Heat Budget of Water Flowing through Hells Canyon and the Effect of Flow Augmentation on Snake River Water Temperature

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Summary

An analysis of the heat budget of Snake River water flowing through Hells Canyon was developed to evaluate the impacts of flow augmentation on river temperature. Snake River water warms as it flows through Hells Canyon in the summer. In the winter the water cools. Mixing of waters from the Imnaha and Salmon tributaries cools the Snake River in the autumn and winter. Late winter through early spring and in the late summer, these tributaries warm the Snake River and in the summer, the Snake River may be either warmed or cooled by the tributaries. A heat budget model indicates that flow augmentation from Hells Canyon Dam has a small and variable effect on Snake River temperature. The effect of augmentation is greatest in the summer and increases linearly with the amount of flow augmentation. The heat budget model indicates that a 10,000 cfs flow augmentation can increase or decrease temperature by $\pm$ 0.5^{o}C at RM 180. Because in the summer water from Hells Canyon Dam is warmer than the water from the tributaries, the Snake River summer temperatures can be lowered by minimizing the flow from Hells Canyon Dam.

Setting

The Snake River above Lower Granite Reservoir (LGR) drains southern Idaho and adjacent parts of Oregon, Nevada, Utah, Washington, and Wyoming. Major tributaries flowing into the Snake River in the 50-mile reach upstream from LGR include the Clearwater and Salmon Rivers, which drain the mountains of central Idaho. The Imnaha and Grande Ronde Rivers enter this reach of the Snake River from the west. Upstream from this portion of the Snake River are a series of dams called the Hells Canyon Complex. These dams include the Hells Canyon, Brownlee, and Oxbow (Figure 1). Most of the tributaries to the Snake below Brownlee Dam are free flowing with the notable exception of the North Fork, Clearwater River where Dworshak Dam is located.

Flow augmentation has been used in recent years to provide 427 kaf of water through the Hells Canyon Complex. The augmentation has increased flows by up to 15 kcfs through the lower Snake River in the spring or summer. The Snake River experiences a 20 degree temperature variation over the year, with December/January temperatures of 4^{o} C and July/August temperatures of 24^{o} C. Air temperature in the Snake River Basin ranges from below zero to 30^{o} C. The temperature of Snake River water downstream of the Hells Canyon Complex depends on the temperatures and flows of the water released from Hells Canyon Dam, the temperature and flows of the tributaries, and the air temperature. This mix of Hells Canyon releases, tributary flows, and air temperature produces varying Snake River water temperatures. During the spring and summer, the air temperature is generally warmer than the water temperature resulting in the river warming as it flows downstream. In the winter, the air temperature is generally cooler and the river cools as it flows downstream. The exact temperature of each tributary depends on the elevation and local climate of the tributary subbasins. The Snake River temperature above the Hells Canyon Complex is also determined by air temperature, but the seasonal pattern of water temperature for releases from Hells Canyon Dam is complicated by the reservoirs of the three dams, which isolate the water from the atmosphere. Thus, because a number of factors determine the temperature of flows from each water source, increased flows from the Hells Canyon Complex may either warm or cool the water of the Snake River downstream of the complex.

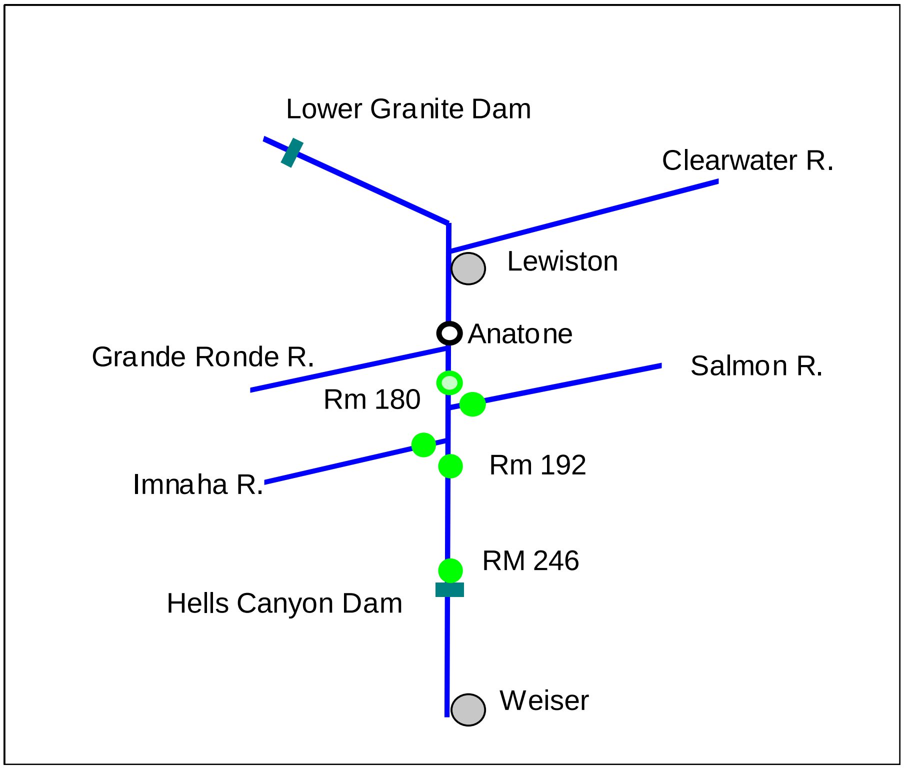

Figure 1. Location of data points at Lewiston; Anatone; River Miles 180, 192, 246; the confluences of the Salmon and the Imnaha Rivers; and Weiser.

Observations

For this analysis, temperatures and flows were compiled from the Internet (DART, USGS), and records provided by Idaho Power Company.[1] The temperature of water flowing out of the Hells Canyon Complex and through Hells Canyon increases and decreases over the seasons as it exchanges heat with the air and mixes with water from the tributaries. The air temperature ultimately controls the seasonal river temperature. In the Snake River Basin, the highest air temperatures occur in August and the lowest air temperatures occur in February. The general pattern for the air temperature at Lewiston, downstream from Hells Canyon on LGR, is illustrated in Figure 2. Above Hells Canyon, the seasonal temperature variation is larger. At Weiser, on Brownlee Reservoir, the summer air temperature can be 10^{o} to 15^{o} C warmer than at Lewiston (Figure 3).

