



# FISH PASSAGE CENTER

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## MEMORANDUM

TO: Dave Statler, NPT

*Michele DeHart*

FROM: Michele DeHart

DATE: July 14, 2011

RE: Benefits of spill for juvenile fish passage at hydroelectric projects

In response to your request, to assess fish passage characteristics with and without spill, the FPC staff has reviewed the available monitoring information regarding the benefits of spill for fish passage through the Columbia and Snake Rivers. The FPC has reviewed and summarized observations of juvenile fish passage characteristics developed through annual monitoring of downstream passage in the Smolt Monitoring Program and smolt-to-adult return rates from life cycle monitoring conducted through the Comparative Survival Study (CSS). In particular we have summarized the observations from monitoring and the results of various analyses regarding the benefits of spill for fish passage. We utilized the CSS developed model simulation analyses to address your question regarding juvenile fish survival with and without spill. Our primary conclusions from our review follow:

- Increasing proportion of spill provided for fish passage at hydroelectric projects has resulted in higher juvenile spring/summer Chinook, fall Chinook, sockeye and steelhead survival and faster juvenile fish travel time through the FCRPS.
- Increasing spill proportion provides mitigation for low flows through the hydrosystem. In observations of years with similar flow and water travel time, juvenile fish survival and fish travel time are improved in years with higher average spill.
- Spill proportion and water travel time (i.e.flow) are correlated with smolt-to-adult return rate. Increasing spill proportion and faster water travel time (i.e.higher flow) result in higher smolt-to-adult return rate.
- Fresh water passage conditions affect early ocean survival. Spill proportion and water travel time affect ocean survival of Chinook and steelhead.
- Increasing spill proportion allows a higher proportion of downstream migrants to avoid power house passage. Powerhouse passage through juvenile bypass systems decreases smolt-to-adult return rates. Direct estimates of project survival do not capture the delayed mortality effect of project passage and therefore underestimate project impact on juvenile survival and adult return.

- Model simulations indicate that juvenile survival could be significantly increased and juvenile fish travel time could be decreased by increasing spill proportion in low flow periods.

**Increasing proportion of spill provided for fish passage at hydroelectric projects has resulted in higher juvenile Chinook, sockeye and steelhead survival and faster fish travel time through the FCRPS**

In the Draft 2010 FPC Annual Report (Section IV), the FPC staff estimated the survival rates for weekly cohorts of Snake River wild Chinook, hatchery Chinook and combined hatchery and wild steelhead in the LGR-MCN reach using standard CJS methods over migration years 1998-2010. This report also provided seasonal survival rates for Snake River sockeye (combined hatchery and wild) in the LGR-MCN reach over 1998-2010. Finally, this report provided survival estimates of bi-weekly cohorts of Snake River hatchery sub-yearling Chinook over migration years 1998-2010.

As in annual reports from previous years, environmental variables associated with each of the above cohorts were generated based on fish travel time and conditions at each dam along the reaches. Among the environmental variables that were estimated were average spill percentage and median fish travel time. The spill percentage at downstream dams were averaged over a seven-day window around the median passage date at each dam, and the travel time to the next dam was used to adjust the start date of the calculations. For example, steelhead travel time from LGR to LGO for the earliest release cohort in 2005 (detected at LGR from 4/17 to 4/23) was estimated to be 5.0 days based on 378 detections. Average spill percentage over the time period of April 22 to April 28 at LGO was then calculated. At each downstream dam, average spill percentage was calculated in a similar manner. Since no PIT-tag detection data were available until 2005 at IHR, travel time to IHR was estimated as 43% of the total travel time from LMN to MCN (corresponding to the distance to IHR relative to the distance to MCN). The overall average spill percentage was the average of these dam-specific calculated values for spill percentage. Fish travel time estimates were the median fish travel time (LGR-MCN) for each cohort.

**Survival: Increasing spill proportion has increased juvenile fish survival through the hydrosystem**

Reach survival estimates and environmental variables for all cohorts will be available in a separate appendix of the Final 2010 Fish Passage Center Annual Report, which will be posted on the FPC web-site on August 31, 2011. Weighted regression analyses of average spill percentage and juvenile reach survival (LGR-MCN) were conducted for each species. Juvenile survival estimates were log-transformed ( $\text{Ln}(\text{Surv}_{\text{LGR-MCN}})$ ). In order to do weighted regressions with these log-transformed survival estimates, it was necessary to calculate the variance of a log-transformed variable. Weighting for these regressions was based on the inverse of this variance. For log normally distributed random variables, the variance of  $\log(x)$  is (Blumenfeld 2001):

$$\text{Var}[\log(x)] = \log(1 + [\text{cv}(x)]^2) \tag{1}$$

Based on these weighted regression analyses, increasing spill percentage resulted in higher juvenile Chinook, sockeye, and steelhead survival through the FCRPS (Figures 1 through 6). Furthermore, for all species, it is evident that providing spill in a low flow year (e.g., 2007 and 2010) resulted in increased juvenile reach survival, when compared to low flow years with no spill (e.g., 2001) (Figures 1 through 6).

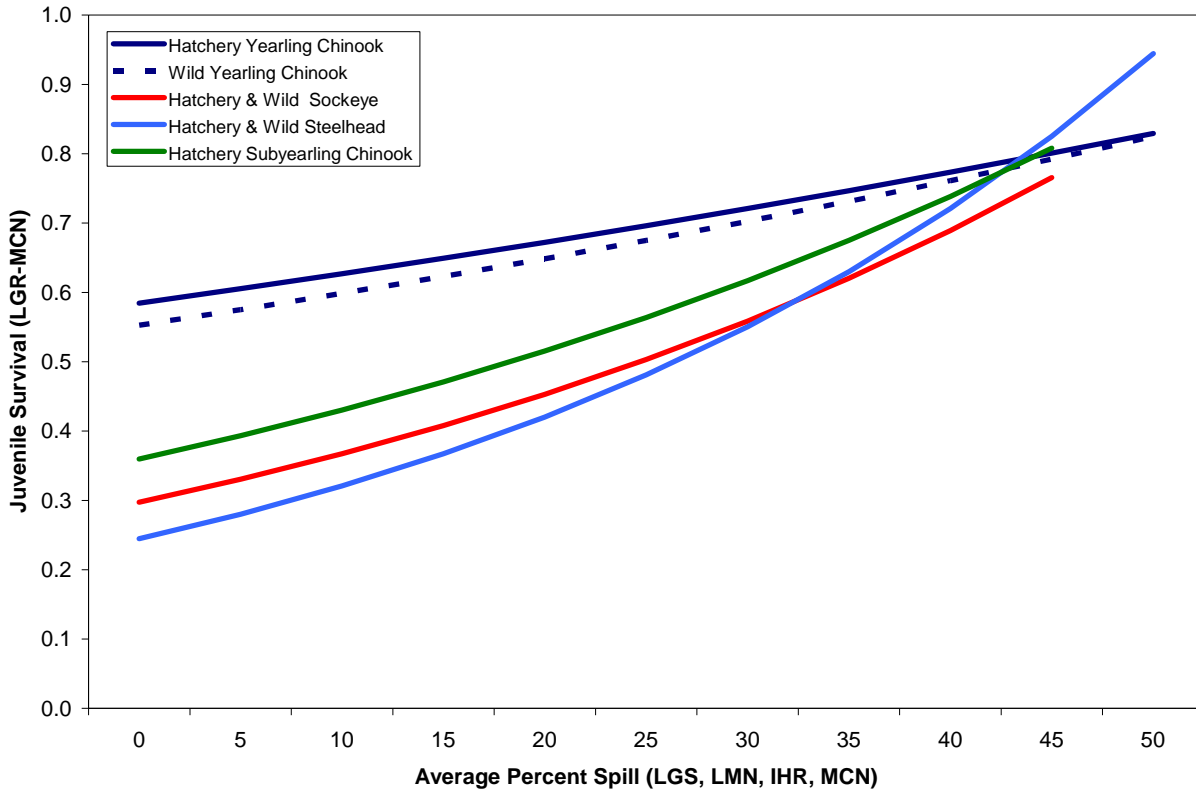


Figure 1. Weighted regression analyses of average spill percent and juvenile survival (LGR-MCN) for yearling Chinook, sockeye, steelhead, and subyearling Chinook (1998-2010).

