Project Report

ESSA

Interagency stream temperature database and high-resolution stream temperature model for British Columbia: *A pilot project (Year 2)*

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Prepared for Pacific Salmon Foundation

Interagency stream temperature database and high-resolution stream temperature model for British Columbia

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A pilot project (Year 2)

October 27, 2017

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Suggested Citation:
Porter[1], M., M. C. Morton[1], Nelitz[1], M., K. Kellock[2] M., Leslie-Gottschligg[1], K. Chezik[3] and E. Jones[2]. 2017. Interagency stream temperature database and high-resolution stream temperature model for British Columbia: A pilot project (Year 2). Prepared for Pacific Salmon Foundation by ESSA Technologies Ltd.

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Acknowledgements

We would like to thank the project contributors (listed in Appendix 1) for their interest and helpful assistance with this project. Their guidance has been invaluable. We would also like to thank the various providers of regional stream temperature data without which the current project could not have been attempted. Data providers within BC included Christian St. Pierre (Ministry of Forests, Lands and Natural Resource Operations), David Hutchinson and Lynne Campo (Environment and Climate Change Canada), Howard Stiff, Margot Stockwell and Shannon Anderson (Fisheries and Oceans Canada), Jeremy Damborg and Shawn Stenhouse (British Columbia Conservation Foundation), and many others from past data compilation efforts in British Columbia. Water temperature data from the US Okanagan basin was obtained from the USFS/USDA's NorWeST stream temperature project. We are grateful for this data and for the regular support provided by USFS staff throughout the duration of our modeling efforts. Funding for this project was provided by the Great Northern and North Pacific Landscape Conservation Cooperatives.

1 Introduction

Water temperature plays a fundamental role in structuring freshwater ecosystems. It influences the physiology and behavior of fish through all life history stages, affecting growth, survival and distribution of individuals and populations, as well as species interactions within fish communities (Caissie 2006). Moreover, evidence suggests that changing climate conditions have led to warming of streams across western North America and future projections suggest that warming will continue for the foreseeable future (Isaak et al. 2010; Isaak et al. 2012). Such thermal changes can lead to fragmentation of freshwater habitats across the landscape, especially for vulnerable species such as bull trout and Pacific salmon. Managers of aquatic ecosystems across the Great Northern and North Pacific Landscape Conservation Cooperatives need to consider the implications of climate change and other stressors on their management actions (e.g., riparian management, flow management, aquatic connectivity, habitat restoration, aquatic species conservation). Yet in British Columbia broad-scale planning efforts are, at present, only possible by using crude climate surrogates like air temperature or elevation, which can be weakly correlated with stream temperatures (Wenger et al. 2011). In British Columbia a regulatory tool is available that allows managers to designate "Temperature Sensitive Streams" (TSS) to protect critical fish-bearing streams that could be altered by stream heating due to forest harvesting in riparian and upslope areas as well as climate change (Reese-Hansen et al. 2012). This regulatory tool, however, has had limited application and its use could be enabled by more reliable information on stream temperature conditions to support decision making. Spatial statistical models for river networks like those that have been developed previously by the NorWeST stream temperature project for the Pacific US have potential for providing a stronger base of information and potentially could be used with existing stream temperature data and data collected in the future to develop consistent, high spatial resolution predictions for streams and river reaches within BC regions.

The stream temperature modeling infrastructure described within this report is intended to provide the starting basis for a science-based tool that can be used to enhance management, monitoring, and coordination of stakeholder engagement around aquatic resources in British Columbia and internationally with the US This work leveraged the technologies, protocols, and advancements made through the NorWeST project funded for the US portion of the Great Northern and North Pacific Landscape Conservation Cooperatives (Isaak et al. 2011; website: http://www.fs.fed.us/rm/boise/AWAE/projects/NorWeST.html), while also integrating the related experience and data that has been developed in British Columbia (e.g., Moore et al. 2013; Hague and Patterson 2014; Parkinson et al. 2015). The work builds on existing spatial layers and compilations of data from existing agency temperature monitoring efforts in British Columbia, with the purpose of providing consistent modeling frameworks and sets of reference conditions. The intent in Year 2 of this project was: (1) to refine NorWeST modeling methods/protocols for one of the pilot study areas initially evaluated in Year 1 - the Nicola basin, and (2) to apply NorWeST modeling methods and protocols to a selected Canada/USA transboundary watershed, the Okanagan Basin. A key focus of Year 2 was to determine whether it would be possible to develop a workable SSN stream temperature model for a transboundary watershed, which, to our knowledge, had not been attempted to date. Pilot areas were selected for testing based on perceived availability of useable time series temperature data as guided by the project's Technical Advisory Group. Application of NorWeST project methods required working with new spatial layers and data sets to test the transferability of protocols for eventual wider scale application across the northern portions of the GNLCC and NPLCC in British Columbia. Initial outputs from this project include the beginning of an interagency stream temperature database for British

Columbia and spatially continuous maps of stream temperature derived from basin-scale temperature models for our pilot watersheds.

As demonstrated through NorWeST applications elsewhere, outputs from the modeling exercise are intended to provide credible scientific information on stream temperatures at spatial scales and resolutions relevant for planning that should (1) help reduce and quantify uncertainty when planning for future climate conditions in British Columbia, and (2) facilitate communication with the public and among agencies about potential climate change effects. In particular, this information could significantly reduce uncertainties associated with climate change impacts on stream ecosystems by quantifying the total amount and locations of thermally suitable habitat for different species under different climate scenarios (e.g., bull trout, Pacific salmon, or any aquatic species of concern). In the northwestern US where NorWeST temperature scenarios have previously been developed, the information has been rapidly adopted in regional climate vulnerability assessments for bull trout, cutthroat trout, and salmon, used in decision support tools, and is enabling a suite of applications related to traditional assessments of thermal conditions and monitoring efforts in streams (e.g., cumulative effects, TMDL regulatory standards) (Isaak et al. 2014). The accuracy of the NorWeST stream temperature predictions, their ease of use within GIS, and development from data collected by those working in the local aquatics community has translated to rapid adoption and use in decision making (Isaak et. al. 2017).

While the primary objective of this project is to develop SSN models to provide an accurate description of historical summer stream temperatures in pilot watersheds within British Columbia (as a proof of concept), the larger goal is for the approach and resulting information to ultimately to help frame a science-based decision support tool such that planning efforts, regulatory tools, and management actions around aquatic environments in British Columbia can be implemented more efficiently and with greater confidence. Specific sub-objectives for this pilot project were:

(1) compile stream temperature data from various sources for the selected pilot study areas (and more broadly across the province as time and budget allowed);
(2) develop the base architecture for a comprehensive, interagency stream temperature database maintained by the Pacific Salmon Foundation (PSF) where these data can be housed in the future;
(3) pilot existing NorWeST protocols for application to the spatial layers and stream temperature data in pilot watersheds in British Columbia and a Canada/USA transboundary region;
(4) develop spatial statistical network-derived stream temperature models that incorporate important climate drivers and geomorphic factors; and
(5) use the models to predict historic and potential future patterns in stream temperatures for streams in the pilot watersheds using publicly available 1:20K (BC provincial Freshwater Atlas) or 1:24K (International Joint Commission (IJC) harmonized hydrology) stream networks as the GIS-based modeling framework.

2 Methods

To develop the NorWeST-based empirical model of stream temperature a series of steps were required in this project to calculate the response variable (stream temperature metric) and the explanatory predictor variables (landscape and climatic influences) used in the model.

2.1 Knowledge transfer

To leverage the experience, methodologies, and protocols developed for the NorWeST project by the US Forest Service (USFS), members of the ESSA project team engaged with key members of the Boise Aquatic Sciences Laboratory on a regular and continuing basis to learn how to apply and adapt the methods developed by the USFS to the spatial and tabular data sets available for British Columbia and the US Pacific northwest. Guidance on the project was also provided by a broader Stream Temperature Modeling Technical Advisory Group composed of representatives from Fisheries and Oceans Canada (DFO), BC Ministry of Environment (BC MOE), BC Ministry of Forests, Lands, and Natural Resources (FLNRO), Pacific Climate Impacts Consortium (PCIC), Simon Fraser University (SFU), and the University of British Columbia (UBC) (see Appendix 1 for the project`s Technical Advisory Group representatives).

2.2 Compilation of stream water temperature data

As a first step to understanding empirical relationships, it was necessary to compile time-series temperature data from as many sources as possible. PSF developed a relational database for the project (see Appendix 2 for database structure) to support both data compilation and stream temperature modeling needs. A request was then distributed to the project's Technical Advisory Group and other aquatic professionals across British Columbia for access to stream temperature data that had been collected by various agencies and organizations in British Columbia. This activity also leveraged a recent past BC provincial water temperature data compilation effort (i.e., Nelitz et al. 2008). Locations of seasonal time series data obtained from these sources and input into our database are presented for the Nicola and Okanagan basin pilot areas in Figures 1 and 2 respectively. A formal data sharing agreement (see Appendix 3) was developed by the PSF to ensure there was a clear understanding among contributors about potential uses of their data, while still allowing contributors to publish any research associated with these data.

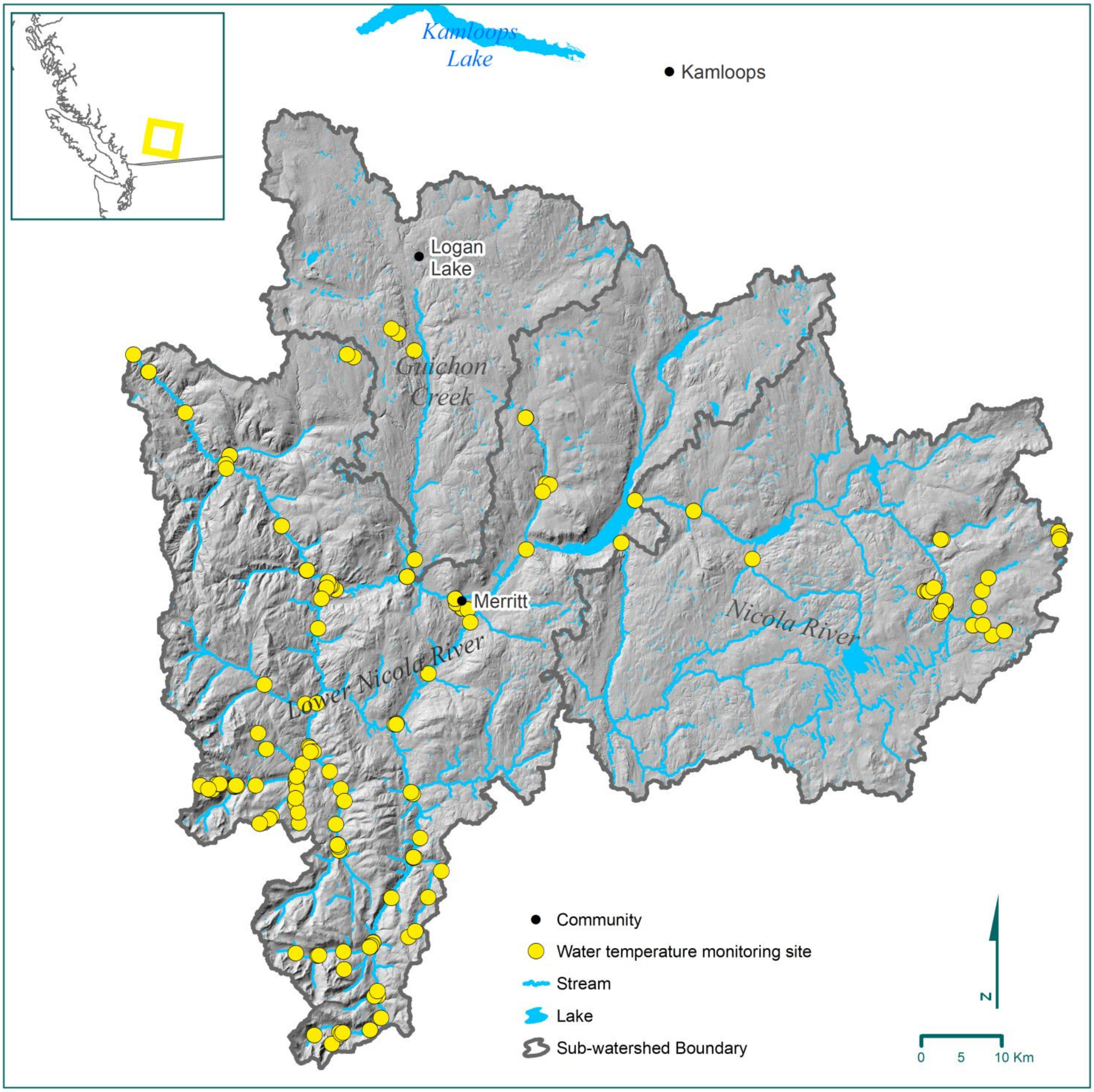


Figure 1. Locations of monitoring stations in the Nicola Basin (pilot study area). Seasonal time series stream temperature data were measured at 164 unique thermograph sites from 1994 to 2010 to yield 215 records of mean August water temperature for analyses.

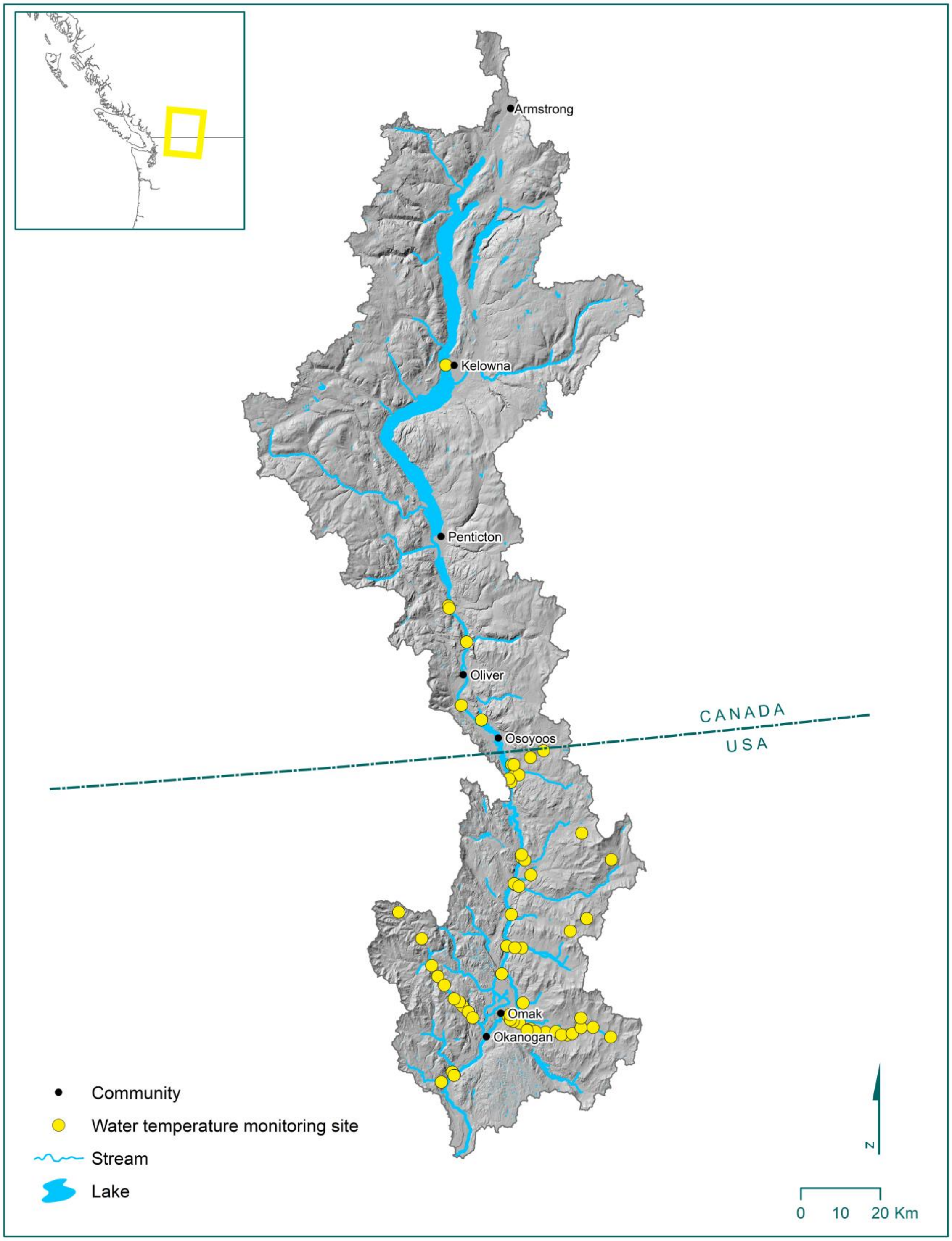


Figure 2. Locations of monitoring stations in the Okanagan basin (pilot study area). Seasonal time series stream temperature data were measured at 64 unique thermograph sites from 2001 to 2015 to yield 201 records of mean August water temperature for analyses.

While there was some continued exploration of broader stream temperature data availability across the province, data entry for the Year 2 report focused exclusively on sampling locations located within the two selected pilot study areas. These data were collected by a wide range of individuals from provincial and federal agencies, academia, and the forest industry across a range of years and seasons. Data were available in a variety of formats (e.g., different temporal resolutions, file types, and data arrangements). Given that data were provided in different formats, we ensured that all data were summarized as daily maximum, average, and minimum temperatures. No temperature data were edited or deleted from what was originally provided. All data were visually inspected to ensure no data was erroneous and each station-year captured the summer maximum. Additionally we developed R-coded script based on a simple spline model of reference conditions to provide an additional coarse level QA/QC filtering of the data. We used this model as a second-level of screening of all new water temperature datasets acquired for the pilot study areas before using in analyses (see Appendix 4). Data deemed inappropriate were flagged and removed from our analyses. For older data that was available from the previous provincial data compilation summary (i.e., Nelitz et al. 2008) we did not have sufficient scope within the current project to undertake such second level data quality filtering, and assumed the assembled data had been sufficiently cleaned for model analysis. For all appropriate station-years, summer stream temperatures were summarized as the mean August water temperature (i.e., the response variable for our modeling), consistent with the metric most commonly used for stream temperature modeling within the NorWeST Project (Isaak et al. 2017). For the Nicola basin recent, useable water temperature datasets were available between 1994 and 2010 (extent of consistently available stream temperature data) while in the Okanagan Basin more recent stream temperature data was obtainable (2001- 2015) to support analyses of baseline condition in each basin.

For each monitoring station, data providers also supplied geographic coordinates of site locations. This information was used to geo-reference associated reach segments and for delineating upstream watershed areas and reach contributing areas (RCA) that were used for calculating landscape influences on monitoring stations. For cases where station locations were not clear (i.e., incomplete coordinates provided) we contacted the data providers in an attempt to confirm stream location. Once all available locations were mapped in our pilot study areas we created a 100m buffer to identify adjacent stations and potential duplicates within the data set. For cases where potential overlap was identified, temperature records were checked to see if recorded values were identical. If so, duplicate stations were removed from the database for analysis, with those stations with a more complete time series of data selected for inclusion. Once monitoring site locations were determined these were “snapped” to the closest adjacent stream reach segment within the hydrology layers used for mapping and subsequent GIS-based analyses (i.e., provincial 1:20K Freshwater Atlas layer for the Nicola basin; 1:24K National Hydrography Dataset (NHD) layer for the Okanagan basin (transboundary)).

2.3 Processing of the stream network

British Columbia’s 1:20K Freshwater Atlas[1] was used as the basis for developing the spatial statistical stream-network model for the Nicola Basin (http://geobc.gov.bc.ca/base-mapping/atlas/fwa/) while the 1:24K NHD transboundary “harmonized” stream network was used for modeling in the Okanagan Basin. The transboundary geospatial dataset is stored in the U.S as part of the NHD and Watersheds Boundary Dataset that are managed by the USGS (www.waterdata.usgs/gov), and in Canada by Natural Resources Canada (NRC) as part of the National Hydro Network accessible through

[1] BC’s **Freshwater Atlas** (FWA) is a standardized dataset for mapping the province's hydrological features. The atlas defines watershed boundaries by height of land and provides a connected network of streams, lakes and wetlands. Each stream in the province has its own watershed (the land drained by that stream) but it is also linked to the other streams and watersheds around it. The atlas was designed to be the definitive source for mapping freshwater features in B.C.

Geogratis (www.geogratis.gc.ca/geogratis). This transboundary geospatial data represents a seamless hydrology for each transboundary basin to provide for a consistent representation of drainage basins along the international border (IJC 2015). Required "reconditioning" of the stream network for the Nicola and Okanagan was done by GIS specialists with ESSA and PSF with guidance from USFS personnel following established protocols (Peterson and Ver Hoef 2014; Peterson 2013). These protocols have been applied previously in the NorWeST stream temperature project (Isaak et al. 2011) to recondition the NHDPlus stream layer for the Pacific US As part of the model development process the hydrology network topology was checked for errors that sometime occur at tributary confluences or the flow directionality that is assigned to stream reaches. Processing steps for fitting the spatial statistical stream-network models were done using the ArcGIS custom toolset STARS (Spatial Tools for the Analysis of River Systems: Peterson 2013; Peterson and Ver Hoef 2014;) as described in the USFS`s guidance document NationalStreamInternetProtocol_Version4-7-2015. The specific processing steps as applied by ESSA/PSF for reconditioning of the BC 1:20K Freshwater Atlas hydrology for analyses within the two pilot basins is described in Appendix 5.

2.4 Derivation of landscape predictors

Watershed and stream segment characteristics were derived using existing datasets and spatial data layers for British Columbia and Washington that have been similarly applied in other recent BC provincial and NorWeST stream temperature modeling studies (Nelitz et al. 2008; Moore et al. 2013; Isaak et al. 2014; Isaak et al. 2017). Predictors in this category included relatively static geomorphic features of the river network, valley bottoms, and upstream watersheds that have been hypothesized to affect stream temperatures. Geomorphic predictors that were summarized include: watershed contributing area, reach contributing area, stream network drainage density, elevation, channel slope, lake area, wetland area, water storage area (wetland + lake combined), channel bankfull width (with width based on modeled estimates derived from K_2 and Q_2 values) (for the Nicola Basin) and stream order (for the Okanagan Basin, as information required for modeling of bankfull width was not possible to obtain for the US portion of the drainage).

2.5 Derivation of climate predictors

Climate data for British Columbia and northern Washington (i.e., summer air temperature, annual precipitation, and summer precipitation were obtained from the ClimateWNA data portal (see Hamann and Wang 2005; Spittlehouse 2006; Wang et al. 2012)). To characterize the spatial variation in site macro-climate, monthly normals of air temperature and precipitation were generated using the ClimateWNA[2] application (Hamann and Wang 2005; Spittlehouse 2006). Annual July and August mean air temperatures across the time matching the period of record for stream temperature observations in each of the pilot basins was used as an index of the general summer thermal climate. Monthly precipitation was summed to yield estimates of the average annual precipitation, and the annual average precipitation in the July/August summer period. Latitude was also included as a model predictor.

An important source of variability in regional stream temperature modeling is the effect of interannual variability in hydroclimatic conditions. To characterize interannual variability in climate at each location, a time series of daily air temperature was generated for the reference period 1994 to 2010 (for the Nicola) and for 2001-2015 (for the Okanagan) by interpolation of data from surrounding climate

[2] ClimateWNA home page, available at: http://cfcg.forestry.ubc.ca/projects/climate-data/climatebcwna/#ClimateWNA

stations using the application developed by Stahl et al. (2006). For each year, the interpolated daily air temperatures for July and August were averaged for each station. These July/August means were then expressed as a deviation from the average July/August temperature over the reference period:

$$\text{Equation (1) } \delta T_a(i,t) = T_a(i,t) - T_{ref}(i)$$

where $T_a(i,t)$ is July/August air temperature for station "i" and year "t," $T_{ref}(i)$ is the mean July/August air temperature for the reference period (1994-2010 for the Nicola Basin and 2001-2015 for the Okanagan Basin), and $\delta T_a(i,t)$ is the deviation for station "i" and year "t."

2.6 Derivation of hydrologic information

Many studies have shown that stream temperature varies with discharge (e.g., Hockey et al. 1982; Gu et al. 1988), as stream flow determines the volume of water available for heating. We created (as in Isaak et al. 2010) an annual summer flow index (i.e., Basin Flow Index in the model) for the Nicola Basin for the 1994-2010 time period using Water Survey of Canada (WSC) hydro-metric gauge station data on unregulated streams. Flow was averaged for July and August across sites and years. Years with fewer than 25 days data in these summer months were excluded. These summer month averages were then averaged across WSC gauge locations for a single basin-scale annual summer Basin Flow Index value for the Nicola. Development of a parallel Basin Flow Index for the Okanagan was not possible as only a very limited number of gauging stations (in the US and Canada) provided summer flow data over the required time period. For the Okanagan, ClimateWNA-derived total August precipitation each year was substituted as a predictor of general summer flow conditions across the basin.