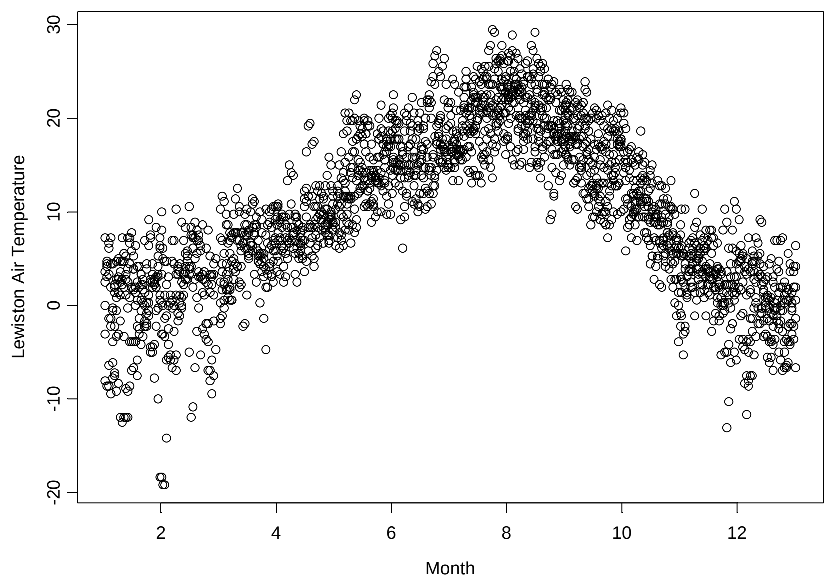

Figure 2. Monthly air temperature (^{o}C) at Lewiston, 1991-1997.

[1] **Data is available at: http://www.cbr.washington.edu/data/snake.temperature**

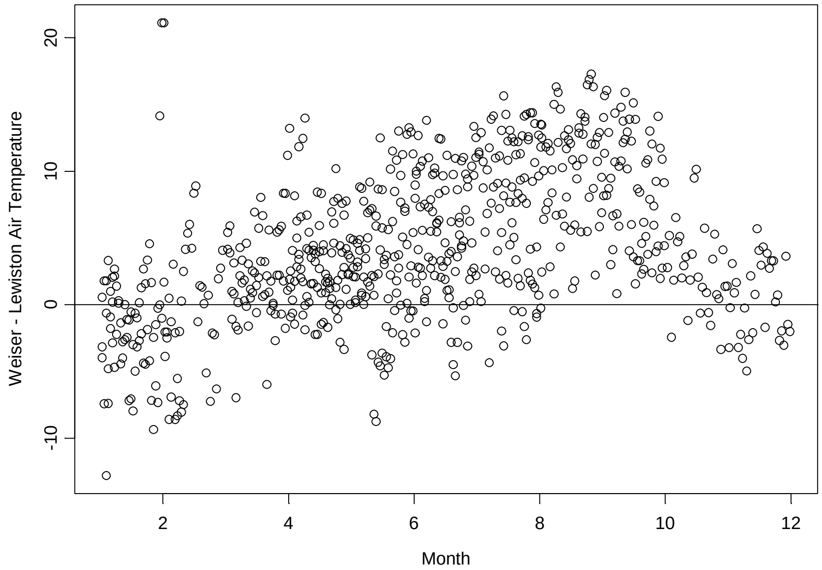

Figure 3. Seasonal difference in air temperature between Weiser and Lewiston, 1995-1997.

At RM 192, a consistent seasonal water temperature pattern is evident with lows below 4^{o} C occurring in February and highs over 22^{o} C occurring in August (Figure 4).

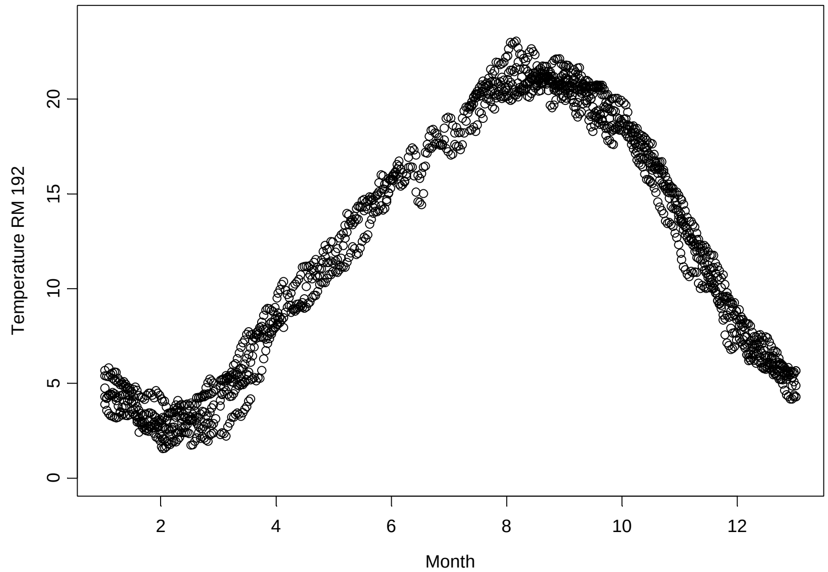

Figure 4. Seasonal temperature distribution at Snake River Mile 192, 1991-1997.

The difference in temperatures upriver compared to downriver also exhibits a seasonal pattern. This is illustrated by comparing the river temperature at RM 246, just below Hells Canyon Dam, with the river temperature at Anatone, which is below the confluence of the Grande Ronde River (Figure 5). Generally, the water is cooler downstream in the fall and winter and warmer in the early spring and late summer. During the summer juvenile fall chinook migration from Hells Canyon, the water may be either warmer or cooler downstream. The temperature of Snake River water at RM 192 (just upstream of the confluence of the Imnaha River) is warmer in the summer and cooler in the fall and winter than at RM 246 (Hells Canyon) (Figure 6).

