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DETERMINISTIC LAKE AND STREAM TEMPERATURE MODELLING: MAINTAINING OPTIMAL WATER TEMPERATURES FOR KOKANEE AND RAINBOW TROUT THROUGH INFORMED DESIGN

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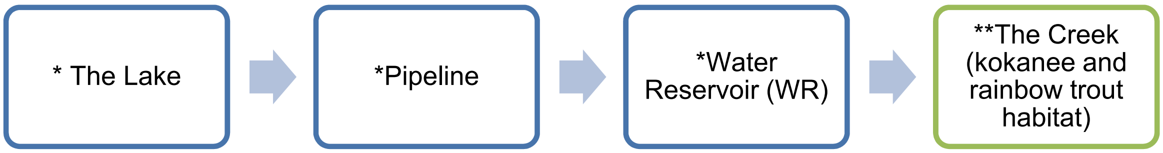
Abstract: Stream temperature is an important indicator of habitat quality for fish of all life stages. However, stream temperature is often overlooked when designing mitigation systems, with the focus being on the effects of development on stream flow, depth and velocity. A number of simple deterministic water temperature models exist for lakes, channels, and pipelines that can be utilized to optimize key design parameters for mitigation systems. Knight Piésold Ltd. (KP) used water temperature modelling to support the preliminary design of a water supply system for a proposed mine in BC. The water supply system will augment flows to an existing stream to support kokanee and rainbow trout populations. The proposed water supply system includes an intake in a nearby lake, a pump and pipeline conveyance system, and a small reservoir with low level and surface outlets. KP modelled the water temperatures throughout the supply system and in the receiving stream using three models: a one-dimensional Fresh Water Lake model (FLake), a heat transfer pipeline model, and the Stream Segment Temperature model (SSTEMP). Baseline models of the existing lake and stream were completed to assess model suitability and to calibrate model parameters. Operation models were then developed using long-term site specific climate inputs for the project. The models were run with various design considerations to maintain stream temperatures within optimal ranges to support various life stages of the kokanee and rainbow trout populations. Modelling identified those periods in which conditions similar to baseline could not be fully achieved and additional mitigation measures were required.

1 INTRODUCTION

Flow mitigation is required to minimize the impacts of a proposed mining project in British Columbia on kokanee and rainbow trout habitat. A Water Supply System (WSS) will be used to augment stream flow reductions in a fish bearing stream (the Creek). The WSS will consist of an intake in a nearby lake (the Lake), a pipeline with a booster pump station, a Water Reservoir (WR) located on the Creek, and outlet works from the WR. Water from the WSS will provide the minimum seasonal Instream Flow Needs (IFN) for both fish species. The purpose of this study was to use water temperature modelling to support the preliminary design of the WSS by determining if the seasonal variation in water temperatures could be maintained within baseline conditions, or optimal ranges, to support various life stages of the kokanee and rainbow trout populations. This paper briefly describes the temperature modelling approach, the results of the modelling and the recommendations that resulted from the study.

2 WATER TEMPERATURE MODELLING APPROACH

There are three major components that contribute to the overall thermal regime of the WSS: the Lake, the pumped pipeline and the WR. The combined thermal regimes of these components ultimately contribute to the water temperatures in the Creek supporting kokanee and rainbow trout. Water temperatures for each of the elements shown on Figure 1 were modelled separately and in sequence following the downstream direction.



* Denotes elements within the WSS

** Denotes the open channel stream downstream of the WSS

Figure 1: Elements modelled separately and in sequence following the downstream direction.

Temperature assessments were conducted to address the possible range of water temperature conditions that could occur within each of these elements by considering the long-term mean monthly, and minimum and maximum daily values for various key parameters. The input climate parameters for each model were based on long-term climate data (about 40 years) for the site that was developed through regression analysis with regional data based on the short-term data collected on site. Using the minimum and maximum daily temperatures derived from the long-term natural climate record provided a thermal range over which the WSS is predicted to operate.