Figure 3 shows the locations of the thirteen Water Survey of Canada (WSC) flow gauges used for calculation of a derived Basin Flow Index (annual average July/August flow) within the Nicola River pilot study area.

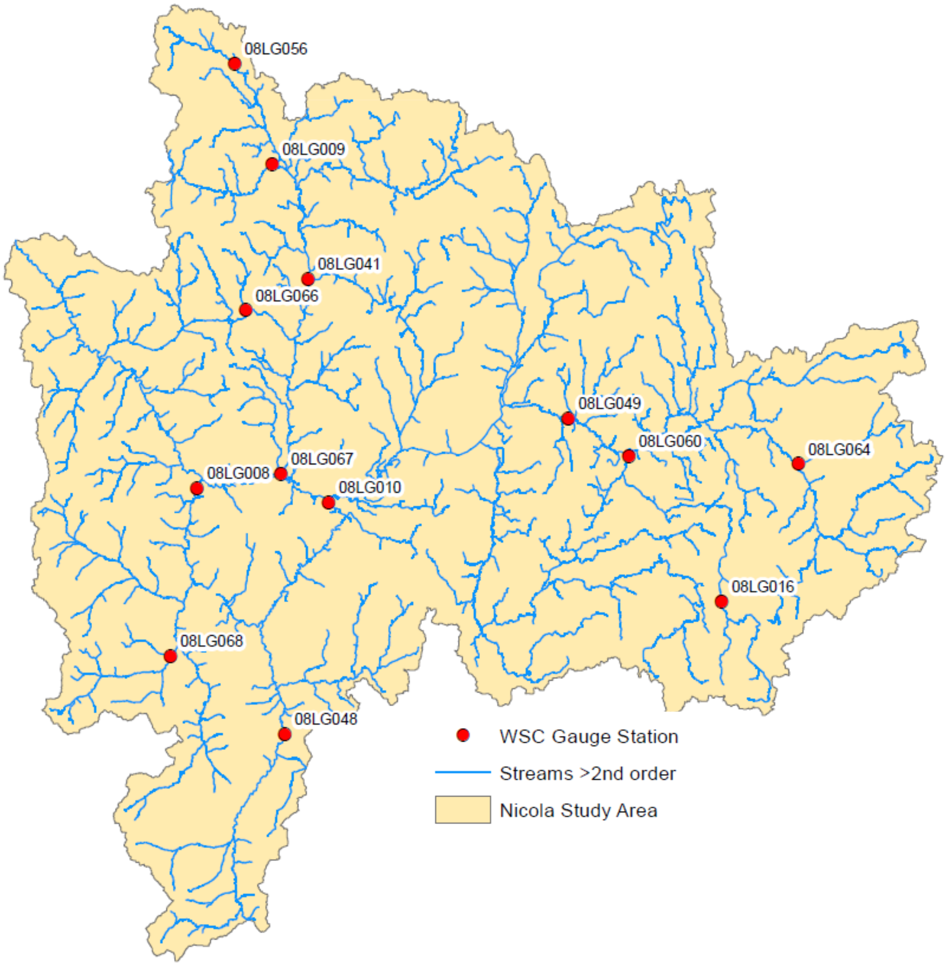


Figure 3. Location of Water Survey of Canada (WSC) gauges (n = 13) used for calculation of a single annual mean summer (July/Aug) discharge value for the Nicola Basin (i.e. Basin Flow Index). WSC gauges located below large regulated dams that could influence flow were not included in derivation of the Index.

2.7 Stream temperature modeling

The intent for this project was to create a spatial statistical stream network (SSN) model (information at: http://www.fs.fed.us/rm/boise/AWAE/projects/SpatialStreamNetworks.shtml) to predict summer stream temperature based on stream, landscape and climate characteristics, while additionally incorporating the spatial geometry of the stream network within the basin. Spatial statistical models account for the unique forms of spatial dependence (i.e., longitudinal connectivity, flow volume, and flow direction) inherent to stream networks (Peterson and Ver Hoef 2010; Ver Hoef and Peterson 2010). These spatial models also accommodate clustering and non-independence among observations and are well suited to applications involving databases aggregated from multiple agencies. Isaak et al. (2010; 2014) provide examples using the spatial statistical models with interagency temperature databases. All statistical modeling and analyses within this project employed the GLM/SSN software package for R (Ver Hoef et al. 2014).

Using the STARS application information on co-variates (landscape, climate and hydrology predictors) was then transferred to each of the water temperature station locations, as well as to the prediction points (32,813,608 points for the Nicola Basin and 39,168 points for the Okanagan Basin – for both basins using average 1 km spacing) that had been generated by STARS across the basin stream networks (see Appendix 5 for the workflow steps required for this process). Appendix 6 provides a summary of the landscape co-variates used for stream temperature modeling and details the sources/methods used for their derivation. As is standard with NorWeST modeling no transformations were undertaken on model co-variates. We developed both linear GLM models (non-spatial) and SSN (spatial statistical network) models (for comparison) to predict mean August stream temperature over the historical reference period.

Consistent with the approach used in Isaak et al. (2010) we developed alternative candidate spatial and non-spatial models for comparison based on static geomorphic predictors, dynamic climate and hydrology predictors, combinations of both static and dynamic predictors, and a global model that included all predictors. Each model combination was also adjusted based on multiple covariance component matrices for further comparison. For the Nicola Basin, 3,235 models were ultimately tested and for the Okanagan Basin 2,498 models were tested, each with different combinations of predictor variables and spatial stream covariance models (see Ver Hoeff et al 2014 for details). Model selection was conducted using a multi-metric statistical approach. Model results were evaluated using four objective functions: 1) Minimum Akaike Information Criterion (AIC), 2) Minimum Root Mean Squared Prediction Error (RMSPE), 3) Maximum proportion of cases where the true value lands within the 90% confidence interval of the model (cov.90), and 4) Minimum combined multi-metric score incorporating all three objective functions (MMS). AIC is a measure of the relative quality of statistical models for a given set of data. It is intended to deal with the competing trade-offs between the goodness of fit of the model and the complexity of the model. The top model for each metric was selected and evaluated. If, upon evaluation, any covariates returned NA results (e.g., due to collinearity with another variable), the next best model without NA covariate results was selected. Models were evaluated with and without outliers for comparison and the models with outliers removed were used as the final 'selection set'. To help address the problem of equifinality (multiple possible solution states), we evaluated all models with the exact same objective function results. If a top candidate model contained only a single covariate (e.g. Elevation), we also included the next best model in our evaluation. This approach resulted in 5 models in both the Nicola and Okanagan final selection sets. Each selected model was then evaluated based on AIC, RMPSE, and cov.90 objective function scores, as well as a predictive r^2 based on leave-one-out cross validation (a "pseudo" r^2 metric) (as in Isaak et al. 2017). For each watershed, the model that performed best across all four metrics was considered a top candidate model. Results were then compared with objective function scores for equivalent non-spatial multiple linear regression model to evaluate the degree of model improvement delivered by the inclusion of spatial stream covariance models. A final model selection was made based on a combination of objective function scores and level of improvement for each score relative to the equivalent non-spatial model.

Through the process of model comparisons a "best" model was identified for predicting mean August temperature within the reference period. The "best" model algorithm for each basin was then applied to prediction points along the stream networks in the Nicola ad Okanagan for generation of high-resolution maps of reference period summer thermal conditions in basin streams based on the derived watershed characteristics and climate variables.

As an initial exploratory analysis within Year 2 of the project as to how stream conditions might change in the future the selected "best" SSN models for both the Nicola and Okanagan basins were used for prediction of stream temperature change under some different possible climate scenarios. ClimateWNA-modeled estimates of the mean July/August air temperature, mean annual precipitation, and mean August precipitation within each of the basins was determined for projected future time periods (2020, 2050, and 2080). Projected air temperatures and precipitation at the three future time periods were determined across two alternative climate models (CGCM3 A2, run 4, and HADCM3 B1, run 1) which are considered to represent illustrative model scenarios for exploring potential climate change impacts within British Columbia (Murdock and Spittlehouse 2011). For the Nicola Basin the Basin Flow Index values were adjusted for each of these future time periods based on past detailed modeling of projected stream flow changes under CGC and HADCM models undertaken in the adjacent Thompson Basin (Nelitz et al. 2009), with the generalized assumption that projected changes in average stream flows across the Thompson Basin could be similarly applied to the Nicola Basin (for initial exploratory analyses). Based on this evaluation we reduced the Nicola Basin Flow Index value by a varying amounts in each future time period compared to our baseline reference condition: for the CGCM model (2020 – 13%, 2050 - 18%, 2080 - 28%) and for the HADCM model: 2020 - 21% 2050 - 39%, 2080 - 52%). As it was not possible to generate a Basin Flow Index for the Okanagan Basin, future August precipitation (from ClimateWNA modeled data) was used as a surrogate of potential changes in future summer flows. The respective modelled data inputs were then applied to the "best" SSN models for the Nicola and Okanagan basins to generate adjusted prediction point values across the stream networks and generate maps indicating predicted summer thermal conditions (i.e., mean August temperature) within each basin during the future time periods.

3 Results

3.1 Predicting Maximum Weekly Average Temperature

3.1.1 Overview of monitoring station characteristics

After data quality checking, a total of 215 observation records of mean August stream temperature were available from 1994-2010 for modeling analyses from 164 monitoring stations within the Nicola Basin pilot study area and a total of 201 observation records available from 64 monitoring stations (located in Canada and the US) within the Okanagan Basin study area. The number of years of data at each station ranged up to seven years in the Nicola study area, but most stations had only one or two years of data (Figure 4). A much higher frequency of observations were available for the Okanagan Basin, with the number of years of data at each station ranging up to ten years. While most stations in the Okanagan only provided one year of data, there were many stations with multiple years of data (Figure 5).

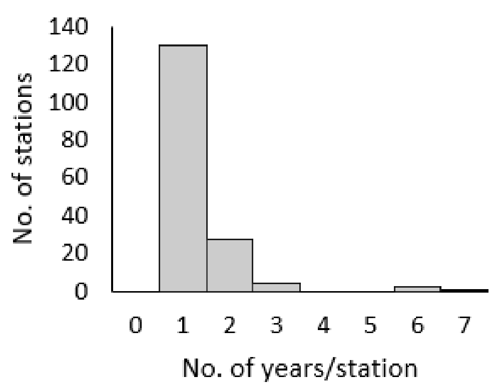


Figure 4. Distribution of number of years of data per station in the Nicola Basin (n = 164 sites).

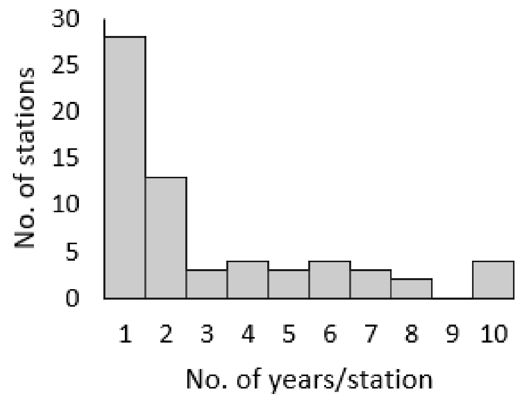


Figure 5. Distribution of number of years of data per station in the Okanagan Basin (n = 64 sites) (represents a combination of B.C and Washington water temperature stations).

Table 1 and Figure 6 present summary statistics for water temperature observations at the monitoring stations and for the measured covariates (geomorphic, climate, hydrology) used to build the stream temperature model for the Nicola Basin. There was a wide spread of watershed areas captured for analysis across the 164 stations in the Nicola Basin, ranging from 0.2 to 6894 km2. Modelled bankfull widths for station stream reaches ranged from 0.9 m to 61 m, stream reach gradients ranged from <0.1 to 13.5% and station elevations ranged from 261m to 1761m. The percentage of water storage area in each of the station watershed catchment areas ranged from <0.1% to 9.3%.The mean August stream temperature at each station across the 1994 to 2010 reference period ranged from 6.9 to 21.0 ^{o}C, with a mode in the interval of 10 to 15 ^{o}C (Figure 7).

Table 1. Descriptive statistics of response and predictor variables in the data set used to build stream temperature models for the Nicola Basin pilot study area.

Variable	Code	*n*	Mean	Median	SD	Min.	Max.
Response Variable							
Mean August water temperature (^{o}C) (1994-2010)	AvgAugTemp	215	14.0	13.4	3.4	6.9	21.0
Predictor Variables							
1) Geomorphic							
Elevation (m)	Elevation	164	781.7	948.0	571.2	261.0	1761.0
Latitude (deg)	Latitude	164	50.0	50.0	0.2	49.6	50.4
k_2 value	K2	164	0.5	0.6	0.3	<0.1	0.9
Q_2 value (m^3/s)	Q2	164	34.0	12.3	52.6	0.1	368.2
Bankfull width (m)	Wb	164	14.6	11.1	11.4	0.9	60.8
Stream gradient (%)	Gradient	164	2.7	2.4	2.3	<0.1	13.5
Watershed contributing area (km^2)	h2oRcaKm2	164	603.6	79.1	1469.1	0.2	6894.3
Lake area in watershed (km^2)	h2oLakeKm2	164	10.5	0.5	30.4	<0.1	121.3
Wetland area in watershed (km^2)	h2oWetKm2	164	6.9	0.5	18.0	<0.1	76.3
Storage area (lakes + wetlands) in watershed (km^2)	h2oStrgKm2	164	17.4	1.0	48.4	<0.1	197.6
% of watershed that is lake	h2oLakePct	164	1.1	0.5	1.4	<0.1	7.3
% of watershed that is wetland	h2oWetPct	164	1.0	0.8	1.0	<0.1	4.4
% of watershed that is water storage (lakes + wetlands)	h2oStrgPct	164	2.1	1.3	2.0	<0.1	9.3
Total stream length in watershed (km)	h2oStrKm	164	1526.3	185.7	3784.5	0.3	17849.8
Stream density in watershed (km/km^2)	h2oStrDen	164	2.5	2.5	0.6	0.7	4.8
Reach catchment area (km2)	rcaAreaKm2	164	0.4	0.2	0.4	<0.1	2.2
Lake area in reach catchment area (km2)	rcaLakeKm2	164	<0.1	<0.1	<0.1	<0.1	<0.1
Wetland area in reach catchment area (km2)	rcaWetKm2	164	<0.1	<0.1	<0.1	<0.1	<0.1

Storage area (lakes + wetlands) in RCA (km2)	rcaStrgKm2	164	<0.1	<0.1	<0.1	<0.1	<0.1
% of reach catchment area that is lake	rcaLakePct	164	0.1	<0.1	0.7	<0.01	12.8
% of reach catchment area that is wetland	rcaWetPct	164	0.2	<0.1	1.4	<0.01	12.8
% of RCA that is water storage (lakes + wetlands)	rcaStrgPct	164	0.2	<0.1	1.6	14.3	14.3
2) Climate							
Average of average July/August temperatures (1981-2010)	T08Norm	17	14.3	14.3	0.0	14.3	14.3
Average of average annual precipitation (mm) (1981-2010)	PPTYrNorm	17	557.0	557.0	0.0	557.0	557.0
Annual deviation from the July/Aug air temperature norm (for each year from 1994-2010)	DV_1994 to DV_2010	17	-1.6	-1.8	0.9	-3.2	-0.2
Annual average July/August air temperature for (each year from 1994-2010) (°C)	AvgT08_1994 to 2010	17	14.4	14.1	0.9	12.7	15.8
Annual precipitation (for each year from 1994-2010) (mm)	AvgYrPPT_1994 to 2010	17	566.6	566.4	81.0	441.0	717.1
Annual August precipitation (for each year from 1994-2010) (mm)	Avg08PPT	17	14.0	13.4	3.4	7.0	21.0
3) Hydrology							
Annual summer Basin Flow Index (July/August discharge mean) (for each year from 1994-2010) (m3/s)	BnFlw_1994 to 2010	17	1.75	1.58	1.20	0.74	5.46

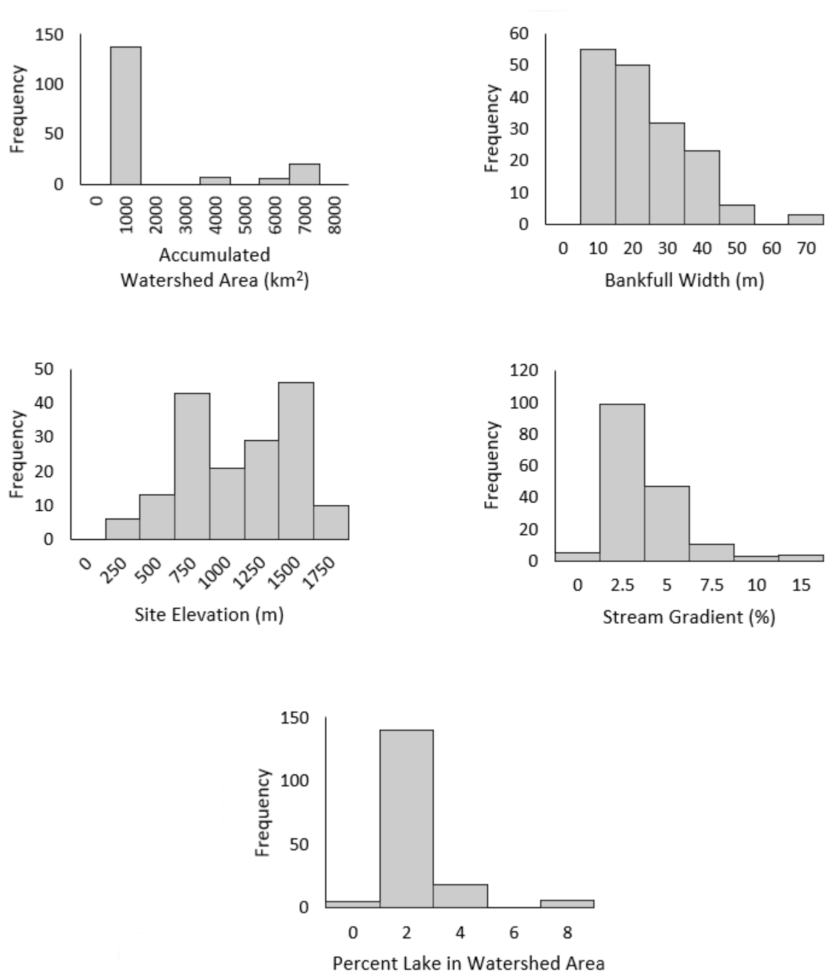


Figure 6. Histograms of key characteristics for watershed catchments within the Nicola Basin used in the analyses (n = 164 sites).

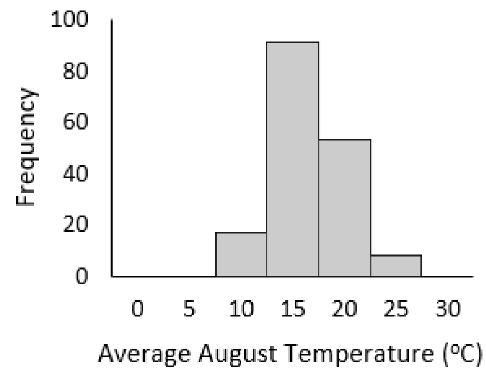


Figure 7. Histogram of mean August stream temperatures for stations in the Nicola Basin included in the analyses (n = 215 observations).

Table 2 and Figure 8 present summary statistics for water temperature observations at the monitoring stations and for the measured covariates (geomorphic and climate) used to build the stream temperature model for the Okanagan Basin. Watershed areas for monitoring stations ranged from 0.2 to 10,299 km^2. Stream reach gradients ranged from <0.1 to 16.4%, station elevations ranged from 244m to 1367m, and mapped stream orders ranged from 1st to 8th order. The percentage of water storage area in each of the station watershed catchment areas ranged from <0.1% to 16%.The mean August stream temperature at each station across the 1994 to 2010 reference period ranged from 7.8 to 25.2 ^oC, with a mode in the interval of 15 to 20 ^oC (Figure 9).

Table 2. Descriptive statistics of response and predictor variables in the data set used to build stream temperature models for the Okanagan Basin pilot study area.

Variable	Code	*n*	Mean	Median	SD	Min.	Max.
Response Variable							
Mean August water temperature (ºC) (2001-2015)	AvgAugTemp	201	17.9	17.7	3.8	7.8	25.2
Predictor Variables							
1) Geomorphic							
Elevation (m)	Elevation	64	507.0	383.5	284.1	244.0	1367.0
Latitude (deg)	Latitude	64	48.6	48.5	0.3	48.3	49.9
Stream gradient (%)	Gradient	64	3.0	2.2	3.2	<0.1	16.4
Watershed contributing area (km^2)	h2oRcaKm2	64	1521.3	261.2	3058.1	<0.1	10298.7
Stream order	StreamOrde	64	5	6	1.7	1	8
Lake area in watershed (km^2)	h2oLakeKm2	64	43.8	0.1	134.2	<0.1	483.3
Wetland area in watershed (km^2)	h2oWetKm2	64	5.2	1.3	9.8	<0.1	35.1
Storage area (lakes + wetlands) in watershed (km^2)	h2oStrgKm2	64	49.0	1.8	141.4	<0.1	518.4
% of watershed that is lake	h2oLakePct	64	1.0	<0.1	2.6	<0.1	15.8
% of watershed that is wetland	h2oWetPct	64	0.6	0.4	1.2	<0.1	9.3
% of watershed that is water storage (lakes + wetlands)	h2oStrgPct	64	1.5	0.6	2.9	<0.1	16.0
Total stream length in watershed (km)	h2oStrKm	64	1910.3	674.7	3647.0	0.2	14430
Stream density in watershed (km/km^2)	h2oStrDen	64	2.6	2.2	3.4	0.1	27.8
Reach catchment area (km2)	rcaAreaKm2	64	0.7	0.3	1.0	0.0	6.1
Lake area in reach catchment area (km2)	rcaLakeKm2	64	<0.1	<0.1	<0.1	<0.1	<0.1
Wetland area in reach catchment area (km2)	rcaWetKm2	64	<0.1	<0.1	<0.1	<0.1	0.2
Storage area (lakes + wetlands) in RCA (km2)	rcaStrgKm2	64	<0.1	<0.1	<0.1	<0.1	0.2
% of reach catchment area that is lake	rcaLakePct	64	0.2	<0.1	1.2	<0.1	9.5

% of reach catchment area that is wetland	rcaWetPct	64	1.3	<0.1	4.1	<0.1	19.6
% of RCA that is water storage (lakes + wetlands)	rcaStrgPct	64	1.5	<0.1	4.2	<0.1	19.6
2) Climate							
Average of average July/August temperatures (1981-2010)	T08Norm	15	18.0	18.0	0.0	18.0	18.0
Average of average annual precipitation (mm) (2001-2015)	PPTYrNorm	15	453.7	453.7	0.0	453.7	453.7
Annual deviation from the July/Aug air temperature norm (for each year from 2001-2015)	DV_2001-2015	15	0.4	0.5	0.8	-0.8	1.6
Annual average July/August air temperature for (each year from 2001-2015) (°C)	AvgT08_2001 to 2015	15	18.4	18.5	0.8	17.2	19.7
Annual precipitation (for each year from 2001-2015) (mm)	AvgYrPPT_2001 to 2015	15	426.9	423.8	51.5	337.6	501.2
Annual August precipitation (for each year from 2001-2015) (mm)	Avg08PPT	15	19.5	10.7	19.9	3.1	66.8

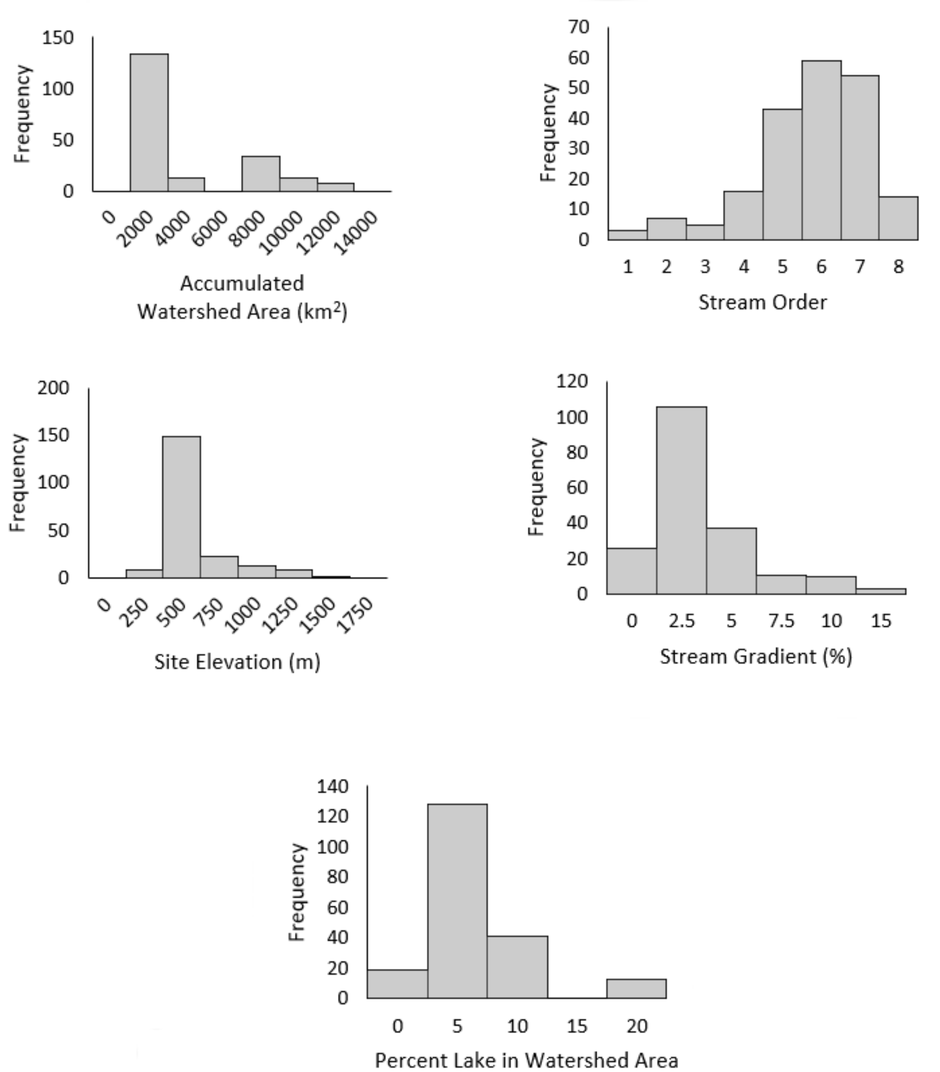


Figure 8. Histograms of key characteristics for watershed catchments within the Okanagan Basin used in the analyses (n = 64 sites).