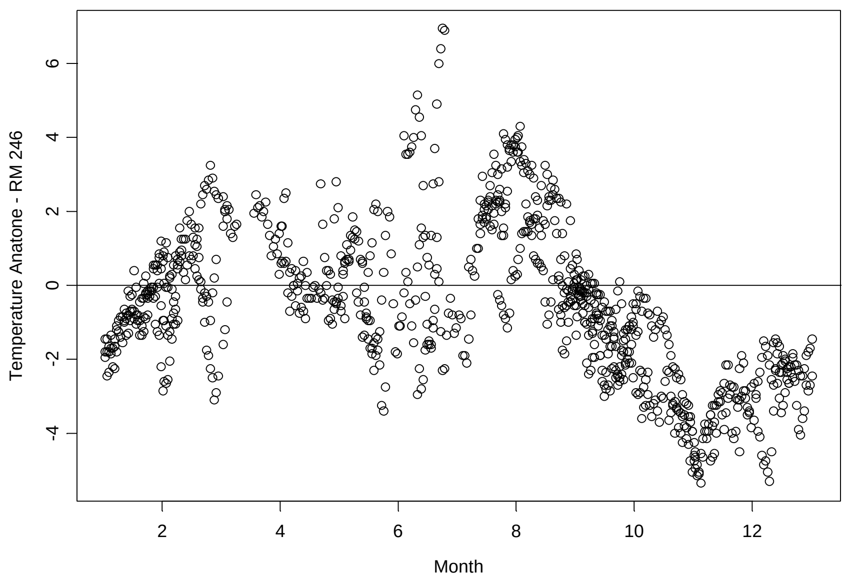

Figure 5. Temperature difference between Anatone and Hells Canyon Dam (RM 246), 1991-1997. Positive values indicate warming.

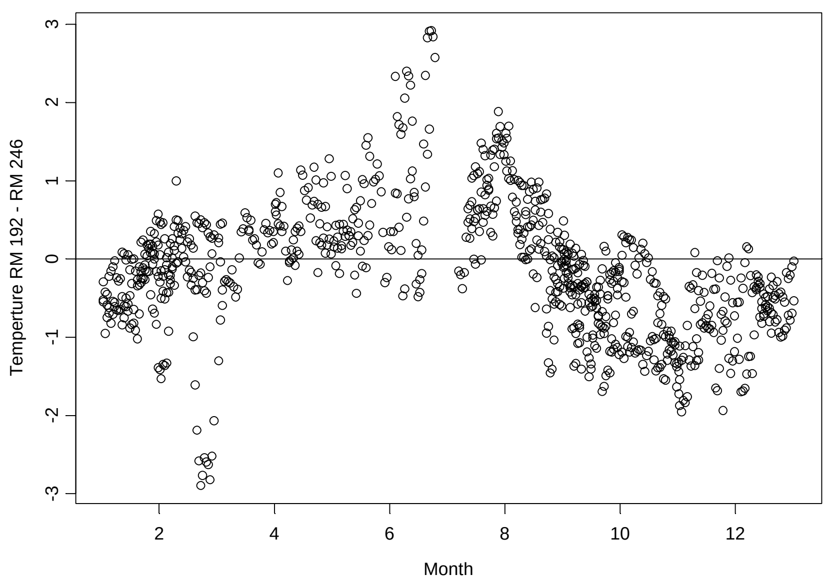

Figure 6. Temperature difference between RM 246 and RM 192, 1991-1997. Positive values indicate warming.

Although there are seasonal patterns of flow and water temperature at Hells Canyon Dam, the two properties are uncorrelated as illustrated in Figure 7.

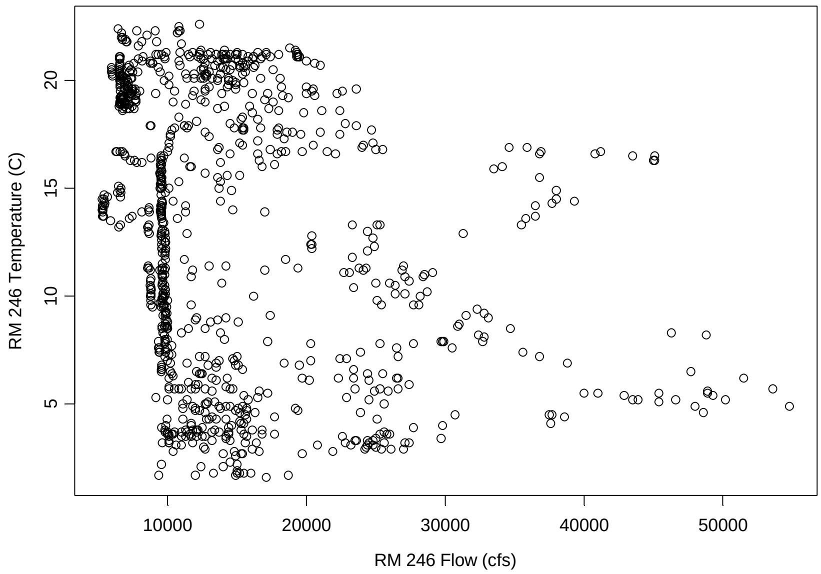

Figure 7. Flow vs. temperature from Hells Canyon Dam.

However, the air temperature and water temperature in the system are correlated as is evident from a plot of air temperature and water temperature at Lewiston (Figure 8).

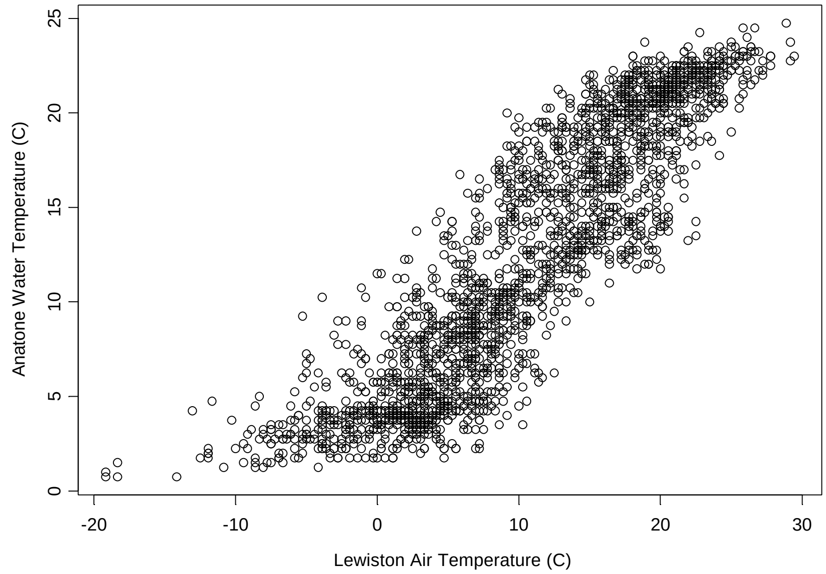

Figure 8. Anatone water temperature vs. Lewiston air temperature, 1991-1997.