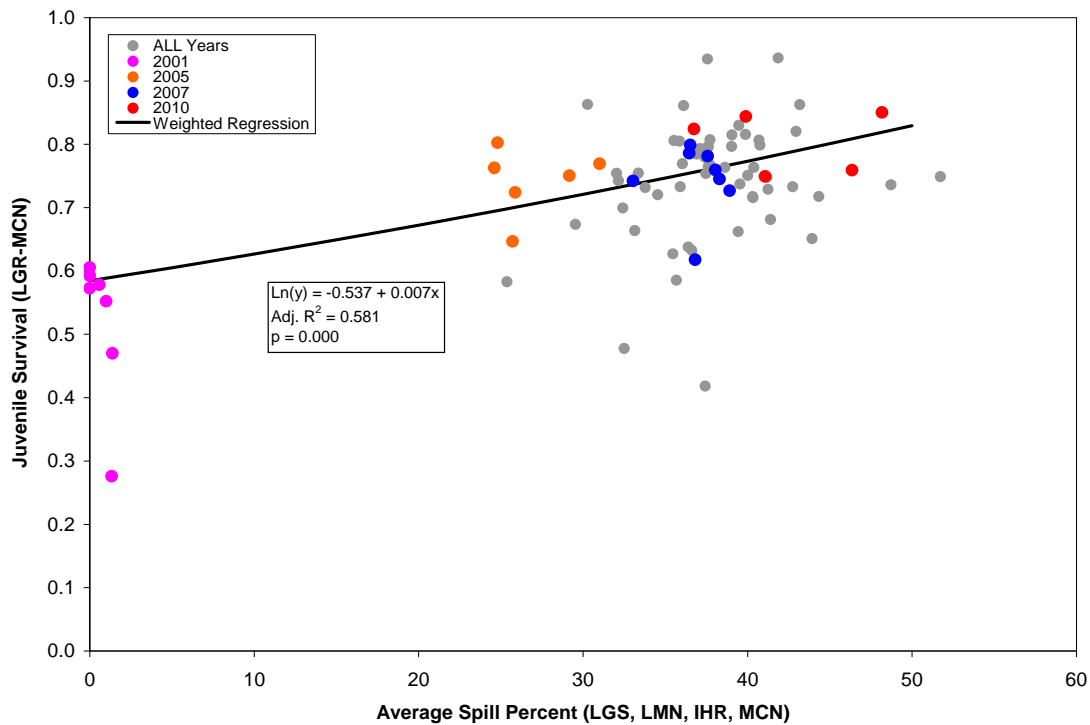


Figure 2. Weighted regression analysis of average spill percent and juvenile survival (LGR-MCN) for hatchery yearling Chinook. Weighted regression line is for all years (1998-2010).

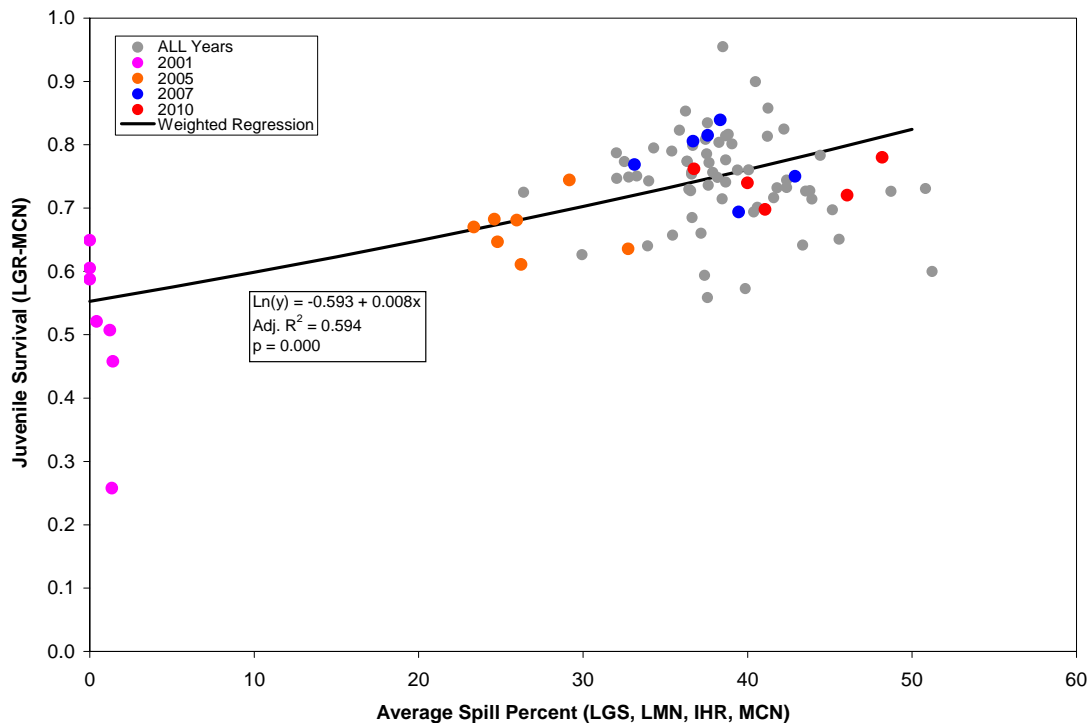


Figure 3. Weighted regression analysis of average spill percent and juvenile survival (LGR-MCN) for wild yearling Chinook. Weighted regression line is for all years (1998-2010).

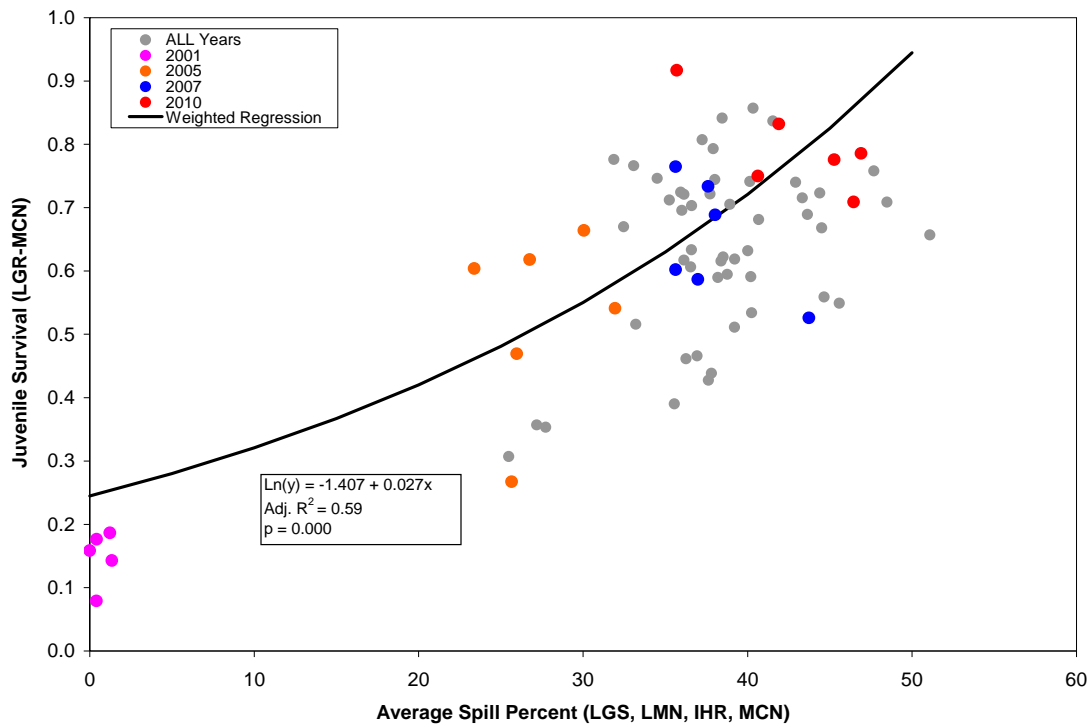


Figure 4. Weighted regression analysis of average spill percent and juvenile survival (LGR-MCN) for hatchery and wild steelhead. Weighted regression line is for all years (1998-2010).