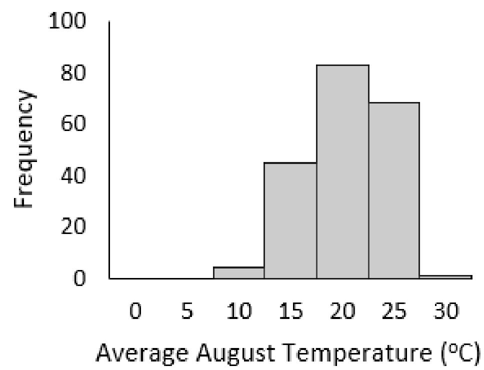


Figure 9. Histogram of mean August stream temperatures for stations in the Okanagan Basin included in the analyses (n = 201 observations).

3.1.2 Statistical modeling of mean August stream temperatures

Table 3 provides a summary of model comparison results for the Nicola and Okanagan respectively, showing the better models for each basin as defined by the four diagnostics employed. The final "best" models that were selected for basin stream temperature mapping are described in detail in Tables 4 and 5 for the Nicola Basin and Okanagan Basin respectively. The "pseudo" r^2 for the best Nicola Basin SSN model was 0.85, while the best SSN model for the Okanagan Basin had a "pseudo" r^2 = 0.93. The final "best" SSN model for the Nicola Basin showed a 1.4% to 39.4% improvement over its non-spatial GLM equivalent model across the four diagnostic elements (AIC, RMSPE, cov. 90, and "pseudo" r^2). Improvements in the SSN Okanagan Basin model over its non-spatial GLM equivalent model were less, ranging from 1.4% to 16.6%.

Table 3. Inputs and final diagnostic results for Nicola and Okanagan Basin stream temperature models (table is split into two sections below – the Model ID number links between the table sections). Relative model quality, as defined within each diagnostic element, is represented by a graduated color scale (green to red; best to worst). The final "best" model selected for each basin based on an integration of the four model diagnostic elements is captured in the table within red box highlighting (i.e., NIC10 and OK8). Improvement (%) between the spatial statistical model (SSN) and the equivalent non-spatial general linear model (GLM) with the same inputs is also provided for each diagnostic element.

Model ID	spatial stream network moving avg. model component	multiple regression model component
NICOLA		
NIC1	Spherical.tailup + Spherical.taildown + Nugget	AugAvgTemp ~ Elevation + Latitude + Wb + GRADIENT + rcaAreaKm2 + rcaStrKm + rcaStrgKm2 + rcaStrgPct + rcaStrDen
NIC2	Mariah.tailup + Exponential.taildown + Exponential.Euclid + Nugget	AugAvgTemp ~ Latitude
NIC3	Exponential.tailup + Mariah.taildown + Nugget	AugAvgTemp ~ Elevation
NIC4	NA	AugAvgTemp ~ Elevation + Latitude + Wb + GRADIENT + rcaAreaKm2 + rcaStrKm + rcaStrgKm2 + rcaStrgPct + rcaStrDen
NIC5	NA	AugAvgTemp ~ Latitude
NIC6	NA	AugAvgTemp ~ Elevation
NIC7	LinearSill.tailup + Nugget	AugAvgTemp ~ Elevation + Latitude + Avg08PPT + AvgT08 + AvgYrPPT + h2oRcaKm2 + h2oStrKm + h2oStrDen + h2oStrgKm2 + h2oStrgPct
NIC8	Exponential.tailup + Mariah.taildown + Nugget	AugAvgTemp ~ Elevation
NIC9	Mariah.tailup + Spherical.taildown + Nugget	AugAvgTemp ~ Elevation + BnFlw + AvgT08 + AvgYrPPT
NIC10	Exponential.tailup + LinearSill.taildown + Nugget	AugAvgTemp ~ Elevation + Latitude + BnFlw + AvgT08 + AvgYrPPT + Wb + GRADIENT + rcaAreaKm2 + rcaStrgKm2 + rcaStrgPct + rcaStrDen
NIC11	NA	AugAvgTemp ~ Elevation + Latitude + Avg08PPT + AvgT08 + AvgYrPPT + h2oRcaKm2 + h2oStrKm + h2oStrDen + h2oStrgKm2 + h2oStrgPct
NIC12	NA	AugAvgTemp ~ Elevation + BnFlw + AvgT08 + AvgYrPPT
OKANAGAN		
OK1	Mariah.tailup + Exponential.Euclid + Nugget	AugAvgTemp ~ Elevation + Latitude + AvgT08 + AvgYrPPT + StreamOrde + Gradient + rcaAreaKm2 + rcaStrgKm2 + rcaStrgPct + rcaStrDen
OK2	LinearSill.tailup + LinearSill.taildown + Exponential.Euclid + Nugget	AugAvgTemp ~ Elevation + AvgT08 + Avg08PPT + h2oAreaKm2 + h2oStrKm + h2oStrDen + h2oStrgKm2 + h2oStrgPct
OK3	Spherical.tailup + LinearSill.taildown + Nugget	AugAvgTemp ~ Elevation + Avg08PPT + AvgT08 + AvgYrPPT
OK4	Exponential.tailup + Exponential.Euclid + Nugget	AugAvgTemp ~ Elevation + Latitude + AvgT08 + AvgYrPPT + StreamOrde + Gradient + rcaAreaKm2 + rcaStrgKm2 + rcaStrgPct + rcaStrDen + h2oAreaKm2 + h2oStrKm + h2oStrDen + h2oStrgKm2 + h2oStrgPct
OK5	NA	AugAvgTemp ~ Elevation + Latitude + AvgT08 + AvgYrPPT + StreamOrde + Gradient + rcaAreaKm2 + rcaStrgKm2 + rcaStrgPct + rcaStrDen
OK6	NA	AugAvgTemp ~ Elevation + AvgT08 + Avg08PPT + h2oAreaKm2 + h2oStrKm + h2oStrDen + h2oStrgKm2 + h2oStrgPct
OK7	NA	AugAvgTemp ~ Elevation + Avg08PPT + AvgT08 + AvgYrPPT
OK8	Mariah.tailup + Spherical.taildown + Exponential.Euclid + Nugget	AugAvgTemp ~ Elevation + Latitude + AvgT08 + AvgYrPPT + StreamOrde + Gradient + rcaAreaKm2 + rcaStrgKm2 + rcaStrgPct + rcaStrDen
OK9	Spherical.tailup + Mariah.taildown + Exponential.Euclid + Nugget	AugAvgTemp ~ Elevation + Latitude + AvgT08 + AvgYrPPT + h2oAreaKm2 + h2oStrKm + h2oStrDen + h2oStrgKm2 + h2oStrgPct
OK10	Spherical.tailup + Spherical.taildown + Nugget	AugAvgTemp ~ Elevation + Avg08PPT + AvgT08 + AvgYrPPT
OK11	Exponential.tailup + Spherical.taildown + Exponential.Euclid + Nugget	AugAvgTemp ~ Elevation + Avg08PPT + AvgT08 + AvgYrPPT
OK12	Exponential.tailup + LinearSill.taildown + Exponential.Euclid + Nugget	AugAvgTemp ~ Elevation + Latitude + AvgT08 + Avg08PPT + StreamOrde + Gradient + rcaAreaKm2 + rcaStrgKm2 + rcaStrgPct + rcaStrDen

NICOLA

		Score				% Improvement from NSP Equiv			
Model ID	**Initial Objective Function**	**AIC**	**RMSPE**	**cov.90**	**Pseudo R2**	**AIC**	**RMSPE**	**cov.90**	**Pseudo R2**
	Best Spatial (with outliers)								
NIC1	Min AIC	841.10	1.54	0.94	0.79	5.2%	18.7%	3.0%	10.9%
NIC2	Min RMSPE	861.38	1.53	0.94	0.79	17.3%	62.5%	3.0%	42.5%
NIC3	Max cov.90	880.79	1.56	0.96	0.79	16.2%	58.0%	1.0%	40.5%
NIC1	Min MMS	841.10	1.54	0.94	0.79	5.2%	18.7%	3.0%	10.9%
	Non-spatial equivalents								
NIC4	Min AIC (n8)	884.53	1.83	0.92	0.70	-	-	-	-
NIC5	Min RMSPE (n2)	1010.48	2.48	0.92	0.46	-	-	-	-
NIC6	Max cov.90 (n1)	1023.17	2.46	0.95	0.47	-	-	-	-
NIC4	Min MMS (n8)	884.53	1.83	0.92	0.70	-	-	-	-
	Best Spatial (outliers removed)								
NIC7	Min AIC	776.01	1.29	0.92	0.83	28.0%	61.5%	-1.7%	23.3%
NIC7	Min RMSPE	776.01	1.29	0.92	0.85	28.0%	61.5%	-1.7%	24.5%
NIC8	Max cov.90.a	880.79	1.56	0.96	0.79	16.2%	58.0%	1.0%	40.5%
NIC9	Max cov.90.b	887.96	1.54	0.95	0.79	15.2%	59.6%	0.0%	40.5%
NIC10	Min MMS	786.89	1.31	0.94	0.85	13.1%	39.4%	1.4%	16.6%
	Non-spatial equivalents								
NIC11	Min AIC	993.51	2.09	0.93	0.64	-	-	-	-
NIC11	Min RMSPE	993.51	2.09	0.93	0.64	-	-	-	-
NIC6	Max cov.90.a	1023.17	2.46	0.95	0.47	-	-	-	-
NIC12	Max cov.90.b	1027.88	2.44	0.94	0.48	-	-	-	-
NIC11	Min MMS	890.09	1.83	0.93	0.71	-	-	-	-

OKANAGAN

		Score				% Improvement from NSP Equiv			
Model ID	**Initial Objective Function**	**AIC**	**RMSPE**	**cov.90**	**Pseudo R2**	**AIC**	**RMSPE**	**cov.90**	**Pseudo R2**
	Best Spatial (with outliers)								
OK1	Min AIC	659.80	1.15	0.90	0.91	2.5%	0.7%	0.0%	0.1%
OK2	Min RMSPE	688.72	1.04	0.90	0.93	2.5%	6.0%	0.0%	0.8%
OK3	Max cov.90	699.80	1.15	0.93	0.91	1.5%	0.0%	0.5%	0.0%
OK4	Min MMS	684.05	1.08	0.90	0.92	0.8%	3.8%	-0.6%	0.1%
	Non-spatial equivalents								
OK5	Min AIC	676.31	1.16	0.90	0.91	-	-	-	-
OK6	Min RMSPE	705.68	1.10	0.90	0.92	-	-	-	-
OK6	Max cov.90	710.12	1.15	0.92	0.91	-	-	-	-
OK7	Min MMS	689.29	1.12	0.91	0.91	-	-	-	-
	Best Spatial (outliers removed)								
OK8	Min AIC	611.29	0.99	0.91	0.93	10.6%	16.6%	1.4%	2.5%
OK9	Min RMSPE	638.35	0.93	0.89	0.94	9.7%	18.1%	-0.1%	-
OK10	Max cov.90.a	699.80	1.15	0.93	0.91	1.5%	-0.1%	0.5%	0.0%
OK11	Max cov.90.b	699.88	1.15	0.93	0.91	1.5%	-0.1%	0.5%	0.0%
OK12	Min MMS	614.13	0.97	0.90	0.94	10.1%	19.6%	-0.1%	2.9%
	Non-spatial equivalents								
OK5	Min AIC	676.31	1.16	0.90	0.91	-	-	-	-
OK6	Min RMSPE	700.39	1.10	0.89	-	-	-	-	-
OK7	Max cov.90.a	710.12	1.15	0.92	0.91	-	-	-	-
OK7	Max cov.90.b	710.12	1.15	0.92	0.91	-	-	-	-
OK5	Min MMS	676.31	1.16	0.90	0.91	-	-	-	-

KEY

Best → **Worst**

Final selected model

Table 4. Summary of the selected “best” rated SSN regression model (NIC10) for the Nicola Basin.

Call: glmssn(formula = AugAvgTemp ~ Elevation + Latitude + BnFlw + AvgT08 + AvgYrPPT + Wb + GRADIENT + rcaAreaKm2 + rcaStrgKm2 + rcaStrgPct + rcaStrDen

ssn.object = put.noOutliers, CorModels = c("LinearSill.tailup", "Exponential.Euclid"), addfunccol = "afvArea", EstMeth = "REML")

Residuals:

Min	1Q	Median	3Q	Max
NA	-1.23115	0.08831	1.48525	NA

Coefficients:

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-1.271e+02	1.472e+02	-0.864	0.38865
Elevation	- 3.346e-04	2.793e-04	-1.198	0.23244
Latitude	2.610e+00	2.941e+00	0.887	0.37592
BnFlw	-2.842e-01	1.112e-01	-2.555	0.01137 *
AvgT08	5.342e-01	1.379e-01	3.873	0.00015 ***
AvgYrPPT	2.246e-03	1.450e-03	1.549	0.12286
Wb	1.216e-01	2.396e-02	5.077	< 2e-16 ***
GRADIENT	-1.761e-01	7.748e-02	-2.273	0.02408 *
rcaAreaKm2	-1.051e-01	3.837e-01	0.274	0.78438
rcaStrgPct	4.294e-01	2.285e-01	1.879	0.06165
rcaStrDen	1.114e-01	5.377e-02	2.072	0.03952 *

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Correlations between individual model co-variates (predictors) in the Nicola Basin and the mean August stream temperature response variable in the “best” SSN model are provided within scatterplots in Figure 10. A number of predictors were quite strongly correlated with summer stream temperature. Strongest correlations were between mean August stream temperature and bankfull width (r = 0.72), gradient (r = -0.61), latitude (r = 0.57), elevation (r = -0.55), and Basin Flow Index (r = -0.3). The direction of most correlations with summer stream temperature were generally as would be expected from general physical principles across all the predictors although in some cases correlations were quite weak (and the strong positive correlation with increasing latitude (r = 0.57) seems counter intuitive). Observed values vs. SSN model-fitted mean August stream temperature predictions yielded a relatively even scatter for the range of predicted values (Figure 11). Prediction errors conform generally to a normal distribution with a slight bimodal skew (Figure 12).

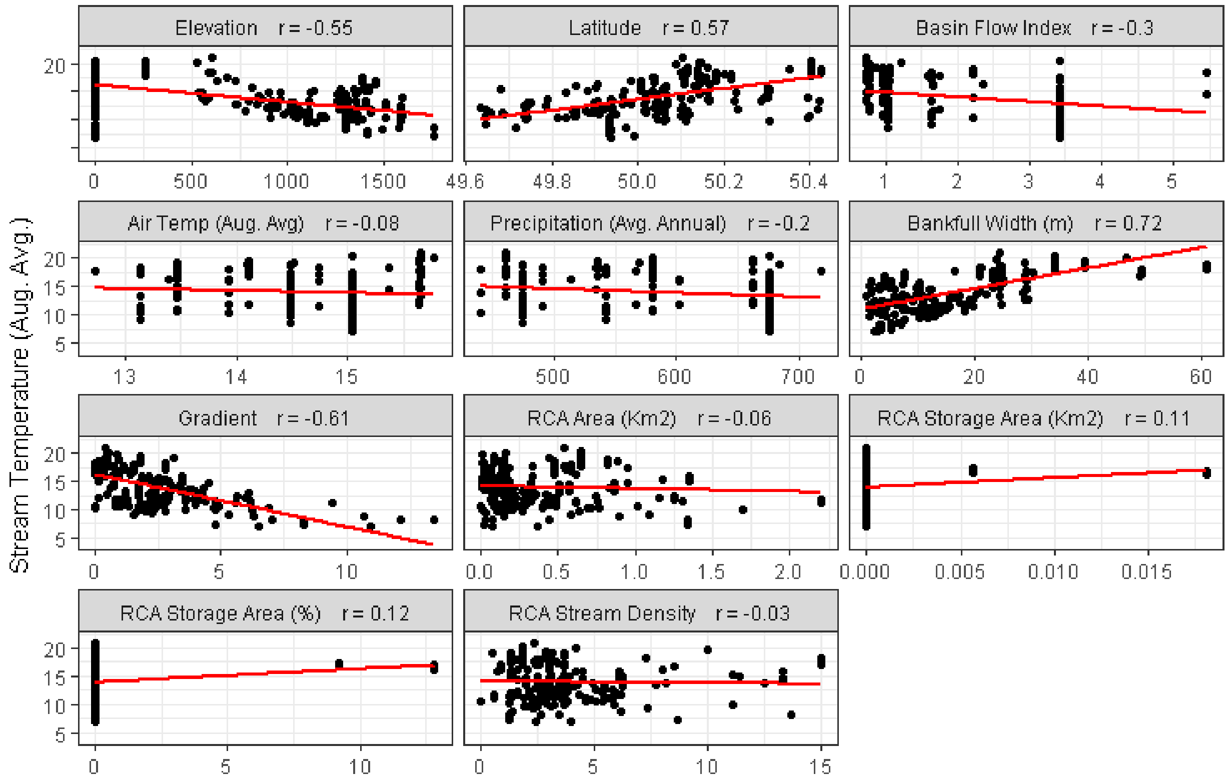


Figure 10. Plots of correlations between mean August stream temperature and key model predictor covariates across Nicola Basin temperature monitoring observations (n = 215).

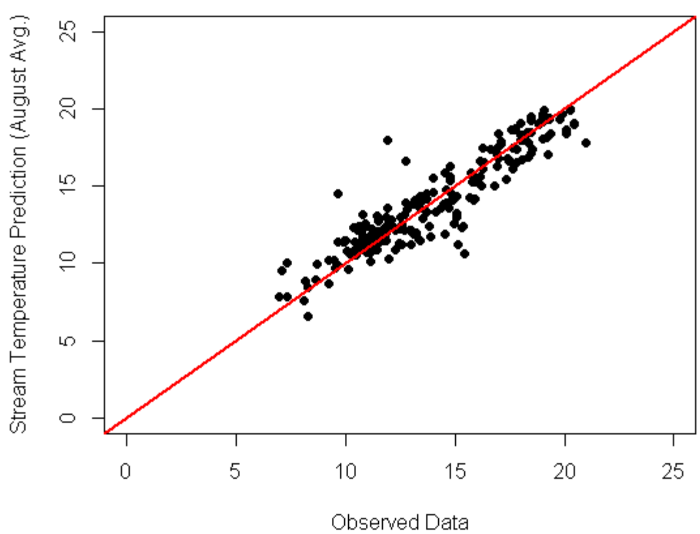


Figure 11. Observed vs. fitted mean August stream temperature predictions based on the selected "best" SSN regression for the Nicola Basin. Note that each point represents a single August temperature observation (n = 215) collected from 164 stream temperature monitoring stations within the basin across the years (1994-2010).

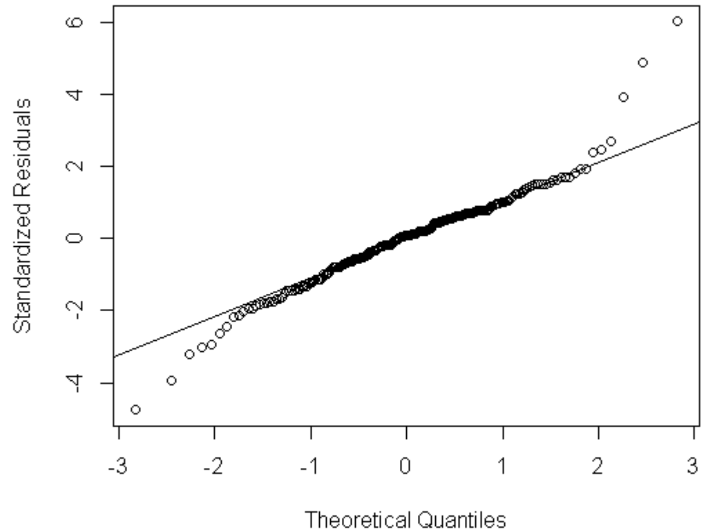


Figure 12. Normal probability plot of prediction errors (predicted – observed) for Nicola Basin sites.

Table 5. Summary of the selected "best" rated SSN regression model (OK8) for the Okanagan Basin.

Call: glmssn(formula = AugAvgTemp ~ Elevation + Latitude + AvgT08 + AvgYrPPT + StreamOrde + Gradient + rcaAreaKm2 + rcaStrgKm2 + rcaStrgPct + rcaStrDen,

ssn.object = put.noOutliers, CorModels = c("LinearSill.taildown"), addfunccol = "afvArea", EstMeth = "REML")

Residuals:

Min	1Q	Median	3Q	Max
NA	-1.02112	-0.02599	1.00406	NA

Coefficients:

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-1.068e+02	3.142e+01	-3.398	0.00083 ***
Elevation	-6.566e-03	9.839e-04	-6.674	< 2e-16 ***
Latitude	2.315e+00	6.417e-01	3.608	0.00040 ***
AvgT08	7.006e-01	1.047e-01	6.692	< 2e-16 ***
AvgYrPPT	-3.095e-03	1.282e-03	-2.415	0.01671 *
StreamOrde	6.597e-01	1.664e-01	3.964	0.00011 ***
Gradient	-1.778e-01	6.628e-02	-2.683	0.00796 **
rcaAreaKm2	-3.273e-01	2.404e-01	-1.361	0.17512
rcaStrgKm2	2.899e+01	1.088e+01	2.664	0.00840 **
rcaStrgPct	-1.290e-01	8.796e-02	-1.466	0.14427
rcaStrDen	3.160e-02	4.981e-02	0.634	0.52662

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Correlations between individual model co-variates (predictors) in the Okanagan Basin and the mean August stream temperature response variable in the "best" SSN model are provided within scatterplots in Figure 13. A number of predictors were quite strongly correlated with summer stream temperature. Strongest correlations were between mean August stream temperature and elevation (r = -0.75), stream order (r = 0.74), gradient (r = -0.54), and (r = -0.3). The direction of the correlations with summer stream temperature were generally as would be expected from general physical principles across all the predictors although in some cases correlations were quite weak and, as in the Nicola model, there was an unexpected strong positive correlation with latitude (r = 0.44). Observed values vs. SSN model-fitted mean August stream temperature predictions yielded a very tight fit for the range of predicted values (Figure 14). Prediction errors conform generally to a normal distribution with a potential bimodal skew (Figure 15).