2.1 Temperature Modelling for the Fresh Water Source and Water Reservoir

Modelling of the daily thermal changes in the fresh water source, the Lake, and the WR was conducted using the FLake fresh water lake model. FLake, developed in Germany (Mironov 2008), is capable of estimating the vertical temperature structure and mixing conditions in lakes over time. The model is based on a two-layer parametric representation of the evolving temperature profile and on integral budgets of heat and kinetic energy for the layers. The model was developed as a lake parameterization scheme for use in numerical weather predictions and climate modelling, but it has also been used as a stand-alone lake model for many studies in Europe and North America (Mironov et al. 2005, Kirillin 2010, Kirillin et al. 2011, Bernhardt et al. 2012, Semmler et al. 2012). It is incorporated into the Canadian Regional Climate Model version 5 (CRCM5) developed by Le Centre ESCER in Montreal (Martynov et al. 2012).

The FLake model for the Lake was calibrated using two years of measured temperature data in the Lake and concurrent climate data as shown on Figure 2. The calibrated parameters from the Lake model were also used for the WR model. The calibrated models were then run with the synthetic climate data series developed for the project. Daily results were used to calculate the mean monthly, and daily minimum and maximum epilimnion and hypolimnion temperatures, and epilimnion thicknesses for each water body.

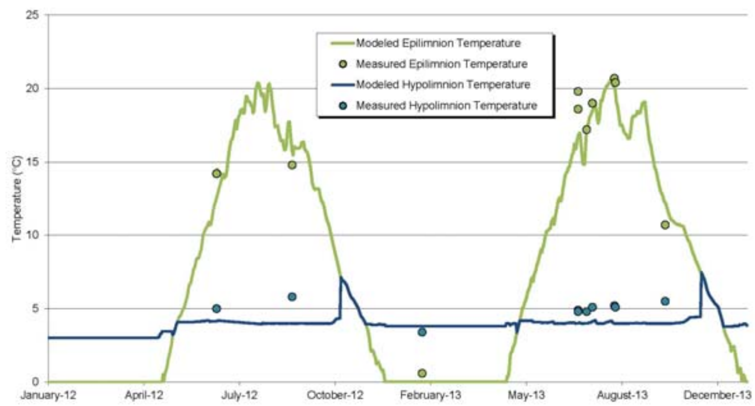


Figure 2: Temperature calibration of the Lake model.

2.2 Temperature Modelling for the Pipeline

Outputs from the Lake temperature modelling were used as inputs to the pipeline temperature modelling assuming that the intake would be located in the Lake hypolimnion. Assessments of water temperature changes along the pipeline were conducted using a heat transfer model developed by KP after Kwon (1998) that calculates steady-state heat transfer to or from the water in a pipeline, including temperature increases resulting from pumping inefficiencies. The model considers heat transfer effects from conduction, convection and radiation, and takes into account the pipeline material, flow magnitude as well as the water, air and soil temperatures. A sensitivity analysis was conducted to evaluate the impact of different pipeline materials, soil temperatures, and soil thermal conductivity on the modelled pipeline water temperatures.

2.3 Temperature Modelling for the Creek with Kokanee and Rainbow Trout Habitat

Temperature variations in the Creek with kokanee and rainbow trout habitat were simulated using the Stream Segment Temperature Model (SSTEMP) Version 2.0 developed by the U.S. Geological Survey (USGS). SSTEMP was developed to aid biologists and engineers in predicting the consequences of stream manipulation on water temperatures. SSTEMP is a mechanistic, one-dimensional heat transport model that predicts water temperatures as a function of stream distance and environmental heat flux (Bartholow 2004). The SSTEMP model was calibrated using concurrent water temperature and stream flow data at two locations along the Creek. An example of the calibration is presented on Figure 3. The calibrated model was then run to estimate the baseline and project impacted temperatures for various flow conditions and at two locations, one for rainbow trout habitat and a second location further downstream for kokanee habitat.

