Sensitivity of salmon survival to temperature in the mainstem Snake and Columbia Rivers

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Introduction

Recent analyses of PIT tag data suggests that juvenile migration survival is strongly correlated with river temperature (Anderson 2003, Connor et al. 2003, Smith et al. 2003). Because of this relationship there is a renewed interest in the possible value of using cool water releases from reservoirs in the Snake River system to increase survival of the juvenile migrants through the hydrosystem. In this white paper we explore the impact of such temperature control actions on survival of juvenile migrants through the hydrosystem. We examine the relationship of Snake River chinook salmon and steelhead survival to environmental conditions using a water heat budget model and a juvenile passage survival model.

Modeling

The effect of temperature on survival depends on the timing and location of fish in the river. In this analysis, three groups of fish are assumed to begin migration on specific days of the year over a 21 year period from 1975-1995 and their survival is modeled in response to the temperatures and other in-stream conditions through the use of the CRiSP model, version 1.7. This model is equivalent to CRiSP 1.6 (Anderson et al. 2000) but it uses a reservoir survival equation based on Anderson (2003). Flow and spill conditions are extracted from flow archives maintained by Columbia Basin Research as provided by the Army Corps of Engineers while temperatures in each reservoir are modeled using the EPA's 1-D Heat Budget model (EPA 2001).

Our immediate goal is to model the impacts of reservoir release schedules on the temperature throughout the river system and anticipate the biological response to the actions. For this to be effective, we use a survival model that is calibrated for a temperature-survival relationship, and provide temperature inputs that would result from such withdrawals when the water is mixed with the existing flows. Mixing and warming (or cooling) due to atmospheric conditions is simulated with the EPA Heat Budget model. Initially, we demonstrate the sensitivity of survival to variations in annual conditions as a retrospective analysis. Subsequently, we assume that there is an unlimited supply of cool water available in the storage reservoirs such that the inputs to the hydrosystem can be completely controlled.

For each hypothetical set of environmental conditions, a release of yearling chinook, subyearling chinook and steelhead are tracked as they move through the hydrosystem with the CRiSP1.7 passage model. The release timing is identical in all scenarios. The hydrosystem operations other than spill and flow are set to reflect conditions in the years of operation. The hydrosystem operations including fish guidance efficiency and spill efficiency are set to reflect 2002 conditions. In the scenarios no fish are transported.

CRiSP data requirements

Survival is a function of temperature in CRiSP1.7 as developed by Anderson (2003). Management actions such as altering spill and flow also affect survival due to their influence on Total Dissolved Gas levels and travel time variation, etc (Anderson et 2000). All of these factors are tracked through the hydrosystem as the smolts migrate. Temperatures can be modeled within CRiSP1.7 based on historic trends and general reservoir dynamics or introduced directly at multiple sites in the hydrosystem if they are known (historic) or anticipated (modeled).

CRiSP1.7 runs with water temperatures and flows specified at headwater locations and proceeds with management operations through input files or a graphical user interface to move water and fish through the hydrosystem. Flow and spill levels are obtained from historic records and remain unaltered in all simulations. Temperature values are specified at in-stream locations (dams and river confluences) and headwaters as daily averages and vary between the different scenarios.

Sources of CRiSP1.7 temperature inputs for simulations

The most conspicuous approach to deriving temperature for analyses is to use the historical temperature records. These are available on the DART website (www.cbr.washington.edu/dart/river.html/). In this analysis we used temperatures at dams and river confluences as determined by the EPA "Columbia River 1-D heat budget model" (EPA 2001). The EPA Heat Budget model is run with various assumptions, and the temperature outputs at corresponding passage (CRiSP) model locations reported for direct use as inputs to CRiSP. We use this as the basis for all temperature values in these simulations.

In order to use the modeled values with confidence, they need to be sufficient for adequately creating historic conditions. This is not the same as being identical to historic observations. Observation errors, monitoring equipment biases and other influences weaken the quality of the observations as representing the conditions. During calibration of the EPA Heat Budget model, the developers estimated the difference between the observed and predicted temperatures when the model was run for the years 1990-1994 in a predictive mode i.e. without the use of observation data to filter the system state at each day's iteration. These predictive results are detailed in Appendix D of the EPA report (EPA 2001) and summarized here for illustration purposes (Table 1). The modeled and observed value discrepancies were considered acceptable. In practice, when the heat budget model is run, water temperatures at each location and time step are processed with a Kalman filter (EPA 2001) so that both a modeled temperature and an observation contribute to the reported value and the input to the next computation. This approach has the effect of reducing the discrepancy between the reported and observed values.

Table 1. Difference of EPA Heat Budget model accuracy is demonstrated by the difference between the mean observed and model predicted temperatures over the years 1990-1994.

Site	Mean difference °C	Standard deviation of difference
BON Mar-Apr.	0.9	1.0
BON May-June	0.4	1.2
BON July-Aug	-0.4	1.4
LGS Mar-Apr.	1.1	1.1
LGS May-June	-0.2	1.2
LGS July-Aug	0.1	1.5

There is some danger in creating arbitrary input scenarios for use in CRiSP. Travel time and survival are functions not only of temperature, but also flow and spill and these three variables are functionally related. The strongest factors affecting the relationship of these variables include rainfall, snow pack, in-season precipitation, air temperature, and solar radiation and together they create flows at particular temperatures throughout the year. Therefore, the predictions can become erroneous if we arbitrarily combine flow and temperature profiles from different sources and years or try to synthesize the environmental conditions completely.

Modeling scenarios

In the CRiSP passage model, juvenile migrants were “released” in the tailrace of Lower Granite Dam as three distinct stocks one month apart. Their migration rates were based on the calibrations of the CRiSP model using PIT tag data up through 2002. Subyearling chinook were released on day of the year 78. Steelhead were released on day 108. Yearling chinook were released on day 138. The use of CRiSP is described in Anderson et al. (2000).

We use flow, spill and temperature records for 21 years of operations on the Snake and Columbia rivers as the basis for studying in-river survival variability, and then adjust the inputs to the system to correspond to management actions that would altered the headwaters temperature (Dworshak Reservoir on the North Fork of the Clearwater River and the Snake River at Anatone, WA). Also, we compared the survival in these scenarios to hypothetical scenarios where water temperatures were kept at a specified value for the entire length of the river. This effectively demonstrates the sensitivity of survival to specific temperatures. Thus, the scenarios differ only in water temperatures as follows:

1. <u>Retrospective run</u>. Use only EPA modeled temperatures.
2. <u>Constant temperature inputs.</u> All tributary temperatures were held at 12^{o} or 16°C.
3. <u>Constant temperatures</u>. Temperature is fixed throughout the entire river and year.