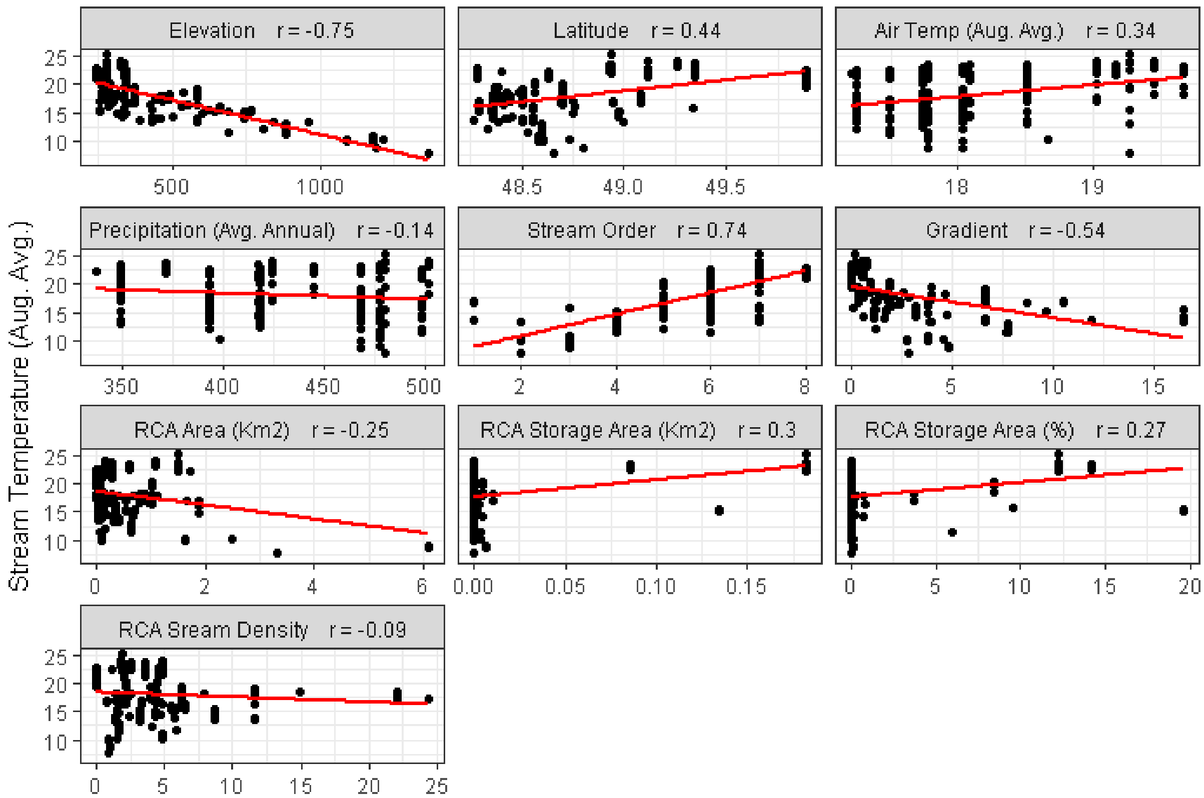


Figure 13. Plots of correlations between mean August stream temperature and key model predictor covariates across Okanagan Basin temperature monitoring observations (n = 201).

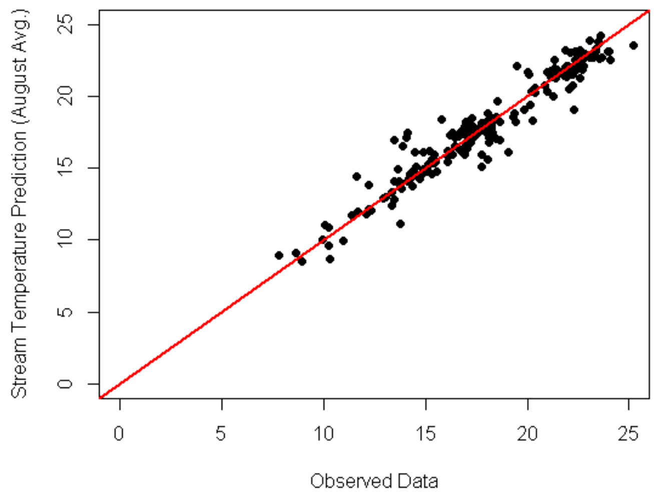


Figure 14. Observed vs. fitted mean August stream temperature predictions based on the selected "best" SSN regression for the Okanagan Basin. Note that each point represents a single August temperature observation (n = 201) collected from 164 stream temperature monitoring stations within the basin across the years (2001-2015).

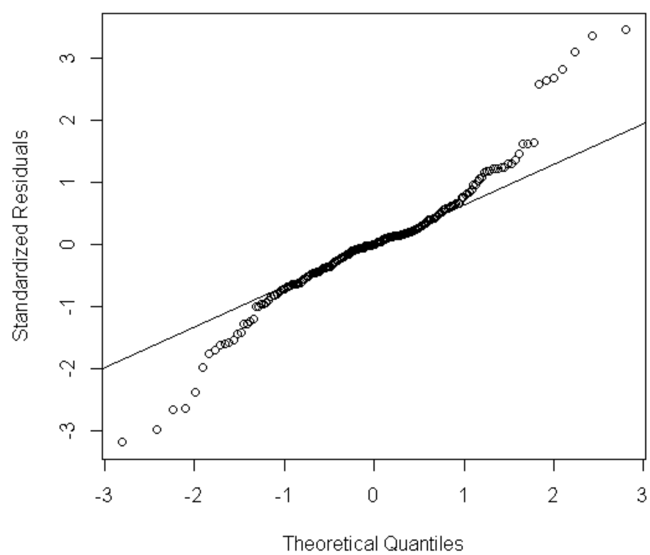


Figure 15. Normal probability plot of prediction errors (predicted – observed) for Okanagan Basin sites.

3.1.3 Summer temperature mapping

Mapping of reference period (1994 – 2010) mean August stream temperature (based on the "best" model) at prediction points along the stream network for the Nicola Basin is presented in Figure 16. Qualitative comparisons of measured temperatures to predicted values at monitoring sites indicated that the model seemed to provide a realistic representation of summer thermal habitats across the basin and was generally consistent with thermal mapping from recent (coarser watershed-scale) modeling exercises that have also covered the Nicola Basin (Nelitz et al. 2008). There were no obvious basin-wide spatial patterns to modelled temperature prediction errors at observation sites (Figure 17). Future projected stream temperatures in the Nicola Basin under modeled representative climate change scenarios are presented in Figure 18 (CGCM model) and Figure 19 (HADCM model).

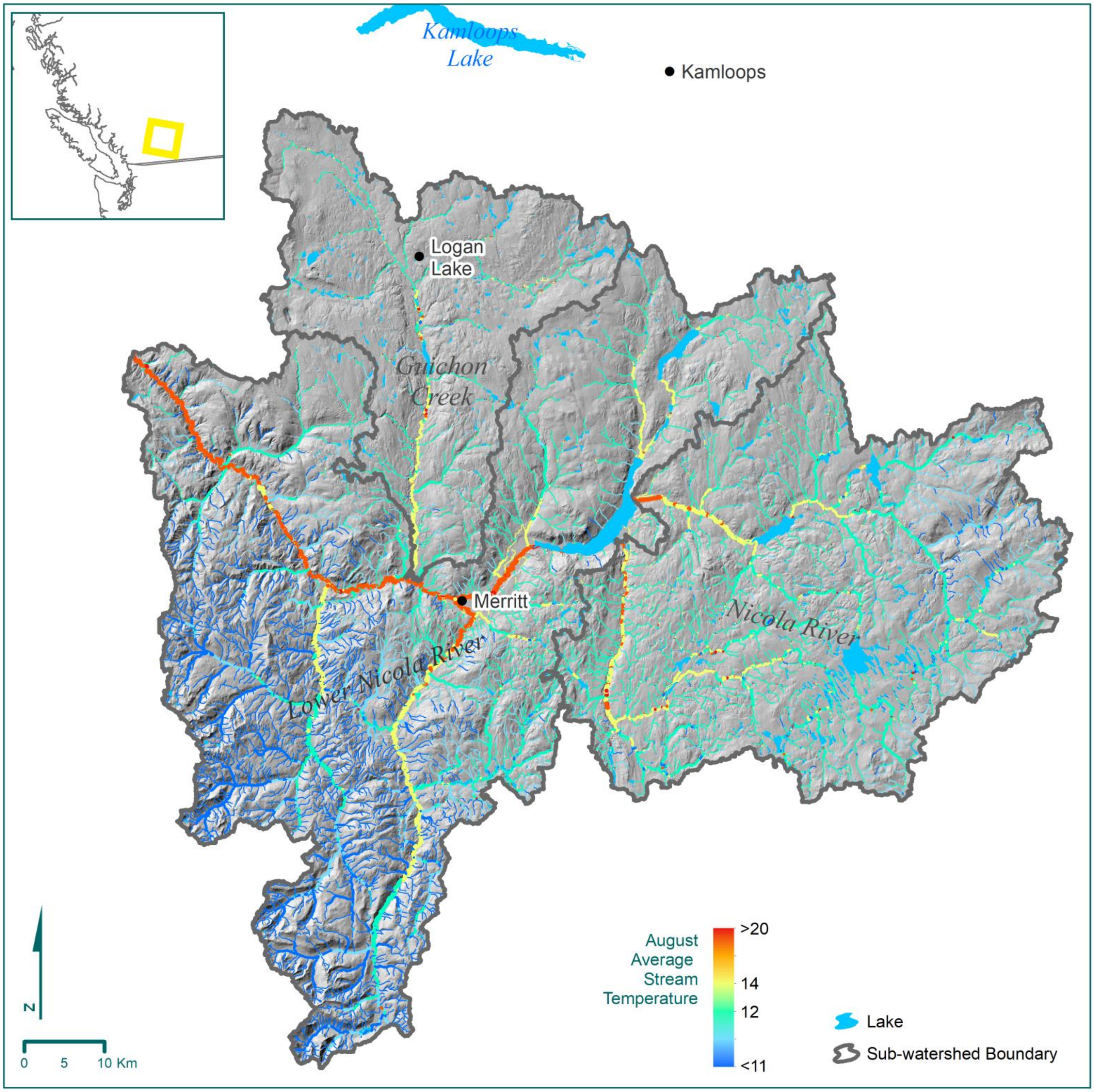


Figure 16. Map of predicted mean August water temperature along the stream network (1st order streams removed for better visualization) in the Nicola Basin during the reference period (1994-2010) based on the selected "best" model for the basin. Stream temperature predictions are colour coded (see legend) to represent predicted water temperature for each stream reach.

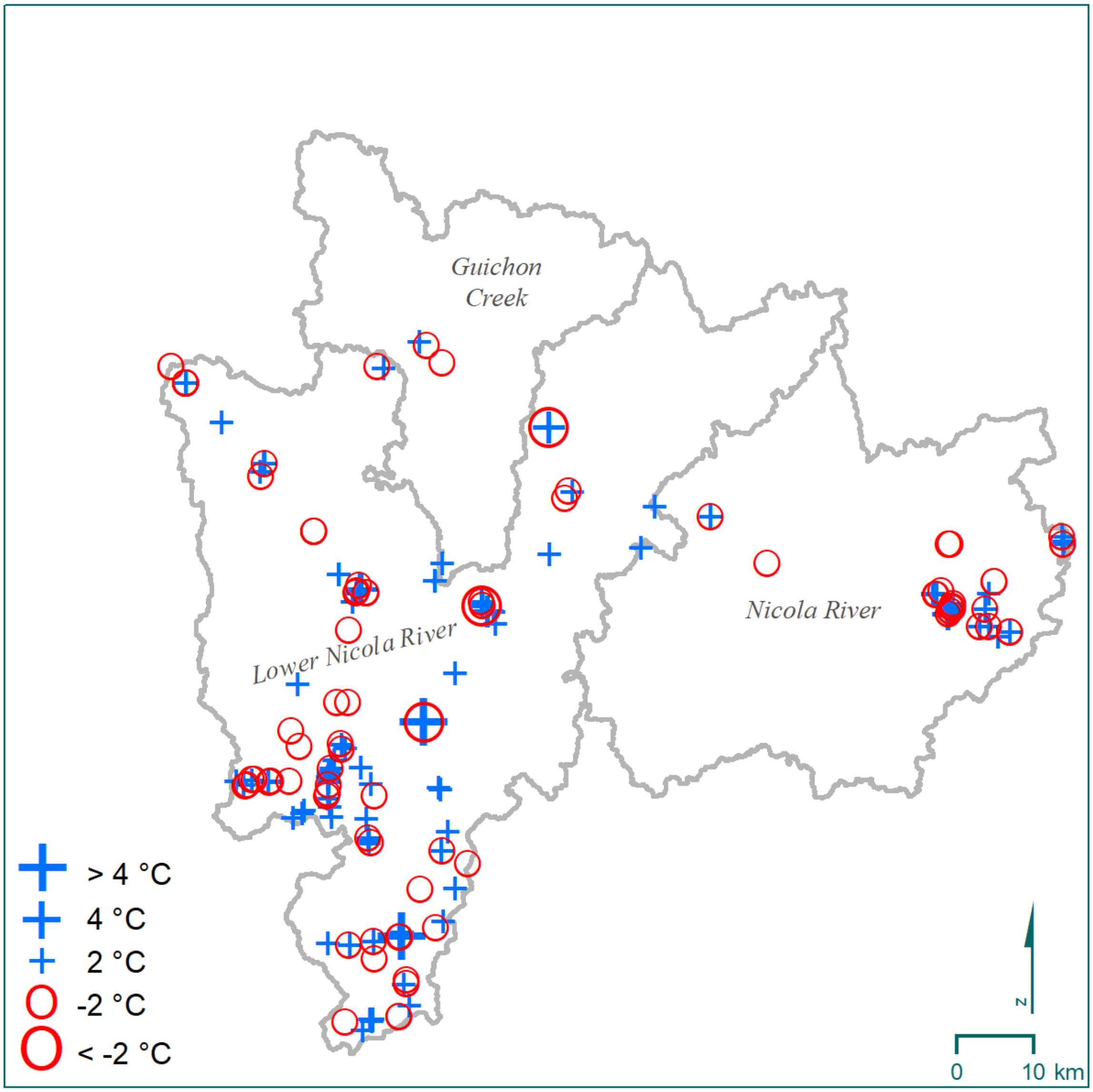
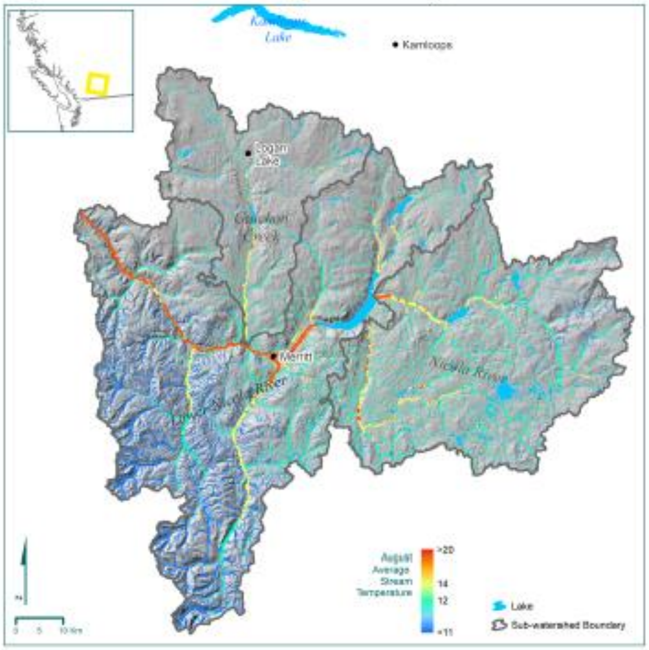
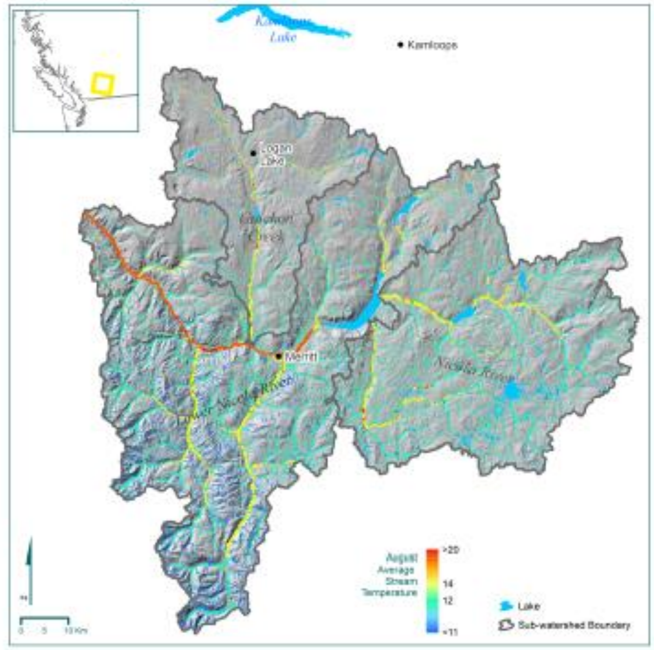


Figure 17. Spatial pattern of prediction errors at stream temperature observation sites within the Nicola Basin.

a) Historic Baseline (1994-2010)



b) 2020 (CGCM)



b) 2050 (CGCM)

c) 2080 (CGCM)

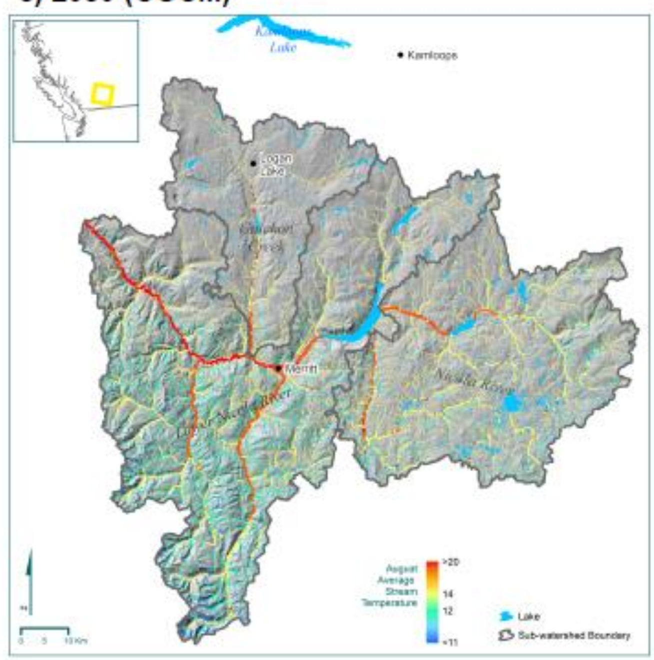


Figure 18. Changes in mean August stream temperatures in the Nicola Basin predicted by our selected "best" SSN temperature model for the basin resulting from projected changes in air temperature, precipitation, and basin flow within the CGCM3 A2, run 4 climate scenario (ClimateWNA).

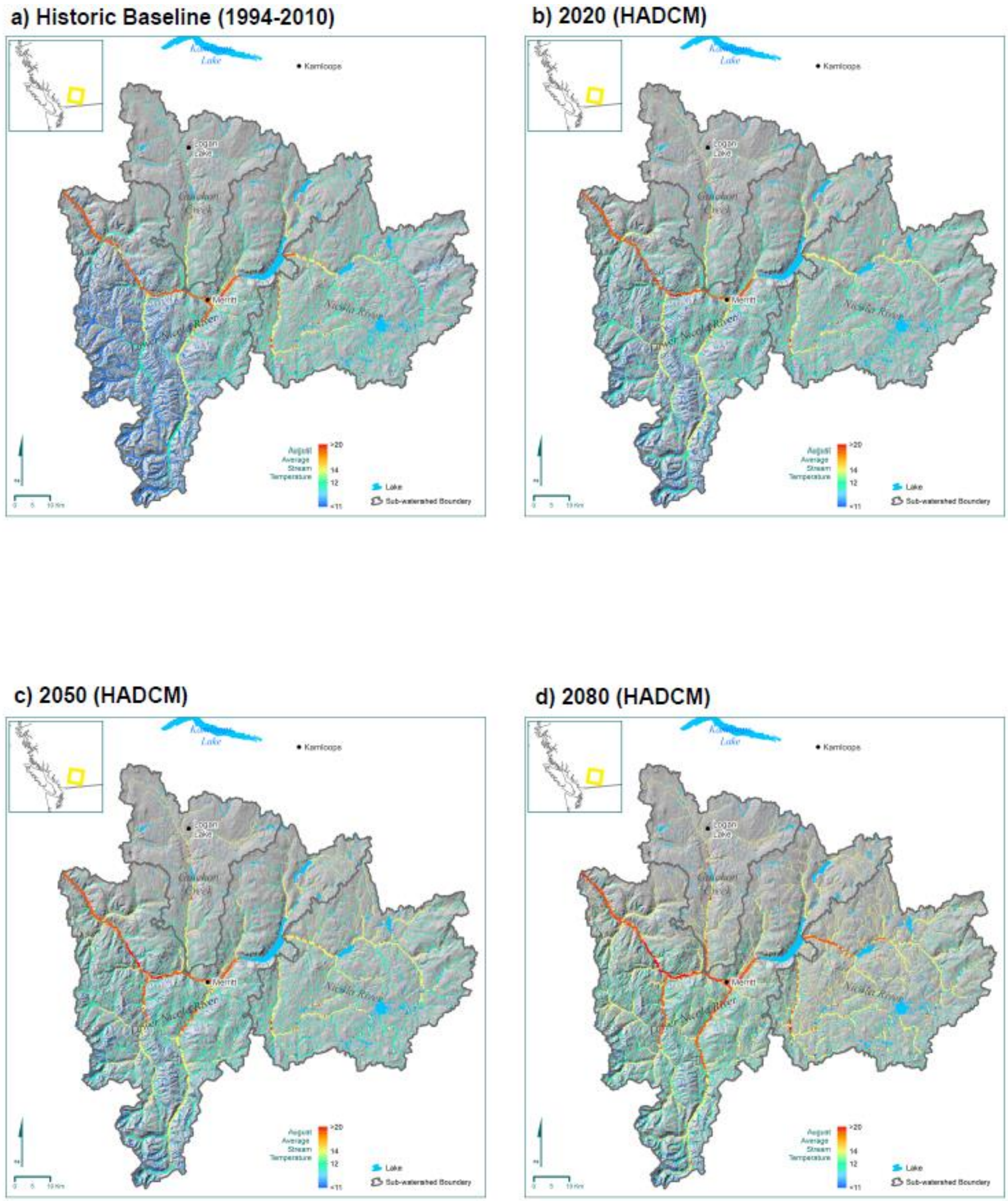


Figure 19. Changes in mean August stream temperatures in the Nicola Basin predicted by our selected "best" SSN temperature model for the basin resulting from projected changes in air temperature, precipitation, and basin flow within the HADCM3 B1, run 1 climate scenario (ClimateWNA).

Mapping of reference period (2001-2015) mean August stream temperature (based on the “best” model) at prediction points along the stream network for the Okanagan Basin is presented in Figure 20. Qualitative comparisons of measured temperatures to predicted values at monitoring sites indicated that the model seemed to provide a realistic representation of summer thermal habitats across the basin. There were no obvious basin-wide spatial patterns to modelled temperature prediction errors at observation sites (Figure 21). Future projected stream temperatures in the Nicola Basin under modeled representative climate change scenarios are presented in Figure 22 (CGCM model) and Figure 23 (HADCM model).

