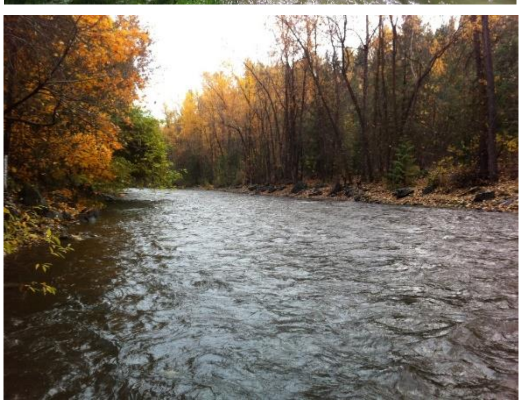
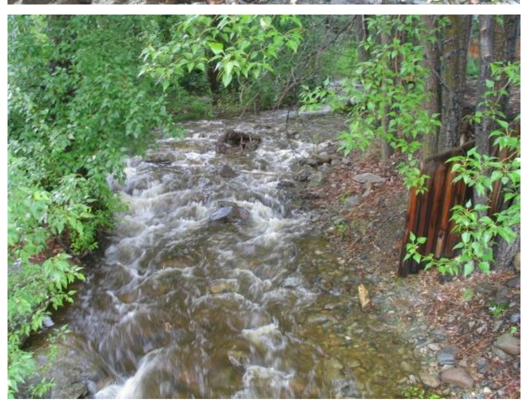
Associated Environmental

FINAL REPORT

Okanagan Basin Water Board

Okanagan Hydrologic Models for Long-term Water Planning & Management



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February 14, 2020
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Nelson Jatel, P.Ag.
Water Stewardship Director
Okanagan Basin Water Board
1450 KLO Rd.
Kelowna, BC V1W 3Z4

Re: FINAL REPORT - OKANAGAN HYDROLOGIC MODELS FOR LONG-TERM WATER PLANNING & MANAGEMENT

Dear Mr. Jatel:

Associated Environmental Consultants Inc. is pleased to provide this final report summarizing the results of the Okanagan Hydrologic Modelling Project and the development of the Okanagan Hydrologic Modelling Environment (Version 1).

If you have any questions, please contact the undersigned.

Yours truly,
Associated Environmental Consultants Inc.

Lawrence Bird, M.Sc.
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EXECUTIVE SUMMARY

This report describes the development and first application of Okanagan Hydrologic Modelling Environment (OHME) Version 1 (OHME V1), an open source hydrologic modelling framework for the Okanagan Basin based on the Raven Hydrological Modelling Framework (Raven). Developed for the Okanagan Basin Water Board (OBWB), OHME is a hydrologic modelling system that improves on previous hydrologic model efforts and provides the basis for ongoing and future hydrologic assessments in support of regional water management and planning. OHME is an efficient and flexible platform serving as the primary deliverable of the Okanagan Hydrologic Modelling Project (OHMP).

After a comprehensive model review and selection process, the Model Selection Team selected Raven as the core hydrologic model within OHME. OHME embeds Raven and the Ostrich Optimization Software Toolkit (OSTRICH) within a flexible broader modelling environment. Within OHME, Raven can be easily reconfigured to varying degrees of hydrologic complexity and spatial extents and can accept a wide variety of climate, geophysical, and land use inputs. It can be efficiently calibrated using scalable and economical cloud computing infrastructure and sophisticated hydrologic model calibration methodologies. Governance of OHME is facilitated via open-source licensing and a structured version control model. OHME will be effectively leveraged and further developed by a wide range of users (e.g., private sector consultants, local and regional governments, and academic researchers) for a diverse spectrum of Okanagan hydrologic applications, from detailed watershed-specific studies to whole-basin investigations.

