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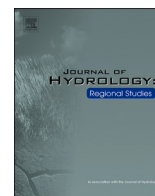
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# A coupled streamflow and water temperature (VIC-RBM-CE-QUAL-W2) model for the Nechako Reservoir

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## ABSTRACT

*Study region:* Nechako Reservoir, British Columbia, Canada.

*Study focus:* Hydrological regulation affect both hydrological and thermal conditions in the reservoir and downstream reach, subsequently disrupting fish habitats. This paper aims at developing an integrated model simulating physical processes that govern the quantity and quality of inflow, reservoir, and outflow water of the Nechako Reservoir. Such a model would help stakeholders understand the response of in-reservoir water temperature stratification and downstream water temperature to changes in inflow and reservoir operation under future climate change.

*New hydrological insights for the region:* The model was calibrated against historical reservoir levels and in-reservoir and outlet water temperature field data. The integrated model simulated accurately the wide variation of reservoir levels as well as the in-reservoir water temperature at Kenney Dam and the outlet temperature. Sensitivity analysis shows that reservoir water temperature particularly the epilimnion is sensitive to changes in both meteorological and hydrological forcing. Forcing the model with different outflow scenarios shows the weak sensitivity of temperature of water released to outflow rates. Given epilimnion water releases at the spillway, the Summer Temperature Management Program could be inefficient to provide cool water in the Nechako River during the critical period of salmon migration in a warming climate. However, colder water remains available at depth at Kenney Dam to potentially mitigate and better control downstream water temperature.

## 1. Introduction

Flow regulation affects reservoir hydrological and thermal dynamics by altering water levels, heat exchange (Yang et al., 2022), thermal structure, ice-formation and breakup (Huokuna et al., 2022). Specifically, dams alter air-water temperature interactions, particularly in cases where hypolimnion releases can increase the time lag between air and water temperatures and significantly change water temperature dynamics downstream (Kędra and Wiejaczka, 2016). These changes in downstream flow and thermal dynamics subsequently affects the river ecosystem particularly fish movement and survival (Moore et al., 2022). Depending on the in-take water temperature through epilimnetic or hypolimnetic (bottom) release, reservoirs are likely to release water that is either too warm or too cold for the downstream aquatic environment (Olden and Naiman, 2010).

In a changing climate, warming air temperature can exacerbate the impact of flow regulation on both the reservoir and the

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downstream river reach. A number of studies have evaluated the impact of climate change on reservoir water surface temperature and thermal stratification (e.g., Obregon et al., 2011; Lee et al., 2018; Lewis et al., 2019; Morales-Marin et al., 2021; Paulsson and Widerlund, 2022; Soares et al., 2021; Yaghouti et al., 2022) and reservoir performance and hydropower generation (e.g., Raje and Mujumdar, 2010; Ashofteh et al., 2013; Jahandideh-Tehrani et al., 2015; Qin et al., 2020; Zhong et al., 2020; Xu et al., 2022). The impact of climate change on inflow volume, water demand and water temperature are often evaluated separately. However, majority of reservoirs serve different purposes and managers need to consider trade-offs between hydropower generation and environmental needs such as minimum flow or downstream water temperature requirements for fish habitats. Therefore, a holistic approach that considers both changes in inflow cycle and subsequent changes in reservoir thermal stratification is critical to understand how water control could affect reservoir performance and its influence on downstream river water temperature.

Numerical hydrodynamic models are widely used to capture both the reservoir balance and thermal stratification (e.g., GLM, Hipsey et al., 2019; CE-QUAL-W2, Cole and Wells, 2006; ELCOM, Hodges et al., 2000). These models rely on equations for heat transport, inflow transport and outflow transport according to the reservoir geometry, flow rates and climatic conditions to simulate water temperature. A number of studies have used these models to evaluate the response of reservoir thermal stratification to changes in air temperature and precipitation (e.g., Obregon et al., 2011; Prats et al., 2017; Lee et al., 2018; Azadi et al., 2021; Morales-Marin et al., 2021; Yaghouti et al., 2022). However, to also assess the impact of climate on reservoir inflow generally requires a hydrological model forced with outputs of general circulation models (Olsson et al., 2016). Linking hydrodynamic models with hydrological models enables reservoir stakeholders to design reliable water management strategies under climatic changes that could influence operations

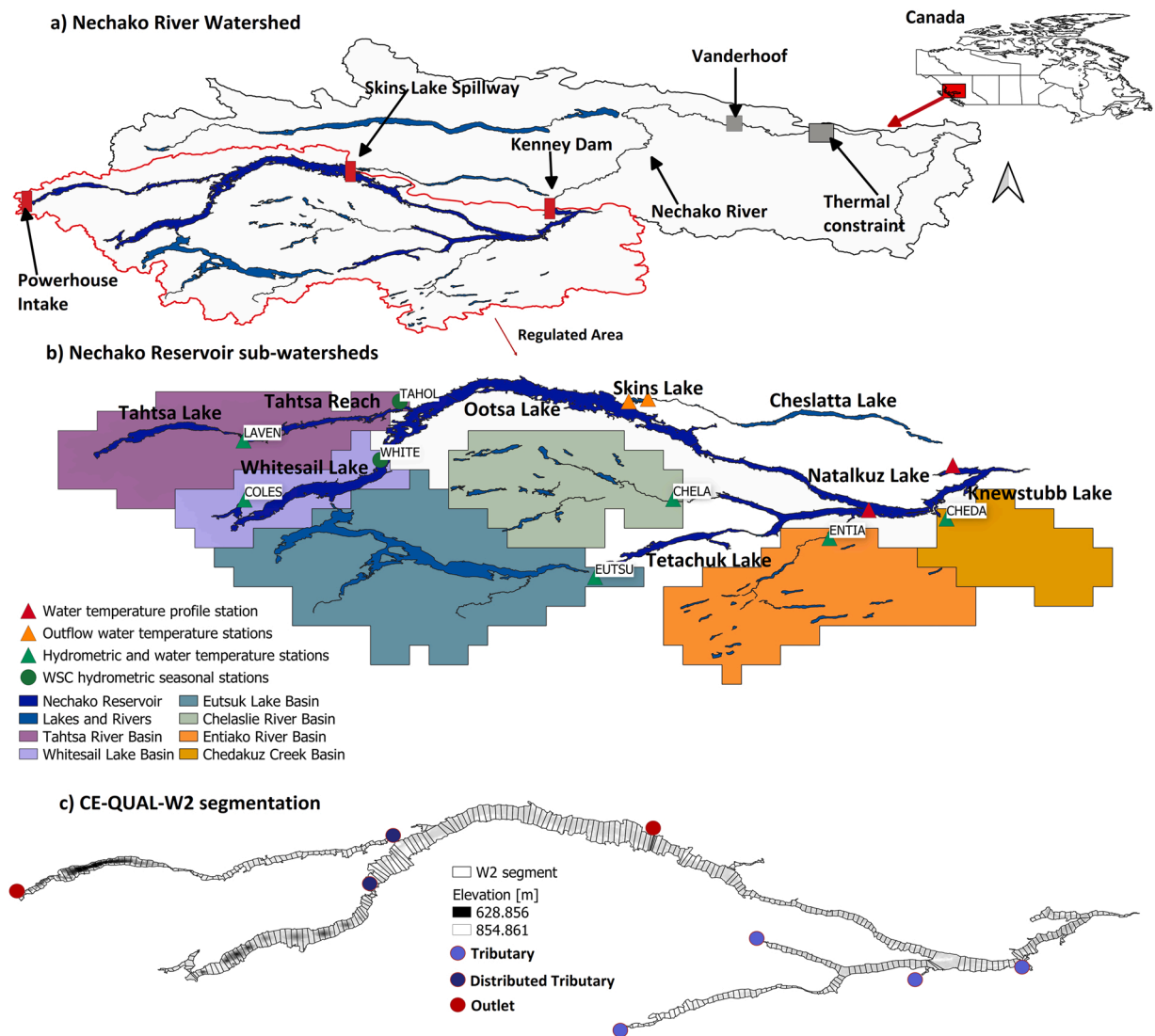


Fig. 1. The Nechako River Watershed (a), Nechako Reservoir sub-watershed delineation by VIC-GL (b), and CE-QUAL-W2 representation and segmentation of the Reservoir (c).

and environmental sustainability.

This paper describes the development of a model of sufficient complexity to describe hydrological and hydrodynamic processes in a large multi-basin reservoir by linking a hydrologic model (*Variable Infiltration Capacity* (VIC) model; Liang et al., 1999, 1996), a stream water temperature model (*River Basin Model*, RBM, Yearsley, 2012, 2009) and a hydrodynamic model (*CE-QUAL-W2*, Cole and Wells, 2006). The proposed model is implemented to the Nechako Reservoir which regulates the Nechako River (a tributary of the Fraser River) in British Columbia, Canada. This river serves as valuable habitat for several fish species (Northcote and Larkin, 1989; NFCP, 2016) and as a critical migration corridor for various species of salmon (Fraser Basin Council, 2015; Levy and Nicklin, 2018). Numerous studies have examined the impact of the reservoir regulation on the water quantity and quality of the Nechako River since 1978 (e.g. Kellerhals et al., 1979, Blachut, 1988, Hartman, 1995, Mitchell et al., 1995, Rood and Hamilton, 1995, French and Chambers, 1997, Macdonald et al., 2007, Albers et al., 2016). However, only few studies have addressed water temperature within the Nechako Reservoir itself, or the temperature of water released from the reservoir. These studies were focused on the capacity of a proposed release facility at Kenney Dam to provide cold water to the Nechako River to ensure favorable downstream conditions for salmon species and were limited to the area immediately upstream of the dam. To our knowledge, there is no study that has taken an integrated view of the entire Nechako Reservoir, including inflow from the upstream drainage area.

Accordingly, the intent of the proposed modelling system is to provide a prognostic prediction of the temperature of reservoir outflows, which is intended to serve as an upstream boundary condition for future thermal modelling scenarios. The model could also be linked to a reservoir operation model to manage and regulate temperature of water released.

Using the Nechako Reservoir as a case study, the main objectives of this paper are to 1) demonstrate the accuracy of our combined modelling system in describing reservoir hydrology, hydrodynamics and temperature, and then to use the developed model to explore 2) the sensitivity of the reservoir thermal structure to surface forcing (air temperature, wind speed, longwave radiation and solar radiation), and 3) the impact of flow regulation on reservoir thermal stratification and outflow water temperature.

## 2. Study area

The Nechako Reservoir, located in the upper Nechako River, was created in the early 1950 s by the construction of the Kenney dam and nine additional saddle dams, which flooded and linked the rivers and lakes Ootsa, Intata, Whitesail, Chelaslie, Tetachuk, Tahtsa and Natakuz into a single reservoir (Fig. 1). The names of the original lakes are still used as the names of the various reaches of the reservoir. The Kenney dam impounds approximately 14,020 km<sup>2</sup> of the upper portion of the Nechako River Basin and the reservoir itself is composed of two main branches that extend 200 km east-west and 57 km north-south. The northern branch is composed of Whitesail, Tahtsa and Ootsa Lakes (Fig. 1b), and in the southern branch of the reservoir, the unregulated Eutsuk Lake drains into Tetachuk Lake, and water then flows to Natakuz and Knewstubb Lakes. The latter is directly upstream of the Kenney Dam, which consists of two perpendicular basins, Knewstubb and Big Ben Arms extending East-West and Knewstubb Mid-reach extending north-south (Imam et al., 2013).

Kenney Dam was built 90 km southwest of Vanderhoof at the outlet of Knewstubb Lake (Fig. 1a). It eliminated flows into the

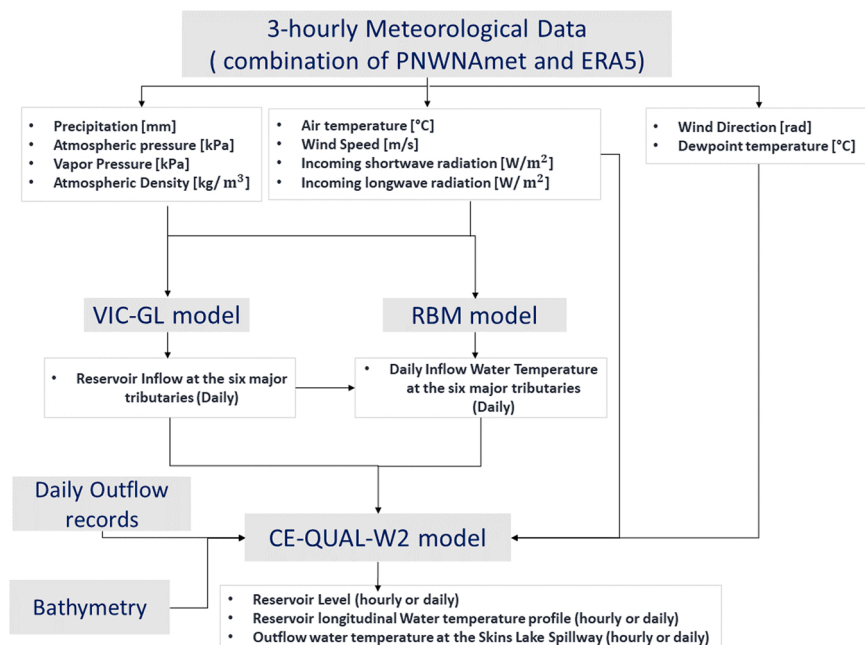


Fig. 2. Proposed modelling framework.

