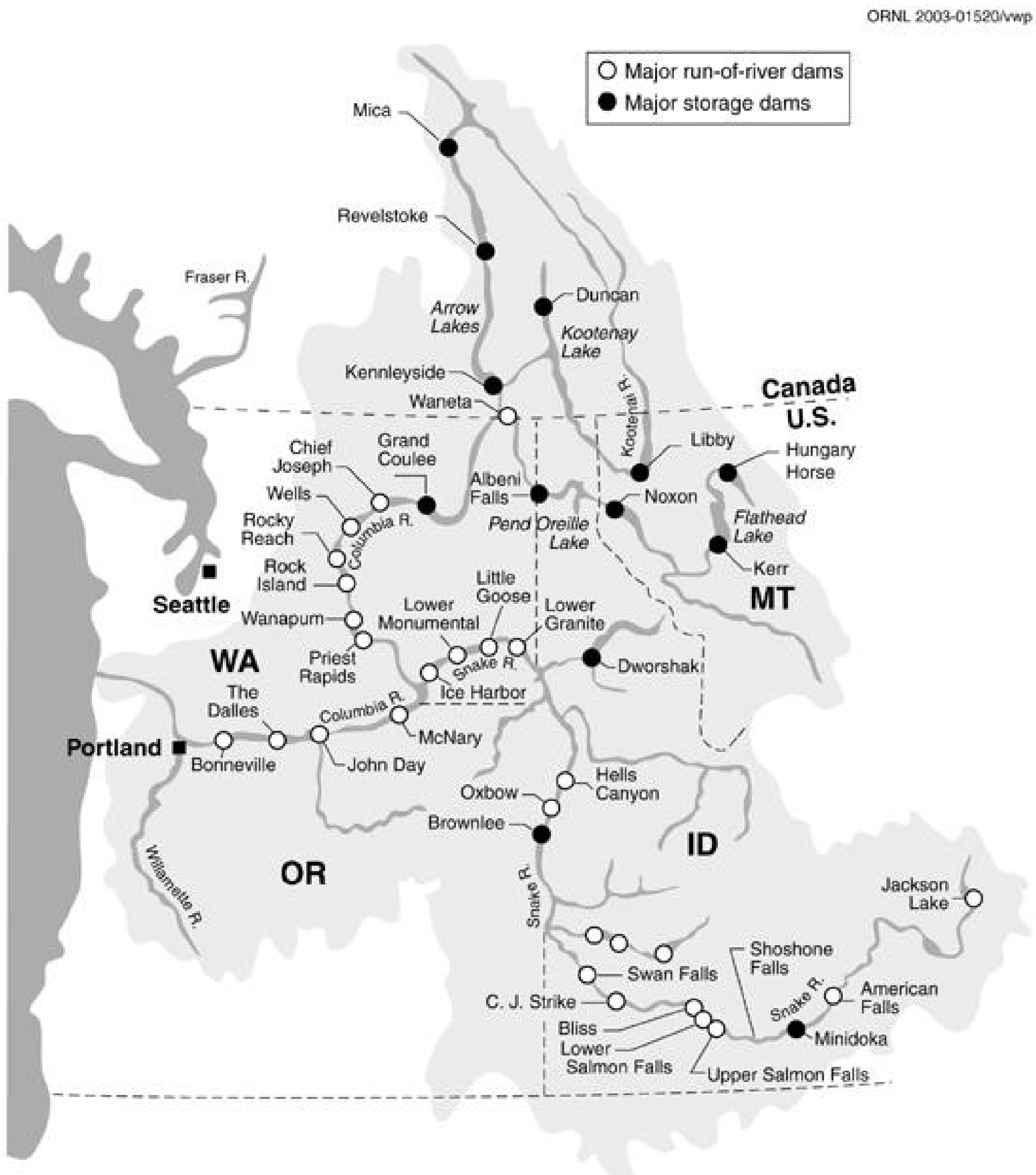

Figure 1. Columbia River basin showing storage reservoirs and run-of-the-river, non-storage reservoirs.

In the 1994 Fish and Wildlife Program, the Council proposed a specific hypothesis to be tested describing the relationship between flow, water velocity, and fish travel time and survival (NWPPC, 1994). The region's scientific teams have concerned themselves with this issue since at least 1981 when Sims and Ossiander of NOAA Fisheries plotted the annual average survival estimates for yearling chinook salmon against average flows during the period of outmigration from 1973 through 1979 (Sims and Ossiander, 1981). That study formed the basis for the Council's adoption of the water budget (McConnaha, 1993). Analyses based largely on the Sims and Ossiander model have been updated and refined continually to the present, using an increasing accumulation of additional and more refined data on fish movements and survival.

Procedure:

In developing the following response, the ISAB queried many scientists for their current research and analysis related to the debate concerning benefits of flow augmentation. One ISAB member attended the December 11, 2002 briefing of the Council where presentations were made by Karl Dreher of the Idaho Department of Water Resources, John Williams and Bill Muir of NOAA Fisheries, Chris Van Holmes of the University of Washington, and Bruce Suzumoto and John Fazio of Council staff. In addition, the ISAB arranged briefings on December 16, 2002 from Steve Smith of NOAA Fisheries, Margaret Filardo of the Fish Passage Center, Howard Schaller of the U.S. Fish and Wildlife Service, and Charles Petrosky of Idaho Fish and Game. Written reports were provided by these speakers, as well as by W.E. Connor of the U.S. Fish and Wildlife Service. Many other sources were consulted as shown in the references list at the end of this report, and in the acknowledgements. The Fish Passage Center, DART, and NOAA Fisheries responded to specific requests for additional data and analyses. In addition to reviewing the work of others, ISAB members conducted independent analyses of these and other data. The ISAB and its predecessor, the ISG, have been engaged in study of the issue in responding to previous requests from the Council or NOAA Fisheries. Reports resulting from these studies are cited in the text and the list of references.

II. Current Status of Scientific Knowledge

Snake River

After careful study of currently available evidence, we have concluded that, for the Snake River, the analysis of effects of river flow on survival of juvenile salmon and steelhead conducted by NOAA Fisheries' statistician, Steve Smith, is the most complete, up to date, and credible. That analysis includes a mathematical approach to describe a "broken stick model."[3] That study develops an estimate of a breakpoint in the data (i.e., a rather sharp change in the slope of curves fitted to the data) for yearling chinook and steelhead at average weekly Snake River flows of about 100 kcfs as measured at the lower Snake River projects, Figure 2. It is unclear if the breakpoint is related to a change in the instantaneous rate of mortality, to a change in the length of time spent in reaches of the river, or to a combination of factors. These relationships are discussed further throughout the text below, and Appendix 4 specifically discusses the effects of the instantaneous rate of mortality.

While there are different mathematical and statistical methods available for arriving at more precise estimates of the "breakpoint", it is unlikely that there is a distinct best point

[3] There are other terms used in the statistical literature to describe this phenomenon, but we choose to use the terminology first employed by Chapman et al., 1991 in the present context. There may be more precise methods of arriving at the point, but the method used by Smith is probably adequate for now.

under all conditions, and these NOAA Fisheries estimates should adequately serve for management purposes. The "broken stick" model reveals that there is a strong effect of flow on survival of yearling chinook and steelhead when average weekly flows in the Snake River are below the 100 kcfs breakpoint, and indicates no apparent relationship when flows are above that level. Under the current strategy of augmenting flows in order to correct the losses caused by development and operation of the hydrosystem, it would be necessary to provide sufficient average weekly flow of 100 kcfs during the period of outmigration of yearling chinook and steelhead, predominantly in late April, all of May, and early June each year. When natural flow is above that level in those months, no augmentation would be justified based on the current data, since no improvement in survival can be shown to occur. When flow is as low as in the years 1973 and 2001, it would undoubtedly tax the storage capacity of reservoirs in the Snake River to provide flows as high as 100 kcfs through the period of outmigration.

According to the analysis by John Fazio, in low flow years, the Council's proposed amendments would provide the same amount of flow as the BiOp during April and May at Lower Granite Dam, and somewhat less in June. By that time, the yearling chinook and steelhead outmigration is near its normal end, so the effect of reduced flows on their survival would probably not be substantial. We also conjecture that effects of reduced flows might be avoided with a different approach to management of the system.[4] This possible alternative to the current "flow augmentation" will be discussed below.

The situation is different with fall chinook that migrate later in the year, travel through the system more slowly, and experience higher levels of mortality while migrating in-river than do yearling chinook and steelhead. Fall chinook migrate through the lower Snake River predominantly in July and August, when river flows typically will have declined below the apparent 100 kcfs breakpoint for the other fish. Plots of weekly survival of fall chinook versus average weekly flow during outmigration suggest a breakpoint somewhere between 40 kcfs and 50 kcfs (figure 3). During low flow years, the Council's proposed amendments to the Fish and Wildlife Program would provide about the same flows in April and May at Lower Granite as the BiOp, but lower flows (by about 7.5 KCFS – a 17% reduction in expected flows as compared to the BiOp) than does the BiOp in July, a little less during the first two weeks of August (by 3.5%), but more during the last two weeks of August at Lower Granite Dam (by about 7.5 kcfs – roughly 30%), Figure 4, and Table 1. The result is likely to be a larger negative effect on survival of fall chinook than on yearling chinook and steelhead, judging by flows in the 30% of driest years in the record.[5] Again, we conjecture that there may be a way of ameliorating those effects on fall chinook, which may improve the survival of all three stocks

[4] Bruce Suzumoto used SIMPAS to estimate changes in survival that might result from the Council's proposed modifications. But he says, "SIMPAS is not highly sensitive to changes in flows. Another regional model might be better to estimate the effect of flow changes on total system survival". (Suzumoto, B. 2002. Mainstem juvenile survival: CRiSP modeling results. Memorandum of December 2, 2002 to Council members)

[5] The CRiSP analysis depends upon assumptions about spill amounts and spill effectiveness that may or may not be met, and it depends upon a specified effect of flow on survival, which we believe is improved upon by the NOAA FISHERIES "broken stick" model.

whenever weekly average flows decline to below 100 kcfs. To adequately explain this proposal, it is necessary to provide sufficient background, based on our interpretation of the current status of scientific information. We will then answer the Council's questions. In the process of doing so, the necessary foundation for our proposal will be established.

Figure 2. Plots of survival at various flow rates for yearling chinook and steelhead 1995-2001 illustrating a broken stick model (from Steve Smith presentation to ISAB, December 16, 2002).

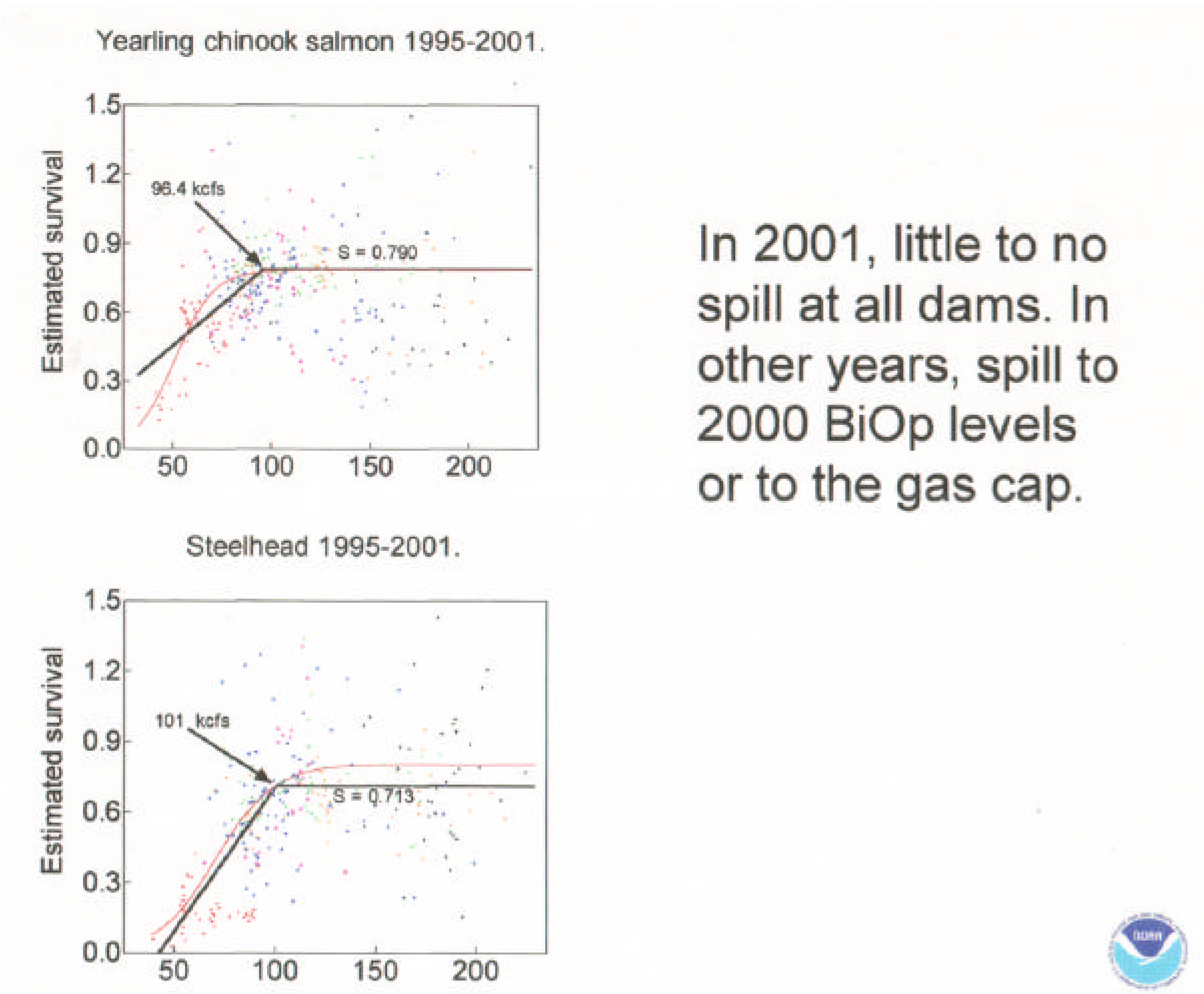

Figure 3. Relationship of Survival with Flow for Fall Chinook in the Snake River 1999 and 2000 (from Berggren attachment to Fish Passage Center Memo of 10/27/2000).

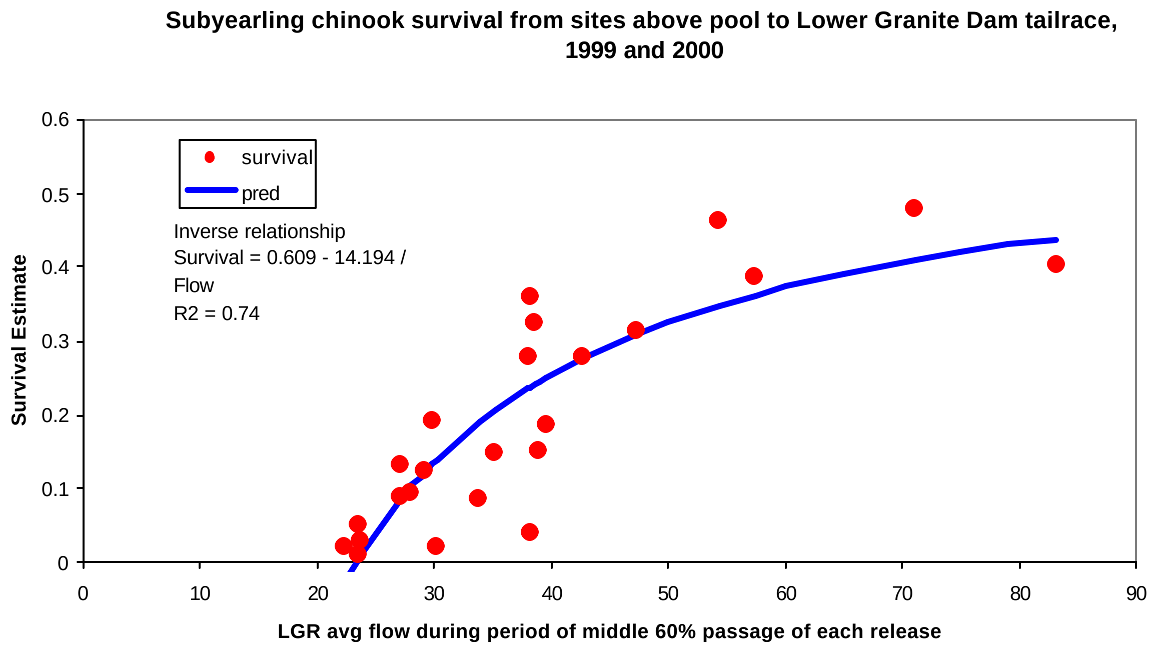

Figure 4 and Table 1. Fish and Wildlife Program Draft Mainstem Amendment compared to BiOp: Flows at Lower Granite (averaged over the driest 30%). (From John Fazio presentation to the ISAB, December 16, 2002).

