Toward a Resolution of the Flow/Survival Debate and the Impacts of Flow Augmentation and Water Withdrawal in the Columbia/Snake River System

By James J. Anderson
Columbia Basin Research, School of Aquatic and Fishery Science
University of Washington

December 4, 2003

Introduction

The National Marine Fisheries Service (NMFS) 2000 Biological Opinion for the operation of the Federal Columbia River Power system defined adequate water quality, quantity, and velocity as essential features of the critical habitat of the juvenile salmon migratory corridor. To meet these features NMFS established a series of Reasonable and Prudent Actions (Actions 14-39) related to water management. Of particular significance RPA 14 calls for seasonal flow targets at Snake and Columbia River dams and RPA 27 restricts water depletions in the basin until the recovery is achieved (NMFS 2000). These RPAs are based on a controversial "flow/survival" hypothesis, established more than two decades ago, which states that more flow would benefit juvenile salmon during their migration, with more flow being provided by augmentation from reservoir releases or fewer water withdrawals (Anderson 2001). In 2003, hypotheses on the factors affecting smolt survival have undergone significant revision and review. These include updates of the data and new analyses by National Oceanographic and Atmospheric Administration (NOAA) (Williams et al. 2002), the Columbia Basin Fish and Wildlife Authority (CBFWA) (FPC 2003; Petrosky et al. 2003), and Columbia Basin Research of the University of Washington (CBR) (Anderson 2003a, b). In addition, reviews were conducted for the Northwest Power and Conservation Council (NPCC) (Giorgi et al. 2002; ISAB 2002), and a review requested by Washington State is being conducted by the National Research Council (NRC). Although these new analyses and reviews examine essentially the same information, they treat the information differently, and reach conclusions that are similar in some aspects but radically different in terms of the effect of flow changes on smolt survival. This white paper discusses these analyses and demonstrates that the information now exists to resolve the issue of the impacts of flow augmentation and water withdrawals on smolt survival.

Hypotheses on factors affecting in–river survival

The analyses and reviews of the impact of flow alteration on smolt survival conducted to date can be divided into three independent hypotheses, developed by CBFWA, NOAA and CBR. All three analyses include new PIT tag observations and correlate estimated smolt survivals with water quality properties. The analyses use different data groupings; the CBFWA and NOAA estimate survival through the Snake and Columbia hydrosystem for data blocked by the week of arrival at Lower Granite Dam. The CBR analysis blocks data by the daily arrival at the dam. All analyses estimate the average environment experienced by the fish for the respective data blocks. While the analyses used somewhat different selections of the data and grouped them differently (Table 1) these differences are not significant to the conclusions reached in the analyses.

Table 1. Comparisons of survival analysis approaches.

Analysis Group	Data Treatment			Survival Covariates						Type of Analysis
	Years	River Reach	Block Size	Spill[1]	Flow[2]	FTT[3]	WTT[4]	Tem[5]	Tu[6]	
CBFWA	1998-2001	LGR-IHR	week	●			●	●		MLR[7] model on yearly data
NOAA	1995-2001	LGR-MCN	week		●					Graphical analysis on yearly data
CBR	1995-2002	LGR-MCN	day	●		●		●	●	ET[8] model on seasonal and yearly data

1) Proportion of river spilled experienced by fish during migration. 2) Average flow experienced by fish over migration. 3) Fish travel time. 4) Water travel time. 5) Average temperature experienced by fish over migration. 6) Average turbidity experienced by fish over migration. 7) Multiple liner regression model. 8) Ecological theory model. LGR = Lower Granite Dam, IHR = Ice Harbor Dam, MCN = McNary Dam.

Major differences can be seen among the approaches. CBFWA combines data over all years in multiple linear regressions and demonstrates in-river smolt survival correlated with the proportion of water spilled, water travel time (WTT) (a calculated surrogate for flow), and water temperature. CBFWA demonstrates that survival could be linearly related to WTT for data combined over years (Figure 1). CBFWA does not present analyses for survival within years, claiming that within-season relationships would not appear because juvenile survival is the result of many direct and indirect environmental and biotic variables, described as averages over a period of time, and although variations within a year exist, the in-season variations are not sufficient to characterize it (Petrosky et al 2003).

NOAA (Williams et al. 2002) analyzes smolt survival between LGR and MCN for the years 1995 through 2001. The survival data are blocked into weekly groups and graphically correlated with an index representative of the flow experienced by the fish during the migration. Combining data for all years, the authors suggest that the flow/survival pattern could be described by a hockey stick curve with a linear flow-dependent part at low flows and a flow-independent part at high flows. The threshold for the break in the curve is about 100 kcfs (Figure 2).

The CBR analysis is derived from ecological theory for the survival of smolts through dams, how smolts interact with their predators, and how temperature, exposure time, and turbidity affect predator/prey interactions (Anderson 2003a; Anderson et al. in review). The significance of each variable was determined by fitting the model to survival data of the passage of chinook and steelhead data migrating through the Snake/Columbia river system. The spill proportion and distance traveled were the most important variables. The coefficient describing the effects of travel time was small indicating that travel time contributed generally less than 5% to the reservoir survival through the hydrosystem (Anderson 2003a). Neither fish travel time nor travel velocity, both of which correlated with flow, were important factors in determining the change in survival within years or between years.

The CBR model is fit to data grouped between years and within years. That is, the model is fit to data for all years combined and to data from each year to explore the seasonal variations in survival within each year. Both the between-year and within-year data sets were fit well by the model; temperature is a major variable accounting for differences in survival between years and within each year (Figure 3). However, because of the within-year and between-year flow and temperature relationships (Figure 4), the observed flow and survival relationships are also fit by the model for between-year (Figure 5) and within-year data (Figure 6).