The first successful application of OHME V1 was carried out for 19 important watersheds in the basin. The results of these hydrologic simulations demonstrate the ability of OHME users to develop and apply complex watershed models within an efficient and automated framework. In OHME V1, the 19 Raven-simulated watersheds are discretized using a semi-distributed approach that disaggregates landscapes into unique hydrologic units. OHME V1 leverages this aspect of Raven such that the 19 watersheds are embedded within a broader framework that encompasses the entire Okanagan Basin domain. A total of 343 sub-basins, 47 reservoirs, and 29,196 Hydrologic Response Units (HRUs) were developed for the current OHME spatial domain, with individual HRU characteristics calculated based on high resolution land use, hydrologic, climate, and geophysical datasets. The design approach taken to embed individual watershed models within a single Okanagan OHME domain has significant operational benefits. For example, OHME can be easily configured by users to simulate single watersheds, multiple watersheds, or the entire basin as part of model runs. The design allows for additional watersheds or watershed areas to be added to the OHME domain.

Within OHME V1, the Hydrologiska Bryåns Vattenbalansavdelning (HBV-EC) conceptual hydrologic model framework was chosen as the base hydrologic Raven configuration. The implementation of HBV-EC within the Raven environment provides a suitable representation of the Okanagan landscape that matches model complexity to regional hydrologic processes. Because of Raven's flexibility, numerous possible model configurations are available to future OHME users beyond HBV-EC. Future hydrologic assessments using OHME may choose a different conceptual framework that best suits assessment-specific needs. Common to all frameworks is the need to capture regional water management practices in hydrologic simulations. In coordination with the core Raven Development Team, representations of water management were developed within Raven source code to robustly reflect Okanagan water management processes. For example, OHME V1 allows users to specify watershed(s) water demand to be supplied by upland reservoirs and/or automatically estimate the contribution of downstream water demand from each reservoir, based on reservoir capacity.

To manage the diverse set of data inputs within OHME V1, an extensive set of R-based data input processing tools was developed to facilitate data access and translation into formats amenable to Raven. Provision of these tools within

OHME ensures that future users can apply new input datasets in a transparent, repeatable, robust, and documented manner. For example, users can apply different climate data (i.e., to explore the hydrologic impact of future climate change), land use data (i.e., to explore potential forestry, agricultural, or development scenarios), or land cover, soil, or vegetation data (i.e., to explore hydrologic model sensitivity to evolving model inputs). Using these data input processing tools, updated historical climate data (Associated 2019b), water demand data from the Okanagan Water Demand Model (OWDM), water management datasets (e.g., reservoir operations and water diversions), and multiple other geophysical, land use, land cover, and observation datasets were processed by Raven within OHME V1.

The OSTRICH framework and scalable parallelized Canada-based Google Cloud Platform (GCP) multi-core computing resources were leveraged to perform computationally expensive OHME V1 calibration exercises rapidly across all 19 watersheds. This powerful OSTRICH/GCP calibration framework represents a core aspect of OHME, and – beyond it's initial application - is intended to support future calibrations integral to ongoing Okanagan water management and decision making.

This framework was used to calibrate key parameters of the 19 watersheds against several observational calibration target datasets. As many relevant calibration datasets as possible were included in OHME V1, even if they did not have records for the OHMP period of interest (i.e., 1996-2017), to allow future users maximum calibration flexibility. Extensive work was undertaken to identify a calibration approach that best addressed the multi-watershed nature of the OHMP. This included testing of global model calibration approaches using Water Survey of Canada (WSC) hydrometric data, watershed-specific calibrations targeting naturalized flow estimates, and a further range of hybrid, step-by-step calibration methods. Hydrologic model performance during and after calibration was assessed through a variety of means, including via standard hydrologic quantitative performance assessments such as the Nash-Sutcliffe model efficiency coefficient (NSE). In addition, qualitative examination and expert judgment were applied to identify and improve model characteristics.

In conclusion, OHME V1 satisfies the technical specifications identified by the OBWB (OWSC, 2018). For example, OHME V1 can:

- Be easily configured to simulate both individual Okanagan watersheds and combined watershed systems;
- Vary spatial and temporal model complexity and resolution on a per-watershed basis;
- Vary internal process representations to reflect important watershed and use-case specific needs;
- Use best-in-class evolving land use, hydrologic, climate, and geophysical datasets;
- Link with the OWDM;
- Be easily updated in the future;
- Output hydrologic data at user-selectable locations for comprehensive data analysis; and
- Undertake a wide variety of hydrologic studies, including future climate change assessments.