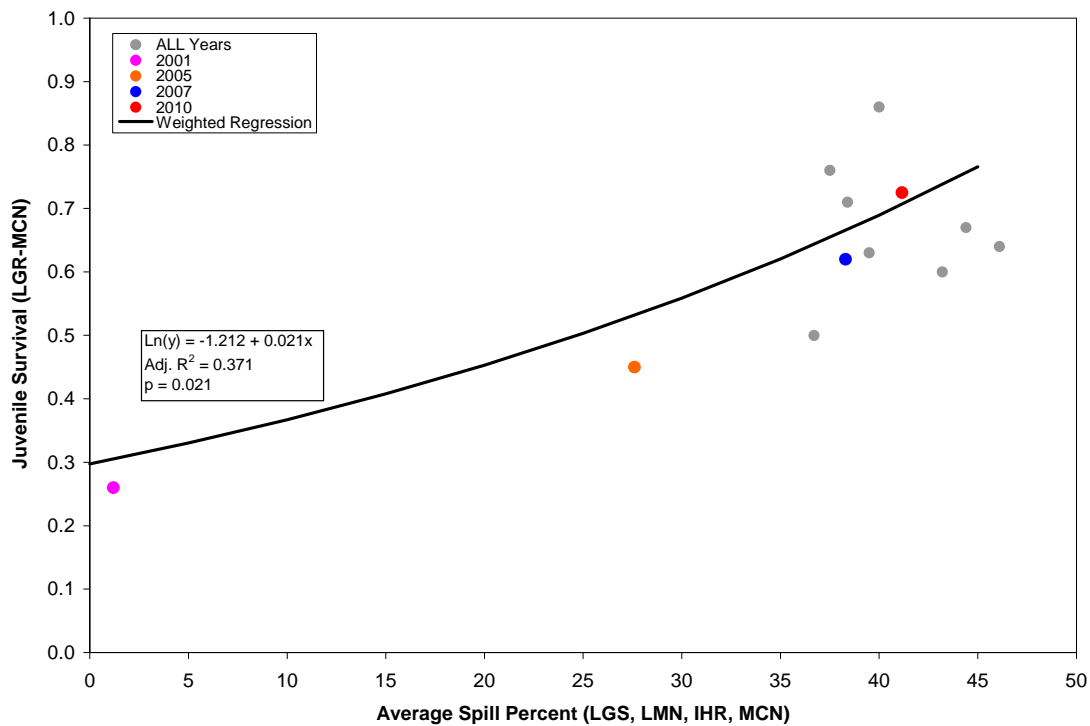


Figure 5. Weighted regression analysis of average spill percent and juvenile survival (LGR-MCN) for hatchery and wild sockeye. Weighted regression line is for all years (1998-2010, except 2004).

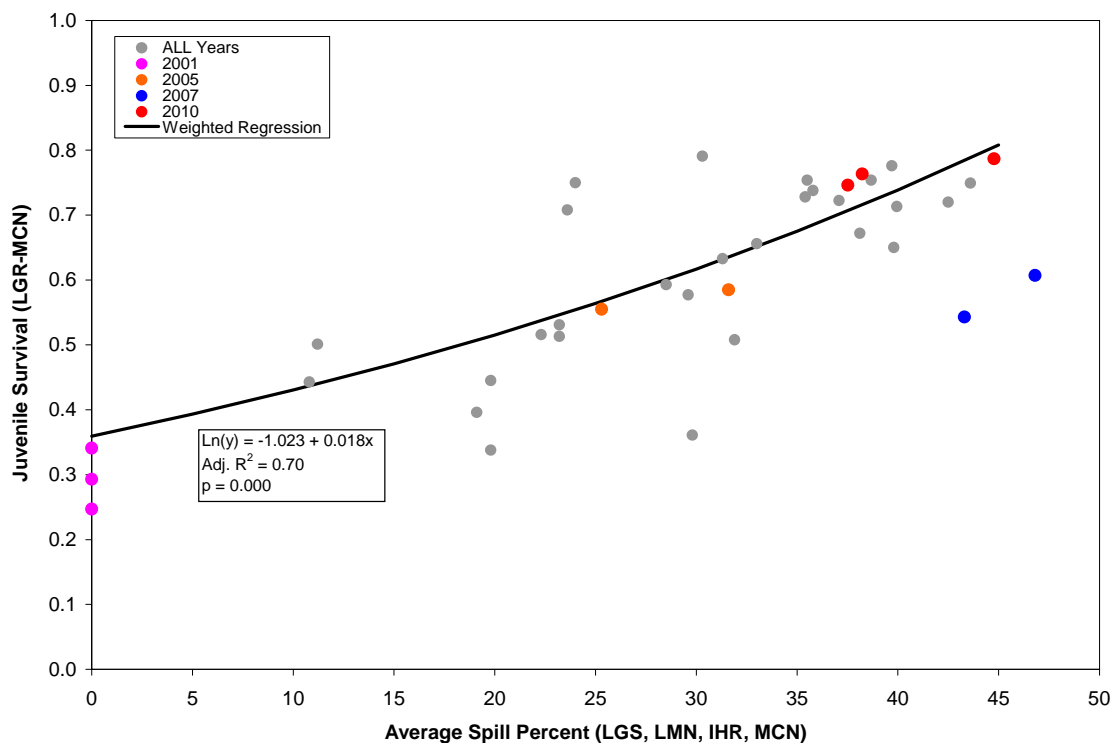


Figure 6. Weighted regression analysis of average spill percent and juvenile survival (LGR-MCN) for hatchery subyearling Chinook. Weighted regression line is for all years (1998-2010).

## TRAVEL TIME

### **Increasing spill proportion at hydroelectric projects also decreased juvenile salmon and steelhead travel time through the Columbia and Snake Rivers FCRPS.**

The following plots are the result of linear regression analyses of average spill percentage and median fish travel time for each species. There were not transformations of the variables in these regressions and no weighting. Based on these regression analyses, increasing spill percentage resulted in faster fish travel times for juvenile Chinook, sockeye and steelhead through the FCRPS (Figures 7 through 11). Furthermore, for all species it is evident that providing spill in a low flow year (e.g. 2007 and 2010) resulted in decreased fish travel time, when compared to low flow years with no spill (e.g. 2001) (Figures 7 through 11).