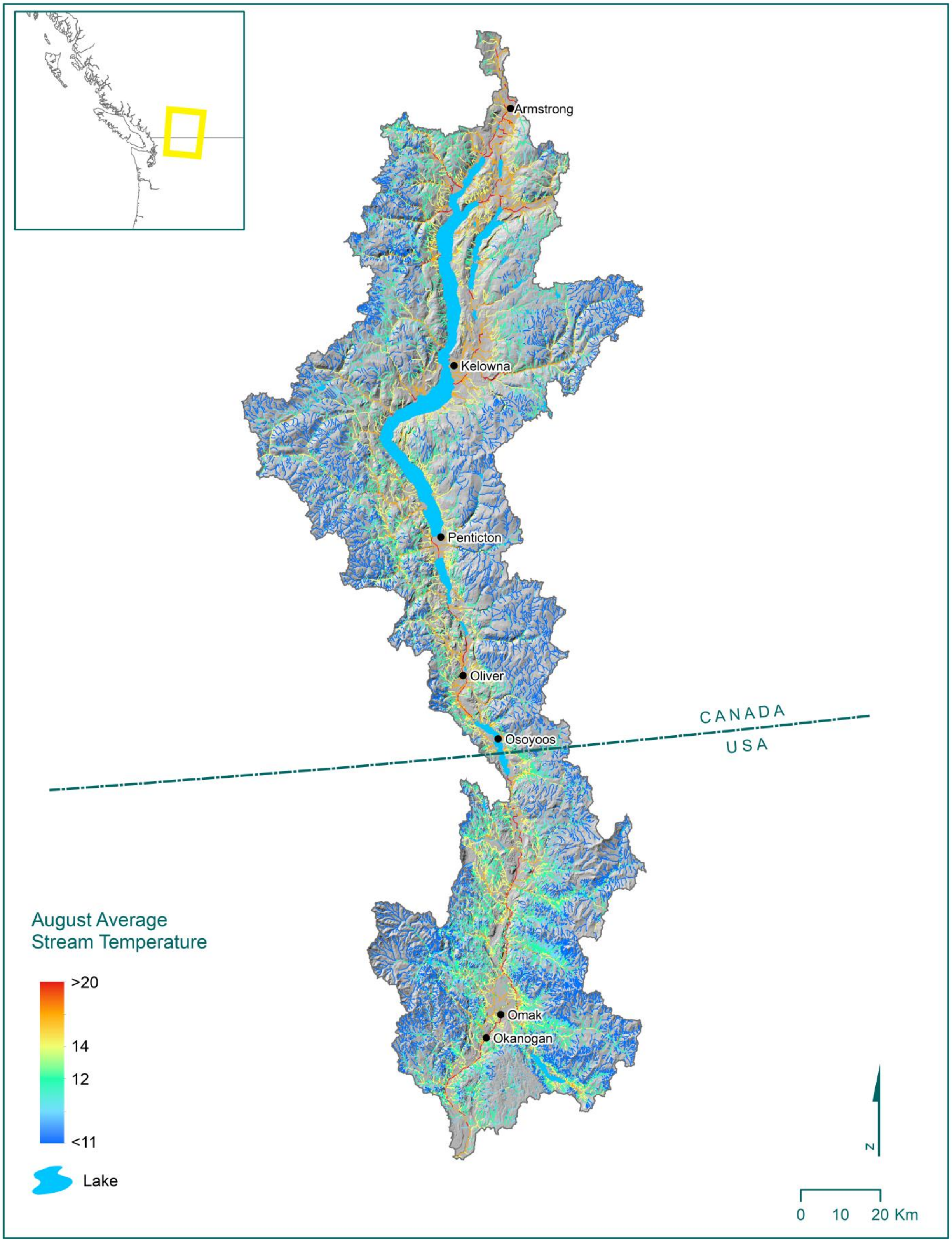


Figure 20. Map of predicted mean August water temperature along the stream network (1st order streams removed for better visualization) in the Okanagan Basin during the reference period (2001-2015) based on the selected "best" SSN model for the basin. Stream temperature predictions are colour coded (see legend) to represent predicted water temperature for each stream reach.

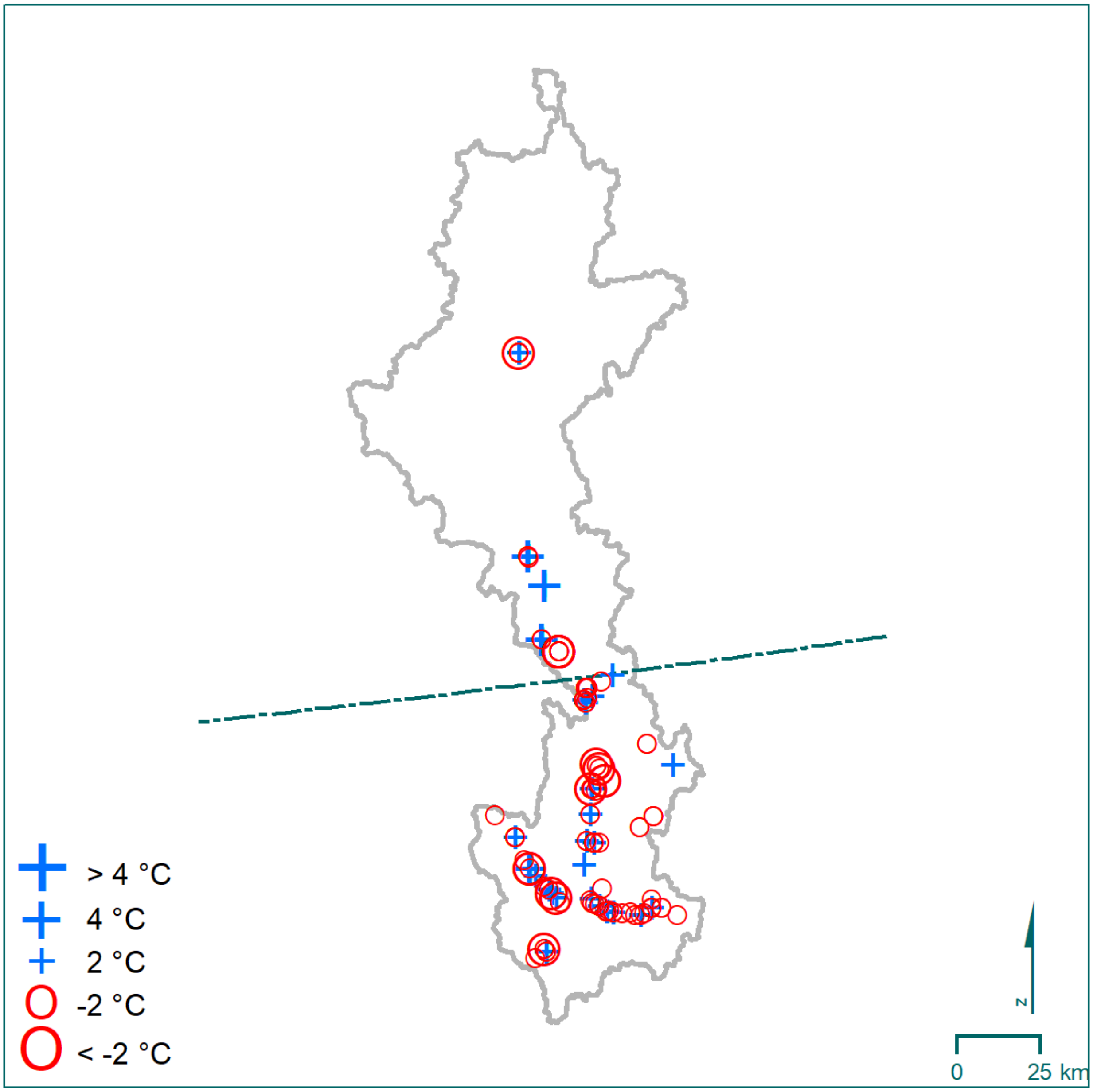


Figure 21. Spatial pattern of prediction errors at stream temperature observation sites within the Okanagan Basin.

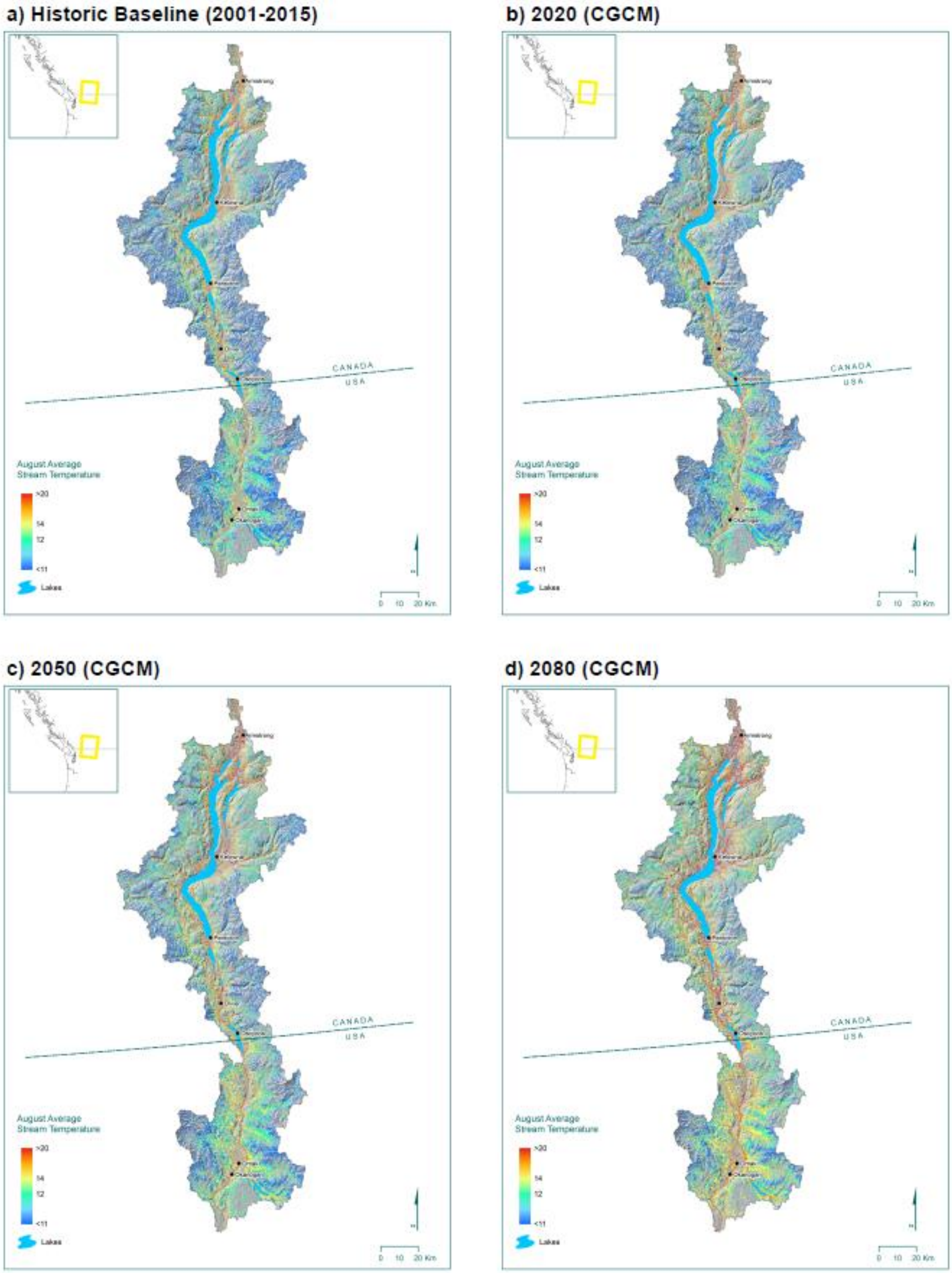


Figure 22. Changes in mean August stream temperatures in the Okanagan Basin predicted by our selected "best" SSN temperature model for the basin resulting from projected changes in air temperature and precipitation within the CGCM3 A2, run 4 climate scenario (ClimateWNA).

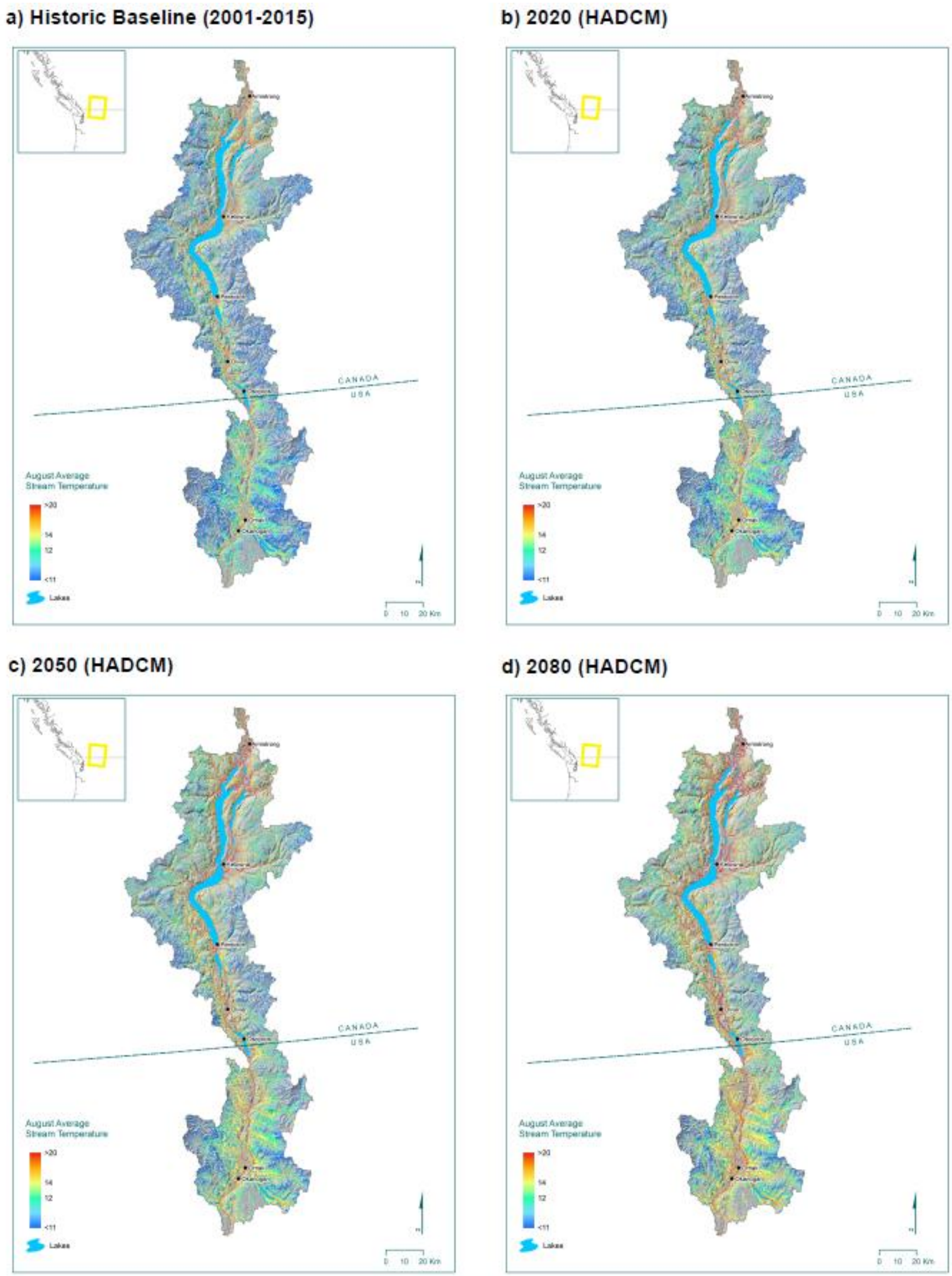


Figure 23. Changes in mean August stream temperatures in the Okanagan Basin predicted by our selected "best" SSN temperature model for the basin resulting from projected changes in air temperature and precipitation within the HADCM3 B1, run 1 climate scenario (ClimateWNA).

4 Discussion

Relationships represented in this report for describing summer stream temperature in the Nicola and Okanagan Basins were consistent with general understanding of the physics governing stream temperature regimes and the "best" SSN regression models presented in this report for predicting mean August stream temperature displayed quite good model fit across a suite of diagnostics. Mapped representations of average summer temperature throughout the Nicola stream network seemed consistent with expectations from past modeling exercises. Model fit could potentially also be improved in the future through development and inclusion of additional predictor variables that may have important influences on stream temperatures (e.g., extent of riparian canopy closure, base flow, etc.).

The current models presented in this report provides our initial representation of mean August stream temperatures in the Nicola and Okanagan Basins during single reference periods (1994-2010 for the Nicola, 2001-2015 for the Okanagan). Modelled stream temperature predictions from the reference period have been used within this report to provide the base frame for initial exploration of the potential effects of alternative climate scenarios on summer stream temperatures in our pilot basins. Outputs from the SSN models can be used to evaluate the sensitivity of stream temperatures to changes in summer air temperature, precipitation, flow and other variable influences. Within this report we undertook an initial exploration of the effect of future climate change scenarios on summer stream temperature in our two pilot basins (which includes, uniquely, a transboundary watershed, the Okanagan), as has been done previously for areas of the US Pacific Northwest within the USFS's NorWeST stream temperature project.

5 Recommendations/Next Steps

The project demonstrates an initial "proof of concept' for transferring stream temperature modeling approaches and protocols developed previously by the USFS for the US Pacific northwest for use with British Columbia's spatial layers and datasets, as well as with the "harmonized" transboundary hydrology layer developed for the International Joint Commission. Learning in this regard was focused on attempting to apply the required processes across designated pilot study areas in separate areas of the province as well as within a transboundary watershed. The successful completion of these initial exercises in Year 2 of this project and the considerable learning that has been developed through the process suggests that there is good potential to now move forward effectively towards broader application of NorWeST approaches within BC watersheds where data allow.

Acquire additional stream temperature data: Acquiring sufficient time series stream temperature data to build predictive models for British Columbia watersheds can be very problematic. No centralized system currently exists for housing provincial temperature datasets and the extent of available legacy datasets is uncertain. Tracking down and obtaining datasets is currently based primarily on networking with individual data custodians which can be a time consuming process, as are the required QQ/QC processes before working with the data. Legacy datasets acquired generally represent data acquired for very different purposes than basin-scale temperature modeling, so tend to be spatially clustered and often are concentrated on only certain stream sizes. While we were successful at obtaining a fair number of temperature datasets widely distributed within our Nicola pilot study area it has been difficult to obtain sufficient data across other BC watersheds to develop basin temperature models (e.g., insufficient stream temperature data available for NE Vancouver Island to develop a model for that region in Year 1 of this project). Considerable stream temperature data will be required to generate robust stream temperature models more broadly across the province and difficulty in acquiring legacy time series datasets of stream temperature data from BC watersheds is likely to be the norm. Additional efficiencies will need to be developed in acquiring temperature data that may exist across the province, centralizing this data for broad useage (as piloted within the database developed for this project by PSF), identifying where data gaps currently exist (and thus where modeling may currently not be feasible), and working to fill those gaps to help inform future analyses. Development of Canada/US transboundary stream temperature models (as piloted within this report for the Okanagan Basin) may in fact be easier than for basins located solely within BC boundaries. The extensive water temperature datasets assembled in the US for the NorWeST project provide a strong base of temperature data to inform the models, requiring perhaps only limited supplementation from temperature datasets in BC sections of the transboundary basins for model refinement. For basins located solely within BC boundaries it may be beneficial in next stages to explore analytical approaches that could use spot temperature data (which is much more commonly available in BC) to somehow reflect time series patterns. Such approaches (i.e. transforming spot data if data sufficiently comprehensive) have been employed in some river systems in BC to generate reasonable time series approximations (K. Hyatt, pers. comm.). This could allow modeling of stream temperature in BC basins even where time series temperature data is limited.

Improve existing model: Spatial models outperformed their nonspatial counterparts, as indicated by lower RMSPE, lower AIC values, and other diagnostics (e.g., 16.6% and 2.5% improvement in “pseudo” r^2 for the Nicola and Okanagan basins respectively). Although the current “best” SSN regression models developed to date for the Nicola and Okanagan Basins captured a substantial amount of variation in mean August stream temperature across the sampled streams there is still a considerable amount of variation left unexplained. Further improvements to the model fit could likely be achieved through 1) integration of additional streams and years of temperature data if these could be obtained, 2) incorporation of additional dynamic predictors into the model, such as changes in the extent of forest cover or other land disturbances, or a changing base flow index. Determining how best to incorporate additional predictors to improve current modelling efforts was something beyond our scope in Year 2 of the project and would be productive to explore in subsequent stages.

Improve model processing: Running of SSN models is a highly demanding computer processing exercise. Single model runs for our pilot basins often required multiple hours to complete, making it a long exercise to explore alternative model structures. At the completion of our project we have undertaken some initial explorations of moving model processing from single machines to a Cloud environment[3], and have found processing to be up to 25% faster in the Cloud. We have not fully evaluated the full processing speed benefits of such an option but would suggest that this is likely to

[3] The Cloud environment explored for this processing was a "compute optimized" system on Amazon Web Services which provides 32 virtual central processing units (vCPUs), 60GB of RAM, and 2x320GB SSD storage devices. This system offers fast, cost effective high performance for intensive processing like that associated with spatial stream network modelling. A major advantage to the Amazon Web Services system we tested is the ability to run repetitive tasks in parallel across up to 31 CPUs rather than a single CPU.

be a low-cost solution for allowing much easier generation of these process-demanding SSN models to make a larger provincial-scale roll-out of such temperature models more feasible.

Develop models in other areas: To further evaluate the prospect of developing these models more broadly across BC and the potential synergy with ongoing efforts by the NorWeST project in the US Pacific Northwest the methods that have been piloted for this report should be extended to other areas of the province, particularly in transboundary watersheds where there is the potential to “piggyback” on already assembled NorWeST temperature datasets. Focusing next stages on transboundary watersheds will help to better identify where longer term efficiencies could be achieved between US and BC efforts for networking, data sharing, and integrating shared modeling analyses to allow seamless development of predictive stream temperature models than span national boundaries.

Further develop centralized data repository: As indicated earlier, the time and effort required to acquire stream temperature data for use in the initial modeling exercises across Year 1 and 2 of this project were considerable. The efficiency of further modeling efforts would be greatly enhanced if a centralized database of provincial water temperature data was in place. PSF has initiated development of such a provincial-scale temperature database within this project, with a standardized data sharing agreement now in place for coordinating data from willing data providers. For this database to develop more fully as a hub for accessing temperature data will require the long-term interest and support of the various provincial and federal management agencies. Ultimately, as the extent of legacy temperature datasets in the province may currently be limited, such a data repository would have the likely benefit of allowing for more clear identification of existing data gaps and spurring the development of new monitoring plans to supplement.

Consider range of model uses: High spatial resolution SSN stream temperature models that we have developed for the Nicola and Okanagan basins (and that could now be developed for other areas of the province) could be used for a range of purposes. Use of robust, predictive temperature models (as previously suggested in Nelitz et al. 2008) could include:

- exploring the potential predicted effects of changing climate variables on stream temperatures and identifying possible thermal refuge areas for fish and other biota;
- using predictions of stream temperature as a basis for identifying potential opportunities for habitat restoration actions or adaptation strategies (e.g., areas where observed summer stream temperature is much higher than predicted may suggest influences from human activities and suggest where localized restoration actions might be beneficial);
- using predictions of temperature along stream networks to provide a useful additional basis for establishing stratification frameworks for sampling of fish or other aquatic species in BC (based on known species thermal thresholds), or for monitoring of water quality or other attributes;
- improving modelling for other elements beyond stream temperature (e.g. stable isotopes) using predictive SSN-based stream models and supporting improved predictive modelling of fish species distributions, especially for temperature sensitive species (e.g. bull trout).

Awareness raising: The novel approaches and results of the pilot work to date should be of interest to provincial resource management agencies and ENGOs. Developing and hosting a webinar to allow broad dissemination of the project activities and results is intended as a final follow-up to the Year 2 project work and submission.