Nechako River at this point and backed water westward via Knewstubb and Nataalkuz lake into Ootsa Lake (Swain and Girard, 1987). Reservoir levels in the Nechako reservoir are affected by discharge at its two outlet locations. Most outflow is used for power production and diverted to the Kemano powerhouse from the west end of the reservoir in Tahtsa Lake via a 16 km tunnel drilled through the Coast Mountains (NHC, 2003). Any surplus water is released midway along the reservoir from Ootsa Lake through a spillway into Skins Lake, which is 75 km west of the Kenney Dam. The spillway redirects water through the Cheslatta River to rejoin the Nechako River downstream of Kenney Dam, bypassing approximately 9 km of the original channel course. Spillway flows provide water for downstream fish habitat and other uses.

The reservoir regulation significantly influenced water quantity and quality in the Nechako River (Macdonald et al., 2012). To provide adequate spawning and migration conditions to salmonid species a Summer Temperature Management Program (STMP) was adopted in 1983. The aim of the STMP is to decrease the frequency of water temperature > 20 °C between July 20th and August 20th (critical period for salmon migration) at Finmoore, the thermal constraint location shown in Fig. 1a, by increasing water release at the Skins Lake Spillway.

### 3. Data and methods

To develop a modelling framework that provides an integrated view of the Nechako Reservoir from the inflow feeding the reservoir, the in-reservoir dynamics to water leaving the system through regulation, different models are linked (see Fig. 2). The 2-dimensional (longitudinal and vertical) CE-QUAL-W2 (henceforth W2) hydrodynamic model is used to simulate the hydrodynamic regime of the reservoir. This model requires upstream boundary conditions (i.e., inflow and inflow water temperature) and downstream boundary conditions (i.e., outflows). VIC-GL, a version of the VIC model upgraded at PCIC that accounts for glacier processes (Schnorbus, 2018), is used to simulate inflows at the sub-basin outlets (Fig. 1b, Table 1). The stream water temperature model, RBM, is used to simulate inflow water temperature. Table 2 provides a summary of the stages of calibration and validation for each component (VIC-GL, RBM and CE-QUAL-W2) of the modelling chain.

This section describes the data requirements for this modeling framework as well the implementation of each component model. Section 3.1 presents the meteorological data necessary to drive the models. Water quantity and quality data required to calibrate the models are described in Section 3.2. These datasets include discharge and water temperature required to calibrate VIC-GL and RBM as well as reservoir level, outflows, temperature of the water column, and temperature of outflows to calibrate the W2 model. Section 3.3 describes the implementation of VIC-GL and RBM, Section 3.4 describes the implementation of the W2 model, and the bathymetry required to describe the reservoir geometry and develop the computational grid of W2 model is presented in Section 3.5. Section 3.6 describes the sensitivity analysis methodology to evaluate the impact of surface meteorology and outflow regulation on the reservoir thermal stratification and temperature of water released at the Skins Lake Spillway.

#### 3.1. Meteorological forcing

The selected modelling framework (see Fig. 2) requires gridded meteorological forcing data of air temperature, precipitation, dewpoint temperature, wind speed and direction, incoming solar and longwave radiation, atmospheric density, and atmospheric pressure at a 3-hour timestep. The data are for 1945–2018 to cover the period for which both discharge and water temperature observations are available for reservoir model calibration and validation. The requisite data was produced by merging two datasets: PNWNAmet (Werner et al., 2019) and ERA5 reanalysis (Copernicus Climate Change Service (C3S) (C3S) (C3S), 2017). PNWNAmet provides gridded observations of daily maximum and minimum temperature, and precipitation at a spatial resolution of 0.0625° (6-km) for the period 1945–2012. Sub-daily values of precipitation and temperature, and the additional required meteorological variables were estimated using the MT-CLIM algorithm (Bohn et al., 2013). The ERA5 dataset provides temperature, precipitation, dew point temperature, surface pressure, shortwave and longwave radiation as well as northward and eastward wind components at a 0.28125° (31-km) spatial resolution for the period 1980–2019. Vapour pressure was estimated as a function of dew point temperature whereas atmospheric density was estimated from air temperature and surface pressure. Wind speed and wind direction were estimated from northward and eastward wind components. The ERA5 data were disaggregated from 0.28125° spatial resolution to the PNWNAmet data resolution using a second-order conservative interpolation procedure REMAPCON2 (Schulzweida, 2019). A temporally consistent dataset spanning 1945–2018 was created by merging variables from both datasets, except for wind direction,

**Table 1**

List of Nechako Reservoir sub-watersheds.

Basin	Station name	Abbreviation	WSC flow record period
Whitesail Lake Basin	Whitesail River near Ootsa Lake	WHITE	May 1930 to Aug 1952
	Coles Creek Above Troitsa Creek	COLES*	Jan 1993 to Mar 1996
Tahtsa River Basin	Tahtsa River near Ootsa Lake	TAHOL	May 1930 to Sep 1952
	Laventie Creek Near the Mouth	LAVEN*	Sep 1976 to Dec 2018
Eutsuk Lake Basin	Eutsuk River at Outlet of Eutsuk Lake	EUTSU*	Jan 1993 to May 2013
Entiako River Basin	Entiako River near the Mouth	ENTIA*	Apr 1992 to Dec 1995
Chedakuz Creek Basin	Chedakuz Creek at the Mouth	CHEDA*	Apr 1992 to Dec 1995
Chelaslie River Basin	Chelaslie River near the Mouth	CHELA*	Jan 1993 to Dec 1995

\* Stations with water temperature data available from Triton Environmental Consultants (1994).

**Table 2**

Description of the calibration and validation steps applied to each component of the model system.

Model	Period		Target Variable	Forcing
	Calibration	Validation		
VIC-GL	01/01/1979 – 12/31/2017	n/a	Total reservoir inflow	Meteorology
	01/01/1946 – 08/30/1952	n/a	WHITE & TAHOL inflow	
	01/01/1993 – 12/31/1995	01/01/2004 – 12/31/2012	EUTSU inflow	
	01/01/1993–03/31/1995	n/a	COLES inflow	
	01/01/1977–12/31/1994	n/a	LAVEN inflow	
	04/01/1992 – 12/31/1995	n/a	ENTIA & CHEDA inflow	
	01/01/1993 – 12/31/1995	n/a	CHELA inflow	
	07/06/1994 – 13/10/1994	n/a	Tributary water temperature	
	07/06/1994 – 13/10/1994	n/a	Tributary water temperature	
CE-QUAL-W2	n/a	01/01/1986 – 12/31/2017	Bathymetry / reservoir volume	Meteorology, observed inflow, and observed outflow
	n/a	01/01/1986 – 12/31/2017	Reservoir water level	
	n/a	25/06/1994 – 10/10/1994	Water temperature @ Kenney Dam and Natalkuz Lake	
	n/a	Summer 2016 and 2017	Outflow temperature @ spillway	

which is only available from 1980 onward. As air temperature and precipitation from PNWNAmet is considered more accurate than ERA5, we used the PNWNAmet-based data for 1945–2012 and extended the data by concatenating ERA5 air temperature and precipitation for 2013–2018. Conversely, incoming shortwave and longwave radiation, wind speed, air pressure, vapor pressure and atmospheric density from ERA5 are deemed more accurate than those estimated from PNWNAmet using MTCLIM. Therefore, we used ERA5-based data from 1980 through 2018, and only used PNWNAmet-based data for the earlier period of 1945–1979. The procedure for generating the forcing data is described in detail in the accompanying [Supplementary Material](#).

### 3.2. Water quantity and quality dataset

#### 3.2.1. Tributary inflow and inflow water temperature

Daily discharge data for all the major tributaries (see [Fig. 1b](#), and [Table 1](#)) to the Nechako Reservoir were obtained from Water Survey Canada (WSC). Discharge data for the Whitesail Reach (WHITE) and Tahtsa River (TAHOL) tributaries are seasonal and only available prior to reservoir construction (1930–1955). The record period for the remaining stations is between 1992 and 1996, except EUTSU and LAVEN where the records extend to 2013 and 2018, respectively (see [Table 1](#)).

River water temperature records were provided by Triton Environmental Consultants ([Triton, 1994](#)). These data derive from studies that investigate the potential for a cold water release facility at Kenney Dam. Water temperature measurements were collected at the WSC gauging sites at the outlets of the EUTSU, ENTIA, CHEDA and CHELA sub-basins, plus to two additional locations COLES and LAVEN, shown in [Fig. 1b](#) from June 7–9 until 12–13 October 1994, depending on location. Note that water temperature data is not available for WHITE and TAHOL. The data were recorded at 10-minute intervals and averaged to an hourly timestep. For model calibration and validation, the temperature data was further averaged to the daily mean. Over the period of record, a maximum water temperature of 20.9 °C was observed at CHELA, whereas a minimum water temperature of 1.5 °C was observed at the LAVEN station. The stations CHELA, CHEDA, ENTIA have a similar daily water temperature regime, with values around 11 °C in early June, reaching maxima around 19 °C in July, then dropping to 7.5 °C in late September/ early October. At these stations, the mean water temperature for the period of record is around 13.3 °C for CHELA and ENTIA and 12.5 °C for CHEDA. Water temperature at EUTSU, located on the south arm of the reservoir, is warmer in comparison, with a mean value of 15 °C. Water temperature at the LAVEN station did not exceed 11 °C during the period of record with a mean value of 7 °C.

#### 3.2.2. Reservoir level, inflow and outflow

Outflows at the Spillway and the powerhouse diversion, which provide the downstream boundary conditions of the model domain, were provided by Rio Tinto. Daily Powerhouse outflows are available from January 1, 1955, and daily outflows at the spillway are available from June 15, 1955. In addition, Rio Tinto has estimated daily total reservoir inflow for the same record period. The total net inflows were reconstructed using a water balance approach and estimated as the change in storage (using observations of surface level change) plus total outflow on a daily basis. Formally, daily inflows ( $Q_{inflow}$ ) are obtained as the sum of reservoir volume difference over a day ( $dS/dt$ ), water release at the spillway ( $Q_{SLS}$ ) and powerhouse intake ( $Q_{PH}$ ) i.e.  $Q_{inflow} = dS/dt + Q_{SLS} + Q_{PH}$ . Therefore, the inflow

estimates are potentially biased by the net difference between precipitation and evaporation over the reservoir surface area. Using mean annual precipitation from PNWNAmet (475 mm) and mean annual lake evaporation estimates (500–700 mm) from the Hydrological Atlas of Canada (Canadian National Committee for the International Hydrological Decade, 1978), the annual inflow bias is estimated to be very small, ranging between < 1–3% of average annual inflow. About 60% of inflow is diverted to the powerhouse and the remaining 40% is released through the spillway. In times of high inflows, the percentage of water released at the spillway is increased to maintain the reservoir surface below its maximum operating level. Historic reservoir water level records from 1955 to 2019 were also provided by Rio Tinto. On average the surface elevation is maintained at levels between 850.7 m (in April) and 852.5 m (in July). The inter-annual variation of Nechako water surface elevation is between 0.98 m and 3.92 m.

### 3.2.3. Water temperature profiles and temperature of outflow

Water temperature profiles collected during summer 1994 at Kenney dam and Nataalkuz Lake were provided by Triton Environmental Consultants (Triton, 1994). The records were measured every 10 min and averaged to an hourly timestep. Measurements were taken every 2 m beginning at a depth of 1 m below the surface to a depth of 57 m and 45 m at Kenney dam and Nataalkuz Lake, respectively.

Observations of the temperature of water released at the Skins Lake Spillway were provided by Rio Tinto. These data were recorded during the summers of 2016 and 2017. The water temperature data was recorded approximately 300 m below the spillway during summer 2016. However, this station was subject to large variations in stage, flow and turbulence and water temperature recordings were relocated to a site 1 km downstream during summer 2017. These data were recorded every 10 min and averaged to an hourly timestep.

