Stream Temperature Modeling in a Complex River System; an Evaluation of River Temperature Response to Probable Influential Factors in the Middle Snake River, Idaho

Submission in partial fulfillment of a Master's of Science Degree at the University of Idaho

Submitted: May, 2012

Primary Researcher**:** Andrew Knight, University of Idaho

Primary Research Advisor- Timothy Link – Associate Professor of Forest Hydrology, University of Idaho

Research Advisor- Jack Harrison, HyQual, P.A.

College of Graduate Studies Review- Dr. Jan Boll, Environmental Science Program Director, College of Graduate Studies, University of Idaho

TABLE OF CONTENTS

Table of Contents i

Abstract ii

1. Problem Statement 1

2. Introduction 2

 2.1. Location Description 2

3. Background 3

 3.1. Temperature 3

 3.2. Biota 3

 3.3. Water Quality Standards 4

 3.4. Temperature Modeling and Applications 5

4. Research Questions and Objectives 9

5. Methods 10

 5.1. General Information 10

 5.2. Site Information 10

 5.3. Data Collection 11

 5.4. QUAL2Kw Water Quality Model 13

 5.5. Parameter Estimation for Model Calibration 18

 5.6. Evaluation of Calibrated Model Performance 20

 5.7. Temperature Sensitivity Model Simulations 21

6. Results 24

 6.1. Model Calibration 24

 6.2. Temperature Sensitivity Scenario Simulations 30

7. Discussion 47

 7.1. Sources of Uncertainty/Information Gaps 47

 7.2. QUAL2Kw as an Appropriate Tool 49

 7.3. Temperature Sensitivity Scenario Simulations 50

 7.4. Biological Implications 53

8. Acknowledgements 54

9. Literature Cited 55

Appendix 58

ABSTRACT

Water temperature is an important characteristic of aquatic ecosystems due to its influential effects on biological and chemical processes, and the biota therein (Benyahya, 2007; Caissie, 2006). Climate change, streamflow alterations, ground to surface water flux, and land use changes can alter temperature regimes in aquatic systems (Caissie, et al., 2007; Cristea and Burges, 2010; Roth, et al., 2010). Understanding how these and other factors affect stream temperature is important for the preservation of ecological integrity of these aquatic systems (Rivers-Moore and Jewitt, 2007). Traditionally, a stream temperature effect resulting from changes in influential factors has been measured and evaluated post-perturbation. When approached in this manner the impacts of natural or anthropogenic alteration may be found to have deleterious ecological effects, but only after the hydrologic or land use changes have been implemented, or, after significant climate change or ground/surface water gains or losses have occurred. The more recent development of publicly available and user-friendly stream temperature models improves the ability for resource managers to reasonably assess how changes in influential factors may affect stream temperature (Moore and Lorentz, 2004; Caissie, et al., 2007). In many cases, the application of an appropriate temperature model to a system of interest provides valuable information for managers to make well informed decisions concerning water resources (Ferrari et al., 2007; Norton and Bradford, 2009). This study sought to: **1)** Calibrate a temperature model for the Middle Snake River, **2)** Evaluate the sensitivity of river temperature to river headwater flow, spring tributary flow, surface tributary temperature, and surface tributary flow, and **3)** Identify information gaps that may affect model performance. QUAL2Kw calibration results showed good agreement between observed and predicted temperatures, indicating that the model has application potential in the Middle Snake. Results indicate that temperature in the Middle Snake is largely dominated by river headwater flow conditions, although all other evaluated factors influence river temperature to some degree.

1. PROBLEM STATEMENT

An information gap currently exists with respect to an inability to predict the effect of river flow, groundwater, tributaries, and meteorological factors on Middle Snake River temperature. A better understanding of these components and their influence on river temperature would likely foster better informed management decisions. Such an understanding may be gained, in part, with the use of an appropriate temperature model. However, development of such a temperature model for the Middle Snake River is no trivial task, and to our knowledge has been limited to the works performed by Harrison (IPCO, 2009), Myers and Parkinson (1996), and U.S.EPA (2002). Five reservoirs, many tributaries, countless spring surface inflows, limited knowledge of ground/surface water interactions, and substantial irrigation diversions and returns all pose substantial challenges to the development of a functional temperature model for this system. Despite these complexities, it is prudent that we continue to pursue a better scientific understanding of the factors that regulate temperature in the Middle Snake River. Such efforts will aid the future preservation and/or restoration of ecological integrity in this ecosystem.

2. Introduction

2.1. Location Description

The Snake River is a major river that provides a host of ecosystem services and serves as a foundational resource for many rural and urban areas in its vicinity. The Middle Snake generally flows from east to west across Southern Idaho and is described by the U.S. Environmental Protection Agency (EPA) as a 150km stretch of the Snake River extending from Milner Dam downstream to King Hill, ID (U.S. EPA, 2001)(**Figure 1**). This portion of the Snake River drains a land area of approximately 22,300 square km below Milner Reservoir (U.S. EPA, 2001). Based on 20 years of record (1991-2010), the Middle Snake below Milner reservoir has annual mean flows of 2,243, 2,546, and 9,117 cubic feet per second at Milner, Kimberly, and King Hill, respectively. The significant between-location differences in the mean flows are primarily due to the diversion of most , if not all, of the Snake River at Milner Dam (U.S. EPA, 2002), and substantial spring contributions upstream of King Hill that comprise the majority of Snake River flow below the Thousand Springs area. In 1980, Kjelstrom (1992) found that spring groundwater sources contributed ~5,150 cubic feet per second of flow to the Middle Snake, although this contribution has decreased in recent years (Blew and Bowling, 2009). The mean and median date on which maximum daily mean temperature occurs at Milner Dam is August 3, with a date range of 7/24-8/11, based on 13 years of record.

3. BACKGROUND

3.1. Temperature

The influence of temperature on aquatic ecosystems can have profound and cascading effects (Benyahya, et al. 2007; Norton, Bradford, 2009; Rivers-Moore, Lorentz, 2004; Roth et al. 2010). At a basic level, temperature can be a regulator of biological processes affecting oxygen, photosynthesis and decomposition (Benyahya, et al. 2007; Norton, Bradford, 2009). In some cases, small increases in temperature can have large ecological consequences (Coutant, 1999; Martins, et al. 2010). Relative to current river temperatures, an increase in stream temperature has been shown to increase the growth of several rooted macrophyte species that dominate the Middle Snake (Barko, Smart, 1981; Davison, 1991; Madsen and Adams, 1989). This increased load of organic matter will require more oxygen to facilitate decomposition. Increased temperature will likely accelerate the decomposition process as well (Carpenter, Adams, 1979). Therefore, it is likely that elevated temperature will reduce dissolved oxygen, as has been observed in other studies (Benyahya et al., 2007). In a system already described as eutrophic due to high levels of anthropogenically derived nutrient inputs (U.S.EPA, 2001), an increase in temperature may further exacerbate the current condition of nuisance aquatic growth in the Middle Snake River. Directly, cold water retains relatively more oxygen than warm water; therefore it stands that increased temperature will have both direct and indirect negative effects on dissolved oxygen conditions.

3.2. Biota

Elevated stream temperature can profoundly impact cold-water species such as salmonids and invertebrates (Benyahya, et al., 2007; Caissie, 2006; Gooseff, et al., 2005; Martins, et al., 2011); therefore, it is important that stream temperature and its causal factors are understood for species conservation. Potential thermal pollutant stressors to these biota result in part from anthropogenic influences such as urbanization, agriculture, and reservoirs (Roth, et al. 2010). Natural perturbations such as climate change and shifting hydrologic and vegetation trends also influence the environmental conditions for aquatic organisms (Gooseff, et al., 2005; Roth, et al., 2010). The Middle Snake supports a myriad of biota, several of which are unique to this system. Threatened or endangered fish and macroinvertebrate species include White Sturgeon (*Acipenser transmontanus*), Snake River Physa (*Physa natricina*), Bliss Rapids snail (*Taylorconcha serpenticola*), Utah Valvata (*Valvata utahensis*) and Banbury Springs Lanx (*Lanx sp*.) (U.S.EPA, 2002). Optimum spawning temperatures (13-16^{o}C) are well documented for White Sturgeon in the Columbia River (Parsley and Beckman, 1994) and high temperatures (>20^{o}C) during the spring spawning period have been reported to limit White Sturgeon recruitment in the Middle Snake River (Lepla and Chandler, 1995a). Thermal tolerances of the macroinvertebrate community in the Middle Snake are generally not well understood (Richards, et al., 1999). The aquatic vegetation community in the Middle Snake is dominated by *Ceratophyllum demersum*, *Potamogeton pectinatus*, and *Potamogeton crispus* (U.S.EPA, 2002). Research by Madsen and Adams (1989) showed that *Ceratophyllum demersum* has a photosynthetic optimal temperature of 30^{o}C, suggesting the potential for increased aquatic growth with increasing temperature in the Middle Snake.

3.3. Water Quality Standards

A Total Maximum Daily Load (TMDL) is a measure of the total amount of pollutant that a water body can receive and still meet water quality standards (IDEQ, 2010). The Idaho Department of Environmental Quality (IDEQ) has identified many beneficial uses in the Middle Snake River, including domestic water supply, cold water biota, salmonid spawning, and recreation (*e.g*. boating, fishing, swimming)(IDEQ, 2010). These beneficial uses, as well as the ecological integrity of the system can be adversely affected by an excess of pollutants such as nitrogen, phosphorus, sediment, and temperature (Caissie, 2006, U.S. EPA, 2001). Numeric criteria standards of 19°C and 22°C (IDEQ, IDAPA 58.01.02) have been established for maximum daily average and maximum daily maximum temperatures, respectively, for protection of coldwater designated biota. A TMDL has yet to be established for stream temperature in the Middle Snake. Therefore, the total amount of heat that can be added to the system without exceeding applicable temperature thresholds remains unknown. It is recognized that existing temperature impairment of the Middle Snake River poses significant challenges to meeting cold-water biota and salmonid spawning designations (IDEQ, 2010). As part of developing a temperature TMDL, the IDEQ has identified that there is potential benefit in numerical temperature modeling for investigating the effects of different mainstem flows and tributary temperatures on mainstem river temperatures (IDEQ, 2007).

3.4. Temperature Modeling and Applications

The benefits of applying a temperature model to the Middle Snake River are certainly not limited to the development of a TMDL. In fact, such models can be used to evaluate the influence of physical, meteorological, and hydrological factors on stream temperature, regardless of TMDL objectives (Buisson and Grenouillet, 2008; Caissie et al., 2007; Martins et al., 2011). Harrison modeled the effects of increased headwater flow on temperature in the Middle Snake using the one-dimensional USGS SSTEMP model. Simulation results from this work generally indicated a decrease in river temperature in cooler months with increased headwater flow; however, the comparison to a pre-existing baseline flow condition during the warmest summer months did not yield a straightforward assessment of flow effects on temperature during this period (IPCO, 2009). The EPA developed RBM10 is a dynamic one-dimensional model that has also been used to model temperature with and without dams in the Middle Snake (Myers and Parkinson, 1996). Results from this work indicate good agreement between measured data and predicted temperatures. Results from these model simulations indicated a model bias toward under prediction of temperature. The authors contend that the observed bias was most likely due to incomplete knowledge of the temperature of inflows, particularly springs (U.S. EPA, 2002). Similarly, RBM10 was utilized by EPA to develop Total Maximum Daily Load criteria for temperature in the Lower Snake River. While the dynamic RBM10 may lend to increased model resolution, this aspect also increases the user complexity such that a level of expertise is required to construct and perform model simulations. Temperature model calibration and simulations have been positively demonstrated on many other river systems with sufficient reliability for management applications (Bilhimer, et al., 2002, Caissie, 2006). Recently developed models such as QUAL2KW and SNTEMP with a one-dimensional steady-state basis are publicly available, user friendly, and effectively capture heat-flux components, have resulted in increased modeling applications. These user-friendly temperature modeling tools afford resource managers and researchers the ability to evaluate likely scenarios in a system of interest without requiring a high level of modeling expertise.

3.4.1. Climate

Components of climate that are likely to directly affect stream temperature include short and long-wave radiation, relative humidity, air temperature, and wind (Chapra, 1997). Long and short-term climate change can influence each these components, thus affecting stream temperature. If climate change lends to a net increase in solar radiation it will exert a direct effect on stream temperature, particularly on relatively un-shaded streams. Solar radiation has been shown to be a primary driver of thermal regimes in streams with little shade, whereas well-shaded streams are likely to show relatively greater response to air temperature (Chapra, 1997). It is likely that the large, open channel characteristics of the Middle Snake would show a greater response to variations in solar and long-wave radiation compared to smaller well shaded streams (Chapra, 1997; Cristea and Burges, 2010). Where determination of meteorological model input parameters are concerned, it is important to consider spatial distances from data monitoring sites as well as potential microclimate influences resulting from features such as deep vertical canyons that may affect shading and air temperature (Benyahya, 2010). Climate change models now afford us the ability to reasonably predict future meteorological conditions. When coupled with outputs from climate change models, temperature models can be used to predict the likely effects of future climate change on stream temperatures (Gooseff et al., 2005; Cristea and Burges, 2008). In fact, the growing concern about potential ecological consequences of climate change on aquatic systems has sparked widespread application of temperature models in efforts to predict the thermal future of many streams (Norton and Bradford, 2009; Martins et al., 2011; Gooseff et al., 2005).

3.4.2. Hydrology

Hydrology can strongly influence the thermal regimes of large rivers (Chapra, 1997). The influences of mainstem and tributary streamflow, velocity, as well as the relative temperatures of each are often major contributors to downstream temperature conditions (Chapra, 1997). For purposes of constructing a temperature model, it is important to account for the hydrologic contributions from upstream mainstem river sources, tributary and agricultural drains, and ground/surface water interactions. In the Middle Snake, the abundance of surface and groundwater spring inflows contribute significantly to shaping the thermal patterns of the river in this hydrologically complex reach (U.S. EPA, 2001; Baldwin, et al. 2006). This spring-water influence adds a great deal of complexity to the development of a model with respect to flow accounting for dispersed groundwater and surface water contributing sources. Additionally, these springs originate from discrete aquifer flowages that differ in temperature signatures (Baldwin et al., 2006). Much of the land area surrounding the Middle Snake is utilized for agriculture and as such there are substantial surface and subsurface flow contributions from irrigation returns. Irrigation returns are difficult to account for in model development due to their erratic flow patterns and high temperature variability. Perhaps a more dominant hydrologic feature of this system is the 5 reservoirs located within the Middle Snake. While the reservoirs are considered run of river, with very short retention times and little to no thermal stratification (Myers, et al., 1995), they do exhibit different hydrologic characteristics (*e.g*. channel slope, width, velocities) than do the free flowing reaches (U.S. EPA, 2001).

The above described spring source inflows to the Middle Snake River have been decreasing by approximately 30 cubic feet per second (cfs) annually over the last 17 years as a result of groundwater pumping, precipitation patterns, and agricultural practices, with similar trends predicted in the future (Blew and Bowling, 2009). How these spring inflow reductions will affect temperature in the Middle Snake is unknown. Temperature modeling has been performed with good success under similar scenarios where water is diverted from a river or in situations where tributary inflows are decreasing (Meier et al., 2003). The thermal regime of the Middle Snake suggests that reduced spring inflows would lead to decreased winter temperatures and increased summer temperatures as a result of reduced spring inflows. A properly calibrated model may reveal the magnitude of these expected temperature effects in the Middle Snake.

Inter-annual and seasonal streamflow conditions in the Middle Snake are highly variable and are primarily the result of the timing of runoff events and agriculture needs (U.S.EPA, 2001). However, Snake River streamflows are also governed by reservoir hydroelectric operations and the timed release of augmentation flows to facilitate the outmigration of salmon downstream of the Middle Snake (U.S.EPA, 2001; IPCO, 2009). Recent proposals to release relatively large volumes of reservoir water downstream to the Middle Snake have been met with uncertainty from resource regulators, not due to known deleterious temperature effects, but rather because the effects are simply unknown (IDEQ letter, 2010; U.S. D of I letter, 2010). A suitable temperature model may help reveal the likely temperature effects of reservoir operations, or other actions, and potentially assist in guiding management decisions.

4. Research Questions and Objectives

The proposed study seeks to elucidate on several questions pertaining to the calibration and use of a temperature model for the Middle Snake. Such questions include: can temperature be effectively modeled in this complex system with the selected model, and how does river temperature respond to changes in tributary flow and temperature, or river headwater flow parameters? If the calibrated model results in a reasonable prediction of temperature then it will be considered sufficient for addressing research objective 2. Considering these questions and existing knowledge of the system, the primary objectives of this research are to: **1) Calibrate QUAL2Kw model for reasonable prediction of Middle Snake river temperature for a 1-day synoptic event occurring on the date of historic daily mean maximum river temperature, 2) Evaluate the sensitivity of river temperature to river headwater flow, spring tributary flow, surface tributary (i.e. non-spring) temperature, and surface tributary flow, and 3) Identify information gaps that may affect model performance**.

5. METHODS

5.1. General Information

The study was conducted from February, 2011 through May, 2012, with field data collection occurring in June-August, 2011. Data collection was focused on the date of historic daily mean maximum temperature at Milner Reservoir outflow in order to evaluate river temperature during the most critical period for coldwater biota. The evaluation was limited to a single 24-hour period as dictated by the selected model. The mean and median date of historic daily mean maximum temperature at Milner Reservoir outflow occurs on August 3rd; therefore, we focused data collection efforts on this date. Due to time limitations and the broad geographic study area, field data was collected from August 1st-3rd. Data collected on 8/1 and 8/2 were used as surrogates for the 8/3/2011 analysis.

5.2. Site Information

5.2.1. Access and Documentation

Several private landowners, municipalities, and fish hatcheries were contacted in order to obtain tributary site access, data, or both. River and tributary sites were documented using a Trimble GeoXT® GPS unit along with photo points (**Figures A-1 and A-2**).

5.2.2. River Sites

Reconnaissance visits were made to the 10 identified reach node locations to determine the feasibility of deploying and recovering temperature loggers. All river sites with the exception of Twin Falls inflow were bank accessible. The Twin Falls inflow site was accessed via boat. River temperature and streamflow data collection locations are shown in **Figures 1, 2, A-3 and Table 1**.

5.2.3. Tributary Sites

Tributaries for which temperature and streamflow data were obtained are summarized in **Table A-7** by model reach**.** All tributary sites were located within 0.5 miles from the inflow to the river in efforts to reduce variability between the point of measure and conditions at the inflow to the river. Continuous temperature data were collected on several major surface tributaries (**Table A-1**) in order to capture the diel temperature cycle, thus increasing model input resolution. These continuous temperature loggers were recovered on August 16th-18th. Temperature was assumed to be relatively constant in spring tributaries compared to surface tributaries; therefore, surface tributaries were given priority for collecting 24-hour temperature data and only instantaneous temperatures were collected on spring sources due to resource limitations (**Table A-1**). Instantaneous streamflow measurements were collected for tributaries where gage data were not available (**Table A-1**).