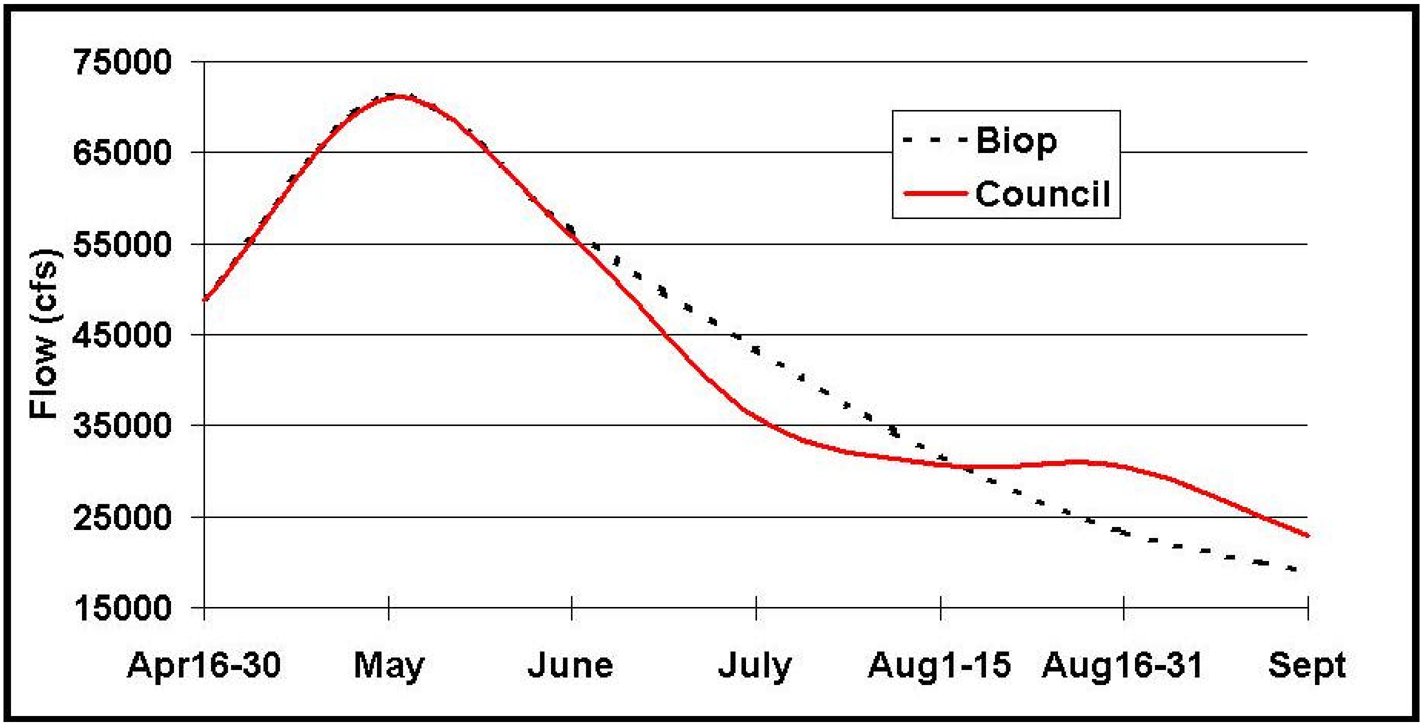

Table 1. Changes to Summer Flows at Lower Granite Dam (average of driest 30%)

	July	August 1-15	August 16-31	September
Percent Change	- 17%	- 3.5%	30%	20%
BiOp Flow (kcfs)	43	32	23	19
Council Flow (kcfs)	36	31	31	23

Mid Columbia and Lower Columbia Reaches[6]

In the early 1980s the mid-Columbia PUDs sponsored juvenile salmonid survival studies that extended throughout the reach from above Wells Dam to below Priest Rapids Dam. (Chapman and McKenzie, 1980; McKenzie et al., 1982; 1983) These were intended to provide base line information on per project mortality rates, and were not designed to extract information on effects of factors like flow, temperature, or other variables. Since that time, the Fish Passage Center has conducted studies to measure smolt travel time and survival through the mid-Columbia Reach to McNary Dam. We depend upon the summary provided by Giorgi et al. (2000) for the following information on effects of flow on travel time in the mid-Columbia Reach: Flow appears to be the most influential factor affecting migration speed of steelhead and sockeye; for yearling chinook no effect of flow on migration speed has been found (only level of smoltification affected migration speed); for subyearling chinook no environmental variable was found to affect migration speed in the mid-Columbia.

The mid-Columbia PUDs have conducted travel time and survival studies of yearling chinook, and steelhead since 1998 using PIT tag and radiotracking technologies. Rocky Reach Dam is equipped with a PIT tag detector. Survival estimates are available for hatchery chinook and steelhead for the reach of river from upriver hatcheries to Rocky Reach Dam. McNary Dam is the next project that can detect PIT tags. Survival estimates are available for the reach from Rocky Reach to McNary Dam that were conducted by the Fish Passage Center. These limited data do not show a relationship of travel times of yearling chinook and steelhead with flow, though it appears there may be a threshold of flow at about 70 kcfs below which movement may be slowed. However, earlier studies with more data have shown clear effects of flow on travel time of steelhead and sockeye in the mid-Columbia Reach (Giorgi et al., 1993; Berggren and Filardo, 1997). Calendar date is the most important determinant of migration speed.

The studies to date do not indicate any statistically significant effect of flow on survival of juvenile salmonids in the mid-Columbia Reach, other than in the Hanford Reach, where it has been clearly established that stable flows are required during spawning of fall chinook, incubation of eggs, emergence of fry, and now emigration of fry from the Reach (e.g. Tiffan et al., 2002). More information on this subject is provided under the heading of Effects of Flow on Survival in the text below and in the Appendix.

Lower Columbia Reach

Recoveries of PIT tagged fish from the mid-Columbia suggest that date of arrival at Bonneville Dam is key to their successful movement out of the river. Current evidence indicates that steelhead are likely to residualize between McNary and The Dalles if they are late, and yearling chinook are likely to die in place. Chinook are quite dependent upon flow for determining their movements in the Lower Columbia Reach.

[6] We thank Shane Bickford of Douglas County PUD for the following information on studies of travel time and survival of juvenile salmonids in the mid-Columbia Reach (personal communication).

PIT tagged fish from the Snake River are also recovered in the Lower Columbia Reach, providing information on travel time and survival (Bill Muir briefing). PIT tag detectors are now present at all of the lower river dams except The Dalles Dam. A major finding has been that there appears to be no benefit to transporting subyearling chinook from McNary Dam. These would primarily be fish from the mid-Columbia Reach, because Snake River fish are collected upstream for transportation. Survival of fish migrating in-river from McNary to below Bonneville Dam in these studies is higher than transported fish. Water temperature strongly affects survival of fish, but so do several other environmental variables. An experiment would be needed to separate the effects.

Findings and Synthesis: What Mechanisms Operate on Survival of Juvenile Salmonids When Flow is Reduced?

The following sections of the report develop a different viewpoint on the relationship of river flow and survival of outmigrating juvenile salmonids. We use the word "different", but we note that it is not a new viewpoint. Researchers of NOAA Fisheries were working 30 years ago under a project entitled "Effects of Power Peaking Operations on Juvenile Salmon and Steelhead Trout Migrations (Sims, Bentley, and Johnsen, 1977, 1978). They were clearly ahead of their time. Study techniques available at that time were not adequate for the task of documenting the effects they sought. That situation has changed recently with the development of the PIT tag for estimating mortality over short reaches and time intervals, and small radio tags that permit following immediate reactions of salmonid smolts to river conditions. We believe that viewpoint on power peaking sheds light on the mechanism that leads to the relationship. It does not negate previous studies that have demonstrated relationships of survival, flow, and other factors. But the mechanism that is suggested leads to a recommendation for a strategy other than simple flow augmentation. We believe the new strategy might reduce mortalities of juvenile salmonids induced by development and operation of the hydroelectric system in a way that could prove to be an additional or alternative for the flow augmentation strategy.

Effects of Flow on Operation of the Hydrosystem. Analysis of the Broken Stick Model: What are the mechanisms that could explain the broken stick model?

The hydroelectric system is cooperatively managed according to the "Pacific Northwest Coordination Agreement" (PNCA), an agreement among the various owners and operators of the major hydroelectric facilities in the Northwest (Logie, 1993). In the Columbia Basin, because the volume of water reaching lower river (run-of-the-river) projects is dependent upon releases from upstream, coordination is essential in order to optimize power production from the system as a whole, and to make it possible for lower river projects to maintain their reservoir elevations within allowable limits (Specified by the Federal Energy Regulatory Commission (FERC) or the BiOp). Water releases are coordinated on an hourly basis in the mainstem Columbia and Snake rivers. A summary of the Coordination Agreement was provided in ISG (2000-12). More details are provided in Logie (1993). The Agreement went into effect in 1965, and its term extends until June 30, 2003. The Council has long expressed a particular interest in protection of fall chinook in the Hanford Reach, having received and acted upon recommendations from the ISAB on several occasions. The Coordination Agreement is a key piece in the ability to accomplish the Council's measures for protection of fall chinook in the Hanford Reach, one of the few healthy populations of salmon in the Columbia Basin.

Hydraulic capacity[7] of the run-of-the-river projects is a factor that affects the volume of water released from upstream storage reservoirs, after the requirements for flood control are met. In the mid-Columbia Reach the hydraulic capacity of each project is about 200 kcfs. In the four lower Snake River projects, hydraulic capacity is about 130 kcfs at each powerhouse, except Ice Harbor where it is 110 kcfs (DART web site). There is an additional factor in the Snake River because the hydraulic capacity of the projects upstream of the lower Snake River projects is less, about 30 kcfs at Hells Canyon, Oxbow, and Brownlee dams, and 10 kcfs at Dworshak Dam. The generating capacity per unit volume of water is greater at Hells Canyon, Oxbow, Brownlee and Dworshak than the four lower Snake River projects due to their higher head and turbines installed to accommodate the head. Therefore, when Snake River flows decline to the neighborhood of 40 to 50 kcfs, it seems likely that these four powerhouses become the focus of optimization for power production out of the Snake River portion of the system.[8] The result is likely to be that, as long as upper Snake River flows are above about 30 kcfs, there must be spill at the three Hells Canyon complex projects unless they can store the water for slow release later. Brownlee reservoir has some storage capacity that can be used for this purpose. Oxbow and Hells Canyon dams are run-of-the river projects, as are the four lower Snake River projects. Thus emerges a picture of "power peaking" operations in the lower Snake River.

In summary, as long as inflow is higher than about 100 kcfs, all of the powerhouses can operate at full hydraulic capacity. Spill will be required at the dams in the Hells Canyon complex when flow exceeds their hydraulic capacity at about 30 kcfs. When upstream inflow declines to the neighborhood of 100 kcfs and below, flows are likely regulated first to optimize production out of the four lower river projects, and intermittent releases from the Hells Canyon complex are likely to be the result. These intermittent flows likely increase in frequency, duration, and magnitude as the inflow declines further. When a breakpoint of near 30 kcfs inflow into Brownlee reservoir is reached, the focus on power operations will likely shift to the Hells Canyon complex, Hells Canyon, Oxbow and Brownlee, because those projects, having higher head, can produce more power per unit of water[9]. Thus, at flows of about 30 kcfs and below, intermittent flows out of Brownlee, and thus Oxbow and Hells Canyon dams likely will become more frequent, of longer

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[7] Hydraulic capacity is the volume of water that can be passed through the turbines at the particular powerhouse.

[8] 1255 MW total for the Hells Canyon complex (1715.4MW including Dworshak) to provide 40 kcfs at Lower Granite, compared to 1098.5 MW for the four lower Snake R. powerhouses at 40 kcfs

[9] Another factor that enters the picture at Brownlee Dam and other Snake River storage reservoirs is that the state of Idaho does not allow water to be spilled at any upstream project for flow augmentation for fish. However, spill can take place when necessary to accommodate high inflow, and presumably to enhance power operations. Still another factor is that Idaho Power is not a party to the Pacific Northwest Coordination Agreement, so is likely to shift as early as feasible to maximize power production out of the Hells Canyon complex of dams.

duration, and of greater magnitude as inflow decreases. Side flows from Dworshak Dam (10 kcfs) and the tributaries above Lower Granite will contribute additional flow, perhaps an additional 10 to 20 kcfs. As measured at Lower Granite Dam another break in operations will thus likely be exhibited in the neighborhood of 40 to 50 kcfs (30 + 10 + 10).

The lower the flow, the greater the frequency, duration and magnitude of episodes of hourly flow fluctuations through the hydrosystem, Table 2.

Table 2 is a compilation of episodes of flow fluctuations during the same period in the years 1999 and 2000 for which Berggren, 2000 estimated weekly survival rates for fall chinook migrating out of the Snake River. Figure 5 illustrates an example of hourly fluctuations that were observed during one time period in July 1999. We used COE hourly flow records out of Lower Granite Dam, which is the same location used for the average weekly flow measurements used by Berggren. At flows less than 50 kcfs reductions in flow occurred an average of once a day, and amounted to a 23 % reduction in flow, for an average of 5 to 6 hours before flow was restored to a level that existed prior to the reduction. At higher flows, such as in the range of 100 to 150 kcfs, such episodes of flow reduction occurred less frequently, an average of one every two days, were of smaller magnitude, about 14% of flow and were of about the same duration. Such episodes of hourly fluctuation at lower Granite Dam must be considered in the context of the implications throughout the Snake River hydropower system. Thus, while Table 2 depicts the flows out of Lower Granite Dam, those hourly flows represent flows arriving at Lower Granite Dam from upstream, (because there is little or no storage capacity in Lower Granite reservoir) i.e. releases from Hells Canyon Dam, Dworshak Dam, and side flow from tributaries, and they are flows that will be passed on to the three lower Snake River projects below Lower Granite Dam.

Figure 5. Example of Hourly Flow Fluctuations in the Snake River 1999

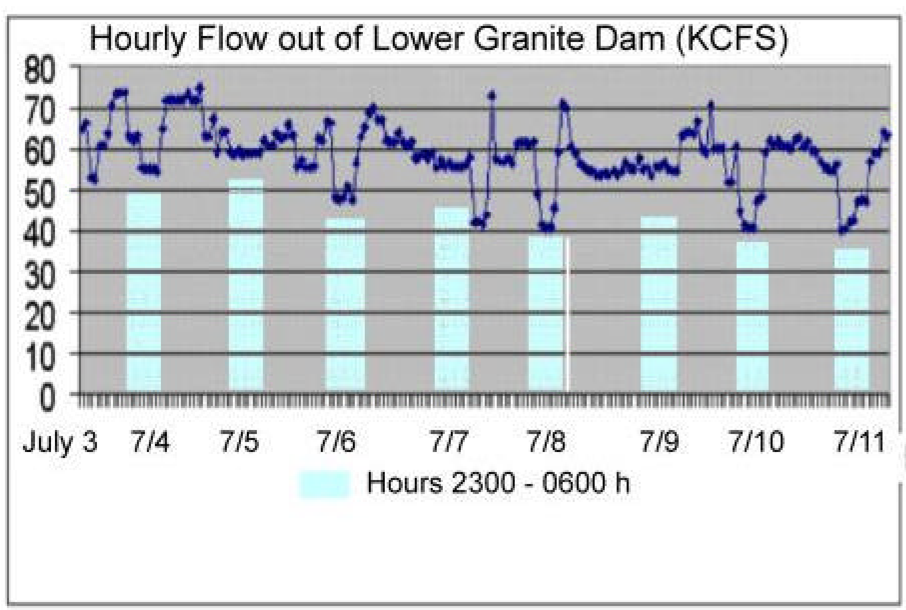


Table 2. RAPID FLUCTUATIONS IN FLOW (HOURLY)
LOWER GRANITE DAM JUNE AND JULY 1999 AND 2000

I. FREQUENCY OF FLOW FLUCTUATIONS

FLOW (KCFS)	#EPISODES	#DAYS	RATIO E/D
<50	44	44	1.00
50-100	35	49	0.71
100-150	11	19	0.57
150+	1	5	0.2

II. EXTENT OF FLUCTUATION

FLOW	NUMBER OF EPISODES AT PERCENT FLUCTUATION								
(kcfs)	10%	15%	20%	25%	30%	35%	40%	45%	AV.%
<50	8	8	5	7	7	7	2	1	23.4
50-100 9	11	12	1	1	1	-	-	-	16.3
100-150	7	2	-	-	-	-	-	-	14.1
150+	1	-	-	-	-	-	-	-	15.0

AVERAGE 18 PERCENT[10]

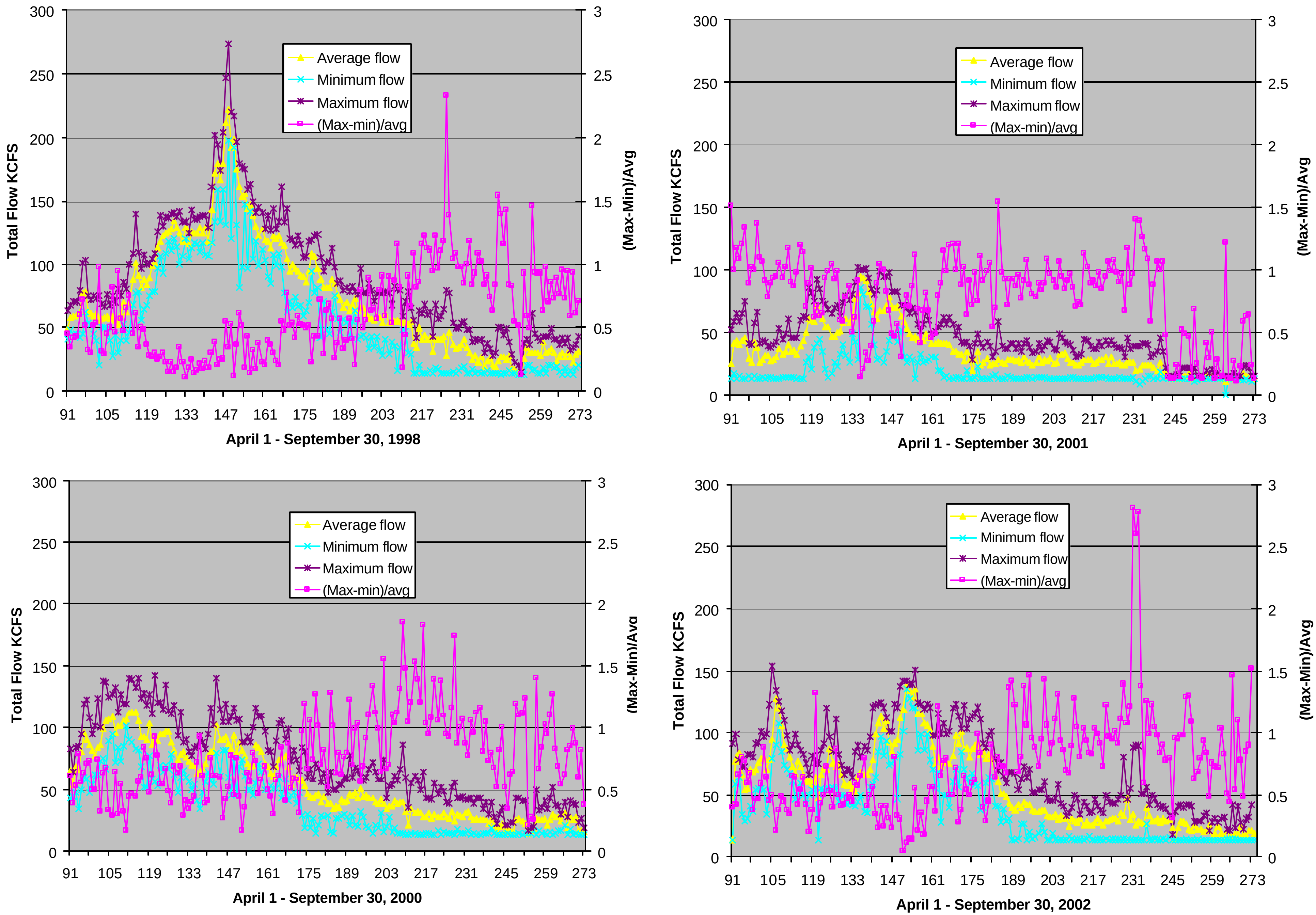
III. TIME OF DAY 58 NIGHT (2400h – 0600)
34 OTHER

IV. DURATION OF FLUCTUATION (HOURS)
AVERAGE 5-6 RANGE 1-8 HOURS

We demonstrated, by independent analysis of flow data for Lower Monumental Dam from 1995-2002, that there are flow fluctuations at all times of year, but that the fluctuations are a greater percentage of the daily average flow at times when average flows are low. These relationships are shown in Figure 6.