The tributaries that enter the Snake River between RM 192 and RM 180 typically have temperatures different from the Snake River. The Snake River is generally warmer than the Imnaha and Salmon Rivers; however, in early spring the Snake River is several degrees cooler than the tributaries. Throughout most of the summer, the Snake River is warmer, but at the end of the summer, the difference is variable and the Snake River may be either warmer or cooler than the tributaries (Figure 9 and Figure 10). The effect of these tributaries on Snake River water temperature is evident from the plot of the temperature at RM 192 relative to RM 180 (Figure 11). The Imnaha and Salmon tributaries typically cool the Snake River in the spring, fall, and winter. During the summer, the tributaries may warm or cool the Snake River.

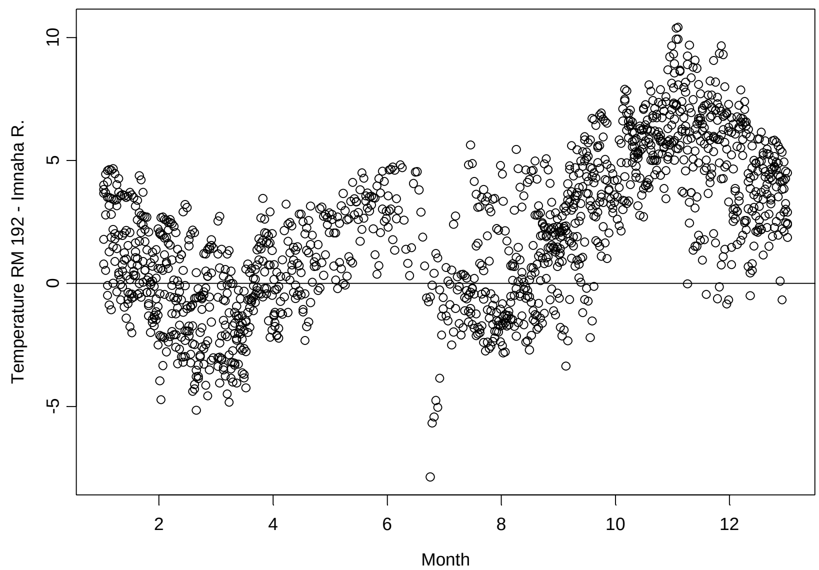

Figure 9. Difference between the Snake and Imnaha Rivers, 1991-1997. Positive numbers indicate the Snake River is warmer.

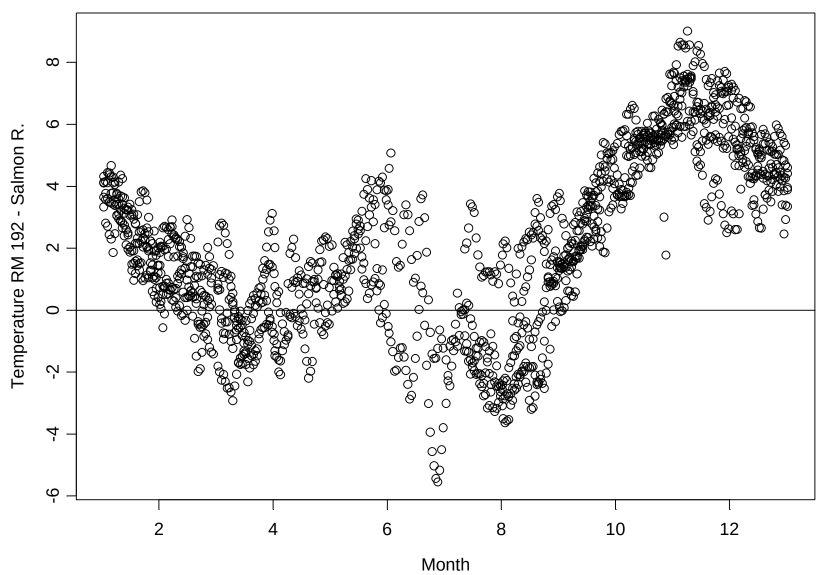

Figure 10. Difference between the Snake and Salmon Rivers, 1991-1997. Positive numbers indicate the Snake River is warmer.

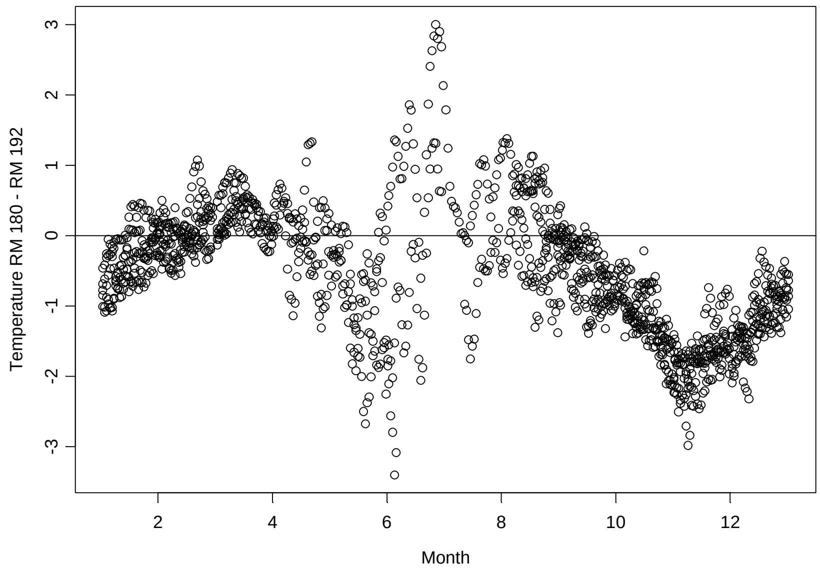

Figure 11. Temperature difference between RM 192 and RM 180, 1991-1997. Positive values indicate river warming.