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Appendix 1

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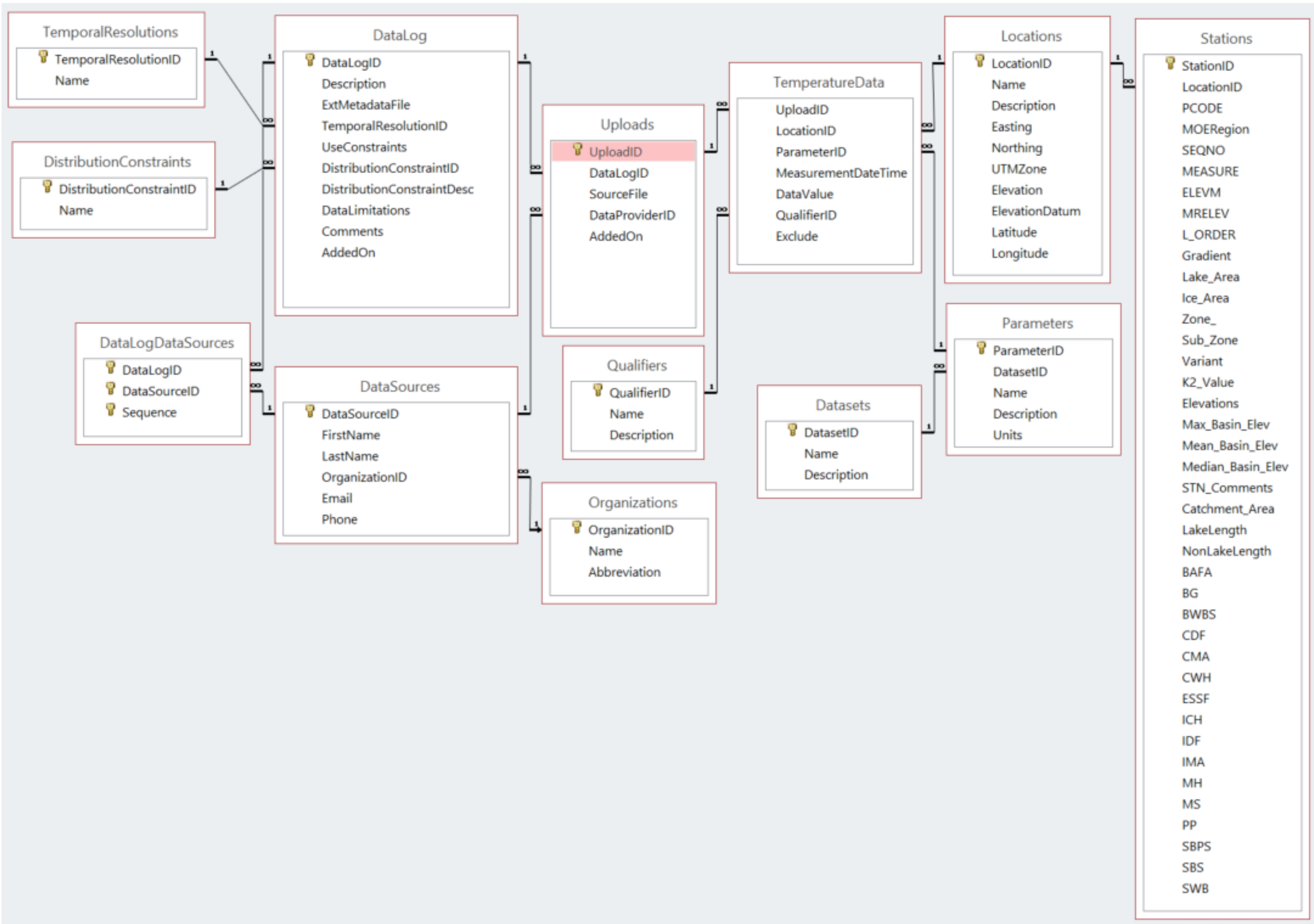
Appendix 2

Pacific Salmon Foundation Water Temperature Database Structure



Appendix 3

Stream Temperature Modeling Pilot Project: Data Sharing Agreement

Background

Water temperature plays a fundamental role in structuring freshwater ecosystems. It influences the physiology and behavior of fish through all life history stages, affecting growth, survival and distribution of individuals and populations, as well as species interactions within fish communities. Moreover, evidence suggests that changing climate conditions have led to warming of streams across western North America and future projections suggest that warming will continue for the foreseeable future. Such thermal changes can lead to fragmentation of freshwater habitats across the landscape, especially for vulnerable species such as bull trout and Pacific salmon. Managers of aquatic ecosystems need to consider the implications of climate change and other human activities in land-use planning and management decisions (e.g. riparian management, flow management, aquatic connectivity, habitat restoration, aquatic species conservation). Yet in British Columbia (BC) broad-scale planning efforts are, at present, only possible by using crude climate surrogates like air temperature or elevation, which can be weakly correlated with stream temperatures. In BC, a regulatory tool is available that allows managers to designate “Temperature Sensitive Streams” (TSS) to protect critical fish-bearing streams that could be altered by stream heating due to forest harvesting in riparian and upslope areas as well as by more general climate change effects. This TSS regulatory tool, however, has had limited application in the province to date and its application could be better enabled by providing a stronger base of information to support use of the tool.

The Pacific Salmon Foundation and ESSA Technologies Ltd. in collaboration with the BC Ministry of Environment, BC Ministry of Forests, Lands and Natural Resource Operations, Fisheries and Oceans Canada, Pacific Climate Impacts Consortium, University of British Columbia, and the US Forest Service are undertaking a project funded by the Great North and North Pacific Landscape Conservation Cooperative entitled, "*Towards developing an interagency stream temperature database and high-resolution stream temperature model for British Columbia.*" The goal of this project is to provide an assessment and description of historical stream temperatures and thermal habitat distributions for aquatic species in BC drainages. This will be achieved by:

- Compiling stream temperature data from various sources across the province;
- Developing the technical architecture for a stream temperature database;
- Piloting existing protocols for spatial data processing in two pilot watersheds (one coastal, one interior);
- Developing a stream temperature model that incorporates important and relevant explanatory variables; and
- Using the model to predict historic patterns of stream temperature in the pilot watersheds.

Use of Data and Rationale for a Data Sharing Agreement

To support development of the underlying model, the project team needs to compile water temperature data collected within BC, from headwater streams to major rivers. There is no single agency or organization conducting a centralized monitoring program for water temperature in BC, thus the need to approach and request data from individuals or organizations conducting their own monitoring. Once compiled, these data will first be integrated into a centralized database. Next, GIS analyses will be completed to determine watershed characteristics associated with these monitoring locations. These data will then be used to develop a stream temperature model. Finally, these data will be hosted by the Pacific Salmon Foundation. The project team will not conduct unique analyses or publish any results based on data provided by a single data contributor. Any publishable results will be the outcome of regional- or provincial-scale analyses that integrate many disparate data sets. This data sharing agreement is intended to provide clarity about how data will be used and ensure data providers are supportive of these applications.

All datasets used in this project will be stored in the Pacific Salmon Foundation's Salmon Data Library[4], on a secure server which is routinely backed up. Datasets stored in the Salmon Data Library can be restricted, password-protected and accessible for a defined user group, or available to the public, depending on the conditions specified by the data provider.

Agreement

This agreement is between the Pacific Salmon Foundation (the Data Recipient) and undersigned data provider. The data provider agrees the stream temperature data provided to the project team can be used for the purposes described above. Additionally the data provider agrees to the sharing of their data as specified in the table below.

Data sharing permission level	**(Yes/No)**	**Conditional***
I give permission to use my data in the model		
I give permission to use my data for sharing daily summaries/monitoring site locations		
I give permission to disseminate my raw data to other interested parties if requested		
I give permission for my data to be made publicly available via PSF's Salmon Data Library		
I give permission for third-parties to redistribute data, e.g., in reports		

*If conditional, please specify conditions under which data could be shared at this permission level (e.g. date, agencies, etc.)

The Data Provider grants the Data Recipient use of their data in perpetuity, subject to the terms specified in this agreement. The Data Recipient will destroy all electronic copies and return all physical copies of the data to the Data Provider should they request the material be removed.

The Data Provider

Organization Name: ______________________

Signature: _______________________________

Name: ________________________

Date: ________________________

The Data Recipient

Organization Name: Pacific Salmon Foundation

Signature: _______________________________

Name: ________________________

Date: ________________________

[4] The Salmon Data Library can currently be accessed at datalibrary.skeenasalmonprogram.ca. The URL is subject to change.

Appendix 4

Water Temperature Data Gathering and Cleaning

Data gathered for this project in the Nicola River, North-East Vancouver Island, and Okanagan River pilot study areas were procured from multiple sources through staff at Fisheries and Oceans Canada (DFO), BC Conservation Foundation (BCCF), Environment and Climate Change Canada (ECCC), and BC Ministry of Forests, Lands, and Natural Resource Operations (FLNRO). These data sets and locality meta-data were filed and stored in their original format. For processing, files not already .csv formatted were exported into .csv format (with no change in underlying data). These .csv files were read into the program R by location group. Thus, if many data files were provided for the same location they were imported and combined together as an object in R.

Once read into R the data were parsed, using the dplyr package, into temperature and date/time columns and were converted to represent doubles and POSIXct-dates respectively. These data were plotted using the ggplot2 package and viewed for abnormalities. Typically data errors consisted of:

1. Leading and trailing data points that are unusually high or low relative to data either following or preceding these points, representing when the data were placed in the water or removed.
2. Periods of high variance in the data suggesting a dewatering event where the temperature logger was exposed to the air.
3. Temperatures below freezing suggesting the logger was either encased in ice or dewatered but covered by snow.

Points of this nature were identified by comparing to multiple reference years at the same site (as described in Sowder and Steel 2012) (see Figure A1) and flagged for exclusion from analyses along with a qualifying ID providing the rational for exclusion. These erroneous data were not removed from the database.

Once the data were properly cleaned the data were collated into the database. Cleaning and collating data and meta-data into the database was facilitated and streamlined by functions developed and packaged for the ESSA database. The rDatabaseBuildTools is locally stored and greatly enhances the consistency of data incorporation while making the entire process of data cleaning, incorporation and summarization entirely reproducible.

On a single occasion regression splines were used to facilitate the exclusion of data-points exhibiting intermittent air exposure. In this instance, a regression spline was used to model an early period in the data where no air exposure was present. This model was then applied to the later period in order to identify data points outside the normal variability for water temperatures at the site.

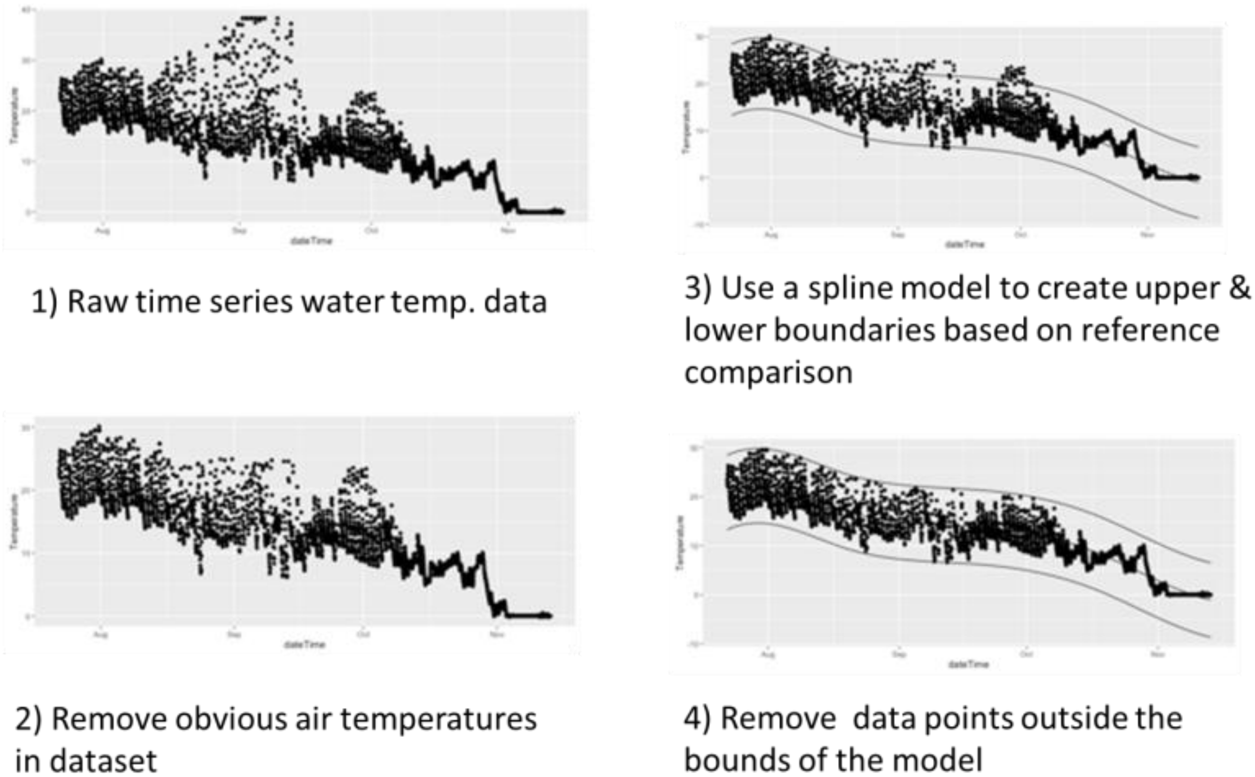


Figure 4A-1. Steps in filtering and cleaning new water temperature datasets for removal of extreme temperature variability.

Reference:

Sowder, C. and E.A. Steel. 2012. A note on the collection and cleaning of water temperature data. Water (4): 597-606.

Appendix 5

Project Stream Reconditioning and Model Attribute Processing Steps Workflow

1.0 STREAM RECONDITIONING

Step 1000. REMOVE ORPHANS
1100. Create a new layer for identifying orphans

- Input: FWA_STRM_N_LINE_[watershed].shp
- USFS documentation: NationalStreamInternetProtocol_Version4-7-2015.pdf
    - Pg 8-9 – isolated networks
- Description: Export stream network to a new file. This creates a duplicate copy of the original stream network.
- Output: 1100_[watershedname].shp

1110. Identify orphans

- Input: 1100_[watershedname].shp
- Description: Select "EDGE_TYPE" = 1400 AND "CWB_WS_CD" = '999-999999'.
- Output: same as input

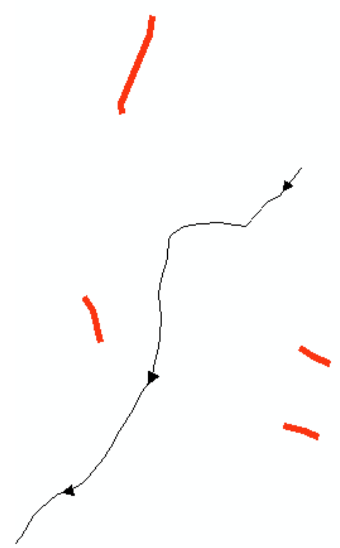


Figure A5-1. Orphans are thick red lines, black lines are streams with flow direction depicted by arrows

1120. Create and populate [Orphan] = 1. Orphans are identified by [Orphan] = 1.

- Input: 1100_[watershedname].shp
- Description: Add a field to 1100 output named [Orphan] (short integer). Calculate [Orphan] field to 1 for all selected records.
- Output: same as input

1200. Create stream layer with orphans removed

- Input: 1100_[watershedname].shp
- Description: Switch selection from Step 1110. Export.
- Output: **1200_[watershedname]_orphansremoved.shp**

Step 2000. REMOVE BRAIDS

2100. Add [Braid] field to identify braids. [Braid] = 0 means not a braid, 1 = braid

- Input: 1200_[watershedname]_orphansremoved.shp
- USFS documentation: NationalStreamInternetProtocol_Version4-7-2015.pdf
  - Pg 9-10 – removing braids and diverging flow
- Description: Add a field to 1800 output named Braid (short integer). Leave Braid field as 0 for all records.
- Output: same as input

2200. Create fishnet grid to help systemize the visual search for braids

- Input: none (creating new file)
- Description: Create polygon fishnet grid (Fishnet grid tool - Arcmap) using an appropriate grid cell size (7.5kmx7.5km grid cells were used for the Nicola watershed) using 2100 input as extent. Geometry type is polygon. Fishnet label (point .shp) can be deleted.
- Output: 2200_[watershed]_fishnet.shp

2300. Add field to fishnet grid to record checked status

- Input: 2200_[watershed]_fishnet
- Description: Add a field to 2200 output named Checked (short integer). Leave Checked field as 0 for all records.
- Output: same as input

2400. Visually identify braids in a systematic fashion using the fishnet grid

- Input: 1200_[watershedname]_orphansremoved.shp
- Description: Visually inspect the entire watershed for braids using fishnet grid to ensure no areas are missed. As fishnet grid cells are checked for braids change Checked field to 1. When a stream segment that looks like a braid is identified the following steps should be followed to determine which portion to identify as a braid.
  - 1) Determine the BLU_LN_KEY of the stream mainstem,
  - 2) if the braid is simple (ie. one stream loop off the mainstem with no other streams connected to it) change the Braid value to 1 for the portion of the stream that has a different BLU_LN_KEY. If the braid is more complicated complete step 1 then
  - 3) look at the flow direction of the streams by symbolizing with an arrow at the end (this shows you water flowing downstream from headwaters) and change the Braid value to 1 for the stream(s) that are not needed for the additional streams to flow into the mainstem,
  - 4) if still not obvious which section to change the Braid value to 1, change the value for the shortest segment that still allows all additional streams to flow downstream into the mainstem.
- Output: same as input

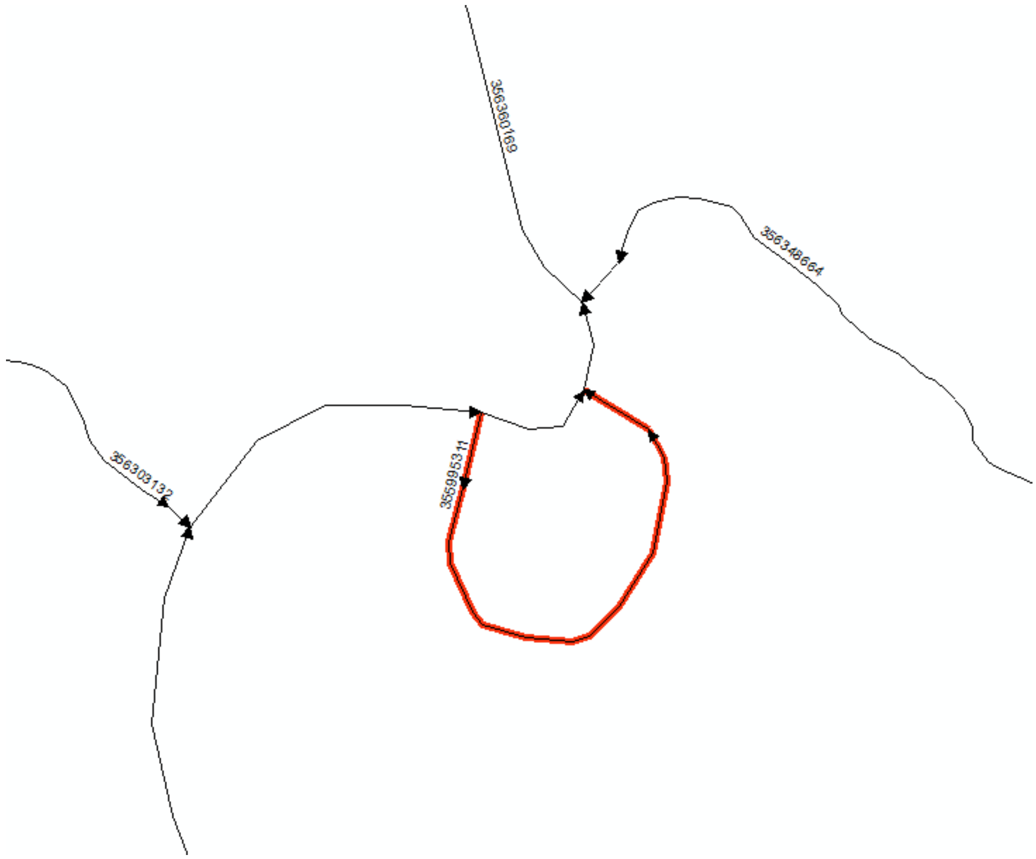


Figure A5-2. Simple braid. Braids are thick red lines, black lines are streams with flow direction depicted by arrows. Labels are BLU_LN_KEY.

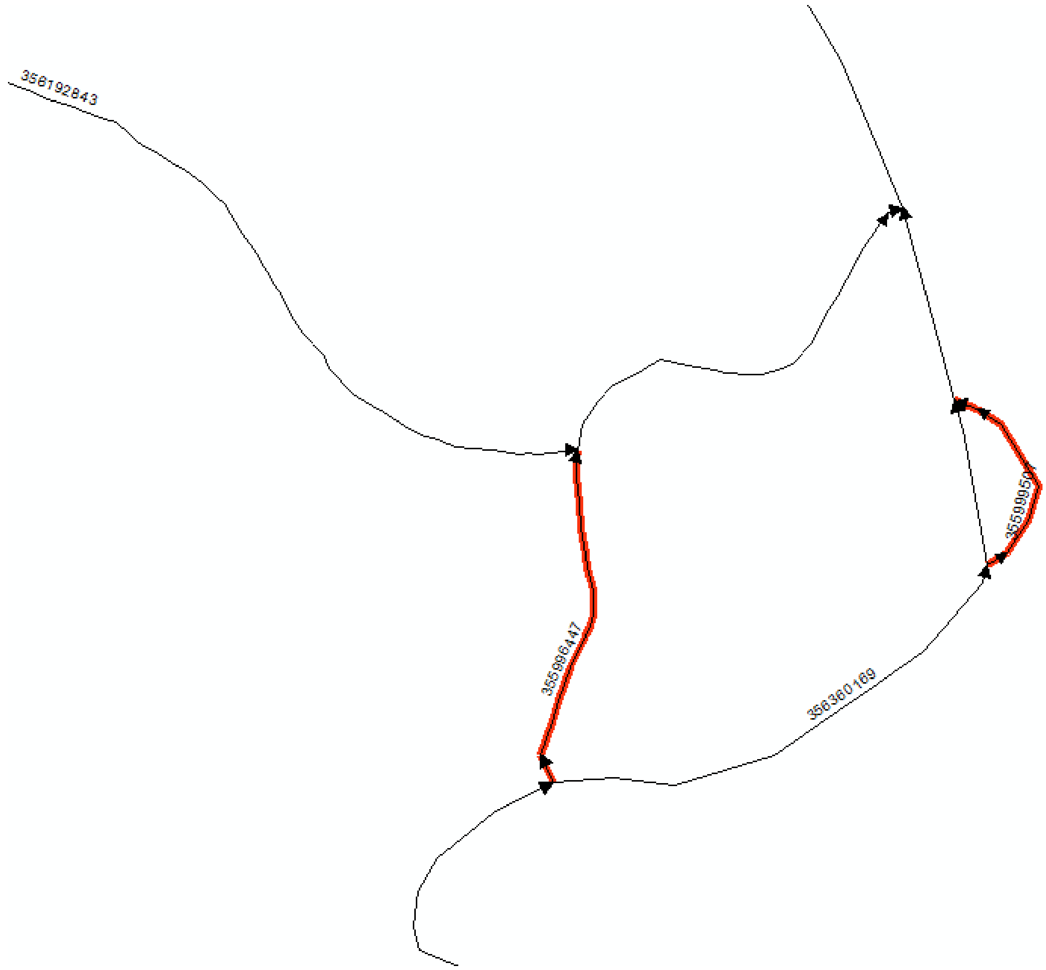


Figure A5-3. Complex braid (left) and simple braid (right). Braids are thick red lines, black lines are streams with flow direction depicted by arrows. Labels are BLU_LN_KEY.

2500. Create new shapefile with braids removed

- Input: 1200_[watershed]_orphansremoved.shp
- Description: Select by attributes on 1200 where braid = 0. Export.
- Output: **2500_[watershed]_braidsremoved.shp**
- Ensure streams are digitized in the correct direction by symbolizing the linework with “arrow at end”. If the streams are digitized in the incorrect direction they must be flipped using ArcMap’s “Flip line” tool. The tool will overwrite the old output so a new file is not created. FWA streams were digitized in the wrong direction for the Nicola and Vancouver Island study areas.

3000. BUILD THE LANDSCAPE NETWORK

3100. Export shapefile with braids removed to a new shapefile for topological editing.

- Input: 2500_[watershed]_braidsremoved.shp
- Description: Export 2500 to 3100_[watershed]_reconditioned.shp
- Output: 3100_[watershed]_reconditioned.shp

3200. Create new folder

- Input: none
- Description: Create a new folder called "LSN1"
- Output: LSN1 folder

3300. Create Landscape Network (LSN)

- Input: 3100_[watershed]_reconditioned.shp
- USFS documentation: NationalStreamInternetProtocol_Version4-7-2015.pdf
  - Pg 6 - 3.3.1 STARS
  - Pg 10 - Building the Landscape Network
- USFS documentation: 2_Reconditioning_NHDPlusV2_Protocol.docx
  - Pg 1 – Build LSN
- USFS documentation: STARS_tutorial_2.0.0
  - Pg 11-13 – Build a Landscape Network
- USFS documentation: STARS_vignette2014
  - Pg 3-6
- Description: Run Arc Toolbox: STARS_V2.0.3>Pre-processing>Polyline to Landscape Network tool. The tool produces a personal geodatabase with five components : nodes, edges, relationships, noderelationships, nodexy. The program failed to produce a LSN if any of these components are missing. This creates the landscape network which contains both the topology of a graph and the geometry of the nodes, and reaches. Nodes represent stream topologic breaks such as confluences, stream sources, or stream outlet points. Edges represent flow paths from node to node.
- Outputs: LSN1\ lsn.mdb. Output lsn must contain .mdb file extension.