### 3.3. VIC-GL and RBM implementation

The volume and temperature of reservoir inflow is simulated using the Variable Infiltration Capacity (VIC) model (Liang et al., 1994, 1996) coupled to the one-dimensional stream temperature River Basin Model (RBM) (Yearsley, 2009, 2012). VIC is a spatially distributed land surface model that simulates both water and energy balances. In this study VIC-GL, a version of the VIC model upgraded at PCIC that accounts for glacier processes, is used (Schnorbus, 2018). RBM is a gridded stream temperature model that uses a one-dimensional mixed Eulerian-Lagrangian approach. Water temperature is simulated by tracing water parcels and their flow characteristics (i.e., speed) along the channel network. For a specific segment of the channel network, water temperature is calculated from the local air-water surface heat exchange, and from heat advected from upstream and tributary inflow (Van Vliet et al., 2012). VIC-GL and RBM require meteorological forcing data that includes air temperature, total precipitation, wind speed, atmospheric pressure, solar radiation, and atmospheric density. Both VIC-GL and RBM operate on a spatial grid of 1/16° and provide output at a daily temporal resolution. Base VIC and RBM are described in detail in Cherkauer and Lettenmaier (1999), Yearsley (2009, 2012), and Van Vliet et al. (2012). The modification of VIC into VIC-GL is described in Schnorbus (2018).

The daily modelling VIC-GL-RBM framework is configured to model inflow volume and temperature from the six main tributaries that supply the Nechako Reservoir (see Fig. 1, Table 1) as identified according to WSC stations. These six sub-basins account for 70% of the upstream drainage area and, using precipitation distribution as a proxy, approximately 80% of the total inflow volume. The remaining area is mainly covered by the reservoir, and many small tributaries of insignificant size.

The hydrologic model was separately calibrated at each major tributary using Nash Sutcliffe Efficiency (NSE, Nash and Sutcliffe, 1970) and NSE of log streamflow (LNSE) to account for both low and high flows. The sub-basins WHITE and TAHOL were calibrated using a multi-site calibration that consist of constraining the model with the outlet (i.e., TAHOL and WHITE) stations as well as the upstream stations LAVEN and COLES. As only seasonal data are available for WHITE and TAHOL, the objective function included only the NSE for these stations, whereas both the NSE and LNSE of simulated flows were used at LAVEN and COLES stations. The calibration period for CHEDA, CHELA, ENTIA and COLES is the same as the flow record period (Table 1). The calibration for EUTSU station is 1993–1995 and the period from 2004 to 2012 is used for validation. Note that flow for the period between 1995 and 2004 are not available for this station. The calibration period for WHITE and TAHOL stations is 1946–1952. The calibration period for LAVEN is 1977–1994. Because of insufficient data, the model was validated for EUTSU station only.

Due to uncertainties caused by meteorological forcing and calibration data among other factors, hydrologic model outputs are often biased. Bias also results due to our deliberate choice to model only major inflow tributaries. The bias often appears as an underestimation of the variance of streamflow and inaccurate representation of the tails of the streamflow distribution, particularly in the extreme high flows (e.g., Farmer and Vogel, 2016; Farmer et al., 2018; Mizukami et al., 2019). Because the W2 model is highly sensitive to inflow data, post-processing of the simulated inflows is performed to correct any model deficiencies. Bias correction is applied using a quantile mapping approach, which is widely used and extensively described in the literature (e.g., Teutschbein and Seibert, 2012; Maraun, 2013; Spellman et al., 2018). This method consists of matching the model's simulated inflow distribution to the distribution of observed inflow magnitude. Bias correction is applied to the total simulated inflows using observed total inflows because they are available for sufficiently long period to derive the inflow distribution, unlike observed local streamflow. The total simulated inflow is computed as the sum of the streamflow at the 6 major tributaries.

After the bias correction of the total simulated inflows, bias corrected inflow at each tributary is estimated according to the mean contribution of each tributary to the total inflow as follows:

$$\hat{Q}_i(t) = \omega_i \hat{Q}_T(t) \quad (1)$$

where  $\hat{Q}_T(t)$  is the bias corrected total inflow at timestep  $t$  and  $\omega_i$  is the climatological contribution of tributary  $i$  to the total inflow defined as  $\omega_i = \frac{\bar{Q}_i}{\bar{Q}_T}$  where  $\bar{Q}_i$  is the average flow at tributary  $i$  and  $\bar{Q}_T$  is the average total inflow.

The RBM model is calibrated independently for each sub-basin by minimizing the mean absolute error (MAE) of daily average water temperature from June to October 1994 at each individual water temperature station shown in Fig. 1b. Note that because of insufficient water temperature data, RBM could not be validated.

### 3.4. CE-QUAL-W2 implementation

In this study the CE-QUAL-W2 model (W2) is chosen as it is a 2-dimensional (longitudinal and vertical) hydrodynamic and water quality model that simulates water surface elevation and temperature as well as several other water quality variables. The 2-dimensional nature of the model is well suited for relatively narrow and long waterbodies such the Nechako Reservoir (Cole and Wells, 2018). Other relevant features include the ability to simulate the onset growth and breakup of ice cover and the use of selective withdrawal calculations based on outlet geometry, outflow, and density. This model is open source and maintained by Portland State University, USA for Windows environment. This study uses a Linux version of the W2 model (Bornstein et al., 2022) which is available on an open-source GitHub project (<https://github.com/WQDSS/CE-QUAL-W2-Linux>). Details of CE-QUAL-W2 model can be found in Cole and Wells (2018) and only a short overview is presented here.

The W2 model is based on 2-D hydrodynamic time dependent differential equations that require initial and boundary conditions. To start a W2 simulation, the user must specify initial conditions of water surface elevation and water quality variables (only water temperature in this case). The degree to which the initial conditions affect the accuracy of the W2 model simulation depends upon the reservoir residence time and the duration of the simulation (Debele et al., 2008). The impact of initial conditions diminishes with decreasing residence time and/or longer simulation periods. In this study, the period between 1985 and 2017 is set as the simulation period. The initial water surface elevation is set to the observed reservoir level at the beginning of the simulation, whereas initial water temperature is set to 0 °C. Given that the Nechako Reservoir is mostly a shallow system, and the simulation period is long, the effect of the initial conditions on simulated water temperature will be negligible.

Boundary conditions required by W2 are surface boundary conditions, inflow, and outflow. The surface boundary conditions affect the water-atmosphere processes at the reservoir surface and include heat exchange, solar radiation absorption, and wind stress. Therefore, the model requires meteorological forcing data that includes air temperature, dew point temperature, wind speed and direction, and cloud cover (see Fig. 2). Precipitation is an optional meteorological input and is considered as an inflow that is supplied for each branch. As VIC-GL is calibrated against reconstructed inflows (see Section 3.4) that already account for reservoir evaporation and precipitation, W2 is run with evaporation and precipitation excluded from the water budget. The model uses cloud cover to calculate both shortwave radiation from sun angle relationship and longwave radiation. The model can use measured shortwave radiation by activating this option in the configuration file. As cloud cover data are not available, modifications were made such that longwave radiation is read from the meteorological file instead of calculating this flux from cloud cover. For each waterbody of the Nechako Reservoir, timeseries of the required meteorological forcing data (see Fig. 2) are extracted from the gridded PNWANmet-ERA5 data and supplied to the model at 3-hourly timestep. Note that the requirement for wind direction means that W2 can only be operated from 1980 to 2018.

The W2 model allows different types of inflow boundary conditions. Inflows can be supplied as upstream inflow (i.e., branch inflow), or as point or non-point sources called tributary and distributed tributary inflows. Four major tributaries feed the southern branch of the Nechako Reservoir (see Fig. 1c). Daily inflows are supplied as tributary inflow at the corresponding locations except for the Eutsuk River, which is supplied as branch inflow. Sub-basins in the northern branch of the Nechako Reservoir include Whitesail Lake Basin, and Tahtsa Lake and Tahtsa Reach (see Fig. 1). Discharge at the outlet of these basins is supplied to the W2 model as distributed tributaries for branch 1, representing the Whitesail Lake, and branch 5, representing Tahtsa Lake and Tahtsa Reach. The corresponding inflow water temperature at each tributary must also be supplied.

Outflow can be specified as a lateral withdrawal or as a downstream release from the reservoir through spillways, gates, pumps, etc. Lateral withdrawals are outflows that can be specified for any active cell of any W2 segment whereas the downstream outflows can only occur at the downstream segment of a branch. In this study, both water release at the Skins Lake Spillway and water withdrawal at the west end of the reservoir are identified as lateral withdrawals in the model. The outlet of the Nechako Reservoir at the Skins Lake Spillway consists of two gates which are opened at different water levels. However, the outflow data is only available as the total from both gates. Therefore, outflow was modelled using a single gate configured as a withdrawal with the W2 selective withdrawal algorithm used to determine the reservoir source layers. The selective withdrawal algorithm determines the vertical zone limits based on the outflow, outlet geometry and in-pool densities (Cole and Wells, 2018). Then it assigns flow for each layer within the identified withdrawal zone. This algorithm requires setting upper and lower boundary layers from which outflows do not occur. In this case an upper layer limit was set as the surface layer and a bottom layer limit was adjusted to equal the observed water temperature of the outlet.

The W2 model allow inputs at different timesteps. Hence, meteorological forcing is supplied at 3-hourly timestep whereas hydrological inputs (inflow, inflow water temperature and outflows) are supplied at daily timestep. According to the literature, the W2 model is relatively insensitive to hydraulic parameters, dispersion coefficients, and bottom friction parameters for the Chezy friction model and default values were used (Cole and Wells, 2018).

### 3.5. Bathymetry and W2 computational grid

Bathymetry is a key element in the development of the computational grid for the W2 model. Three different data sources were used to estimate Nechako Reservoir bathymetry. The first data set consisted of depth measurements taken in Tahtsa Lake in 2016 and a small area upstream of the Skins Lake spillway in 2019, which were provided by Rio Tinto. A second data set consisted of bathymetry contours that were reconstructed from aerial photos collected before impoundment of the reservoir (made available by Triton Environmental). As such the bathymetry contours are only available for the reservoir volume located between the current and pre-impoundment lake surfaces; it does not provide bathymetry for lakes and river volume that existed prior to impoundment. Lastly, the bottom elevations for the pre-existing lakes were constrained using pre-impoundment spot measurements taken from hand-drafted bathymetry maps produced in 1951/52 by the BC Department of Recreation and Conservation (scanned copies are available via <http://a100.gov.bc.ca/pub/fidq/viewBathymetricMaps.do>). A digital elevation model of reservoir bathymetry was estimated using ordinary Kriging on the combined elevation data sets.

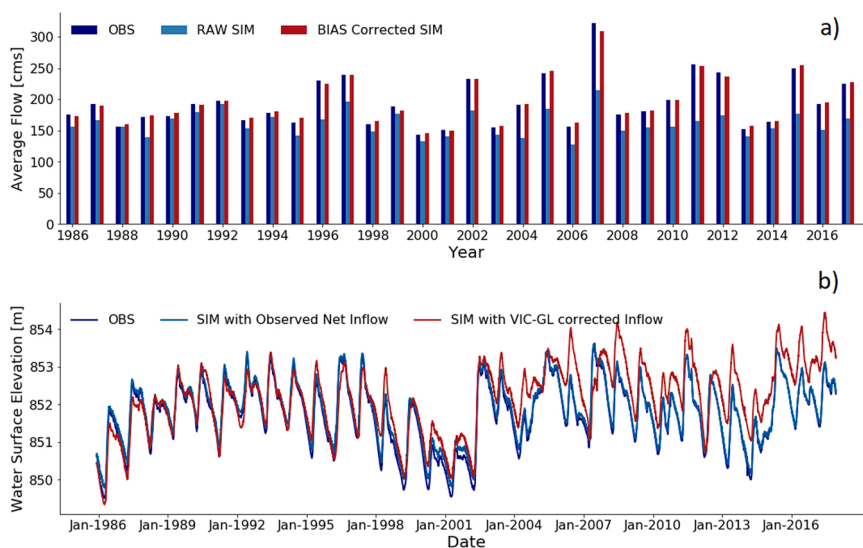
The W2 model is configured onto a computational grid by discretizing the reservoir along the longitudinal and vertical dimensions, whereby the longitudinal dimension is divided into segments and each segment is divided into vertical layers. Each grid cell is, therefore, characterized by its longitudinal location (i.e., segment), depth and cross-sectional width. The W2 allows for a variable grid, and the segment spacing is fixed to 1 km for most grid cells. However, at lake connections, the segment spacing was increased to ensure that branches only flow into a single segment, and the segment spacing upstream of the spillway is decreased to between 300 and 500 m. The depth and cross-section width of the computational grids were determined using reservoir bathymetry.