Snake River Heat Budget Model

To quantitatively understand the Snake River heat budget and characterize the effect of flow from Hells Canyon Dam on the downstream water temperature, a simplified heat budget model can be applied. The model considers atmospheric heating and cooling, and mixing of temperatures from the tributaries that flow into the Snake River. Figure 12 illustrates a simplified diagram of a river with atmospheric heat exchange as water flows downstream between points a and b. At point c a tributary with a different temperature enters the river. In the short reach from b to d, the primary temperature change is the result of the mixing of water from the tributary at c. Atmospheric heat exchange is ignored in this reach.

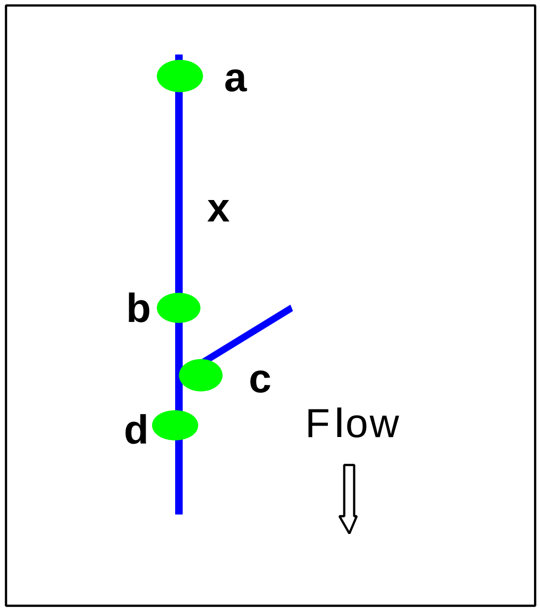

Figure 12. River schematic for temperature model. Water exchanges heat with the atmosphere flowing from a to b and then mixes with water from tributary at point c to result in the river temperature at point d.

General Heat Budget Equations

The Newton heat exchange formula is used to describe the exchange of heat between the river and the atmosphere as the water flows between points a and b. The rate of change in water temperature depends on the difference between the water θ and air temperatures θ_{air} and can be described

$$\frac{d\theta}{dt} = r(\theta_{air} - \theta)$$

where *r* is an exchange coefficient depending on the river geometry and the atmospheric conditions. As the water flows downstream, it approaches the air temperature in an exponential manner giving temperature as a function of time as

$$\theta(t) = \theta_{air} - (\theta_{air} - \theta_a)\exp(-rt)$$

where θ_a is the temperature at point a. This can be simplified by first expanding the exponential terms as the series $\exp(-rt) = 1 - rt/1! + (rt)^2/2!$ ..... Note that values of rt are less than 1, corresponding to a short travel time over a reach relative to the time it takes for the water to reach the air temperature. Consequentially the series can be approximated by the first term in t and the temperature at b can be defined

$$\theta_b = \theta_{air} - \alpha(\theta_{air} - \theta_a) \tag{1}$$

where the incremental thermal exchange is characterized by the coefficient α, which is defined $\alpha = r\Delta t$ where Δt is the time it takes the water to flow between points a and b.

The change in water temperature due to mixing with the tributary can be defined by a heat conservation equation

$$\theta_d = \frac{\theta_b F_b + \theta_c F_c}{F_b + F_c} \tag{2}$$

where F_b and F_c are flows of the two rivers at their confluence.

Atmospheric Heat Exchange Between RM 246 and RM 192

To understand the effects of atmospheric heating on the Snake River, eq(1) is used to define the seasonal temperature variations between RM 246 (point a) and RM 192 (point b) shown in Figure 6. Over this reach, no tributaries flow into the Snake River; therefore, the temperature differential is only due to atmospheric heat exchange. To characterize the rate of exchange, a representative seasonal pattern of atmospheric temperature for the river reach between RM192 and RM 246 is used. Figure 3 indicates that the air temperature at Weiser is warmer that Lewiston in the summer. Over the years 1995-1997, the seasonal air temperature differences between Lewiston and Weiser can be described by a linear regression (Figure 13) giving

$$\theta_{Weiser}\ (C) = 0.3 + 1.43 * \theta_{Lewiston}$$

with a residual standard error of 4.32, R-squared = 0.8782, N = 580, F-statistic = 4167 on 1 and 578 df, P-value = 0. The standard error of the intercept and slope are 0.3 and 0.02 respectively. Assuming air temperature changes linearly with distance, the Hells Canyon temperature (halfway between Lewiston and Weiser), is half the temperature difference between these two points. Therefore, the equation for the representative Hells Canyon temperature is

$$\theta_{air} = 1.21 * \theta_{Lewiston} \tag{3}$$

Note that the intercept of the regression is dropped because it was not significantly different from zero.

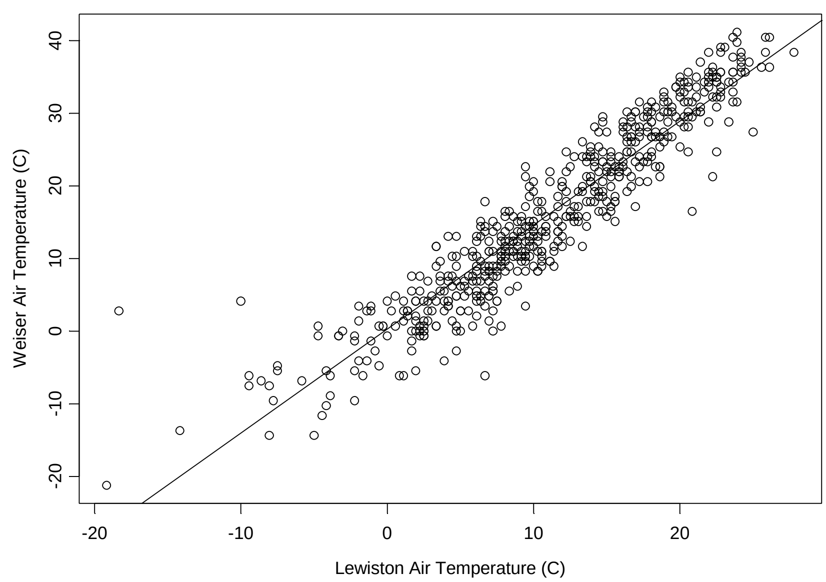

Figure 13. Lewiston vs. Weiser air temperatures, 1995-1997.