5.3. Data Collection

5.3.1. Temperature Data

Continuous temperature data in both river and tributary sampling locations were collected using HOBO Water Temp Pro V2® temperature data loggers set to record in 30 minute intervals. Temperature loggers were deployed at each node location several weeks prior to 8/3/2011. As a precautionary measure, return visits were made to these sites a few days prior to 8/3 to verify that the loggers had remained in the water, avoided vandalism, and remained functional. All temperature loggers were recovered on August 16th-18th. NIST certified thermometer measures were collected at the time of logger deployment and recovery as a quality assurance measure. A single point measure with the NIST thermometer was used to collect instantaneous temperatures in identified tributaries that did not contain continuous data loggers. Lateral temperature variation at river temperature data collection sites was not measured; however, these data loggers were in located in areas of the river that were visually well mixed and not directly subjected to major spring influences from upstream sources. Measured river temperatures are assumed to be representative of river conditions. Temperature data types (i.e. continuous or instantaneous) for respective tributaries are shown in **Table A-1**. Additionally, fish hatcheries located at Blue Lakes outflow, Crystal Springs, Niagara Springs, and Clear Lakes outflow, as well as the Twin Falls wastewater treatment plant were contacted in order to obtain information on effluent temperature and flow. River and tributary temperature data are summarized in **Table A-2**.

5.3.2. Streamflow Data

River streamflow data were obtained from USGS and Idaho Power operated gages. The mean daily streamflow measured at each gage on August 3rd was used for model input. These mean values were used as the representative steady-state flow condition as required by the model for achieving streamflow balance, despite daily flow variability that approached 1,200 cfs at some gaged locations due to reservoir operations. Fish hatcheries provided streamflow data for Blue Lakes outflow, Billingsley Creek, Crystal Springs, Niagara Springs, Briggs Creek, and Clear Lakes (**Table A-1**). An Idaho Power Company operated gage was used to obtain streamflow data for the Malad River (**Table A-1**). The City of Twin Falls provided streamflow data for the Twin Falls Waste Water treatment facility. Where gage data were not available a Marsh-McBirney Flowmate 2000® flow meter was used to collect tributary streamflow information. Channel width and depth criteria were used to determine the necessary number of velocity measurements for in-field flow data collection (**Table A-3**). Time constraints necessitated a lower resolution approach to in-field streamflow data collection, where on many occasions the combined interval width, depth, and velocity accounted for >10% of the total streamflow. Streamflow data types (i.e. gage or instantaneous) for tributaries are shown in **Table A-1**. Streamflows for river and tributary sites are summarized in **Table A-4**.

5.3.3. Meteorological Data

Meteorological data that included air temperature, dew point temperature, wind speed, and solar radiation parameters were drawn from USBOR Agrimet weather reporting stations in Twin Falls and Glenn's Ferry, Idaho (**Tables A-5 and A-6**). As noted in the parameter estimation section, data values for all meteorological parameters were interpolated for reaches located in between reporting stations with values from Twin Falls being applied to all reaches located upstream of Shoshone Falls.

5.3.4. Channel Width and Depth

Channel width information was obtained through use of the Idaho Power Enviroviewer® mapping tool. Bathymetric data provided by Idaho Power Company was used to estimate river channel depth, specifically, at locations above and below hydroelectric dams. National Geographic TOPO® software was used to estimate channel elevations where bathymetric data were not available. Individual reaches were divided into 5 equidistant segments, yielding points of measure for channel width within each reach. The averages of these measures within each reach were used as the reach boundary condition. Initial measures were performed at, or near the head of each reach, after which measures were made at the aforementioned equidistant locations to the downstream end of the reach.

5.4. QUAL2Kw Water Quality Model

The temperature model selected for use in this study was the QUAL2Kw stream network temperature and water quality model developed by the U.S. EPA. This model was selected for use due to its public availability, user-friendly Microsoft Excel interface, and ability to handle discrete and diffuse source inflows affecting heat-flux. QUAL2Kw is a one-dimensional, steady-state model that assumes vertically and horizontally mixed conditions. Typical of deterministic models, QUAL2Kw uses components of heat-flux to predict a dynamic heat budget for a 24-hour diurnal period. The model is calibrated by adjusting input parameters to achieve optimal agreement between measured data and model output. The QUAL2Kw framework includes the following elements:

- One dimensional. The channel is well-mixed vertically and laterally.
- Branching. The system can consist of a mainstem river with branched tributaries.
- Steady state hydraulics. Non-uniform, steady flow is simulated.
- Diel heat budget. The heat budget and temperature are simulated as a function of meteorology on a diel time scale.
- Heat and mass inputs. Point and non-point loads and withdrawals are simulated.

5.4.1. Model Construction

Due to the longitudinal distance of river being modeled, the model dictated that the Middle Snake be divided into multiple reaches, each with discrete boundary conditions. Based on these model requirements, we divided the Middle Snake River into 9 individual reaches **(Figures 1 and 2, Table 1)**. Measured or calculated data were used for all input parameters where possible. However, for many parameters the necessary data were unavailable or sparse in nature. Assumptions were made to fill data gaps for required model inputs when data were unavailable or limited.

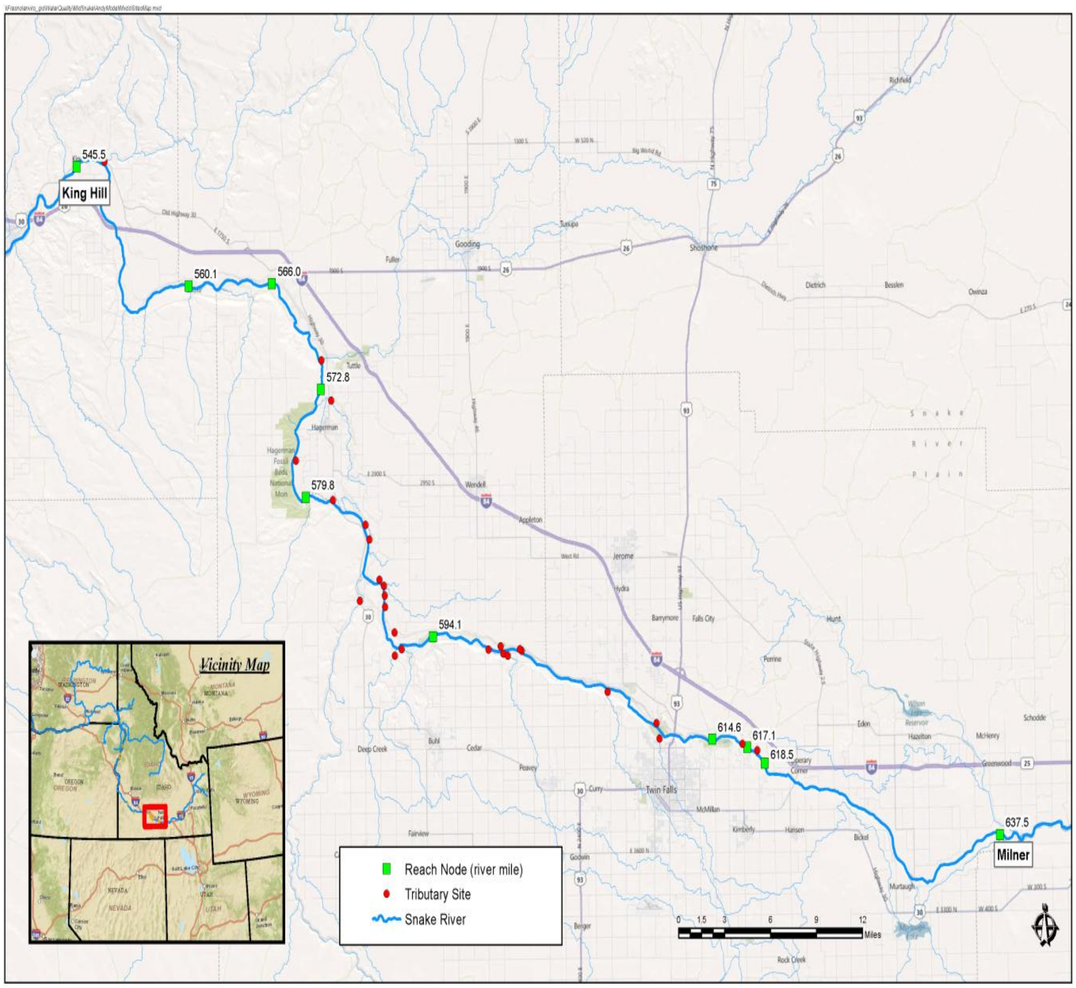


Figure 1
Study area map from Milner to King Hill, Idaho, indicating river reach nodes for individual reaches, described in river miles, and tributary sampling locations. Aquaculture operations for which flow and temperature data were obtained are not shown on map.

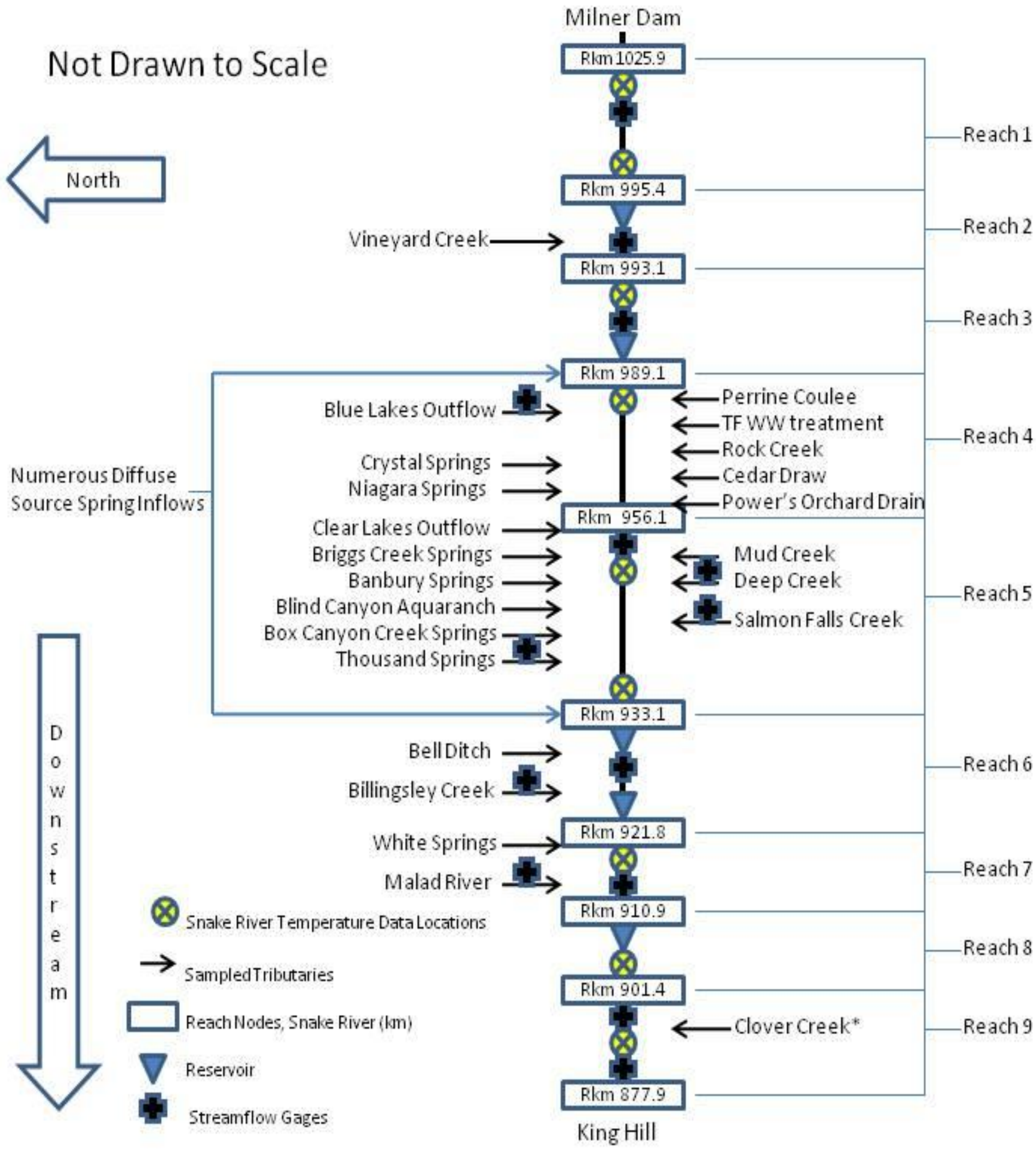


Figure 2

Schematic diagram of the Middle Snake indicating locations of river reaches and nodes, reservoirs, major inflows, and river temperature and streamflow data collection sites. The asterisk indicates that Clover Creek flows in from the north. Aquaculture operations for which flow and temperature data were obtained are not indicated in this diagram, nor are diffuse spring and surface inflows that occur along the extent of the study area.

Table 1
Individual reaches described in Snake River kilometers, and associated location descriptions.

Reach	Reach Boundaries (River km)	Reach description
1	Rkm 1025.9 to 995.4	Milner dam to Twin Falls inflow
2	Rkm 995.4 to 993.1	Twin Falls inflow to Twin Falls outflow
3	Rkm 993.1 to 989.1	Twin Falls outflow to Shoshone outflow
4	Rkm 989.1 to 956.1	Shoshone outflow to Buhl
5	Rkm 956.1 to 933.1	Buhl to Upper Salmon Falls Inflow
6	Rkm 933.1 to 921.8	Upper Salmon Falls Inflow to Lower Salmon Falls Outflow
7	Rkm 921.8 to 910.9	Lower Salmon Falls Outflow to Bliss Inflow
8	Rkm 910.9 to 901.4	Bliss Inflow to Bliss Outflow
9	Rkm 901.4 to 877.9	Bliss Outflow to King Hill

5.4.2. Model Inputs

Model inputs include the parameters shown in **Table 2**.

Table 2
Model input parameters by major category.

	Parameter		Parameter		Parameter
General	date	Physical	channel azimuth/aspect	Temperature	temperature-groundwater
	duration of simulation		Manning's N		temperature-tributaries
	elevation-upstream		reach length		temperature-water upstream
	elevation-downstream		bank slope		temperature-air
	latitude		bed slope		
	longitude		channel width		
	time zone		channel depth		
Flow	discharge-tributary		channel shade		
	discharge upstream/downstream	Weather	relative humidity		
	flow velocity		percent sun/clouds		
	ground/surface water flux		solar radiation		
	travel time		wind speed		

5.5. Parameter Estimation for Model Calibration

Baseline conditions were established for all general, physical, streamflow, and model input parameters based on available measured information, and assumptions where needed. Time sensitive flow, temperature, and meteorological information were used to coincide with the date of model validation occurring on August 3rd. Model validation was performed using the established (e.g. channel geometry) and timing-sensitive (*e.g.* flow and climate) baseline information. Model output temperature results from validation runs were compared to measured data at the 9 reach nodes. Discrepancies between model temperature output and measured temperature data were addressed by adjusting input parameter values within probable limits until model results were reasonably similar to measured data.

5.5.1. Flow Balance

Preliminary model runs suggested that the volume and temperature of inflow sources was likely to substantially affect river temperature relative to many other input parameters. Even with an extensive effort to collect and obtain flow and temperature information for tributary sources there were substantial discrepancies in the between-node river streamflow balance which was not accounted for by our available tributary data. Further, the amount of water diverted from the river for irrigation purposes was unknown. Flow balance resolution was addressed by generally evaluating the hydrologic characteristics of individual model reaches. Mapping resources, collected data, and observations during field data collection were used to qualitatively guide the proportional assignment of diffuse spring and surface inflow contributions by reach. That is, reaches with greater amounts of measured spring inflows, relative to surface inflows, were assigned a higher proportion of diffuse spring contributions. Conversely, reaches with greater surface to spring inflows were assigned relatively more non-spring diffuse inflow contributions. The diffuse spring and surface source flow contributions assigned to model reaches for achievement of river streamflow balance are shown in **Table 3**.

Table 3

Spring and surface diffuse flows as assigned to model for achievement of river flow balance at reach node locations. Flows are reported in cubic meters per second. Relative percent contributions for diffuse inflows combine to equal the flow discrepancy. Measured inflow and flow balance discrepancy combine to equal the total of all inflows to each respective reach.

Reach Node Location	Measured Inflows to Reach (m^3/s)	Flow Balance Discrepancy (m^3/s)	% Diffuse Surface Flows (m^3/s)	% Diffuse Spring Flows (m^3/s)
Twin Falls inflow	0	8.9	60% (5.32)	40% (3.55)
Twin Falls outflow	0.2	0	NA	NA
Shoshone outflow	0	0	NA	NA
Buhl	22.9	21.8	60% (13.1)	40% (8.73)
Upper Salmon outflow	48.1	35.2	20% (7.05)	80% (28.14)
Lower Salmon outflow	3.4	0	NA	NA
Bliss inflow	37.1	6.8	20% (1.36)	80% (5.45)
Bliss outflow	0	0	NA	NA
King Hill	0.1	11.2	20% (2.25)	80% (9.98)

5.5.2. Temperature

Temperatures for unmeasured spring and surface flows used to achieve river flow balance were established by taking average values from measured data. Average temperature for all measured spring inflows from Milner to King Hill was 15.6°C with a range of 14.6-17.0°C. Rather than utilizing the mean spring temperature, a temperature of 16°C was applied to all diffuse spring inflow sources to capture some level of additional warming that occurs as diffuse sources flow across heated basalt, or, warming that occurs in hatchery effluent settling ponds. Average surface tributary temperature for all reaches combined was 20.8°C. This mean value was increased to 22°C for diffuse surface tributary model inputs, based on the assumption that many of these unmeasured surface inflow sources were comprised agriculture return drains that have substantially elevated temperature due to overland flow and conveyance through small ditches and canals.

5.5.3. Meteorology

Due to linear distance between climate reporting stations, solar radiation, air temperature, dew point temperature, and wind speed data were interpolated for reaches located in between the Glenn's Ferry and Twin Falls reporting stations, and data from Twin Falls were applied to all reaches located upstream of Twin Falls. Reported station values for wind were reduced by 1/3 for reaches located above Shoshone Falls (Rkm989.1) to account for likely lower wind speed within these deep canyon sections.

5.5.4. Hydraulic model

In the absence of rating curves, Manning's equation was utilized as the hydraulic model in QUAL2Kw. Based on guidance from the QUAL2Kw user manual (Pelletier and Chapra, 2008), and considering the substrate, slope, sinuosity, and vegetation components of the Middle Snake, a Manning's roughness coefficient of 0.040 was used for model calibration.

5.5.5. Reservoirs

Reservoirs were accounted for by incorporating the QUAL2Kw feature for weirs. For reaches with dams at the downstream boundary, weirs were constructed by using the average channel width for the reach, essentially creating a dam that spans the entire channel width. Weir height was determined by subtracting the spillway elevation from the forebay channel bed elevation.

5.6. Evaluation of Calibrated Model Performance

The degree to which the calibrated model outputs represent measured data was assessed by a straightforward evaluation of minimum, maximum, and mean temperature differences between observed and predicted temperature. Additionally, the root-mean-square error (RMSE), which is a function of the relationship between observed and predicted temperatures and differences between the two (Caissie, et al., 2007; Willmott, et al., 1985) was used to evaluate temperature discrepancies between observed and predicted values occurring at the same time step to elucidate on diel temperature shifts that are not sufficiently addressed by comparing minimum, maximum, and mean temperature differences.

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{N} (O_i - P_i)^2}{N}}$$

Where N is the number of daily temperature observations, O is the observed temperature, and P is the predicted water temperature. As the model produces predicted temperatures on an hourly basis these values were compared to corresponding hourly measured data; therefore, N=24 for evaluation of each reach.