[10] An "episode" is apparent from an examination of hourly flow records. It appears as a sudden, sharp reduction in flow, followed by some fluctuations to a minimum, followed in turn by a return to flow that was present before the reduction. The ISAB included only reductions that exceeded 10%, assuming that smaller reductions may not be important.

Figure 6. Daily Flow Fluctuations at Lower Monumental Dam, April 1 - September 30 (1998, 2000, 2001, and 2002)



Effects on Fish: Review of Premises that Would Explain Effects of Flow on Survival

Giorgi et al. (2002) identified the premises that have governed the mainstem measures adopted to improve survival of migrating juvenile salmonids. With respect to flow augmentation the operating premise has been:

Premise 1. Increasing water velocity in reservoirs increases smolt migration speed, which results in improved survival. The mechanism has been thought to operate through reducing the time of exposure to predatory fish or birds, or exposure to warming waters. The ISAB (ISAB 2002-1) suggested two possible additional mechanisms: reductions in flow below dams leads to reduced primary and secondary production in tailwaters, which lessens the food supply, particularly for fall chinook that feed as they migrate (ISG, 2000-12). Interruptions of flow due to power operations becomes more frequent, is of longer duration, and is of greater magnitude as flows decrease, Table 2. These flow interruptions exacerbate all of the factors that enter into survival of migrating juvenile salmonids, including the potential for smolts to travel upstream and to be stranded (Tiffan et al. 2002).

Premise 2. Lowering water temperature in the summer improves migratory and rearing conditions for juvenile and adult salmonids, ultimately improving survival. This premise is being addressed through releases of cold water from the depths of Dworshak reservoir. Unlike the flow augmentation from upper Columbia River and upper Snake River projects, which we believe is impossible to identify as discrete bodies of water, releases from Dworshak are identifiable (through model analysis) by their cooler temperature, at least as far downstream as the tailrace of lower Granite Dam (Dreher et al., 2001), or possibly to Ice Harbor (1 –2 degrees Bennett et al., 1997). It is of utmost importance to note that the effectiveness of Dworshak releases for this purpose are strongly affected by the relative volume of flow from the Hells Canyon complex. In fact, if not closely coordinated for the benefit of fish, the resulting sharp fluctuations of temperature and drying of the shore zone in the mainstem Snake River might do more harm than the good intended. The CRiSP model can be used to illustrate and evaluate this issue (Andersen, Hinrichsen and Van Holmes, 2000).

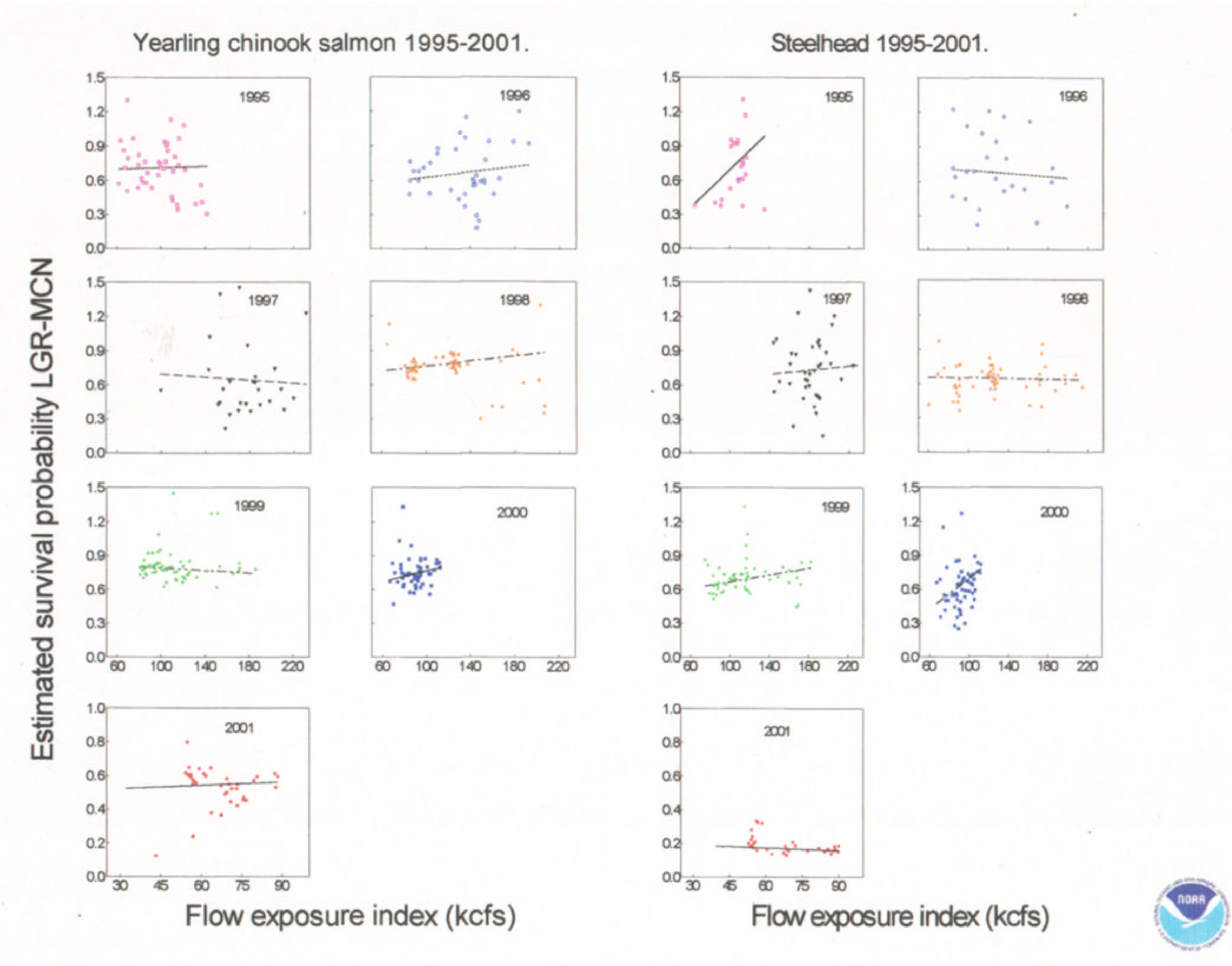
While the mechanisms hypothesized to operate to reduce or increase survival when flow is low are all reasonable, none of them has actually been shown to cause a reduction or increase in survival. Results to date have been from observational studies where conclusions and predictions are based on correlations of survival with various factors. In other words, no study has shown that predation increases because flow decreases in the Columbia or Snake rivers, that the cold water releases from Dworshak reservoir actually cause improved survival of salmonids, or that turbid water causes a decrease in predation. The one exception appears to be with fall chinook in the Hanford Reach, where it has been demonstrated that fluctuations in flow have led to stranding and direct mortality of these juveniles (e.g. Wagner et al., 1999; Tiffan et al., 2002). Actually, we believe all of these factors may be acting together to reduce the survival of juvenile salmonids migrating out of the Snake River. However, we have some new conjectures about the mechanisms that may be involved in causing the effects. We discuss these further below.

As previously mentioned, Steve Smith of NOAA Fisheries conducted a mathematical analysis to identify the point of intersection of the two segments of the broken stick model identified for yearling chinook and steelhead in the Snake River. His estimate is 96.4 kcfs for yearling chinook and about 101 kcfs for steelhead, which means that at flows below about 96.4 kcfs there is a significant positive effect of flow on average annual survival of yearling chinook, while at flows above that level there is no effect discernable with these data, Figures 2 and 3. Note also that our Table 2 shows that the frequency, duration, and magnitude of flow fluctuations become increasingly apparent the further flow declines below 150 kcfs. This is not surprising, considering that the hydraulic capacity of the four lower Snake River projects is 110 to 130 kcfs. What we observe from this overview is that as river flow declines from spring to summer and reaches about 130 kcfs, flows are likely to become more intermittent, due to interruption of flow in the effort to optimize returns from power production. The estimate for the point of intersection of the two segments of the broken stick coincides with this change in hydropower operations. The point of intersection must be viewed as just that – an estimate, which comes close to identifying the flow level at which flow more frequently becomes intermittent. We conclude that intermittent flow associated with Snake River flows less than 130 kcfs could explain the broken stick model.

On its face, a breakpoint or zone in the flow-survival relationship would suggest a high value for flow augmentation at daily average flows below this level. With this logic, any incremental addition of daily average flow below the breakpoint would have a proportional increase in survival, on average. This thinking is similar to the present paradigm, except that it applies only to the lower average flows. However, if the mechanism(s) affecting survival differ above and below the flow breakpoint, then adding more water below that flow may not sufficiently raise survival without concurrent change in the true mechanisms. To be specific, since the further one looks below the breakpoint the greater the percentage of daily average flow that is fluctuated hourly in dam discharges, then supplying more stable discharges may be more effective in improving smolt survival than simply supplying more water. Conceivably, even the lowest survival estimates obtained at the lowest flows, near 10-20% could be raised to the level seen at 100 kcfs (80%) if flows were stabilized (Figure 7). Clarifying the mechanisms affecting smolt survival should allow water managers to evaluate and contrast the alternative risks and benefits among relevant management options (hydro cycling, maintaining storage reservoir elevations, irrigation, etc.).

Further discussion of these topics is included in Appendices.

Figure 7. Within year plots of survival versus flow for yearling chinook and steelhead 1995-2001 illustrating a broken stick model (from Steve Smith presentation to ISAB, December 16, 2002).



IV. Answers to Questions

Council Questions

1. *What is the evidence and to what extent will flow augmentation from storage reservoirs result in the same environmental attributes as higher flow under natural conditions? In other words, how sound is the scientific approach of research that looks at correlations of fish movement and survival in relation to natural variations of environmental conditions such as flow, temperature, and turbidity, and then extrapolates to infer that man-made additions of flow will result in the same environmental attributes? Are there studies that more directly measure the effects of flow augmentation? If so what are the results of those studies?*

Answer:
Flow augmentation from storage reservoirs, as presently configured will not necessarily produce the same environmental attributes as higher flow under "natural" conditions because there is no requirement to provide the extra water in a "natural" way. The seasonal hydrograph in the Columbia Basin is so far from the hydrograph that prevailed before construction of the hydrosystem that the amount of flow that is at stake in the present discussions about flow augmentation is too small to restore "natural" conditions in that sense. Also, the observed correlation of annual aggregate smolt survival with gross measures of flow during the outmigration period remain unexplained; i.e., it is not known what specific attributes of the annual variation in conditions associated with gross measures of flow during the outmigration period are most important or causally responsible for the changes in smolt survival. For this reason we have no way of knowing whether the flow increments that are provided by the present flow augmentation policy will or will not induce conditions that enhance smolt survival. Finally, we can identify a number of respects in which even the short timeframe (hourly) variation in flow under present flow management is distinctly different from natural flows in several ways, and is likely to adversely affect smolt survival.

At flows below hydraulic capacity of powerhouses in the lower Snake River or mid-Columbia River, there are frequent hourly interruptions of flow, a characteristic of a regulated river as contrasted with an unregulated (or normative) river. The ISAB provided a review of literature on this subject as a set of appendices to their Hungry Horse/Libby review (ISAB 97-3). Higher flows without a requirement for stable releases at the proper temperatures are not guaranteed to have the beneficial result of a change in the direction of "normative." Intermittent flows, on an hourly time scale, are not characteristic of the normative river and are most likely to be disruptive to downstream migration of juvenile salmonids, and to lead to decreased survival within the affected reaches.

Because it is not possible to identify the portion of flow that consists of augmentation, it is not possible to conduct a more direct measurement of the effects of flow augmentation. The ISAB previously advised that to assess the effects directly, there would need to be a study specifically designed to isolate and measure the effects (ISG 1996, 2000), as have others (Skalski, Mundy and McConnaha 1989).

2. *To what extent will incremental flow augmentation within a year have the same effect on survival as the year-to-year changes in flow that are also accompanied by year-to-year changes in climate and ocean conditions?*

> *A. Relevant to the draft mainstem amendments, to what extent will changes in reservoir release strategies that could result in decreases in spring and summer flows of approximately 10% or less have a statistically significant effect on juvenile salmon and steelhead survival?*
>
> *B. A linked question is what scientific evidence exists that decreased travel time as a result of flow augmentation will result in increased juvenile survival*?

Answer:
Based on a literal interpretation of studies reviewed, incremental flow augmentation of the magnitude presently mandated within a year is not likely to have a dramatic beneficial effect on in-river smolt survival of outmigrants. This conclusion holds most likely for yearling chinook and perhaps fall chinook, particularly if the water is provided by intermittent dam discharges, rather than provided as steady flow. Effects of the current amount and management of flow augmentation on subsequent estuary and ocean survival are unknown, but are important to investigate.

A. Decreases of 10% in spring and summer flows are not likely to have deleterious effects on reach survival in the lower Snake River, provided that the remaining flows are maintained at or above an approximate breakpoint of 100 kcfs for spring migrants. Below approximately 100 kcfs, steady levels of flow or other management alternatives may be needed to avoid deleterious effects.

It is important, however, to distinguish between the reality of an effect and its detectability in the context of a particular monitoring program. We note that the wording of the question in terms of "statistical significance" of the effect is inappropriate. Statistical significance is a property of the inference from the data (e.g., the sample size); it is not a property of the effect itself. Any positive effect on smolt survival potentially benefit the salmon depending on downstream mortality rates, regardless of whether the effect is large enough to be recognizable from our measurements against the background of variation from other causes. Detectability is a function of the intensity and accuracy of our measurements, which may matter to us and to our decisions, but which is of no direct consequence to the salmon. Detectability will be a predictable problem for our ability to evaluate effects of a 10% change in flow. This problem arises because 10% is a small change in flow compared to natural variation in flow, and because the plausible changes in survival associated with this small intervention are likely to be small compared to variation in survival from other natural and unnatural causes. That is, a small signal is hard to detect in the presence of large noise.

We also need to be sensitive to the possible additive nature of "small effects." In the context of a complicated recovery plan that is attempting to manage an entire ecosystem and attempting to achieve improvements in all stages of the salmon life cycle, neglect of too many small effects—even effects that are too small to measure by monitoring—may consign the salmon to death by a thousand cuts. Small effects could still matter.

B. Decreased travel time and survival through a particular reach are linked. Assuming a constant rate of instantaneous mortality, the more time spent in a reach, the higher the total mortality. The more critical questions are whether instantaneous mortality rates are increased in a given reach as a result of low flow (or other factors such as temperature, particle travel time, turbidity and calendar date), and whether decreased travel time through a reach results in decreased mortality rates measured downstream. Survival throughout the life history of a fish is the element of concern. Reduced or increased travel time may be disadvantageous, as John Williams pointed out, if it results in arrival in the estuary and ocean at times when conditions are not favorable for their survival (i.e., when the instantaneous rate of mortality experienced there may be larger). Unfortunately practically nothing is known about favorable times for arrival. The region is operating on the established fact that development and operation of the hydroelectric system has resulted in a shift in timing of outmigration of juvenile salmonids toward later times of arrival.

The paradigm that faster movement of smolts to the estuary and ocean is always favorable for ultimate survival needs to be evaluated (we did not include that as part of our scope of work). Most of the reach survival studies we reviewed make this assumption. Increased migration rate and survival in the studied reaches (primarily the lower Snake River) does not ensure survival in lower reaches. The fish have to spend their time somewhere and continue to be subject to: perhaps increased survival rate, perhaps the same survival rate, or perhaps a decreased survival rate. We see a need for more specific analysis of the relationship between survival rates in the upper reaches of the rivers, survival rates in the lower reaches, date of arrival of smolts at the estuary and their subsequent ocean survival. We see the need for continuing analyses of the effect of annual flow during the outmigration period by separating measurement of in-river survival and ocean survival, with special attention to the more detailed mechanisms having to do with temperature, smolt condition, date of arrival in the estuary, and measures of ocean state.

3. *Are the statistical methods used in recent flow-survival analyses rigorous and technically sound? Did the analyses properly incorporate and treat 2001 low-water-year data?*

Answer:
Yes, insofar as possible. As discussed further below (see Appendix 1), technical soundness does not necessarily mean that any given statistical method is the most appropriate approach.

CRITFC Questions

1. *To what extent do system flood control operations lead to conflicts, if any, between resident and anadromous fish? What modifications to system operations could help to accommodate the needs of both anadromous and resident fish? Would the actions in the Council's draft amendment improve or lessen instream conditions for growth and survival of anadromous and native resident fish? The actions in CRITFC amendment? The ODFW amendment?*

   Answer:
   The ISAB draws upon some past reviews that touch on this subject, such as our review of Hungry Horse/Libby (ISAB 97-3). We called attention to the well-established fact that storage reservoir drawdowns result in adverse effects on resident fish populations and their associated fisheries. We recommended that an effort be made to balance the needs of resident fishes upstream against those of juvenile salmon downstream. We identified the Rule Curves developed by Brian Marotz in Montana as being reasonable approaches to resolving difficult policy issues with biological implications. And we pointed out, as did Al Wright, that the subject of tradeoffs of benefits to salmon versus detriments to resident fishes is one of the subjects deserving of high priority action by the Council. With additional time, the ISAB could review the recent literature and consider this question in more depth.