To estimate the heat exchange through Hells Canyon, a linear regression of water temperature vs. air temperature was performed where the air temperature in Hells Canyon is defined by eq(3). The equation is

$$\theta_{RM\,192} - \theta_{air} = \alpha(\theta_{RM\,246} - \theta_{air}) \tag{4}$$

Using data from 1991 through 1997 the regression gives: $\alpha = 0.9045$ with a standard error of 0.0028, residual standard error = 0.5543, multiple R-squared = 0.9919, N = 823, F-statistic = 100919 on 1 and 822 df (Figure 14).

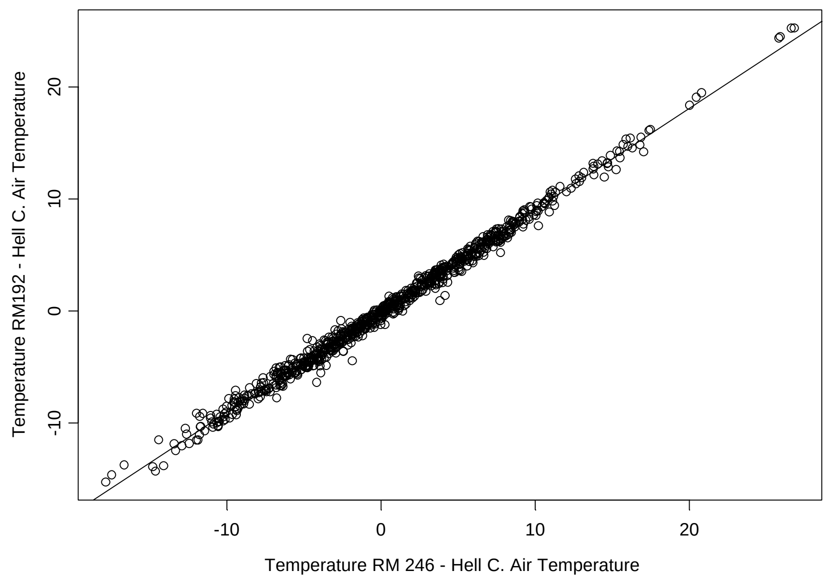

Figure 14. Regression of eq(4).

Additionally, for this analysis, the heating/cooling that occurs through Hells Canyon is assumed independent of flow augmentation level. This assumption is supported by distribution of the residuals from the regression of eq(4). The residuals exhibit a slight trend when plotted against flow (Figure 15) (residual (^{o}C) = 0.08 -0.000014 *flow(cfs)) but the effect is small and can account for only a 0.1^{o}C difference in temperature change over a 10,000 cfs change in flow.

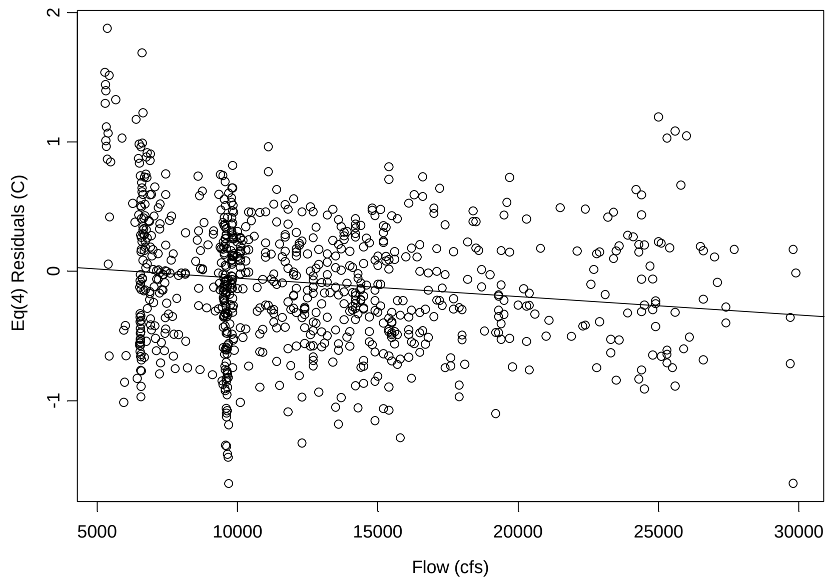

Figure 15. Residuals of eq(4) vs. flow shows no significant trend.

The temperature at RM 192 can now be approximated in terms of the river temperature at Hells Canyon (RM 246) and the air temperature in Hells Canyon by the equation

$$\theta_{RM\,192} = 0.9\theta_{RM\,246} + 0.1\theta_{HellsC.air} \tag{5}$$

As is illustrated by a plot of the difference between the Hells Canyon air temperature based on eq(3) and water temperature at RM 192 (Figure 16), in the summer the river is heated as it flows through the canyon. Between RM 246 and RM 192, the water temperature changes by approximately 10% of the difference between the air and the water temperature. Therefore, in the summer the Snake River water warms about 1^{o}C as it flows through the canyon and in the winter, it cools by about the same amount.

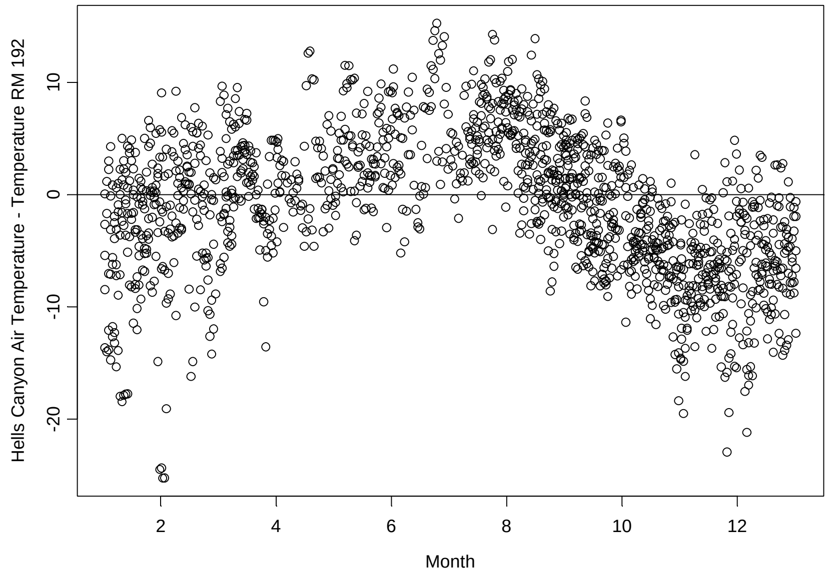

Figure 16. Difference between air and water temperature at RM 192.