The three analyses all exhibit relationships between flow measures and survival for data grouped between years (Table 2). The CBFWA analysis produces a linear regression between survival and WTT, and the NOAA and CBR analyses produce hockey stick relationships between survival and flow. So, using data grouped between years, it might be concluded that smolt survival relates to flow directly or to some attribute related to flow. However, this hypothesis must be rejected when looking at the within-year data. The CBFWA analysis specifically states that the survival-WTT relationship was not evident within a year. The NOAA in an earlier analysis demonstrated no consistent flow/survival relationships for spring chinook and steelhead (Smith et al. 2002). In contrast, the CBR analysis, which does not include flow, fit well for within-year flow/survival patterns. The inability of flow-based explanations to reproduce the within-year patterns is strikingly illustrated by plotting the NOAA flow-based hockey stick model and the CBR temperature-based model against the within-year flow/survival relationship for spring chinook in 2001 (Figure 6). In fact, no explanation based on flow is able to fit the observed within-season survival patterns because flow exhibits a seasonal peak while survival generally declines over the season.

Table 2. Comparison of model fits to data between years.

Analysis Group	Spring chinook		Steelhead	
	N	r-square	N	r-square
CBFWA	66	0.65	26	0.87
CBR	1015	0.71	315	0.82

Although survival through the Snake River and McNary Dam can be correlated with flow using between-year data blocks, a relationship is not evident for 163 groups of PIT tagged fall chinook smolts migrating through John Day Reservoir between June 21 and August 8 over the years 1999-2002 (Figure 7). Individual and combined year regressions of flow against survival showed no statistically significant relationship with p-values ranging between 0.69 to 0.345 and r-squares from 0.018 to 0.075. The survival vs. flow slopes of the regressions ranged between -0.002 to 0.0019 for individual years and was 0.0004 for the combined year data.

In addition to considering how well the flow and temperature based models fit or do not fit data, their theoretical bases also need to be considered. The NOAA model has no theoretical basis, and is simply two straight lines fit by eye through a cloud of data. The CBFWA model has no theoretical basis either, although there is a reference to the success of the transition to seawater depending on physiological condition changes over time, and arrival at estuary within the "biological window" (Petrosky et al. 2003). However, this reference to the transition to seawater does not address how survival in the hydrosystem is related to water travel time. Only the CBR model has a basis in ecological mechanisms: the probability of encounters between resident predators and migratory smolts (Anderson et al. in review) and the effect of temperature on predator and prey activities (Anderson 2003a). In essence, in the model smolts pass through a gauntlet of stationary predators; their mortality depends on the number of predators encountered, which depends on migration distance, and temperature, which affects predator metabolic activity.

Delayed mortality effects

Although we can soundly reject the flow alteration/survival relationship as a factor in fish survival through the hydrosystem, how river flow and especially flow augmentation may affect the survival of fish in the estuary and ocean must still be considered. Researchers have demonstrated that the condition of the juvenile fish during their freshwater life stage is correlated with their return rate as adults (Beckman et al. 1999; Ward and Slaney 1988) and have hypothesized that the timing of ocean entry affects adult survival (Budy et al. 2002). This link between freshwater experience and ocean survival is sometimes referred to as "delayed mortality"; although the issue is complex, we can estimate the relative importance of flows on delayed mortality. In particular, we can estimate the effect of flow augmentation and water withdrawals on delayed mortality to within an order of magnitude. To do this, we consider how these flow actions incrementally affect fish travel time and water temperature, two factors that may relate to delayed mortality.

Fish travel time, while not affecting survival in the hydrosystem, does affect the estuary arrival time and the total duration of exposure of the migrating fish to the river environment. Increased water temperature, besides affecting migration survival directly, can also increase the fishes' metabolic demand during migration. Together these factors could decrease the condition of the fish entering the ocean and so increase their mortality rate. The fractional change in delayed mortality from flow augmentation and water withdrawals will be approximately proportional to the incremental change in river temperature and travel time from the actions. The CRiSP smolt passage model (CBR 2003), which has been calibrated with 15 years of PIT tag data, quantifies the effect of flow alteration on travel time. For example the model predicts that each change in flow by 1000 cfs measured at Lower Granite Dam changes the spring chinook travel between the Salmon River and Bonneville Dam by 2 hours. Therefore, water withdrawals that decrease flow by 1000 cfs would increase a 26 day travel time to 26 days and two hours. A one million acre feet flow augmentation from Dworshak Reservoir over a 40-day period would decrease the travel time from 26 to 25 days. Thus, water withdrawals should have unmeasurable and insignificant impacts on fish travel time and major flow augmentations should decrease travel time by less than 5%. Therefore, the effect of these actions on delayed mortality through a change in migration time is small to insignificant.

The impact of these flow altering actions on delayed mortality through temperature can be made in a similar manner. First, flow augmentation may increase or decrease the water temperature. Flow augmentation from the Dworshak Reservoir decreases river temperature through the upper dams of the lower Snake River. However, because river temperatures closely follow air temperatures (Mohseni et al. 1998) the temperature impact deceases with distance from the source of augmentation as the water equilibrates with the air temperature. The impact is greatest for fish traveling between Dworshak and Lower Granite Dam (Connor et al. 2003), but the effect of Dworshak water downstream is greatly reduced, and the impact on fish survival through the hydrosystem is very small (Beer and Anderson 2003). Furthermore, flow augmentation from the Brownlee Reservoir on the upper Snake River can increase downstream river temperature (Anderson 2000), and thus would have a small negative impact on smolt survival (Anderson et al. 2000). Thus, over a two week migration period, the total degree days of exposure of fish with flow augmentation in the Snake River is essentially the same as the exposure without augmentation.