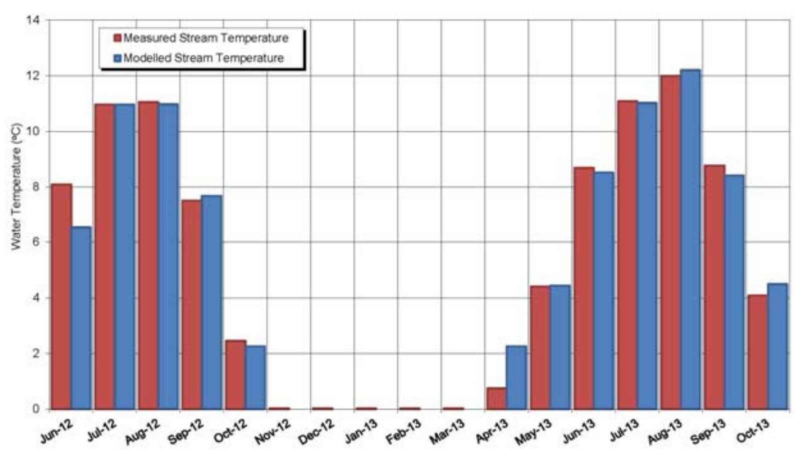


Figure 3: Temperature calibration of the Creek model.

Both the baseline and project conditions were modelled using the long-term mean monthly, and minimum and maximum daily air temperatures in each month derived from the synthetic climate data set developed for the project. These air temperatures were used in combination with various outflow options from the WR (low level and surface outlet), or direct discharge from the pipeline. The resulting water temperature ranges were then used to evaluate changes between the baseline and augmented flow conditions in the Creek to assess the various WR outlet and pipeline discharge options.

3 Temperature Modelling Results

3.1 Temperature in the Water Supply System

The temperature modelling for the Lake confirms in-situ observations of the Lake being dimictic with full overturn in the spring and fall, and with the thermocline (epilimnion thickness) deepening throughout the fall as the Lake cools and overturns. The epilimnion temperatures increase substantially in the summer, while the epilimnion thickness exceeds 5 m from August to November. This result indicates that if the intake was located shallower 10 m, it is likely that the warm epilimnion water would be withdrawn into the WSS. The modelled long-term epilimnion and hypolimnion temperatures are illustrated on Figure 4. The maximum and minimum daily values represent the highest and lowest daily values for each month within the entire modelling record, respectively, and show the full range of temperatures that may potentially occur in the Lake.

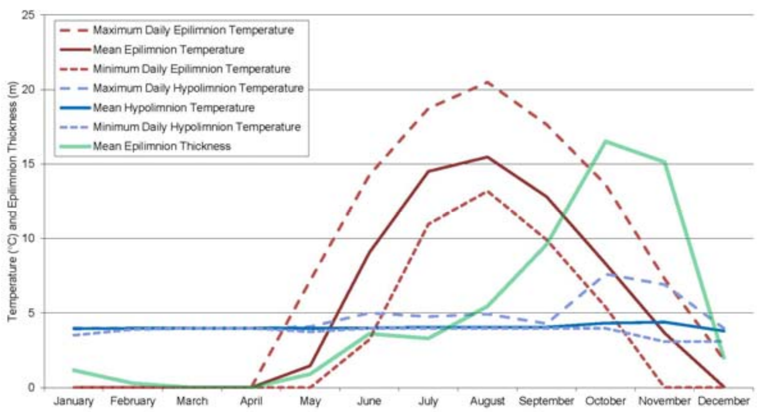


Figure 4: Range of long-term epilimnion and hypolimnion temperatures in the Lake

The water temperature change in the pipeline is predicted to be within ±1°C based on mean monthly intake water and air/soil temperatures. The general trend for the pipeline is cooling in the winter months and heating in the summer months. The analysis demonstrated that under extreme conditions the winter heat loss within the pipeline could be such that freezing may occur if the intake water temperature was between 0°C and 3°C. For this reason, an intake in the Lake epilimnion is not recommended.