Scenario 1: Retrospective Run

In order to characterize environmental conditions relative to each other, we ranked each year according to a meteorological index (Figure 1) and a flow index (Figure 2). The flow index is the average daily flow (feet^{3}•s^{-1}) recorded at the USGS gaging station at Anatone, WA on the Snake River between two specified dates during the juvenile fish migration. Several possible meteorological indices influence water temperature (solar radiation, wind speed, dry bulb temperature), and they interact to determine the heat flux that warms or cools the water as it moves downstream. For this initial screening we use the average dry bulb temperature (°C) at Lewiston, ID between the same two specified dates during which the fish migrate. Finding the 25% and 75% quantile for both the flow and radiation rankings gives an index of high, normal and low years for the flow and temperature indices. For example, 1992 was a warm year with the highest solar radiation out of the 21 years and one of the lowest flow years. The migration dates during which the averaging is calculated begins 10 days before the release of the yearling chinook in the CRiSP1.7 model and ends 10 days after the release of the subyearling chinook, thus 81 days from day 68 to day 148.

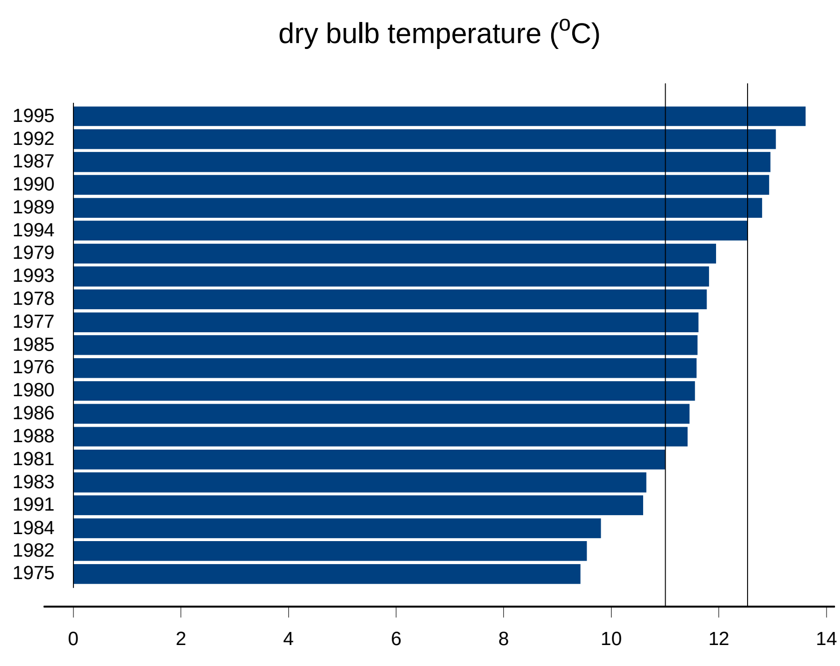

Figure 1. Ranked average daily dry bulb temperature at Lewiston over 21 years. The vertical lines delineate the 25% and 75% quantiles.

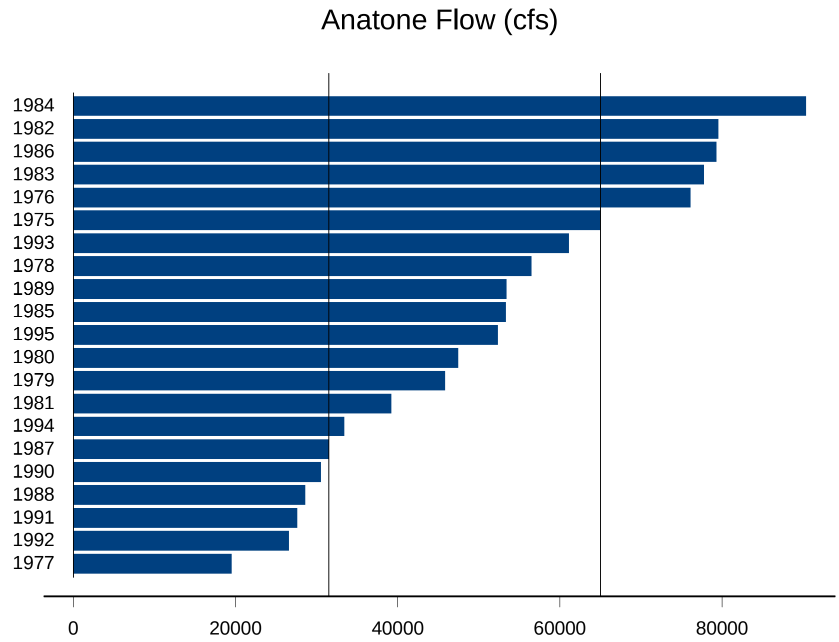

Figure 2. Ranked average daily flows at Anatone for 21 years. The vertical lines delineate the 25% and 75% quantiles.

For the 21 years of flow, spill and temperatures, Figure 3 through Figure 5 depict the variability in survival as the fish move downstream from the release site at Lower Granite Dam tailrace to the Estuary. Survival is modeled for flow and temperature conditions over the years 1975-1995. The annual variability in the survival profile is greatest for steelhead (Figure 4), intermediate for yearling chinook (Figure 3) and the least for subyearling chinook (Figure 5). As a consequence of the annual variability and the total passage survival, the year-to-year variability of the percent of a release reaching the estuary is very small for subyearling chinook and very large for steelhead.