These characteristics of OHME represent a significant upgrade from previous modelling efforts. Together, they will ensure that the OHME framework remains an excellent basis for a diverse range of Okanagan-specific hydrologic applications, studies, and assessments. By design, OHME remains 'future-proofed' as input datasets, Raven capabilities, and computing frameworks rapidly evolve. This ensures that OHME will remain well-placed to support Okanagan hydrologic studies and regional water management planning and decision making into the future.

This report closes with a set of recommendations to benefit future OHME development and use. These recommendations include:

- Develop a web-based user interface, basic training, and a customized user-specific training framework;

- Improve the quantity and quality of input data;
- Monitor and apply Raven modelling advances (e.g., integration of a groundwater model) using version controlling;
- Further develop watershed-specific and application-specific Raven conceptual designs for user needs;
- Further develop watershed-specific and application-specific OSTRICH calibration and sensitivity assessment procedures for user needs;
- Develop robust software support mechanisms to support OHME maintenance, distribution, and governance;
- Develop robust scientific support mechanisms to support OHME use and development; and
- Integrate OWDM algorithms directly into OHME.

ACKNOWLEDGEMENTS

Associated Environmental Consultants Inc. (Associated) acknowledges the contribution of the following individuals and groups to this project:

- Dr. James Craig, University of Waterloo
- Nelson Jatel, OBWB (Project Manager)
- Dr. Brian Guy, Associated Engineering Group Ltd. (OBWB Technical Support)
- Okanagan Hydrologic Modelling Project Steering Committee Members:
    - Dr. Bernard Bauer, University of British Columbia
    - Dr. Denise Neilsen, Agriculture and Agrifoods Canada
    - Dr. Craig Nichol, University of British Columbia
    - Rod MacLean, City of Kelowna
    - Shawn Reimer, Government of British Columbia
- Okanagan Hydrologic Modelling Project Model Selection Team Members:
    - Dr. Katrina Bennett, Los Alamos National Laboratory
    - Dr. Georg Jost, BC Hydro
    - Lars Uunila, Polar Geoscience
- Ron Fretwell, RHF Systems
- Ted van der Gulik, Partnership for Water Sustainability in BC
- Dr. Joel Trubilowicz, Northwest Hydraulic Consultants

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GLOSSARY

Term / Abbreviation	Definition
ChyMS (Canadian Hydrologic Model Stewardship)	*National Research Council software service and server, which hosts computational hydrology tools including Raven.*
GCP (Google Cloud Platform)	*A cloud-based computing platform where OHME is currently based.*
OBWB (Okanagan Basin Water Board)	*A regional body with a mandate to promote water management activities that benefit the entire Okanagan basin.*
OWSDP (Okanagan Water Supply and Demand Project)	*A three-phase water resource state of knowledge project, spanning 2005-2013.*
OBHM (Okanagan Basin Hydrology Model)	*A primary hydrologic model deliverable of the OWSDP Phase 2.*
OWDM (Okanagan Water Demand Model)	*A spatial model describing water demand.*
OBWAM (Okanagan Basin Water Accounting Model)	*A water management model deliverable from OWSDP Phase 2.*
OHMP (Okanagan Hydrologic Modelling Project)	*The project described by this report.*
OHME (Okanagan Hydrologic Modelling Environment)	*A comprehensive, open source software-based, Okanagan hydrologic modelling framework. OHME is the primary deliverable of the* OHMP.
OHME V1 (Okanagan Hydrologic Modelling Environment Version 1)	*The version of OHME delivered at the close of the OHMP project.*
R (R statistical computing language)	*A free software environment for statistical computing, scientific workflow development and graphics generation.*
VM (Virtual Machine)	*A cloud-based computer that is built on-demand and accessed via remote networking*

1 INTRODUCTION

This document describes the successful development and first application of Version 1 (V1) of Okanagan Hydrologic Modelling Environment (OHME), a comprehensive hydrologic modelling framework for the Okanagan Basin based on the Raven Hydrological Modelling Framework (Raven). Development and application of OHME was carried out as the primary aspect of the Okanagan Hydrologic Modelling Project (OHMP). OHME V1 is an efficient and flexible platform for hydrologic analyses of Okanagan basin watersheds in support of regional water management and planning. OHME embeds Raven and the Ostrich Optimization Software Toolkit (OSTRICH) within a flexible, open-source, version-controlled, cloud-based, computationally efficient environment. OHME can be rapidly reconfigured to account for varying levels of hydrologic complexity and spatial extents and can accept a wide variety of climate, geophysical and land use inputs. It can be efficiently calibrated using a range of sophisticated calibration methodologies using highly scalable cloud computing capabilities. Governance of OHME is facilitated via open source licensing and a structured version control and distribution model.