For most layers the vertical grid spacing was fixed at 2.2 m. However, Whitesail and Tahtsa Lakes are much deeper than the other lakes in the Nechako Reservoir, resulting in many inactive layers within the computational grid. Therefore, vertical layers lower than an elevation of 777 m, which is the bottom elevation at Kenney Dam, were spaced every 4.4 m. The cross-sectional width for each grid cell was estimated using the QGIS plugin CE-QUAL-W2\_Bathymetry ([https://plugins.qgis.org/plugins/create\\_bathymetry/](https://plugins.qgis.org/plugins/create_bathymetry/)) according to the estimated bathymetry. The final model grid has 425 segments and 86 layers. W2 allows modelling a system with multiple waterbodies where each waterbody has its own water quality parameters and meteorological forcing. To account for climate variability, the Nechako Reservoir is modeled as 6 waterbodies and 18 branches according to the pre-existing lakes (see Fig. 1c).

Bathymetry data is a key constraint on the accuracy of water surface elevation and water temperature simulations in the W2 model (Alcantra et al., 2010; Xie et al., 2017). Hence, the accuracy of the bathymetry was evaluated by forcing W2 with observed total inflows and observed meteorological data and comparing the simulated to the observed water surface elevation for the period spanning 1986–2017. The resulting model simulation shows good agreement with the observed water surface elevation, with a mean error of 0.11 m and a RMSE of 0.13 m (see Fig. 3b). Although this is not a strict validation of the estimated bathymetry (errors are also introduced via model parametrization and the meteorological data), it suggests that to a first order the volume of the reservoir is represented with reasonable accuracy.

### 3.6. Sensitivity analysis

To assess the sensitivity of water temperature to surface meteorology, a 20% increase is applied individually to each of the following input forcings: incoming longwave radiation, incoming shortwave radiation, air temperature and wind speed. The impact of



**Fig. 3.** Annual mean observed, bias -corrected, and raw VIC-GL simulated total inflows (a), and observed and simulated water surface elevation with CE-QUAL-W2 supplied with observed net inflows and VIC-GL bias corrected inflows for the period 1986–2017 (b).

air temperature is evaluated by increasing air temperature by 2 °C. The reservoir water temperature is simulated repeatedly by increasing one forcing element each time, and vertical temperature profiles are evaluated at the two key locations of Kenney Dam and the Skins Lake Spillway.

Flow regulation at the Nechako Reservoir has altered both downstream streamflow volume and seasonality. Average water release is approximately 32 m<sup>3</sup>/s at Skins Lake Spillway during fall and winter to support Chinook salmon (see Fig. 4a). The water release is increased during summer in response to warming trends to support sockeye salmon migration during the STMP period. The increased flow release during summer has created an unnatural peak flow in late July as opposed to the natural peak flow occurring in June. To assess the impact of flow regulation on the outflow thermograph, we evaluate the response of water temperature to changes in outflow seasonality and volume at the spillway. To do so, we consider two scenarios for outflow at the Skins lake spillway: 1) a 'combined-regulated' scenario where water release at the spillway is the total of the historical spillway and powerhouse intake flows ( $Q_{SLS}+Q_{PH}$ ), and 2) a 'natural' outflow scenario where water release at the spillway is equal to net inflow (see Fig. 4a). The first scenario evaluates changes to outflow volume at the spillway, but where flow seasonality remains regulated, and the second scenario mimics a natural outflow regime where outflow is unregulated. In each scenario, diversion to the powerhouse is set to zero.

## 4. Results

### 4.1. Model performance

#### 4.1.1. Inflow and inflow water temperature

Table 3 presents the performance of VIC-GL model to simulate streamflow at the outlet of the main tributaries of the Nechako Reservoir during the calibration period whereas Fig. 5 presents observed and simulated time series at these locations. The performance of VIC-GL varies by location with NSE ranging from 0.42 (ENTIA) and 0.78 (EUTSU) and a bias between 4% and 16%. Low flows are relatively well produced with a LNSE ranging from 0.46 (CHEDA) and 0.8 (EUTSU). LNSE is not reported for TAHOL and WHITE because the data are seasonal at these stations. Hence, these values would not be representative of the model performance reproducing low flows.

The total simulated inflows are evaluated for the period 1979–2017. Despite the good performance of VIC-GL at the station scale, the volume and timing of the total simulated inflows at the major tributaries do not adequately match the total historical inflow. The model annual bias is variable and substantially underestimates inflow during the high inflow years (see Fig. 3a). The model bias is caused by the underestimation of peak flows during high years and runoff from creeks and small tributaries that is not considered in the model. The model bias is 16 % whereas the NSE is 0.53. Given the tendency of VIC-GL to underestimate inflows, bias correction is applied to the simulated total inflows via quantile mapping as described in Section 3.3. Fig. 3a compares observed and corrected simulated annual mean inflows. The corrected mean annual inflows show good agreement with the observed net inflows and the NSE of the corrected net inflow timeseries is 0.76 with a bias of 0.65 %.

The model simulations from 1979 to 2017 are used to estimate the climatological contribution of each tributary to the total inflow. The EUTSU and TAHOL sub-basins are the major tributaries that feed the reservoir with 35 % and 33 % of total inflow respectively. The WHITE tributary contributes 16 % to the total inflow whereas the sub-basins ENTIA and CHEDA contribute 5 % and 2 % respectively.

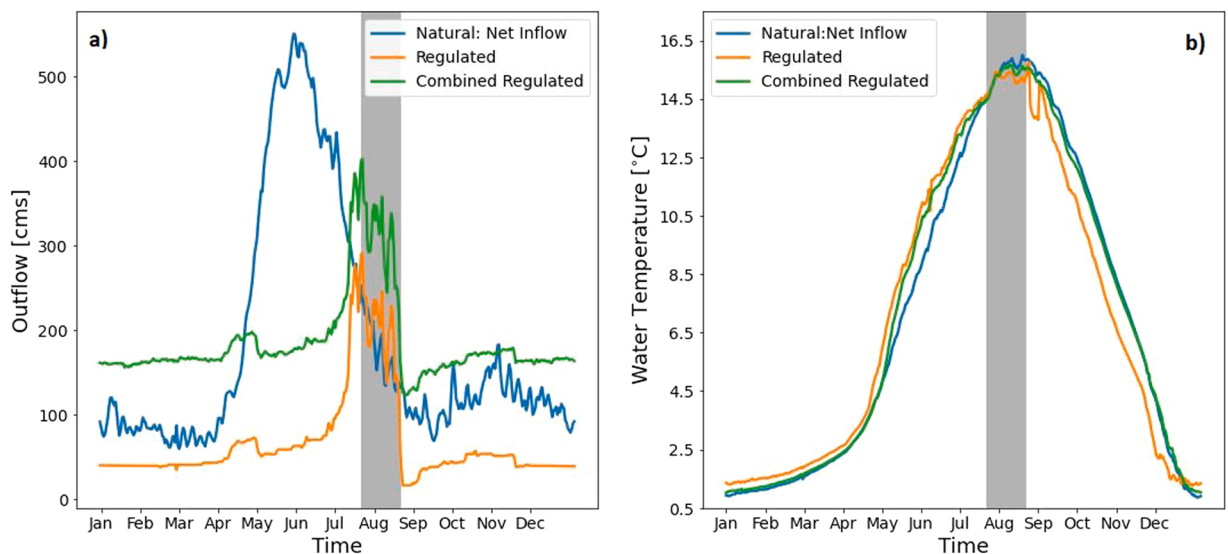
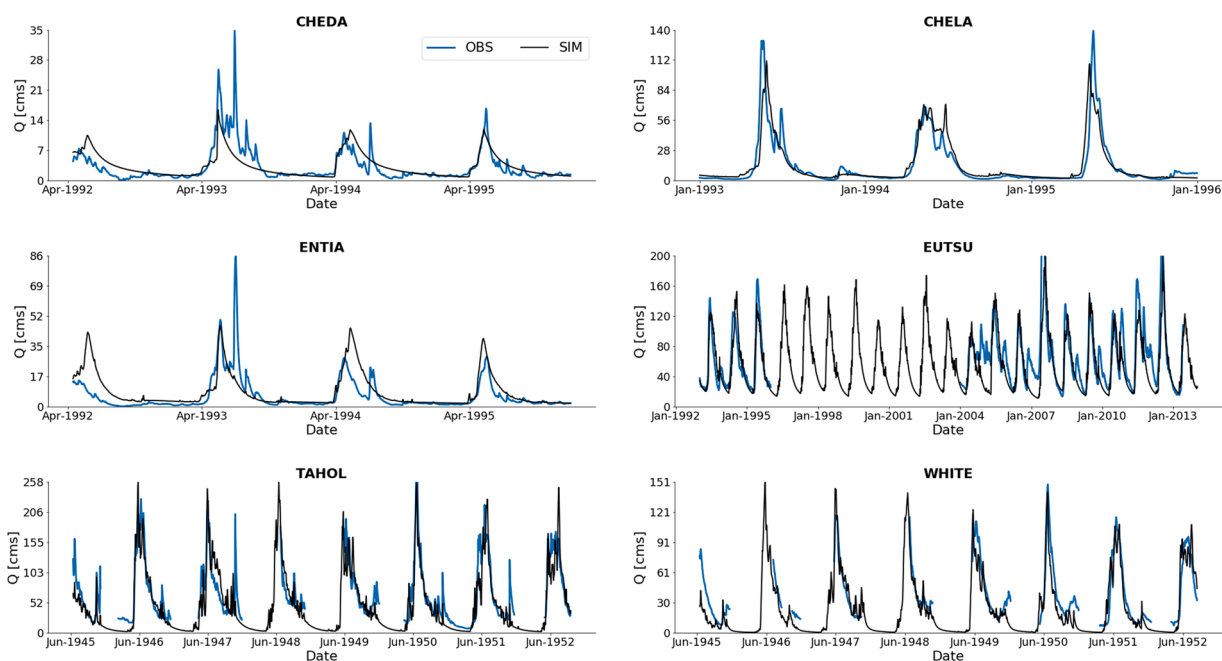


Fig. 4. Average daily spillway outflow for reference simulation ('Regulated') and the two outflow scenarios ('Regulated Combined' and 'Natural') (a), with associated temperature of water released (b) for the period 1986–1998. The shaded area corresponds to STMP period (July 20th to August 20th).

**Table 3**

Performance of the calibrated VIC-GL at the 6 major tributaries of the Nechako Reservoir during calibration (validation period).

Basin	NSE	LNSE	Bias (%)
CHEDA	0.54	0.46	4
CHELA	0.75	0.78	4
ENTIA	0.42	0.52	4
EUTSU	0.78(0.62)	0.80(0.35)	1(14)
TAHOL	0.72	-	9
WHITE	0.73	-	16



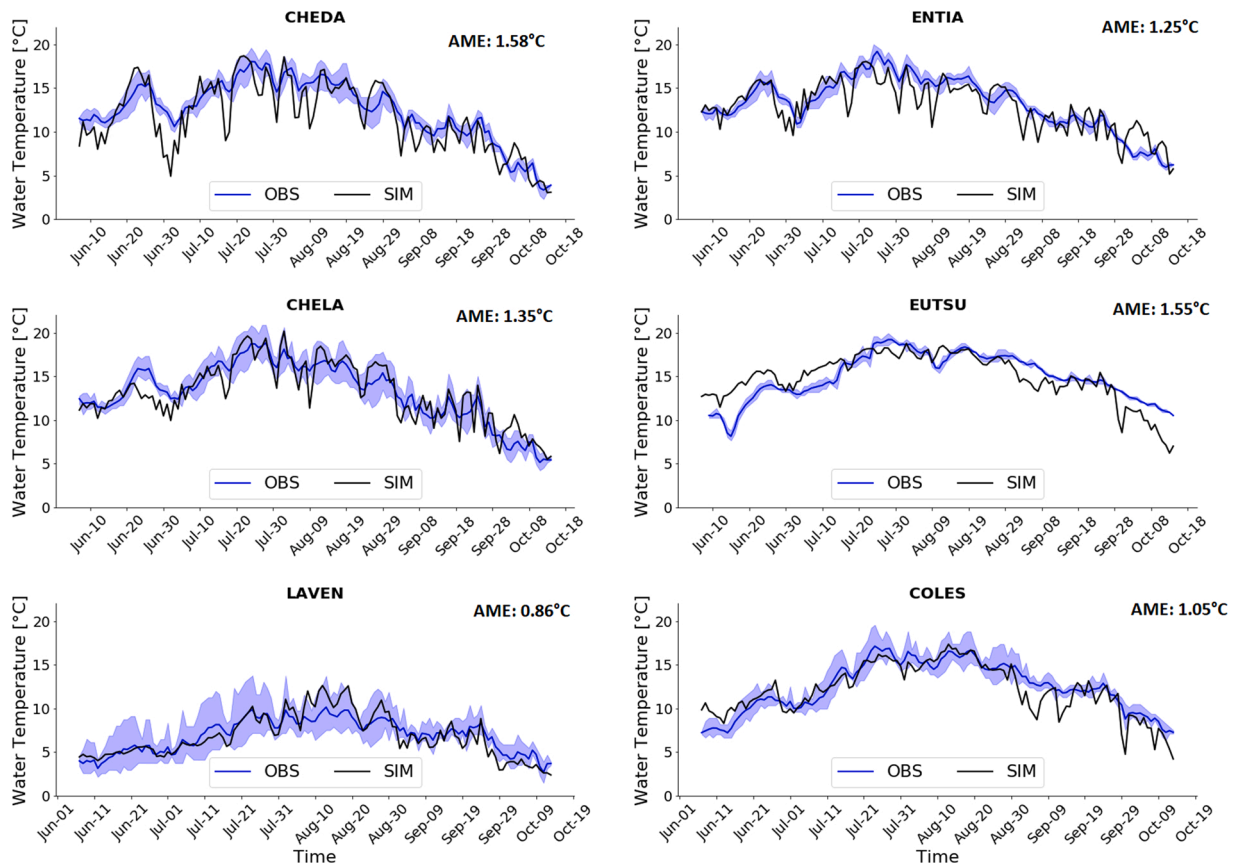
**Fig. 5.** Observed and simulated streamflow at each hydrometric station during the calibration period. Timeseries of EUTSU basin covers both calibration (1993–1995) and validation (2004–2013).