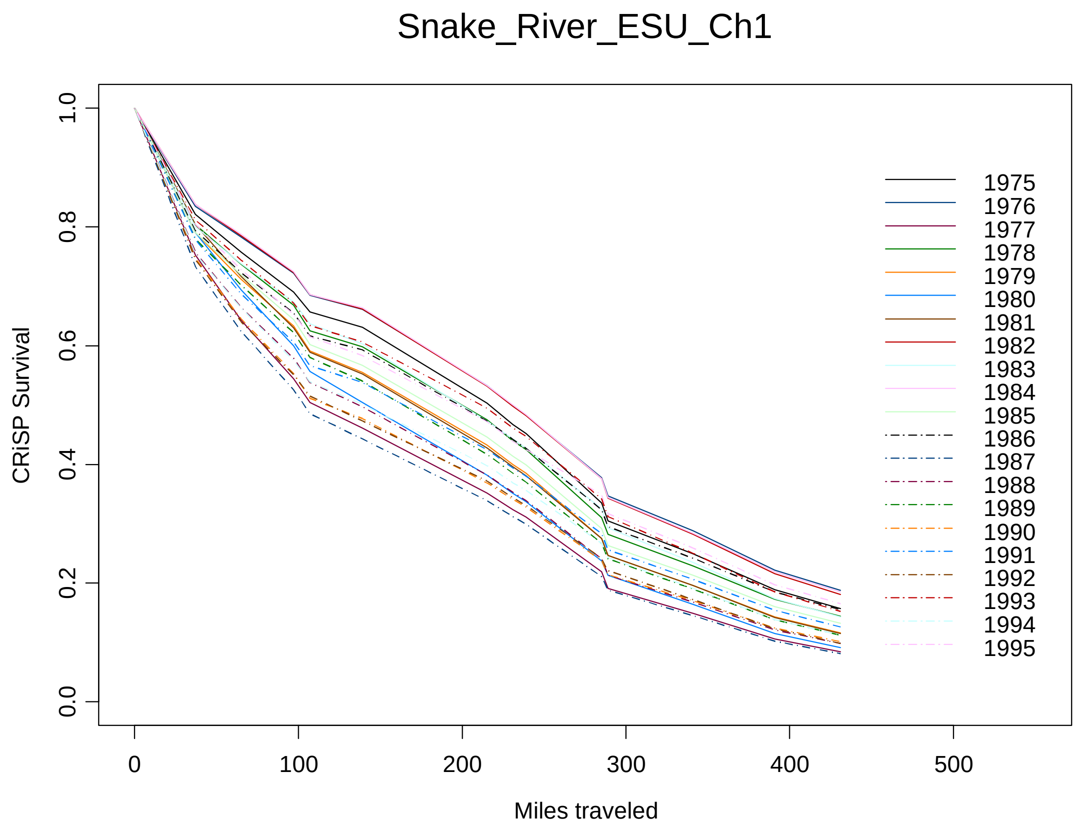

Figure 3. Modeled survival of yearling chinook released at Lower Granite Dam through the hydrosystem over 21 years.

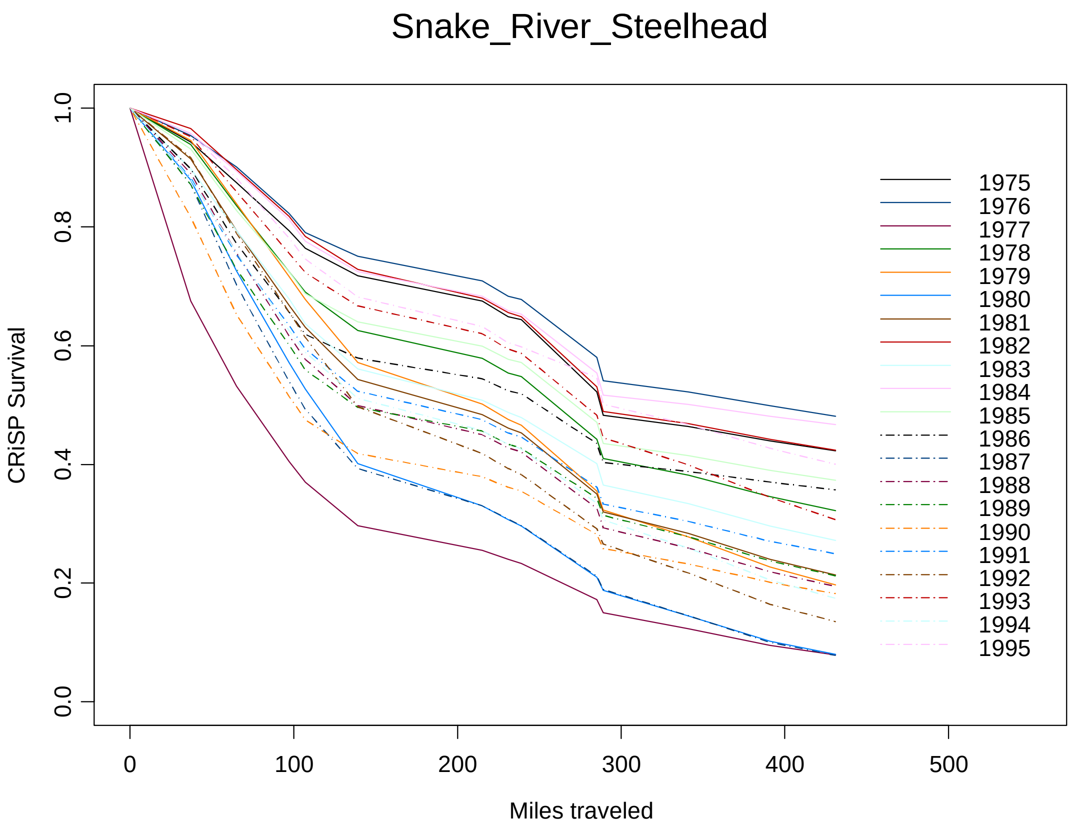

Figure 4. Modeled survival of steelhead released at Lower Granite Dam through the hydrosystem over 21 years.

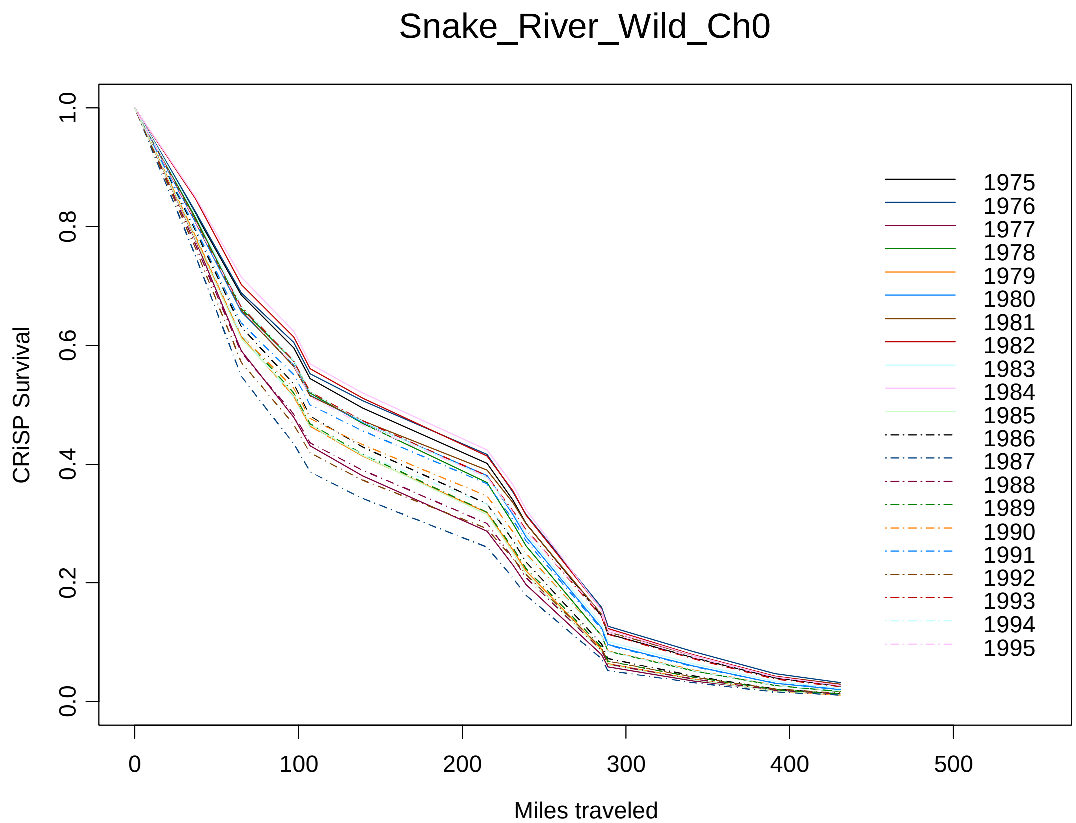

Figure 5. Modeled survival of subyearling chinook released at Lower Granite Dam through the hydrosystem over 21 years.