4000. IDENTIFY AND EDIT TOPOLOGICAL RESTRICTIONS

4100. Check Network Topology

- Input:
  - Network node: lsn\nodes
  - Node class field: node_cat
  - Landscape network edge feature class: lsn\edges
  - search tolerance: 75 (this should be 75 for the first LSN and can be reduced to 10 for subsequent LSNs)
- USFS documentation: NationalStreamInternetProtocol_Version4-7-2015.pdf
  - Pg 10-13 - Identifying and Editing Topological Restrictions
- USFS documentation: 2_Reconditioning_NHDPlusV2_Protocol.docx
  - Entire document after “Build LSN”
- USFS documentation: STARS_tutorial_2.0.0
  - Pg 13-17 – Check Network Topology
- USFS documentation: STARS_vignette2014
  - Pg 6-7
- Description: Run Arc Toolbox: STARS_V2.0.3>Pre-processing>Check Network Topology.
- Output: node_errors.shp

4110. Join node description categories to node error points

- Input: node_errors.shp
- Description: Join "nodes" feature class to "node_errors.shp" by attributes on the [pointid] field so node_errors.shp points have error categories as an attribute.
- Output: none

4120. Add a field to node_errors.shp to track if error has been checked

- Input: node_errors.shp
- Description: Add a field to node_errors.shp named [Checked] (short integer). Leave [Checked] as "0".
- Output: same as input

4130. Add a field to track outlet edits

- Input: 3100_[watershed]_reconditioned.shp
- Description: Add a field to 3100 named [Outlet] (short integer). Leave [Outlet] as "0".
- Output: same as input

4140. Add a field to track topological edits

- Input: 3100_[watershed]_reconditioned.shp
- Description: Add a field to 3100 named [Moved] (short integer). Leave [Moved] as "0".
- Output: same as input

4200. Identify node error points by category (outlet, downstream divergence, confluence, pseudo, source)

- Input: node_errors.shp
- Description: To identify outlet errors open "node_errors" attribute table and select by attributes where [node_cat] = 'Outlet'. Do the same thing for all the other error categories once the outlet errors have been addressed. As errors are addressed change the [Checked] value in node_errors.shp to “1”.
    - *Outlet nodes*: Visually examine the selected outlet nodes to determine if they are true outlets. For true outlets edit the [Outlet] field value to "1". For errors that require a spatial adjustment of 3100 change the [Moved] value to "1". Ensuring edges are snapped usually solves the problem.
    - *Downstream Divergence errors:* Confirm segments are digitized in the correct direction and delete any braids. Ensure edges are snapped. Manually fix any errors in 3100 and change the [Move] value to “1”. **This error type is not permitted in an .ssn object.**
    - *Confluence errors:* To fix converging streams, move the smaller segment(s) about 25m away from the convergence. Ensure edges are snapped. For any moved segments, add a “1” to the [Moved] field. **This error type is not permitted in an .ssn object.**
    - *Pseudo nodes:* Large numbers of pseudo nodes are undesirable in a LSN because they increase the storage space required for the .ssn object in R.
    - *Source:* Visually inspect to ensure that they are true sources. For any moved segments, add a “1” to the [Moved] field.
- Output: in memory selection

4300. Start editing outlet errors

- Input: 3100_[watershed]_reconditioned.shp
- Description: Start editing 3100_[watershed]_reconditioned.shp.
- Output: none

4310. Visually identify and flag node errors

- Input: 3100_[watershed]_reconditioned.shp
- Description: Visually examine the selected outlet nodes to determine if they are true outlets. For true outlets edit the [Outlet] field value to "1". For errors that require a spatial adjustment of 3100 change the [Moved] value to "1".
    - In the Nicola watershed some errors were true outlets and others were the result of disconnected stream reaches. To fix the disconnected stream reach problem adjacent streams that intersected the [node_cat] = “Outlet” were merged together and then split at the node error. See Outlet Node Error Example.docx for an example. The [Moved] field value was changed to “1”. Ensure that stream reaches have identical attributes before merging them. Some outlets were incorrectly flagged because the line segments weren’t snapped together, this issue was resolved by snapping the endpoint of the disconnected stream segments to the other stream segment. Some outlet errors

were a result of incorrect flow direction. This was corrected in editing mode by double clicking the stream segment with the incorrect stream flow to highlight it, right clicking and choosing “flip”.

- Output: same as input

4320. Manually edit outlet errors

- Input: 3100_[watershed]_reconditioned.shp
- Description: Manually edit outlet errors that need to addressed.
- Same as input

4330. Manually edit all other error types

- Input: 3100_[watershed]_reconditioned.shp
- Description: Manually edit errors that need to addressed. Repeat steps 4200 – 4320 for each error type.
- Same as input

4400. Create new folder.

- Input: none
- Description: Create a new folder called "LSN2"
- Output: LSN2 folder

4500. Create new LSN and re-check errors

- Input: 3100_[watershed]_reconditioned.shp
- Description: Repeat steps 3300 - 4320 until no errors remain.
- Output: LSN2\ lsn.mdb. Output lsn must contain .mdb file extension.

5000. IDENTIFY DOWNSTREAM DIVERGENCES

5100. Identify complex confluences

- Input: lsn.mdb
- USFS documentation: NationalStreamInternetProtocol_Version4-7-2015.pdf
  - Pg 10-13 - Identifying and Editing Topological Restrictions
- USFS documentation: 2_Reconditioning_NHDPlusV2_Protocol.docx
  - Entire document after “Build LSN”
- USFS documentation: STARS_tutorial_2.0.0
  - Pg 13-17 – Check Network Topology
- USFS documentation: STARS_vignette2014
  - Pg 6-7
- Description: Run Arc toolbox: STARS_V2.0.3 > Pre-processing > Identify Complex Confluences
- Output: 3seg_confl.txt

5110. Identify and edit complex confluence errors

- Input: 3100_[watershed]_reconditioned.shp
- Description: Visually identify errors identified in 3seg_confl.txt and manually edit Complex Confluence errors. If 3seg_confl.txt is empty there are no errors.
- Output: **3100_[watershed]_reconditioned.shp**

2.0 CREATING PREDICTED TEMPERATURE POINTS

Generate predicted temperature points at a specified interval.

- Input:
  - 3100_[watershed]_reconditioned.shp (Reconditioned stream network)
  - [watershed]_Lakes.shp (Lake polygons)
- USFS documentation: Covariate Processing Procedures_NHDPlusV1.docx
  - Pg 4-5 - Prediction Points and 1 km Stream Model
- Description: Modify and run "TemperaturePredictionPoints10-1_NoET.py" to create prediction points. For the Nicola watershed 2km points were used.
  - Modify the path, input, and output file names in the script
  - If desired spacing for predicted points isn't 1km than the script must be modified accordingly
  - The script currently uses an Advanced ArcMap license and a full version of ETGeowizards – if the user does not have access to these programs and license levels than alternate tools must be used. They can either be written into the script or run manually.
  - For the Nicola watershed the script was run twice because a full version of ETGeowizards was not available. A work around was created by following these steps:
    1. Run the TemperaturePredictionPoints10-1_NoFullET.py script
       - It will fail after the print command "Generating 2 km segments and prediction points for streams" because the ETGeowizards "Split Polylines" tool requires a full registered version
       - After the script fails complete the following steps manually.
    2. Calculate the stream segment lengths
       - Input: t_NHD_Dissolve.shp
       - Field name: LENGTH, Type: Double
       - Open attribute table -> right click [LENGTH] field -> Calculate geometry
    3. Select segments <=4km and export the selected segments to a new shapefile
       - Input: t_NHD_Dissolve.shp
       - Output: t_NHD_Dissolve_short.shp
    4. Switch the selection and export the selected streams to a new shapefile
       - Input: t_NHD_Dissolve.shp
       - Output: t_NHD_Dissolve_long.shp
    5. Create a point at the midpoint of each short segment
       - Tool: Feature to Point (ArcMap)
       - Input: t_NHD_Dissolve_short.shp
       - Output: t_PredictionPointsShort.shp
       - Inside: Checked
    6. Create points every 2km for each long segment
       - Tool: Create Station Points (ET GeoWizards)
       - Input: t_NHD_Dissolve_long.shp
       - Output: t_2kmPointsLong.shp
       - Distance: 2000
    7. Split long segments at 2km points. This creates long segments that are <= 2km
       - Tool: Split Line at Point (ArcMap)
       - Input: t_NHD_Dissolve_long.shp
       - Point: t_2kmPointsLong.shp
       - Output: t_NHD_Dissolve_long_2km.shp
       - Search Radius: 0.25
       - Ensure there is the same number of points (t_2kmPointsLong) as there are segments (t_NHD_Dissolve_long_2km). If not change the search radius to a larger value.
    8. Create a point at the midpoint of each long segment

        - Tool: Feature to Point (ArcMap)
        - Input: t_NHD_Dissolve_long_2km
        - Output: t_PredictionPointsLong
        - Inside: Checked
    9. Merge long and short stream segments
        - Input: t_NHD_Dissolve_short, t_NHD_Dissolve_long_2km
        - Output: t_Split2km
    10. Merge long and short prediction points
        - Input: t_PredictionPointsShort, t_PredictionPointsLong
        - Output: t_PredictionPointsTemp
  - Re-run script.
        - Make sure this line is commented out "#arcpy.gp.ET_GPSplitPolylines("t_NHD_Dissolve.shp", "t_Split2km.shp", "SegmentLength", "2000")"
        - Final Outputs: [watershed]_2kmDataModel.shp (2km streams), [watershed]_Predicted (2km predicted points)

3.0 INCORPORATING OBSERVED AND PREDICTED TEMPERATURE POINTS INTO THE LSN

Snap observed and predicted temperature points to the reconditioned stream network and incorporate them into the new LSN.

Snap Observed Temperature Points to Stream and Incorporate into the LSN

- Input:
  - Sample points: observed temperature points
  - Edges: lsn.mdb\edges
  - Output snapped points: lsn.mdb\sites
  - Search radius: check points to see what makes sense (75 was used for the Nicola sites)
- USFS documentation: STARS_tutorial_2.0.0.pdf
  - 13. Incorporating Sites into the LSN (Pg 30-32)
- USFS documentation: NationalStreamInternetProtocol_Version4-7-2015.pdf
  - Import the Observed Sites and Prediction Points into the LSN (Pg 20 -22)

Description: Run Arc toolbox: STARS_V2.0.3 > Pre-processing > Snap Points to Landscape Network. Look at the points beforehand to determine an appropriate search radius. A search radius of 75 was used for the Nicola watershed. Ensure there is the same number of 'sites' as 'observed points', as any points outside of the search radius will not be transferred to the 'sites' point file. Manually examine 'sites' to ensure that they snapped to the correct stream linework.

Snap Predicted Temperature Points to Stream and Incorporate into the LSN

- Input:
  - Sample points: [watershed]_Predicted
  - Edges: lsn.mdb\edges
  - Output snapped points: lsn.mdb\preds
  - Search radius: 1
- USFS documentation: STARS_tutorial_2.0.0.pdf
  - 13. Incorporating Sites into the LSN (Pg 30-32)
- USFS documentation: NationalStreamInternetProtocol_Version4-7-2015.pdf
  - Import the Observed Sites and Prediction Points into the LSN (Pg 20 -22)
- Description: Run Arc toolbox: STARS_V2.0.3 > Pre-processing > Snap Points to Landscape Network. Look at the points beforehand to determine an appropriate search radius. A search

radius of 1 was used for the Nicola watershed because the predicted points were generated from the stream network. Ensure there is the same number of 'preds' as 'predicted points', as any points outside of the search radius will not be transferred to the 'preds' point file. Manually examine 'preds' to ensure that they snapped to the correct stream linework.

4.0 CALCULATE UPSTREAM DISTANCE FOR EDGES AND SITES IN STARS

- Follow instructions in STARS_tutorial_2.0.0.pdf
  - 15. Calculate Upstream Distance (Pg 35-36)
- Follow instructions in NationalStreamInternetProtocol_Version4-7-2015.pdf
  - 7. Calculate Upstream Distance for Edges and Sites in STARS (Pg 22-24)

5.0 ACCUMULATING WATERSHED ATTRIBUTES

- Follow instructions in STARS_tutorial_2.0.0.pdf
  - 12. Accumulating Watershed Attributes (Pg 30)
- Input:
  - Tool: Accumulate Values Downstream
  - Landscape network feature class: lsn.mdb\edges
  - Output accumulate field name: len_accum
  - Field to accumulate: SHAPE_LENGTH (stream length)
  - Sites feature class(es): lsn.mdb\sites; lsn.mdb\preds

6.0 CREATING REACH CONTRIBUTING AREAS (RCA)

- Follow instructions in STARS_tutorial_2.0.0.pdf
  - 9. Creating Reach Contributing Areas (Pg 17 – 24)
- The output file location must be a file geodatabase (.gdb)
- If an error is generated while running any of the raster tools try saving the output file to the ArcMap default gdb (ex. C:\Users\xxx\Documents\ArcGIS\Default.gdb)

7.0 CALCULATING THE RCA AREA

- Follow instructions in STARS_tutorial_2.0.0.pdf
  - 11. Calculating the RCA Area (Pg 28 – 29)

8.0 ACCUMULATING WATERSHED ATTRIBUTES

- Follow instructions in STARS_tutorial_2.0.0.pdf
  - 12. Accumulating Watershed Attributes (Pg 30)

9.0 CALCULATING RCA ATTRIBUTES

- Follow instructions in STARS_tutorial_2.0.0.pdf
  - 10. Calculating RCA Attributes (Pg 24 – 28)
- Elevation
  - Tool: Extract Values to Points (ArcMap)
  - Input point feature: predicted station points or sites
  - Input raster: demfill
  - Output point features: elevation_sites
  - Interpolate values at the point locations – not checked
  - Append all the input raster attributes to the output point features – not checked

  - Add [ELEVATION] field (long integer) to predicted station points attribute table
  - Join elevation raster to predicted station points using [ID] field
  - Calculate [ELEVATION] field using [RASTERVALU]
  - Remove join
- Latitude
  - Set data frame coordinate system to geographic (GCS_North_American_1983)
  - Add [LATITUDE] field (double) to predicted station points
  - Right click [LATITUDE] field -> calculate geometry-> y coordinate of point -> use coordinate system of the data frame -> decimal degrees
- K2
  - Convert k2 polygons to raster
    - Tool (Arcmap): Polygon to Raster
    - Input features: k2_polygons
    - Value field: k2
    - Output raster dataset: k2
    - Cell assignment type: MAXIMUM_AREA
    - Priority field: none
    - Cellsize: 25
  - Extract k2 values from raster to prediction points
  - Tool (ArcMap): Extract Values to Point
    - Input point features: prediction points or sites
    - Input raster: k2
    - Output point features: k2_pts.shp
    - Interpolate values at the point locations – not checked
    - Append all the input raster attributes to the output point features – not checked
  - Add [k2] field (double) to predicted station points attribute table
  - Join k2 point file to predicted station points using [ID] field
  - Calculate [k2] field using [RASTERVALU]
  - Remove join
  - Add [Q2] field (double)
  - Add [Wb] field (double)
  - Calculate bankfull width using these formulas
    - Q2 = K2A^0.75 (where A = accumulated catchment area [h2oRcaKm2])
    - Bankful width (Wb) is then calculated as Wb = c * Q2^0.5 (where c = 3.17 for BC streams)
  - To calculate k2 value for edges use a spatial join (k2 polygons, each line will be given the all the attributes of the polygon that: is closest to it, k2_lines)
  - Add [k2] field (double) to edges
  - Calculate edges [k2] field using k2 field (K2_1) from k2_lines
- Lake Area/Wetland Area/Glacier Area
  - Follow the same steps to calculate lake, wetland and glacier areas
  - Follow instructions in STARS_tutorial_2.0.0.pdf
  - 10. Calculating RCA Attributes (Pg 25 – 30)
  - Replace “grazing” raster with “lake” raster
  - Step 6 – Add the RCA attributes to the edges attribute table will calculate
  - Calculate % using lake contributing area/contributing area *100
    - h2oLakeKm2/h2oRcaKm2*100
    - This gives the % of the larger contributing area that is lake
- Stream Density
  - Follow instructions in STARS_tutorial_2.0.0.pdf
  - 10. Calculating RCA Attributes (Pg 24 – 28)
  - Stream length field name: rcaStrKm

  - Use "sum" attribute instead of "area"
  - Sum * cell size * 0.001 = stream length for each RCA
  - Remove join
  - Add field "rcaStrDen"(double)
  - Stream density for each RCA: "rcaStrKm" (stream length in km)/"rcaRcaKm2" (RCA area in km2)
  - Accumulate stream length downstream
  - Tool: Accumulate values downstream (STARS)
    - Landscape Network Feature Class: lsn.mdb\edges
    - Output Accumulate field name: h2oStrKm
    - Field to accumulate: rcaStrKm
  - Use accumulated stream length to calculate accumulated stream density
  - Add field "h2oStrDen" (double)
  - "h2oStrDen" = h2oStrKm/h2oRcaKm2
- BEC Zones
  - Give each BEC zone a unique number, this will become the raster value
  - Add [BEC_ZONE] field (short integer) to BEC shapefile
  - Convert BEC polygons to raster
    - Tool (Arcmap): Polygon to Raster
    - Input features: bec_polygons
    - Value field: BEC_ZONE
    - Output raster dataset: bec_zone
    - Cell assignment type: MAXIMUM_AREA
    - Priority field: none
    - Cellsize: 25
  - Follow instructions in STARS_tutorial_2.0.0.pdf
  - 10. Calculating RCA Attributes (Pg 25 – 30)
  - [MAJORITY] field is the BEC zone for the majority of the RCA
  - To determine the % of the RCA that is within each zone separate rasters must be created for each zone
  - Follow instructions in STARS_tutorial_2.0.0.pdf
  - 10. Calculating RCA Attributes (Pg 26 – 27)
  - To calculate % of RCA for each zone
    - BEC zone/rcaRcaKm2*100
- Stream Gradient
  - Extract streams and associated elevations from (25 m resolution) DEM
    - Tool: Extract by Mask (ArcMap)
    - Input raster: demfill
    - Input raster or feature mask: edgegrid
    - Output raster: streams_elev
  - Create slope raster:
    - Tool: Slope (ArcMap)
    - Input raster: streams_elev
    - Output raster: slope
    - Output measurement: PERCENT_RISE
    - Z factor: 1
  - Calculate mean slope value for stream reaches
    - Tool: Zonal statistics as Table(ArcMap)
    - Input raster: edgegrid
    - Zone field: Value
    - Input value raster: slope
    - Output table: slope_mean.dbf
    - Ignore NoData: checked

        - Statistics type: ALL
    - Add [Gradient](double) field to edges
    - Join slope_mean.dbf to edges (reachid, slope_mean.dbf, Value)
    - Calculate [Gradient] field equal to slope_mean.dbf [MEAN]
    - Remove join
    - Edges that don't have an associated gradient value are too short relative to the raster cell size to be given a value. These edges should be given a value of -999.
    - To solve this problem select reaches with no raster value and create a layer from selected features (edges_nogradient)
    - Create a raster (edges_short) for reaches with no gradient
        - Tool: polyline to raster (ArcMap)
        - Input features: edges_nogradient
        - Value field: reachid
        - Output raster: edges _short
        - Cell assignment type: MAXIMUM_LENGTH
        - Priority field: none
        - Cellsize: 25
    - Follow the above instructions from "Create slope raster" to calculate [Gradient] field to add gradient to edges with a missing gradient. If the values don't make sense (ex. Too large) then keep the values as -999
    - To transfer edges gradient values to preds perform a spatial join
- Stream Order
    - Already calculated for FWA 1:20K streams ([STREAM_ORD])
    - Spatial join of preds to edges – creates point file called "stream_order_preds" with edges attributes
    - Add [Stream_Ord] (short integer) field to preds
    - Join "stream order_preds" point file to preds using [ID] and calculate preds [Stream_Ord] field = stream order [STREAM_ORD] field
- Temperature and Precipitation
    - Use ClimateBC tool – free online download (http://cfcg.forestry.ubc.ca/projects/climate-data/climatebcwna/)
    - Use help.rtf to set up data correctly
    - For normal climate data follow the steps below:
        - Choose "Multi-location" -> More Normal Data -> Normal_1981_2010.nrm -> All variables
        - Calculate data relevant to project
    - For the Nicola and Vancouver Island study areas the following were calculated from the normal climate data:
        - Average of average July/August temperature [JulAugTemp] = (Tave07 + Tave08) / 2
        - Annual precipitation [PPT_Annual] = PPT01 + PPT02 + PPT03 + PPT04 + PPT05 + PPT06 + PPT07 + PPT08 + PPT09 + PPT10 + PPT11 + PPT12
        - Precipitation as snow in winter [PAS_Winter] =PAS_wt
        - Annual precipitation as snow [PAS_Annual] = PAS01 + PAS02 + PAS03 + PAS04 + PAS05 + PAS06 + PAS07 + PAS08 + PAS09 + PAS10 + PAS11 + PAS12
    - Join climate data spreadsheet to station points on [ID] and [ID2] fields
    - For annual climate data follow the steps below:
        - Choose "Multi-location" -> Annual Data -> Year_xxxx.ann -> All variables
        - Calculate data relevant to project
    - For the Nicola and Vancouver Island study areas the following were calculated from the annual climate data for the years 1981-2014:

        - Average of average July/August temperature [T0708_1981] = (Tave07 + Tave08) / 2
        - Annual precipitation [PPT_1981] = PPT01 + PPT02 + PPT03 + PPT04 + PPT05 + PPT06 + PPT07 + PPT08 + PPT09 + PPT10 + PPT11 + PPT12
        - Precipitation as snow in winter [PASwt_1981] =PAS_wt
        - Annual precipitation as snow [PAS_1981 = PAS_wt + PAS_sp + PAS_sm + PAS_at
    - Join climate data spreadsheet to station points on [ID] and [ID2] fields
    - Calculate Tref values for annual data for observation stations
        - [Tref_81_14] = sum of all [T0708_xxxx] fields divided by the number of years of annual data
    - Calculate annual climate variability for observation stations [DV]
        - Use Ta(i,t) – Tref(i) where Ta(i,t) is Jul-Aug air temperature for station i and year t and Tref(i) is the mean Jul-Aug air temperature for the reference period (1981-2014)
        - e.g. [DV] = [T0708_1994] – [TREF_81_14]
        - calculate this for each station and year for which there are MWAT observations (1994 to 2010)

10.0 CALCULATE WATERSHED ATTRIBUTES

- Follow instructions in STARS_tutorial_2.0.0.pdf
    - 14. Calculate Watershed Attributes (Pg 32 – 34)

11.0 CALCULATE UPSTREAM DISTANCE

- Follow instructions in STARS_tutorial_2.0.0.pdf
    - 15. Calculate Upstream Distance (Pg 35 – 36)
    - Calculate for edges
- Input:
    - Tool: Upstream Distance – Edge
    - Edges feature class: lsn.mdb\edges
    - Length field: shape_length
- Calculate for sites and preds
- Input:
    - Tool: Upstream Distance – Sites
    - Length field: shape_length
    - Site Feature Classes: lsn.mdb\sites, lsn.mdb\preds

12.0 CALCULATE SEGMENT PROPORTIONAL INFLUENCE

- Follow instructions in STARS_tutorial_2.0.0.pdf
    - 16. Calculate Segment Proportional Influence (Pg 35 – 38)
- Input:
    - Tool: Segment PI
    - Edge field to calculate PI for: lsn.mdb\edges
    - Output PI Field: areaPI

13.0 CALCULATE ADDITIVE FUNCTION

- Follow instructions in STARS_tutorial_2.0.0.pdf
    - 17. Calculate Addictive Function (Pg 38 – 40)

- Input:
  - Tool: Additive Function - Edges
  - Edges feature class: lsn.mdb\edges
  - Output Field: afvArea
  - Segment PI: areaPI
- Calculate for sites and preds
- Input:
  - Tool: Additive Function - Sites
  - Edges feature class: lsn.mdb\edges
  - Edges AFV Field: afvArea
  - Sites Feature Classes: lsn.mdb\sites, lsn.mdb\preds

14.0 APPEND BASIN FLOW INDEX AND TEMPERATURE RESPONSE VARIABLE (MWAT)

- Basin flow index
  - Input: Annual basin flow index text file received from Kyle Chezik.
  - Add fields [Bn_Flw_19XX] to observation sites table.
  - Join to station points by LocationID.
  - Copy/calculate values from joined fields to Bn_Flw_19XX fields.
- MWAT
  - Input: MWAT csv file received from Kyle Chezik.
  - Add fields [MWAT_19XX] to observation sites table.
  - Join to station points by LocationID.
  - Copy/calculate values from joined fields to MWAT_19XX fields.

15.0 CREATE SSN OBJECT

- Follow instructions in STARS_tutorial_2.0.0.pdf
  - 18. Create SSN Object (Pg 40 – 44)
- Input:
  - Tool: Create SSN Object
  - Edges feature class: lsn.mdb\edges
  - Observed Sites Feature Class: lsn.mdb\sites
  - Site ID Field: SiteID
  - Prediction Sites Feature Class Names: lsn.mdb\preds

16.0 DATA CHECKING, CLEANING, RESHAPING (FOR CONSTRUCTED LSN.SSN OBJECT)

Add/remove attributes (ArcGIS option)

- Required if new variables need to be removed or added to the edges, sites and preds shapefiles
- Input:
  - Observed points feature class: lsn.mdb\sites
  - Predicted points feature class: lsn.mdb\preds
  - Edges feature class: lsn.mdb\edges
- Tools: ArcGIS
- Edges to points:
  - Add new fields to point shapefiles
  - Join ‘sites’ with ‘edges’; select ‘Join data from another layer based on spatial location’; select ‘is closest to it’ (radio button); save new shapefile to working directory
  - Use Field Calculator to populate empty fields using joined data

  - Remove all redundant fields from points shapefile (Properties > Fields; deselect; Export to new shapefile)
- Points to points:
  - Same as above
  - NOTE: all attribute names in sites and preds should match. Remove those that don't. Populate with 0s in preds where necessary.
- Edges:
  - If any unnecessary attributes in edges shapefile after above processes, remove them to reduce STARS re-processing time.
- NOTE: If data are in wide format with multi-year attributes, they will need to be reshaped in R to long format and run through the STARS process again.
- NOTE: Northing and Easting attributes should be removed.