2. *What studies linking fish populations and reservoir operations exist for the operations of these projects? What evidence indicates a relationship between primary and secondary productivity and the growth and survival of resident fish populations in these reservoirs? What is the evidence of the effect of water retention times on primary and secondary productivity and what is the relationship to age-specific resident fish growth and survival? Is there empirical evidence of reduction in the populations of resident fish in Libby, Hungry Horse, and Grand Coulee reservoirs due to reservoir elevations? What is the general health of resident fish populations in these reservoirs? Is there evidence suggesting any recruitment failures that these populations have experienced year-class failures in recent years (ten to twenty years)? Is this evidence linked to reservoir operations? Which operations? Other effects? Please coordinate with the CBFWA Resident Fish Committee in answering these questions.*

   Answer:
   See the ISAB 97-3 review of Hungry Horse/Libby, especially Appendix 5. There is a large body of scientific literature on the subject of operations of these projects and their links with fish populations. There are studies dealing specifically with local situations that are referenced in the ISAB report on Hungry Horse/Libby. In addition, there is an even larger body of relevant literature that has been produced nationally and internationally dealing with the same issue. The ISAB reviewed both, in the Appendix to the Hungry Horse/Libby review. It has been concluded, based on numerous examples, that drawdowns of reservoirs and rivers lead to reductions in basic productive capacity of those bodies of water, leading in turn to reductions in

carrying capacity for fish. The larger and more frequent the drawdowns the more severe the negative effects become on the associated biota.

3. *In terms of life cycle and ecological processes affecting overall population health, identify mechanisms that would be impacted by changes in flow? Given the various influences of flow over the life cycle of anadromous fish, what is the proper context of consideration of incremental benefits generated from reach survival estimates? What is the risk of judging benefits of flow management regimes solely on incremental survival changes estimated from short reach survival studies?*

   Answer:
   The ISAB has begun to assemble a discussion of several hypotheses for how changes in flow probably affect smolts, using an ecological and life-cycle context. It is clear that there is more to the subject than changes in average daily flow, incremental in-river survival changes, and survival over short reaches. This review of hypotheses is incomplete at this time, but it is provided here in its present state as an indication. Also, see the answer to part B of the Council's second question above.

4. *What information would be necessary to eliminate or reduce flow targets considering the effects of flow over the life cycle and NWPPC program objectives? (The NWPPC program discusses SARs as a goal, the program flow changes will reduce the potential of achieving those SARS re: AT analysis).*

   Answer:
   Each distinct hypothesis about life cycle effects of flow changes would require its own set of data for testing. In addition, to obtain data capable of resolving the signal from the noise, each might require a different deliberate experiment. As one example, our analysis of hourly flow fluctuations, which are more frequent, of longer duration and greater magnitude at low flows than at high flows, suggests that an increase in smolt survival in a given river reach might be achieved with no net increase in average flow, provided that the hydrosystem is required to maintain stable flows during the period of outmigration of juvenile salmonids. All of the data comport with this interpretation: simply adding a small amount of bulk flow to existing levels of flow without reducing the current level of hourly variation is probably not providing much improvement, if any, in reach survival.

Additional General Questions from the Council

1. *Do the Council's proposed departures from NOAA Fisheries BiOp with regard to spring and summer flows pose a risk to the survival of fish populations, including listed ESUs? If so what are the risks and how significant are they?*

Answer:
It is not possible to carry out a formal risk analysis in the limited time and with the limited data available. However, our judgement is that substituting a requirement for stable flows during the period of outmigration of juvenile salmonids could lead to larger improvements in reach smolt survival than would be realized with a 10% increase in bulk

flow with continued large hourly fluctuations. That prediction could lead to a number of specific recommendations, e.g., that hourly fluctuations in flow should be strictly limited to some specified small percentage of the predicted base flow for that month.

We point out that decisions to implement actions that have any potential for adversely affecting an ESU that is listed under the ESA will be required to satisfy a burden of proof that no harm is likely to be done as a result of that action.

2. *Will these proposed changes provide benefits for upriver fish populations, including listed ESUs? If so, what are the benefits and how significant are they?*

Answer:
The Council's proposed actions are likely to provide benefits for upriver populations, as the ISG previously pointed out. Depending upon how the water is managed, benefits could accrue to listed populations of Kootenai River sturgeon, and possibly to bull trout populations that inhabit reservoirs for which productivity should increase as drawdowns become less drastic. Furthermore, the fisheries in the affected reservoirs should benefit from the stabilized flows, as well as associated fisheries industries. With additional time, the ISAB could review the recent literature and consider this question in more depth.

Implications for Council's Proposed Mainstem Amendments

The ISAB's flow augmentation review has implications for the Council's proposed mainstem amendments. Council staff summarized the effects of the proposed amendments on Snake River flows compared to flows recommended by the 2000 Biological Opinion (John Fazio presentation to ISAB; Figure 4, Table 1). Council staff anticipates some decrease in river discharges during the annual peak flows in late spring when yearling chinook salmon and steelhead migrate (amounting to less than 10% of generally high discharges). However, the greater impact would occur in the summer during declining flows when underyearling chinook salmon are migrating.

The spring reductions in flow under the Council's proposed plan would generally occur at levels higher than the postulated breakpoint in flow survival curves. Thus, no discernable effects on survival of spring migrants would be predicted under the broken-stick or similar model.

In contrast, the proposed summer reductions in discharge would often occur below the postulated breakpoint. Thus, discernable reduction in survival of fall chinook underyearlings would be anticipated from the Council's action. If diminished volume of water in the river is truly the cause of decline in survival, then maintaining flows at the BiOp levels should have proportional benefits for survival. Preserving flows above the breakpoint for maximum survival is problematic, however, given the limited amount of stored water available.

There are likely other mechanisms affecting survival below the flow breakpoint, however, as the ISAB review has identified. These mechanisms include the practice of fluctuating dam discharges within a day that is most prominent at lower flows, reduced attraction flows in dam forebays at lower flows, and diminished migration cues for fish in more slowly moving and/or hydraulically complex reservoirs. If such an operational feature occurs at the dams or in the reservoirs concurrent with lower flows, then maintaining daily average flows could be less essential than modifying operations. These mechanisms may be more amenable to management correction than the amount of water in the hydrosystem.

The current practice of transporting smolts by barge or truck from the lower Snake River reduces the risk to migrants from factors affecting their survival in this reach and farther downstream. This will remain true if the Council's proposed amendment is adopted. The ISAB and its predecessor advisory groups have previously acknowledged the benefits, especially at low flows, and risks of transportation. However, our present analysis has focused on the fate of smolts migrating in the river. Operational measures (such as stabilized flows) that improve in-river survival in the lower Snake River may relieve some of the need for transportation.

Appendices

Appendix 1. Review of Fish Passage Center Findings on Flow Effects

The region has relied on analyses by the Fish Passage Center (FPC) for much of its understanding of the effects of flow (river discharge) on the migration rates and survival of downstream-migrating smolts. Although review of the FPC's analyses was not explicitly included in the Council's set of questions, it was necessary for understanding of the prevailing views of flow effects and the efficacy of flow augmentation. Such a review of the FPC's analyses is important background for answering the questions asked of the ISAB by the Council.

The work of the Fish Passage Center that relates smolt travel time and survival to water travel time and flow is of high technical quality, but its basic model and methods of presentation are now inadequate to make confident predictions for management, and other interpretations of the accumulated data are needed. Much of the FPC's position in support of flow augmentation is based on several oft-repeated and recently updated analyses (FPC correspondence of October 14 and December 9). We comment on several of the technical details of these analyses below.

1. The relationship between water transit time and flow for Snake River hatchery chinook salmon and steelhead. The FPC notes that there is a close relationship between the water transit time and the corresponding flow between points on the Snake River. Figure 8 shows water transit time during the migration period of two migratory fish groups, steelhead and hatchery chinook, presumably calculated over slightly different migration dates. It is not surprising that FPC finds a close relationship between flow and water transit time, because water transit time is calculated from flow. As we understand it, the FPC first determined the dates during which specific groups of PIT-tagged fish were in the river. They then determined the average reservoir elevations on those inclusive dates and calculated the respective average reservoir volumes (there is some variation in volume of water in the river-reservoir system from one time to another, but it is not large). The average total discharge for those same dates was used to calculate a volume replacement time or water travel time (days) between Lower Granite Dam and Ice Harbor Dam.

Figure 8. Water transit time from LGR to IHD vs. average discharge (Figure 1 of FPC October 14, 2002 memo).

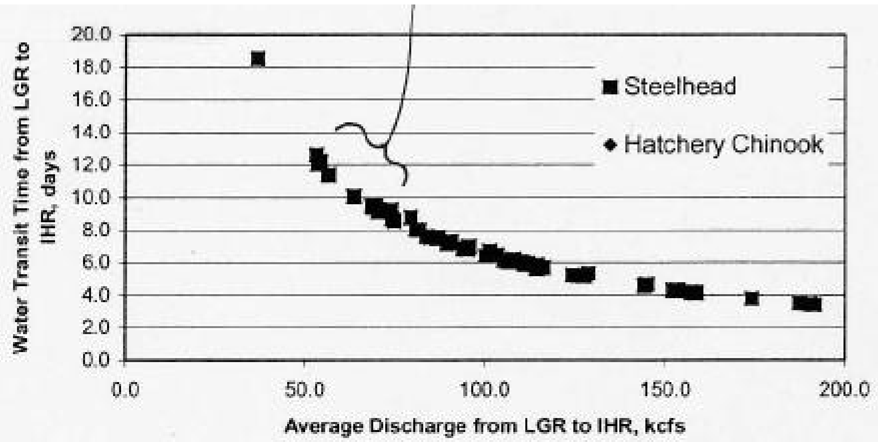


Figure 1. Relation between water transit time and flow for Snake River hatchery chinook and steelhead.

The ISAB considers the method scientifically acceptable as an estimate of theoretical water particle travel time averaged over several days. It is not a direct measure of water travel time that would be influenced by reservoir hydraulics and short-term variations in flow. It is, at best, a rough approximation.

The shape of the curve is informative. Assuming the accuracy of the highest water transit time plotted, the relationship appears to show increasingly longer water transit times as flow declines, especially noticeable below about 50-60 kcfs, although the relationship is a continuous curve. This accelerated increase in water transit times per unit of flow is important for evaluation of the next figures from the FPC and helps to explain the "broken stick" or similar models for the relationship between survival and flow.

2. The relationships between fish travel times and water transit time. The FPC compared median fish travel times to McNary Dam for each group of fish released at Lower Granite Dam with the respective water transit time calculated as above. They applied simple linear regression to the data, obtaining fairly poor fits for chinook (r^2= 0.5-0.6) but better fits for steelhead (r^2=0.87), where 1.0 is a perfect fit. They acknowledged that alternative models might better fit the relationships.

Figure 9. Fish transit time vs. water transit time for wild yearling chinook, hatchery yearling chinook, and steelhead (Figures 2-4 of FPC October 14, 2002 memo).

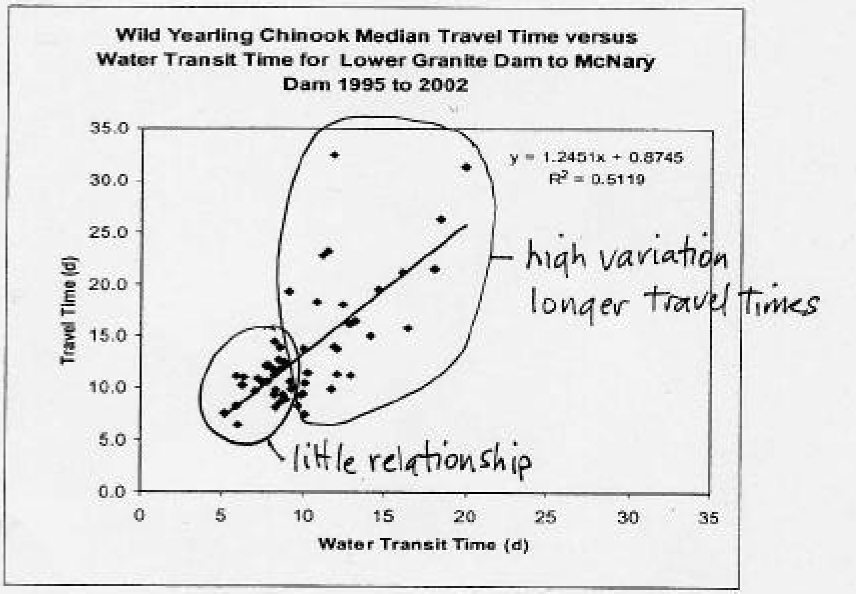


Figure 2. Wild Yearling Chinook travel time versus water transit time.

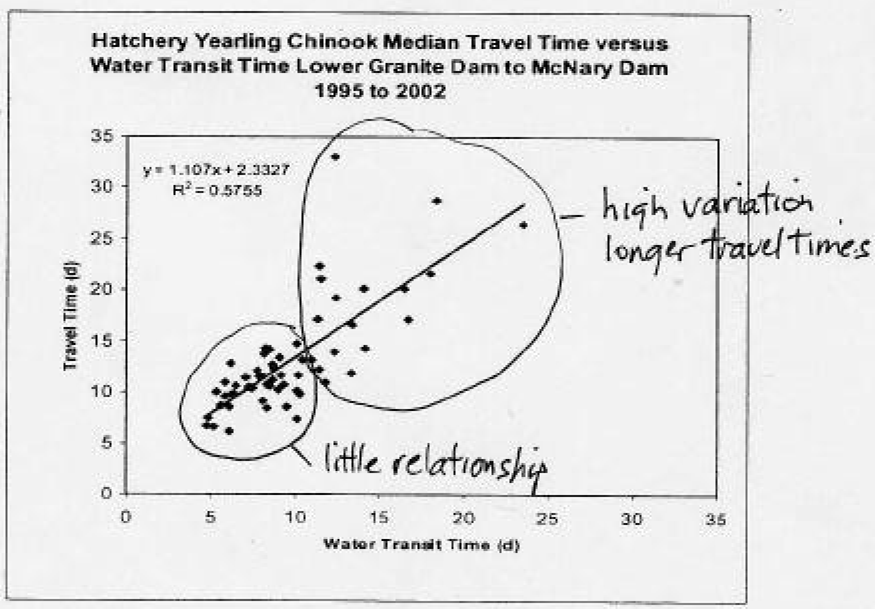


Figure 3. HatcheryYearling Chinook travel time versus water transit time.

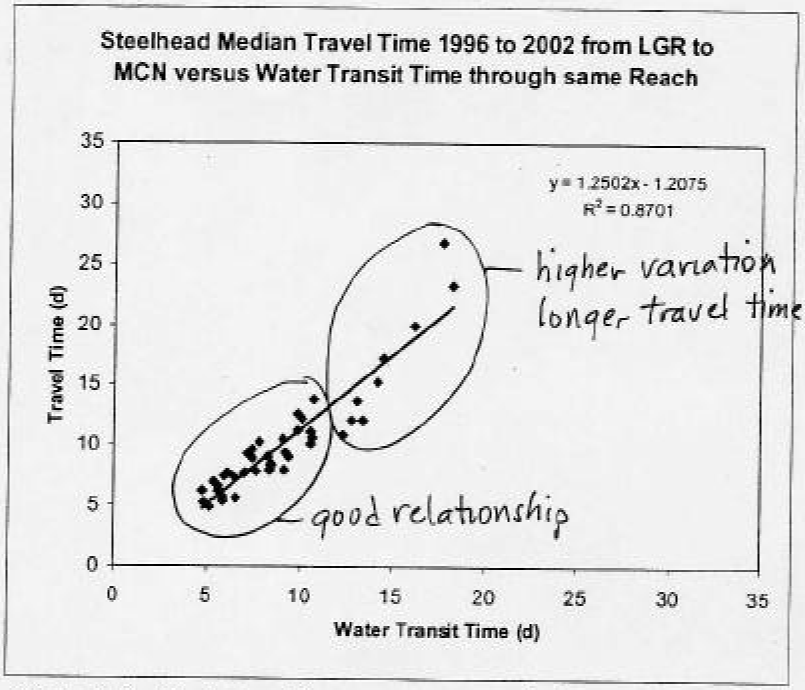


Figure 4. Steelhead travel time versus water transit time

Use of a theoretical, calculated water transit time that reflects highly averaged flow conditions to compare with measured fish travel times is legitimate scientifically, and is an effort to translate flow rates into something that is likely to have a direct influence on fish, but it seems to obscure the desired objective: to relate fish migration rates to flow rates. If nothing else, it interferes with effective communication of methods and results. Management options include altering flow rates and reservoir elevations, each of which must be entered into calculations to relate to the figures presented by the FPC. Thinking to future management, river managers should be capable of getting current data and computing water transit time on an instantaneous basis, managing flow and temperature, etc. Perhaps a surface plot showing the relationship of water transit time to flow and volume would relate the three.

Taken at face value, however, the plots are informative. Chinook salmon travel time is poorly related to water transit time at flows below that corresponding to about 10-12 d water transit time. Above that flow level, the travel times for both hatchery and wild chinook salmon show high variation, with the fish travel times considerably longer than those for the 5-10 day water transit times. Steelhead show a fairly tight relationship of fish travel times to water transit times at flows above that corresponding to about 12 d water transit time; below that flow level the few data points also show more scatter. Using the FPC’s figure for the relationship between water transit time and flow (Figure 8), the 10-12 d water transit time is equivalent to an average weekly Snake River discharge rate of about 50-60 kcfs. These figures suggest that different mechanisms probably affect smolt migration rates in the Lower Snake River above and below average flow rates of about 50-60 kcfs. The regression equations obtained by the FPC should be recomputed to allow for the different relationships across water transit times.

3. Relationship of smolt survival to water transit time (as a surrogate for flow). The FPC plotted smolt survival against water transit time (as a surrogate for flow rate), using the same groups of PIT-tagged smolts followed from Lower Granite Dam to McNary Dam that were used in the fish and water travel time analyses. Survival showed an apparent downward trend at higher water transit times (lower flows) for wild and hatchery yearling chinook salmon and steelhead, and these trends were quantified with curvilinear regressions. The regressions had generally poor fits for chinook but better for steelhead (r^2 values were approximately 0.3, 0.4, and 0.7, respectively).

Figure 10. Survival vs. water transit time for wild yearling chinook, hatchery yearling chinook, and steelhead (Figures 7-9 of FPC October 14, 2003 memo).