The impact of water withdrawals on river temperature may also be positive or negative, depending on whether the temperature of the withdrawal's return flow is higher or lower than the river temperature. Returns from surface runoff or municipal waste water may be warmer than the river water while subsurface returns may be cooler. However, whatever the effect, the magnitude of change in the river temperature is proportional to the amount of water withdrawn relative to the river flow. A 1 kcfs return flow that is 1^{o}C warmer than a 100 kcfs river flow would increase the river temperature by 0.01^{o}C. We are fairly safe in concluding that the impacts of water withdrawals of this magnitude have an insignificant and unmeasurable impact on river temperature and therefore on delayed mortality or direct in-river survival.

Exploring larger impacts

Although we can reasonably conclude that incremental flow augmentation and withdrawals on the order of a several kcfs have unmeasurable impacts on in-river survival and delayed mortality, we need to consider whether larger flow alterations outside the ranges considered here may have some catastrophic impact on the ecosystem and fish survival. Although such projections are speculative, we can evaluate the potential problems by addressing some of the ecological pathways through which the environment affects salmon. In particular, we can explore whether increased impacts proportionally degrade the ecosystem or if there are critical thresholds at which the system degrades. Below we address critical thresholds related to flow and temperature.

The flow threshold

Intuitively, when flow is reduced to zero, hydrosystem survival is zero. The NOAA between-year analysis (Williams et al. 2002) demonstrated a hockey stick pattern where survival became dependent on flow at a threshold of 100 kcfs. The CBR analysis showed that this break was generated by temperature, not flow. Furthermore, an analysis presented to the IASB indicates that the flow/survival threshold is much lower than the one postulated by NOAA (Anderson 2003b). Data shows that Dworshak hatchery spring chinook survival to Lower Granite Dam between 1990 and 2001 was independent of flow over a range 34 to 133 kcfs (Figure 8). The CBR model fits this data well and indicates that the flow/survival break point is on the order of 25 kcfs and is very sharp. Furthermore, the model provides a mechanism for the break point. When the fishes' migration velocity, which is determined by flow, drops below the random velocity between the predator and fish, survival no longer depends on the distance through the predator gauntlet. Because the fish movement is predominantly random below the threshold, the number of predators encountered depends on the migration time. Therefore, below the flow threshold, flow affects survival through its effects on migration time. Thus, both evidence and theory suggest that flow only affects fish survival below the lowest flow ever observed in the Columbia/Snake River system. The ISAB hypothesis that variable water velocities caused by reservoir seiches would produce a flow/survival relationship is fully supported by the CBR model. However, the CBR model and the data indicated the break point is much lower than the ISAB suggested.

Impacts of withdrawal on temperature and survival

Recently the effect of very large water withdrawals on smolt survival were investigated (Olsen 2003). The analysis, based on the CRiSP passage model, withdrew up to 80% of the 2001 summer flow from Hanford Reach. The analysis estimated the effect of the withdrawal on temperature using a flow/temperature relationship derived from historical data at McNary Dam. With the relationship, an 80 kcfs flow reduction from withdrawal increased river temperature by 0.8°C. The impact on various stocks was mixed. Snake River spring chinook and steelhead stocks were virtually unaffected by Hanford withdrawals because the fish migrated prior to the July-August withdrawal period. Snake

River fall chinook were unaffected because these were transported in barges. However, fish that migrated from the Okanogan would experience a significant decrease in survival from their release point to Bonneville tailrace (survival = 2% with 0 withdrawal, survival = 0.5% with 80 kcfs withdrawal). This preliminary impact analysis suggests that survival decreases gradually with increasing withdrawals and only for stocks that directly experience the reduced flows.

The impacts of global warming

Although the impacts of global warming on Columbia/Snake River salmon have been of interest for some time, only recently has it been possible to assess the possible impacts. A model study by Payne et al. (in press) explored the impacts of global warming on air temperature and river flow in the Columbia River system. Air temperature was projected to increase over the century by 2^{o}C while the annual precipitation was projected not to change (Figure 9). The model predicted that flow volume would not change, although the flow profile would shift to higher winter flows and lower summer flows as a consequence of the warming (Figure 10).

Even though future climate predictions are highly uncertain, we may surmise from this study that spring flows may be similar to what they are today but that spring temperatures may be warmer several decades in the future. In the summer, however, we may expect both the flows and temperatures to be similar to conditions in the 2001 low flow year. If these predictions were accurate, the water policies of today will have to be reconsidered. Perpetuating existing flow policies would be even more wasteful than they are currently, and would limit the ability of water managers to allocate water appropriately in a new climate regime.

Water management and the Precautionary Principle

The current Columbia/Snake River water policies are based to a large degree on the "Precautionary Principle," which is a response to uncertainty in the face of risks to the environment. In sum, it promotes acting to avoid serious or irreversible potential harm, despite lack of scientific certainty as to the likelihood, magnitude, or causation of that harm (PPP 2003). Although the Precautionary Principle is accepted by some resource managers and is intuitively reasonable, there are problems with its application. Reliance on the Precautionary Principle has sparked major controversy, raising issues around equity, "green protectionism," conflicts between environment and development priorities, the use of sound science, and the role of stakeholders in decision-making concerning risk (PPP 2003). Of particular concern is that reliance on the Precautionary Principle diminishes the motivation to scientifically manage resources and resolve uncertainties. This trend is especially evident in Columbia River flow management. For several decades, the argument has focused almost entirely on flow alteration, increasing river flows and continued reworking of the hypothesis for how flow is the single and essential variable for water management (Anderson 2001). This approach has been protected by the Precautionary Principle. Enough information is available, and the conclusions found within that information are sufficiently certain, to discard the existing flow alteration policy.

References

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

Anderson, J.J., R.A. Hinrichsen and C. VanHolmes. 2000. Effects of Flow Augmentation on Snake River Fall Chinook. Report to the Committee of Nine and the Idaho Water Users Association. (www.cbr.washington.edu/papers/jim/flowaug_fch.pdf).