1.1 Project Background

Water supply within the Okanagan Basin is determined by the amount of rainfall and snowfall, and the storage capacity of reservoirs and aquifers; thus, water shortages and/or excess water (i.e., flood and drought) are major concerns that could escalate in the future. During dry years, water purveyors impose conservation measures to ensure that both human and environmental needs are met. However, with increased water demand, water suppliers will likely need to continue to augment their water demands through additional surface water and groundwater withdrawals, upland reservoir and mainstem lake storage, and management. Increasing water withdrawals and storage could impact Environmental Flow Needs (EFN), downstream water licences, and water availability to all users. Balancing water supply and use, the effects of future climate change, the role of water in land use and economic development, and the protection of the ecological functions provided by water relies on good scientific, socio-economic, and governance information.

In 2004, the BC Ministry of Environment and the Okanagan Basin Water Board (OBWB) initiated the Okanagan Water Supply and Demand Project (OWSDP). The OWSDP was a three-phase program focused on improving the state of knowledge of the water resources of the Okanagan Basin. Phases 1 and 2 were completed in 2005 and 2010, respectively, and Phase 3 was completed in 2013.

During Phase 2, three custom models were developed for simulating water supply and demand in the Okanagan:

- Okanagan Basin Hydrology Model (OBHM) – a hydrologic (i.e., a water supply) model;
- Okanagan Water Demand Model (OWDM) – a water demand model; and
- Okanagan Basin Water Accounting Model (OBWAM) – an accounting model that combines water demand and water supply.

A Surface Water Hydrology and Hydrologic Modelling Study was completed (Summit 2009) prior to developing the OBHM. This study documented the current state of knowledge of surface water flows in the Okanagan Basin and developed naturalized streamflow data for inclusion within the OBHM. In turn, the OBHM provided a basis for the OBWAM, which was supplemented by the OWDM.

The OWSDP Phase 2 models are useful for examining future water conditions and estimating the influence of climate change and human water use on streamflow. The OBHM is a physically-based, deterministic, spatially disaggregated hydrologic model using the MIKE SHE modelling platform. It simulates physical processes and creates estimates of runoff from each 500m x 500m grid cell at a temporal scale of one hour, with output at each tributary watershed aggregated to weekly resolution. However, the OBHM displayed some important limitations:

- Groundwater was represented via a simplistic linear reservoir;
- Limited hydro-meteorological records and spatial datasets were applied;
- The model only ran for the entire Okanagan watershed, with each run taking approximately 40 hours;
- Lack of framework was provided for further model development, improvement, and use outside the OWSDP;
- The model input and output were managed through the OkWater Database, which is difficult to use;
- Environmental Flow Needs (EFNs) were treated in an overly simplistic manner;
- The model incorporated insufficient knowledge of groundwater-surface water interactions across alluvial fans; and
- Output was only provided by default at tributary mouths, with output at other locations requiring an impractically high level of MIKE SHE expertise.

The OWDM was developed by the BC Ministry of Agriculture and Agriculture and Agri-Foods Canada. The outdoor water use component of the model is driven by the same 500 m x 500 m climate grid used to drive the OBHM. Indoor water use is also modelled by the OWDM.

The OBWAM combines the OWSDP and OWDM and extracts water from streams at the points of diversion to provide a residual streamflow. It routes surface flows through Okanagan Lake and down the Okanagan River, through Skaha Lake, Vaseux Lake, and into Osoyoos Lake. It accounts for evaporation from these lakes. Key OBWAM limitations are as follows:

- Modelled lake evaporation is unconstrained by validation measurements;
- It has a limited ability to accurately represent operations of the Okanagan Lake Regulation System;
- The representations of watershed management are overly simplistic;
- There is a lack of knowledge necessary to simulate inter-basin transfers into and out of the Okanagan Basin;
- The model uses multiple Excel spreadsheets to organize input data, subjecting it to error; and
- The outputs can be viewed using a web-based tool, but the tool has not been widely adopted.