Add/remove attributes (R option)

- Required if new variables need to be removed or added to the observed and predicted point files
- Input:
  - Observed points feature class: lsn.mdb\sites
  - Predicted points feature class: lsn.mdb\preds
  - Edges feature class: lsn.mdb\edges
- Tools: ArcGIS; R
- Export attribute table for desired shapefile to excel file (.xlsx)
- Import excel file into R (read.xlsx) as data frame
- Subset data frame to exclude unwanted variables (improves processing time)
- Add/calculate data frame columns as desired
- NOTE 1: If data are in wide format with multi-year attributes, they will need to be reshaped in R to long format and run through the STARS process again.
- NOTE 2: all attribute names in sites and preds should match. Remove those that don't. Populate with 0s in preds where necessary.
- NOTE: Northing and Easting attributes should be removed.

Reshape data from wide to long form

- Required if annually repeated variables were appended to attribute table
- Input:
  - Observed points feature class: lsn.mdb\sites
  - SSN folder: lsn.ssn
- Tools: R
- Import excel file into R (read.xlsx) as data frame (clean up as above)
- Strip out the desired text that will become the column label (strsplit(as.character)) (see SSN_Processing.R)
- Reshape data using dcast() function (see SSN_Processing.R)
- There should be repeated LocationIDs for each site but single columns for each annually repeated variable and one new column for year
- Remove all rows without MWAT observations in the 'sites' data frame
- Remove all rows with strange values (e.g. -999) in the 'preds' data frame
- Write 'sites' and 'preds' to .xlsx (.csv seems finicky)
- Data are now in long form and can be re-processed in STARS
- NOTE 2: all attribute names in sites and preds should match. Rename anything as required.

Re-processing in STARS

- Required if original lsn.ssn data needed to be reshaped

- Input:
  - ‘sites’ and ‘preds’ .xlsx files from previous step
  - ‘edges’ shapefile from lsn.ssn object
- Tools: ArcGIS; STARS
- Add ‘site’ and ‘preds excel tables created above to ArcGIS
- Add X Y values; edit projection so NAD 1983 GCS (no PCS)
- Export to shapefile
- Project exported shapefile to NAD 1983 BC Environmental Albers PCS
- Add edges shapefile to map (from lsn.ssn)
- PRIOR TO PROCESSING IN STARS:
  - Ensure all field names in ‘sites’ and ‘preds’ .xlsx files match. MWAT in ‘preds.xlsx’ will be populated with 0s (not yet predicted)
  - It is good practice to minimize the number of significant digits in the ‘sites’ and ‘preds’ excel files prior to import into ArcGIS as this will improve processing time. Only Lat/Long should be 6-8 significant digits.
- See STARS steps 3-8; 10-13 above to generate new SSN object with long-form data

17.0 MODELS USING SSN & R

- Model selection and diagnostics for non-spatial and spatial models using SSN
- Input:
  - lsn.ssn with long form data
- Tools: SSN package in R
- See: vignette("SSN") for detailed steps (adding this code directly in R will open the vignette pdf)
- Import SSN to R
  - Extract observed points data frame
  - Extract predicted points data frame, replace any Gradient = 0 values with NA & insert back into LSN object
- Non-spatial model selection
  - Use observed points data frame as source data to run main effects model combinations
  - NOTE: we ran for non-transformed variables and transformed variables (4 vars); also with only T0708, only JulAugTemp and with both together.
  - Run stepwise AICc model selection in glmulti() package to get ‘bestmodels’
  - Not enough support to choose any of the top models so need to do model averaging
  - Split into candidate model sets using standard <2 delta AICc threshold
  - Use model.avg() function to run model averaging on the different candidate sets
  - Compare AICc results
  - Evaluate summary stats
  - Best model has highest R2 value; lowest AICc score
- Spatial model selection
  - Create distance matrices
  - Test all models run during non-spatial model selection using glmssn() function
  - CorModels = c("Exponential.tailup", "Exponential.taildown","Exponential.Euclid") for all
  - addfuncol = afvArea
  - Best option has highest R2 value
- Remove outliers and re-run
  - For both non-spatial and spatial models
  - Run histograms to visually check for reasonable outlier thresholds
  - Use SSN vignette instructions to re-classify outliers as NA and reinsert to SSN object
  - Re-run models with outliers removed; check diagnostics (see SSN vignette)
- Try different CorModels and re-run

  - For spatial models only
  - Re-run all models using the SSN object with outliers removed
  - Check diagnostics (see SSN vignette)
  - Best model has highest R2 and lowest AIC
- Predictions (non-spatial)
  - Create object of selected model using lm() and SSN data frame with outliers removed as source data
  - use predict() function to predict MWAT values based on model in ‘preds’ points table
  - Subset resulting predicted points data frame to include only MWAT values >0
  - Export to .csv or .xlsx for use in ArcGIS

18.0 PLOTS & GRAPHS USING SSN & R

- See SSN_Processing.R:
  - Observed vs predicted scatterplot with trendline for selected model
  - QQplot for selected model
  - Correlation plots for MWAT vs all variables (including those not in selected model)
  - Model averaged importance of terms

19.0 MAPS IN ARCGIS

- Input:
  - .csv or .xlsx tables for predicted and observed points (step 15)
  - ‘edges’ shapefile from most current iteration of LSN object
  - Pre-prepared basemap with lakes
- Tools: ArcGIS
- Add preds and sites tables to ArcMap
- Add X Y data
- Export to shapefile
- Project exported shapefile to NAD 1983 BC Environmental Albers PCS
- Add edges shapefile to map (from lsn.ssn)
- To get MWAT predictions along edges:
  - Add MWATpred field to edges
  - Join predicted points to edges using ‘rid’
  - Use Field Calculator to populate MWATpred with MWAT from prediction points
  - Unjoin
  - Add field to edges called bin_xxxx (where xxxx is indicative of the predictive model name)
  - Use Python script in Field Calculator to classify MWATpred into bins in the bin_xxxx field (see example below):

Pre-Logic Script Code:

```
def ReClass(MWATsp):
  if (MWATsp <= 8):
    return 0
  elif (MWATsp >8 and MWATsp <=11):
    return 8
  elif (MWATsp >11 and MWATsp <=14):
    return 11
  elif (MWATsp >14 and MWATsp <=17):
    return 14
  elif (MWATsp > 17 and MWATsp <=20):
```

```
    return 17
  else:
    return 20
```

spin:

```
ReClass( !MWATsp! )
```

  - Classify stream network using bin values and the STREAM_ORD field for line thickness. There should be 6 values in the colour ramp for bin values and 4 values in the size ramp for STREAM_ORD. Exclude STREAM_ORD = 1
- To get MWAT predictions as points
  - Use the predicted points shapefile and classify in the same way as edges above (e.g. need to create bins, but do not do multi-attribute classification – no need to classify points by stream order)

Appendix 6

Model Covariate Data Processing Elements

Covariates						
Spatial Scale	**Covariate**	**Input Data**	**Input Attributes/Features Used**	**Processing**	**Outputs**	**Notes**
Stream Edges Reach Contributing Area (RCA) and Accumulated Watershed Area (h2o)	Lake Area (RCA and accumulated watershed area) (km2)	Lake raster	Reclassed lake raster	Follow instructions in STARS_tutorial_2.0.0.pdf Calculating RCA Attributes (pg 25-30). Replace "grazing" raster with "lake" raster. Follow these steps if don't have access to STARS tutorial. Reclass lake raster. Lake cell = 1, other = NoData. Open Zonal Statistics as Table tool. Input: rcagrid, zone field: VALUE, input raster: lake, output: lake_area.dbf. Value attribute is equivalent to the reachID. Add field [rcaLakeKm2] (double) to edges attribute table. Join the dbf table to the edges attribute table using reachID. Calculate [rcaLakeKm2] field = lake_area.Area*0.000001. Remove the join. Set NULL [rcaLakeKm2] values to 0. To calculate values for the accumulated watershed area follow instructions in STARS_tutorial_2.0.0.pdf Accumulating Watershed Attributes (pg 30). Follow these steps if don't have access to STARS tutorial. Run STARS>Calculate>Accumulate Values Downstream tool. Input: edges, Output: h2oLakeKm2 (accumulated km2 lake area), field to accumulate: rcaLakeKm2 (rca lake area).	Stream edges with RCA and accumulated watershed lake area values	RCA lake area is used as one of the inputs for the accumulated watershed area so it must be calculated first.
Stream Edges Reach Contributing Area (RCA) and Accumulated Watershed Area (h2o)	Lake Area %	Lake and RCA area values	Lake, RCA, and accumulated watershed area values	For the RCA calculate % lake area using lake contributing area/reach contributing area*100. This gives the % of the larger contributing area that is lake. For the accumulated watershed area calculate % lake area using lake contributing area/accumulated watershed area*100.	Stream edges with RCA and accumulated watershed lake % values	
Stream Edges Reach	Glacier area (RCA and	Glacier raster	Reclassed glacier raster	Follow instructions in STARS_tutorial_2.0.0.pdf Calculating RCA Attributes (pg 25-30).	Stream edges with RCA and	RCA glacier area is used as one of

Contributing Area (RCA) and Accumulated Watershed Area (h2o)	accumulated watershed area) (km2)			Replace "grazing" raster with "glacier" raster. Follow these steps if don't have access to STARS tutorial. Reclass glacier raster. glacier cell = 1, other = NoData. Open Zonal Statistics as Table tool. Input: rcagrid, zone field: VALUE, input raster: lake, output: glacier_area.dbf. Value attribute is equivalent to the reachID. Add field [rcaGlacierKm2] (double) to edges attribute table. Join the dbf table to the edges attribute table using reachID. Calculate [rcaGlacierKm2] field = glacier_area.Area*0.000001. Remove the join. Set NULL [rcaGlacierKm2] values to 0. To calculate values for the accumulated watershed area follow instructions in STARS_tutorial_2.0.0.pdf Accumulating Watershed Attributes (pg 30). Follow these steps if don't have access to STARS tutorial. Run STARS>Calculate>Accumulate Values Downstream tool. Input: edges, Output: h2oGlacierKm2 (accumulated km2 glacier area), field to accumulate: rcaGlacierKm2 (rca glacier area).	accumulated watersheds with glacier area values	the inputs for the accumulated watershed area so it must be calculated first. These steps are the same as for the lakes.
Stream Edges Reach Contributing Area (RCA) and Accumulated Watershed Area (h2o)	Glacier Area %	Glacier and RCA area values	Glacier, RCA, and accumulated watershed area values	For the RCA calculate % glacier area using lake contributing area/reach contributing area*100. This gives the % of the larger contributing area that is glacier. For the accumulated watershed area calculate % glacier area using glacier contributing area/accumulated watershed area*100.	Stream edges with RCA and accumulated watersheds with glacier % values	
Stream Edges Reach Contributing Area (RCA) and Accumulated Watershed Area (h2o)	Stream Density (km/km2)	BC FWA stream network	Stream length	Follow instructions in STARS_tutorial_2.0.0.pdf Calculating RCA Attributes (pg 24-28). Stream length filed name: rcaStrKm. Use "sum" attribute instead of "area". Sum*cell size*0.001 = stream length for each RCA. Remove join. Add field [rcaStrDen] (double). Stream density for each RCA: "rcaStrKm" (stream length in km)/"rcaRCAKm2" (RCA area in km2) Accumulate stream length downstream using STARS Accumulate Values Downstream tool. Landscape network feature class: lsn.mdb\edges, Output accumulate field name: h2oStrKm, Field to accumulate: rcaStrKm. Use accumulated	Stream edges with RCA and accumulated watersheds stream density values.	

				stream length to calculate accumulated stream density. Add field [h2oStrDen] (double). [H2oStrDen] = h2oStrKm/h2oRcaKm2.		
Stream Edges Reach Contributing Area (RCA) and Accumulated Watershed Area (h2o)	Stream Gradient (%)	DEM, slope raster	Elevation, slope	Extract streams and associated elevation from DEM using Extract by Mask tool. Input raster: demfill, Input raster or feature mask: edgegrid, Output raster: streams_elev. Create slope raster using Slope tool. Input raster: streams_elev, Output raster: slope, Output measurement: PERCENT_RISE, Z factor: 1. Calculate mean slope value for stream reaches using Zonal statistics as Table tool. Input raster: edgegrid, Zone field: value, input value raster: slope, Output table: slope_mean.dbf, Ignore NoData: checked, Statistics type: ALL Add [Gradient] (double) field to edges. Join slope_mean.dbf to edges (reachID, slope_mean.dbf, Value). Calculate [Gradient] field equal to slope_mean.dbf [MEAN]. Remove join. Edges that don't have an associated gradient value are too short relative to the raster cell size to be given a value. These edges should be given a value of -999.	Stream edges with gradient values.	
Stream Edges Reach Contributing Area (RCA) and Accumulated Watershed Area (h2o)	Biogeoclimatic (BEC) Zones (km2)	BEC polygons	BEC Zones	Give each BEC zone a unique number, this will become the raster value. Add [BEC_ZONE] field (short integer) to BEC shapefile. Convert BEC polygons to raster using Polygon to Raster tool. Input features: bec_polygons, Value field: BEC_ZONE, Output raster dataset: bec_zone, Cell assignment type: MAXIMUM_AREA, priority field: none. Follow instructions in STARS_tutorial_2.0.0.pdf Calculating RCA Attributes (pg 25-30). Follow these steps if don't have access to STARS tutorial. Replace "grazing" raster with "bec1" raster. Reclass BEC raster. BEC cell = 1, other = NoData. Open Zonal Statistics as Table tool. Input: rcagrid, zone field: VALUE, input raster: lake, output: bec1_area.dbf. Value attribute is equivalent to the reachID. Add field [rcaBECZONEKm2] (ex. rcaCWHKm2) (double) to	Stream edges with RCA and accumulated watershed BEC zone area values.	This process can also be done for BEC subzones.

				edges attribute table. Join the dbf table to the edges attribute table using reachID. Calculate [rcaBECZONEKm2] field = bec1_area.Area*0.000001. Remove the join. Set NULL [rcaBECZONEKm2] values to 0.		
Stream Edges Reach Contributing Area (RCA) and Accumulated Watershed Area (h2o)	Biogeoclimatic (BEC) Zones Majority	BEC rasters	BEC Zones	[MAJORITY] field from the bec1.dbf is the BEC zone for the majority of the RCA. The majority BEC zone is the one with the largest area. To calculate the majority BEC zone for the RCA determine which RCA BEC zone has the largest area and populate the [rcaBGCMaj] field with the coresponding BEC Zone numerical value. To calculate the majority BEC zone for the accumulated watershed determine which watershed BEC zone has the largest area and populate the [h2oBGCMaj] field with the coresponding BEC Zone numerical value.	Stream edges with RCA and accumulated watershed majority BEC zone.	Area values must be calculated for BEC zones before majority.
Stream Edges Reach Contributing Area (RCA) and Accumulated Watershed Area (h2o)	Biogeoclimatic (BEC) Zones %	BEC rasters	BEC Zones	To determine the % of the RCA that is within each zone separate rasters must be created for each zone. Follow instructions in STARS_tutorial_2.0.0.pdf Calculating RCA Attributes (pg 26-27). Calculate % of RCA for each zone using BEC zone/rcaRCAKm2*100. Calculate the % of watershed for each zone using BEC zone/h2oRCAKm2*100	Stream edges with RCA and accumulated watershed BEC zone area %.	Area values must be calculated for BEC zones before %.
Station Points and Prediction Points	Elevation (m)	DEM	Raster cell values	Extract elevation values (raster cell values) from the raster using the Extract Values to Points tool. Interpolate values at point locations was NOT checked. Add [ELEVATION] field to station points. The output elevation point file was joined to the station points using the [ID] field and the [ELEVATION] field for the station points was calculated using the [ELEVATION] field from the output point file.	Station points with elevation values.	The DEM had already been formatted prior to this step. Formatting included burning the streams into the DEM and filling in the sinks.
Station Points and Prediction Points	Latitude	Coordinate system	ArcMap data frame coordinate system	Set data frame coordinate system to geographic (GCS_North_American_1983). Add [LATITUDE] field (double) to station points. Right click [LATITUDE] field -> calculate geometry -> y coordinate of point -> use coordinate system of the data frame -> decimal degrees.	Station points with latitude vales.	
Station Points and Prediction Points	K2	K2 polygons	k2 value	Convert k2 polygons to raster using Polygon to Raster tool. Use MAXIMUM AREA for cell assignment type. Extract k2 values from raster to station points using the Extract Values	Station points with k2 values	

				to Points tool. Interpolate values at point location NOT checked. Add [k2] field (double) to station points. Join k2 raster to station points using [ID] field. Calculate [k2] field using [RASTERVALU]. Remove join. Calculate bankfull width using te these formulas. • Q2 = k2A^0.75 where A= accumulated catchment area • Bankfull width (Wb) = c*Q2^0.5 where c=3.17 for BC streams		
Station Points and Prediction Points	Lake Area (km2)	Edges stream network	Edges watershed lake area, edges RCA lake area	To calculate the accumulated values for the station points follow instructions in STARS_tutorial_2.0.0.pdf Calculate Watershed Attributes (pg 32-34). Follow these steps if don't have access to STARS tutorial. Run STARS>Calculate>Watershed Attributes tool. Site feature class: sites and preds, Landscape Network Edges: lsn.mdb\edges, Edge watershed attribute name: h2oLakesKm2, Edge RCA attribute name: rcaLakesKm2, New Site watershed: h2oLakesKm2	Station points with lake values for accumulated watershed areas.	Values must be calculated for the edges before the points. Same process as glaciers and wetlands.
Station Points and Prediction Points	Lake Area %	Edges stream network	Edges watershed lake area, edges RCA lake area	For the RCA calculate % lake area using lake contributing area/reach contributing area*100. This gives the % of the larger contributing area that is lake. For the accumulated watershed area calculate % lake area using lake contributing area/accumulated watershed area*100.	Station points with lake % values for accumulated watershed areas	Values must be calculated for the edges before the points. Same process as glaciers and wetlands.
Station Points and Prediction Points	Glacier Area (km2)	Edges stream network	Edges watershed glacier area, edges RCA glacier area	To calculate the accumulated values for the station points follow instructions in STARS_tutorial_2.0.0.pdf Calculate Watershed Attributes (pg 32-34). Follow these steps if don't have access to STARS tutorial. Run STARS>Calculate>Watershed Attributes tool. Site feature class: sites and preds, Landscape Network Edges: lsn.mdb\edges, Edge watershed attribute name: h2oGlacKm2, Edge RCA attribute name: rcaGlacKm2, New Site watershed: h2oGlacKm2	Station points with glacier values for accumulated watershed areas.	Values must be calculated for the edges before the points. Same process as lakes and wetlands.
Station Points and Prediction	Glacier Area %	Edges stream network	Edges watershed glacier area, edges RCA glacier	For the RCA calculate % glacier area using glacier contributing area/reach contributing area*100. This gives the	Station points with glacier % values for	Values must be calculated for the

Points			area	% of the larger contributing area that is glacier. For the accumulated watershed area calculate % glacier area using glacier contributing area/accumulated watershed area*100.	accumulated watershed areas	edges before the points. Same process as lakes and wetlands.
Station Points and Prediction Points	Wetland Area (km2)	Edges stream network	Edges watershed wetland area, edges RCA wetland area	To calculate the accumulated values for the station points follow instructions in STARS_tutorial_2.0.0.pdf Calculate Watershed Attributes (pg 32-34). Follow these steps if don't have access to STARS tutorial. Run STARS>Calculate>Watershed Attributes tool. Site feature class: sites and preds, Landscape Network Edges: lsn.mdb\edges, Edge watershed attribute name: h2oWetKm2, Edge RCA attribute name: rcaWetKm2, New Site watershed: h2oWetKm2	Station points with wetland values for accumulated watershed areas.	Values must be calculated for the edges before the points. Same process as lakes and glaciers.
Station Points and Prediction Points	Wetland Area %	Edges stream network	Edges watershed wetland area, edges RCA wetland area	For the RCA calculate % wetland area using wetland contributing area/reach contributing area*100. This gives the % of the larger contributing area that is wetland. For the accumulated watershed area calculate % wetland area using wetland contributing area/accumulated watershed area*100.	Station points with wetland % values for accumulated watershed areas	Values must be calculated for the edges before the points. Same process as lakes and wetlands
Station Points and Prediction Points	Stream density (km/km2)	Edges stream network	Edges watershed stream length, edges RCA stream length	To calculate the accumulated values for the station points follow instructions in STARS_tutorial_2.0.0.pdf Calculate Watershed Attributes (pg 32-34). Follow these steps if don't have access to STARS tutorial. Run STARS>Calculate>Watershed Attributes tool. Site feature class: sites and preds, Landscape Network Edges: lsn.mdb\edges, Edge watershed attribute name: h2oStrKm2, Edge RCA attribute name: rcaStrKm2, New Site watershed: h2oStrKm2	Station points with stream density values.	Values must be calculated for the edges before the points.
Station Points and Prediction Points	Stream Gradient (%)	Edges stream network	Edges Gradient	Add [Gradient] (double) field. Join edges to station points using [ID] field. Calculate station points [Gradient] = Edges [Gradient].	Station points with stream gradient values.	Values must be calculated for the edges before the points.
Station Points and Prediction	Stream Order	Edges stream network	Edges stream order	This is already calculated for FWA 1:20K streams. If stream order is present in original stream dataset follow these steps.	Station points with stream order	Stream order must be present

Points				Spatially join station points to stream edges. Add [Stream_Ord] (short integer) field to station points. Join "stream order' point file to station points using [ID] field and calculate station points [Stream_Ord] field = stream order [STREAM_ORD] field.	values.	for edges before they can be transferred to the points.
Station Points and Prediction Points	Biogeoclimatic (BEC) Zones (km2)	Edges stream network	Edges BEC zones	To calculate the accumulated values for the station points follow instructions in STARS_tutorial_2.0.0.pdf Calculate Watershed Attributes (pg 32-34). Follow these steps if don't have access to STARS tutorial. Run STARS>Calculate>Watershed Attributes tool. Site feature class: sites and preds, Landscape Network Edges: lsn.mdb\edges, Edge watershed attribute name: h2oBECZONEKm2, Edge RCA attribute name: rcaBECZONEKm2, New Site watershed: h2oBECZONEKm2	Station points with BEC zone values.	Values must be calculated for the edges before the points.
Station Points and Prediction Points	Biogeoclimatic (BEC) Zones Majority	Edges stream network	Edges BEC zones	To calculate the majority BEC zone for the RCA determine which RCA BEC zone has the largest area and populate the [rcaBGCMaj] field with the corresponding BEC Zone numerical value. To calculate the majority BEC zone for the accumulated watershed determine which watershed BEC zone has the largest area and populate the [h2oBGCMaj] field with the corresponding BEC Zone numerical value.	Station points with BEC zone majority values.	Values must be calculated for the edges before the points before majority BEC zone can be calculated.
Station Points and Prediction Points	Biogeoclimatic (BEC) Zones %	Edges stream network	Edges BEC zones	Calculate % of RCA for each zone using BEC zone/rcaRCAKm2*100. Calculate the % of watershed for each zone using BEC zone/h2oRCAKm2*100	Station points with BEC zone %.	Values must be calculated for the edges and points before % can be calculated.
Pilot Study Areas	Basin Flow Index (m3/s)	Stream flow data	WSC flow gauge data (as available)	We created a flow index for each of the pilot study areas using Water Survey of Canada (WSC) hydro-metric gauge station data on unregulated streams. Flow was averaged for July and August across sites and years. Years with fewer than 25 days data in these summer months were excluded. These summer month averages were then averaged across WSC gauge locations for a single basin-scale annual summer flow index value.	Pilot study area-scale annual average summer flow index	Information from WSC gauges below regulated dams within a pilot study area were not included in the Basin Flow Index derivation.

Project Report

Environmental & Cumulative Effects Assessment

Climate Change Adaptation & Risk Reduction

Aquatic Species at Risk & Water Resource Management

Terrestrial Ecology & Forest Resource Management