Anderson, J.J. 2001. History of the Flow Survival Relationship and Flow Augmentation Policy in the Columbia River Basin. www.cbr.washington.edu/papers/jim/flow_survival_history.html

Anderson, J.J. 2003a. An analysis of smolt survival with implications to flow management. Presented to the National Research Council committee evaluating Water Resources Management, Instream Flows, and Salmon Survival in the Columbia River Basin, Washington. February 6 2003.

Anderson, J.J. 2003b. Response to the ISAB Review of Flow Augmentation: Update and Clarification Feb 10, 2003. http://www.nwcouncil.org/library/isab/2003-1/comments/janderson.pdf

Anderson, J.J., E. Gurarie, R.W. Zabel. In review. The predator-prey ecological neighborhood from mean free path length theory and application to juvenile salmonids in the Snake River Basin.

Beckman, B.R., W.W. Dickhoff, W.S. Zaugg, C. Sharpe, S. Hirtzel. 1999. Growth, smoltification, and smolt-to-adult return of spring chinook salmon from hatcheries on the Deschutes River, OR. Transactions of the American Fisheries Society. 128: 1125-1150.

Beer, W.N. and J.J. Anderson. 2003. Sensitivity of juvenile salmon survival to temperature in the mainstem Snake and Columbia Rivers. Columbia Basin Reach Draft report.

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

Columbia Basin Research (CBR) 2003. CRiSP 1: Columbia River Salmon Passage model. www.cbr.washington.edu/crisp/crisp.html.

Connor,W.P., H.L. Burge, J.R. Yeasley and T.C. Bjorn. 2003. Influence of flow and temperature on survival of wild yearling fall chinook salmon in the Snake River. North American Journal of Fisheries Management 23: 362-375.

Fish Passage Center (FPC). 2003. February 26, 2003 - USFWS, CRITFC, IDFG, ODFW - Comment on the Independent Scientific Advisory Board’s (ISAB) draft document “Review of Flow Augmentation: Update and Clarification” as it relates to the Northwest Power Planning Council’s Draft Mainstem Amendments. www.fpc.org/fpc_docs/joint-technical/32-03.pdf

Giorgi, A., M. Miller and J. Stevenson. 2002. Mainstem Passage Strategies in the Columbia River System: Transportation, Spill, and Flow Augmentation. Northwest Power and Conservation Council. Report 2002-2. www.nwcouncil.org/library/2002/2002-3.htm

Independent Scientific Advisory Board (ISAB). 2002. Review of Giorgi et al. Report "Mainstem Passage Strategies in the Columbia River System: Transportation, Spill, and Flow Augmentation". ISAB Document 2002-1. www.nwcouncil.org/library/isab/isab2002-1.htm

Mohseni, O. H.G. Stefan and T.R. Erickson. 1998. A nonlinear regression model for weekly stream temperatures. Water Resources Research 34: 2685-2692.

National Marine Fisheries Service (NMFS) 2000. Biological Opinion: Reinitiation of consultation of the Federal Columbia River Power System, including the juvenile fish transportation program, and 19 Bureau of Reclamation Projects in the Columbia Basin. National Marine fisheries Service Northwest Region. Dec 21 2000.

Payne, J.T., A.W. Wood, A.F. Hamlet, R.N. Palmer and D.P. Lettenmaier, 2004. Mitigating the effects of climate change on the water resources of the Columbia River basin, Climatic Change (in press).

Precautionary Principle Project (P.P.P.) 2003. www.pprinciple.net/the_precautionary_principle.html

Petrosky, C ., M. Filardo, H. Schaller, T. Nigro. 2003. The effects of mainstem flow and water velocity on salmon and steelhead populations of the Columbia River. Columbia Basin Fish and Wildlife Authority Presentation, August 20, 2003

Olsen, D. 2003. Analysis of the irrigation withdrawals on smolt survival.

Smith, S. G., W. D. Muir, E. E. Hockersmith, J. G. Williams, and J. R. Skalski. 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

Ward, B.R. and P.A. Slaney. 1988. Life history and smolt-to-adult survival of Keogh River steelhead trout (Oncorhynchus mykiss) and the relationship to smolt size. Canadian Journal of Fisheries and Aquatic Sciences 45: 1110-1122.

Williams, J.G., B. Muir, S.G. Smith, R. Zabel. 2002. Status of Columbia River salmon and links to flow: What we do and do not know. Presentation to Northwest Power Planning Council December 11, 2002.