5.7. Temperature Sensitivity Model Simulations

Following model calibration, simulations were performed to test the sensitivity of river temperature to several probable temperature affecting factors. Specific parameters of interest were adjusted to evaluate river temperature sensitivity to the respective parameter, with all other calibrated model baseline parameters remaining unadjusted. Parameters for which sensitivity simulations were performed include; headwater river flow, spring tributary flow, surface tributary (i.e. non-spring) temperature, and surface tributary flow. Additionally, initial model runs suggested that the temperature effects from the probable influential factors were less influential than expected, likely as a result of exceptionally high river flows that occurred during the study period. Therefore, we performed sensitivity scenarios for select parameters under a baseline condition that represented the 20 year median flow at Milner. The performed sensitivity scenario model simulations are described below.

5.7.1. Headwater River Flow

River flow sensitivity simulations were performed by increasing and decreasing flow to conditions to represent the 10, 25, 75, and 90th percentiles of historic flows based on a 20 year period of record at Milner dam.

5.7.2. Spring Tributary Flow

Spring tributary flow sensitivity simulations were performed by reducing spring origin tributary flows by 5, 10, and 20% below the baseline condition. The spring flow parameter alterations were uniformly applied to discrete and diffuse sources over the entire length of modeled reaches from Milner to King Hill.

5.7.3. Non-Spring Tributary Temperature

Non-spring tributary temperature sensitivity simulations were performed by decreasing tributary temperatures by 1 and 2^{o}C below baseline conditions for discrete and diffuse non-spring sources. The non-spring tributary temperature parameter alterations were uniformly applied to discrete and diffuse sources over the entire length of modeled reaches from Milner to King Hill.

5.7.4. Non-Spring Tributary Flow

The non-spring tributary flow sensitivity simulation was performed by decreasing flows by 25% below baseline conditions for non-spring discrete source tributaries and diffuse sources combined. The non-spring tributary flow parameter alterations were uniformly applied to discrete and diffuse sources over the entire length of modeled reaches from Milner to King Hill.

5.7.5. Median Headwater Flow Baseline Condition

Using a baseline condition of the 20 year median flow at Milner dam, sensitivity simulations were performed for 2^{o}C non-spring surface tributary temperature reduction, 20% spring tributary flow reduction, and 25% non-spring surface tributary flow reduction scenarios.

6. RESULTS

6.1. Model Calibration

The calibrated baseline model generally showed good agreement between measured and predicted values as indicated by predicted model outputs for mean temperature showing a maximum difference of 0.64^{o}C from measured data, for all reaches. Based on these findings we considered the calibrated model baseline to be sufficiently optimized in moving forward with parameter sensitivity scenario model runs, and, that QUAL2Kw is likely to be an appropriate tool for temperature modeling in this system. Despite close agreement, the model consistently under predicted temperatures, particularly the daily maximums, for all reaches. The observed diel temperature flux exceeded the predicted flux at most reach node locations with the exceptions of Buhl, Bliss inflow, and King Hill, which had slightly greater predicted flux than was observed.

Graphical model output for predicted and corresponding observed temperatures is shown in **Figure 3**. Model calibration results are summarized in **Figure 4, Table 4.** Model outputs for river water balance, velocity, and depth were each within the plausible bounds of expected conditions (**Figures A-3 to A-5**). The model appeared to substantially over predict river travel times (**Figure A-6**) when compared to independently calculated results produced using HEC-RAS modeling and measured flows between dams. QUAL2Kw predicted travel times from Milner to Bliss were approximately 1.8 and 5.4 times greater than HEC-RAS and measured results, respectively.

Temperature differences were statistically evaluated by using the root mean square error (RMSE), which indicated agreement within 0.5^{o}C between observed and predicted temperature for all reach node locations with the exception of Buhl (0.65^{o}C) (**Table 5**).

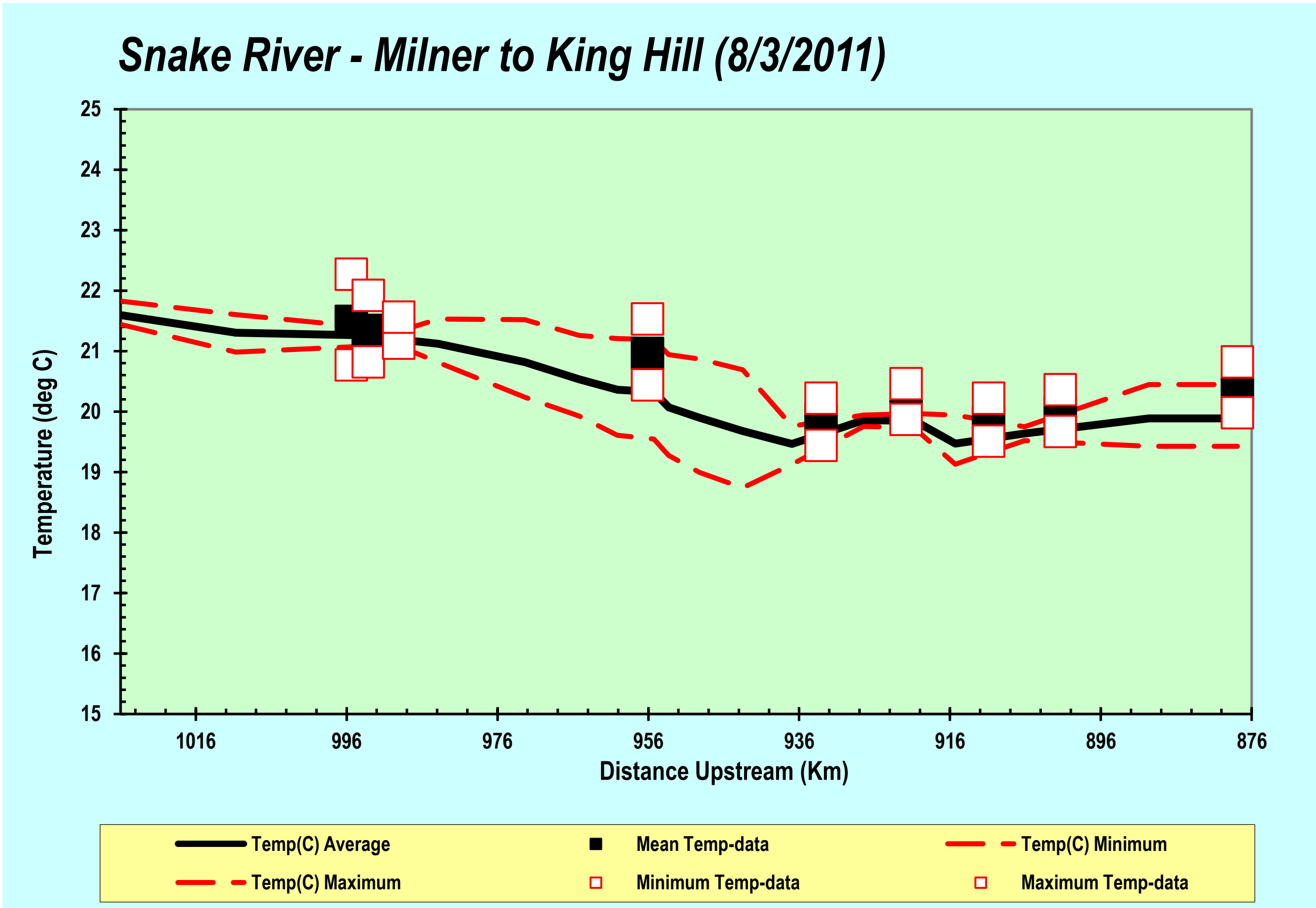


Figure 3
Model output plot indicating minimum, maximum, and mean predicted temperatures. Box plot points indicate the minimum, maximum, and mean observed temperatures. The observed temperature at river kilometer 995.4 represents the reach node at Twin Falls inflow, with points extending downstream at each reach node to King Hill (river km 877.9).

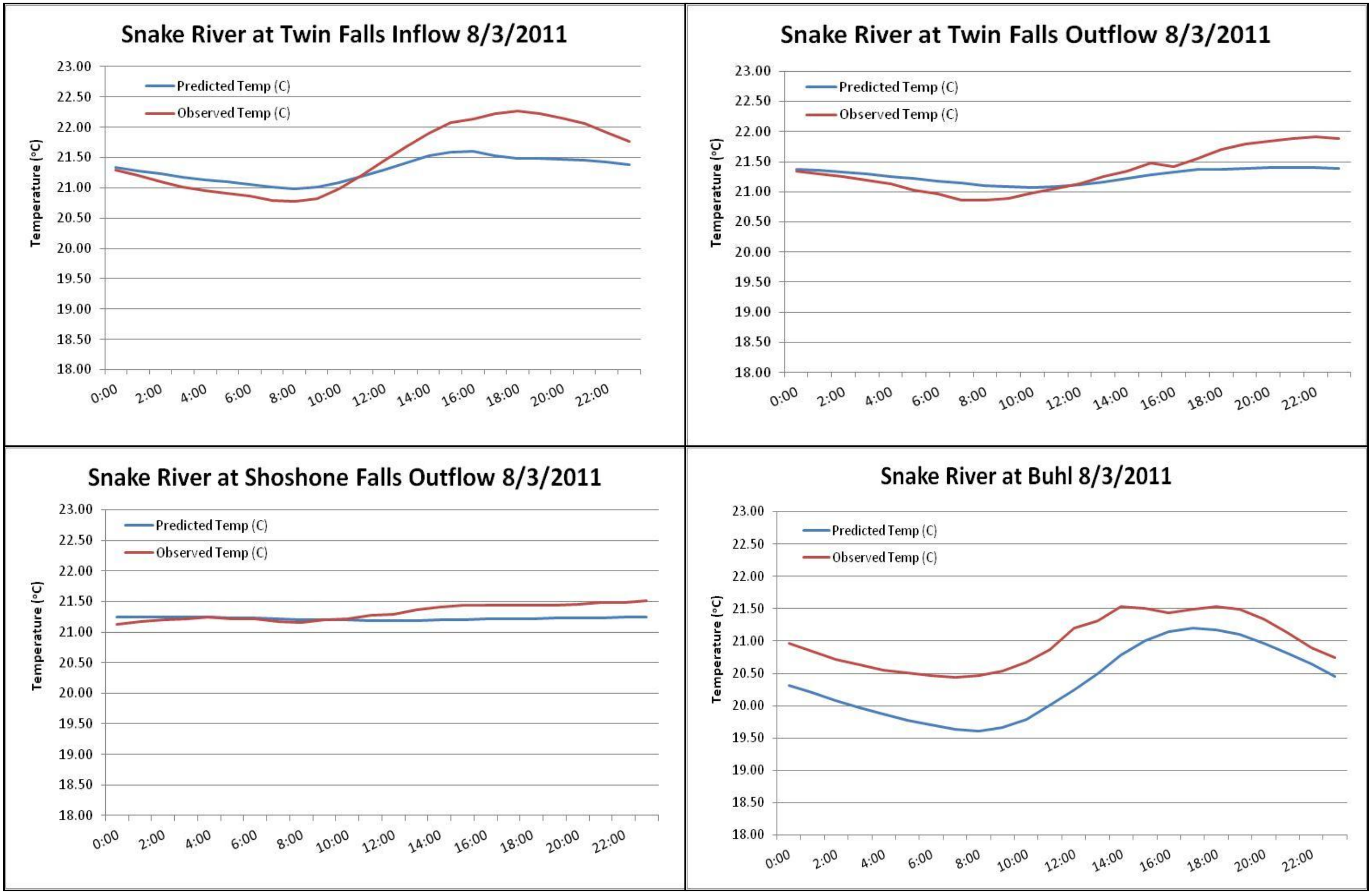


Figure 4
Comparison of model output predicted temperature and observed temperature by Snake River reach node location.

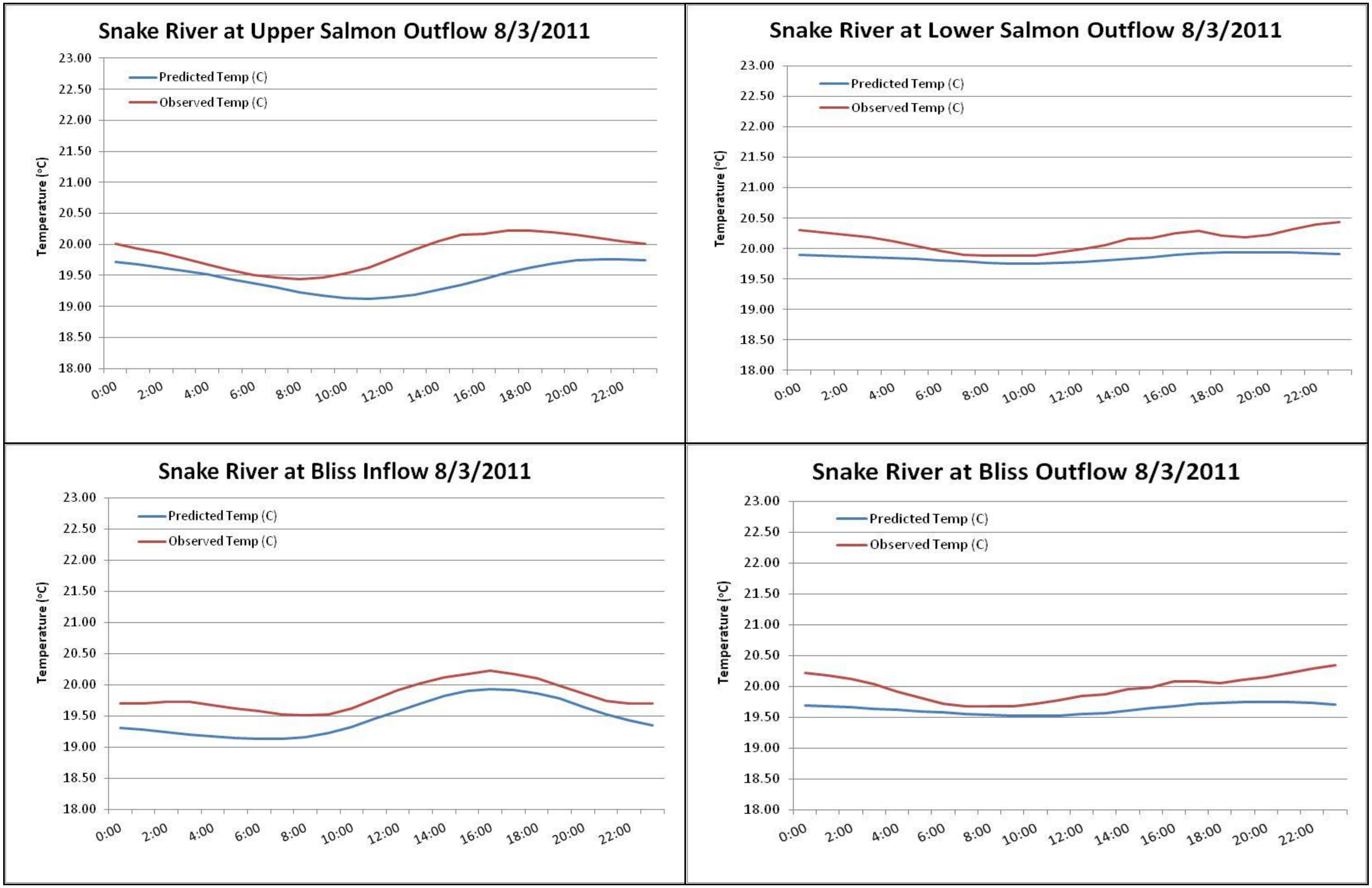


Figure 4

Comparison of model output predicted temperature and observed temperature, by Snake River reach node location.

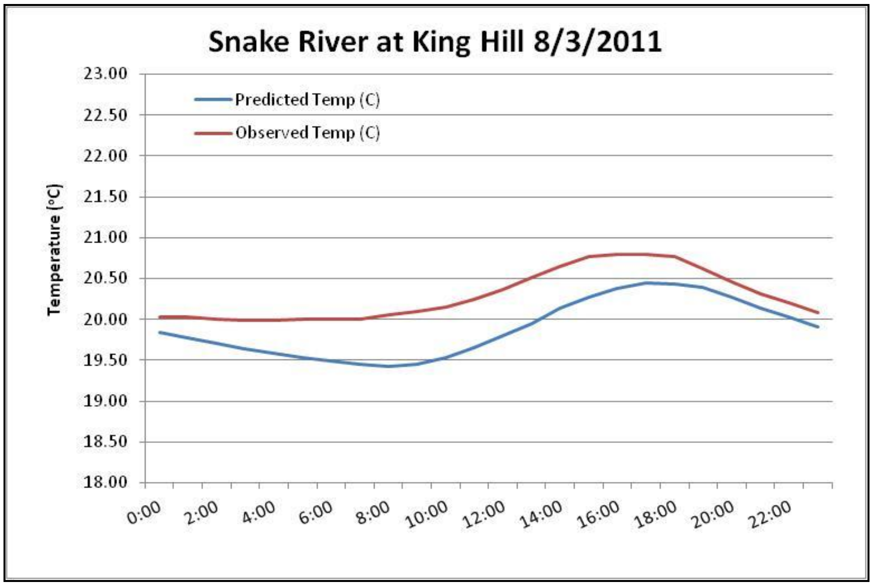


Figure 4
Comparison of model output predicted temperature and observed temperature, by Snake River reach node location.

Table 4

Summary of results for model baseline predicted temperatures, observed temperatures, and the difference between the two. Negative values for temperature difference indicate an under prediction of temperature, positive values indicate an over prediction.

			Predicted	
Downstream end of Reach	**Location River (km)**	**Temp(C) Average**	**Temp(C) Minimum**	**Temp(C) Maximum**
Twin Falls inflow	995.4	21.27	20.96	21.58
Twin Falls outflow	993.1	21.24	21.05	21.38
Shoshone Falls outflow	989.1	21.19	21.16	21.22
Buhl	956.1	20.32	19.57	21.16
Upper Salmon outflow	933.1	19.44	19.10	19.73
Lower Salmon outflow	921.8	19.83	19.73	19.92
Bliss reservoir inflow	910.9	19.45	19.11	19.92
Bliss reservoir outflow	901.4	19.62	19.50	19.73
King Hill	877.9	19.87	19.41	20.43
			Observed	
Downstream end of Reach	**Location River (km)**	**Temp(C) Average**	**Temp(C) Minimum**	**Temp(C) Maximum**
Twin Falls inflow	995.4	21.49	20.77	22.27
Twin Falls outflow	993.1	21.34	20.82	21.92
Shoshone Falls outflow	989.1	21.32	21.13	21.56
Buhl	956.1	20.96	20.44	21.53
Upper Salmon outflow	933.1	19.87	19.44	20.22
Lower Salmon outflow	921.8	20.14	19.87	20.46
Bliss reservoir inflow	910.9	19.81	19.51	20.22
Bliss reservoir outflow	901.4	19.98	19.67	20.36
King Hill	877.9	20.29	19.98	20.82
			Temperature Difference	
Downstream end of Reach	**Location River (km)**	**Temp(C) Average**	**Temp(C) Minimum**	**Temp(C) Maximum**
Twin Falls inflow	995.4	-0.22	0.19	-0.69
Twin Falls outflow	993.1	-0.10	0.23	-0.54
Shoshone Falls outflow	989.1	-0.13	0.03	-0.34
Buhl	956.1	-0.64	-0.87	-0.37
Upper Salmon outflow	933.1	-0.43	-0.34	-0.49
Lower Salmon outflow	921.8	-0.31	-0.14	-0.54
Bliss reservoir inflow	910.9	-0.36	-0.40	-0.30
Bliss reservoir outflow	901.4	-0.36	-0.17	-0.63
King Hill	877.9	-0.42	-0.57	-0.39

Table 5
Calculated root mean square errors for evaluation of difference between predicted and observed temperature.