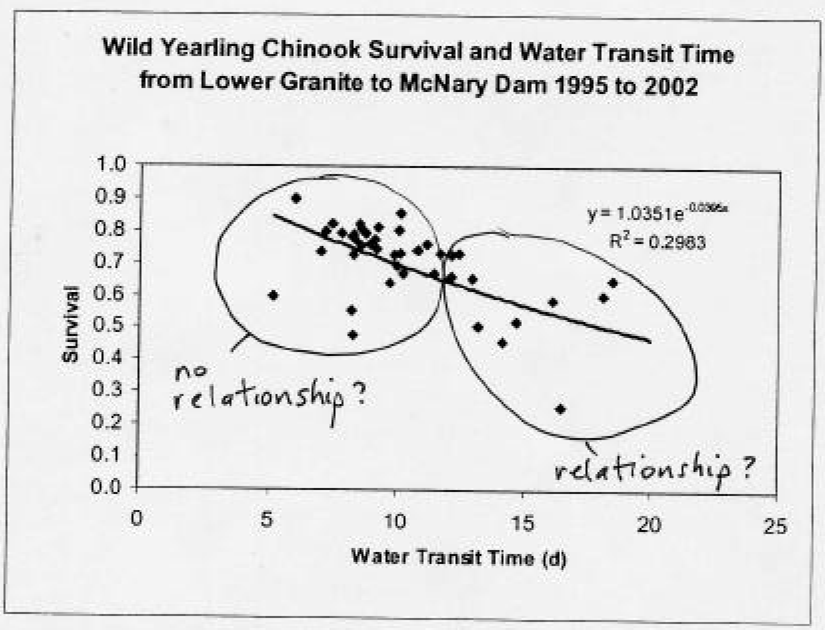


Figure 7. Water Transit time versus survival for wild yearling chinook.

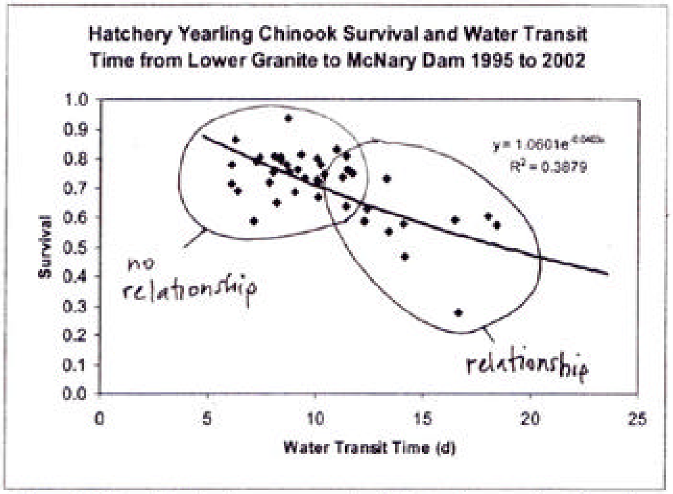


Figure 8. Water Transit time versus survival for hatchery yearling chinook.

Again, a break about 10-12 da.

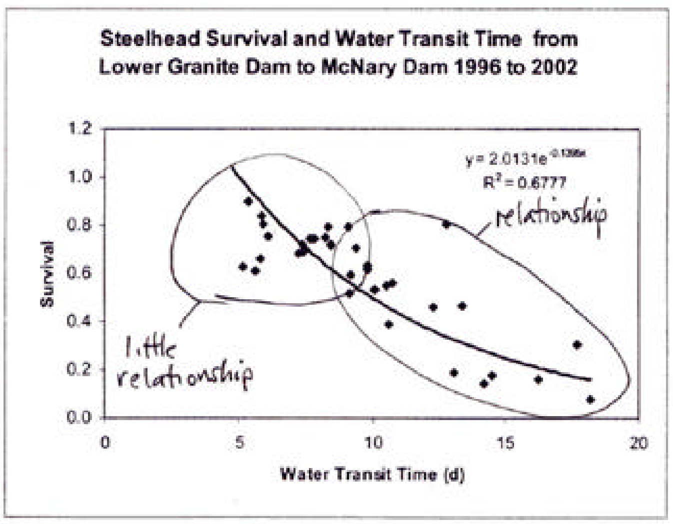


Figure 9. Water Transit time versus survival for steelhead.

from FPC October 14, 2002 memo

There are two aspects to a low r^2, and these have different implications for the predictive power of the regression and the adequacy of the model being used. Simple scatter, which can be the cause of a low r^2 merely means that there is noise in the data or random noise in the underlying relationship. On the other hand, an appearance of a different underlying shape than the one that is being fit suggests that the model that is being "fit" could be the wrong model. The choice of model will limit the shapes that can be fit. Also, the range of shapes that a model is capable of assuming will greatly affect the distance over which data influence the resulting estimate. Generally, the greater the complexity of the model, the more the estimates in one portion of the range will be independent of the data from other portions of the range. For this reason, with limited quantities of noisy data, a more complex model may be a better fit to the data, but the confidence about the estimates in a restricted range will be weaker.

The shallow curve trends fit by the FPC's regression analyses seem forced in comparison to a visual inspection of the pattern in the data. A visual inspection of the data suggests a better fit would be obtained from a model that was capable of turning a sharper corner, or that consisted of two straight line segments with two different slopes in the relationship in two different ranges of values for flow, i.e., a so-called "broken stick" model. Broken stick and more complex models are known as multiphase. There are known statistical methods to estimate objectively the location of the breakpoint (Seber and Wild 1989, Hastie and Tibshirani 1990). There are also a variety of statistical techniques, such as smoothing splines, for objectively fitting arbitrary curved shapes, and there are a variety of statistical techniques allowing for different degrees of tightness of curves.

If a broken-stick model were to be fitted to the FPC plots, there is apparent high in-river smolt survival at flows above that corresponding to about 10-12 d water transit time with essentially no detectable relationship to flow within this range for wild and hatchery chinook and only a slight relationship for steelhead. At lower flows, there is apparently a decline in survival with increasing water transit time, although the data show much scatter. Using FPC's figure (Figure 8) again to convert water travel time to flow rates indicates that the change in survival occurs near 50-60 kcfs. In other words, in-river smolt survival appears from the FPC data as if it could be independent of flow above about 50-60 kcfs up to about 180 kcfs, which is the limit in the data.

For flow management purposes, a more quantitative definition of alternative models, including the broken-stick model, for survival vs. water transit time (flow) is desirable. These statistical methods rely on models that are "non-linear" in the coefficients to be estimated and require customized computing software not usually available in the commonly used statistical software packages. Flow-survival data that the ISAB reviewed from NOAA Fisheries suggests a breakpoint somewhat higher, near 100-100 kcfs (Steve Smith presentation, unpublished analysis). Dr. Smith's pilot analysis was non-subjective, but involved an assumption to allow ordinary least squares theory to be used to fit the model, namely, that the line above the break-point had zero slope. The ISAB recognizes the value of fitting such models to these data. We recommend that the pilot analyses be expanded to take full advantage of the theory of fitting and comparing multiphase models with and without breakpoints. Also, see Appendix 4, where a model is developed on the assumption of a constant instantaneous rate of mortality.

Because both fish travel time and survival data from the FPC appear to exhibit similar broken stick patterns with breakpoints apparently near 50-60 kcfs, the ISAB believes that it would be fruitful to examine the physical and biological mechanisms in the river-reservoir system that might be causing such discontinuity in the relationship. Intermittent flows brought about by hydropower operations are a likely cause, as we discuss elsewhere. Deciphering the mechanisms behind the different fish travel times and survival rates is likely to lead to more mechanistic and technically supportable water management approaches than would sole reliance on simple regressions assuming a highly constrained shallow curvilinear relationship over the entire range. Knowledge of mechanisms will provide independent knowledge as to the range of plausible models that should be fit statistically, and will confer higher confidence in the resulting estimates.

Appendix 2. Survival Estimates for Juvenile Salmonids

In this appendix, we make several points about survival of different species and life stages, as developed from newly acquired data, and contrast the situation in the Snake and Columbia rivers. The appendix is a work in progress, as new information is received nearly daily. A later section explores several hypotheses, including the current one used by the FPC, to explain the travel time and survival data in ways that may point to new hydrosystem management approaches.

Because the circumstances differ for the Snake River, the upper mainstem Columbia (the mid-Columbia Reach), and the lower Mainstem Columbia River, we separate the list of findings below according to the respective reaches. We also separate the list of findings for yearling chinook, fall chinook, steelhead and sockeye. Coho are being reintroduced both in the mid-Columbia Reach and Snake River, but there are as yet insufficient data available on survival of their juveniles to make any conclusions with respect to their responses to flow. Data on survival of sockeye juveniles are also lacking.

The process of ISAB review involves evaluation of inputs of various types from numerous diverse sources. We felt it to be important in this case to document the findings we arrived at after careful review. These findings served as a basis for our answers and for our recommendations.

Flow Augmentation *per se*

Finding: Direct effects of flow augmentation cannot be isolated for measurement, with the exception of releases from Dworshak, which are labeled by the temperature of water released.

In his presentation to the Council on December 11, 2002, Karl Dreher for the Idaho Department of Water Resources and at the December 16 ISAB briefing Margaret Filardo of the Fish Passage Center both said that the flows provided as augmentation, under present policy and management, are not identifiable. Former Council member Kai Lee reached the same conclusion in the chapter he wrote in NRC 1996. Since the augmentation flows, other than those from Dworshak, are not identifiable under present operations, their effects cannot be directly measured in the river as associated changes in measurements of survival of juvenile salmonids. The Fish Passage Center, beginning with their fist annual report (and restated in their December 10, 2002 letter to Council member Karier in answer to his question 3), reported they have been unable to identify in the river, the specific volume of water intended for the water budget or flow augmentation. The reason for the inability to identify the masses of water that constitute flow augmentation is that the volumes released by the COE and BPA simply supplement (augment) what would have been the normal release in the particular water year being experienced, i.e. the timing of release of that volume of water is shifted to conform to the BiOp's requirements for passage of juvenile salmonids. Thus, the water is not treated differently than the other portion of the seasonal flow, as it is used for power production, and some may be spilled or used for other purposes. This is also true for releases from

Dworshak Dam. Dworshak releases are a special case, which we will discuss further in a later section.

It is important to observe at this point that flow augmentation does not necessarily lead to spill, but on the other hand that some of the augmented flow may be used to satisfy requirements in the FWP or BiOp to provide specified spill volumes at particular dams in order to achieve targets for total survival of juvenile salmonids passing the dam. In fact system operators normally take care to avoid spill that might result directly from augmentation, since that would be considered to be "involuntary" spill. "Involuntary" spill, as a rule, occurs only when high flows lead to exceeding the power system's ability to divert flow through the powerhouses (i.e. exceeding the hydraulic capacity of the individual project). "Involuntary" spill then is a separate and distinguishable strategy from spill called for in the FWP and the BiOp for the purpose of improving the overall survival of juvenile salmonids as they pass a hydropower dam. (See Whitney et al, 1997.)

1. Snake River

Yearling chinook

Finding: By comparing a series of average annual survival estimates for yearling chinook and annual flows averaged during the period of outmigration for a series of years from 1973 to 2001, a positive relationship has been demonstrated, i.e. survival is higher in years of higher average flows in the Snake River.
For yearling chinook in the Snake River, when annual average survival estimates are plotted against average river flow during the outmigration for the same year, NOAA Fisheries has demonstrated that there is higher average survival of migrating juveniles in years when average river flows are higher.

Finding: The relationship demonstrated for yearling chinook is well described by a "broken stick" model, first suggested by Chapman et al. 1991. Examination of the plot of points for average survival of yearling chinook against average annual flow shows an increase in survival with flow up to a point beyond which increases in flow do not bring further increases in survival (Figure 2).
NOAA Fisheries estimates the point of intersection of the two lines occurs at a flow of 96.4 kcfs for yearling chinook and 101 kcfs for steelhead. Beyond that point (about 100 kcfs) no relationship of survival and flow can be demonstrated.

Finding: Estimates of survival of yearling chinook within a year are best limited to the years 1995 to 2001, because those are the years when detections of PIT tagged juveniles were sufficient to arrive at usable estimates. Survival in the year 2001 was significantly related to flow. In the data provided by NOAA Fisheries it is apparent that the flows during that year were less than 100 kcfs during the migration, the only year for which the average flow was that low. In addition, date of release from the hatchery and degree of smoltification have been shown to affect travel time and survival of yearling chinook in the Snake River. For fall chinook, because

environmental variables are highly correlated with one another (flow, temperature, and turbidity) it has not been possible to determine whether one factor is more important than another (Smith et al. in press).

That there was only one year during which it was clear that there was a within-year relationship of flow and survival) is puzzling when taken together with the fact, stated previously, that a significant relationship has been found in analyses of annual average estimates of survival and flow. A close examination of the figures provided by NOAA Fisheries (S. Smith and J. Williams) shows that the data for none of the other years suggests a significant within-year trend of survival related to flow, Figure 7. However, it seems that survival was lowest in years when flows were low, below about100 kcfs for the duration of the outmigration, as in 2001 Continuing observations are necessary.

For now, we provide a conservative and literal conclusion that the volume of water available in a particular water year directly affects the average survival of juvenile yearling chinook migrating out of the Snake River. In terms of practical application of augmented flow within a particular year, an assumption might be made that the line that describes the relationship for multiple years might be used to predict the effects of increments of increased survival to be expected from increments of flow within a year. However, it ought to be possible to test this assumption by within-year analyses, and the analyses conducted have not succeeded in verifying the validity of such an assumption. Probably, the range of flows that have occurred within a given year during the period when yearling chinook are migrating downstream, generally is not broad enough, and the within-year variation with flow has not be sufficiently decoupled from variation in confounding factors such as temperature and date. The exception seems to be when average flow is less than 100 kcfs, under which condition the short-term flow survival relationship is strong enough, even for a restricted range of flow variation, to make it detectable relative to the variability in survival brought about by other factors. Note that we expect the broken stick model to apply here, so that in years of flow above hydraulic capacity of powerhouses there will be a weak or no relationship, whereas in low flow years, there very likely will be a stronger relationship.

Fall Chinook

Finding: For fall chinook there is no lengthy series of annual measurements of average survival such as is available for yearling chinook. Short series (four years, each providing one point for analysis) produced what the authors felt (Connor et al. 1998) demonstrated higher rates of PIT tag recovery at Lower Granite Dam of fall chinook tagged upstream in years having higher average flow during the annual outmigration. On the other hand, Andersen, Hinrichsen, and Van Holmes, in an analysis of average annual survival estimates for the years 1995 through 1998, found no significant effect of average annual flow on survival to Lower Granite Dam (Andersen et al., 2000, page 19). But the latter authors found that analyzing weekly PIT tag detections provided sufficient data to identify a significant relationship of flow and survival to Lower Granite Dam (page 11). A similar study (because it plotted weekly rate of survival against weekly average flow) by the FPC for the

combined years 1999 and 2000, showed a strong relationship of survival with flow, higher flows during the two years being associated with higher survival (Figure 4). But pooling survival estimates from the two years was necessary to obtain a large enough sample size to yield a significant estimated relationship because the range of flows in the individual years was not sufficient.

Within a year, a significant effect of flow on survival of fall chinook to Lower Granite Dam has been demonstrated (Andersen, Hinrichsen and Van Holmes, December, 2000 submission to the Council, re. review of the Giorgi et al. report). However, those authors found no significant effect of average annual flow and average survival between years.

Steelhead

Finding: Survival of juvenile steelhead generally has followed the same pattern annually as yearling chinook, with the exception of 2001, when steelhead survival was much lower (Giorgi et al., 2002, referring to Zabel et al. in press). Giorgi et al. felt that the reason for low estimates of survival of steelhead in 2001, a year of unusually low flows and associated factors, was increased residualization of the smolts, rather than mortality per se. It is apparent that part of the "mortality" estimated for steelhead in 2001was due to residualization, the failure of fish to continue their migrations out of the system (Bill Muir, John Williams personal communications). John Williams of NOAA Fisheries has described observing a "rainbow trout" fishery that developed above McNary Dam that was based upon steelhead smolts that had failed to emigrate. Incidentally, the same phenomenon has been observed in the mid-Columbia Reach (Shane Bickford, personal communication).

2. Mid-Columbia Reach

In the text proper, we have summarized what information is available on survival estimates of juvenile salmon as they might be affected by flow in the mid-Columbia Reach, and we will not repeat it here. We do provide relevant information on the Hanford Reach fall chinook, which are adversely affected by unstable flows.

Fall Chinook

Finding: An estimated 2 million juvenile fall chinook were killed in the Hanford Reach during their outmigration in 2001. This compares with losses of 93,000 in 1999, losses of 45,000 in 2000, and losses of 67,000 in 2002.[11]

It is well established that mortalities of juvenile fall chinook in the Hanford Reach are brought about by fluctuations in flow, which lead to their stranding and death as the water level recedes too rapidly for them to adjust. The volumes of flow are not the same in every year, as they are set according to criteria in the Vernita Bar Agreement with the objective of maintaining appropriate boundaries for spawning, rearing and incubation of

[11] Information taken from Tiffan et al. unpublished proposal #35036 for FY2003; response to comments by the ISRP, and from Tiffan, Garland and Rondorf, 2002. In the proposal Tiffan cites Murray, 2002 as the source, but omitted that from his list of references. He also cites CRSS, 2000, with no listing in his references. In the joint publication they cite Hoffarth, Unpublished as the source of numbers.

fall chinook in the Hanford Reach. In 1999 an interagency agreement was reached that is intended to supplement the Vernita Bar Agreement for protection of fall chinook.[12] The supplement is intended to provide stabilized flows to encompass the period after emergence of fry from the gravel when they are still in the shallows feeding and beginning to emigrate. That supplement spells out permissible magnitudes of flow fluctuations for five different levels of river flow. The permissible fluctuations range from about 25% to 43% of average river flow. For weekdays, average flow under the Agreement is to be calculated as a rolling 5-day average of the previous five weekdays, and for weekend days as the BPA Friday Priest Rapids Dam estimates for Saturday and Sunday. This provision introduces the potential for fluctuations of even larger magnitude between weekend days versus weekdays. In 2001, hourly regulation of flow at times brought about water level fluctuations of 6 to 9 vertical feet (Tiffan, unpublished proposal #35036 and MCRSS 2001). It is evident from the result in the year 2001 that provisions of the supplement are inadequate for protection of fall chinook fry in some years, such as 2001, when flows were low and protection measures were relaxed. We note several omissions in the supplement. The supplement includes no stipulation of limits to either duration or frequency of fluctuations. We observe that the permissible magnitudes of fluctuation are as large as those observed at Lower Granite Dam, where there is no effort being made to stabilize flows for salmonid fry. See Table 1 in the main body of the text. Tiffan et al. (2002) analyzed the situation in terms of available rearing area for fall chinook under various flow volumes. The model they developed can be used to estimate the area of near-shore habitat that likely will be exposed at a given flow, or that will result from reductions in flow that are permitted under the present agreement. They conclude that the provisions of the agreement are inadequate for the protection of juvenile fall chinook rearing in the Hanford Reach.

3. Mainstem Columbia River Below McNary Dam

Finding: Average annual survival of up-river, i.e. mid-Columbia fall chinook from McNary Dam to John Day Dam is higher in years of higher average flows (Muir). This observation is based on four data points (four years). A possible explanation for this is that the reservoir above John Day Dam is a primary location where significant predation by northern pikeminnow has been documented and predation is facilitated by lower flows.