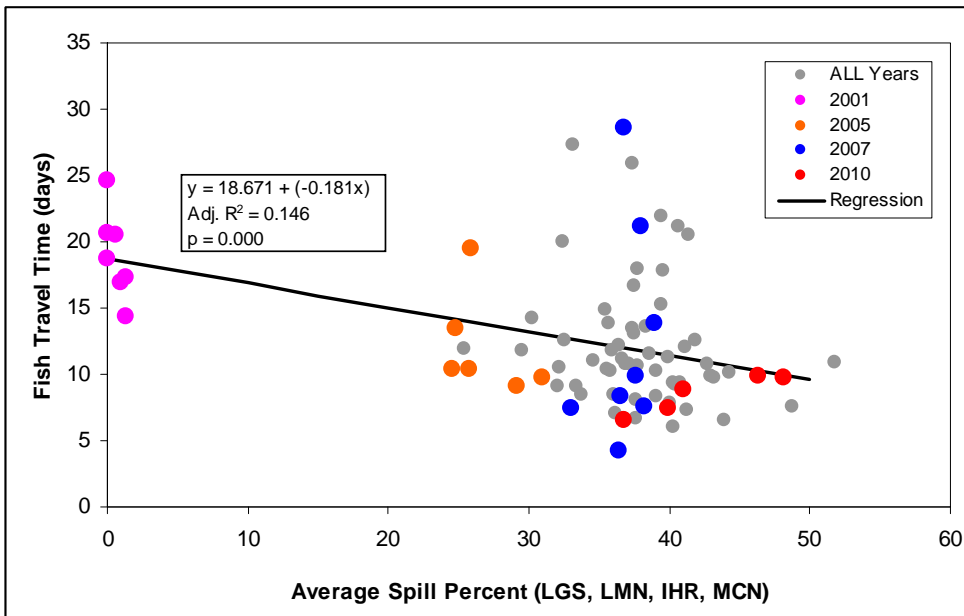


Figure 7. Linear regression analysis of average spill percent and fish travel time (LGR-MCN) for hatchery yearling Chinook for migration years 1998-2010.

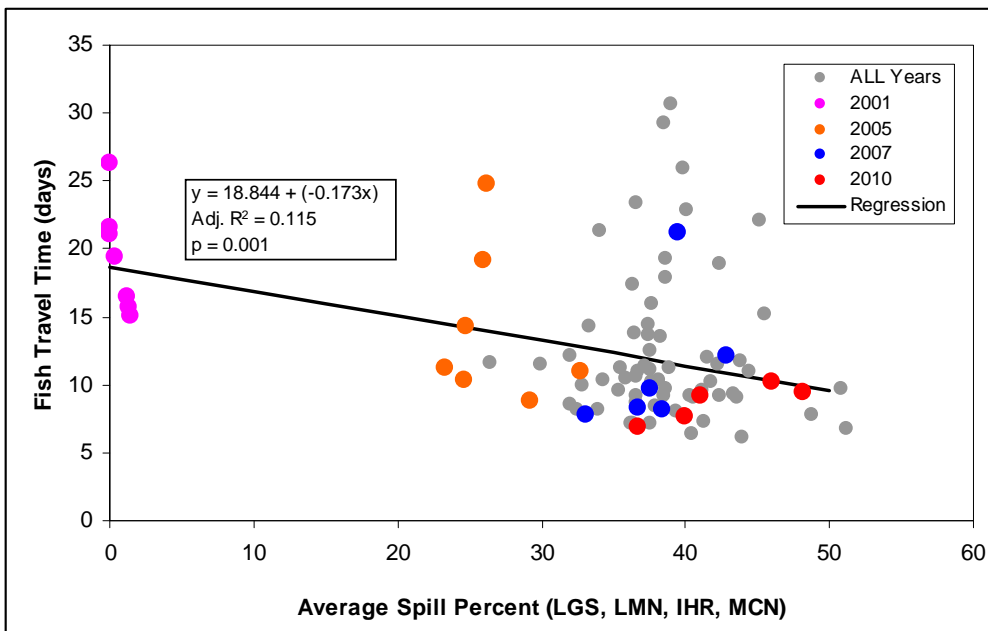


Figure 8. Linear regression analysis of average spill percent and fish travel time (LGR-MCN) for wild yearling Chinook for migration years 1998-2010.

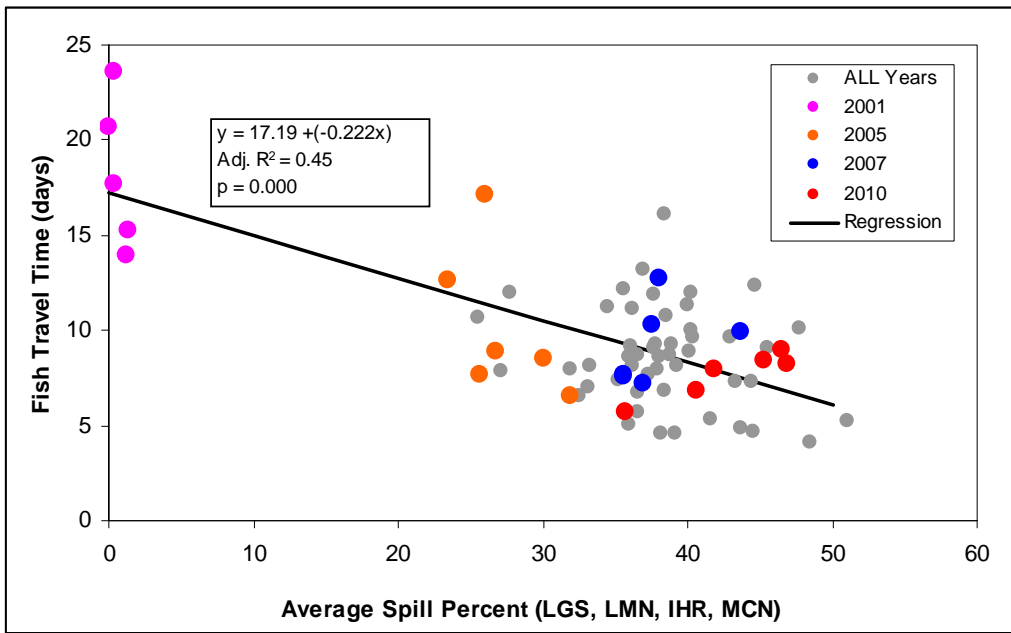


Figure 9. Linear regression analysis of average spill percent and fish travel time (LGR-MCN) for hatchery and wild steelhead for migration years 1998-2010.

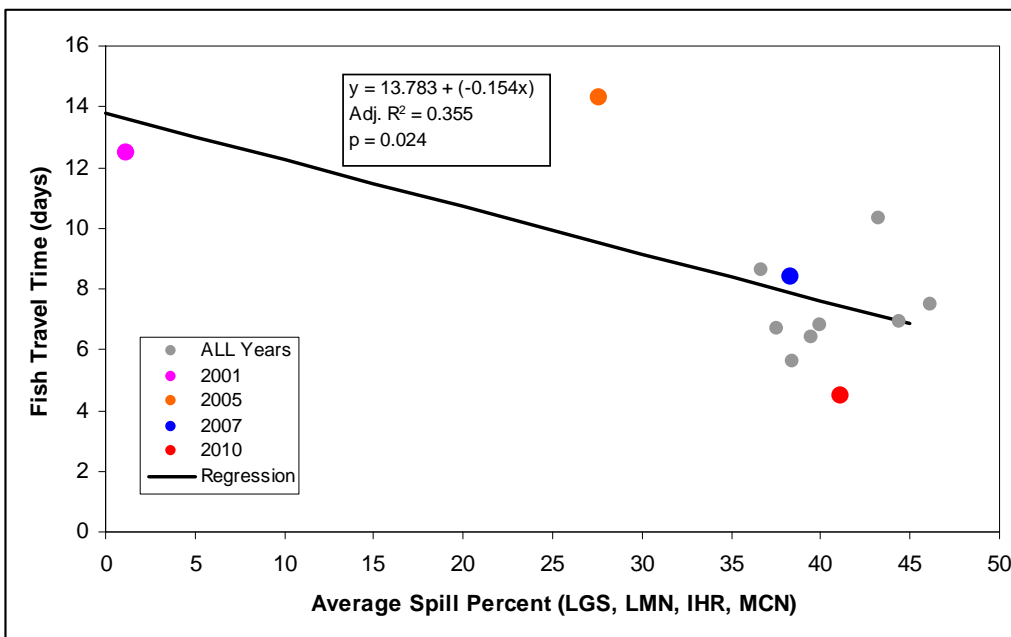


Figure 10. Linear regression analysis of average spill percent and fish travel time (LGR-MCN) for hatchery and wild sockeye for migration years 1998-2010 (excluding 2004).