Figure 6 through Figure 8 show the partition of survival between the upper and lower portions of the migration each year. For each bar the upper black portion depicts survival in the upper section of the river (Lower Granite Dam tailrace to McNary Dam tailrace) and the lower orange portion depicts survival through the lower river (McNary Dam tailrace to Bonneville Dam tailrace). Yearling chinook experience equal survivals (i.e. mortalities) in both portions of the migration (Figure 6). Steelhead experience greater survival in the lower portion and greater mortality in the upper portion (Figure 7). Subyearling chinook experience greater mortality in the lower portion of their migration (Figure 8).

Note in the simulations depicted in Figure 3 through Figure 8 that the survival patterns are significantly different between species in terms of the overall survival, where the mortality is distributed over the migration, and the year-to-year variation in survival.

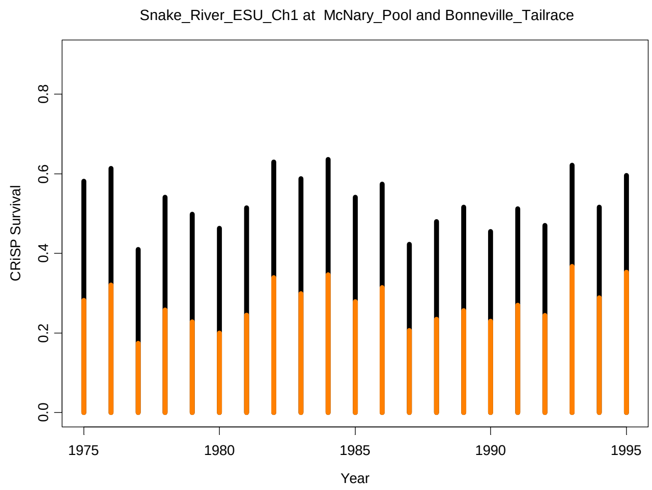

Figure 6. Modeled yearling chinook survival from Lower Granite Dam to McNary tailrace (upper part of bar) and Bonneville tailrace (lower part of bar).

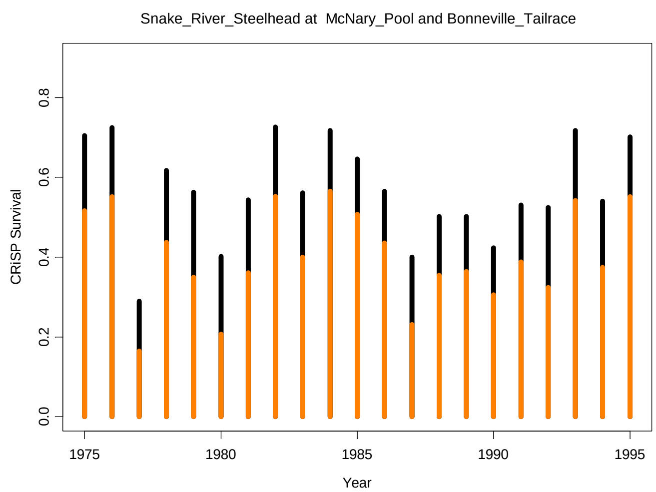

Figure 7. Modeled steelhead survival from Lower Granite Dam to McNary tailrace (upper part of bar) and Bonneville tailrace (lower part of bar).

Figure 8. Modeled subyearling chinook survival from Lower Granite Dam to McNary Tailrace (upper part of bar) and Bonneville tailrace (lower part of bar).

Scenario 2: Low temperature input

The simulations illustrated in Figure 9 through Figure 11 explore the temperature impact of water released into the Clearwater and Snake Rivers. The river temperature was simulated with the EPA Heat Budget model fixing the inputs from the Dworshak Reservoir and the in flowing temperature at Anatone WA on the Snake River.

For subyearling chinook, a 12^{o} C headwater temperatures results in higher survivals through the hydrosystem but the effect diminishes by the time the fish reach the lower river (Figure 9). The steelhead in 1995 (Figure 10) had the greatest difference in survival for a change in temperature. For other years the change in steelhead survival with temperature was nil as is observed for yearling chinook (Figure 11).

Thus, we note that although the 21 years of simulations were important for the determining the variability in survival over a wide range of environmental conditions, the initial conditions had little impact on fish survival to the estuary. Even with temperature inputs to the Clearwater and Snake River constrained to 12°C, survivals in the lower river barely improve (< 0.1% change in survival).

This is consistent with the EPA model results for Scenario 3 in which the input temperatures are constrained to be less than 16 °C. At a certain point into the Snake River system of impoundments, the frequency of temperature excursions above a threshold was essentially the same as when the observed headwater inputs were used. This means that as water moves downstream through the impoundments, the initial conditions matter less and less and current local environmental is more important. This is the result of the slow travel times of the impounded waters in the reservoirs, and the degree of warming or cooling due to head exchange with the atmosphere.

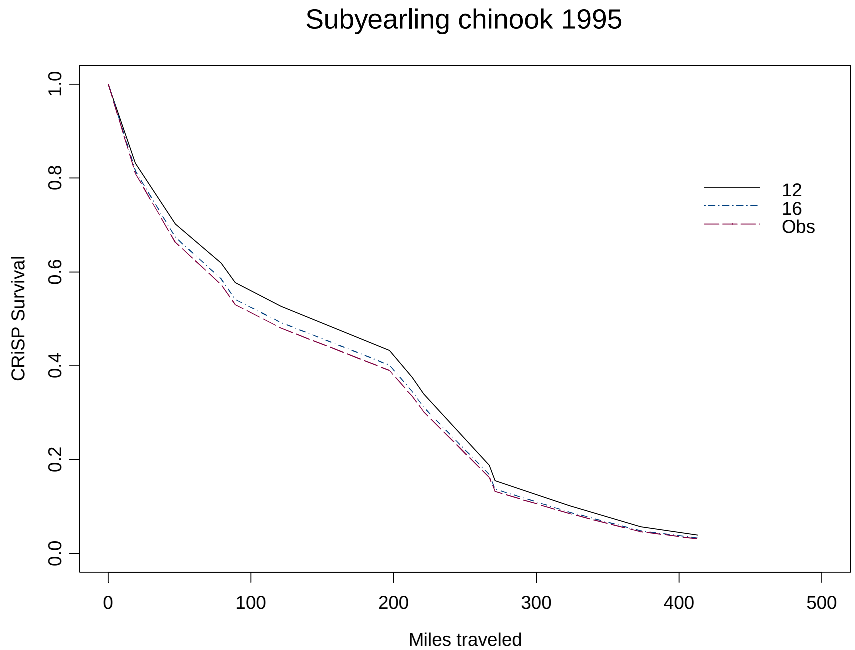

Figure 9. Constraining North Fork Clearwater and Snake River input temperatures to be ≤ 12°C or ≤ 16°C has little impact on the survival of subyearling chinook released at Lower Granite Dam.