[12] As a result of a previous review, the ISAB recommended to the Council that the existing Vernita Bar Agreement be supplemented to provide protection for emigrating fry of fall chinook (ISAB 99-5). The Vernita Bar Agreement is described in ISG, 2000, NWPPC Doc. 2000-12, pp. 451-2. The extension of the Agreement subsequently called for by the Council is developed on an interim basis annually. The 2002 agreement may be viewed at
www.nwd.wc.usace.army.mil/tmt/documents/fish/2003/hanford_fall_chinook.pdf

Appendix 3. Alternative Hypotheses for Explaining Current Data on Smolts and Flow

The sufficiency of flow (river discharge) as a predictor of survival for out-migrant salmon and steelhead smolt for purposes of flow management decisions has been questioned by the Idaho Water Users, the Idaho Council members, and others. The importance of river discharge is argued by the Fish Passage Center through graphs they have produced relating salmon/steelhead smolt survival to water travel time, which is a function of river flow (e.g., Figures 9 and 10). Similar graphs of survival versus water travel times or flow have been developed by NOAA Fisheries. When data are aggregated over sufficient years to attain a wide range of average river flows (including the low flow year of 2001), statistically significant linear relationships can be demonstrated using standard regression techniques. However, as more years and more survival estimates have been added over time, the purported linear relationship takes on a "broken stick" appearance (first suggested by Chapman et al. 1991). The broken stick model also agrees closely with the rather sharp changes in the slope at about the same "breakpoint" of other curves fitted to the data. In these models, the portion of the survival data at longer water travel times (lower river flows) shows a relationship with water travel time (flow) and another portion at shorter water travel times (higher flows) shows little relationship (FPC data discussed in Appendix 1; NOAA Fisheries analyses by Smith et al.).

The broken stick model postulated to describe the relationship of average annual survival estimates for yearling chinook to average annual flows during outmigration, based on data obtained from 1973 to 1979, has been fitted by the NOAA Fisheries after accumulation of PIT tag data from 1995 to 2001. Under the broken-stick model, water might be managed for fish without much regard for water flow rates above about 100 kcfs, for example, yet be intimately tied to flow for fish migrating at lower flow rates. However, hydrosystem management would be benefited by knowing what environmental changes occur in the vicinity of the breakpoint and below that affect fish survival. With such knowledge, there may be causative factors other than the quantity of water that could be managed to benefit fish. The mechanisms by which fish survival differs with flow are not clear. This section discusses several alternative hypotheses and the evidence that does or does not support each of them.

Velocity Hypothesis:

The prevailing hypothesis has pointed to different river velocities at different flow rates as the primary influence on smolt survival (FPC 2002). Analysts have presumed that the river-reservoir system flows at a faster velocity when there is higher volume of discharge. It is also assumed that faster smolt migration means less time available for negative influences of predation, disease, high temperature, high dissolved gas, or other damaging factors, and thus higher survival at higher flows. In support of the velocity assumption, the FPC has calculated probable average water travel times through the Lower Snake River as a function of flow (average daily river discharge) and the volume of the river-reservoir system during times when migrating salmon and steelhead are present (Figure

8). The volume differs somewhat from one migration period to another, depending on reservoir elevations during actual migrations. The pattern of water travel times results from the gross replacement of the available water volume in the river-reservoir reach by the amount of inflow. Similarly, the FPC has assumed that fish migrate essentially passively and that their travel times will be similar to the water travel times, or at least directly related to them. This assumption is tested by plots of fish travel times in relation to water travel times, which generally show a statistically significant relationship, with fish traveling faster at short water travel times (=higher water velocities)(Figures 9-10).

The relevance of the velocity hypothesis for water management is the assumption that an increased river discharge through water management (e.g., flow augmentation) will cause water to travel faster through the hydrosystem (higher velocities) and thus fish will migrate faster. Thus, management for higher flows, through flow augmentation or other means, is expected to lead to higher smolt survival during the outmigration. If the velocity hypothesis is correct, the year-to-year data relating flow (water travel time) to survival are both relevant and predictive.

We believe there is more to the relationship than is revealed by the type of analysis that has been used. The estimates of velocity can be faulted on several grounds. First, actual measured velocities in the reservoirs of the lower Snake River at different flow rates are few (but see Venditti et al. 2000), at least as could be determined by the ISAB in inquiries among regional researchers. Second, the gross water replacement formula for estimating velocities does not consider details of channel hydraulics or reservoir circulation, as has been pointed out by Dreher et al., 2000. Such details will influence how river discharge translates to water velocities seen by fish (and resulting fish movements). Flows (and therefore channel velocities and water travel times) also are not constant through daily cycles due to fluctuating flows at hydropower facilities. At the lowest flows, we determined that the pulses of high and low discharge induce an oscillation (seiche) in the reservoirs that can induce reverse flow. The broken-stick pattern between flow and survival suggests that there is more involved than simple average velocity relationships across the range of possible flows. In addition to recognition of a broken-stick type of relationship it is apparent that fish travel times tend to have a greater variability at longer water travel times (equivalent to lower river flow rates) than at shorter water travel times (higher flow rates) (See Appendix 1). As discussed earlier, this suggests some difference in mechanisms at different flows. Beyond flow (water travel time and velocity), there are other co-occurring factors that can affect smolt survival. NOAA Fisheries has identified especially temperature and turbidity. Flow augmentation from Dworshak Dam in late summer to bring Snake River temperatures closer to optimal for salmon (Karr et al. 1998) is an example of capitalizing on known temperature effects that go beyond just velocity. These factors need not be related to velocity, thus reducing the predictive power of flow.

Fluctuating Flow Hypotheses:

As we have pointed out, one change in hydrosystem operations that occurs across a range of seasonal daily average flow rates is the amount of within-day fluctuation caused by variable hydropower generation. Each day has variable flow on an hourly basis (Figures 5 and 6). The ranges between minimum and maximum flows do not differ greatly among different average flows, but the fluctuation range is a higher proportion of the daily average flow when the daily average flow is low (Figure 6). This means that the fractional within-day variation in flow (and probably river velocities and fish travel times) seen in a river or reservoir is greater at lower average flows than it is at higher average flows. For 1998, for example, the daily variation in flow from Lower Monumental Dam was a small percentage of the daily average flow (10-20%) during May and June. This contrasts with the fluctuations being a high percentage of daily average flow in July and August, the period of outmigration of fall chinook, often exceeding 100%.

The mechanism by which this flow fluctuation might affect smolt survival is open to speculation, although circumstantial evidence points to some likely mechanisms. Also, the relationships of fluctuating flows to the breakpoints in flow-survival curves deserve some discussion in terms of mechanisms. We examined several alternatives, as follows.

Fish Stranding:

We discuss this hypothesis because of the analogy with the Hanford Reach stranding issue rather than its likelihood of being a major mechanism in the Snake River. In the Hanford Reach, stranding of underyearling chinook salmon by fluctuating flows has been identified as an important factor causing mortalities (Wagner et al. 1999; Tiffan et al., 2002). Research has identified that fry of fall chinook, in particular, use shoreline areas for feeding and rearing during the high flows of daytime, but are often left stranded in isolated pools or on large flats and gravel bars when the river flow rapidly decreases. Because of these mortalities, the Vernita Bar Agreement that regulated Priest Rapids Dam discharges during spawning of adults, and incubation of eggs was modified to provide more stable flows during the time when underyearlings are most abundant in the Hanford Reach. A similar problem but to a smaller degree might occur in the lower Snake River. It is likely smaller because the lower Snake River is nearly exclusively a simple channel that is filled by impoundments (having steep sides and few flat zones for stranding). Fluctuations in discharge may still affect survival but probably not to the same level as in the Hanford reach.

Unstable Reservoir Hydraulics Confusing to Fish:

We hypothesized that rapid changes in river discharge at an upstream dam (both increase and decrease) would cause hydraulic instability in the downstream reservoir, potentially affecting local hydraulic patterns and thus migration rates of fish in these unstable flows (and susceptibility to many of the same survival-reducing factors identified by the FPC). Vendetti et al. (2000) observed wandering and upstream swimming by radio-tagged underyearling chinook salmon in Little Goose pool in July-August 1995-1997, as well as large differences in migration rates. Plumb et al. (2001) has observed similar behavior in the Lower Granite pool during the period 1996-2001.

We initially tested this hypothesis by obtaining current (mid-January 2003) hourly data on discharges, forebay elevations, and tailwater elevations for the four lower Snake River dams at low flows from the Corps of Engineers web site. Mid-January typically has the lowest Snake River flows.

We discovered seiches (periodic oscillations of the water surface that involve water movements upstream and downstream; i.e., the "sloshing bathtub") in the lowermost three reservoirs (Little Goose, Lower Monumental, and Ice Harbor) during weekdays but not in Lower Granite reservoir (Figures 11 and 12). The observed seiches, not heretofore reported for the lower Snake River reservoirs, are consistent with the oscillation being caused by pulsing outflows at the three upstream dams (Lower Granite, Little Goose, and Lower Monumental, respectively). Lower Granite reservoir has an undammed portion of river above the head of the reservoir and receives side flow from tributaries, both of which are factors that would damp the effects of oscillations. Dam outflows ranged from zero at night to 10-30 kcfs in daytime. Further support for the oscillations being forced by pulsed discharges came from observation that the oscillations dampened during a weekend of stable flows (about 13 kcfs), but were reinitiated when flows again fluctuated markedly in the following week. Oscillations in Little Goose and Lower Monumental pools had periods of somewhat over two hours, whereas Ice Harbor pool had a complex oscillation with many apparent harmonics or sub-oscillations (befitting the Ice Harbor pool with its more complex morphometry). The oscillations of Little Goose and Lower Monumental pools had single or odd-numbered nodes (centers of oscillation), because the upswings occurred in reverse sequence (mirror image) at forebays and tailwaters. Figure 13 illustrates surface elevation changes and seiche-induced flows in a theoretical lake basin (Lemmin and Mortimer 1986). The tailwater oscillations had higher amplitudes, consistent with shallower water and narrower channels than the forebays. We calculated that seiche-induced flow at a single node in Little Goose Reservoir on one example day would amount to about 10 kcfs, reversing direction every 1.4 hours. During hours of zero discharge from Lower Granite Dam, this flow reversal would actually flow alternately upstream and downstream at 10 kcfs. When the dam discharged its peak of 20 kcfs for the day, the downstream flow at the node would be accelerated to about 30 kcfs and decelerated to about 10 kcfs downstream every 1.4 hours. These complex flows and potential seiches at low flows could be disruptive for downstream migrants and potentially cause the wandering and upstream swimming of radio-tagged smolts observed in Little Goose pool in 1995-1997 by Vendetti et al. (2000) and in Lower Granite pool in 1996-2001 by Plumb et al. (2003). There is a large literature on seiches in lakes and coastal waters, much of it from European limnological research of the late 1800s and early 1900s (e.g., see Hutchinson 1957).

Subsequent to making these analyses and discovering the winter seiches, we obtained hourly records of flows and elevations of tailwaters and forebays for 1995-2002 from DART (courtesy of Chris Van Holmes, University of Washington DART). It appears that flows do not get as low as zero during the months of fish migrations, but that considerable pulsing still occurs at times when downstream migrants are present (e.g., Figure 6). We found that during 2001, the year of the study by Plumb et al. 2000, there were periodic episodes of flow reduction every day but two days of those included in their study. Most, 46 of 60, occurred in the hours from 0100 to 0400h, during which the minimum flow reached about 65% of flow in the preceding and following time intervals, and lasted an average of about 7 hours (some as long as 15 and 18 hours). No seiches were apparent in the records of water elevations during the weeks of fish migrations, although a thorough examination of the data set should be conducted. The documented, large variations in flow through a daily cycle undoubtedly create complex hydraulics that are disruptive to the downstream migration of fish. This alternative hypothesis for decreased survival at low flows should be investigated further.

Figure 11. Little Seiche.

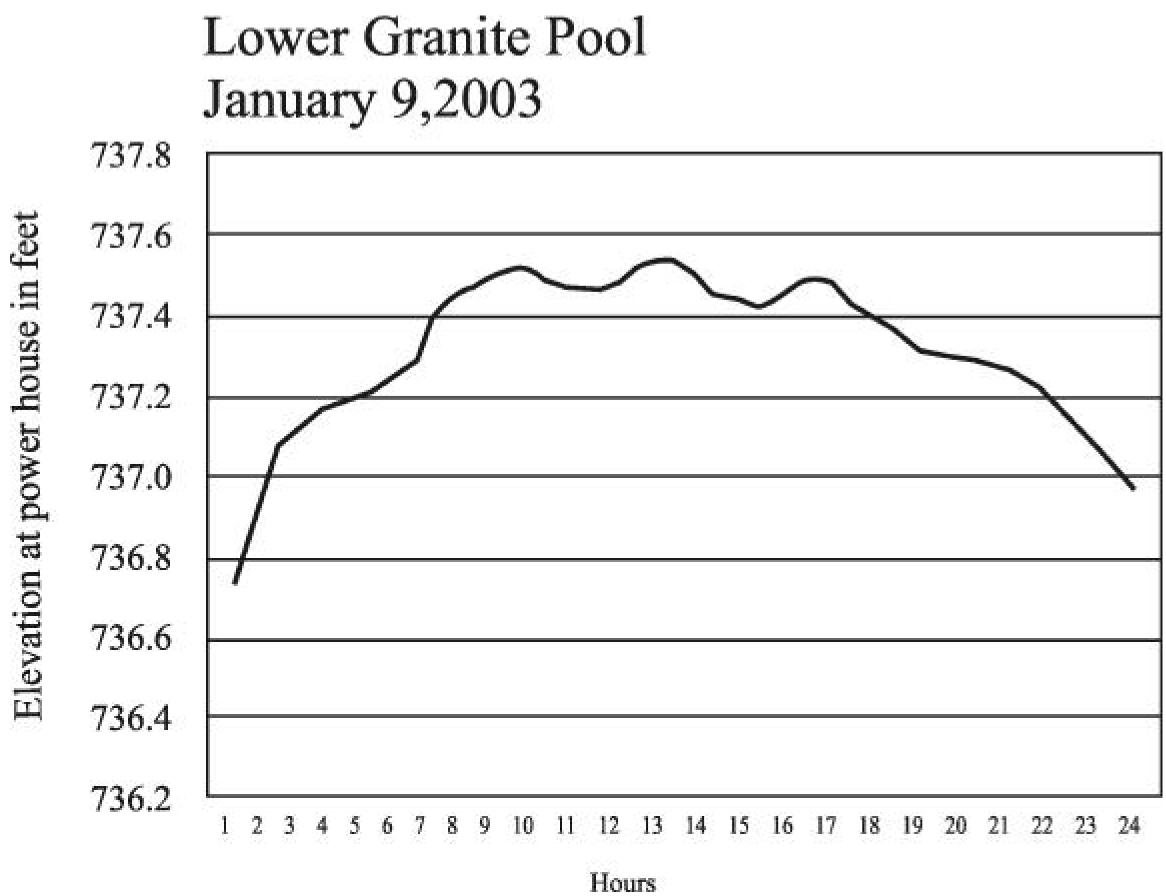


Figure 12. Prominent Seiche.

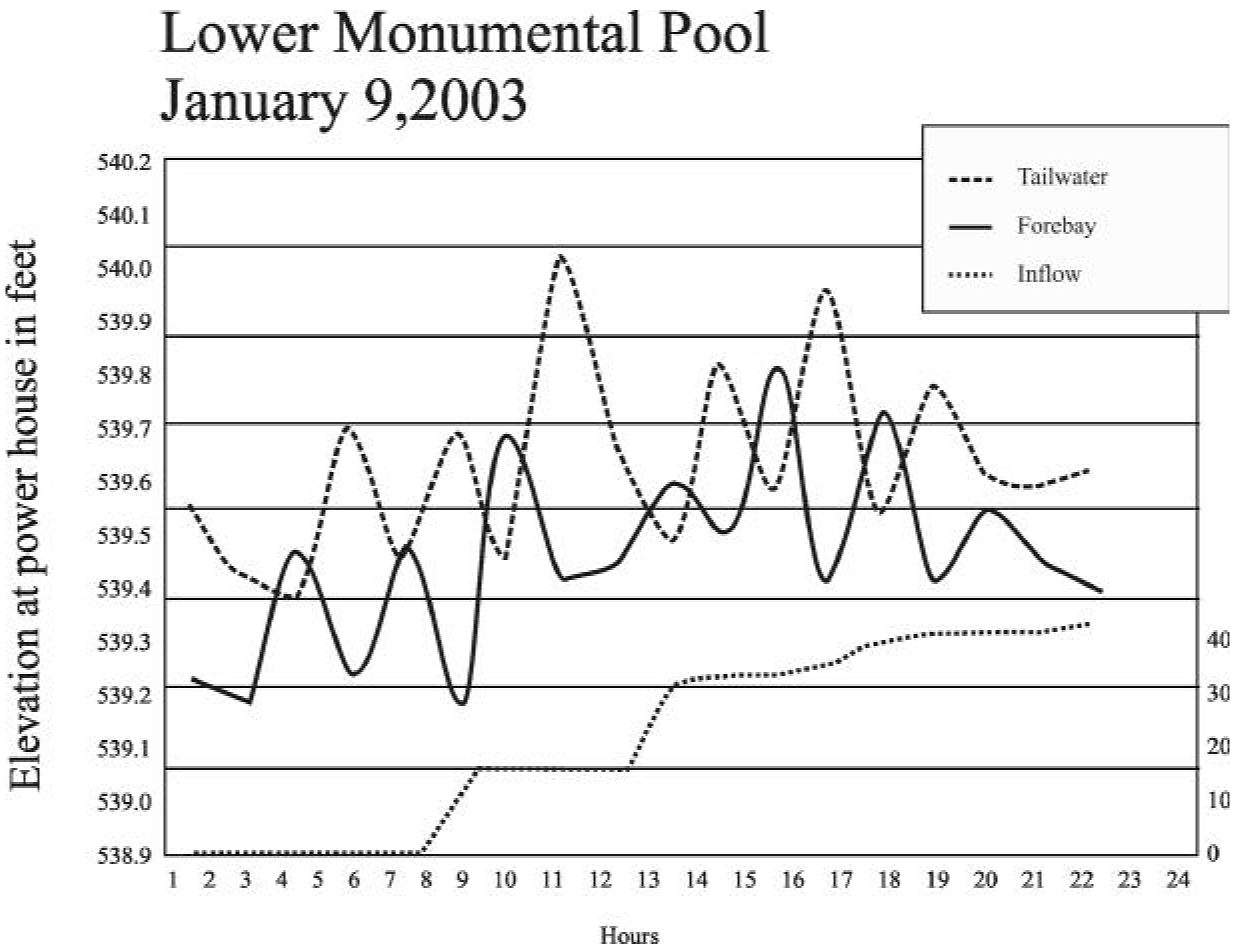
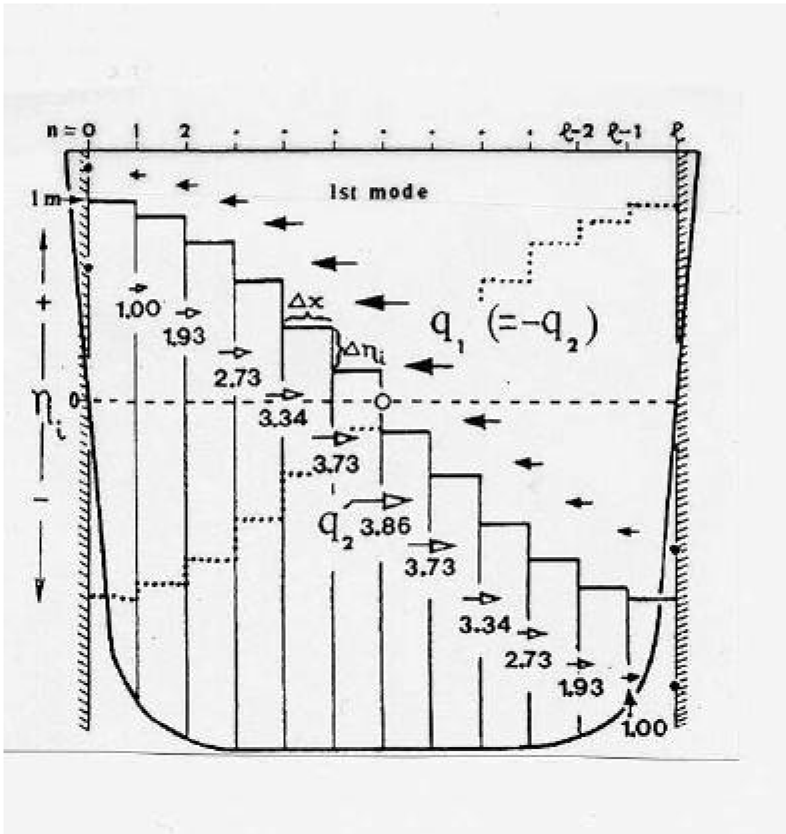


Figure 13. Surface elevation changes and seiche-induced flows in a theoretical lake basin (Lemmin and Mortimer 1986).