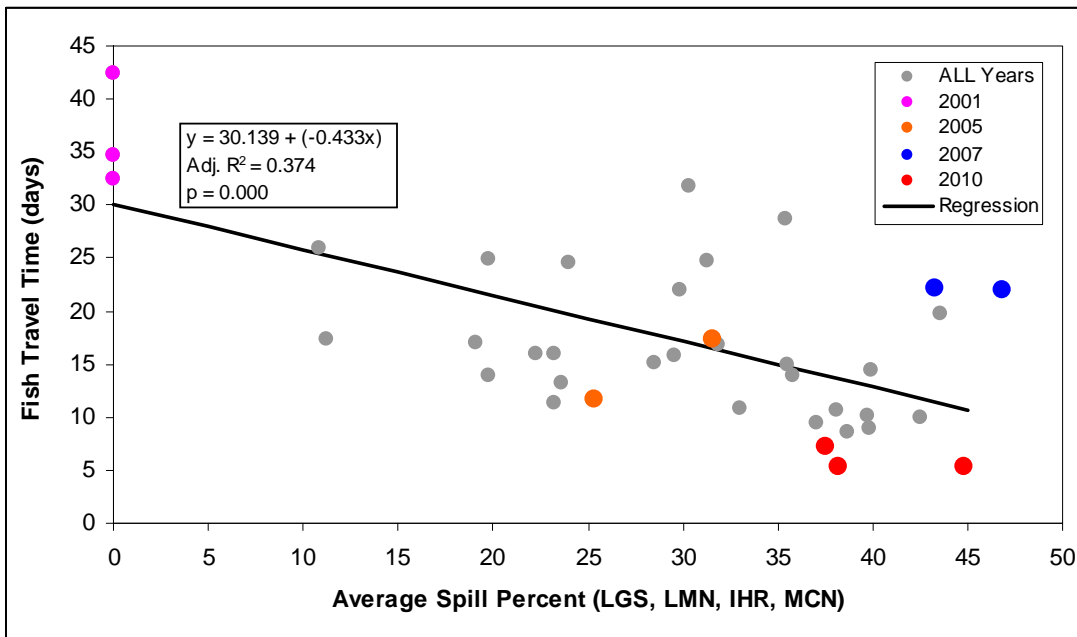


Figure 11. Linear regression analysis of average spill percent and fish travel time (LGR-MCN) for hatchery subyearling Chinook migration years 1998-2010.

**In observations of similar flow and water travel time years, juvenile fish survival and travel time are improved in years with higher average spill.**

Observations and comparison of recent juvenile Chinook and steelhead downstream migration years with similar water transit times but different average spill levels indicate that for Chinook, sockeye and steelhead fish travel time is faster and juvenile fish survival is higher in years with higher average spill proportions. The following plots of observations of water transit time, average spill proportion and juvenile survival in the Lower Granite to McNary river reach illustrate two sets of comparisons of years with similar water transit time; 2005/2007 and 2004/2010.

In the 2005/2007 comparison water transit times were similar but average spill proportion was 27% in 2005 and 40% in 2007 (Figure 13). Chinook, steelhead and sockeye travel times were reduced in 2007 relative to 2005, while survival for all species was significantly increased in 2007 relative to 2005(Figure 13).

In the 2004/2010 comparisons water transit times were similar and slightly faster in 2004 than 2010. Average spill proportion was 33% in 2004 and was 43% in 2010 (Figure12). In addition, surface passage structures (RSWs and TSWs) were in place at all the intermediary dams in 2010 (LGS, LMN, IHR, MCN), but none were in place in 2004. The smolt travel time decreased 19% in 2010 relative to 2004 for Chinook and decreased 33% for steelhead in 2010 relative to 2004 (Figure 12). Chinook survival increased 23% in 2010 relative to 2004 and steelhead survival increased 95% in 2010 relative to 2004 (Figure 12).The vast majority of PIT-tagged sockeye were transported in 2004. Therefore it was not possible to estimate juvenile reach survival for sockeye in 2004.

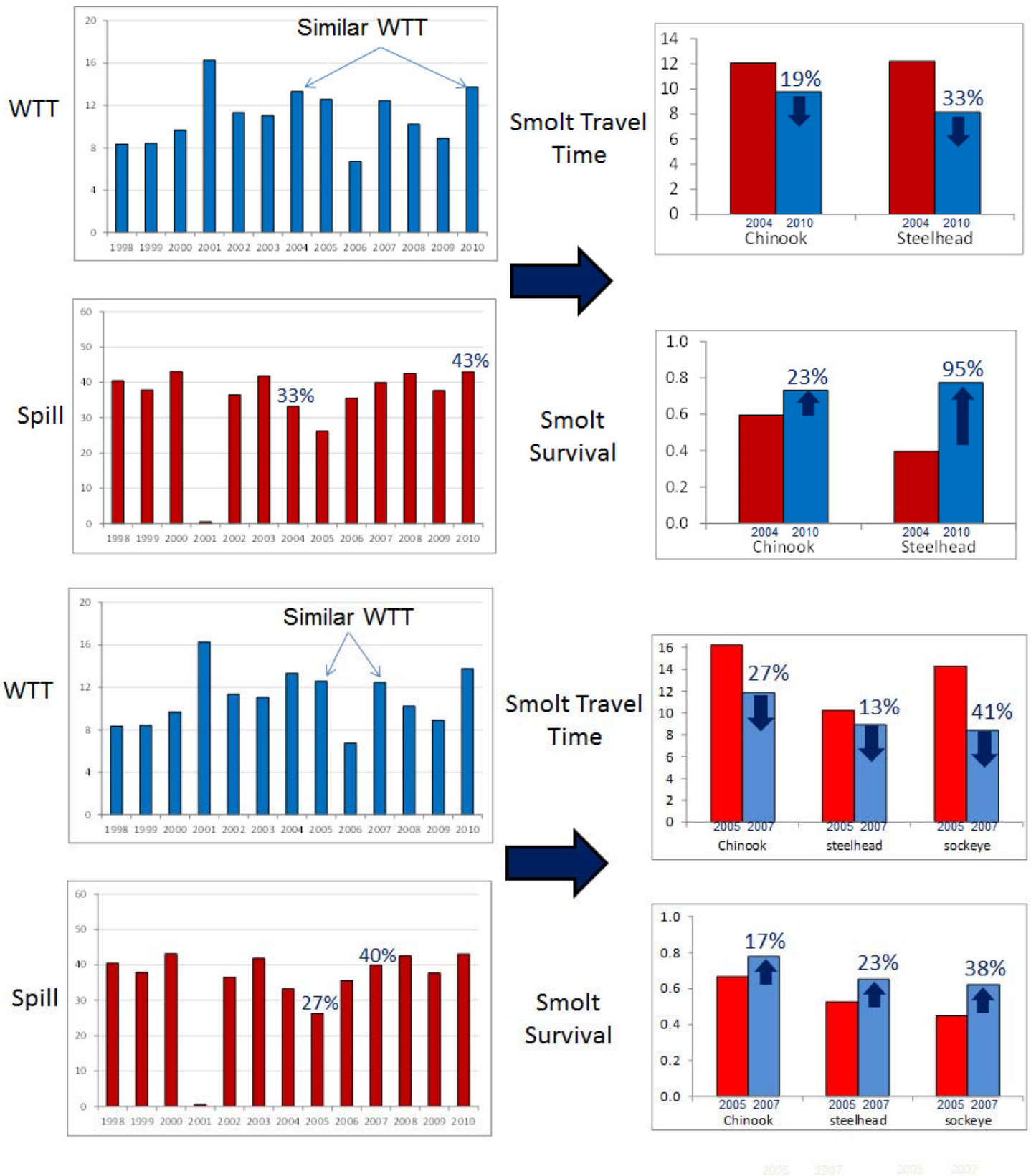


Figure 12. Lower Granite to McNary 1998-2010, Comparison of 2004 and 2010 (upper)  
 Figure 13. Lower Granite to McNary 1998-2010 Comparison of 2005/2007 (lower)