The WR is predicted to be stratified throughout the winter and early summer, and overturn in the spring and late summer/fall. Results of the WR temperature modelling are illustrated on Figure 5. The WR will be smaller and shallower than the Lake, and as a result, it is predicted to undergo a weaker stratification in the winter and summer, and remain fully mixed for longer periods of time in the spring and late summer/fall. Temperatures throughout the depth of the WR are predicted to equalize faster than in the Lake, which is consistent with observed water temperatures in an existing smaller lake close to the Project area. As expected, the modelling confirmed that the climate has a larger impact on the smaller water body compared to the much larger Lake.

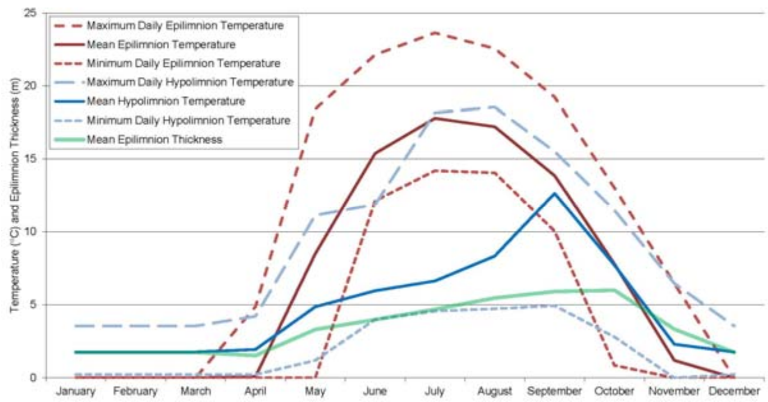


Figure 5: Range of long-term epilimnion and hypolimnion temperature in the Water Reservoir

3.2 Temperatures in the Creek with Kokanee and Rainbow Trout Habitat

Three potential sources of water from the WSS may be used to provide flow to the Creek to meet the IFN. These three sources were assessed separately to evaluate the temperature conditions in the Creek under various air temperature conditions as follows:

- Flows from the WR low level outlet
- Flows from the WR surface outlet, and
- Flows from the pipeline discharging directly to the Creek at the same location as the WR.

The results of the water temperature modelling for each discharge option are illustrated on Figure 6 for the rainbow trout habitat location and Figure 7 for the kokanee habitat location farther downstream. The mean monthly water temperatures are shown as bars, while the minimum and maximum daily water temperatures are indicated as whisker plots. Guidelines for the optimum water temperatures for various life stages of rainbow trout (Figure 6) and kokanee (Figure 7) are also shown for reference (BCMOE 2001). Comparison of baseline and optimum water temperatures indicates that this Creek is cooler than optimal for rainbow trout and kokanee; however, the species living in the Creek are adapted to these cooler temperatures.

The results indicate that the augmented flows in the Creek would be within 1°C of baseline water temperatures in most months, and that this could be achieved by using a combination of various proposed discharge options (e.g. the WR low level outlet, the WR surface water outlet, or direct discharge from the pipeline). An exception would occur in October, when both the Lake and the WR undergo fall turnover and cool slower than the shallow waters in the Creek. Without further mitigation, releases from the WSS in October would result in temperatures 3°C to 5°C above baseline, depending on the distance downstream from the release point. This finding led to additional design considerations to incorporate diversions of undisturbed catchment areas upstream of the project. These diversions would help augment the fall water temperatures, considering they have water temperatures similar to baseline temperatures in the Creek.

The effect of water temperatures released from the WSS on water temperatures in the Creek decreases with distance downstream due to the increased direct influence of air temperatures and other climate parameters. The predicted differences in water temperatures between project and baseline conditions are smaller at the downstream kokanee habitat location than at the rainbow trout habitat location.