Location	RMSE (^oC)
Twin Falls inflow	0.40
Twin Falls outflow	0.26
Shoshone outflow	0.16
Buhl	0.65
Upper Salmon outflow	0.46
Lower Salmon outflow	0.31
Bliss inflow	0.35
Bliss outflow	0.37
King Hill	0.43

6.2. Temperature Sensitivity Scenario Simulations

6.2.1. Headwater River Flow

Sensitivity simulations of the 10, 25, 75, and 90th percentiles of historic flows at the Milner headwater indicate a river temperature decrease from model baseline for all headwater flow scenarios, at all reach node locations (**Figure 5, Table 6**). Mean temperatures at the Twin Falls inflow decreased by 2.3, 1.92, 0.43, and 0.09^{o}C, respectively, for the above scenarios. Mean temperatures at Buhl decreased by 1.73, 1.69, 0.88, and 0.25^{o}C, respectively, for the above scenarios. Mean temperatures at King Hill decreased by 0.54, 0.53, 0.39, and 0.15^{o}C, respectively, for the above scenarios. The greatest temperature decreases occurred at Twin Falls outflow under 10th and 25th percentile flow scenarios. Mean, minimum, and maximum temperatures at Twin Falls outflow decreased by 2.43, 2.39, and 2.45^{o}C, respectively, under the 10th percentile scenario, and 2.06, 2.03, and 2.07^{o}C, respectively, under the 25th percentile scenario. The greatest temperature decreases occurred at Buhl under the 75th percentile scenario, where mean, minimum, and maximum temperatures decreased by 0.88, 1.22, and 0.61^{o}C, respectively. The greatest mean and maximum temperature decrease of 0.26^{o}C occurred at Upper Salmon under the 90th percentile flow scenario, with the greatest minimum temperature decrease of 0.35^{o}C occurring at Buhl.

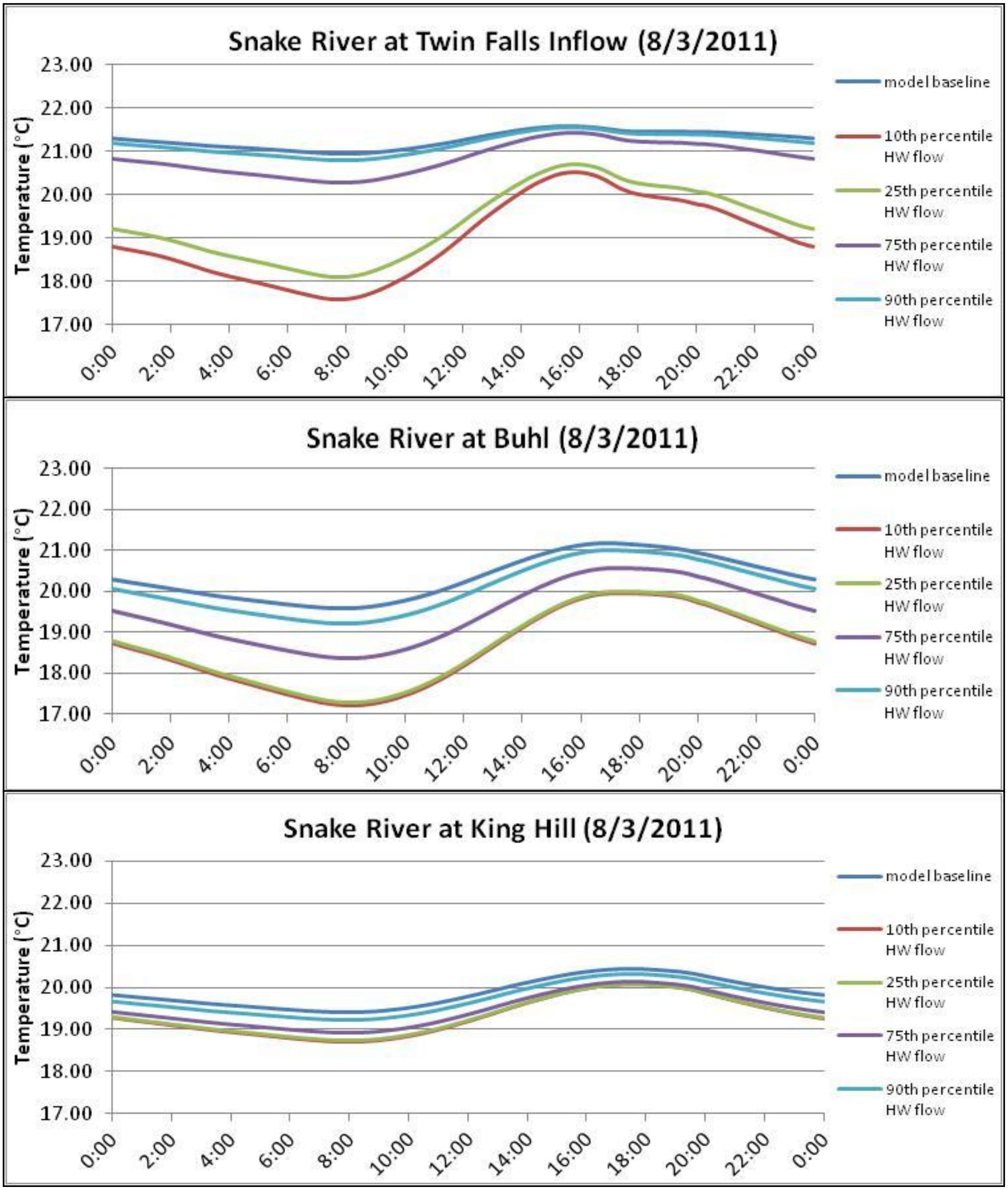


Figure 5

Summary of river headwater flow scenarios for 10th, 25th, 75th, and 90th percentile flow conditions, based on 20 year flow record at Milner dam. Simulation results are shown for Twin Falls inflow, Buhl, and King Hill reach node locations.

Table 6

Summary of results for 10th, 25th, 75th, and 90th percentile river headwater flow scenarios, and comparison with model baseline predicted temperatures. Negative values for temperature difference indicate a reduction of temperature for the given scenario, and positive values indicate a temperature increase. River flow percentiles based on 20 years of record at Milner.

Scenario: 10th Percentile HW Flow		Model Scenario			Model Baseline			Difference from Model Baseline		
Downstream End of Reach	Location River (km)	Temp(C) Average	Temp(C) Minimum	Temp(C) Maximum	Temp(C) Average	Temp(C) Minimum	Temp(C) Maximum	Temp(C) Average	Temp(C) Minimum	Temp(C) Maximum
Twin Falls inflow	995.380	18.98	17.58	20.53	21.27	20.96	21.58	-2.30	-3.38	-1.04
Twin Falls outflow	993.130	18.81	18.66	18.92	21.24	21.05	21.38	-2.43	-2.39	-2.45
Shoshone Falls outflow	989.100	19.51	19.47	19.57	21.19	21.16	21.22	-1.68	-1.69	-1.65
Buhl	956.110	18.59	17.21	19.96	20.32	19.57	21.16	-1.73	-2.36	-1.21
Upper Salmon outflow	933.100	18.14	17.79	18.44	19.44	19.10	19.73	-1.30	-1.31	-1.29
Lower Salmon outflow	921.830	18.99	18.88	19.10	19.83	19.73	19.92	-0.84	-0.85	-0.82
Bliss inflow	910.890	18.58	18.08	19.28	19.45	19.11	19.92	-0.87	-1.03	-0.64
Bliss outflow	901.390	18.90	18.77	19.02	19.62	19.50	19.73	-0.72	-0.73	-0.71
King Hill	877.900	19.33	18.72	20.07	19.87	19.41	20.43	-0.54	-0.68	-0.36
Scenario: 25th Percentile HW Flow		**Model Scenario**			**Model Baseline**			**Difference from Model Baseline**		
Downstream End of Reach	**Location River (km)**	**Temp(C) Average**	**Temp(C) Minimum**	**Temp(C) Maximum**	**Temp(C) Average**	**Temp(C) Minimum**	**Temp(C) Maximum**	**Temp(C) Average**	**Temp(C) Minimum**	**Temp(C) Maximum**
Twin Falls inflow	995.380	19.35	18.11	20.72	21.27	20.96	21.58	-1.92	-2.85	-0.86
Twin Falls outflow	993.130	19.18	19.02	19.30	21.24	21.05	21.38	-2.06	-2.03	-2.07
Shoshone Falls outflow	989.100	19.56	19.54	19.61	21.19	21.16	21.22	-1.63	-1.63	-1.61
Buhl	956.110	18.64	17.27	19.98	20.32	19.57	21.16	-1.69	-2.29	-1.19
Upper Salmon outflow	933.100	18.16	17.82	18.46	19.44	19.10	19.73	-1.27	-1.28	-1.27
Lower Salmon outflow	921.830	19.00	18.89	19.11	19.83	19.73	19.92	-0.83	-0.84	-0.81
Bliss inflow	910.890	18.59	18.09	19.28	19.45	19.11	19.92	-0.86	-1.02	-0.64
Bliss outflow	901.390	18.91	18.78	19.02	19.62	19.50	19.73	-0.71	-0.72	-0.70
King Hill	877.900	19.33	18.73	20.07	19.87	19.41	20.43	-0.53	-0.68	-0.36

Table 6

Summary of results for 10th, 25th, 75th, and 90th percentile river headwater flow scenarios, and comparison with model baseline predicted temperatures. Negative values for temperature difference indicate a reduction of temperature for the given scenario, and positive values indicate a temperature increase. River flow percentiles based on 20 years of record at Milner.

Scenario: 75th Percentile HW Flow		Model Scenario			Model Baseline			Difference from Model Baseline		
Downstream End of Reach	Location River (km)	Temp(C) Average	Temp(C) Minimum	Temp(C) Maximum	Temp(C) Average	Temp(C) Minimum	Temp(C) Maximum	Temp(C) Average	Temp(C) Minimum	Temp(C) Maximum
Twin Falls inflow	995.380	20.85	20.28	21.43	21.27	20.96	21.58	-0.43	-0.68	-0.14
Twin Falls outflow	993.130	20.76	20.56	20.92	21.24	21.05	21.38	-0.47	-0.49	-0.46
Shoshone Falls outflow	989.100	20.67	20.65	20.68	21.19	21.16	21.22	-0.52	-0.51	-0.54
Buhl	956.110	19.44	18.35	20.55	20.32	19.57	21.16	-0.88	-1.22	-0.61
Upper Salmon outflow	933.100	18.64	18.30	18.94	19.44	19.10	19.73	-0.79	-0.80	-0.79
Lower Salmon outflow	921.830	19.27	19.16	19.37	19.83	19.73	19.92	-0.56	-0.57	-0.55
Bliss inflow	910.890	18.87	18.44	19.47	19.45	19.11	19.92	-0.58	-0.67	-0.45
Bliss outflow	901.390	19.12	18.99	19.24	19.62	19.50	19.73	-0.50	-0.51	-0.49
King Hill	877.900	19.47	18.93	20.14	19.87	19.41	20.43	-0.39	-0.48	-0.29
Scenario: 90th Percentile HW Flow		**Model Scenario**			**Model Baseline**			**Difference from Model Baseline**		
Downstream End of Reach	**Location River (km)**	**Temp(C) Average**	**Temp(C) Minimum**	**Temp(C) Maximum**	**Temp(C) Average**	**Temp(C) Minimum**	**Temp(C) Maximum**	**Temp(C) Average**	**Temp(C) Minimum**	**Temp(C) Maximum**
Twin Falls inflow	995.380	21.18	20.81	21.55	21.27	20.96	21.58	-0.09	-0.15	-0.02
Twin Falls outflow	993.130	21.13	20.94	21.29	21.24	21.05	21.38	-0.10	-0.11	-0.09
Shoshone Falls outflow	989.100	21.08	21.05	21.10	21.19	21.16	21.22	-0.11	-0.11	-0.12
Buhl	956.110	20.07	19.21	21.01	20.32	19.57	21.16	-0.25	-0.35	-0.16
Upper Salmon outflow	933.100	19.18	18.83	19.47	19.44	19.10	19.73	-0.26	-0.27	-0.26
Lower Salmon outflow	921.830	19.64	19.53	19.73	19.83	19.73	19.92	-0.19	-0.20	-0.19
Bliss inflow	910.890	19.25	18.88	19.76	19.45	19.11	19.92	-0.20	-0.23	-0.16
Bliss outflow	901.390	19.44	19.32	19.55	19.62	19.50	19.73	-0.18	-0.18	-0.18
King Hill	877.900	19.72	19.23	20.32	19.87	19.41	20.43	-0.15	-0.18	-0.11

6.2.2. Spring Tributary Flow

Sensitivity simulations for the spring tributary flow parameter indicate a river temperature increase from model baseline conditions for 5, 10, and 20% spring tributary flow reduction scenarios at all reach node locations (**Figure 6, Table 7**). Mean temperatures at Twin Falls inflow increased by 0.01, 0.01, and 0.03^{o}C, respectively, for the above scenarios. Mean temperatures at Buhl increased by 0.04, 0.08, and 0.17^{o}C, respectively, for the above scenarios. Mean temperatures at King Hill increased by 0.09, 0.18, and 0.37^{o}C, respectively, for the above scenarios. The greatest effects under all scenarios were observed at King Hill, where mean, minimum, and maximum temperatures increased 0.37, 0.34, and 0.41^{o}C, respectively, under the 20% spring flow reduction scenario.

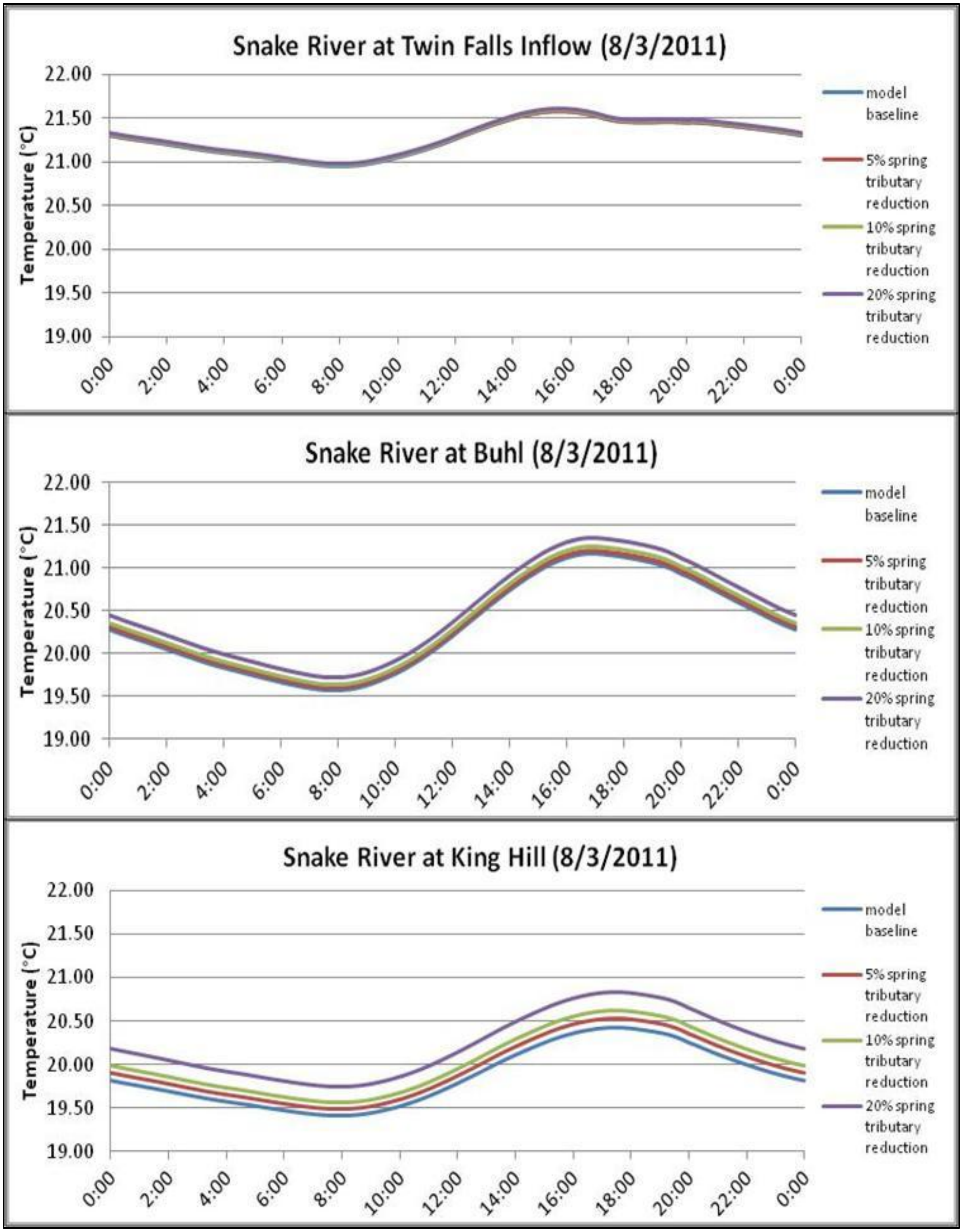


Figure 6
Summary of results for 5, 10, and 20% spring-source flow reduction scenarios, and comparison with model baseline predicted temperatures. Simulation results are shown for Twin Falls inflow, Buhl, and King Hill reach node locations.

Table 7

Summary of results for 5, 10, and 20% spring-source flow reduction scenarios, and comparison with model baseline predicted temperatures. Negative values for temperature difference indicate a reduction of temperature for the given scenario, and positive values indicate a temperature increase.