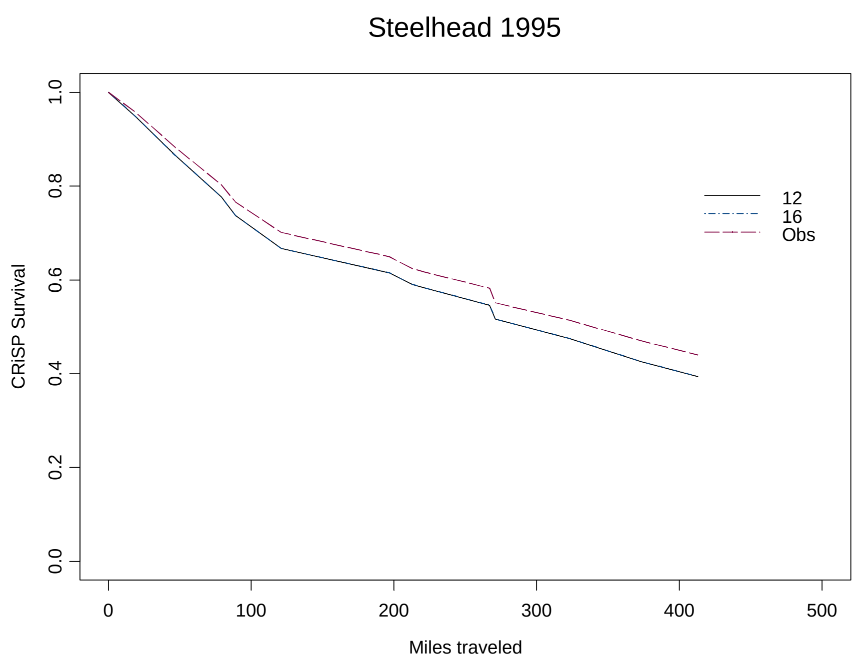

Figure 10. Constraining North Fork Clearwater and Snake River input temperatures to be ≤ 12°C or ≤ 16°C has little impact on the survival of steelhead released at Lower Granite Dam.

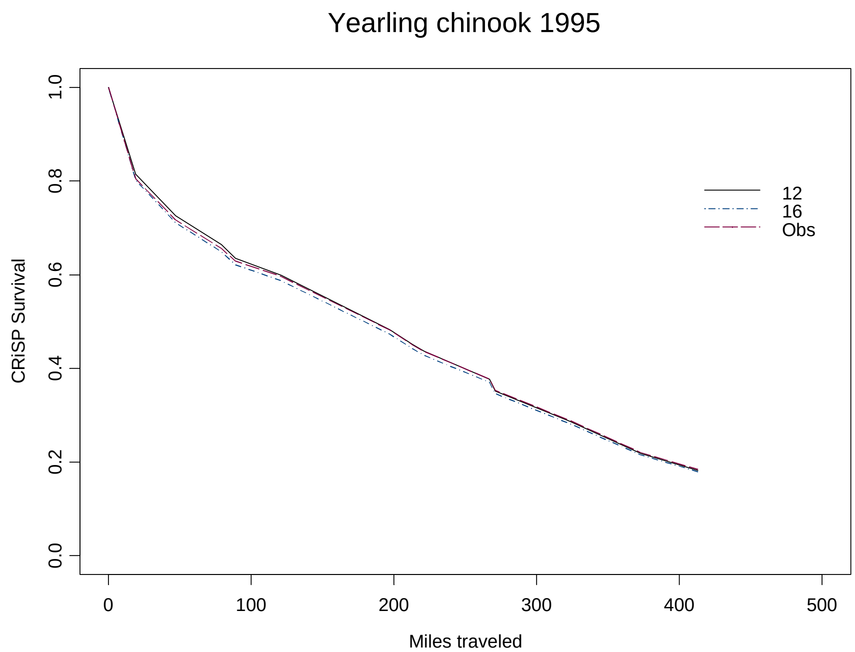

Figure 11. Constraining North Fork Clearwater and Snake River input temperatures to be ≤ 12°C or ≤ 16°C has little impact on the survival of yearling chinook released at Lower Granite Dam.

Scenario 3: Constant Temperatures

While Scenario 2 explores the impact of changing temperature in the headwaters, Scenario 3 explores the impact if temperature is held constant over the entire migration route. Note in Scenario 2 the headwater temperature signal is lost as the water moves downstream because of heat exchange with the atmosphere. In Scenario 3, we demonstrate the significance of the total temperature over the migration by simulating river temperatures from 5° to 25°C and using the flows and spills encountered in 1995. Under these conditions the survival of subyearling chinook can vary from near 0 to 40% (Figure 12). The steelhead simulation shows the greatest effect of temperature on survival (Figure 13) and the yearling chinook survival response to temperature is more similar to the subyearling chinook response (Figure 14).

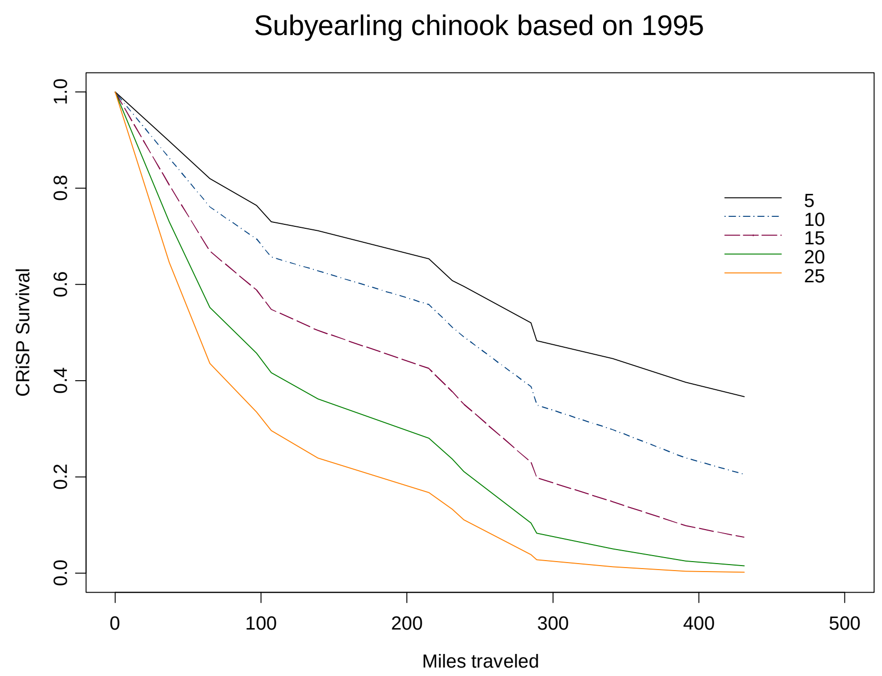

Figure 12. Subyearling chinook survival from release to various points downstream at various five hypothetical temperature levels.