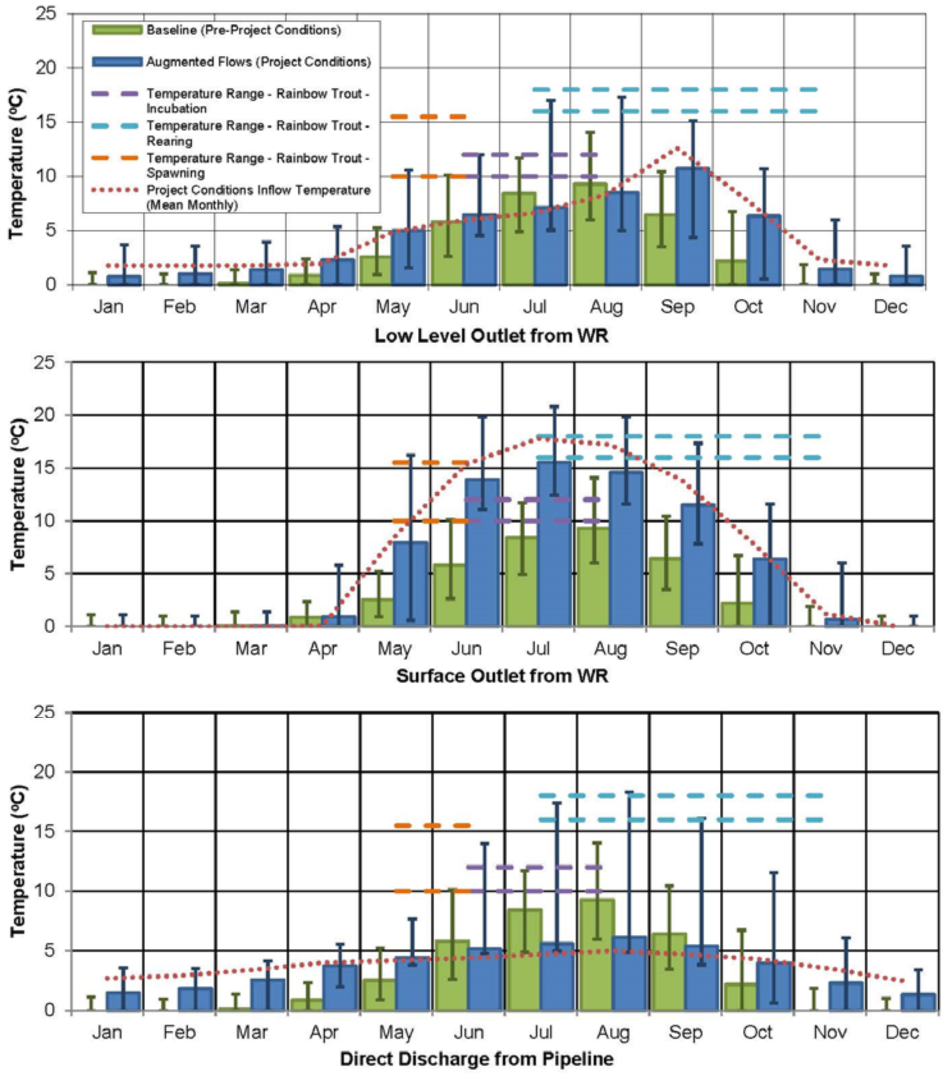


Figure 6: Simulated Creek water temperatures at rainbow trout habitat location

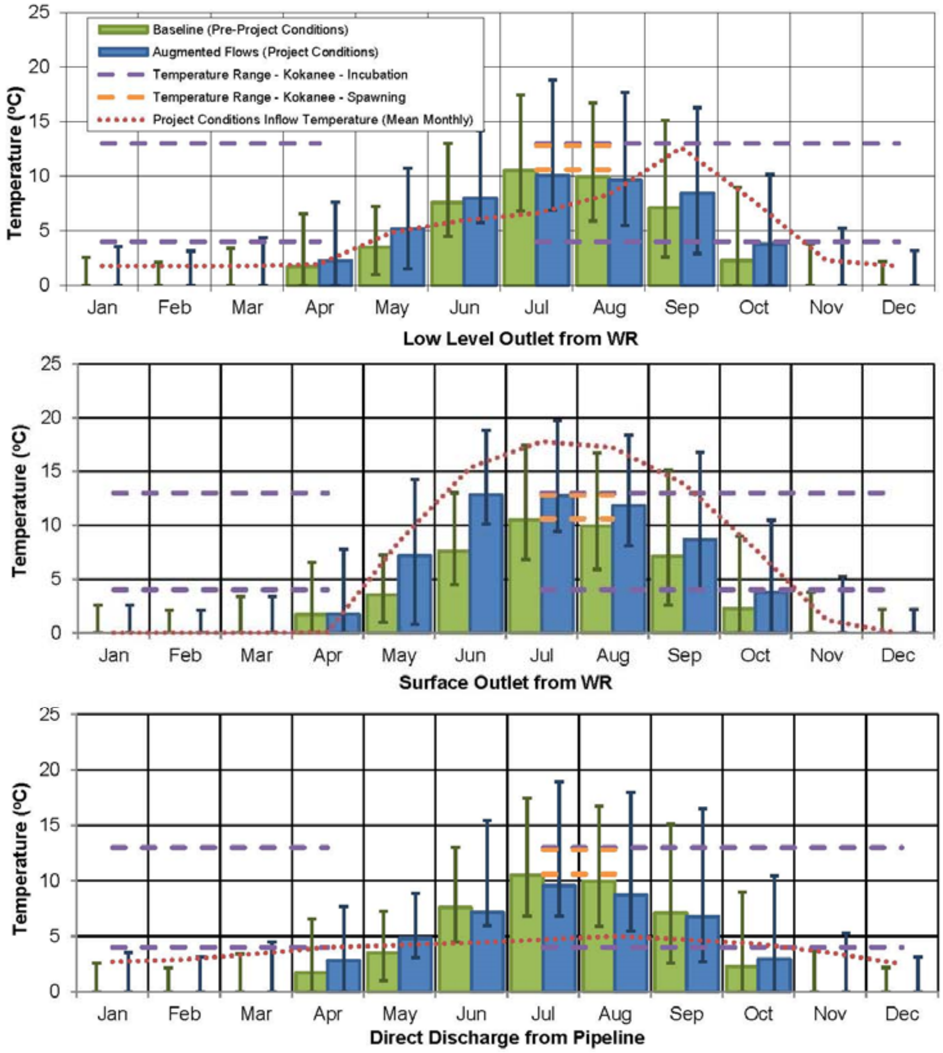


Figure 7: Simulated Creek water temperatures at kokanee habitat location

4 Discussion and Conclusions

The water temperature modelling conducted for the WSS indicates that flows and water temperatures could be augmented within 1°C during project conditions using a combination of the three discharge options from WSS for most of the year, except in October. The Creek temperatures would overall be consistent with baseline conditions, or would be within optimum temperatures (BCMOE 2001). The natural baseline temperatures are sub-optimal for certain life stages of rainbow trout and kokanee; however, the local fish populations are adapted to these suboptimal conditions. The effects of water temperatures released from the WR, or directly from the pipeline, on water temperatures in the Creek decrease with distance downstream from the WR due to the increased direct influence of air temperatures and other climate parameters.

The findings of the initial modelling led to additional design considerations in terms of the placement of the intake in the Lake and incorporation of upstream diversions to augment the fall water temperatures. The water temperature modelling of the Lake and pipeline indicated that the intake in the Lake should be located in the hypolimnion below the thermocline to help minimize the potential for freezing in the pipeline in the winter, while providing cooler temperatures in the summer. In addition, incorporating diversions of undisturbed catchment areas upstream of the project, which have water temperatures similar to baseline temperatures in the Creek, provides mitigation options to help manage the fall temperatures and bring them in line with the observed baseline temperatures.

This study shows the importance of considering not only flows, but also water temperatures when designing mitigation systems in early stages of design so that adaptive management opportunities can be considered.

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