Scenario: 5% Spring Flow Reduction		Model Scenario			Model Baseline			Difference from Model Baseline		
Downstream End of Reach	Location River (km)	Temp(C) Average	Temp(C) Minimum	Temp(C) Maximum	Temp(C) Average	Temp(C) Minimum	Temp(C) Maximum	Temp(C) Average	Temp(C) Minimum	Temp(C) Maximum
Twin Falls inflow	995.380	21.28	20.96	21.58	21.27	20.96	21.58	0.01	0.01	0.01
Twin Falls outflow	993.130	21.24	21.06	21.38	21.24	21.05	21.38	0.01	0.01	0.01
Shoshone Falls outflow	989.100	21.20	21.17	21.23	21.19	21.16	21.22	0.01	0.01	0.01
Buhl	956.110	20.36	19.60	21.21	20.32	19.57	21.16	0.04	0.04	0.05
Upper Salmon outflow	933.100	19.51	19.17	19.80	19.44	19.10	19.73	0.07	0.07	0.07
Lower Salmon outflow	921.830	19.90	19.80	19.99	19.83	19.73	19.92	0.07	0.07	0.08
Bliss inflow	910.890	19.53	19.19	20.00	19.45	19.11	19.92	0.08	0.08	0.08
Bliss outflow	901.390	19.70	19.58	19.81	19.62	19.50	19.73	0.08	0.08	0.08
King Hill	877.900	19.95	19.49	20.52	19.87	19.41	20.43	0.09	0.08	0.10
Scenario: 10% Spring Flow Reduction		**Model Scenario**			**Model Baseline**			**Difference from Model Baseline**		
Downstream End of Reach	**Location River (km)**	**Temp(C) Average**	**Temp(C) Minimum**	**Temp(C) Maximum**	**Temp(C) Average**	**Temp(C) Minimum**	**Temp(C) Maximum**	**Temp(C) Average**	**Temp(C) Minimum**	**Temp(C) Maximum**
Twin Falls inflow	995.380	21.29	20.97	21.59	21.27	20.96	21.58	0.01	0.01	0.02
Twin Falls outflow	993.130	21.25	21.06	21.39	21.24	21.05	21.38	0.02	0.01	0.02
Shoshone Falls outflow	989.100	21.21	21.18	21.23	21.19	21.16	21.22	0.01	0.01	0.01
Buhl	956.110	20.40	19.64	21.26	20.32	19.57	21.16	0.08	0.07	0.09
Upper Salmon outflow	933.100	19.58	19.24	19.88	19.44	19.10	19.73	0.14	0.14	0.15
Lower Salmon outflow	921.830	19.98	19.88	20.07	19.83	19.73	19.92	0.15	0.15	0.15
Bliss inflow	910.890	19.61	19.27	20.09	19.45	19.11	19.92	0.16	0.16	0.17
Bliss outflow	901.390	19.78	19.67	19.90	19.62	19.50	19.73	0.17	0.17	0.17
King Hill	877.900	20.04	19.57	20.62	19.87	19.41	20.43	0.18	0.16	0.20
Scenario: 20% Spring Flow Reduction		**Model Scenario**			**Model Baseline**			**Difference from Model Baseline**		
Downstream End of Reach	**Location River (km)**	**Temp(C) Average**	**Temp(C) Minimum**	**Temp(C) Maximum**	**Temp(C) Average**	**Temp(C) Minimum**	**Temp(C) Maximum**	**Temp(C) Average**	**Temp(C) Minimum**	**Temp(C) Maximum**
Twin Falls inflow	995.380	21.30	20.98	21.61	21.27	20.96	21.58	0.03	0.03	0.03
Twin Falls outflow	993.130	21.27	21.08	21.41	21.24	21.05	21.38	0.03	0.03	0.03
Shoshone Falls outflow	989.100	21.22	21.19	21.25	21.19	21.16	21.22	0.03	0.03	0.03
Buhl	956.110	20.49	19.72	21.36	20.32	19.57	21.16	0.17	0.15	0.19
Upper Salmon outflow	933.100	19.73	19.39	20.03	19.44	19.10	19.73	0.30	0.29	0.30
Lower Salmon outflow	921.830	20.14	20.04	20.24	19.83	19.73	19.92	0.32	0.31	0.32
Bliss inflow	910.890	19.79	19.44	20.28	19.45	19.11	19.92	0.34	0.33	0.36
Bliss outflow	901.390	19.97	19.85	20.08	19.62	19.50	19.73	0.35	0.35	0.35
King Hill	877.900	20.24	19.75	20.84	19.87	19.41	20.43	0.37	0.34	0.41

6.2.3. Non-Spring Tributary Temperature

Sensitivity simulations for the non-spring tributary temperature parameter indicate a river temperature decrease from model baseline conditions for the 1 and 2°C non-spring tributary temperature reduction scenarios at all reach node locations (**Figure 7, Table 8**). Mean temperatures at Twin Falls inflow decreased by 0.04 and 0.08°C, respectively, for the above scenarios. Mean temperatures at Buhl decreased by 0.13 and 0.26°C, respectively, for the above scenarios. Mean temperatures at King Hill decreased by 0.12 and 0.24°C, respectively, for the above scenarios. The greatest effects under both scenarios were observed at Upper Salmon, where mean, minimum, and maximum temperatures decreased by 0.30°C.

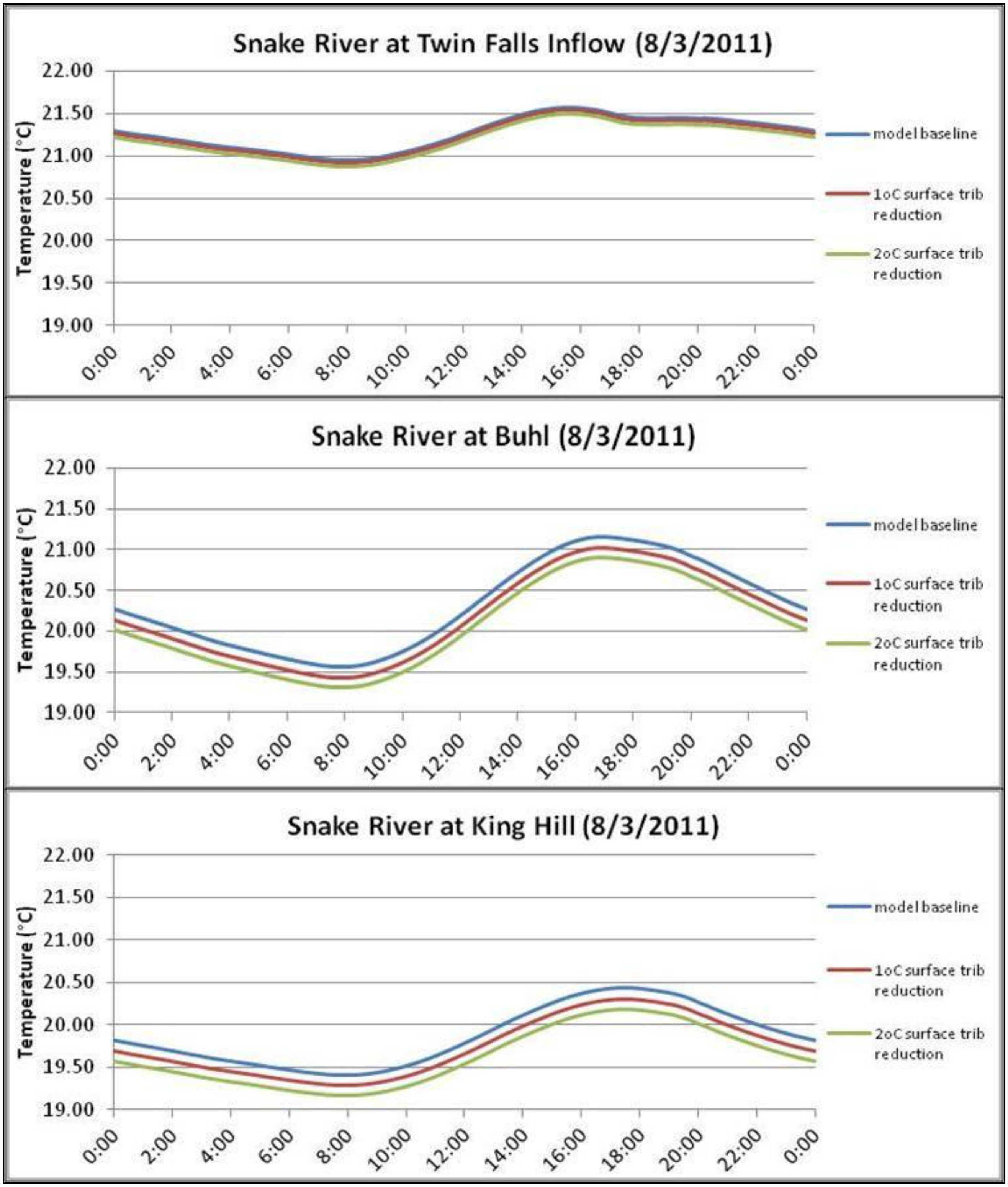


Figure 7
Summary of results for 1 and 2^{o}C non-spring tributary temperature reduction scenarios, and comparison with model baseline predicted temperatures. Simulation results are shown for Twin Falls inflow, Buhl, and King Hill reach node locations.

Table 8

Summary of results for 1 and 2°C non-spring surface tributary temperature reduction scenarios, and comparison with model baseline predicted temperatures. Negative values for temperature difference indicate a reduction of temperature for the given scenario, and positive values indicate a temperature increase.

Scenario: 1°C Surface Tributary Reduction		Model Scenario			Model Baseline			Difference from Model Baseline		
Downstream End of Reach	**Location River (km)**	**Temp(C) Average**	**Temp(C) Minimum**	**Temp(C) Maximum**	**Temp(C) Average**	**Temp(C) Minimum**	**Temp(C) Maximum**	**Temp(C) Average**	**Temp(C) Minimum**	**Temp(C) Maximum**
Twin Falls inflow	995.380	21.23	20.92	21.54	21.27	20.96	21.58	-0.04	-0.04	-0.04
Twin Falls outflow	993.130	21.20	21.01	21.34	21.24	21.05	21.38	-0.04	-0.04	-0.04
Shoshone Falls outflow	989.100	21.15	21.12	21.18	21.19	21.16	21.22	-0.04	-0.04	-0.04
Buhl	956.110	20.19	19.43	21.03	20.32	19.57	21.16	-0.13	-0.13	-0.13
Upper Salmon outflow	933.100	19.29	18.95	19.58	19.44	19.10	19.73	-0.15	-0.15	-0.15
Lower Salmon outflow	921.830	19.69	19.59	19.78	19.83	19.73	19.92	-0.14	-0.14	-0.14
Bliss inflow	910.890	19.33	18.99	19.80	19.45	19.11	19.92	-0.12	-0.12	-0.12
Bliss outflow	901.390	19.50	19.38	19.61	19.62	19.50	19.73	-0.12	-0.12	-0.12
King Hill	877.900	19.75	19.29	20.31	19.87	19.41	20.43	-0.12	-0.12	-0.12
Scenario: 2°C Surface Tributary Reduction		**Model Scenario**			**Model Baseline**			**Difference from Model Baseline**		
Downstream End of Reach	**Location River (km)**	**Temp(C) Average**	**Temp(C) Minimum**	**Temp(C) Maximum**	**Temp(C) Average**	**Temp(C) Minimum**	**Temp(C) Maximum**	**Temp(C) Average**	**Temp(C) Minimum**	**Temp(C) Maximum**
Twin Falls inflow	995.380	21.19	20.87	21.49	21.27	20.96	21.58	-0.08	-0.08	-0.08
Twin Falls outflow	993.130	21.15	20.97	21.29	21.24	21.05	21.38	-0.08	-0.08	-0.08
Shoshone Falls outflow	989.100	21.11	21.08	21.14	21.19	21.16	21.22	-0.08	-0.08	-0.08
Buhl	956.110	20.06	19.30	20.90	20.32	19.57	21.16	-0.26	-0.26	-0.27
Upper Salmon outflow	933.100	19.14	18.80	19.43	19.44	19.10	19.73	-0.30	-0.30	-0.30
Lower Salmon outflow	921.830	19.55	19.45	19.64	19.83	19.73	19.92	-0.28	-0.28	-0.28
Bliss inflow	910.890	19.20	18.87	19.67	19.45	19.11	19.92	-0.25	-0.24	-0.25
Bliss outflow	901.390	19.37	19.26	19.49	19.62	19.50	19.73	-0.24	-0.24	-0.24
King Hill	877.900	19.63	19.17	20.19	19.87	19.41	20.43	-0.24	-0.24	-0.24

6.2.4. Non-Spring Tributary Flow

The sensitivity simulation for the non-spring tributary flow parameter indicates a river temperature decrease from model baseline conditions for the 25% non-spring tributary flow reduction scenario at all reach node locations (**Figure 8, Table 9**). Mean temperatures at Twin Falls inflow, Buhl, and King Hill decreased by 0.01, 0.03, and 0.04^{o}C, respectively. The greatest temperature decrease occurred at Upper Salmon outflow, where mean, minimum, and maximum temperatures decreased by 0.07^{o}C.

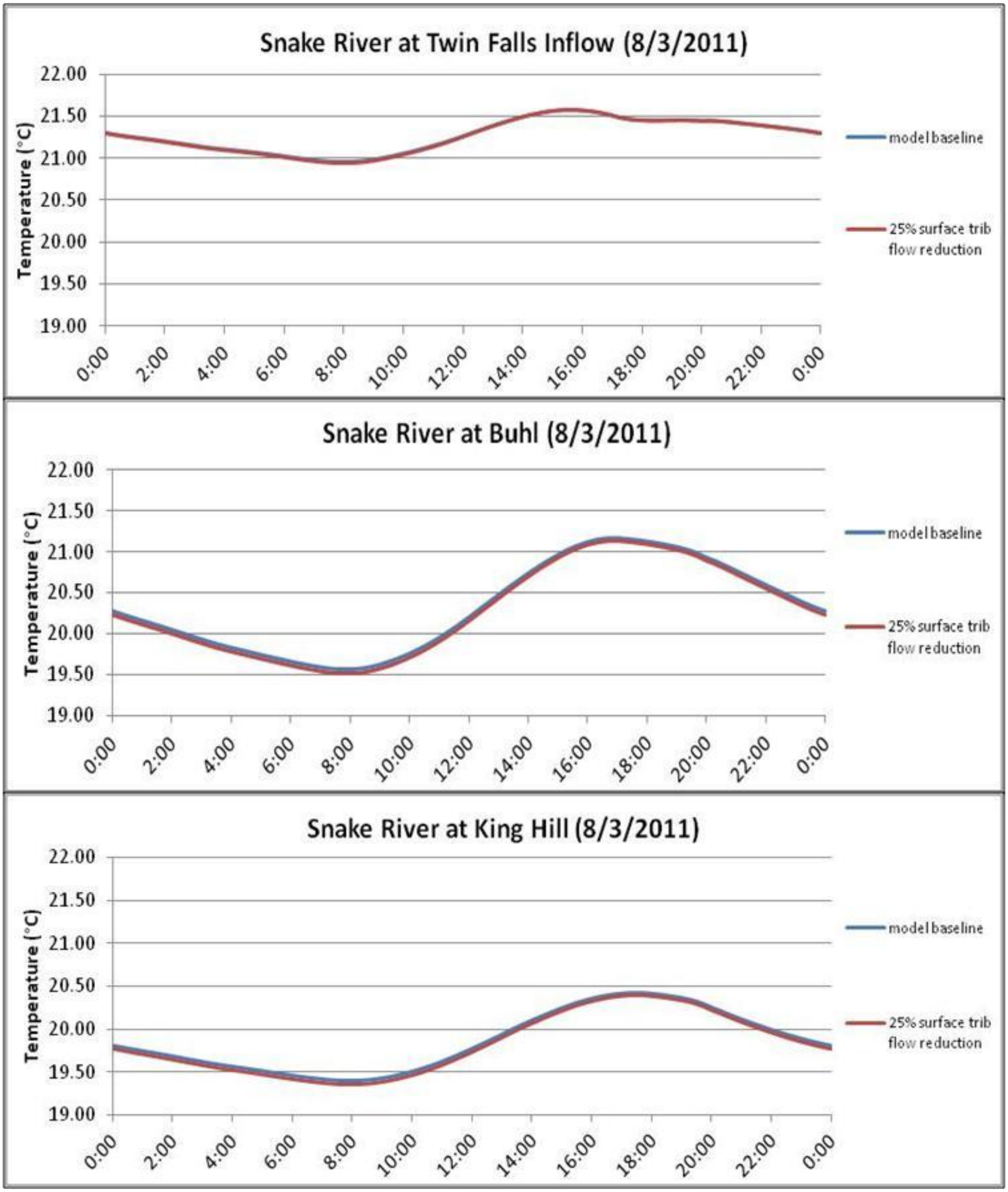


Figure 8

Summary of results for 25% non-spring tributary flow reduction scenario, and comparison with model baseline predicted temperatures. Simulation results are shown for Twin Falls inflow, Buhl, and King Hill reach node locations.

Table 9

Summary of results for 25% non-spring surface tributary flow reduction scenario, and comparison with model baseline predicted temperatures. Negative values for temperature difference indicate a reduction of temperature for the given scenario, and positive values indicate a temperature increase.

Scenario: 25% Surface Tributary Flow Reduction		Model Scenario			Model Baseline			Difference from Model Baseline		
Downstream End of Reach	Location River (km)	Temp(C) Average	Temp(C) Minimum	Temp(C) Maximum	Temp(C) Average	Temp(C) Minimum	Temp(C) Maximum	Temp(C) Average	Temp(C) Minimum	Temp(C) Maximum
Twin Falls inflow	995.380	21.27	20.95	21.57	21.27	20.96	21.58	-0.01	-0.01	-0.01
Twin Falls outflow	993.130	21.23	21.04	21.37	21.24	21.05	21.38	-0.01	-0.01	-0.01
Shoshone Falls outflow	989.100	21.19	21.16	21.21	21.19	21.16	21.22	-0.01	-0.01	-0.01
Buhl	956.110	20.29	19.52	21.14	20.32	19.57	21.16	-0.03	-0.04	-0.02
Upper Salmon outflow	933.100	19.37	19.03	19.66	19.44	19.10	19.73	-0.07	-0.07	-0.07
Lower Salmon outflow	921.830	19.78	19.68	19.87	19.83	19.73	19.92	-0.05	-0.05	-0.05
Bliss inflow	910.890	19.39	19.04	19.87	19.45	19.11	19.92	-0.06	-0.07	-0.04
Bliss outflow	901.390	19.57	19.45	19.68	19.62	19.50	19.73	-0.05	-0.05	-0.05
King Hill	877.900	19.82	19.35	20.40	19.87	19.41	20.43	-0.04	-0.06	-0.03

6.2.5. Median Headwater Flow Baseline Condition

Using a baseline condition of the 20 year median flow at Milner dam, results for the 2^{o}C non-spring surface tributary temperature reduction scenario indicates mean temperature reductions of 0.20, 0.45, and 0.29^{o}C, at Twin Falls inflow, Buhl, and King Hill, respectively. The greatest temperature reductions among all sites for the 2^{o}C non-spring tributary temperature reduction scenario occurred at Buhl. Mean temperatures for this scenario decreased by an additional 0.12, 0.18, and 0.05^{o}C at Twin Falls inflow, Buhl, and King Hill, respectively, relative to temperature reductions under the observed headwater flow scenario. These findings indicate that river temperature response from reduced non-spring tributary temperature increases with decreasing headwater flow.

The 20% spring tributary flow reduction scenario resulted in mean temperature increases of 0.07, 0.25, and 0.44^{o}C, at Twin Falls inflow, Buhl, and King Hill, respectively. The greatest mean and maximum temperature increases for the 20% spring tributary flow reduction scenario occurred at King Hill, with a maximum temperature increase of 0.50^{o}C. Minimum temperature increases for the 20% spring tributary flow reduction scenario were greatest at Bliss outflow (0.41^{o}C). Mean temperatures for this scenario increased by an additional 0.04, 0.08, and 0.07^{o}C at Twin Falls inflow, Buhl, and King Hill, respectively, relative to temperature increases under the observed headwater flow scenario. These findings indicate that river temperature response from reduced spring tributary flow increases with decreasing headwater flow.

The 25% non-spring surface tributary flow reduction scenario resulted in mean temperature decreases of 0.03, 0.11, and 0.06^{o}C, at Twin Falls inflow, Buhl, and King Hill, respectively. The greatest temperature reductions among all sites for the 25% non-spring surface tributary flow reduction scenario occurred at Upper Salmon outflow, where mean, minimum, and maximum temperatures decreased by 0.14^{o}C. Mean temperatures for this scenario decreased by an additional 0.02, 0.08, and 0.02^{o}C at Twin Falls inflow, Buhl, and King Hill, respectively, relative to temperature decreases observed under the observed headwater flow scenario. These findings indicate that river temperature response from reduced non-spring surface tributary flow increases minimally with decreasing headwater flow.