The CHELA tributary contributes 9 % to the total inflow. These estimated contributions are applied to the total bias corrected inflow to estimate bias corrected inflow at each tributary using Eq. (1).

Fig. 6 compares observed and RBM simulated daily water temperature of all tributaries from June to October 1994. In addition, the observed daily maximum and minimum water temperature (extracted from the hourly data) are used to evaluate the model's ability to simulate daily water temperature between these ranges. The MAE values for daily mean temperature range from 0.86 °C at LAVEN station to 1.58 °C at CHEDA station. The model does well in representing the seasonal variability of stream temperatures. The daily variability of water temperature is well represented at the North-west stations (LAVEN and COLES) and CHELA, but it is over-estimated in the southern stations CHEDA and ENTIA. The observed daily variability of water temperature at EUTSU is very low and over-estimated in the simulation. Note that this station is located at the outlet of Eutsuk Lake, which is not explicitly modelled, likely explaining the poor performance of VIC-GL-RBM at this station. Nevertheless, the overall performance of RBM seems satisfactory. Due to the short length of water temperature observations (one summer only) it is not possible to evaluate the model under different climatic conditions.

#### 4.1.2. Reservoir level and thermal conditions

Using the simulated bias corrected inflow and observed Spillway and Powerhouse outflows, we evaluate the accuracy of W2 in representing the water surface elevation for the period 1986–2017. The initial water surface elevation is fixed to the observed reservoir level at the beginning of the simulation period. Then we evaluate model performance to simulate the wide variation of water surface elevation as suggested by Cole and Wells (2018) over the entire period. Comparisons of simulated and observed reservoir levels, using corrected modelled inflow, are depicted in Fig. 3b. The W2 model simulates reservoir levels well for the entire simulation period (1986–2017, Fig. 3), with a RMSE of 0.63 m and mean error of 0.42 m. However, there is an increased bias following 2003 which can be due a remaining inflow bias. Note that bias correction aims at matching distribution of inflows and year to year simulated and observed inflows do not necessarily match. Since actual records of spillway discharge and powerhouse intake are used to simulate



**Fig. 6.** Simulated and observed tributary water temperature for summer 1994. Observed data shown as daily mean (line) with daily minimum and maximum (ribbon).

surface elevation, the bias in timing of inflow might explain the increased bias.

Water temperature profiles are evaluated at an hourly timestep at Kenney Dam and Natalkuz Lake for the summer of 1994. W2 accurately simulates water temperature at the Kenny dam at all depths with a MAE of 0.59 °C and RMSE of 0.72 °C for the entire evaluation period. The MAE of the timeseries at Natalkuz Lake is approximately 1.52 °C and the RMSE is 1.83 °C. The low performance at this location is due the poor model performance in reproducing extreme surface temperature for the period spanning July 12 to July 15. Hourly simulated and observed water temperature profiles are depicted in Fig. 7 for selected dates. The entire timeseries of temperature profiles are supplied in the [supplementary material](#). W2 does well in representing the seasonal progression of surface temperature, which is approximately 15 °C at end-June, reaches a maximum of 22 °C during late July, then decreases throughout September to October. The main features in the seasonal progression of the water temperature profiles are also captured well by W2, including the deepening of the thermocline and epilimnion in June and July and again from August to October, as well as the development of strong stratification from mid-August to mid-October. In both the observations and simulations, the top of the hypolimnion remains at a depth of approximately 30 m and has a water temperature of around 5 °C for the entire evaluation period.

Performance of the W2 model to simulate temperature of water released at the Spillway is evaluated by comparing model simulation to water temperature recorded over summer 2016 and 2017. The MAE of water temperature released at the spillway is 0.21 °C for the period between June to October 2016 and 0.44 °C for the period June to early November 2017. Note that during summer 2017 water temperature was recorded 1.3 km below the spillway whereas during summer 2016 water temperature was recorded 300 m below the spillway. Therefore, summer 2016 observations are likely more representative of the temperature of spilled water than are those collected in summer 2017, which may reflect additional warming in the channel below the spillway. Overall, the model has small bias during summer but underestimates water temperature during autumn.

#### 4.2. Meteorological and outflow sensitivity

To reduce computational time, the period 1986–1998 forms the basis for the meteorological sensitivity analysis and outflow scenarios. We evaluate the thermal sensitivity to a 20% increase in each of the forcing data separately at Kenney Dam and Skins Lake Spillway (Fig. 8). The water temperature profile is most sensitive to changes in incoming longwave or shortwave radiation. A 20% increase in longwave radiation leads to a surface temperature increase of 1.65 °C at Kenney Dam and 1.71 °C at the spillway, and an

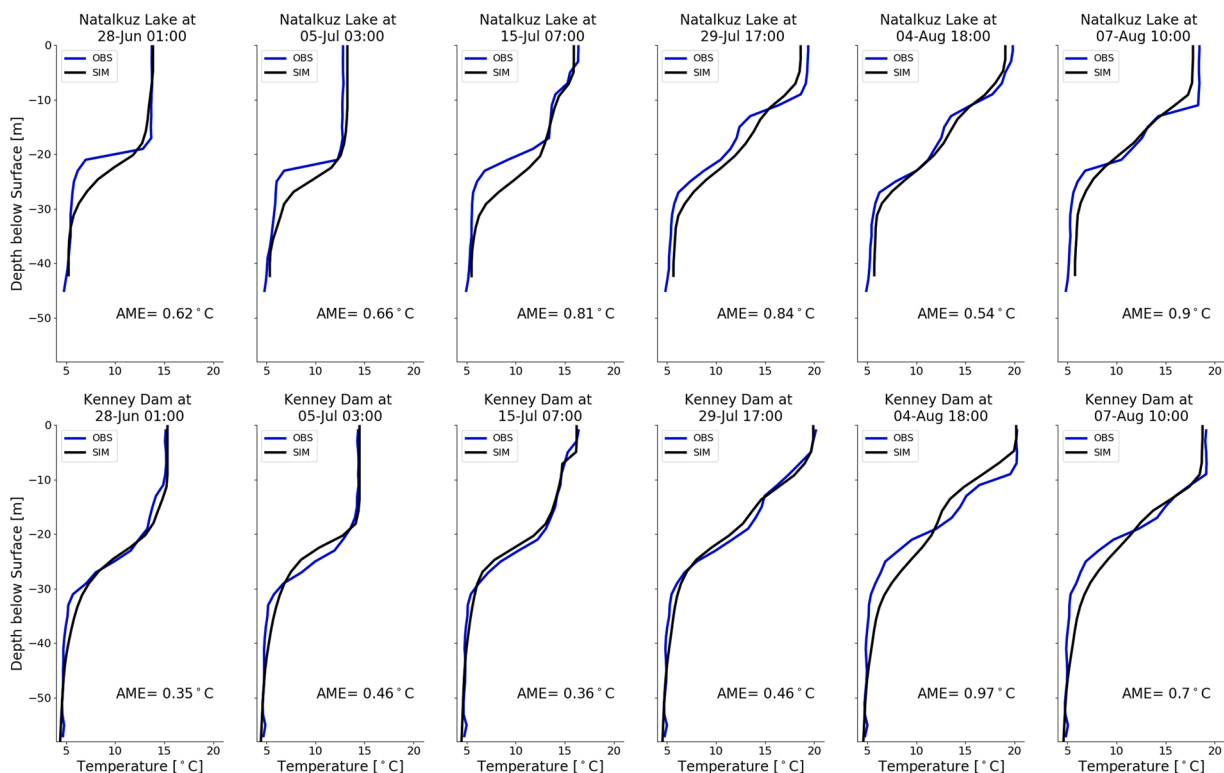


Fig. 7. Hourly simulated and observed water temperature profiles at Natakuz Lake (upper row) and at Kenney Dam (bottom row).

increase in shortwave radiation leads to a surface temperature increase of  $1.14\text{ }^{\circ}\text{C}$  at the spillway and  $1.12\text{ }^{\circ}\text{C}$  at Kenney dam. Increasing air temperature by  $2\text{ }^{\circ}\text{C}$  leads to a  $0.30\text{ }^{\circ}\text{C}$  increase in surface water temperature. Increasing the wind speed by 20 % increases evaporative heat loss, which decreases the temperature at the water surface by  $0.4\text{ }^{\circ}\text{C}$  at both the Kenney Dam and the Skins Lake spillway locations. Increased air temperature, longwave radiation, and solar radiation increases the temperature of the water column up to 30 m below surface level at the Skins Lake spillway and Kenney Dam. Increased wind speed decreases water temperature until about 10 m below surface level and slightly increases water temperature between 10 m and 27 m below surface level. In deeper layers (i.e. below 40 m), the water temperature is insensitive to changes in meteorological input.

At both locations, diverting all outflow to the Skins Lake Spillway has a strong impact on the water temperature profile. Surface temperature is only slightly elevated, and a much weaker temperature gradient develops as compared to the reference simulation (Fig. 8). Consequently, the largest water temperature increase occurs at approximately 20 m below the surface, and water temperature remains elevated throughout the profile at Skins Lake and to a depth of approximately 45 m at Kenney Dam. The result is similar for both outflow scenarios, although the natural flow regime generates the weaker temperature gradient (i.e. largest temperature increase at depth). As mentioned, the surface temperature response is small, being almost negligible at Skins Lake and less than  $0.5\text{ }^{\circ}\text{C}$  at Kenney Dam. At Kenney Dam, water temperature below roughly 45 m is generally insensitive to changes in the outflow regime.

Fig. 4 compares the outflow hydrographs and thermographs at the Skins Lake spillway for the historical outflow scenario, plus the two hypothetical scenarios. In the ‘combined-regulated’ scenario ( $Q_{\text{SLS}} + Q_{\text{PH}}$ ), although the volume of spillway outflow is increased, the seasonality is still highly regulated with large baseflow ( $150\text{--}175\text{ m}^3/\text{s}$ ) throughout much of the year and a large outflow pulse over the STMP period. This contrasts with the ‘natural’ ( $Q_{\text{SLS}} = \text{Net Inflow}$ ) scenario with lower baseflow in fall and winter followed by a large freshet that peaks in June. Releasing outflow by restoring a more natural regime at the spillway leads to releasing cooler surface water during spring and early summer (i.e., during the snowmelt freshet), but warmer water during fall compared to the current water release conditions. Outflow water temperature in the ‘combined-regulated’ scenario adheres more closely to historical release conditions during spring but is warmer in the fall and early winter. During the summer, particularly the STMP period, outflow water temperature for the scenarios does not depart markedly from what transpired under historical outflow conditions.

Results for the meteorological and outflow sensitivity are further synthesized in Fig. 9, which shows the mean variation of water temperature by depth (up to 33 m below the surface) over the year at the spillway. With respect to the reference simulation, increases in the meteorological forcings are most pronounced near the surface, whereas changing the outflow regime has a larger effect on water temperature throughout the profile.