A limited range of future climate scenarios was examined in OWSDP Phase 2. This limitation was partially overcome in Phase 3, in which several relevant General Circulation Models (GCMs) were used to examine a wide range of future climate and land use conditions. However, Phase 3 was limited in scope - new models and better GHG scenarios are now available.

The final OWSDP Phase 2 Water Supply and Demand Project report (Summit 2010) made many recommendations for subsequent work, some of which has been initiated or completed:

- Additional hydrometric stations and groundwater observation wells have been installed;
- New information on groundwater has been obtained by the Ministry of Forests, Lands, Natural Resource Operations, and Rural Development (FLNRORD) and an Integrated Hydrologic Database System (IHDS) has been developed;
- The BC Water Use Reporting Centre has been developed and piloted in the Okanagan;
- Environment Canada (EC) has conducted measurement-based studies on evaporation from Okanagan Lake;
- The regional land use inventory has been updated and improved;
- A study of surface/groundwater interactions along Mission Creek has been completed;
- The effects of climate change on agriculture have been examined more thoroughly;
- Phase 3 work examining additional climate and land-use scenarios has been completed;

- The Okanagan Water Allocation Tool Report (2014) was produced, including recommendations for additional studies and Phase 2 model upgrades;
- Environmental Flow Needs (EFN) Project Phase 1 (Associated 2016) and Phase 2 (ongoing) were initiated to identify EFNs for regional aquatic ecosystems;
- A Streamflow Naturalization project has been completed to update the streamflow naturalization performed during OWSDP Phase 2 (i.e., to determine naturalized streamflows in Okanagan watersheds and their relation to actual (human-influenced) flows);
- The Okanagan Hydrologic Connectivity Model has been developed; and
- The OWDM has improved.

In 2018, OBWB determined that it was an appropriate time to initiate an upgrade of the OBHM and OBWAM, for the following primary reasons:

- The Phase 2 OWSDP report recommended an update after sufficient new information had been obtained to support a model update;
- Since 2010, there has been significant data collection, research, studies, and model upgrades such that notable improvements in the supply and demand models are now possible;
- The Okanagan population and economy continues to grow, the land faces increasing pressure from development, and climate change continues to pressure both water supply and water demand;
- The BC Ministry of Agriculture upgraded the OWDM;
- Under the 2016 *Water Sustainability Act*, groundwater extractions must now be licensed, with potential EFN assessments required of nearby watercourses;
- The OWSDP Phase 2 models demonstrated substantial weaknesses and did not fully achieve their primary objective (i.e., adoption as a decision-support tool by provincial water allocation staff);
- Computing power and flexibility has increased substantially since 2010;
- Reliable and accurate streamflow estimates are required for drought planning and watershed and water use management; and
- Interactions between the local community and academia is resulting in frequent research requests for specialized water supply and demand information.

These determinations formed the basis and motivation for the OHMP. The primary goal of the OHMP was to develop a new hydrologic model framework for the Okanagan Basin (i.e., OHME) that builds on the extensive body of recent Okanagan-specific hydrologic work and provides a significant upgrade to OWSDP Phase 2 modelling, in terms of technical capacity but also in terms of accessibility and use by the broader Okanagan hydrologic community. The objectives of the OHMP are described in Section 1.2.

1.2 OHMP Objectives

In 2018, OBWB retained Associated Environmental Consultants Inc. (Associated) to develop an Okanagan-tailored hydrologic modelling environment to overcome OBHM and OBWAM shortcomings and demonstrate the ability of this environment to simulate historic streamflow conditions for 19 Okanagan Basin watersheds (Figure 1-1). The purpose of the OHMP is to develop and apply a hydrologic model that supports the following activities (OBWB 2018):

- Provincial water allocation decision-making;
- Driving local government hydraulic models;
- Planning for long-term infrastructure needs;
- Flood and drought management;
- Examining climate change adaptation strategies and actions;

- Conducting EFN investigations;
- Channel restoration and management; and
- Other water management activities.