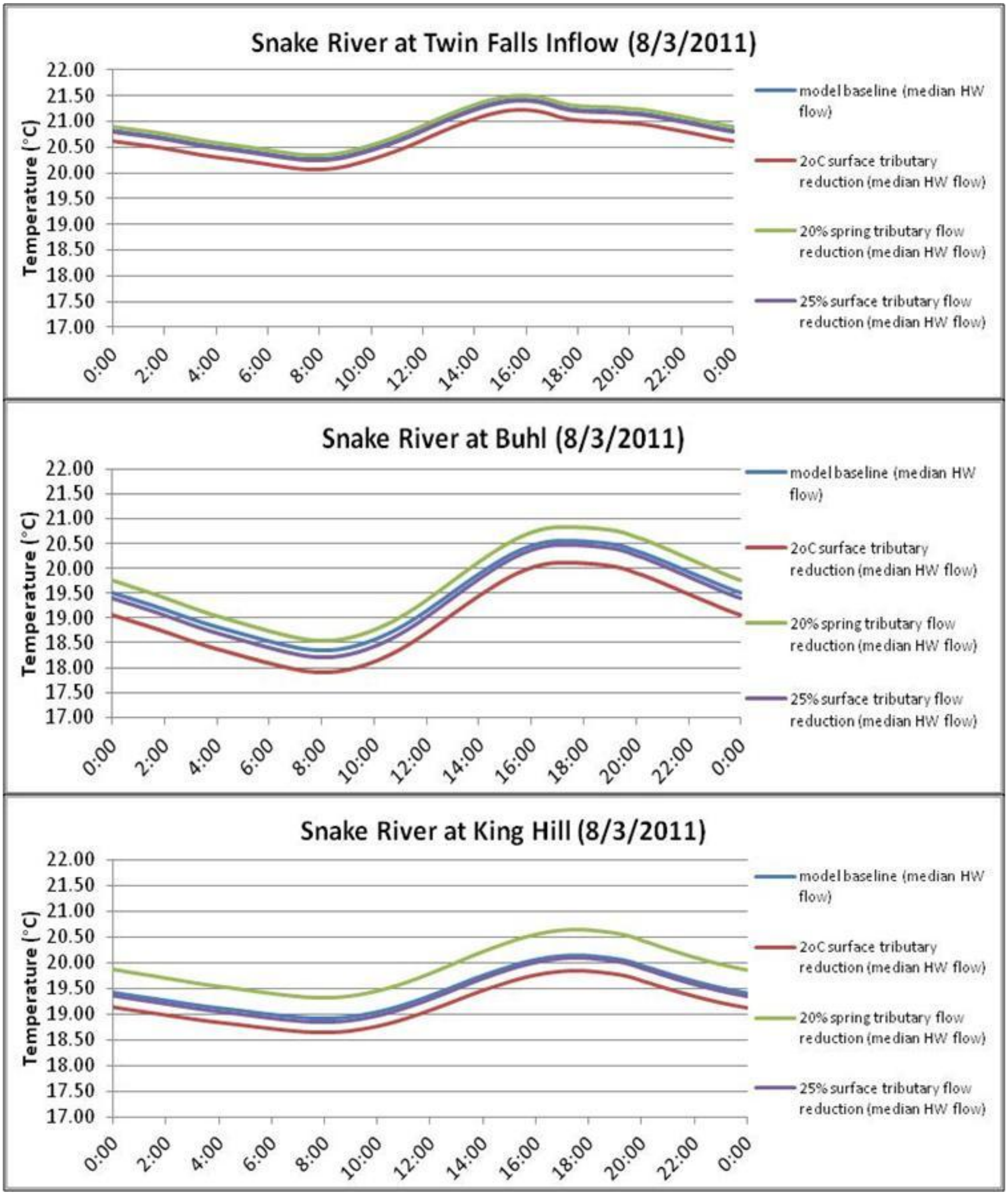


Figure 9

Summary of results for 2^{o}C surface tributary reduction, 20% spring tributary flow reduction, and 25% non-spring tributary flow reduction scenarios, and comparison with the 20 year median headwater flow model baseline predicted temperatures. Simulation results are shown for Twin Falls inflow, Buhl, and King Hill reach node locations.

Table 10

Summary of results for 2^{o}C surface tributary reduction, 20% spring tributary flow reduction, and 25% non-spring tributary flow reduction scenarios, and comparison with the 20 year median headwater flow model baseline predicted temperatures. Negative values for temperature difference indicate a reduction of temperature for the given scenario, and positive values indicate a temperature increase.

Scenario: 2^{o}C Surface Tributary Reduction (Median HW Flow)		Model Scenario			Model Baseline			Difference from Model Baseline		
Downstream End of Reach	Location River (km)	Temp(C) Average	Temp(C) Minimum	Temp(C) Maximum	Temp(C) Average	Temp(C) Minimum	Temp(C) Maximum	Temp(C) Average	Temp(C) Minimum	Temp(C) Maximum
Twin Falls inflow	995.380	20.64	20.08	21.23	20.85	20.28	21.43	-0.20	-0.20	-0.20
Twin Falls outflow	993.130	20.56	20.36	20.72	20.76	20.56	20.92	-0.20	-0.20	-0.20
Shoshone Falls outflow	989.100	20.48	20.46	20.49	20.67	20.65	20.68	-0.19	-0.19	-0.19
Buhl	956.110	18.99	17.90	20.11	19.44	18.35	20.56	-0.45	-0.44	-0.45
Upper Salmon outflow	933.100	18.24	17.90	18.54	18.64	18.30	18.94	-0.40	-0.40	-0.40
Lower Salmon outflow	921.830	18.90	18.79	19.00	19.27	19.16	19.37	-0.37	-0.37	-0.37
Bliss inflow	910.890	18.57	18.14	19.17	18.87	18.44	19.47	-0.30	-0.30	-0.30
Bliss outflow	901.390	18.83	18.70	18.94	19.12	18.99	19.24	-0.29	-0.29	-0.29
King Hill	877.900	19.19	18.64	19.85	19.47	18.93	20.14	-0.29	-0.29	-0.29
Scenario: 20% Spring Tributary Flow Reduction (Median HW Flow)		**Model Scenario**			**Model Baseline**			**Difference from Model Baseline**		
Downstream End of Reach	**Location River (km)**	**Temp(C) Average**	**Temp(C) Minimum**	**Temp(C) Maximum**	**Temp(C) Average**	**Temp(C) Minimum**	**Temp(C) Maximum**	**Temp(C) Average**	**Temp(C) Minimum**	**Temp(C) Maximum**
Twin Falls inflow	995.380	20.91	20.34	21.51	20.85	20.28	21.43	0.07	0.06	0.07
Twin Falls outflow	993.130	20.83	20.62	20.99	20.76	20.56	20.92	0.07	0.07	0.07
Shoshone Falls outflow	989.100	20.73	20.71	20.75	20.67	20.65	20.68	0.06	0.06	0.06
Buhl	956.110	19.69	18.55	20.85	19.44	18.35	20.56	0.25	0.20	0.29
Upper Salmon outflow	933.100	18.98	18.62	19.27	18.64	18.30	18.94	0.33	0.32	0.34
Lower Salmon outflow	921.830	19.65	19.54	19.76	19.27	19.16	19.37	0.39	0.38	0.39
Bliss inflow	910.890	19.25	18.79	19.89	18.87	18.44	19.47	0.38	0.35	0.42
Bliss outflow	901.390	19.53	19.40	19.64	19.12	18.99	19.24	0.41	0.41	0.41
King Hill	877.900	19.92	19.32	20.64	19.47	18.93	20.14	0.44	0.39	0.50
Scenario: 25% Surface Tributary Flow Reduction (Median HW Flow)		**Model Scenario**			**Model Baseline**			**Difference from Model Baseline**		
Downstream End of Reach	**Location River (km)**	**Temp(C) Average**	**Temp(C) Minimum**	**Temp(C) Maximum**	**Temp(C) Average**	**Temp(C) Minimum**	**Temp(C) Maximum**	**Temp(C) Average**	**Temp(C) Minimum**	**Temp(C) Maximum**
Twin Falls inflow	995.380	20.82	20.24	21.41	20.85	20.28	21.43	-0.03	-0.04	-0.02
Twin Falls outflow	993.130	20.73	20.53	20.89	20.76	20.56	20.92	-0.03	-0.03	-0.03
Shoshone Falls outflow	989.100	20.64	20.62	20.65	20.67	20.65	20.68	-0.03	-0.03	-0.03
Buhl	956.110	19.33	18.21	20.47	19.44	18.35	20.56	-0.11	-0.14	-0.08
Upper Salmon outflow	933.100	18.51	18.16	18.80	18.64	18.30	18.94	-0.14	-0.14	-0.14
Lower Salmon outflow	921.830	19.18	19.07	19.28	19.27	19.16	19.37	-0.09	-0.09	-0.09
Bliss inflow	910.890	18.78	18.33	19.40	18.87	18.44	19.47	-0.09	-0.11	-0.07
Bliss outflow	901.390	19.04	18.92	19.16	19.12	18.99	19.24	-0.08	-0.08	-0.08
King Hill	877.900	19.41	18.85	20.10	19.47	18.93	20.14	-0.06	-0.08	-0.04

7. DISCUSSION

7.1. Sources of Uncertainty/Information Gaps

We took a conservative approach with model construction, which is consistent with the idea supported by Seibert and McDonnell (2002) that it is better to have a model that is “less right, for the right reasons”, rather than being “more right, for the wrong reasons”. We achieved this by using measured data and best assumptions to populate the model, rather than adjusting parameters to extreme levels to achieve a desired level of agreement between predicted and observed values. Despite taking this approach, the study had several sources of uncertainty that were likely to affect study results. Further, the consistent under prediction of temperatures produced by the calibrated model may have resulted in conservative temperature changes as a result of sensitivity scenario parameter adjustment. That is, we might expect observed temperatures to be greater than predicted temperatures for many of the sensitivity scenarios.

7.1.1. Hydrology

Incomplete knowledge of system hydrology, including natural tributaries, agriculture returns, irrigation withdrawals from the river, and hyporheic exchange required making substantial hydrologic assumptions in efforts to achieve water flow balance.

The river travel time difference between QUAL2Kw, HEC-RAS, and measured data was a major point of uncertainty in this study. In the absence of rating curves, Manning’s equation was utilized as the hydraulic model in QUAL2Kw. Due to factors such as substrate type and aquatic plant growth, substantial error may have been associated with the Manning’s n roughness coefficient value of 0.04 that was utilized. Further, QUAL2Kw applies the input conditions for a reach node location to the entire length of river extending upstream to the next reach node. This method of calculation may have resulted in reservoir-like flow velocities from reach nodes located at dams being applied to upstream sections of river that are in fact much more riverine. It is uncertain as to which input parameter(s) offset the travel time discrepancy to result in realistic model temperature predictions. Relative to the use of Manning's equation, development of hydraulic rating curves for distinct Middle Snake River habitat types would likely improve the accuracy of flow velocity and water travel time model outputs, each of which can substantially affect water temperature.

Because the model assumes a steady-state flow condition, flow alterations from hydroelectric operations on 8/3/2011 resulted in minimum and maximum daily flow differences that approached 34 cubic meters per second, which likely affected model results.

Although river temperature data collection sites were selected in part, based on visually well-mixed conditions, cross-channel temperature differences at these locations were not evaluated; therefore, it is unknown if measured data were entirely representative of river temperatures. Future studies should attempt to avoid collecting river temperature data in locations where significant spring or non-spring inflows occur within close upstream proximity and consider assessing cross-channel temperatures to determine if in fact the data collection site is representative of overall river temperatures.

7.1.2. Sediment and Substrate

Model input values used for sediment thermal conductivity, sediment thermal diffusivity, and sediment zone thickness were estimated based on typical values for certain sediment types that were provided by the model. After performing model calibration and sensitivity scenario simulations it was recognized that inputs for these parameters had not been adjusted to desired values for some of the reaches. These values were adjusted to what is assumed to be representative of the sediment types in this system and a simulation was performed. Model output from this simulation indicated that the adjustments did not result in temperature changes greater than 0.05^{o}C for any reach. More complete knowledge of these system parameters would improve model resolution; however, the comparative results indicate that these parameters are less likely to be critical in developing a functional model relative to other factors.

7.1.3. Reservoirs

Overall, the model appeared to dampen the magnitude of diel temperature flux in reservoirs, relative to the observed conditions. Additional information on reservoir bathymetry may have improved the way the model handled reservoirs.

7.1.4. Meteorology

Because the meteorological station at Twin Falls is located at an elevation approximately 200 feet above the water surface, and considering the steep basaltic canyon that the river navigates, it is likely that there were considerable differences between the input values that were used and the actual conditions nearer the water surface. The simple incorporation of continuous air temperature loggers at select locations nearer to the water surface would likely be a substantial improvement from the air temperature data obtained from the reporting stations, especially considering the fact that air temperature is a critical factor for calculation of the river heat budget.

7.2. QUAL2Kw as an Appropriate Tool

Based on study findings we conclude that QUAL2Kw is an appropriate tool for 1-day temperature modeling applications in the Middle Snake River system. As the study was limited to a one-day event occurring during a time of historic peak river temperature, it remains unknown as to how the model would perform during times of the year with dramatically different temperature, flow, irrigation, and other environmental conditions. While model performance clearly indicates that it is a sufficient tool for conducting research, additional use of the model in this system would be prudent before it can be defensibly applied for resource management purposes.

Overall, we found the model to be very user friendly with the Microsoft Excel interface, theory manual, and user manual. Ease of use, free and public availability, and active support provided by the USEPA are all attributes that allow the novice modeler to utilize this tool.

7.3. Temperature Sensitivity Scenario Simulations

7.3.1. Headwater River Flow

Relative to all other temperature affecting factors, headwater flow appears to dominate the thermal regime of the Middle Snake River during the summer months under average to high flow conditions. Observed flow at Milner during the study period was 113.3 cubic meters per second (CMS), compared to the 20 year median flow of 37.75 CMS. Streamflow at Milner for July-August, 2011 was in the 96th percentile of historic flows; therefore, all scenarios were performed at reduced headwater flow, relative to observed conditions during the study period. Adjustment of the headwater flow parameter indicates that river temperature increases with increasing headwater flow. This finding was consistent with expectations based on knowledge of the system and previous works (USEPA, 2002), as increasing the amount of very warm river water to a system with substantial cold-water spring influence would be expected to result in a net temperature increase. During winter months it has been documented that headwater flow and temperature are inversely related, where increases in river water that is colder than spring sources results in a net decrease in river temperature (USEPA, 2002). These are important distinctions to make as common knowledge suggests that increased flows are correlated with reduced temperature; however, this is not the case in the Middle Snake River during summer months.

It was recognized that the abnormally high flows during the study period were likely dampening the temperature effects from other influential factors. Therefore, 2^{o}C non-spring surface tributary temperature reduction, 20% spring tributary flow reduction, and 25% non-spring surface tributary flow reduction scenarios were performed using the historic median headwater flow condition to represent “normal” flow conditions. The results from these simulations confirmed that there is in fact a greater temperature response to each of these factors with reduced river flow conditions. Based on this information we might expect the temperature effects of influential factors to become even further pronounced with decreasing headwater flow.

7.3.2. Spring Tributary Flow

Spring tributary flow sensitivity simulations were performed by reducing spring origin tributary flows by 5, 10, and 20% below the observed baseline condition. If the documented decreasing trends in spring tributary flow persist, the 5% (7.6cms), 10% (15.3cms), and 20% (30.5cms) reduction scenarios correspond to 9, 18, and 36 years in the future, respectively. As anticipated, the effects of decreased spring tributary flows are minimal above Buhl and more pronounced downstream of the primary areas of spring contributions. With a maximum predicted temperature increase of 0.41^{o}C at King Hill, we expected the spring tributary component to be a more dominant factor in the thermal regime of the Middle Snake. Further, the 20% spring flow reduction with median headwater flow scenario did not yield the expected degree of temperature increase, as maximum temperatures at King Hill only increased an additional 0.07^{o}C relative to results from the observed headwater flow condition. These findings are consistent with the idea that spring sources dominate the thermal regime when river headwater flow is very low and have a relatively minor effect under conditions of high headwater flow. These findings suggest that even with a 20% reduction in spring tributary flows, the remaining volume of spring water in the system continues to function as an effective thermal buffer across a wide range of river flows, with buffering capability being inversely related to river headwater flow.

7.3.3. Non-Spring Tributary Temperature

The 1 and 2^{o}C non-spring tributary temperature reduction scenarios were selected based on the idea that comparable temperature reductions may be achievable through management practices. The non-spring tributary temperature reduction of 2°C has a substantial cooling effect on river temperature. The cooling effect increases as headwater flow decreases during the summer months. Under a condition of median headwater flow, comparison of results from the 20% spring tributary flow reduction, and 2°C non-spring tributary temperature scenarios indicates that, if achievable, a 2°C reduction in non-spring tributary temperature may nearly offset the temperature increases as a result of reduced spring tributary flow. This finding was somewhat unexpected and may suggest that non-spring tributary temperature exerts more influence on river temperature than commonly thought in the spring-rich Middle Snake.

This information may serve useful in management, where meeting numeric temperature criteria and the thermal tolerances of coldwater biota are concerned. While not explicitly evaluated, these findings give rise to the idea that further increases in non-spring tributary temperature may elevate temperature in the Middle Snake to a greater degree than what might be expected.

7.3.4. Non-Spring Tributary Flow

A 25% reduction in non-spring tributary flow was selected as a scenario that could potentially occur in the future, primarily as a result of ongoing conversion to sprinkler irrigation in agriculture. River temperature showed very little response to reduction of the non-spring tributary flow component, with a predicted temperature decrease of less than 0.1°C among all sites. Comparison of the temperature effects between the non-spring tributary flow and temperature components indicates that non-spring tributary temperature has a greater influence on river temperature than non-spring tributary flow. However, this idea is likely tied to the fact that the mean river temperature at Milner was 21.59°C, with mean non-spring tributary temperatures of 20.8°C (observed discrete sources), and 22°C (estimated diffuse sources). Due to the negligible difference between river and non-spring tributary temperatures we would expect to see very little effect from adjustment of non-spring tributary flow. Based on this temperature relationship, the non-spring tributary flow component would be expected to become increasingly influential as the difference between river and non-spring tributary temperature increases.

7.4. Biological Implications

Lepla and Chandler (1995a) reported that white sturgeon spawning in the Bliss reach occurs from April-June, with an estimated egg incubation period of 5-8 days at 12-16^{o}C. Optimal temperature range for white sturgeon egg incubation is 14-16^{o}C, and temperatures above 20^{o}C are considered lethal for developing white sturgeon embryos (Wang et al., 1987). Lepla and Chandler (1995a) documented sharp temperature increases below Bliss reservoir that exceeded 18^{o}C during the egg incubation period and noted that elevated temperature during incubation may be a potential factor in limiting sturgeon recruitment.

When temperatures approach 20^{o}C during the spawning and egg incubation period, even small temperature increases have the potential to substantially impact the reproductive success of white sturgeon in the Middle Snake. This study has resulted in identification of several factors that influence temperature in this system. If future declines in the Middle Snake white sturgeon population are found to be linked to temperature, knowledge of the temperature affecting factors may prove valuable to resource managers in efforts to ensure the persistence of this population.