**Model simulations indicate that juvenile survival in low flow periods such as the summer migration period and low run-off volume years, could be significantly increased and juvenile fish travel time could be decreased by increasing spill proportion in low flow years.**

In order to address your question regarding a “with and without” spill condition, we relied on CSS analyses, presented in Chapter 3 of the Comparative Survival Study (CSS) Annual Report (Tuomikoski et al, 2010). The CSS has calculated smolt travel time and survival rate estimates using PIT-tagged spring/summer Chinook salmon and steelhead originating from the Snake River Basin. Using these estimates, along with measurements of the corresponding environmental conditions that occurred during smolt outmigration in each year, the CSS has developed models that characterize the effects of various spill levels and water transit times on smolt survival and travel time through the hydrosystem over the period of 1998-2010. In addition to explaining historic patterns of smolt survival and travel time, these models can also be used to simulate what could have occurred if different hydrosystem operations had been implemented.

To illustrate the effects of spill versus no-spill operations, we first used the CSS models to characterize the historic survival and travel time patterns during 2001, a low-flow year when hydrosystem operators elected to terminate spill at the outmigration dams. Figures 14 and 15 show that the CSS model predictions for survival and travel time in 2001 correspond well with the observed survival and travel time estimates for both yearling Chinook salmon and steelhead. To illustrate what could have occurred if different hydrosystem operations had been implemented, we simulated the juvenile travel times and juvenile survival rates that would be expected under a 50% spill operation at the outmigration dams, while maintaining the same flow conditions that occurred in 2001. The simulations indicate that despite the presence of low-flow conditions, survival rates in the river reach between Lower Granite Dam (LGR) and McNary Dam (MCN) could have been much higher if an aggressive spill operation had been implemented in 2001 (Figure 14). For steelhead, the simulated survival rates under a 50% spill operation were expected to be triple the observed survival rates under the no-spill operation that was implemented. Similarly, fish travel times under a 50% spill operation were expected to be 30-50% lower than the observed fish travel times under the no-spill operation that was implemented (Figure 15). These simulations demonstrate that spill is highly influential in determining smolt survival and travel time through the hydrosystem. In addition, these simulations indicate that spill can be an effective tool for mitigating for the effects of low-flow conditions.

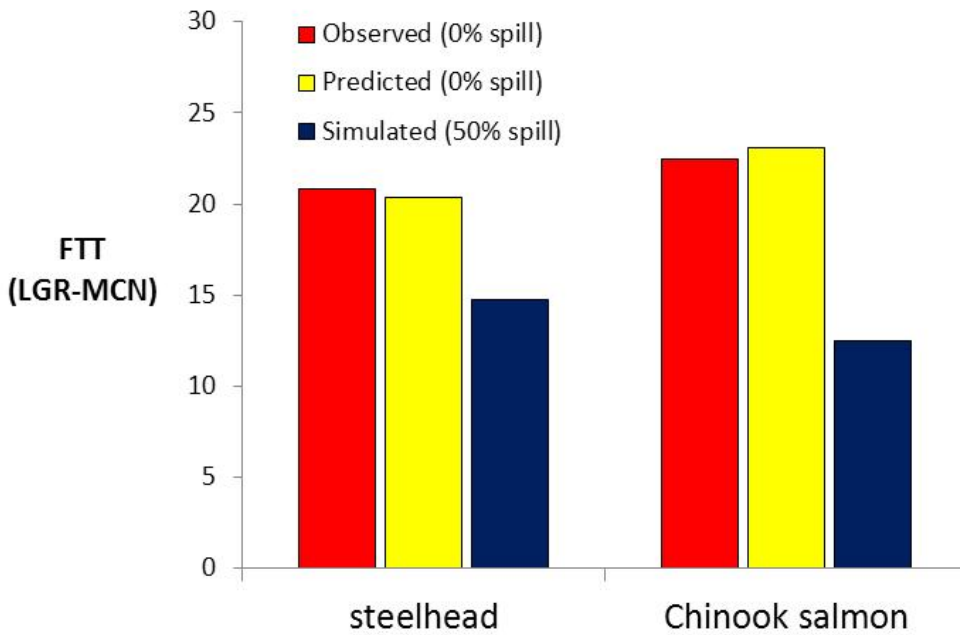


Figure 14. Average fish travel time (FTT, days) for hatchery and wild steelhead (left) and wild yearling Chinook salmon (right) in the LGR-MCN reach during 2001 (red bars), along with the CSS model predictions for average FTT under the 0% spill operation (yellow bars) that was implemented and expected FTT under a simulated 50% spill operation (blue bars) with the same low-flow conditions that occurred in 2001.

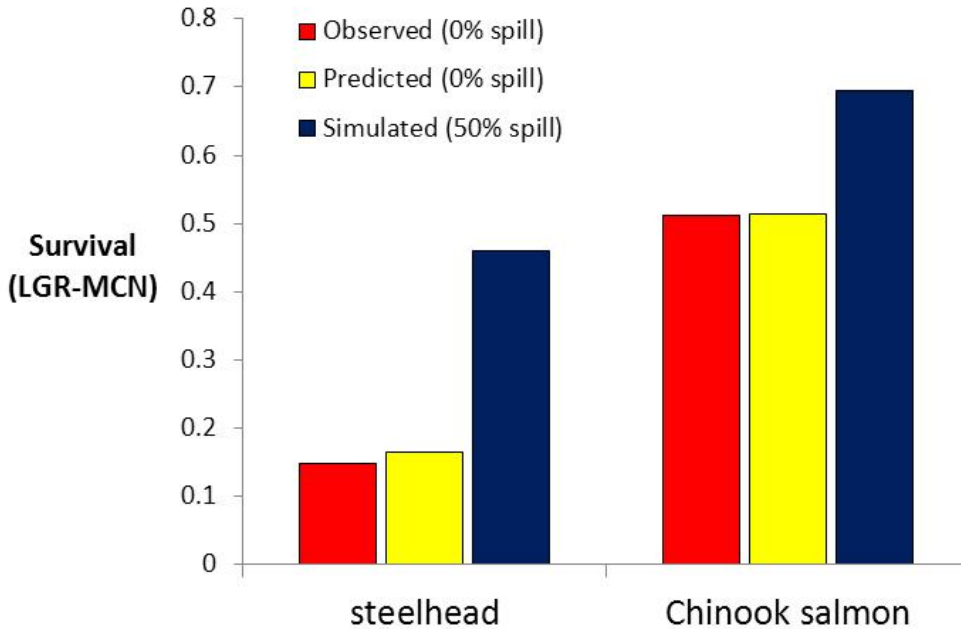
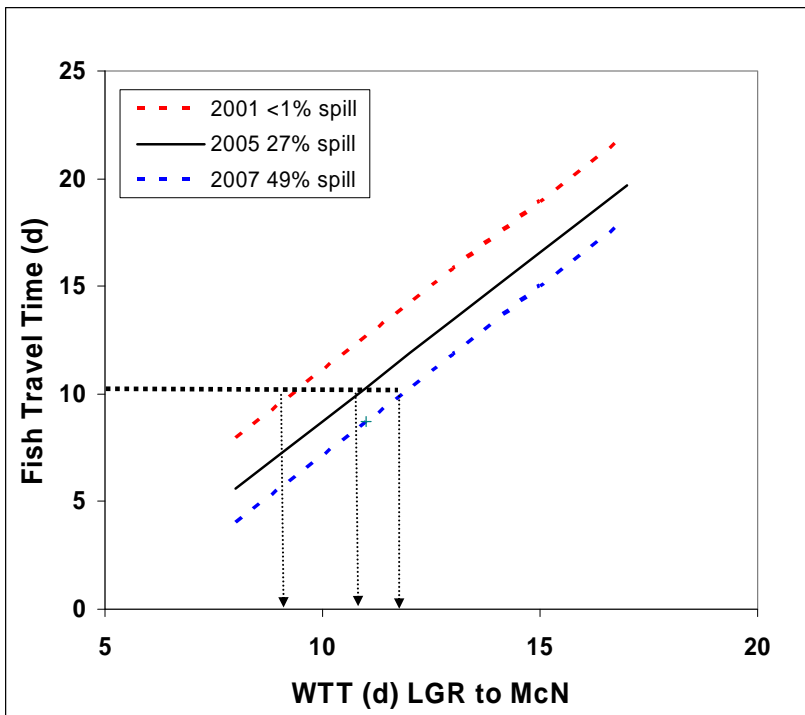