The Heat Budget at the Confluences

To characterize the effect of tributary flows on the Snake River heat budget, the temperature difference between RM 192 and RM 180 is considered. Within this 12-mile reach, the Imnaha and the Salmon Rivers enter the Snake River (Figure 1). Based on eq(2), the temperature at RM 180 can be described

$$\theta_{Rm180} = \frac{\theta_{Salmon} F_{Salmon} + \theta_{Imnaha} F_{Imnaha} + \theta_{Rm192} F_{Rm192}}{F_{Salmon} + F_{Imnaha} + F_{Rm192}} \qquad (6)$$

where F are flows and θ are water temperatures of the respective rivers. To evaluate eq(6), the temperatures and flows from 1991 through 1997 were used to predict the temperature at RM 180 over the same period. A regression of the observed vs. the predicted temperature at RM 180 is illustrated in Figure 17. The regression with 1262 df had a residual standard error of 0.21, a slope of 1.00, (standard error 0.0009), an intercept of -0.17 (standard error 0.01), and R-squared of 0.9989.

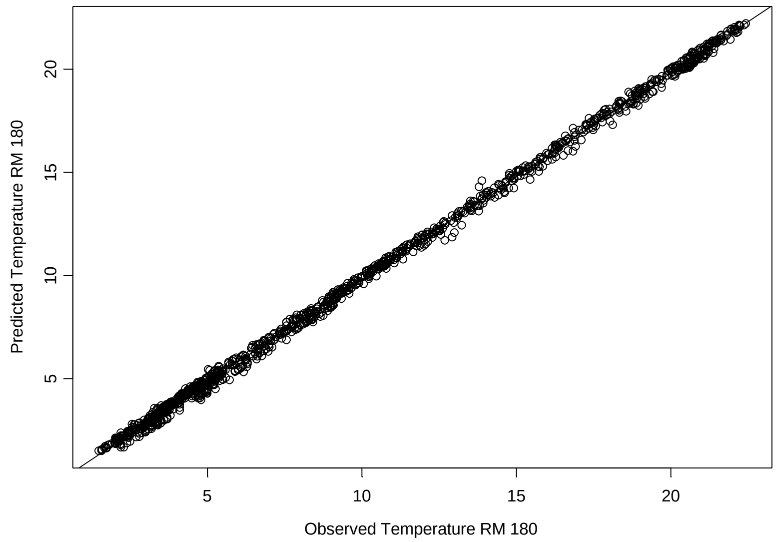

Figure 17. Regression of observed vs. predicted temperature at Snake RM 180, 1991-1997.

Modeling the Effect of Flow Augmentation on Temperature

To model the effect of flow augmentation, the heat budget equation can be used to predict temperatures downstream of Hells Canyon at RM 180. The equation is

$$\hat{\theta}_{Rm180} = \frac{\theta_{Salmon}F_{Salmon} + \theta_{Imnah}F_{Imnah} + \theta_{Rm192}F_{Rm192}}{F_{Salmon} + F_{Imnah} + F_{Rm192}} \tag{7}$$

The flow at RM 192 is determined by the flow from the Hells Canyon Dam; thus the flow augmentation impact on temperature at RM 180 is modeled according to the impact on F_{RM192}. The effects of Upper Snake flow augmentation on downstream temperature at RM 180 can be calculated by changing Snake River flows (F_{RM192}) to reflect different levels of flow augmentation. Using eq(7), the effect of the existing 427 kaf flow augmentation from the Hells Canyon Dam Complex is estimated as the difference in predicted temperature at RM 180. Figure 18 illustrates the difference in river temperatures at RM 180 with the additional 427 kaf. (Note: Insufficient temperature data were available to estimate the temperature impacts of each year.)

The effect of the flow augmentation on temperature can also be illustrated with a plot of the change in temperature with and without the augmentation by month (Figure 19). The modeled impact of flow augmentation on temperature increases with the level of augmentation as is illustrated in Figure 20. Note the temperature may either increase or decrease with augmentation. Finally, because in spring, summer and autumn seasons Hells Canyon Dam water is generally warmer than the tributary water, reducing the flow through Hells Canyon can minimize the temperature at RM 180. This possibility is illustrated in Figure 21, which shows a reduction in temperature with a steady 8,000 cfs flow relative to the observed temperatures with the observed flows. Typical minimum summer flows from Hells Canyon Dam are about 8,000 cfs.