8. Acknowledgements

I would like to thank the many people that provided resource, study design, and field-work support for conducting this research. Idaho Power Company generously provided the resources required to perform this study. Specifically, I thank the following individuals for their direct roles in making this project come to fruition.

-Timothy Link for providing freedom in exploring research topics and project guidance

-Jack Harrison for study design, modeling support, and project guidance

-Brian Hoelscher for the research opportunity and project guidance

-Chris Larsen for field data collection

-Dain Bates for field data collection

-Janak Timilsena for HEC-RAS evaluation of river travel time

9. LITERATURE CITED

Baldwin, J., Winter, G., X. Dai. 2006. (2005) Update, Thousand Springs Area of the Eastern Snake River Plain, Idaho. Ground Water Quality Technical Report No. 27, Idaho Department of Environmental Quality.

Barko, J., Smart, M. (1981). Comparative influences of light and temperature on the growth and metabolism of selected submersed freshwater macrophytes. Ecological Monographs. 51: 219-236.

Benyahya, L., St-Hilaire, A., Ouarda, B., Bobee, B., Ahmadi-Nedushan, B. (2007). Modeling of water temperatures based on stochastic approaches: case study of the Deschutes River. Journal of Environmental Engineering Science. 6: 437-448.

Bilhimer, D., Carroll, J., O'Neal, S., Pelletier, G. (June, 2002). Quality Assurance Project Plan – Wenatchee River Temperature, Dissolved Oxygen, and pH Total Maximum Daily Load Year 1 Technical Study. Washington State Department of Ecology Environmental Assessment Program. Olympia, WA.

Blew, D., Bowling, J. (2009) Spring Discharge Calculations for the Snake River Milner to King Hill Reaches, Review of Kjelstrom Methodologies. Idaho Power. Boise, ID

Carpenter, S., Adams, M. (1979). Effects of nutrients and temperature on decomposition of Myriophyllum spicatum L. in a hard-water eutrophic lake. American Society of Limnology and Oceanography. 24-3: 520-528.

Caissie, D. (2006). The thermal regime of rivers: a review. Freshwater Biology. 51: 1389-1406.

Chapra, S. (1997). Surface Water-Quality Modeling. McGraw-Hill. New York, USA.

Coutant, C. (1999). Perspective on Temperature in the Pacific Northwest's Fresh Water. Environmental Sciences Division, Publication No. 4849, Oakridge National Laboratory. Oakridge National Laboratory, Oak Ridge, Tennessee. 109p.

Davison, I.R. (1991). Environmental effects on algal photosynthesis: temperature. Journal of Phycology. 27: 2-8.

Gooseff, M., Strzepek, K., Chapra, S. (2005). Modeling the potential effects of climate change on water temperature downstream of a shallow reservoir, Lower Madison River, MT. Climate Change. 68: 331-353.

Idaho Department of Environmental Quality (IDEQ). (April, 2010). Upper Snake Rock/Middle Snake TMDL's-5 year review. Idaho Department of Environmental Quality. Twin Falls, ID.

Idaho Department of Environmental Quality (IDEQ). (July 14, 2010). Letter Re: Section 401 Water Quality Certification for FERC No. 2899, Milner Dam Hydroelectric Project, License Amendment. Twin Falls, ID.

Idaho Department of Environmental Quality (IDEQ). Idaho State Water Quality Standards - IDAPA 58.01.02. Boise, ID

Idaho Department of Environmental Quality (IDEQ). (June, 2007). DEQ's Process for PNV TMDL's in the Upper Snake Rock Subbasin. Twin Falls, ID

Idaho Power Company. (December, 2009). Environmental Report Supplementing the Application for License Amendment – Milner Project FERC No. 2899. Idaho Power Company. Boise, ID.

Kjelstrom, L.C. (1992). Streamflow Gains and Losses in the Snake River and ground-water budgets for the Snake River Plain, Idaho and Eastern Oregon. U.S. Geological Survey Open File Report 90-172. Boise, ID.

Knight, A., Naymik, J. (January, 2009). Evaluation of Drain and Tributary Pollutant Sources to C.J. Strike-Swan Falls Reach, Snake River, Idaho. Idaho Power Company. Boise, ID.

Lepla, K., Chandler, J. (1995a). A Survey of White Sturgeon in the Bliss Reach of the Middle Snake River, Idaho. Idaho Power Company. Technical report appendix E.3.1-E of the Bliss license application.

Madsen, J., Adams, M. (December, 1989). The Light and Temperature Dependence of photosynthesis and respiration in *Potamogeton pectinatus* L. Aquatic Botany. 36-1: 23-31.

Martins, E., Hinch, S., Patterson, D., Hague, M., Cookes, S., Miller, K., Lappointe, M., English, K., Ferrel, A. (2010). Effects of river temperature and climate warming on stock-specific survival of adult migrating Fraser River sockeye salmon (*Onchorhynchus nerka*). Global Change Biology. 17: 99-114.

Meier, W., Bonjour, C., Wuest, A., Reichert, P. (August, 2003). Modeling the Effect of Water Diversion on the Temperature of Mountain Streams. Journal of Environmental Engineering. 129: 8(755).

Myers, R., Parkinson, S., Harrison, J. (March, 1998). Tributary Nutrient Loadings to the Snake River – Swan Falls to Farewell Bend, March through October, 1995. Idaho Power Company. Boise, ID.

Myers, R., Parkinson, S. (November, 1996). Water Temperature and Dissolved Oxygen Modeling of the Upper Salmon Falls, Lower Salmon Falls, and Bliss Hydroelectric Projects. Idaho Power Company. Boise, ID.

Myers, R., Pierce, S., Randolph, C. (May, 1995). Descriptive Limnological Study of the Snake River, Idaho: Buhl to King Hill. Technical Report Appendix E.2.2-A. Idaho Power Company. Boise, ID.

Norton, G., Bradford, A. (2009). Comparison of two stream temperature models and evaluation of potential management alternatives for the Speed River, Southern Ontario. Journal of Environmental Management. 90: 866-878.

Parsley, M., Beckman, L. (1993). White Sturgeon Spawning and Rearing Habitat in the Lower Columbia River. North American Journal of Fisheries Management. 14: 812-827.

Pelletier, G., Chapra, S. (July, 2008). QUAL2KWw User Manual (version 5.1)- A Modeling Framework for Simulating River and Stream Water Quality. Washington State Department of Ecology. Publication number: 08-03-xxx.

Richards, D., Misbach, N., Cazier, D., Lester, G. (1999). Habitat Preferences and Spatial Distribution of Three Snail Species: the Endangered Bliss Rapids Snail (*Taylorconcha serpenticola*), the Pebble Snail (*Fluminicola hindsii*), and the exotic New Zealand Mudsnail (*Potamopyrgus antipodarum*) in Banbury Springs, Snake River Drainage Southern Idaho, USA. Ecoanalysts, Inc. Moscow, Idaho.

Rivers-Moore, N.A. Jewitt, G.P.W. (2007). Adaptive management and water temperature variability within a South African river system: What are the management options? Journal of Environmental Management. 82: 39-50.

Rivers-Moore, N.A. Lorentz, S. (2004). A simple, physically-based statistical model to simulate hourly water temperatures in a river. South African Journal of Science. 100; 331-333.

Roth, T.R., Westoff, M.C., Huwald, H., Huff, J.A., Rubin J.F., Berrenetxea, G., Vetterli, M., Parriaux, A., Selker, J.S., Parlange, M.B. (2010). Stream Temperature Response to Three Riparian Vegetation Scenarios by Use of a Distributed Temperature Validated Model. Environmental Science Technology. 44: 2072-2078.

Siebert, J. and McDonnell, J.J.. (2002). On the dialog between experimentalist and modeler in catchment hydrology: use of soft data for multi-criteria model calibration. Water Resources Research. 38: 1231-1241.

United States Department of the Interior. (November, 2010). Comment letter Re: Notice of Application for Non-Capacity Amendment of License for the Milner Hydroelectric Project, FERC No. 2899-136; Twin Falls and Cassia Counties, Idaho. United States Department of the Interior –Office of the Secretary. Portland, OR.

U.S. EPA (Environmental Protection Agency). (2002). Ecological risk assessment for the Middle Snake River, Idaho. National Center for Environmental Assessment, Washington, DC; EPA/600/R-01/017.

Wang, Y.L., Buddington, R.K., Doroshov, S.I. (1987). Influence of temperature on yolk utilization by the white sturgeon *Acipenser Transmontanus*. Journal of Fish Biology. 30: 263-271.

Willmott, Cort J., Ackleson, Steven G., Davis, Robert E., Feddema, Johannes J., Klink, Katherine M., Legates, David R., O'Donnell, James, Rowe, Clinton M.. (September 20, 1985). Statistics for the Evaluation and Comparison of Models. Journal of Geophysical Research. 90: 8995-9005.

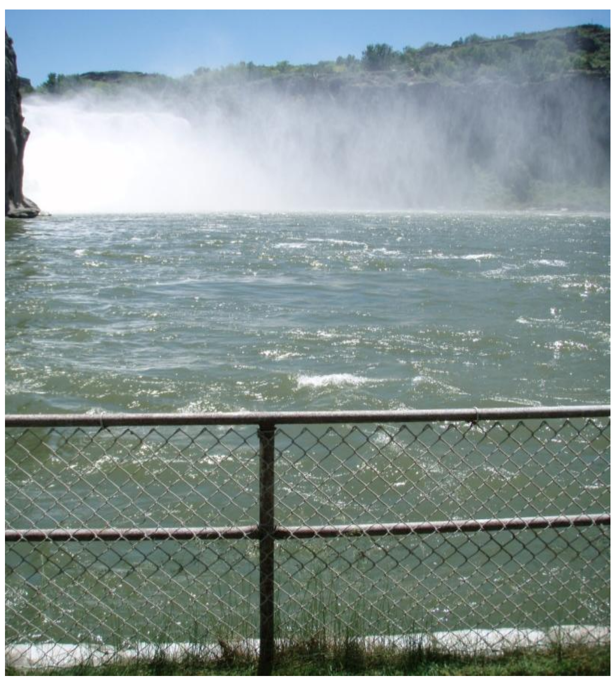
APPENDIX

Figure A-1
Snake River data collection sites

Site Name:	Snake River at Milner
UTM position:	2034480.41E 523522.41N
Snake River Mile:	637.5
Date of Photo:	6/28/2011

Site Name:	Snake River at Twin Falls inflow
UTM position:	1953418.34E 541524.88N
Snake River Mile:	618.5
Date of Photo:	6/28/2011

Site Name:	Snake River at Twin Falls outflow
UTM position:	1947331.24E 545468.20N
Snake River Mile:	617.1
Date of Photo:	6/28/2011



Site Name:	Snake River at Shoshone Falls outflow
UTM position:	1935281.75E 547523.98N
Snake River Mile:	614.6
Date of Photo:	6/28/2011

Site Name: Snake River at Buhl
UTM position: 1839040.57E 573346.23N
Snake River Mile: 594.1
Date of Photo: 6/28/2011

Site Name: Snake River at Upper Salmon Falls inflow
UTM position: 1795087.22E 608346.92N
Snake River Mile: 579.8
Date of Photo: 6/28/2011

Site Name:	Snake River at Lower Salmon Falls outflow
UTM position:	1800317.74E 635505.75N
Snake River Mile:	572.8
Date of Photo:	6/28/2011

Site Name:	Snake River at Bliss Reservoir inflow
UTM position:	1783452.42E 662122.48N
Snake River Mile:	566
Date of Photo:	7/11/2011

Site Name:	Snake River at Bliss Reservoir outflow
UTM position:	1754770.98E 661482.87N
Snake River Mile:	560.1
Date of Photo:	7/11/2011

Site Name:	Snake River at King Hill
UTM position:	1716099.19E 691544.56N
Snake River Mile:	545.5
Date of Photo:	8/4/2011

Figure A-2
Tributary data collection sites

Site Name:	Vineyard Creek
UTM position:	1950738.63E 544765.10N
Snake River Mile inflow:	618
Date of Photo:	8/2/2011

Site Name:	Perrine Coulee
UTM position:	1917055.04E 547746.62N
Snake River Mile inflow:	611
Date of Photo:	8/2/2011

Site Name:	Rock Creek
UTM position:	1899179.94E 559516.45N
Snake River Mile inflow:	606.4
Date of Photo:	8/2/2011

Site Name:	Crystal Springs-upper
UTM position:	1869491.75E 569827.72N
Snake River Mile inflow:	600.3
Date of Photo:	8/3/2011

Site Name: Crystal Springs-lower
UTM position: 1868902.66E 570209.66N
Snake River Mile inflow: 600.1
Date of Photo: 8/3/2011

Site Name: Niagara Springs
UTM position: 1862277.76E 570930.31N
Snake River Mile inflow: 599
Date of Photo: 8/3/2011

Site Name:	Cedar Draw -upper
UTM position:	1864784.16E 568570.70N
Snake River Mile inflow:	599.2
Date of Photo:	8/3/2011

Site Name:	Cedar Draw - lower
UTM position:	1863158.48E 569157.34N
Snake River Mile inflow:	599
Date of Photo:	8/3/2011

Site Name:	Unnamed-Powers Orchard
UTM position:	1858049.51E 570122.15N
Snake River Mile inflow:	598
Date of Photo:	8/3/2011

Site Name:	Briggs Creek
UTM position:	1825713.33E 574439.64N
Snake River Mile inflow:	589.9
Date of Photo:	8/3/2011

Site Name:	Banbury Springs
UTM position:	1822383.11E 580902.88N
Snake River Mile inflow:	588.8
Date of Photo:	8/3/2011

Site Name:	Mud Creek
UTM position:	1828117.04E 570280.88N
Snake River Mile inflow:	591.6
Date of Photo:	8/3/2011

Site Name:	Deep Creek
UTM position:	1825839.61E 568565.08N
Snake River Mile inflow:	591.4
Date of Photo:	8/3/2011

Site Name:	Salmon Falls Creek
UTM position:	1813717.38E 582428.28N
Snake River Mile inflow:	586
Date of Photo:	8/3/2011

Site Name:	Blind Canyon Aquaranch
UTM position:	1822353.96E 583751.37N
Snake River Mile inflow:	588.5
Date of Photo:	8/3/2011

Site Name:	Box Canyon Creek
UTM position:	1822014.80E 586205.04N
Snake River Mile inflow:	587.9
Date of Photo:	8/3/2011

Site Name: Thousand Springs-north channel
UTM position: 1815659.48E 601556.16N
Snake River Mile inflow: 583.8
Date of Photo: 8/3/2011

Site Name: Thousand Springs-south channel
UTM position: 1817027.58E 597813.43N
Snake River Mile inflow: 584.5
Date of Photo: 8/3/2011

Site Name:	Bell Ditch
UTM position:	1791710.73E 617662.42N
Snake River Mile inflow:	577.1
Date of Photo:	8/1/2011

Site Name:	Billingsley Creek
UTM position:	1803843.55E 632737.33N
Snake River Mile inflow:	573.8
Date of Photo:	8/1/2011

Site Name:	Malad River
UTM position:	1800419.26E 642938.87N
Snake River Mile inflow:	571.4
Date of Photo:	8/1/2011

Site Name:	Clover Creek
UTM position:	1725646.77E 692833.98N
Snake River Mile inflow:	547.5
Date of Photo:	8/1/2011

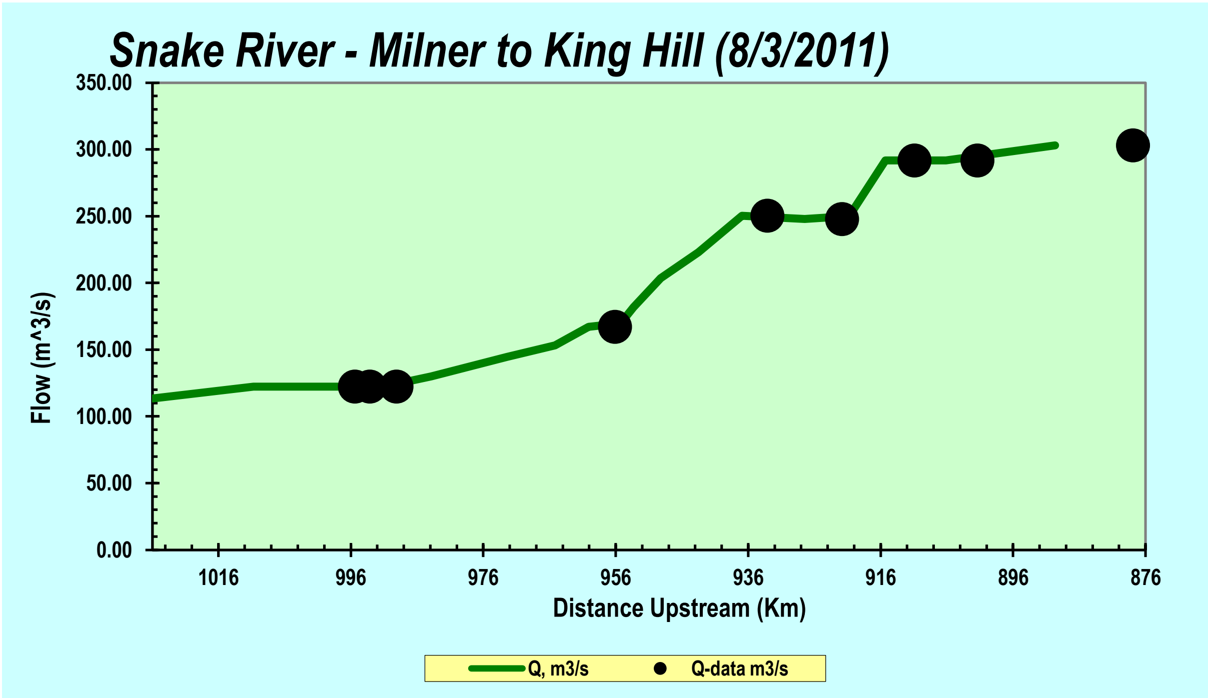


Figure A-3
Graphical model output for river streamflow balance extending from Milner to King Hill, Idaho. Black circles indicated reach node location measured flows.

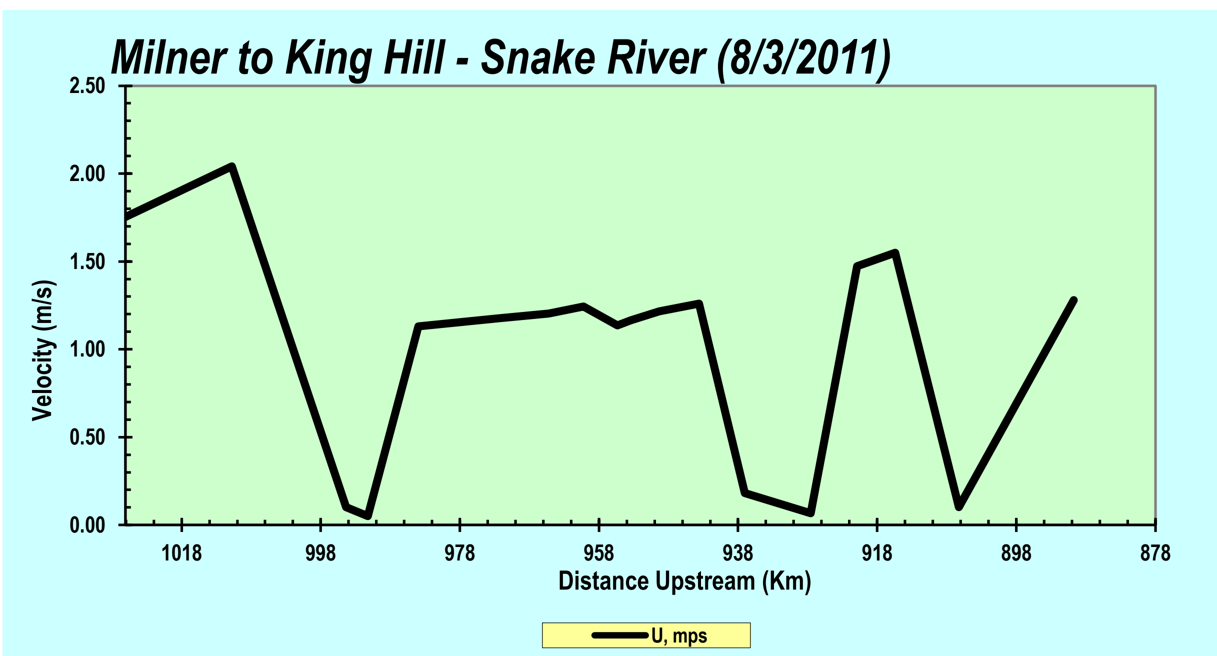


Figure A-4
Graphical model output for river flow velocity extending from Milner to King Hill, Idaho.