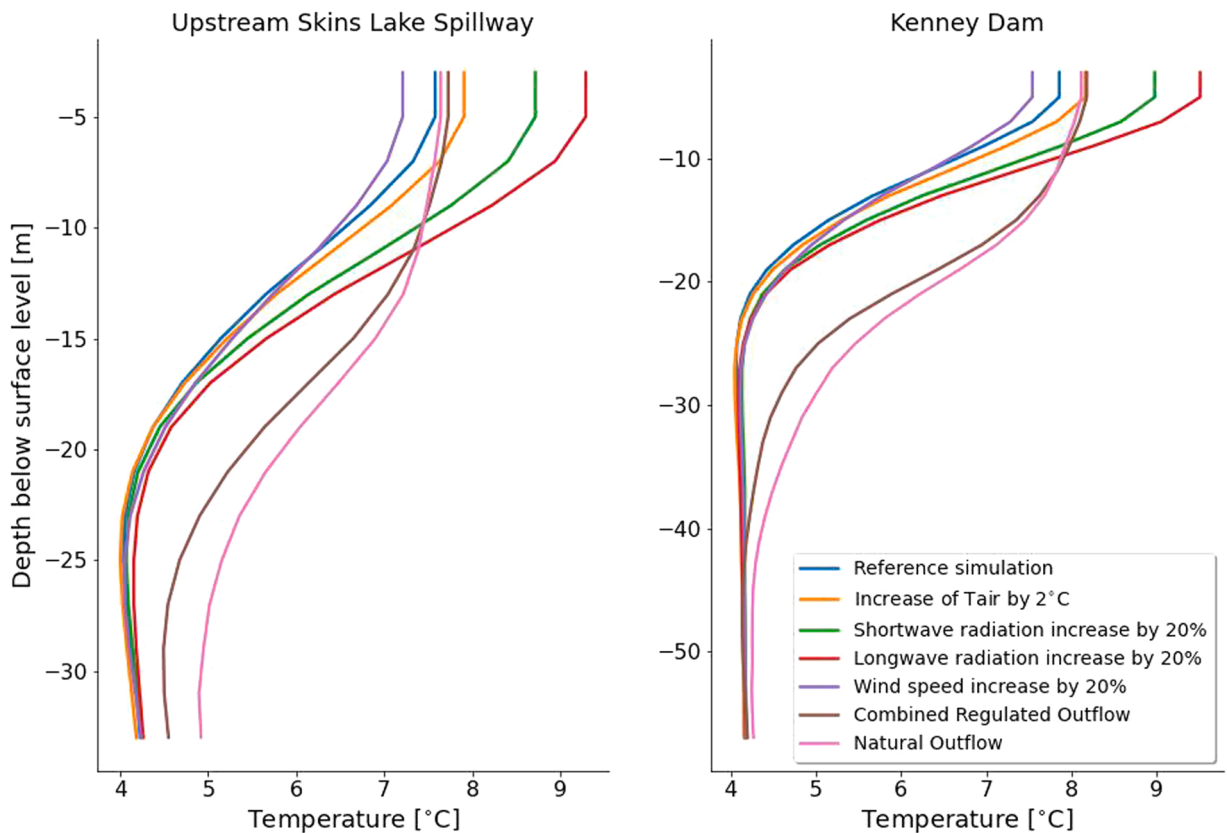


Fig. 8. Sensitivity analysis of input data affecting the water temperature at the Skins Lake Spillway (left) and Kenney Dam (right). Vertical profiles are average simulated water temperature profiles derived by independently changing each input.

## 5. Discussion

The Nechako Reservoir is a large multi-basin reservoir with narrow southern and northern arcs. Implementing a detailed hydrologic model that captures all streams that feeds the reservoir is challenging due to the complex geometry of the reservoir itself and limited data representing the spatial variability of reservoir hydrology to constrain such model. In this paper, the hydrologic model VIC-GL was implemented to the six major tributaries feeding the reservoir. The developed model was able to simulate both the spatial variability of discharge and the overall total volume of inflow. However, the model failed to reproduce the inter-annual variability and high flow years. Inaccuracy of representing high streamflow extreme and streamflow variability may be caused by a precipitation bias. It is likely that the gridded precipitation dataset used here, underestimate extreme precipitation and inter-annual precipitation variability which resulted in poor hydrologic model performance to simulate high inflow years. In our case, modelling only the six major tributaries also contributed to model bias, which manifested as underestimation of actual inflows. The area of the watershed that is not modelled may contribute more inflow during high flow years which could have exacerbated the model bias during high flow years. In addition, inaccuracy of representing high streamflow extreme and streamflow variability is a common issue in hydrological modelling (Farmer and Vogel, 2016; Farmer et al., 2018; Mizukami et al., 2019). When simulated streamflow are routed through a reservoir model, inflow bias may severely affect water resources decisions (Farmer et al., 2018). Hence, bias correction of hydrological model outputs is a necessary step when used as an upstream boundary condition for a hydrodynamic model.

Due to limited records of water temperature of tributaries, temperature of water release and water column in the reservoir, the model was calibrated only to summer temperatures. The model simulates accurately the temperature of the water column and temperature of water released at the spillway during the warmer months of July and August, but underestimates water temperature from mid-September to early October with a bias of 1.26 °C. Additional water temperature measurements extending beyond summer would be necessary to improve the model performance during fall and early spring.

Nevertheless, retrospective simulation shows that the model is able to simulate the wide variation of water surface elevations (Fig. 3), and the seasonality of evaporation flux, water surface temperature, and ice-cover (see Fig. 10). The onset of the ice thaw is around late January and ice break-up occurs around early April (day 97). The freeze back occurs around late November to early December (day 330 at Tahtsa Lake and day 339 at Kenney Dam). Although we have no direct observations of lake ice phenology for the reservoir, these dates are generally consistent with regional estimates. For instance, the Hydrological Atlas of Canada estimates freeze-over (lake completely ice-covered) to occur between November 15th and December 1st and ice-free conditions to occur between April

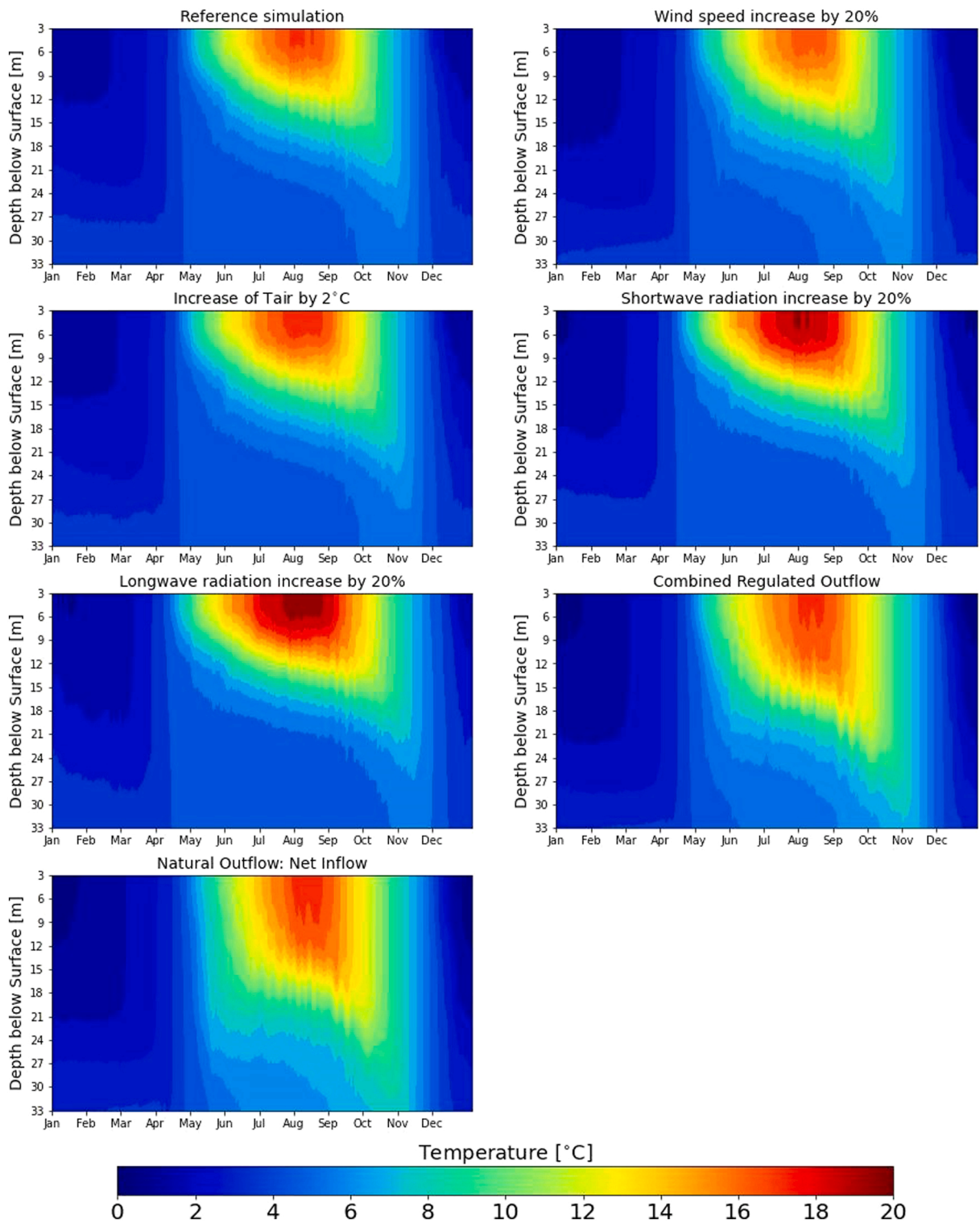
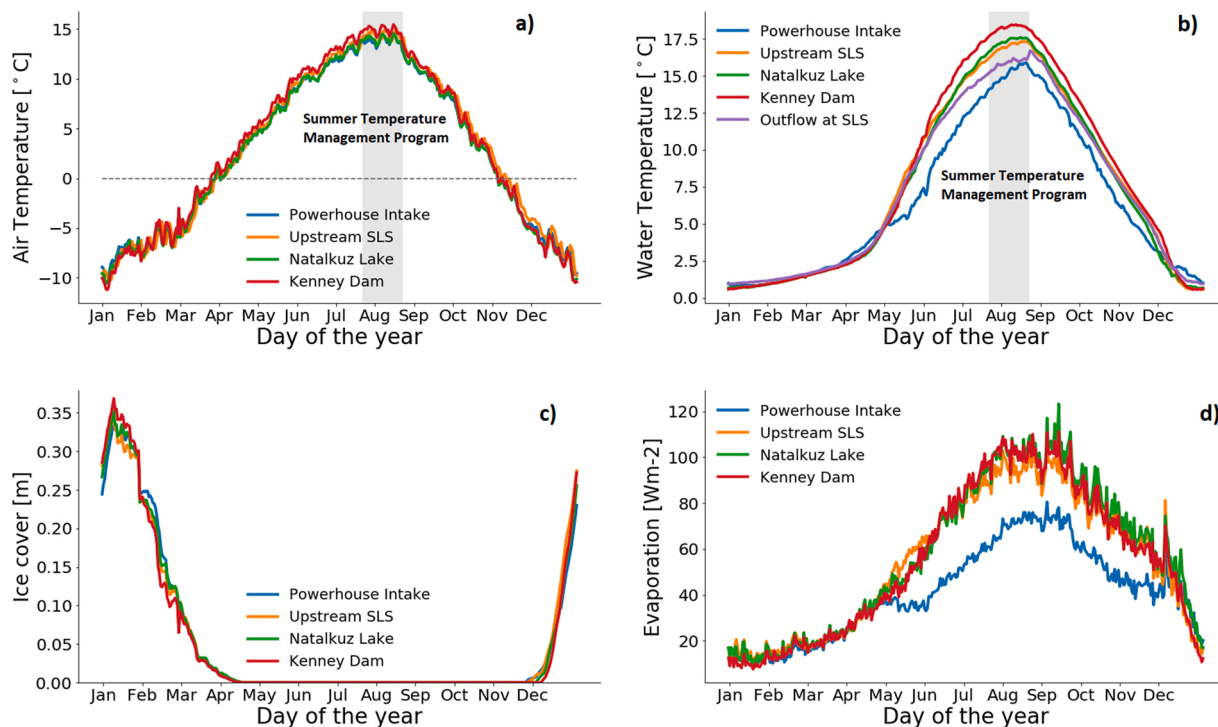


Fig. 9. Average daily temperature profile upstream the Skins Lake Spillway for reference simulation and meteorology and outflow sensitivity simulations.