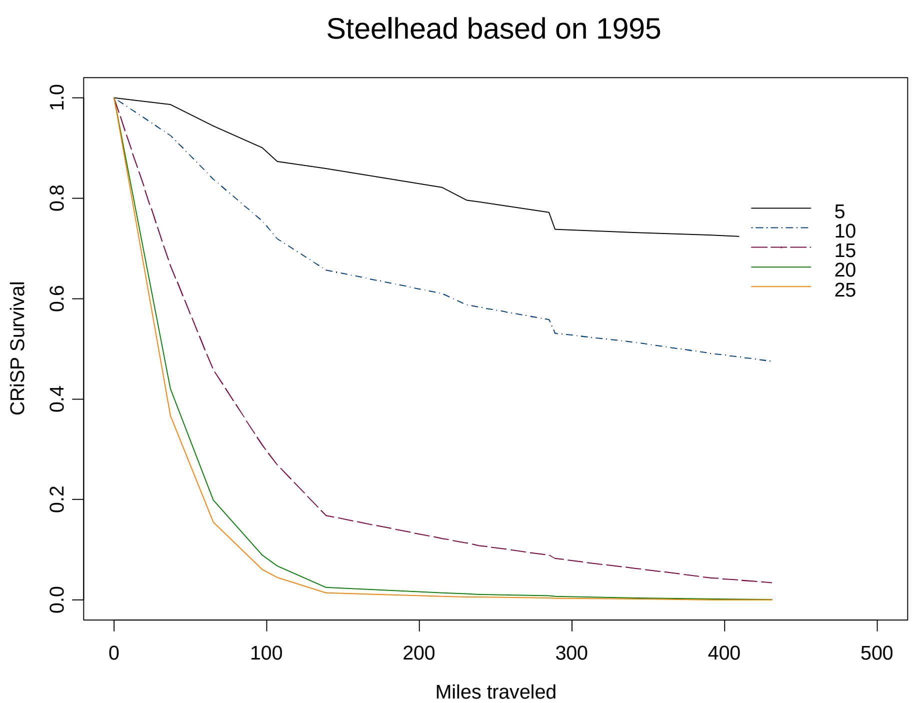

Figure 13. Steelhead survival from release to various points downstream at various five hypothetical temperature levels.

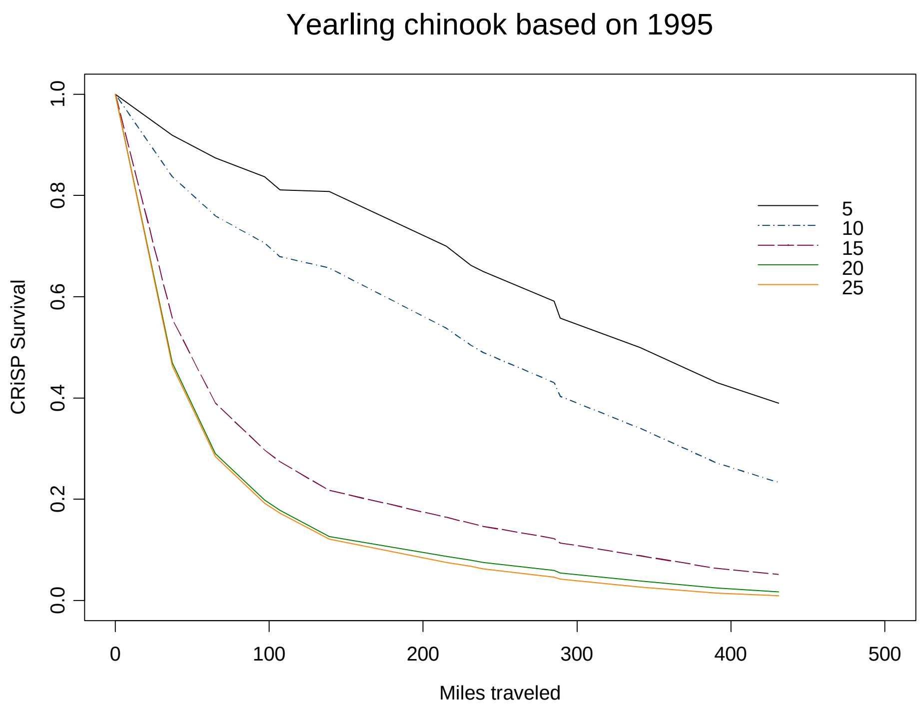

Figure 14. Yearling chinook survival from release to various points downstream at various five hypothetical temperature levels.

In practice, the temperatures cannot be controlled to the extent modeled in Scenario 3, but CRiSP1.7 does predict that within a given temperature range, the flows and spills encountered in the 21 years from 1975 to 1995 can account for some variability in survival. This is illustrated for the subyearling chinook survival between Lower Granite and McNary dams (Figure 15). Assuming constant water temperatures over the river, for increments between 5° and 20°C, the simulated survivals to McNary Dam range $\pm 5\%$. The variation is a result mostly of year-to-year differences in spill and the hydrosystem configuration.

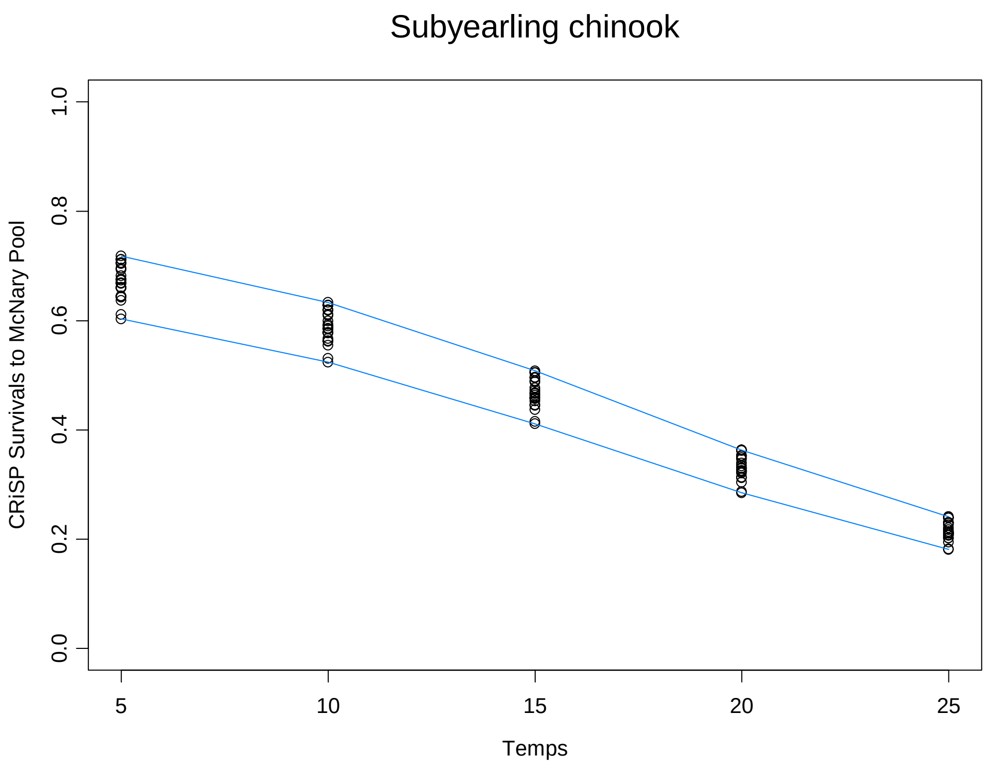

Figure 15. Variability in survival to McNary from Lower Granite Dam for subyearling chinook across a range of five hypothetical river temperatures. The range of variation at each temperature is a result of using flow and spill conditions between the years 1975 to 1995.