Figure 15. Average smolt survival for hatchery and wild steelhead (left) and wild yearling Chinook salmon (right) in the LGR-MCN reach during 2001 (red bars), along with the CSS model predictions for survival under the 0% spill operation (yellow bars) that was implemented and expected survival under a simulated 50% spill operation (blue bars) with the same low-flow conditions that occurred in 2001.

**Spill mitigates for low migration flow. Increasing spill proportion improves fish travel time in low flow periods such as low run-off volume years and the summer migration period. Increasing spill in low water periods can provide some mitigation for the impact of low migration flows on fish travel time. However, high flow and low spill would increase the proportion of fish passing through the power house, resulting in decrease in survival, increase in delayed mortality and decrease in smolt-to-adult return.**

Historical observations through downstream migration monitoring has shown that faster water transit time (increasing flow and velocity) results in faster juvenile fish travel time during the downstream migration. The increase in spill proportion and duration that has occurred in recent years has resulted in faster fish travel times particularly in low flow years. Observations of similar flow year's show that the addition of spill improves fish travel time and survival. The following exercise illustrates the concept of increasing spill proportion as mitigation for low migration flows.



**Figure 16. Steelhead Fish Travel Time versus Water Transit Time in the Snake River during low flow years with varying levels of spill in the reach. The relationship shown was a regression of the FTT and WTT for six release groups in each year. Two indicator variables were introduced to measure year effects.**

From the regression shown in Figure 16 a conceptual spill benefit to steelhead travel time (FTT) could be derived. If the observed improvement in the relation between FTT and WTT were attributed to increased spill proportion from year to year then, given the common slope assumed for the three years, the improvement from spill would be expressed as a decrease in the WTT necessary to achieve the same FTT. For example to achieve a 10 day FTT in 2005 conditions it would have required a 10.8 day WTT (82 Kcfs in Snake River) while in 2007 the same FTT could have been achieved with 11.8 WTT (75 Kcfs) given the improved conditions in that year. For 2001, a year with almost no spill, the same 10 day FTT would have required a 9.3 day WTT or flows of 96 Kcfs in the Snake River. Given the difference in spill proportion in each of these low flow years, it is likely that the improvement in FTT in relation to WTT was largely due to the increased spill, particularly in 2007. Thus achieving a 10 day FTT for steelhead through the Lower Granite Dam to McNary Dam Reach during a low flow year would require either flows of 75 Kcfs with 40% spill or upstream reservoir releases to achieve flows of 96 Kcfs with no spill.

This conceptual exercise only considers fish travel time and does not consider fish survival. In a no spill situation additional upstream reservoir releases would be required to provide the flow to achieve the desired travel time, however fish survival would be lower because a larger proportion of downstream migrants would pass through powerhouse routes.

**Spill proportion and water travel time (flow) are correlated with fish travel time and fish survival.**

Life cycle monitoring through the Comparative Survival Study (CSS) has been conducted for the past thirteen years. The CSS Annual Report, Chapter 3, for 2010 (Tuomikoski et al 2010) included an analyses of the effects of the in-river environment on juvenile fish travel time, instantaneous mortality rates and juvenile survival. Linear regression techniques were used to evaluate the associations between the environmental variables and mean fish travel time and instantaneous mortality. The most important variables for the best fitting models for fish travel time were Water Transit Time (flow), spill, and Julian day. The most important variables for the best fitting models for instantaneous mortality were water transit time (flow), spill and Julian day. Instantaneous mortality was predicted to increase as Julian day increased and instantaneous mortality was predicted to decrease as spill increased.

**Fresh water passage conditions affect early ocean survival. Spill proportion and water travel time affect ocean survival of Chinook and steelhead and smolt-to-adult return rate. Increasing spill proportion and faster water travel time (higher flow) result in higher smolt-to-adult return rate.**

Past analyses have indicated that fresh water migration experience effect ocean survival and adult return. Budy et al. (2002) provide evidence that some estuary and early ocean mortality is related hydrosystem passage experience during downstream migration. This hydrosystem-related delayed mortality (Schaller and Petrosky 2007) is thought to be due to the cumulative effects of stress and its impacts on energetic condition, predation vulnerability, disease and physiology of migrating smolts, which eventually influences levels of delayed mortality. The same hydrosystem factors that cause direct mortality during downstream migration also impose stress on those fish that do survive, under the Budy et al. (2002) hypothesis mortality rates during downstream migration are expected to be positively correlated with mortality rates at later life stages.

Several recent analyses indicate that early ocean survival and fresh water migration passage conditions are correlated. Haeseker et. al. (In Press) concluded that freshwater and marine survival rates of Chinook and steelhead were correlated, indicating that a portion of the mortality expressed after leaving the hydrosystem is related to downstream migration conditions. Figure 17, below shows the relationships between in-river survival, environmental variables (average spill and water transit time), versus adult returns at various levels of ocean productivity. They concluded that across a range of marine conditions, improvements in life stage specific and smolt to adult returns may be achievable through increasing spill percentages and/or reducing water transit times during the juvenile out migration. Petrosky & Schaller (2010) found that survival rates during the smolt to adult and first year ocean life stages for Chinook and steelhead were associated with both ocean and river conditions. Best fit, simplest models indicate that lower survival rates for Chinook salmon are associated with warmer ocean conditions, reduced upwelling in the spring and with slower river velocity during the smolt migration or multiple passages through powerhouses at dams.