Fluctuating Forebay Flows:

The fluctuation of dam discharges within a day by power operations affects the dam's forebay as well as its tailwater. As water in a Snake River reservoir nears an operating powerhouse, its velocity increases progressively within a zone extending about 300 ft upstream of the dam (Adams et al 1997). The velocities attained are proportional to the powerhouse discharge rate. Thus, downstream migrants are exposed to hourly changes in forebay velocities when dam discharges fluctuate.

Fish behavior in the near forebay has been shown to strongly affect the time taken to pass a dam (Plumb et al. 2003). This behavior is related to the daily average river flow rate, with major changes occurring for spring chinook salmon and steelhead near 100 kcfs. Therefore, it is likely that short-term, within-day variations in forebay velocities could cause variations in behavior and affect dam passage times. The variable velocity environment could foster some of the behavioral anomalies seen by Plumb et al. in 2001, a drought year (e.g., upstream movement). These authors noted that powerhouse operations included daily shifts of load from turbines at one end of the powerhouse to the other end. These could also create conditions confusing to migrating fish.

Although the field observations of velocities and fish behavior were conducted at times when flows were at seasonal highs and yearling chinook salmon and steelhead were migrating, the relative intensity of flow fluctuations is greater at lower flows in summer when underyearlings are migrating. The flows experienced in spring 2001 were somewhat representative of flows typically seen later in the year when juvenile fall chinook are migrating. Thus, the strong behavioral responses seen for yearlings are probably magnified for underyearlings.

Fish Orientation Hypothesis:

Fish behavior in different river conditions of velocity and turbulence has been proposed as a guidance mechanism for migration (Coutant 1998, 2000), and it may help explain the broken-stick response of fish survival to differences in water travel time and flow. Changes in behavior associated with fluctuating flows may explain the unusually high rate of residualization of steelhead smolts observed in the year 2001. Behavioral responses may provide opportunities for water management for benefit of fish that include factors other than increasing river flow rates through augmentation.

For years, it has been believed that downstream-migrating salmon and steelhead make use of river currents to assist their downstream movement (Thorpe 1982). Thus, there is a strong demonstrated relationship between fish travel time and water travel time (e.g., Berggren and Filardo 1993). Yet, as shown in telemetry studies by Venditti et al. (2000) and Plumb et al. (2003), smolts lose their downstream orientation in reservoir forebays and show milling behavior and upstream forays extending several miles. While this observation does not negate the relationship found between fish travel time and water travel time, it adds a dimension that probably requires a different approach to amelioration of mortalities experienced in transit. It would appear that the smolts have lost their cues for “downstream” and are searching to relocate the downstream flow (Venditti et al. 2000).

Salmon smolts exhibit several modes of migration. Often salmon smolts swim facing upstream near the surface of the main river channel or thalweg at a very slow velocity relative to the surrounding water (see references cited in Coutant and Whitney 2000). Despite a small component of forward swimming their net movement is downstream. Most smolts will, at times, leave this migration mode and move to shallower water, presumably to feed (underyearling chinook salmon, especially, demonstrate a daily cycle of daytime feeding along shorelines and nighttime movement to river channels where they are displaced downstream). Some, especially steelhead, will also actively swim downstream at times, thus moving at a rate faster than the average water travel time (Muir et al. 1994; Peak and McKinley, 1998; Berggren and Filardo 1993). Nonetheless, downstream displacement is primarily a combination of riverine flow and the intentional positioning of a smolt to maintain its controlled orientation in it.

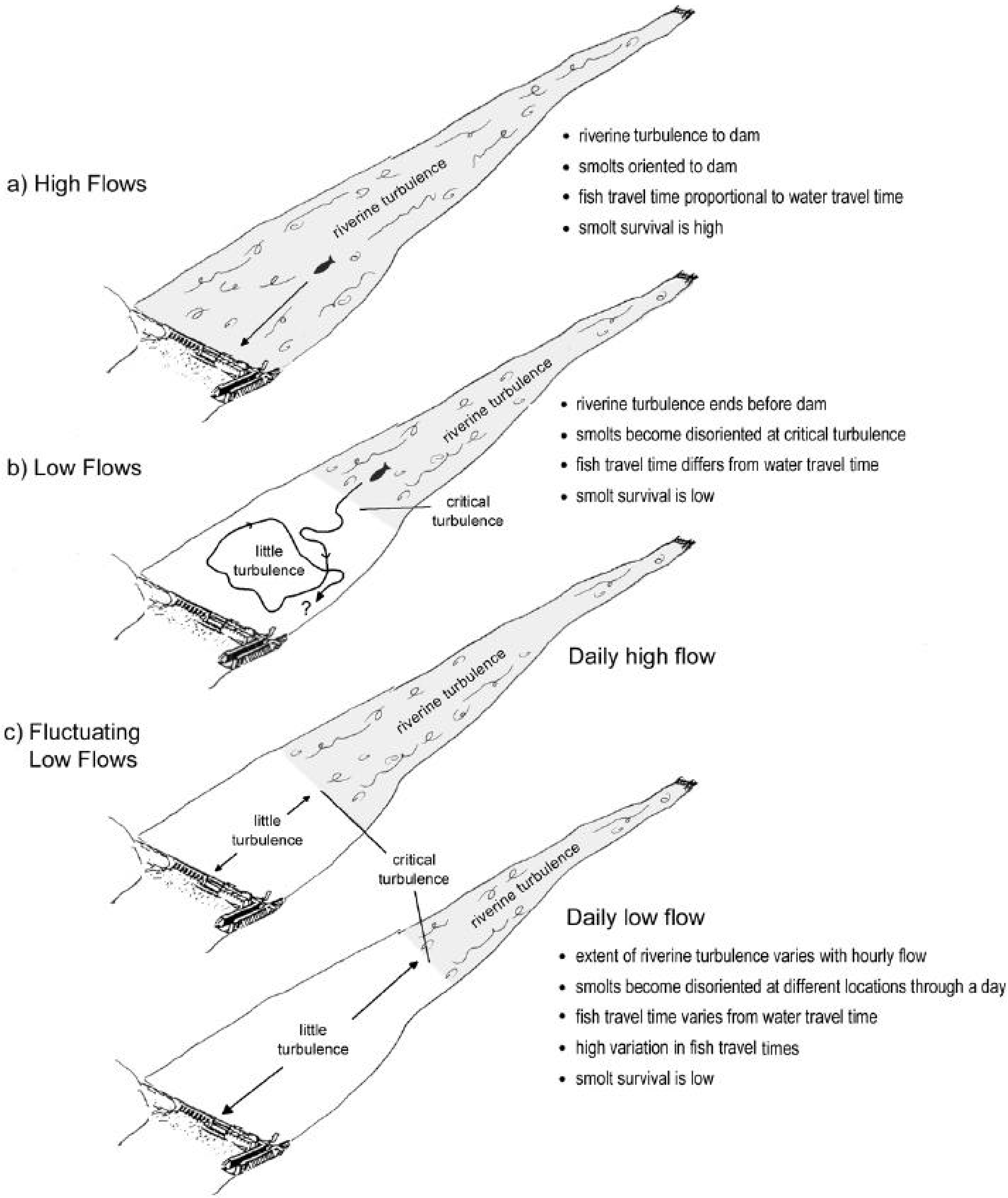
The telemetry studies of wandering smolts in dam forebays and other locations with low river velocities suggest a disappearance of the attachment of smolts to river flows at some combination of river conditions. One possibility is that the river velocity may simply fall below the velocity that smolts swim to maintain their posture, resulting in a net upstream fish movement instead of downstream. However, riverine turbulence has been suggested as an important behavioral cue (Coutant 1998, 2000). It is hypothesized that smolts detect small pressure changes along their bodies (by the lateral line sensory system), which result from turbulence characteristic of a flowing river. So long as this turbulence is sensed, the fish "knows" that it is in a moving flow and it maintains its orientation in the water. When the appropriate level of turbulence is not sensed (a level yet to be determined experimentally or by field observation, which we can call the "critical turbulence"), then the fish leaves its flow-attachment mode and actively swims to relocate the zone of flow. As with other hypotheses, slowed migration presumably results in increased exposure to predators, disease, high temperatures, high dissolved gas, or other damaging factors that reduce survival.

We hypothesize that a major factor determining smolt travel time through reservoirs such as those in the Snake River is the distance downstream that the critical turbulence level extends into the reservoir. Throughout a wide range of fairly high flows, the critical turbulence level is met or exceeded all the way to the dam (Figure 14a). In this case, fish travel time varies with the water travel time through the reservoir, and survival is high because the fish maintain rapid downstream displacement through the whole reservoir. There is no relationship of survival to flow at these high river discharge rates because speedy migration is maintained to and through the dam regardless of flow rate above a certain level. This conjecture conforms to the flat (no relationship) portion of the broken-stick model. However, at low flows the critical turbulence level is not maintained all the way to the dam (Figure 14b). In this situation, fish lose their orientation cue before reaching the dam and are left to wander through the downstream portion of the reservoir, slowing overall migration rate and exposing fish to factors that likely reduce survival. Also, more stored energy is used by the smolts as they must swim actively rather than be displaced passively, thus possibly reducing survival directly or indirectly. Fish travel time and survival are both related to flow at these lower flow rates because at higher flow rates the critical turbulence level will extend closer to the dam and the zone of fish wandering is smaller. This conforms to the portion of the broken-stick model wherein both fish travel time and survival are related to water travel time and flow.

Fluctuating flows would be important in this hypothesis. Relationships between fish travel time and water travel time, as graphed by the FPC and others, are variable among individually PIT-tagged smolts, especially at longer water travel times (lower flows) (Figure 14c). This variability is hypothesized here to result from hourly fluctuating flows from dams throughout a day at lower daily average flows (Figure 6), which alter the rates of downstream displacement and the distance the critical turbulence level penetrates into a reservoir. Different smolts migrating at different times of day can be exposed to different rates of water movement and different locations along the length of reservoir where the critical turbulence level is no longer met. This would yield very different fish travel times for the same daily average flow and daily average water travel time, as has been demonstrated in the FPC analyses.

River modifications other than flow management have been suggested to assist smolts in their migration through reservoirs (Coutant 1998, 2001). These modifications generally consist of passive or active ways to increase turbulence and extend the distance that the critical turbulence level occurs in reservoirs like those on the Snake River. Structural features have been suggested to focus flows and generate riverine turbulence. Active approaches (pumps, propellers) may be useful in certain situations such as approaches to fish bypasses. These approaches for enhancing migration rates through reservoirs deserve more attention. We recognize that their application over the large reaches involved might pose significant engineering problems. Further hydrologic studies would be needed to identify places where they might be useful or necessary. Fish behavioral responses would need to be identified as well. When the alternative to such studies is flow augmentation from limited upstream sources, the additional attention may be justified.

Figure 14. Hypothesized effect of turbulence on smolt migration in reservoirs.



Dam Obstacle Hypothesis:

Migration rates of yearling steelhead and chinook salmon in spring declined to near zero within 400 ft of Lower Granite Dam when daily average flows were less than about 100 kcfs (Plumb et al. 2003). This result emerged from radiotelemetry studies in 1996-2001 at annual average flows that ranged from above the average for recent years to a near record low. The 100 kcfs value is essentially the same as the apparent flow breakpoint seen in flow-survival curves for these species (e.g., FPC data and Smith 2002). This observation suggests that the dam structure or some hydraulic features at the dam (e.g., lack of attraction flow, daily discharge cycle, lack of spill) act as a more prominent barrier at flows below 100 kcfs. These newly released data suggest value in examining dam structures or operations in more detail for potential management avenues below 100 kcfs to increase smolt survival, in lieu of reliance on augmented flow. Flow augmentation would appear to be valuable if it could bring flows above 100 kcfs in order to minimize stalled migration in the immediate dam forebay. That amount of water may not be available. More water alone, however, may not correct operational features that inhibit migration at and below this flow level.

Pulsed Flow Hypothesis:

Pulses of flow have been hypothesized to aid fish migration through reservoirs. This would be generally contrary to hypothesized detrimental effects of flow fluctuations. The pulsed-flow hypothesis suggests that, during low-flow periods, pulses of high flow mixed with periods of little or no flow would stimulate smolts to migrate. The pulses would provide the favorable characteristics of high flows for short periods of time, allowing smolts to be "flushed out" within hours. The hypothesis has its origin in field observations that smolts often increase their passage rate when river discharges increase rapidly.

In the lower Snake River, this hypothesis appears to run counter to the observed data, both for fall chinook salmon that migrate at low flows and at the lower flows in the generally higher flow range when yearling chinook and steelhead migrate. Travel times are longest and survival poorest during periods when flows are fluctuated the most. Thus, as a general rule, intentional pulsing would seem to be counterproductive here.

However, the efficacy of pulsing may depend on the volumes of water involved and coordination of operations of dams to "keep the pulse going", however. From the perspective of the fish orientation hypothesis (above), high flow rates in a pulse may be able to maintain smolt orientation all the way to the dam, but if the dam is not discharging at an appropriate rate to maintain the pulse, the benefit may be lost. In light of the radiotelemetry studies of yearlings, a pulse greater than 100 kcfs may be able to move smolts backed up at the dam during lower flows. In either case, passage rates and survival would be increased. Pulsing would require volumes of water greater than the apparent breakpoint in the flow-survival curves (near 100 kcfs) to be maximally effective. Pulses of lesser magnitude might aid migration rate and survival in proportion to their volume.

The benefits of pulses may occur only during the pulses. Migration might be inhibited (and survival diminished) during the intervening periods of low flow, with no net gain. If seiches are produced, as we observed, the net effect could be counterproductive as an aid to fish migration. The low survival and decreased migration rates already demonstrated during periods of fluctuating flows might be taken as a failed test of the pulse hypothesis, at least in the range of flows experienced. Clearly, the efficacy of intentional pulses has yet to be demonstrated.

This investigation leads to an unexpected recommendation of a measure to improve survival of juvenile salmonids, which we believe could be more effective than simply adding a volume of flow, as in flow augmentation. We believe that stabilization of flows could have a more beneficial effect on survival of juvenile salmonids than simply adding a volume of water, as at present in flow augmentation, where water can be released intermittently.

Appendix 4

NOTES ON THE MATHEMATICS OF REACH SURVIVAL AND FLOW

1 INTRODUCTION

The debate over a flow survival relationship has failed to distinguish between (1) the possible role of flow in governing the speed of smolt outmigration, and (2) the possible role of flow in affecting the mortality *rate* experienced by migrating smolts.

1.1 Speed

The speed of smolt migration determines the amount of time that the smolts will spend in a given reach in the migration corridor. It is not an automatic conclusion that a shorter time is necessarily good, from a life cycle persective. A shorter time in a particular reach definitely lessens the time of exposure to mortality in *that* reach, but after passing that reach, the smolts will still be exposed to mortality, wherever they are. Thus, the reach survival benefit from reducing the time spent in a particular reach will confer a net survival benefit only if that reach is a location of unusually high *instantaneous* mortality compared to other locations during the outmigration.

Furthermore, smolts may be feeding and growing during the outmigration, so the net benefit to production from the time spent in a particular reach will be the balance between growth rate and mortality rate in that reach. The full cost benefit analysis of hurrying the smolts through a particular reach will show a net benefit only if the balance between growth and mortality in that reach is worse than in other reaches where it will spend time during migration.

Finally, the speed of migration affects the date of arrival at the estuary. The condition and physiological state of the smolt is crucial to its survival in the estuary. Calendar date itself seems to play a large role, also, since it is now known from PIT tag studies that the subsequent smolt to adult survival rate varies greatly with date of arrival in the estuary. So, increasing the speed of migration through a reach can be disadvantageous if it brings the smolt to the estuary at too early a calendar date, or in the wrong physiological state. By the same token, decreasing the speed of migration through a reach can also be disadvantageous if it brings the smolt to the estuary a too late a calendar date, or in the wrong physiological state.