Discussion

Although the EPA Heat Budget model does not account for vertical stratification of the water column, which may allow salmonids to seek preferred temperatures and increase Lower Granite Reservoir survival, it does allow for various input scenarios to be examined that include the delivery of temperature controlled water from the headwaters and storage reservoirs. Survival is sensitive to temperatures encountered throughout the river system; however the importance of input temperatures on local conditions diminishes quickly as the water moves through the reservoirs of the Snake and Columbia rivers. Even with complete control of headwater temperatures, such that temperature inputs never exceed specific values, the temperatures downstream are not significantly impacted because of the strong influence of atmospheric heat exchange. This is not readily apparent for the yearling chinook and the steelhead that travel early and thus are not influenced by scenarios that release cool water into the Snake River in the summer. However, subyearling chinook that travel during the warmer days would have some survival benefit initially, but cool water releases from upriver do not influence survival during travel in the lower reaches of the Snake and Columbia.

The relationship of specific environmental conditions to the survival of the fish is dictated by numerous interactions encoded in the EPA/CBR models. However, during the fish migration certain environmental conditions are more important than others. For example, subyearling chinook survival is linearly correlated with dry bulb temperature ($p = 0.00695$) and solar short-wave radiation ($p = 0.0369$) at Lewiston as shown in Figure 16 . Of the three runs the subyearling chinook migration occurs the latest in the season and thus the fish encounter longer, warmer days. Yearling chinook survivals are also related to the dry-bulb temperatures ($p < 0.03$, see Figure 18) but not to the solar short-wave radiation levels. A similar pattern exists for steelhead (Figure 17).

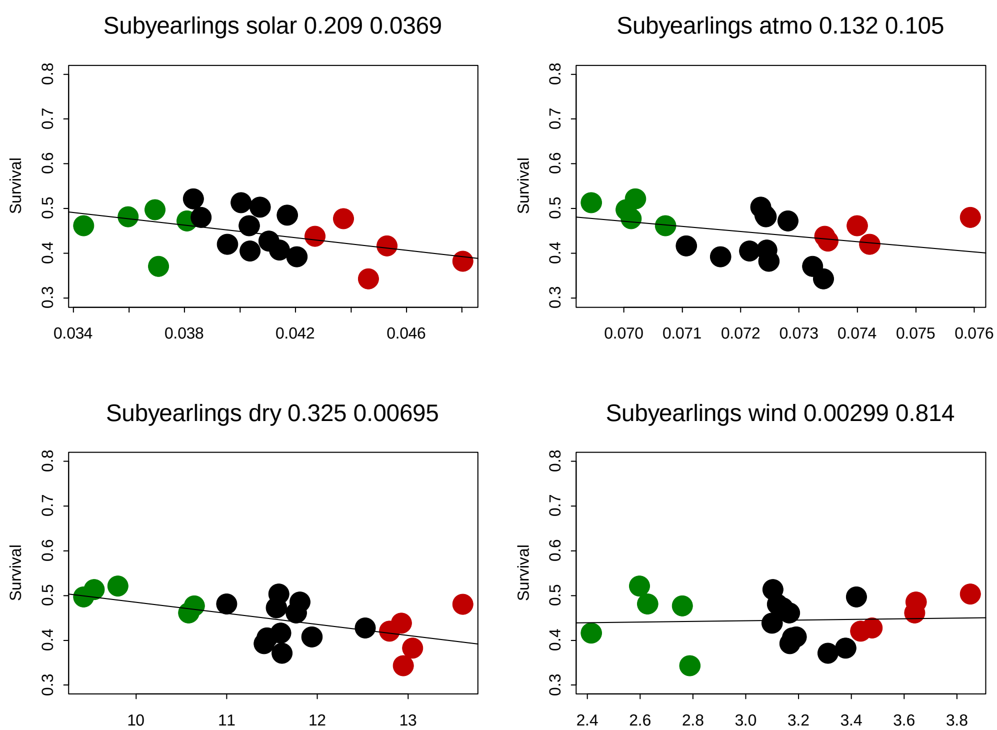

Figure 16. Subyearling survival to MCN related to four atmospheric conditions: "*solar* radiation", "*atmo*spheric long wave radiation", "*dry* bulb temperature", "*wind* speed". ". R^2 and *p* for the drawn linear relationship are included (respectively) in the title. Green dots (shaded points on left) represent lower 25% quartile and red dots (shade points on right) represent upper 75% quartile.

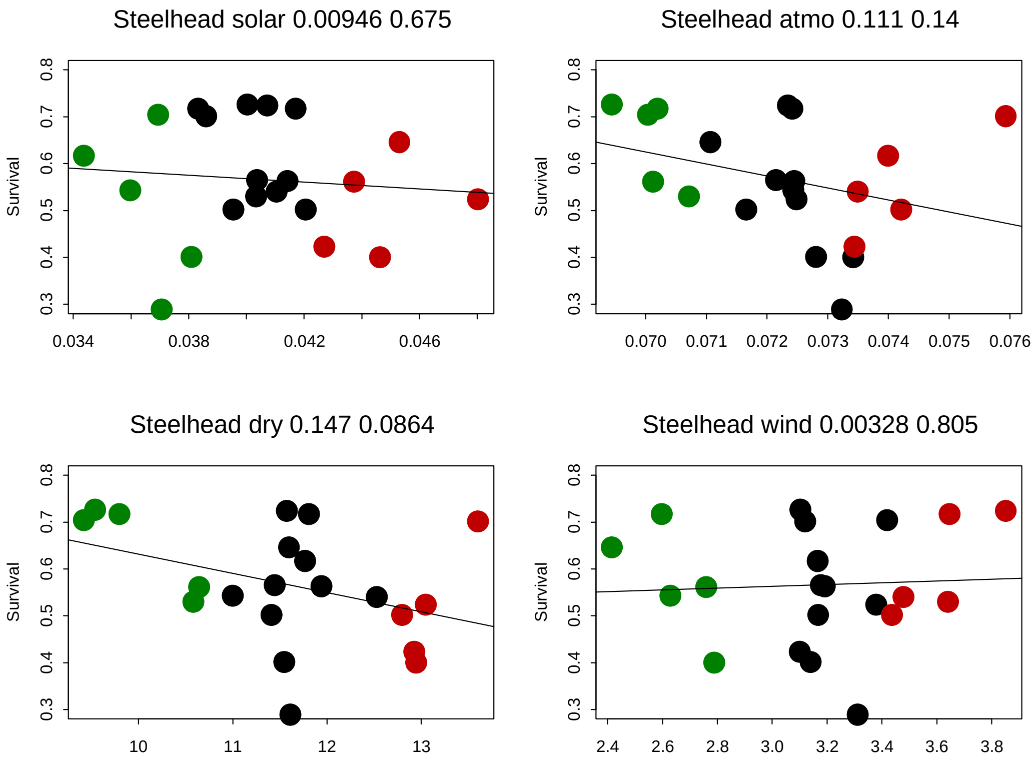

Figure 17. Steelhead survival to MCN to related to four atmospheric conditions: "*solar* radiation", "*atmo*spheric long wave radiation", "*dry* bulb temperature", "*wind* speed". ". R^2 and *p* for the drawn linear relationship are included (respectively) in the title. Green dots (shaded points on left) represent lower 25% quartile and red dots (shade points on right) represent upper 75% quartile.