Figures

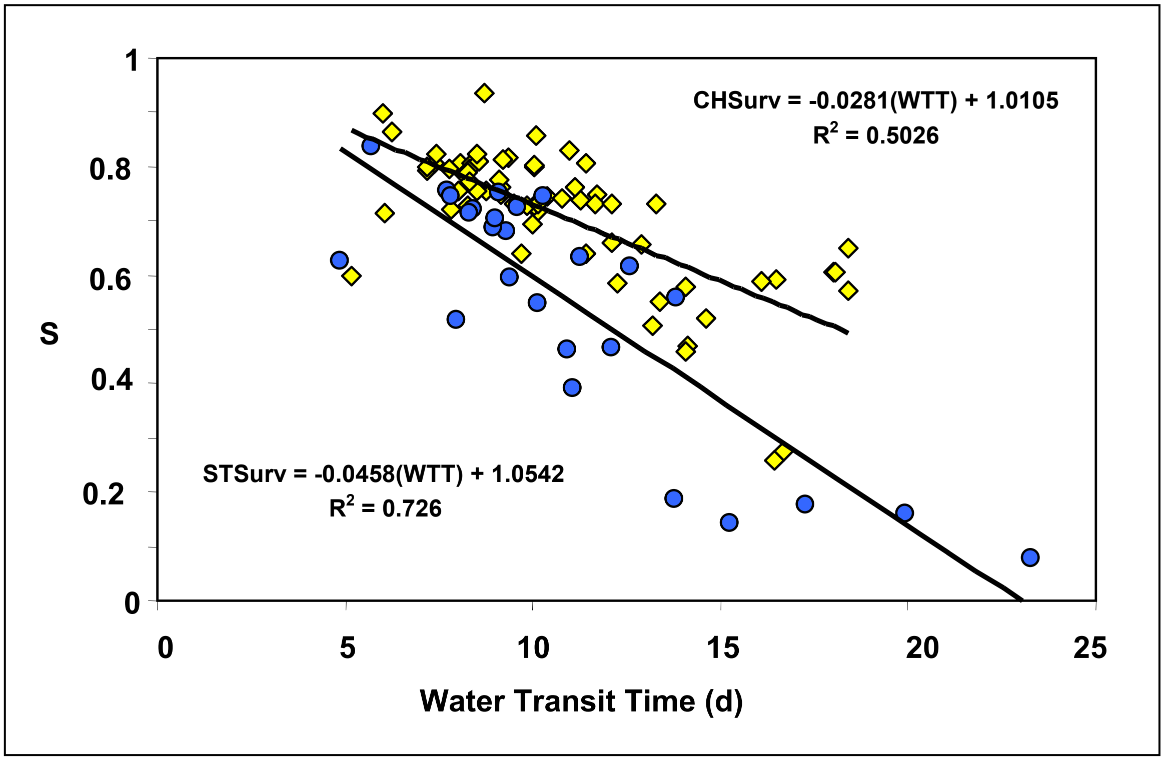
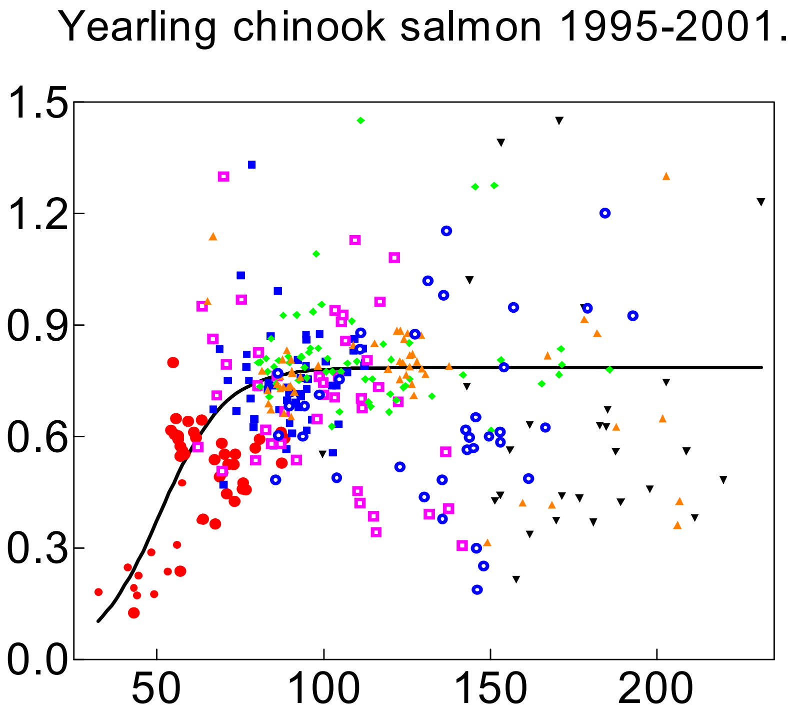


Figure 1. CBFWA relationship between survival (S) and water transit time for Snake River spring chinook (◊) and steelhead (●). Reformatted from Petrosky et al. (2003).



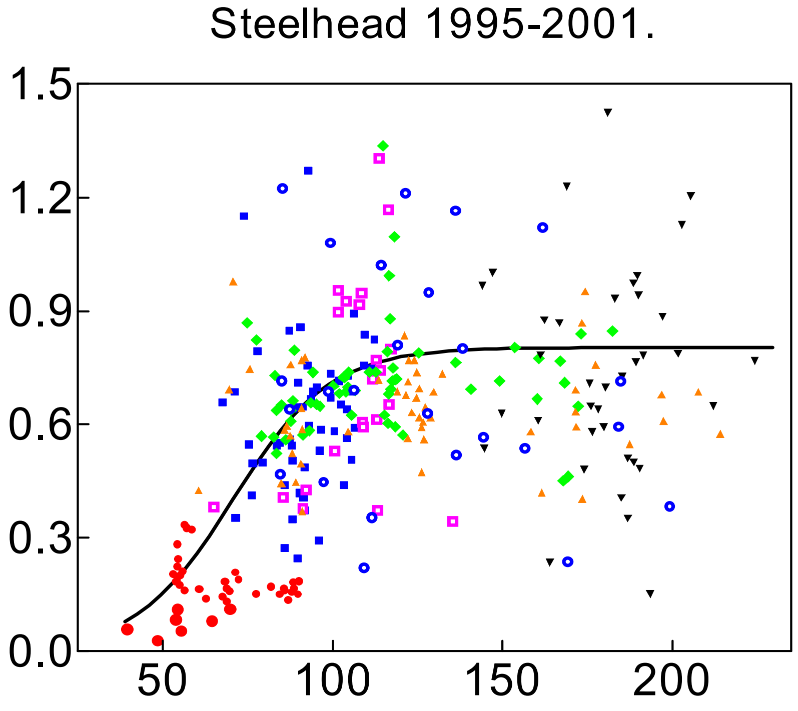


Figure 2. NOAA analysis of flow and survival between Lower Granite Dam and McNary Dams (Williams et al. 2002).