Cast against these model requirements, the overarching objectives of the OHMP are to:
1. Develop an accurate and flexible hydrologic modelling environment that updates the OBHM and can be used as a basis for estimating streamflows at multiple locations and domains within the Okanagan Basin, and for a wide variety of user-specific cases and applications; and
2. Apply Version 1 of this new hydrologic modelling environment to simulate flows for 19 watersheds chosen by OBWB.

Specific goals of the OHMP, as outlined in the Request for Proposals (OBWB 2018), are as follows:
1. Identify an appropriate model software/framework that meets current user needs and addresses the limitations of the OWSDP models. This includes the development of model selection criteria to support identification of relevant/applicable models.
2. Identify, collect, organize, and store all relevant model development datasets from the OWSDP and post-Phase 3 to support development of hydrologic models.
3. Develop hydrologic models for 19 selected watersheds using the recommended modelling software/framework.
4. Calibrate hydrologic models using available hydrometeorological records and EFN streamflow datasets for naturalized and residual streamflow conditions. In addition, complete model verification using a subset of the available information.
5. Develop a technical study report that provides a summary of the work completed and model results.
6. Develop a technical users manual to support the use and application of the hydrologic models and provide a training session on model operation to OBWB staff and other users.
7. Develop an ongoing communication and outreach plan to support the use of the hydrologic models within the Okanagan Basin.

This document describes the development and application of the model to address these goals and satisfy OHMP objectives.

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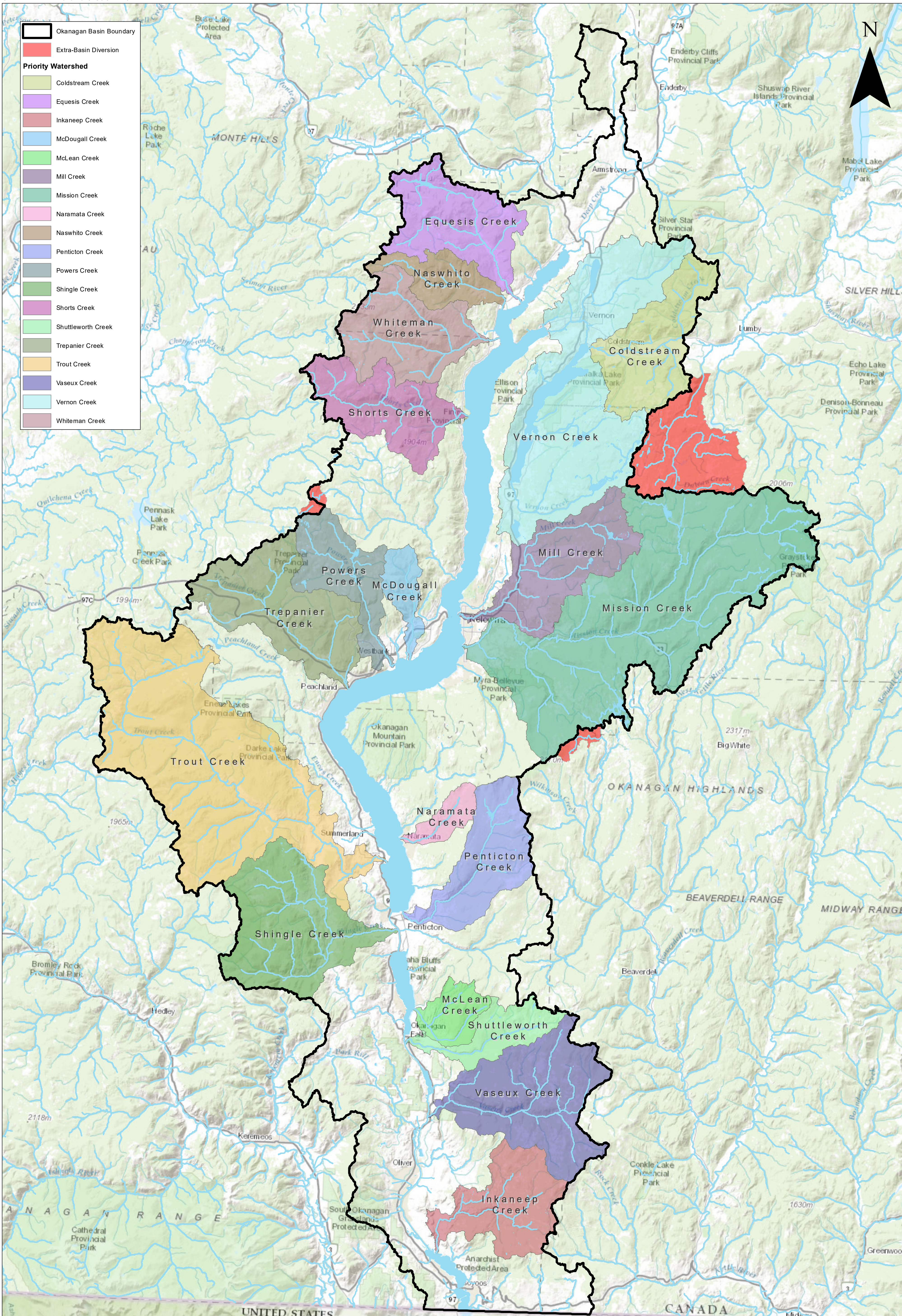