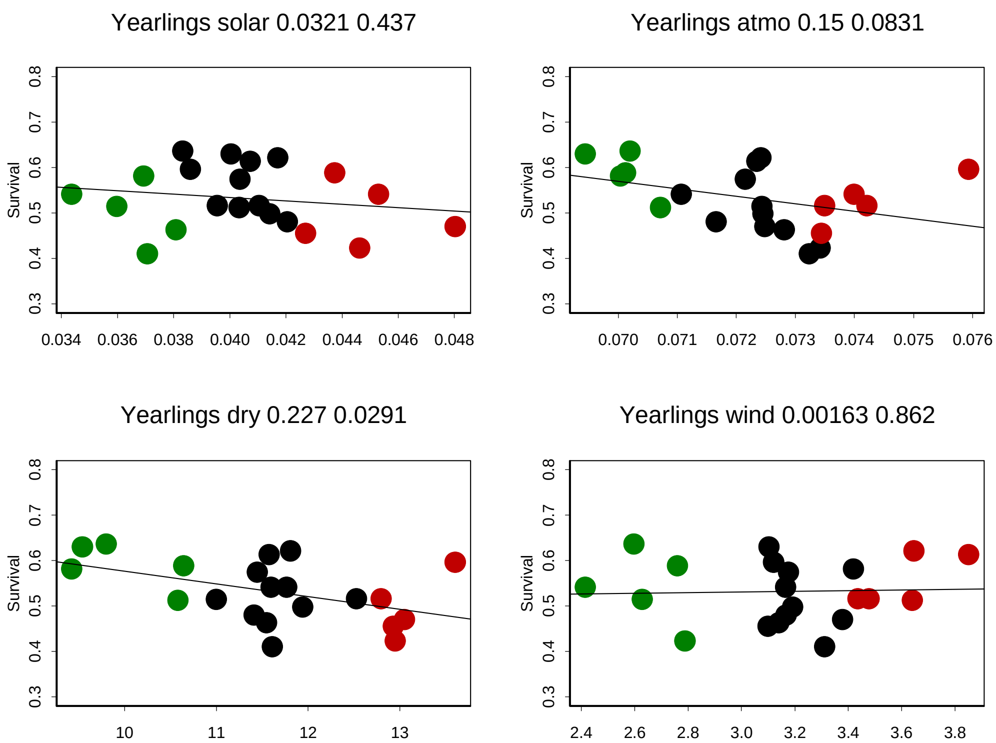

Figure 18. Yearling chinook survival to MCN related to four atmospheric conditions: "solar radiation", "atmospheric long wave radiation", "dry bulb temperature", "wind speed". ". R2 and p for the drawn linear relationship are included (respectively) in the title. Green dots (shaded points on left) represent lower 25% quartile and red dots (shade points on right) represent upper 75% quartile.

Figure 19 shows the wide range of flows and average daily air temperatures encountered during the 21 year modeling period. Flows ranged over a factor of four and average daily air temperatures varied across 4°C. A general pattern exists where years with high flow tend to have lower temperatures. This can be used to distinguish high/low flow years as well as warm/cool seasons.

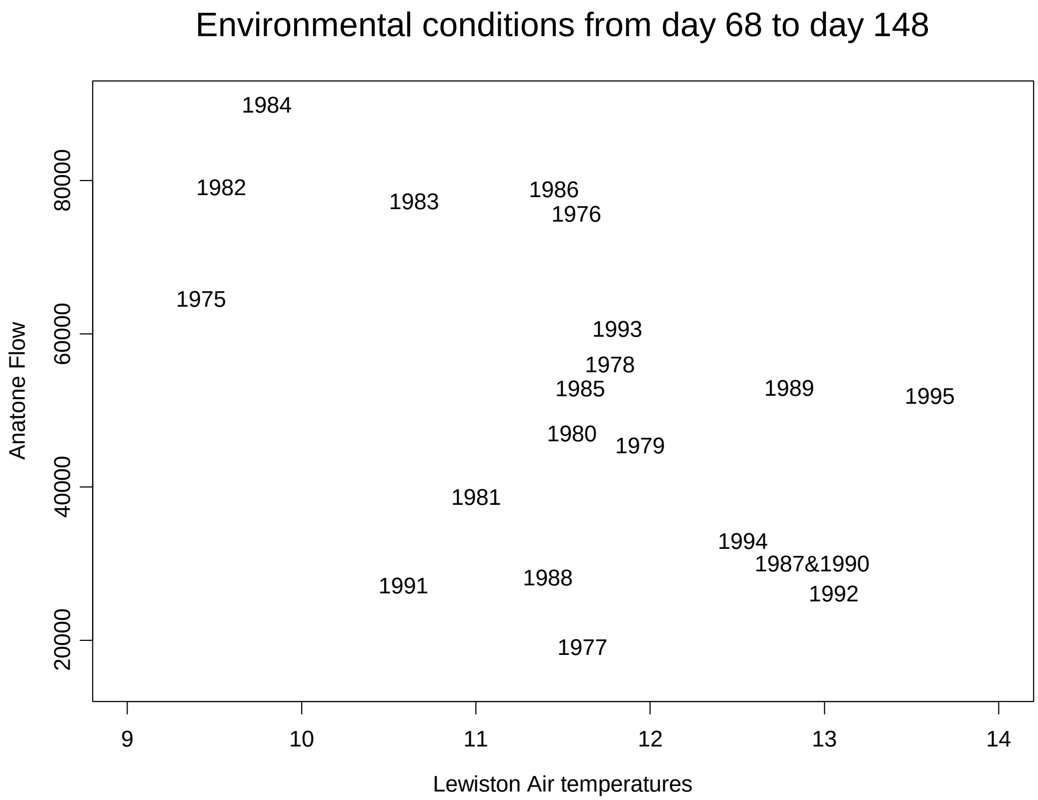

Figure 19. Environmental variables over 21 years. Lewiston average air temperatures (°C) and Anatone, Snake River flows (cfs) during the 81 day modeling window. Year 1990 and 1997 appear to overlap slightly. Example: 1976 was a high flow year with moderate air temperatures. Year 1977 was a very low flow year with moderate air temperatures.

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