15th and May 1st (Allen, 1978). Using data from the Global Lake and River Ice Phenology database (Benson et al., 2000) for nine regional lakes (Anahim, Burns, Hourglass, Kathlyn, Lakelse, Nukko, One Eye, Stuart, and Williston), we obtain a mean freeze-over date of November 27 (day 331) and a mean ice-off date of April 30th (day 120). The variation of ice cover is affected by the location and



**Fig. 10.** Daily mean of air temperature (a), water surface temperature and water temperature released at the Skins Lake Spillway (i.e., Outlet) (b), ice cover (c) and evaporative heat flux (d) for the period 1987–2016 over different segments of the Nechako Reservoir: powerhouse intake, Upstream Skins Lake Spillway (SLS), Natakuz Lake and Kenney Dam. The shaded area corresponds to the STMP period (July 20th to August 20th).

temperature of inflows and outflows, evaporative wind variations over the ice-surface, and effects of water movements on the ice-to-water exchange (Cole and Wells, 2018). The evaporation flux is also spatially variable over the Lake (Fig. 10d). The lower evaporation heat flux at northwestern part of the reservoir (i.e. Tahts Lake) coincides with cooler surface water as compared to the other locations (Fig. 10b). Spatial variability of evaporation due to spatial differences in surface water temperature was observed in other lakes in the region (e.g., Spence and Hedstrom, 2015).

The sensitivity analysis shows that radiation is the dominant heat source to the reservoir. Increased air temperature also warms the epilimnion, whereas increased wind speed cools the epilimnion temperature. These results suggest that reservoir surface temperature is most vulnerable to possible future increases in solar and longwave radiations. However, projected changes in solar radiation over the coming century are uncertain, predominantly due to variation in the treatment of cloud cover and aerosols in global and regional climate models (Bartók et al., 2017; Chen, 2021). Although no literature on projected changes in longwave radiation could be found, rising air temperatures and the associated increase in water vapor would presumably see an increase in downwelling longwave radiation. Our analysis indicates that air temperature is not as dominant a factor in surface heat exchange, and suggests that reservoir water temperature will be less vulnerable to increasing air temperature.

Modifying the outflow rate at the spillway changes the thermal stratification of the reservoir (Fig. 9) but has less overall impact on water temperature at the surface. Although adopting a more natural outflow regime at the spillway would potentially reduce the surface water temperature in the spring, such a regulatory change would be ineffective at reducing the outflow temperature during the critical STMP period in July and August. Overall, the results of the reference simulation and the two outflow scenarios indicate that outflow temperature at the spillway during the STMP is insensitive to any plausible outflow regime. These results agree with the findings of Triton (2021) in that total volume of water released during the STMP does not correlate with the number of exceedances of water temperature above 20  $^{\circ}\text{C}$  at the downstream thermal constraint. Historically, the STMP was efficient at maintaining water temperature in the Nechako River below 20  $^{\circ}\text{C}$  (Macdonald et al., 2012; Fraser Basin Council, 2015). However, this may not be the case under rising air temperatures. For example, summer 2013 saw a record of twenty-two days out of the thirty-day control period (July 20th to August 20th) with water temperature exceeding 20  $^{\circ}\text{C}$  downstream due to channel warming below the reservoir as a result of extreme high air temperatures, despite a record volume of water released from the spillway during the STMP period (Triton, 2021). This suggests that the efficiency of STMP to provide cool water during the sockeye salmon migration could be limited in a warming climate where no management options currently exists to reduce outflow water temperature. Water withdrawal from the hypolimnion at Kenney dam could potentially help regulate water temperature in the Nechako River.

For consideration of a cold-water release facility at Kenney Dam, it has been suggested that a temperature of 10  $^{\circ}\text{C}$  would be necessary to reduce the occurrence of water temperature above 20  $^{\circ}\text{C}$  in the Nechako River above the Stuart confluence during the STMP period (Lawrence and Pieters, 2005). Retrospective simulation shows that the thermocline layer lies between 10 and 30 m, and

water temperatures below 10 °C are available, on average, at depths below 20 m during the STMP period). This is consistent with the findings of Triton (1994) where the depth of the 10 °C isotherm was observed to be between 17 m and 21 m from June through August.

Currently, there is no water release at Kenny Dam. The proposed model would be useful to provide insight on how different selective water withdrawal scenarios at Kenny Dam could impact downstream water temperature requirements. In the same context, the model could also be used to regulate reservoir thermal stratification and water release temperature through reservoir operations (He et al., 2022). To do so, the model should be linked with a reservoir operation model (i.e. decision-making model).

In this study, the VIC-GL and RBM models were used to provide upstream boundary conditions of the CE-QUAL-W2 model whereas historical outflows were provided as downstream boundary conditions. To develop adaptation strategies or for climate change impact assessment, coupling this modelling framework with a reservoir operation model forced with simulated streamflow is critical. Using a reservoir operation model based on a dynamic approach aiming at designing operations to accommodate water use trade-offs, forced with inflow scenarios is an efficient way to anticipate the reservoir adaptation strategies (Giudici et al., 2021).

## 6. Conclusion

Motivated by the need to understand and manage reservoir impacts on water temperature in the Nechako River under future climates, a modelling system able to provide prognostic estimates of in-reservoir water temperature and outflow temperature of the Nechako Reservoir has been developed. Simulation of the Nechako Reservoir system is undertaken by coupling hydrologic, stream water temperature, and hydrodynamic models (VIC-GL, RBM and CE-QUAL-W2). The VIC-GL and RBM models are used to simulate inflow volume and temperature from the surrounding drainage area and the CE-QUAL-W2 model is used to simulate processes controlling reservoir water level and temperature.

VIC-GL performance is reasonable, although bias correction of the model output was necessary given the sensitivity of CE-QUAL-W2 to the inflow data bias. The limited records of the stream water temperature (only one summer) and station discharge did not permit calibration and evaluation of VIC-GL and RBM under different climatic conditions. The CE-QUAL-W2 model was evaluated by modelling the entire period of simulation continuously instead of calibrating and validating on two independent periods. The model is able to simulate the wide variation of water surface elevations. It is also capable of simulating the in-reservoir and outlet water temperature accurately during the warmer months of July and August. However additional data are required to improve the model performance during fall.

Sensitivity analysis of the CE-QUAL-W2 model was conducted using perturbations of surface forcing (solar and longwave radiation, air temperature, and wind speed). The modifications result in changes in both the surface temperature and the temperature gradient with depth, with the model showing the greatest sensitivity to perturbations in incoming solar and longwave radiation. Forcing the model with different outflow scenarios, the results show that outflow water temperature is weakly sensitive to outflow volume during the Summer Temperature Management Program (STMP) period (i.e., July 20th to August 20th), a time which is critical for salmon migration. These findings suggest that the efficiency of STMP to provide cool water downstream would be limited during extreme high air temperatures. However, the direct relationship between water temperature at the spillway and the number of exceedances of water temperature above 20 °C at Finmoore (constraint location) will be the subject of future study.

The integrated model was applied in this paper to simulate the Nechako reservoir under historical operations of water withdrawal at the Powerhouse in-take and water release at the Skins Lake Spillway. It has been demonstrated that the modelling system is able to realistically simulate the volume and thermal dynamics of the Nechako reservoir system. In future work this model will be used to explore the reservoir response to future climates and alternative management strategies.

## CRedit authorship contribution statement

**Samah Larabi:** Conceptualization, Methodology, Software, Validation, Writing – original draft, Writing – review & editing. **Markus A. Schnorbus:** Conceptualization, Methodology, Writing – review & editing. **Francis Zwiers:** Funding acquisition, Writing – review & editing.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data Availability

Data will be made available on request.

## Acknowledgements

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## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.ejrh.2022.101237](https://doi.org/10.1016/j.ejrh.2022.101237).

## References

- Albers, S.J., Déry, S.J., Petticrew, E.L., 2016. Flooding in the Nechako River Basin of Canada: a random forest modeling approach to flood analysis in a regulated reservoir system. *Can. Water Resour. J. / Rev. Can. Des. Ressour. Hydr.* 250–260. <https://doi.org/10.1080/07011784.2015.1109480>.
- Alcantra, E.H., Setech, J.L., Lorenzetti, J.A., et al., 2010. Remote sensing of water surface temperature and heat flux over a tropical hydroelectric reservoir. *Remote Sens. Environ.* 114, 2651–2665.
- Allen, W.T.R., 1978. Freeze-up and break-up of rivers and lakes. Plate 19 in hydrological atlas of Canada. *Fish. Environ. Can.* 34.
- Ashofteh, P.S., Haddad, O.B., Mariño, M. A., 2013. Climate change impact on reservoir performance indexes in agricultural water supply. *J. Irrig. Drain. Eng.* 139, 85–97. [https://doi.org/10.1061/\(ASCE\)IR.1943-4774.0000496](https://doi.org/10.1061/(ASCE)IR.1943-4774.0000496).
- Azadi, F., Ashofteh, P.-S., Chu, X., 2021. Evaluation of the effects of climate change on thermal stratification of reservoirs. *Sustain. Cities Soc.* 66, 102531 <https://doi.org/10.1016/j.scs.2020.102531>.
- Blachut, S.P. 1988. The winter hydrologic regime of the Nechako River, British Columbia, Can. MS Rep. Fish. Aquat. Sci. No. 1964: ix+145p.
- Bartók, B., Wild, M., Folini, D., et al., 2017. Projected changes in surface solar radiation in CMIP5 global climate models and in EURO-CORDEX regional climate models for Europe. *Clim. Dyn.* 49, 2665–2683. <https://doi.org/10.1007/s00382-016-3471->
- Benson, B., Magnuson, J., Sharma, S., 2000. Global Lake and River Ice Phenology Database, Version 1. NSIDC: National Snow and Ice Data Center, Boulder, CO, USA. <https://doi.org/10.7265/N5W66HP8>. August 18, 2021.
- Bohn, T.J., Livneh, B., Oyster, J.W., Running, S.W., Nijssen, B., Lettenmaier, D.P., 2013. Global evaluation of MTCLIM and related algorithms for forcing of ecological and hydrological models. *Agric. For. Meteorol.* 176, 38–49. <https://doi.org/10.1016/j.agrformet.2013.03.003>.
- Bornstein, Y., Dayan, B., Cahn, A., Wells, S., Housh, M., 2022. Environmental decision support systems as a service: demonstration on CE-QUAL-W2 model. *Water* 14, 885. <https://doi.org/10.3390/w14060885>.
- Canadian National Committee for the International Hydrological Decade, 1978. Hydrological atlas of Canada: Atlas hydrologique du Canada. *Fish. Environ. Can.*
- Chen, L., 2021. Uncertainties in solar radiation assessment in the United States using climate models. *Clim. Dyn.* 56, 665–678. <https://doi.org/10.1007/s00382-020-05498-7>.
- Cherkauer, K.A., Lettenmaier, D.P., 1999. Hydrologic effects of frozen soils in the upper Mississippi River basin. *J. Geophys. Res.* 104, 19599–19610.
- Cole, T.M., and Wells, S.A. 2018. CE-QUAL-W2: A two-dimensional, laterally averaged, hydro-dynamic and water quality model, version 4.1, Department of Civil and Environmental Engineering, Portland State University, Portland, OR.
- Cole, T., Wells, S., 2006. CE-QUAL-W2: A Two-dimensional, Laterally Averaged, Hydrodynamic and Water Quality Model, Version 3.5. Civ. Environ. Eng. Fac. Publ. Present.
- Copernicus Climate Change Service (C3S), 2017: ERA5: Fifth generation of ECMWF atmospheric reanalyses of the global climate. Copernic. Clim. Change Serv. Clim. Data Store CDS. (Accessed September 14, 2019).
- Debele, B., Srinivasan, R., Parlange, J.-Y., 2008. Coupling upland watershed and downstream waterbody hydrodynamic and water quality models (SWAT and CE-QUAL-W2) for better water resources management in complex river basins. *Environ. Model. Assess.* 13, 135–153. <https://doi.org/10.1007/s10666-006-9075-1>.
- Farmer, W.H., Vogel, R.M., 2016. On the deterministic and stochastic use of hydrologic models. *Water Resour. Res.* 52, 5619–5633. <https://doi.org/10.1002/2016WR019129>.
- Farmer, W.H., Over, T.M., Kiang, J.E., 2018. Bias correction of simulated historical daily streamflow at ungauged locations by using independently estimated flow durations curves. *Hydrol. Earth Syst. Sci.* 22, 5741–5758.
- Fraser Basin Council, 2015. Nechako Watershed Health Report. 59pp.
- French, T.D., Chambers, P.A., 1997. Reducing flows in the Nechako River (British Columbia, Canada): potential response of the macrophyte community. *Can. J. Fish. Aquat. Sci.* 54, 2247–2254.
- Giudici, F., Anghileri, D., Castelletti, A., Burlando, P., 2021. Descriptive or normative: How does reservoir operations modeling influence hydrological simulations under climate change? *J. Hydrol.* <https://doi.org/10.1016/j.jhydrol.2021.125996>.
- Hartman, G.F., 1995. Impacts of growth in resource use and human population on the Nechako River: a major tributary of the Fraser River, British Columbia, Canada *Impacts. Geo J.* 147–164.
- He, W., Jiang, A., Zhang, J., et al., 2022. Reservoir optimization operation considering regulating temperature stratification for a deep reservoir in early flood season. *J. Hydrol.* <https://doi.org/10.1016/j.jhydrol.2021.127253>.
- Hipsey, M.R., Bruce, L.C., Boon, C., Busch, B., Carey, C.C., Hamilton, D.P., Hanson, P.C., Read, J.S., de Sousa, E., Weber, M., Winslow, L.A., 2019. A General Lake Model (GLM 3.0) for linking with high-frequency sensor data from the Global Lake Ecological Observatory Network (GLEON). *Geosci. Model Dev.* 12, 473–523. <https://doi.org/10.5194/gmd-12-473-2019>.
- Hodges, B.R., Imberger, J., Saggio, A., Winters, K.B., 2000. Modeling basin-scale internal waves in a stratified lake. *Limnol. Oceanogr.* 45, 1603–1620. <https://doi.org/10.4319/lo.2000.45.7.1603>.
- Huokuna, M., Morris, M., Beltaos, S., Burrell, B.C., 2022. Ice in reservoirs and regulated rivers. *Int. J. River Basin Manag.* 20, 1–16. <https://doi.org/10.1080/15715124.2020.1719120>.
- Imam, Y.E., Laval, B., Pieters, R., Lawrence, G., 2013. The strongly damped baroclinic response to wind in a multibasin reservoir. *Limnol. Oceanogr.* 58 (4), 1243–1258.
- Jahandideh-Tehrani, M., Bozorg Haddad, O., Loáiciga, H.A., 2015. Hydropower reservoir management under climate change: The Karoon Reservoir System. *Water Resour. Manag.* 29, 749–770. <https://doi.org/10.1007/s11269-014-0840-7>.
- Kędra, M., Węjaczką, Ł., 2016. Disturbance of water-air temperature synchronisation by dam reservoirs. *Water Environ. J.* 30, 31–39. <https://doi.org/10.1111/wej.12156>.
- Kellerhals, R., Church, M., Davies, L.B., 1979. Morphological effects of interbasin river diversions. *Can. J. Civ. Eng.* 6, 18–31.
- Lawrence, G.A. and Pieters, R. 2005. Hydrothermal Characteristics of the Nechako Reservoir. A report prepared for the Nechako Enhancement Society. 10pp.
- Lee, R.M., Biggs, T.W., Fang, X., 2018. Thermal and hydrodynamic changes under a warmer climate in a variably stratified hypereutrophic reservoir. *Water* 10, 1284. <https://doi.org/10.3390/w10091284>.
- Levy, D.A., Nicklin, P., 2018. A Rep. Prep. Up. Fraser Fish. Conserv. Alliance (UFFCA) Nechako Fish. Conserv. Program 2018 77.
- Lewis, W.M., McCutchan, J.H., Roberson, J., 2019. Effects of climatic change on temperature and thermal structure of a mountain reservoir. *Water Resour. Res.* 55, 1988–1999. <https://doi.org/10.1029/2018WR023555>.
- Liang, X., Wood, E.F., Lettenmaier, D.P., 1996. Surface soil moisture parameterization of the VIC-2L model: evaluation and modification. *Glob. Planet. Change Soil Moisture Simul.* 13, 195–206. [https://doi.org/10.1016/0921-8181\(95\)00046-1](https://doi.org/10.1016/0921-8181(95)00046-1).
- Liang, X., Wood, E.F., Lettenmaier, D.P., 1999. Modeling ground heat flux in land surface parameterization schemes. *J. Geophys. Res.* 104, 9581–9600. <https://doi.org/10.1029/98JD02307>.
- Macdonald, J.S., Morrison, J., Patterson, D.A., 2012. The efficacy of reservoir flow regulation for cooling migration temperature for sockeye salmon in the Nechako river watershed of British Columbia. *North Am. J. Fish. Manag.* 32, 415–427. <https://doi.org/10.1080/02755947.2012.675946>.