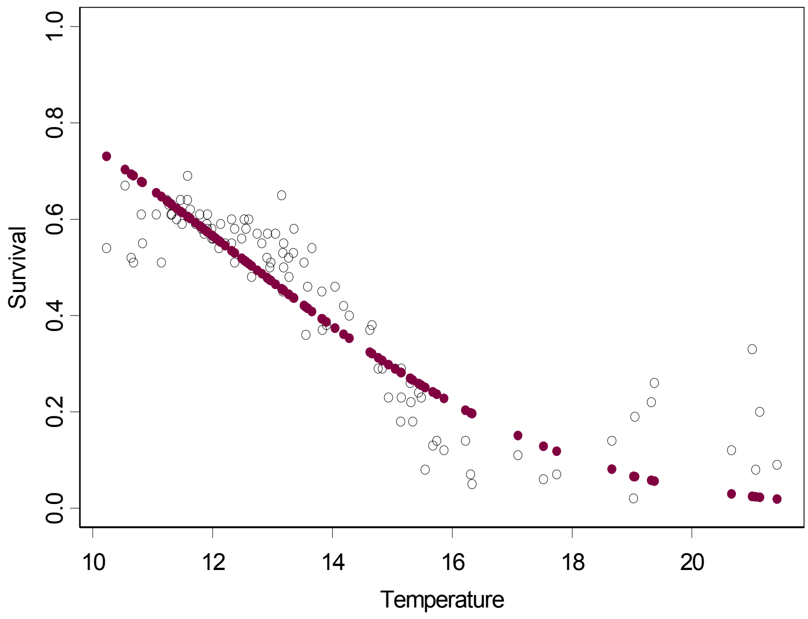


Figure 3. CBR model showing relationship between chinook survival and temperature over the reach LGR and MCN in 2001. Survival estimated with PIT tags designated (○) survival estimated with the CBR model designated (●) (from Anderson 2003a).

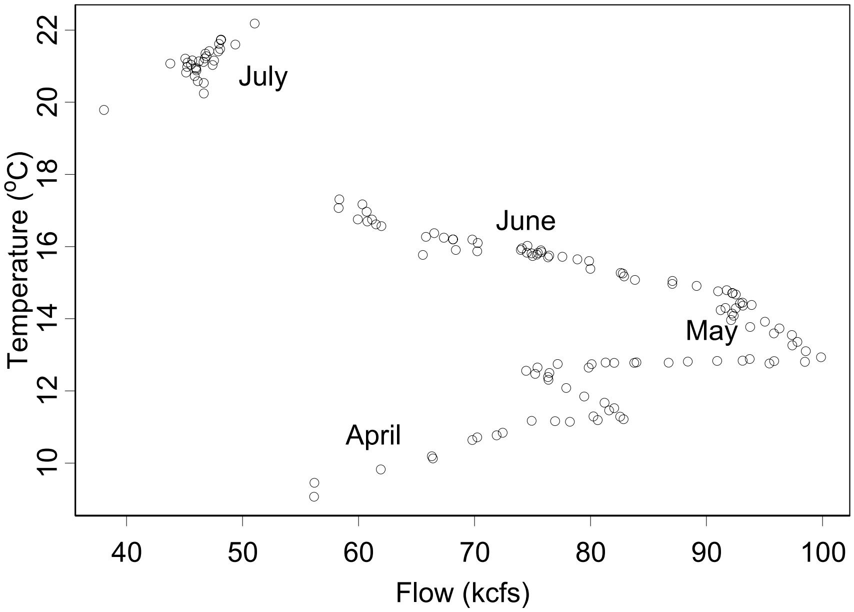


Figure 4. Temperature flow relationship in 2001 in Snake River.

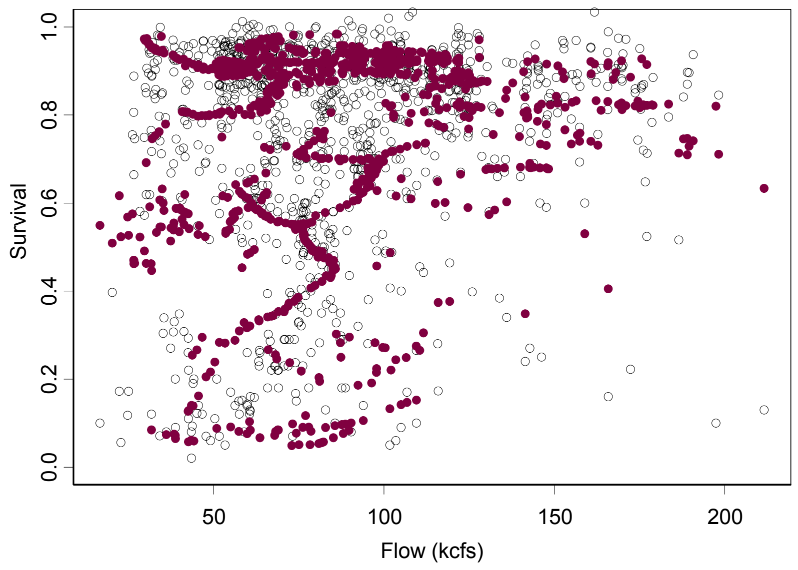


Figure 5. Modeled and observed chinook survival vs. flow over single and multiple reaches between LGR to MCN over the years 1995-2002. Survival estimated with PIT tags designated (○) survival estimated with the CBR model designated (●) (from Anderson 2003a).