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FIGURE 1-1: KEY OKANAGAN WATERSHEDS INCLUDED IN THE OKANAGAN HYDROLOGIC MODELLING PROJECT

Okanagan Basin Water Board

Okanagan Hydrologic Modelling Project

Associated Environmental

2 HYDROLOGIC MODEL REVIEW AND SELECTION

Model review and selection was an important initial step in the OHMP and was performed against a set of metrics that reflect the needs of model users (Section 2.1). Appendix A provides a comprehensive summary of the model review and selection process.

2.1 Model User Needs

OBWB (OBWB 2018) specified that the new hydrologic model developed within the OHMP must:

- Be appropriate for the intended users, including:
  - Local, provincial and First Nation governments;
  - Provincial water allocation officers;
  - Consulting firms; and
  - Academic institutions.
- Allow realistic use of appropriate and currently available (or reasonably expected) input data:
  - Water demand data from the OWDM;
  - Appropriate natural and built land surface data; and
  - High-resolution gridded climate/meteorology input data sources, either from observation or model-based sources.
- Adequately represent spatially-resolved, key hydrologic processes within the Okanagan region for residual streamflow simulation:
  - Improved representation of groundwater relative to the existing OBHM;
  - Realistic natural surface hydrologic processes; and
  - Realistic regulated hydrologic processes.
- Be sufficiently user-friendly and future-proofed:
  - Provide reasonable streamflow estimates for select locations, at user-appropriate temporal resolution.
  - Be flexible at the model configuration level or easy to expand at the source code level, with respect to included model processes and spatial and temporal scales.
  - Be more computationally efficient than the existing OBHM to reduce model simulation turnaround time.
  - Be more user-friendly than the existing OBHM to facilitate successful simulation management by trained users.

2.2 Hydrologic Model Grading and Selection

To provide an objective and unbiased review of available hydrologic models, a Model Selection Team comprising industry-leading hydrologic modelling experts with experience using many hydrologic models and software packages was assembled. The Model Selection Team members are listed in Appendix A. Based on the user needs listed in Section 2.1, the Model Selection Team developed an objective grading framework to support identification of the most appropriate model for hydrologic modelling within the OHMP. The model grading framework is summarized in Table 2-1 and further explained in Appendix A.

Based on a review of relevant hydrologic models, and the experience of the Model Selection Team, eight candidate hydrologic models were selected for assessment:

- University of British Columba Watershed Model (UBCWM);
- Environment Canada modification of the Hydrologiska Bryåns Vattenbalansavdelning Model (HBV-EC);
- WATFLOOD;

- MIKE SHE;
- Hydrologic Engineering Centre – Hydrologic Modelling System (HEC-HMS);
- Variable Infiltration Capacity (VIC) Macroscale Hydrologic Model;
- Raven Hydrological Modelling Framework (Raven); and
- Soil and Water Assessment Tool (SWAT).