Note that measurements of reach survival in just one particular reach do not tell us what the survival is elsewhere, or what the contribution is from time spent in that reach for growth and condition. A comprehensive evaluation of the proper migration speed for a reach will require analysis of measurements of the smolt to adult return rate measured from the head of that reach.

1.2 Mortality Rate

An increase in the mortality rate is unambiguously bad. This is the rate of deaths per unit time. For a given reach, an increase in the mortality rate would indicate that conditions within that reach had become more hazardous.

Instantaneous mortality rate is not measured directly with available observations from smolt monitoring. What is measured is reach survival and smolt to adult return rate. Both of these measures are simple dimensionless fractions giving the number alive at the end of an interval divided by the number alive at the begining. The mortality rate is in units of reciprocal time.

For reach survival, the interval is a defined distance, not time. Thus the cumulated mortality that is expressed in reach survival is a function of the time elapsed in covering that distance, and the instantaneous mortality operating over that time, and speed itself as that determines the time to cover the distance. An interpretation of the patterns observed in the relation between reach survival and travel time or flow requires an understanding of the relation between reach survival, instantaneous mortality, migration speed, and flow.

2 A NULL MODEL FOR REACH SURVIVAL PATTERNS

The starting point for an investigation of the factors influencing reach survival is a *null* model which assumes that the instantaneous mortality is constant, and therefore not affected by flow. Let the constant instantaneous mortality rate be μ. Let the variable flow be f.

Let the distance spanned by a particular reach be a fixed value D. Let the variable time elapsed to traverse the reach be t. Let the variable travel speed be v. The internal relationship between travel time, speed, and distance, is the elementary

$$D = vt \quad . \tag{1}$$

The calculated speed for a water particle is, theoretically, approximately linearly related to flow (as shown in the plots by the FPC). Empirically, smolt migration speed, also appears to be, on average, linearly related to flow, as shown in the plots by the FPC. But the resulting smolt migration speed does not necessarily duplicate the theoretical water particle speed–which is to say, unsurprisingly, that smolt migration is not a simple passive transport in the bulk fluid. Also, the empirical scatter plots of smolt migration speed versus flow show a greatly increased random variation in speed at the lower flows compared to higher flows.

For the moment, let us accept linearity of the migration speed with respect to flow relationship, and treat the proportionality as an empirically determined value c. Thus

$$t = cf \qquad . \tag{2}$$

For a constant instantaneous mortality rate, the survival is a simple exponential decay with time

$$s = e^{-\mu t} \qquad . \tag{3}$$

Taylor expanding the exponential function about zero t, a first order approximation to the relationship between reach survival and travel time, under the null model, is

$$s \simeq 1 - \mu t \qquad , \tag{4}$$

which is a straight line with a negative slope, where the negative of that slope is simply the instantaneous mortality rate. This is consistent with the observed scatter plots relating reach survival to travel time.

The linear flow speed relationship, in equation [2], and the elementary distance speed relationship, in equation [1], when combined, can be solved for travel time as proportional to the inverse of flow

$$t = \frac{D}{cf} \qquad . \tag{5}$$

Substituting this time flow relationship to travel time, gives, for the exact exponential reach survival equation [3], the reach survival flow relationship

$$s = e^{-\frac{\mu D}{cf}} \qquad . \tag{6}$$

Making the same substitution into the Taylor approximation of equation [4] gives

$$s \simeq 1 - \frac{\mu D}{cf} \qquad , \tag{7}$$

which corresponds to a hyperbola with an asymptote at $s = 1$ for large f, and crossing the f axis at $f = \mu D/c$. This approximate appearance of a saturation curve is consistent with the observed trend in the scatter plots of reach survival against flow. But those empirical plots show much greater scatter in the end of the range where reach survival and flow are both large.

So, based on visual inspection, the available data are suggestive of the null model, with no relationship between flow and instantaneous mortality rate, and with a pattern between reach survival and flow that is based simply on the empirical relationship between migration speed and and flow, and the mathematics of the relationship between travel time and speed. An analysis specifically to test for a relationship between flow and instantaneous mortality will have to test for a systematic departure from the pattern derived from the null model.

2.1 A Model of a Flow Survival Rate Relationship

A starting hypothesis for a relationship between flow and instantaneous mortality rate might be the linear model

$$\mu = \mu_0 - \alpha f \qquad , \tag{8}$$

where α is the steepness of the negative slope of the line, and μ_0 is the base mortality rate at zero flow. Note that this model is only reasonable for a modest slope over the range of flows, to keep the mortality rate positive.

Substituting this in the exact exponential of equation [3] for reach survival gives

$$\begin{aligned} s &= e^{-\frac{(\mu_0 - \alpha f)D}{cf}} \\ &= (e^{\frac{\alpha D}{c}})e^{-\frac{\mu_0 D}{cf}} \qquad , \end{aligned} \tag{9}$$

which recapitulates the basic shape of the relationship for a constant mortality rate (with μ_0 now playing that role) modified by a constant multiplicative factor, $e^{\frac{\alpha D}{c}}$. Since the effect on the reach survival flow relationship is multiplicative, it will be strongest where the reach survival is largest, but this is also where the empirical scatter plots show the greatest scatter, so detectability will be a delicate statistical issue.

A test for an influence of flow on instantaneous mortality rate, with this model, would hinge on discriminating α from zero.

3 CONCLUSION

The analyses that have been done to date have not separated an effect of flow on mortality rate from the effect of flow on travel time. Both affect reach survival, but reach survival is not an unambiguous objective from the perspective of the entire life cycle. The benefit of increasing reach survival through reducing travel time depends on a comparison of the growth survival balance within the reach in question and the same balance further downstream, further modulated by the effect of travel time on arrival date in the estuary, which can be too early or too late. Evaluation of the life cycle benefit of the travel time effect, therefore, must rest on statistical analyses of the effect on smolt to adult return rate, not on reach survival.

The benefit of increasing reach survival through reducing instantaneous mortality rate would be unambiguous, but a new kind of statistical analysis would be required to detect such an effect, from the present data collections.

Consolidated References for Text and Appendices

Adams, N. S., D. W. Rondorf, E. E. Kofoot, M. J. Banach, and M. A. Tuell. 1997. Migrational characteristics of juvenile spring chinook salmon and steelhead in the forebay of Lower Granite Dam relative to the 1996 surface bypass collector tests. 1996 annual report to the U.S. Army Corps of Engineers, Contract E-86930151, Walla Walla, Washington.

Andersen, J.J. 2000. Heat budget of water flowing through Hells Canyon and the effect of flow augmentation on Snake River water temperature. Report provided through the University of Washington, Columbia Basin Research, Seattle, WA. Available on the DART web site.16 pp.

Andersen, J.J., R.A. Hinrichsen, and C. Van Holmes, 2000. Effects of flow augmentation on Snake River Fall Chinook. Unpublished report, December, 2000. 62 pp.

Bennett, D.H., M.A. Madsen, M.H. Karr. 1997. Water temperature characteristics of the Clearwater River, Idaho, and Lower Granite, Little Goose, Lower Monumental, and Ice Harbor Reservoirs, Lower Snake River, Washington, during 1991-1993, with emphasis on upstream water releases. Data volume II, project 14-16-0009-1579. Idaho Department of Fish and Game, Moscow ID.

Berggren, T.J. 2000. Subyearling chinook survival to Lower Granite Dam vs flow. Memorandum to FPAC of October 12, 2000, 2pp

Berrgren, T. J., and M. J. Filardo. 1993. An analysis of variables influencing the migration of juvenile salmonids in the Columbia River basin. North American Journal of Fisheries Management 13:48-63.

Chapman, D.A., A. Giorgi, M. Hill, A. Maule, S. McCutcheon, D. Park, W. Platts, K. Pratt, J. Seeb, L. Seeb, and F. Utter. 1991. Status of Snake River chinook salmon. Don Chapman, Consultants, Inc. Boise, Idaho, for the mid-Columbia P.U.Ds; Chelan, County P.U.D, Wenatchee, WA, Douglas County P.U.D., East Wenatchee, WA, and Grant County P.U.D., Ephrata, WA 520 pp.

Chapman, D. W., and D. McKenzie. 1980. Mid-Columbia River system mortality study. Report to mid-Columbia PUDs. Douglas County P.U.D No. 1, East Wenatchee, WA. 23 pp.

Connor, W.P., H.L. Burge, and D.H. Bennett. 1998. Detection of PIT tagged subyearling chinook salmon at a Snake River dam: Implications for summer flow augmentation. North American Journal of Fisheries Management 18:530-536

Connor, W. P., R. K. Steinhorst, and H. L. Burge. In press. Migrational behavior and seaward movement of wild subyearling fall chinook salmon in the Snake River. North American Journal of Fisheries Management

Coutant, C. C. 1998. Turbulent attraction flows for juvenile salmonid passage at dams. Oak Ridge National Laboratory, Report ORNL/TM-13608, Oak Ridge, Tennessee.

Coutant, C. C. 2001. Turbulent attraction flows for guiding salmonids at dams. American Fisheries Society Symposium 26:57-77.

Coutant, C. C., and R. R. Whitney. 2000. Fish behavior in relation to passage through hydropower turbines: a review. Transactions of the American Fisheries Society 129:351-380.

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, ID

Ebel, W.J., C.D. Becker, J.W. Mullan, and H.L. Raymond. 1989. The Columbia River: Toward a holistic understanding. Pages 205-219 in D.P. Dodge, ed. Proceedings of the International Large River Symposium (LARS). Special Publication of the Canadian Journal of Fisheries and Aquatic Sciences.

FPC (Fish Passage Center). 2002. Memorandum from Michelle DeHart to Members' Management Ad Hoc Group entitled "Preliminary Update on Juvenile Migration Characteristics". October 14, 2002. Portland, Oregon

Giorgi, A.E., T.W. Hillman, J.R. Stevenson, S.G. Hays, and C.M. Peven. 1997. Factors that influence the downstream migration rates of juvenile salmon and steelhead through the hydroelectric system in the mid-Columbia River Basin. North American Journal of Fisheries management 17:268-282

Giorgi, A., M. Miller, and J. Stevenson. 2002. Mainstem passage strategies in the Columbia River system: Transportation, spill, and flow augmentation. Unpublished report prepared for the Northwest Power Planning Council, Portland, OR. 98 pp.

Hastie, T.J., and R.J. Tibshirani. 1990. Generalized Additive Models. Monographs on Statistics and Applied Probability 43. Chapman and Hall, London.

Hutchinson, G. E. 1957. A treatise on limnology. Volume I. Geography, physics, and chemistry. John Wiley & Sons, New York.

Independent Scientific Group (ISG). 2000. Return to the River: Restoration of Salmonid Fishes in the Columbia River Ecosystem. Report to the Northwest Power Planning Council. 538 pp. (Available on the Council's web site.)

Independent Scientific Advisory Board (ISAB). Ecological impacts of the flow provisions of the Biological Opinion for endangered Snake River salmon on resident fishes in the Hungry Horse and Libby systems in Montana, Idaho, and British

Columbia. (See especially Appendix 5 – Effects of drawdown on aquatic systems in reservoirs.) (ISAB 1997-3), NWPPC, Portland, OR, March 4, 1997. http:www.nwcouncil.org/library/isab/isab97-3.htm

Independent Scientific Advisory Board (ISAB). Review of Giorgi et al. report “Mainstem strategies in the Columbia River System: Transportation, spill and flow augmentation”. (ISAB 2002-1), Northwest Power Planning Council, Portland, OR.

Independent Scientific Advisory Board (ISAB). Review of Lower Snake River flow augmentation studies. (ISAB 2001-5), Northwest Power Planning Council, Portland, OR

ISG 1995. ISG response to request for review of the Hungry Horse Mitigation Implementation Plan. ISG Report Number 1995-3, June 14, 1995. Available through the Northwest Power Planning Council.

ISG (Independent Scientific Group). 2000. Return to the River 2000. Restoration of salmonid fishes in the Columbia River ecosystem. Report 2000-12, Northwest Power Planning Council, Portland, Oregon.

Karr, M. H., J. K. Fryer, and P. R. Mundy. 1998. Snake River water temperature control project. Phase II. Methods for managing and monitoring water temperatures in relation to salmon in the lower Snake River. Columbia River Intertribal Fish Commission and Fisheries and Aquatic Sciences, Portland, Oregon.

Lemmin, U., and C. H. Mortimer. 1986. Tests of an extension to internal seiches of Defant’s procedure for determination of surface seiche characteristics in real lakes. Limnology and Oceanography 31:1207-1231.

Logie 1993. Power System Coordination: A Guide to the Pacific Northwest Coordination Agreement. U.S. Department of Energy, Bonneville Power Administration, U.S. Department of the Army, Corps of Engineers, North Pacific Division, U.S. Department of the Interior, Bureau of Reclamation, Pacific Northwest Region. Portland, OR. 46 pp

McKenzie, D. D. Carlile and D. Weitkamp. 1983, 1983 System mortality study. Report to mid-Columbia PUDs. Douglas County PUD No. 1, East Wenatchee, WA 25 pp.

McKenzie, D., D. Weitkamp, T. Schadt, D. Carlile, and D. Chapman. 1982. 1982 System mortality study. Report to mid-Columbia PUDs. Douglas County PUD No.1, East Wenatchee, WA, 37 pp.

National Research Council (NRC) 1996. Upstream: Salmon and Society in the Pacific Northwest. Report of the Committee on Protection and Management of Pacific Northwest Anadromous Salmonids for the National Research Council of the national Academy of Sciences. National Academy Press. Washington, D.C. 452 pp.

McConnaha, W.E. 1993. History of flow survival studies in the Columbia Basin. Northwest Power Planning Council. Memorandum to D. Bevan, Chairman, NOAA Fisheries Salmon Recovery Team, Portland, OR. 7 pp

Muir, W.D., A.E. Giorgi, and T.C. Coley. 1994. Behavioral and physiological changes in yearling chinook salmon during hatchery residence and downstream migration. Aquaculture 127:69-82.

NWPPC (Northwest Power Planning Council). 1982. Columbia River Basin Fish and Wildlife Program Pursuant to Section 4(h) of the Pacific Northwest Electric Power Planning and Conservation Act of 1980 (P. L. 96-501). Adopted November 15, 1982, Portland, Oregon.

NWPPC (Northwest Power Planning Council). 1994. Columbia River Basin Fish and Wildlife Program. Report 94-55, Portland, Oregon.

Peak, S., and R.S. McKinley. 1998. A re-evaluation of swimming performance in juvenile salmonids relative to downstream migration. Can.j. Fish. Aquat. Sci. 55:682.687.

Plumb, J. M., M. S. Novick, A. C. Braatz, J. N. Lucchesi, J. M. Sprando, N. S. Adams, and D. W. Rondorf. 2003. Behavior and migratory delay of radio-tagged juvenile spring chinook salmon and steelhead through Lower Granite Dam and reservoir during a drought year. USGS Columbia River Research Laboratory, Cook, Washington. Report for U.S. Army Corps of Engineers, Contract W68SBV00104592, Walla Walla District, Walla Walla, Washington.

Resource Writers, Inc. 1991. The Columbia River System: The Inside Story. Bonneville Power Administration, U.S. Army Corps of Engineers, North Pacific Division, U.S. Department of Interior, Bureau of Reclamation, Pacific Northwest Region, Portland, OR. 82 pp

Seber, B.A.F., and C.J. Wild. 1989. Nonlinear Regression. John Wiley & Sons, New York.

Sims, C.W., W.W. Bentley, and R.C. Johnsen. 1977. Effects of power peaking operations on juvenile salmon and steelhead trout migrations – Progress 1976. Final Report of Research Financed by U.S. Army Corps of Engineers (Contract No. DACW68-77-C-0025). 27 pp

Sims, C.W., W.W. Bentley, and R.S. Johnsen. 1978. Effects of power peaking operations on juvenile salmon and steelhead trout migrations – Progress 1977. Final Report of Research Financed by U.S. Army Corps of Engineers (Contract No. DACW68-77-C-0025). 52 pp

Sims, C. W., and F. Ossiander. 1981. Migrations of juvenile chinook salmon and steelhead trout in the Snake River from 1973 to 1979. NMFS/NOAA Northwest and Alaska Fisheries Center, Seattle, Washington. Report to U. S. Army Corps of Engineers, Portland, Oregon.

Skalski, Mundy, and McConnaha. 1989. Suggested work plan for flow/water budget smolt survival evaluation. Report to ad hoc Committee on Mainstem Research. 6p

Smith, S. S., W. D. Muir, and J. G. Williams. 2002. Factors associated with travel time and survival of migrant yearling chinook salmon and steelhead in the lower Snake River. North American Journal of Fisheries Management 22:385-405.

Suzumoto 2002. Memoranda of November 6, 2002 and December 2, 2002 to Council Members on the subjects of SIMPAS analysis of state proposals, and Mainstem juvenile survival: CRiSP modeling results, 6p and 4p

Thorpe, J. E. 1982. Downstream movements of juvenile salmonids: a forward speculative view. Pages 387-395 in J. D. McCleave, G. P. Arnold, J. J. Dodson, and W. H. Neill, editors. Mechanisms of migration in fishes. Plenum, New York.

Tiffan, K.F., R.D. Garland, and D.W. Rondorf. 2002. Quantifying flow-dependent changes in subyearling fall chinook salmon rearing habitat using two-dimensional spatially explicit modeling. North American Journal of Fisheries Management 22:713-726

University of Washington, Center for Quantitative Sciences. DART

Venditti, D. A., D. W. Rondorf, and J. M. Kraut. 2000. Migratory behavior and forebay delay of radio-tagged juvenile fall chinook salmon in a lower Snake River impoundment. North American Journal of fisheries Management 20: 41-52.

Wagner, P.G., J. Nugent, W. Price, R. Tudor, and P. Hoforth. 1999. 1997-1999 evaluation of juvenile fall chinook stranding on the Hanford Reach. Annual Report to Bonneville Power Administration. Contract 97B130417, Portland, OR

Whitney, R. R., L. D. Calvin, M. W. Erho, Jr., and C. C. Coutant. 1997. Downstream passage for salmon at hydroelectric projects in the Columbia River basin: development, installation, and evaluation. Report 97-15, Northwest Power Planning Council, Portland, Oregon.

Zabel, R.W., S.G. Smith, W.D. Muir, D.M. Marsh, J.G. Williams, and J.R. Skalski. 2002. Survival estimates for the passage of spring-migrating juvenile salmonids through Snake and Columbia river dams and reservoirs. Annual report to Bonneville Power Administration, Portland, Contract DE-AI79-93BP10891. Available on the web at http://www.efw.bpa.gov/cgi-bin/FW/publications.cgi.