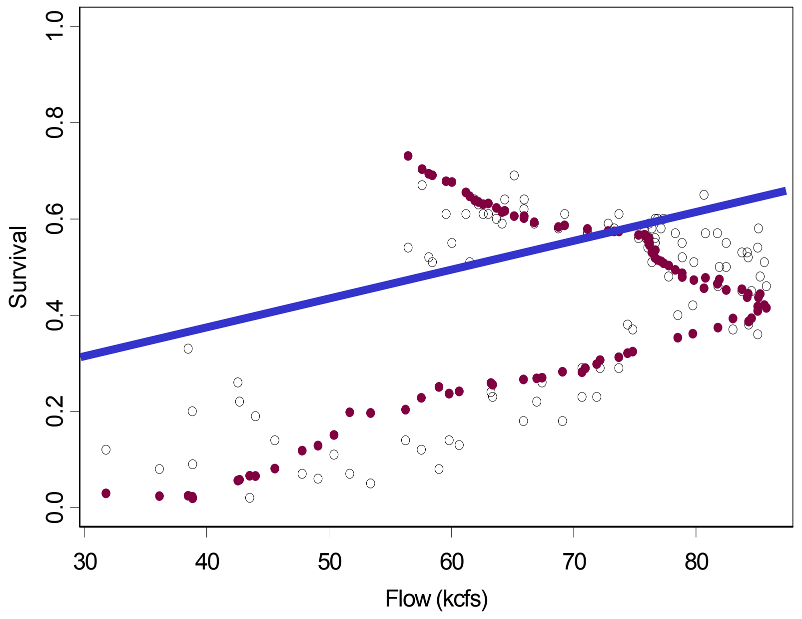


Figure 6. Spring chinook survival vs. flow between Lower Granite Dam and McNary dam for 2001. Survival estimated with PIT tags designated (○) survival estimated with the CBR model designated (●). Line depicts the low flow segment of NOAA's hockey stick flow/survival relationship (from Anderson 2003a).

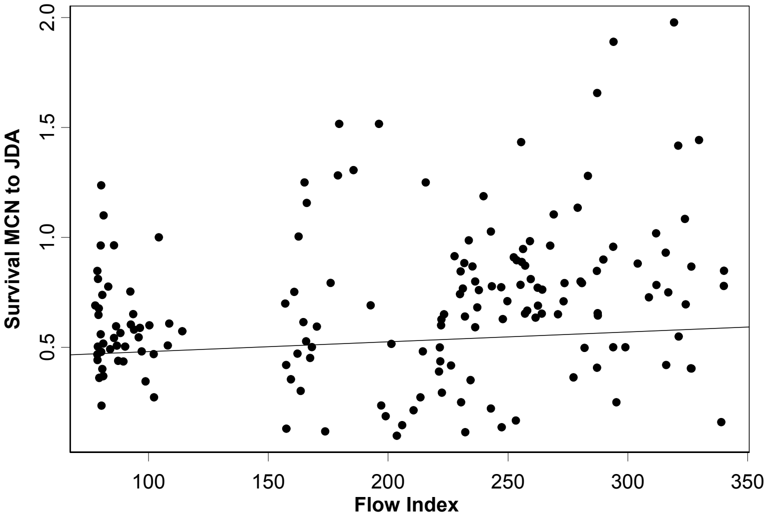


Figure 7. Flow and survival of fall chinook passing though John Day Reservoir between June 21 and August 8 over years 1999 – 2002. Regression line is weighted by the std-err of survival.

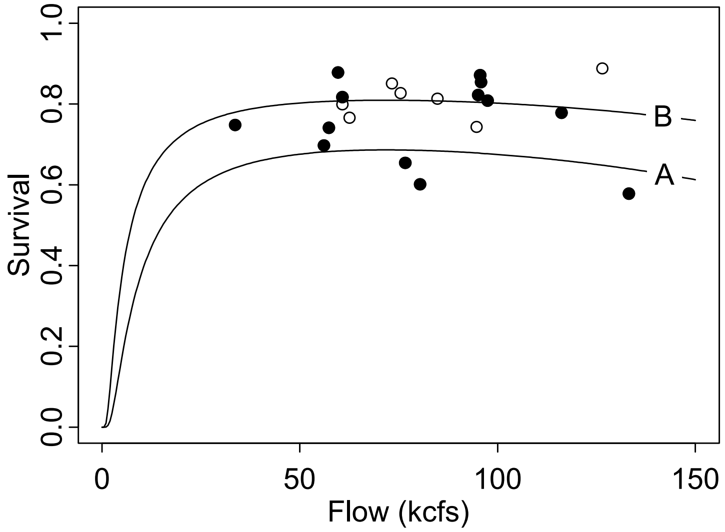


Figure 8. Relationship of flow to smolt survival from Dworshak Hatchery to Lower Granite Dam over the years 1990 and 2001. Curve A models survival with a travel distance X = 116 km and curve B uses X = 64 km. Open points are survivals for release dates greater than Julian Day 100. Solid points are survivals for release dates Julian Day 100 or less (from Anderson 2003b).