- Macdonald, J.S., Morrison, J., Patterson, D.A., Heinonen, J., Foreman, M., 2007. Examination of Factors Influencing Nechako River Discharge, Temperature, and Aquatic Habitats 42.
- Maraun, D., 2013. Bias correction, quantile mapping and downscaling: revisiting the inflation issue. *J. Clim.* 26, 2137–2143. <https://doi.org/10.1175/JCLI-D-12-00821.1>.
- Mitchell, A., C., James, C.B., Edinger, J.E., 1995. Analyses of flow modification on water quality in Nechako river. *J. Energy Eng.* 121–122.
- Mizukami, N., Rakovec, O., Newman, Aj, et al., 2019. On the choice of calibration metrics for “high-flow” estimation using hydrologic models. *Hydrol. Earth Syst. Sci.* 23, 2601–2614.
- Moore, M.J., Paukert, C.P., Brooke, B.L., Moore, T.L., 2022. Lake sturgeon seasonal movements in regulated and unregulated Missouri River tributaries. *Ecology* 15. <https://doi.org/10.1002/eco.2362>.
- Morales-Marin, L.A., Carr, M., Sadeghian, A., Lindenschmidt, K.E., 2021. Climate change effects on the thermal stratification of Lake Diefenbaker, a large multi-purpose reservoir. *Can. Water Resour. J. Rev. Can. Ressour. Hydr.* 46, 1–16. <https://doi.org/10.1080/07011784.2020.1854120>.
- Nash, J.E., Sutcliffe, J.V., 1970. River flow forecasting through conceptual models. Part I—A discussion of principles. *J. Hydrol.* 27 (3), 282–290.
- Nechako Fisheries Conservation Program (NFCP), 2016. Hist. Rev. Nechako Fish. Conserv. Program:1987-2015, p. 33.
- Northcote, T.G., Larkin, P.A., 1989. The Fraser river: a major salmonine production system. *Can. Spec. Publ. Fish. Aquat. Sci.* 106, 1989, pp. 172–204.
- Northwest Hydraulic Consultants Ltd (NHC), 2003. Nechako River Geomorphic Assessment Phase I: Historical Analysis of Lower Nechako River. Final Report, May 2003. BC Ministry of Water, Land and Air Protection. 31pp plus appendices.
- Obregon, O., Chilton, R.E., Williams, G.P., Nelson, E.J., Miller, J.B., 2011. Assessing climate change effects in tropical and temperate reservoirs by modeling water quality scenarios. In: World Environmental and Water Resources Congress 2011. American Society of Civil Engineers, Palm Springs, California, United States, pp. 3897–3906. [https://doi.org/10.1061/41173\(414\)407](https://doi.org/10.1061/41173(414)407).
- Olden, J.D., Naiman, R.J., 2010. Incorporating thermal regimes into environmental flow assessments: modifying dam operations to restore freshwater ecosystem integrity. *Freshw. Biol.* 55, 86–107. <https://doi.org/10.1111/j.1365-2427.2009.02179.x>.
- Olsson, J., Arheimer, B., Borris, M., Donnelly, C., Foster, K., Nikulin, G., Persson, M., Perrtu, A.-M., Uvo, C.B., Viklander, M., Yang, W., 2016. Hydrological climate change impact assessment at small and large scales: key messages from recent progress in Sweden. *Climate* 4, 39. <https://doi.org/10.3390/cli4030039>.
- Paulsson, O., Widerlund, A., 2022. Modelled impact of climate change scenarios on hydrodynamics and water quality of the Rävildmyran pit lake, northern Sweden. *Appl. Geochem.* 139, 105235 <https://doi.org/10.1016/j.apgeochem.2022.105235>.
- Prats, J., Salencon, M., Gant, M., Danis, P.-A., 2017. Simulation of the hydrodynamic behaviour of a Mediterranean reservoir under different climate change and management scenarios. *J. Limnol.* 77 <https://doi.org/10.4081/jlimnol.2017.1567>.
- Qin, P., Xu, H., Liu, M., Du, L., Xiao, C., Liu, L., Tarroja, B., 2020. Climate change impacts on Three Gorges Reservoir impoundment and hydropower generation. *J. Hydrol.* 580, 123922 <https://doi.org/10.1016/j.jhydrol.2019.123922>.
- Raje, D., Mujumdar, P.P., 2010. Reservoir performance under uncertainty in hydrologic impacts of climate change. *Adv. Water Resour.* 33, 312–326. <https://doi.org/10.1016/j.advwatres.2009.12.008>.
- Rood, K.M., Hamilton on, R.E., 1995. Hydrology and water use for salmon streams in the Nechako habitat management area, British Columbia. *Can. Manusc. Rep. Fish. Aquat. Sci.* 2299.
- Schnorbus, M., 2018. VIC-Glacier (VIC-GL): Description of VIC Model Changes and Upgrades. Pacific Climate Impacts Consortium. University of Victoria, p. 39.
- Schulzweida, U., 2019. CDO User Guide.
- Soares, L.M.V., do Carmo Calijuri, M., das Graças Silva, T.F., de Moraes Novo, E.M.L., 2021. Climate change enhances deepwater warming of subtropical reservoirs: evidence from hydrodynamic modelling. *Clim. Change* 166, 21. <https://doi.org/10.1007/s10584-021-03124-x>.
- Spellman, P., Webster, V., Watkins, D., 2018. Bias correcting instantaneous peak flows generated using a continuous, semi-distributed hydrologic model. *J. Flood Risk Manag.* <https://doi.org/10.1111/jfr3.12342>.
- Spence, C., Hedstrom, N., 2015. Attributes of Lake Okanagan evaporation and development of a mass transfer model for water management purposes. *Can. Water Resour. J. / Rev. Can. Des. Ressour. Hydr.* 40 (3), 250–261. <https://doi.org/10.1080/07011784.2015.1046140>.
- Swain, L.G., Girard, R., 1987. Takla-Nechako area Nechako river water quality assessment and objectives. *Tech. Append.* 106.
- Teutschbein, C., Seibert, J., 2012. Bias correction of regional climate model simulations for hydrological climate-change impact studies: Review and evaluation of different methods. *J. Hydrol.* 456–457, 12–29. <https://doi.org/10.1016/j.jhydrol.2012.05.052>.
- Triton Environmental Consultants Ltd, 2021. 2020 summer water temperature and flow management project. *Nechako Fish. Conserv. Program* 44.
- Triton Environmental Consultants Ltd., 1994. Nechako Reserv. Addit. data Collect., p. 43.
- Van Vliet, M.T.H., et al., 2012. Coupled daily streamflow and water temperature modelling in large river basins. *Hydrol. Earth Syst. Sci.* 16, 4303–4432. <https://doi.org/10.5194/hess-16-4303-2012>.
- Werner, A.T., Schnorbus, M.A., Shrestha, R.R., Cannon, A.J., Zwiers, F.W., Dayon, G., Anslow, F., 2019. A long-term, temporally consistent, gridded daily meteorological dataset for northwestern North America. *Sci. Data* 6, 180299.
- Xie, Q., Liu, Z., Fang, X., Chen, Y., Li, C., MacIntyre, S., 2017. Understanding the temperature variations and thermal structure of a subtropical deep river-run reservoir before and after impoundment. *Water* 9, 603. <https://doi.org/10.3390/w9080603>.
- Xu, W., Chen, J., Su, T., Kim, J.-S., Gu, L., Lee, J.-H., 2022. Cascading model-based framework for the sustainability assessment of a multipurpose reservoir in a changing climate. *J. Water Resour. Plan. Manag.* 148, 05021029, 10.1061/(ASCE)WR.1943-5452.0001501.
- Yaghouti, M., Heidarzadeh, N., Nakhaei, N., Ulloa, H.N., 2022. The impacts of climate change on thermal stratification and dissolved oxygen of the Mississippi Lake. *SSRN Electron. J.* <https://doi.org/10.2139/ssrn.4028284>.
- Yang, R., Wu, S., Wu, X., Ptak, M., Li, X., Sojka, M., Graf, R., Dai, J., Zhu, S., 2022. Quantifying the impacts of climate variation, damming, and flow regulation on river thermal dynamics: a case study of the Włocławek Reservoir in the Vistula River, Poland. *Environ. Sci. Eur.* 34, 3. <https://doi.org/10.1186/s12302-021-00583-y>.
- Yearsley, J., 2012. A grid-based approach for simulating stream temperature. *Water Resour. Res.* 48 <https://doi.org/10.1029/2011WR011515>.
- Yearsley, J.R., 2009. A semi-Lagrangian water temperature model for advection-dominated river systems. *Water Resour. Res.* 45 <https://doi.org/10.1029/2008WR007629>.
- Zhong, W., Guo, J., Chen, L., Zhou, J., Zhang, J., Wang, D., 2020. Future hydropower generation prediction of large-scale reservoirs in the upper Yangtze River basin under climate change. *J. Hydrol.* 588, 125013 <https://doi.org/10.1016/j.jhydrol.2020.12>.