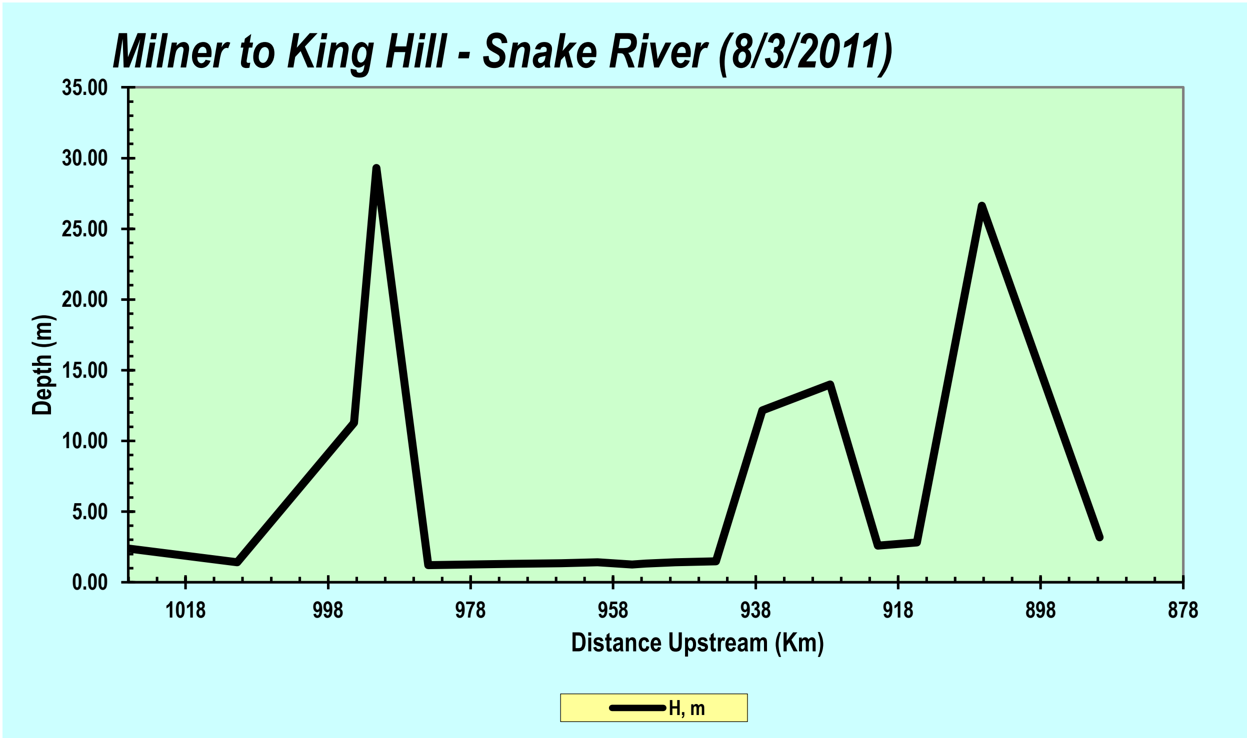


Figure A-5
Graphical model output for river depth extending from Milner to King Hill, Idaho.

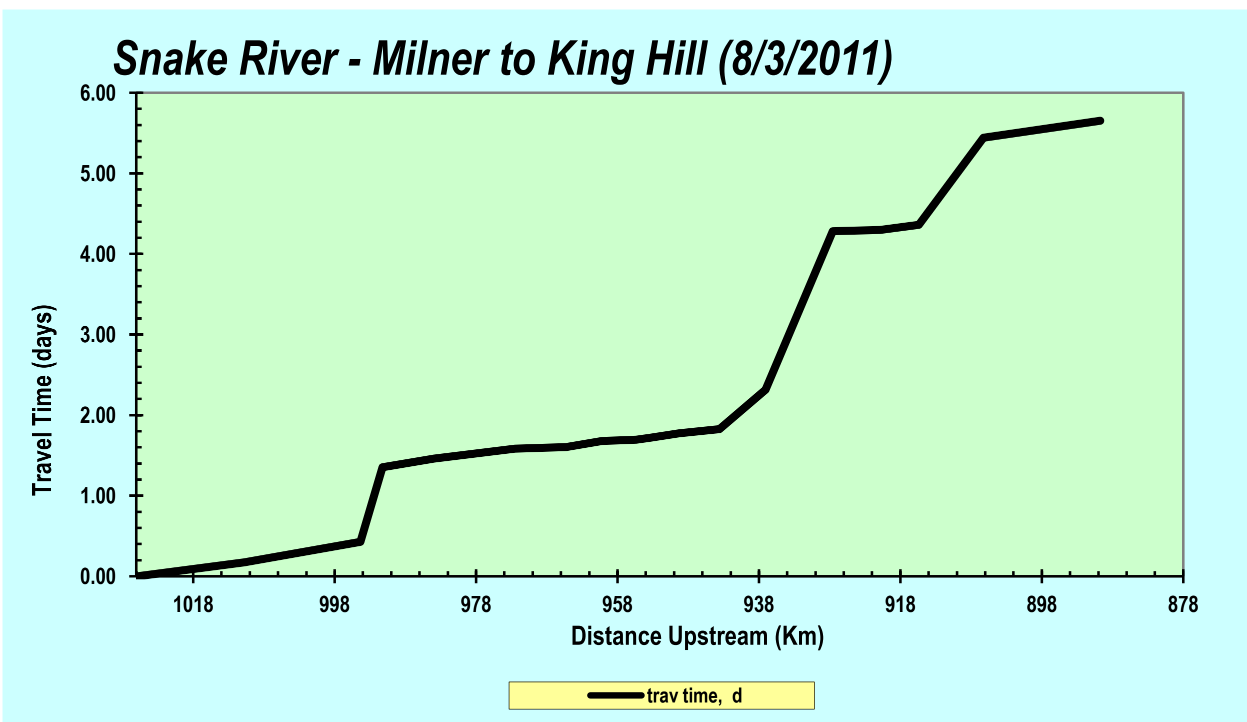


Figure A-6
Graphical model output for river travel time extending from Milner to King Hill, Idaho.

Table A-1
List of tributaries and associated data types for streamflow and temperature.

Tributary Name	Flow Data	Temperature Data
Vineyard Creek	instantaneous	instantaneous
Devils Corral	gage	instantaneous
Perrine Coulee	instantaneous	instantaneous
TF WW treatment	gage	instantaneous
Blue Lakes Outflow	gage	instantaneous
Pristine Springs	instantaneous	instantaneous
Rock Creek	instantaneous	continuous
Cedar Draw	instantaneous	continuous
Crystal Springs	instantaneous	instantaneous
Niagara Springs	instantaneous	instantaneous
Unnamed	instantaneous	instantaneous
Clear Lakes	instantaneous	instantaneous
Salmon Falls Creek	gage	continuous
Mud Creek	instantaneous	continuous
Deep Creek	gage	continuous
Banbury Springs	instantaneous	instantaneous
Briggs Creek	instantaneous	instantaneous
Box Canyon Creek	gage	instantaneous
Blind Canyon Creek	instantaneous	instantaneous
Thousand Springs	gage	instantaneous
Billingsley Creek	gage	instantaneous
Bell Ditch	instantaneous	instantaneous
Malad River	gage	continuous
Clover Creek	instantaneous	instantaneous

Table A-2
Instantaneous and continuous minimum and maximum water temperatures for river and tributary sites on August 3rd, 2011, with some data collected on 8/1 and 8/2 represented here as surrogate for 8/3.

Location	Measurement Type	Instantaneous Temp (°C)	Min Temp (°C)	Max Temp (°C)
Snake River at Milner	Continuous temperature logger	N/A	21.44 @ 9:00	21.84 @ 23:30
Snake River at Twin Falls inflow	Continuous temperature logger	N/A	20.77 @ 8:00	22.27 @ 18:00
Snake River at Twin Falls outflow	Continuous temperature logger	N/A	20.82 @ 7:30	21.92 @ 23:30
Snake River at Shoshone Falls outflow	Continuous temperature logger	N/A	21.13 @ 00:30	21.56 @ 23:30
Snake River at Buhl	Continuous temperature logger	N/A	20.44 @ 7:00	21.53 @ 18:00
Snake River at Upper Salmon Falls	Continuous temperature logger	N/A	19.44 @ 8:00	20.22 @ 17:00
Snake River at Lower Salmon Falls	Continuous temperature logger	N/A	19.87 @ 8:30	20.46 @ 23:30
Snake River at Bliss inflow	Continuous temperature logger	N/A	19.51 @ 8:00	20.22 @ 16:00
Snake River at Bliss outflow	Continuous temperature logger	N/A	19.67 @ 8:30	20.36 @ 23:30
Snake River at King Hill	Continuous temperature logger	N/A	19.98 @ 3:30	20.82 @ 16:30
Vineyard Creek	Instantaneous	17.0 @ 8:55	N/A	N/A
Perrine Coulee	Instantaneous	20.1 @ 12:37	N/A	N/A
TF WW treatment	Continuous temperature logger	N/A	25.0 @ 9:00	25.9 @ 19:00
Blue Lakes Outflow	Instantaneous	15.0	N/A	N/A
Rock Creek	Continuous temperature logger	N/A	16.53 @ 8:00	19.29 @ 17:00
Cedar Draw	Continuous temperature logger	N/A	17.18 @ 7:30	21.4 @ 18:30
Crystal Springs	Instantaneous	14.9 @ 9:10	N/A	N/A
Niagara Springs	Instantaneous	15.1	N/A	N/A
Unnamed-Power's Orchard	Instantaneous	18.8 @ 11:15	N/A	N/A
Clear Lakes	Instantaneous	15.4	N/A	N/A
Salmon Falls Creek	Continuous temperature logger	N/A	18.48 @ 7:00	23.02 @ 15:00
Mud Creek	Continuous temperature logger	N/A	16.70 @ 7:00	20.60 @ 18:30
Deep Creek	Continuous temperature logger	N/A	18.06 @ 7:00	21.65 @ 18:00
Banbury Springs	Instantaneous	17.0 @ 15:45	N/A	N/A
Briggs Creek	Instantaneous	15.1	N/A	N/A
Box Canyon Creek	Instantaneous	14.73 @ 15:35	N/A	N/A
Blind Canyon Ag return powerhouse	Instantaneous	23.43 @ 15:40	N/A	N/A
Thousand Springs-north channel	Instantaneous	15.25 @ 15:05	N/A	N/A
Thousand Springs-south channel	Instantaneous	16.51 @ 15:10	N/A	N/A
Billingsley Creek	Instantaneous	16.9	N/A	N/A
Bell Ditch	Instantaneous	21.1 @ 13:25	N/A	N/A
Malad River	Continuous temperature logger	N/A	15.67 @ 6:00	17.53 @ 15:00
White Springs	Instantaneous	16.4	N/A	N/A
Clover Creek	Instantaneous	23.7 @ 10:00	N/A	N/A

Table A-3
Tributary streamflow measurement criteria.

Stream Width (ft)	# of Flow Measures*	# of Depth Measures
<10	5	5
10-20	7	7
>20	9	9

* indicates single flow measurement at 60% total depth when depth <2.5ft., two flow measurements at 20% and 80% total depth when depth >2.5ft.

Table A-4
River and tributary daily mean and instantaneous streamflows on August 3rd, 2011, with some data collected on 8/1 and 8/2 represented here as surrogate for 8/3.

Location	River kilometer	Streamflow Data Source	Streamflow (m3/s)
Snake River at Milner	1025.96	Idaho Power Company-Joint Water Resources	113.3
Snake River at Twin Falls	993.1	Idaho Power Company-Joint Water Resources	122.3
Snake River at Shoshone Falls	989	Idaho Power Company-Joint Water Resources	122.3
Snake River at Buhl	956.1	Idaho Power Company-Joint Water Resources	167.1
Snake River at Upper Salmon Falls	933.1	Idaho Power Company-Joint Water Resources	250.3
Snake River at Lower Salmon Falls	921.8	Idaho Power Company-Joint Water Resources	247.8
Snake River at Bliss	901.4	Idaho Power Company-Joint Water Resources	291.7
Snake River at King Hill	877.9	Idaho Power Company-Joint Water Resources	303.0
Vineyard Creek	994.6	In-field measurement	0.2
Perrine Coulee	983.3	In-field measurement	0.3
TF WW treatment	981.7	TF WW treatment plant	0.2
Blue Lakes Outflow	978.5	Pristine Springs hatchery	4.7
Rock Creek	975.9	In-field measurement	1.7
Crystal Springs	966.1	In-field measurement and Clear Springs Foods, Inc.	7.4
Cedar Draw	964	In-field measurement	2.7
Niagara Springs	964	In-field measurement, Niagara Springs IPCO hatchery, and Idaho Trout Company	5.3
Unnamed-Power's Orchard	962.4	In-field measurement	0.5
Clear Lakes	954.3	Clear Springs Foods, Inc. and Idaho Trout Company	8.6
Mud Creek	952.1	In-field measurement	2.9
Deep Creek	951.8	In-field measurement	3.5
Banbury Springs	947.6	data not available	2.7
Briggs Creek	949.4	USGS gage	2.4
Blind Canyon Aquaranch	947.1	data not available	1.4
Box Canyon Creek	946.1	USGS gage	9.0
Salmon Falls Creek	943.1	IDWR gage	2.1
Thousand Springs-south channel	940.7	Idaho Power Company	12.7
Thousand Springs-north channel	939.5	Idaho Power Company	2.8
Bell Ditch	928.8	In-field measurement	0.2
Billingsley Creek	923.4	Idaho Trout Company	3.2
White Springs	921	Idaho Trout Company	0.9
Malad River	919.6	Idaho Power Company	36.2
Clover Creek	881.1	In-field measurement	0.1

Table A-5
Hourly meteorological data as reported at the USBR Agrimet station in Twin Falls, Idaho.

DATE	TIME	Air Temperature (°C)	Dew Point Temp (°C)	Wind Speed (m/s)	Hourly Solar Radiation (Watts/m2)
8/3/2011	0:00	19.64	11.42	1.47	0.00
8/3/2011	1:00	17.73	12.19	0.37	0.00
8/3/2011	2:00	15.83	11.15	1.23	0.00
8/3/2011	3:00	14.42	11.53	1.77	0.00
8/3/2011	4:00	15.72	11.36	1.79	0.00
8/3/2011	5:00	15.39	9.94	1.76	0.00
8/3/2011	6:00	15.26	9.17	2.13	0.00
8/3/2011	7:00	12.59	10.30	1.24	7.44
8/3/2011	8:00	15.87	11.77	1.44	49.04
8/3/2011	9:00	19.97	11.69	1.40	96.11
8/3/2011	10:00	22.89	10.70	1.77	143.18
8/3/2011	11:00	25.44	12.02	2.29	183.97
8/3/2011	12:00	27.50	14.83	2.87	215.47
8/3/2011	13:00	29.11	12.16	2.86	234.76
8/3/2011	14:00	30.44	10.87	2.42	241.85
8/3/2011	15:00	31.28	6.51	1.94	220.46
8/3/2011	16:00	31.22	4.99	0.75	90.42
8/3/2011	17:00	28.17	2.34	3.67	56.71
8/3/2011	18:00	29.78	6.93	1.55	55.44
8/3/2011	19:00	31.44	2.75	1.07	84.02
8/3/2011	20:00	27.67	11.64	1.03	33.35
8/3/2011	21:00	22.06	8.79	1.60	1.28
8/3/2011	22:00	21.01	8.92	1.94	0.00
8/3/2011	23:00	17.43	9.80	1.62	0.00

Table A-6
Hourly meteorological data as reported at the USBR Agrimet station in Glenn's Ferry, Idaho.

DATE	TIME	Air Temperature (°C)	Dew Point Temp(°C)	Wind Speed (m/s)	Hourly Solar Radiation (Watts/m2)
8/3/2011	0:00	21.39	8.87	0.34	0.00
8/3/2011	1:00	20.78	10.20	0.54	0.00
8/3/2011	2:00	17.76	10.32	0.91	0.00
8/3/2011	3:00	17.09	10.98	1.60	0.00
8/3/2011	4:00	16.83	10.71	0.32	0.00
8/3/2011	5:00	16.30	10.06	1.65	0.00
8/3/2011	6:00	15.22	10.36	1.38	0.00
8/3/2011	7:00	17.57	10.87	1.56	8.37
8/3/2011	8:00	19.05	12.86	1.68	121.56
8/3/2011	9:00	23.56	11.54	1.89	306.00
8/3/2011	10:00	25.50	10.86	2.90	494.62
8/3/2011	11:00	29.11	10.09	2.43	668.59
8/3/2011	12:00	31.67	8.29	1.95	811.19
8/3/2011	13:00	32.72	12.16	1.95	905.56
8/3/2011	14:00	34.00	7.24	1.61	949.49
8/3/2011	15:00	34.78	9.77	1.62	947.40
8/3/2011	16:00	36.67	-0.54	1.02	888.71
8/3/2011	17:00	36.17	-3.42	1.93	787.37
8/3/2011	18:00	33.89	6.73	2.38	516.35
8/3/2011	19:00	32.00	9.59	1.42	398.62
8/3/2011	20:00	26.61	7.96	1.19	90.18
8/3/2011	21:00	24.39	7.60	1.17	25.34
8/3/2011	22:00	21.72	6.92	1.22	0.81
8/3/2011	23:00	21.56	3.77	0.71	0.23

Table A-7
Major tributaries by model reach.

Reach Number	Major Tributaries	Reach Number	Major Tributaries
1	None	5	Clear Lakes
2	Vineyard Creek	5	Salmon Falls Creek
3	Devils Corral	5	Mud Creek
4	Perrine Coulee	5	Deep Creek
4	TF WW treatment	5	Banbury Springs
4	Blue Lakes Outflow	5	Briggs Creek
4	Pristine Springs	5	Box Canyon Creek
4	Rock Creek	5	Blind Canyon Creek
4	Cedar Draw	5	Thousand Springs
4	Crystal Springs	6	Billingsley Creek
4	Niagara Springs	6	Bell Ditch
4	Unnamed-Powers' Orchard	7	Malad River
		8	None
		9	Clover Creek