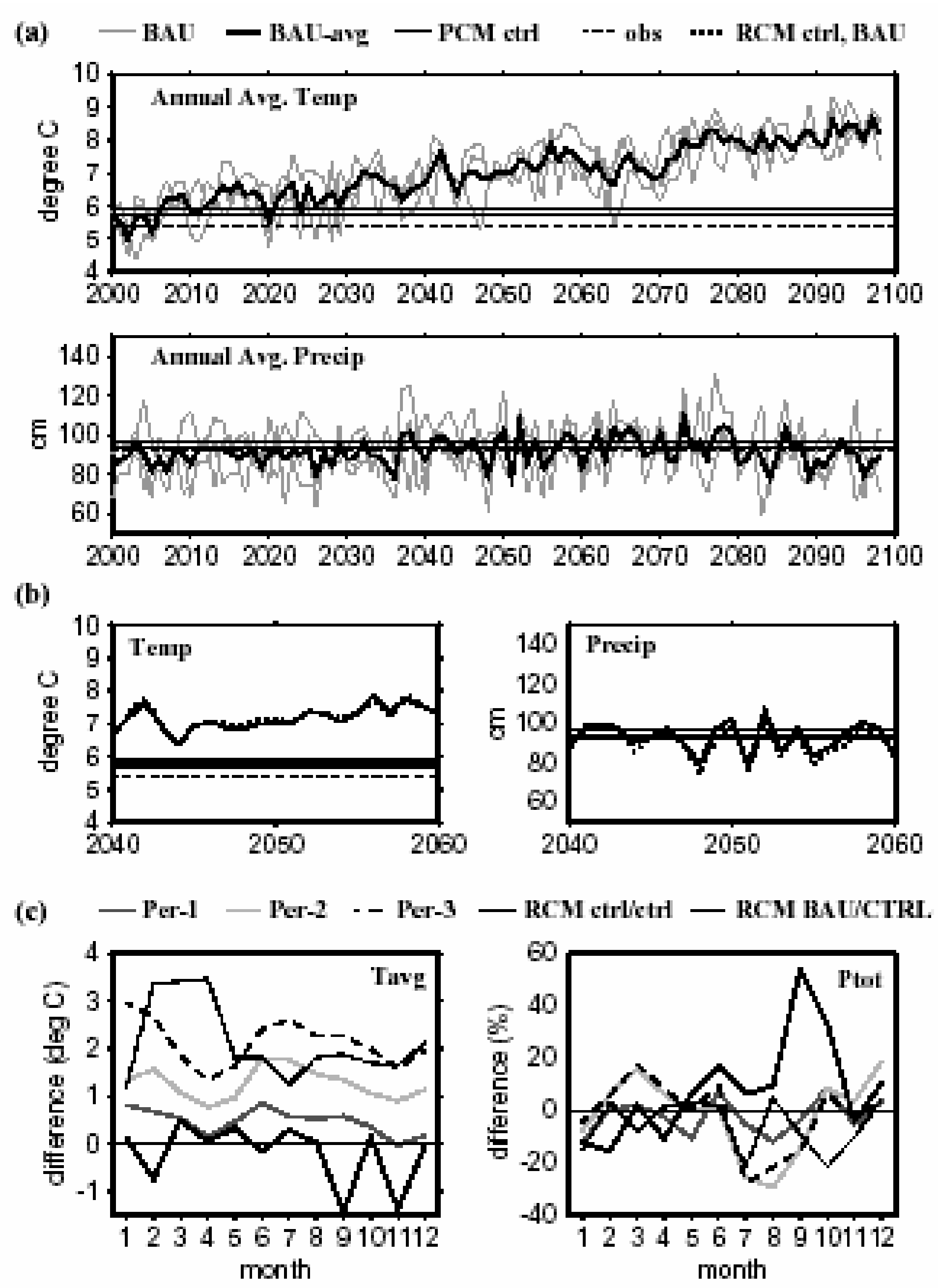


Figure 9. (a) Downscaled PCM BAU climate PNW-average annual total precipitation and average temperature, compared with long-term averages from the PCM and RCM control climates and observations (1950-99); (b) comparison of downscaled RCM and PCM BAU-averaged climate variables (legend from (a)); and (c) CRB-average monthly total precipitation and average temperature: PCM BAU Period average changes relative to PCM control climate ("Per-1 to Per-3"), RCM BAU average changes relative to RCM control climate ("RCM BAU/CTRL"), and RCM control climate difference from PCM control climate ("RCM CTRL/CTRL") (from Payne et al. in press).

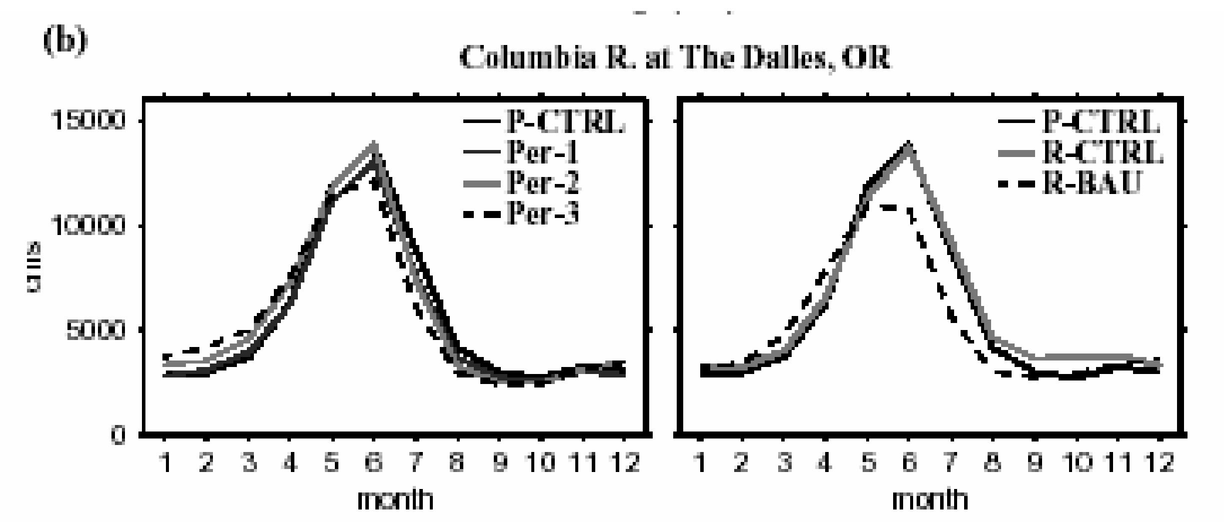


Figure 10. Mean monthly streamflow hydrograph for the Columbia River at The Dalles, OR, for the PCM BAU ensemble average climate and RCM BAU climate, and the PCM and RCM control climate scenarios (from Payne et al. in press).