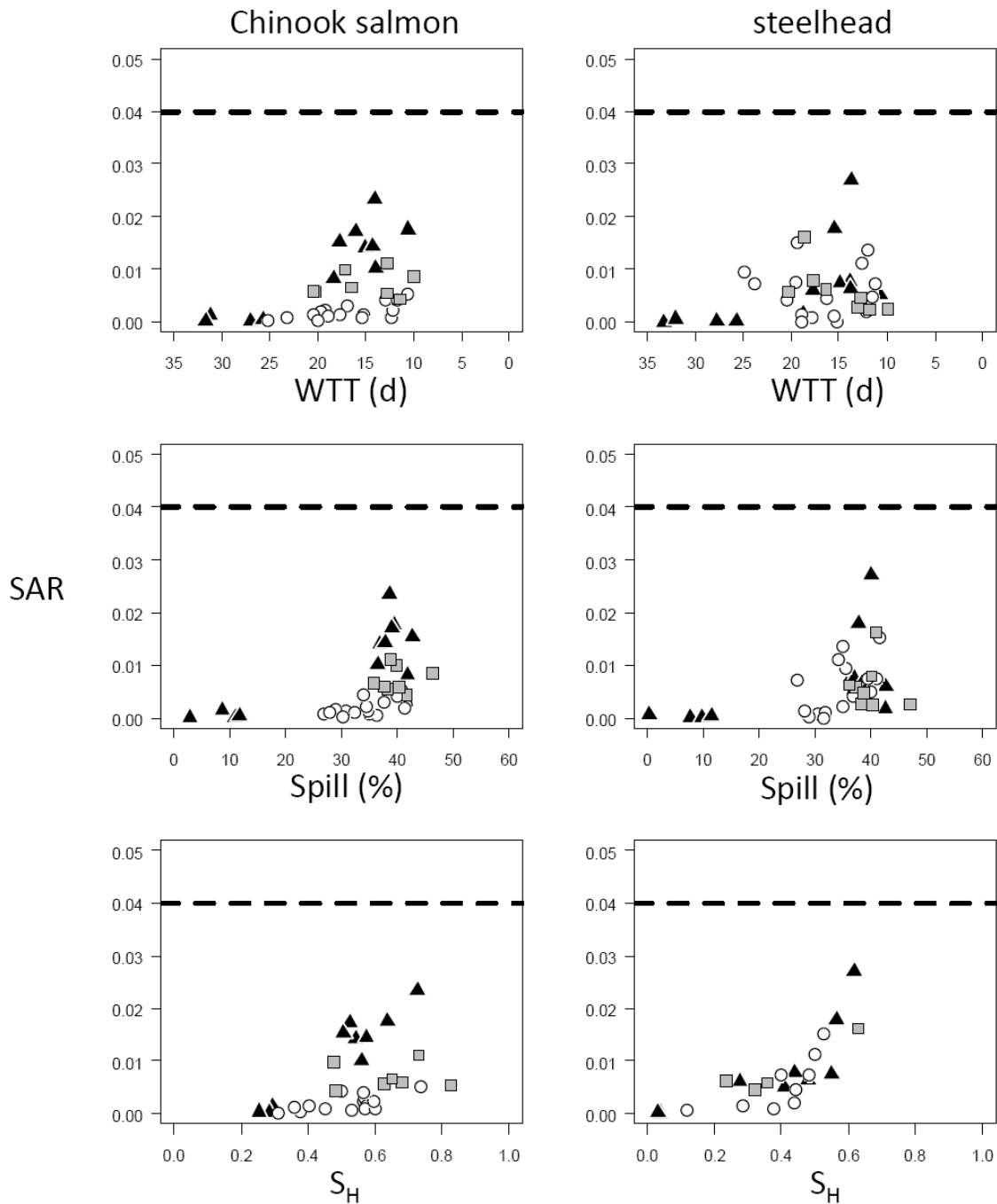


Figure 17. Bivariate plots from Haeseker et al (In Press) of SAR against water transit time (WTT), average percent spill (Spill) and juvenile outmigration survival ( $S_H$ ) for Chinook salmon (left column) and steelhead (right column). Years with negative June-August Pacific Decadal Oscillations (PDO) are denoted by black triangles, years with neutral PDO values near zero are denoted by grey squares and years with positive PDO values are denoted by open circles. The horizontal dashed line at 4% denotes the Northwest Power and Conservation Council (2009) SAR objective.

**Increasing spill proportion allows a higher proportion of downstream migrants to avoid power house passage. Powerhouse passage through juvenile bypass systems decreases smolt-to-adult return rate. Direct estimates of project survival such as those developed to evaluate performance standards, do not capture the delayed mortality effect of project passage and therefore underestimate project impact on juvenile survival and adult return.**

Evidence from several independent analyses indicates that passage through powerhouse bypass systems results in significant delayed mortality of juvenile salmon and steelhead that reduces adult returns. (FPC memorandums; January 28, 2011, October 6, 2010, February 3, 2010, May 21, 2009, [www.fpc.org](http://www.fpc.org)) In addition to increasing levels of delayed mortality, passage through powerhouse bypass systems has also been shown to increase juvenile migration delay. Estimates of direct, route-specific survival do not account for delayed mortality effects that can be quantified with adult returns. Additionally, route-specific survivals do not incorporate the effects of migration delay in terms of decreased survival. Therefore, route-specific estimates underestimate the cumulative effects of powerhouse passage on life-cycle survival of salmon and steelhead. Based on these recent analyses, minimizing juvenile passage through powerhouses would reduce migration delay, reduce delayed mortality and improve adult return rates. Applying these results to project operations, increasing spill levels to dissolved gas limits would minimize juvenile passage through powerhouses and improve adult returns. The effects of bypass systems on juvenile salmon and steelhead travel times and smolt-to-adult return were analyzed in the Comparative Survival Study Annual Status Report for 2010. Three sets of analyses were conducted to evaluate:

1. The effects of bypass systems on fish travel time from Lower Granite Dam to Bonneville Dam.
2. The effects of bypass history on SARs from Bonneville outmigration as juveniles to adult return to Bonneville.
- 3 The effect of bypass passages during the juvenile outmigration, on Lower Granite outmigration as juveniles to adult return at Lower Granite.

The methods for these analyses are described in Chapter 7 of the CSS Annual Status Report for 2010 which is available on the FPC website <http://www.fpc.org/documents/CSS.html>. The analyses of bypass passage on fish travel time identified significant migration delays for juvenile Chinook salmon and steelhead that were bypassed relative to non-bypassed fish. The average magnitude of the delay among the significant cases was 0.69 days (16.6 hours) for Chinook and 0.73 days (17.5 hours) for steelhead. Significant migration delays for bypassed fish were identified in the majority of the year-dam combinations for Chinook (67%) and a large proportion of the cases for steelhead (23-33%). The lower percentage of significant migration delay identified for steelhead was likely due to the smaller sample sizes available for steelhead. The analyses of effects of bypass on post-Bonneville smolt-to-adult return (SAR) indicated that post-Bonneville SARs are lower for bypassed Chinook and steelhead smolts than non-detected smolts. These analyses indicate that subsequent downstream passage experience may further influence smolt-to-adult return rate, with the smolts that pass undetected through the dams expected to have higher smolt-to-adult return rates than those smolts that are bypassed one or more times. Model estimates for Chinook salmon showed a 10% reduction in post-Bonneville SAR per bypass experience at upstream dams. Steelhead showed a 6% reduction in SAR per bypass experience at Snake River dams and a 22% reduction in post-Bonneville SARs per bypass experience at Columbia River dams. For Chinook estimates of bypass effects were similar across Columbia and Snake River dams. For steelhead bypass effects were more severe at McNary and John Day dams.

The third analyses of cumulative bypass effects showed that non-bypassed yearling Chinook LGR/LGR SARs averaged 52% higher, and non-bypassed steelhead SARs averaged 91% higher, than smolts that were bypassed at one or more of the collector facilities



The results of the CSS analyses indicate that route specific estimates of juvenile survival rate as defined from the forebay to tailrace of the projects, or from paired release studies to define project survival are likely to underestimate project impacts because they do not account for the mortality associated with migration delay or the latent mortality associated with project passage.

## References

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  - Lower Monumental bypass effects on Snake River Chinook and steelhead - February 3, 2010
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