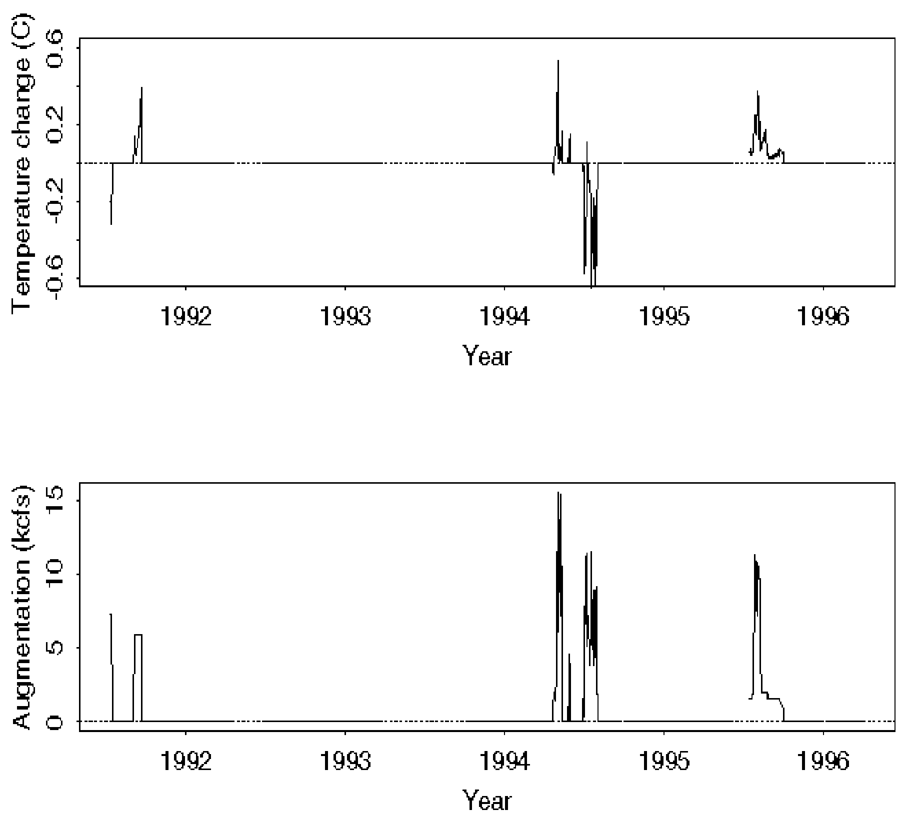

Figure 18. Difference in temperature at RM 180 with and without the existing flow augmentation from Hells Canyon Dam Complex.

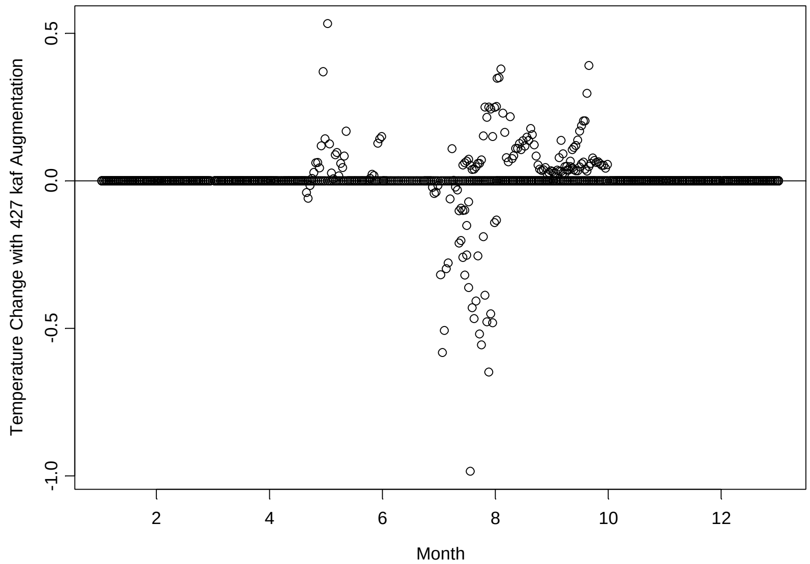

Figure 19. Temperature differential at RM 180 estimated to result from the 427-kaf flow augmentation.

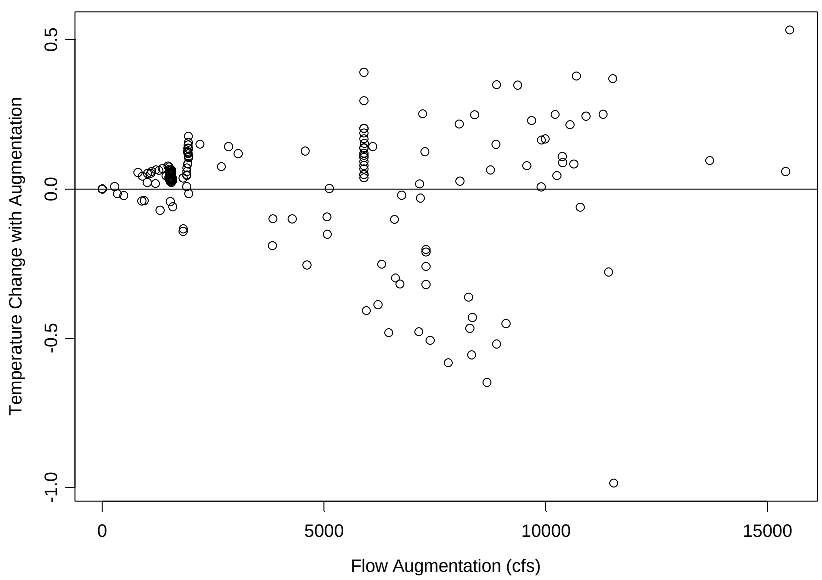

Figure 20. Predicted effect of flow augmentation on temperature at RM 180.

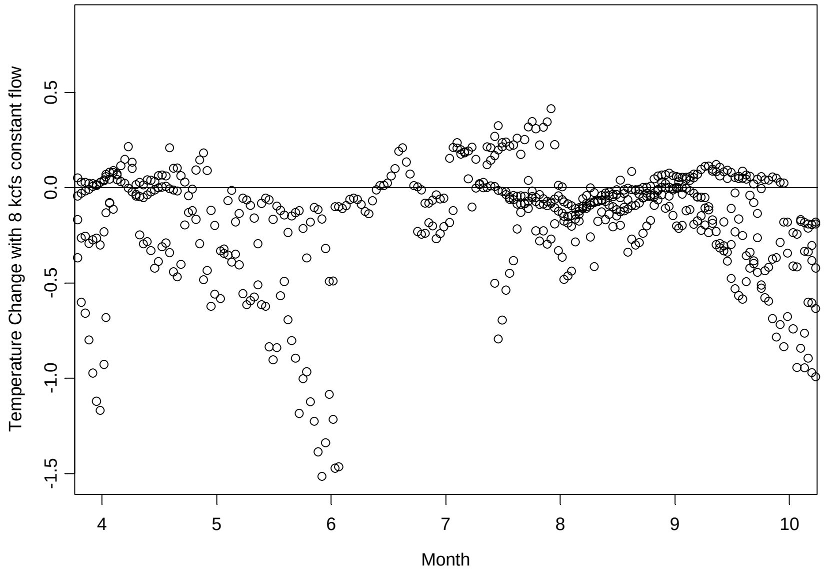

Figure 21. Predicted difference in temperature relative to the existing temperature at RM 180 if Hells Canyon flow were held constant at 8000 cfs. Negative values mean the temperature is cooler with the constant flow relative to the larger actual flow.