Each model was reviewed independently, and relevant information summarized to facilitate an unbiased model grading. Appendix A provides further information on each of the candidate models. Relevant model summaries are included in Table 4-1 of Appendix A. Based on this information, each candidate model was graded using an importance-weighting sum of all model grading criteria (Table 2-1) to identify the most applicable candidate model for the OHMP. The grading was completed using a consensus approach by the Model Selection Team. The results of the model grading are provided in Table 2-2.

The **Raven Hydrological Modelling Framework** (Craig and Raven Development Team 2019) achieved the highest score (306), followed by MIKE SHE (273). As a result, Raven was recommended to the OBWB Project Steering Committee for use within the OHMP, and the Project Steering Committee approved this recommendation in early 2019. The main advantages of Raven, which are described in Section 3.1, are as follows:

- Raven provides flexible discretization options, allowing the landscape to be modelled as a lumped system (i.e., one watershed), semi-distributed (i.e., multiple sub-basins), or fully-distributed (i.e., gridded).
- Raven provides a framework to implement many hydrologic models. For example, near-exact emulation of the HBV-EC, GR4J, and UBCWM hydrologic models has been achieved within the Raven framework; and Raven is a transparent open-source model, providing the flexibility to add additional features, as required.

Table 2-1
Model grading criteria

General Category	Grading Criterion	Importance Weighting	Poor Score (1) Definition	Excellent Score (5) Definition
Model Design and Complexity	Physical Basis	4	*Excessively conceptual or excessively physical.*	*Appropriately physically comprehensive.*
	Inclusion of Necessary Natural Watershed and Climatological Processes	5	*Major natural hydrologic and climatological processes are represented in basic form.*	*All necessary natural hydrologic and climatological processes are represented in complex form.*
	Inclusion of Necessary Regulated Hydrologic Processes	5	*No necessary regulated hydrologic processes are represented.*	*All necessary regulated hydrologic processes are represented.*
	Land Surface Discretization	4	*Excessively lumped or excessively spatially discretized.*	*Appropriately spatially discretized to meet all user needs.*
	Model Output Discretization	3	*Modelled streamflows are provided at one location.*	*Modelled streamflows are provided at multiple locations across the watershed.*
	Temporal Discretization	4	*The model operates only on a daily or greater time-step.*	*The model time-step can be varied.*
Input Data and Calibration	Availability of Required Input Datasets and Default Parameters	5	*No required input data are available.*	*All required input data already exists. No adaptations are required.*
	Integration of Existing Water Demand Datasets	5	*The model does not allow for consideration of water demand for domestic, agricultural, and industrial purposes.*	*The model allows for the computation of water demand for domestic, agricultural, and industrial purposes.*
	Model Calibration	3	*Model calibration procedures are not defined, and model not associated with specific calibration software.*	*Multi-point, multi-variable calibration procedures are well defined and associated with specific calibration software.*
Model Flexibility	Groundwater complexity	3	*No future upgrades to groundwater simulation capabilities are possible.*	*Groundwater capabilities are highly amenable to future improvement/replacement.*
	Flexibility to Configure and/or Update Hydrologic Processes	4	*Hydrologic processes cannot be configured, and no future upgrades are possible.*	*Hydrologic processes can be configured and are highly amenable to future improvement/replacement.*
	Hydraulic Simulation	2	*No hydraulic simulation integration is possible.*	*Fully integrated hydraulic simulation routines exist or can be integrated.*
	Integration for Basin-wide Hydrologic Model	4	*Once developed, individual modelled spatial extents cannot be linked.*	*Full integration between modelled spatial extents can be achieved.*
Model Applicability and Usability	Relation to Existing and Future Okanagan Modelling Efforts	4	*The model is not being used in the Okanagan and is not a candidate model for future modelling exercises.*	*The model is actively being, or has been, successfully used in the Okanagan.*
	Model Developer Support	3	*No formal support and model documentation are not readily available.*	*Extensive model support is available from online and in-person resources, and model documentation is readily available.*
	Usability and Computational Efficiency	4	*The model is slow to complete simulations and has no ability to process simulations concurrently.*	*The model can be fully automated and is amenable to cloud-based processing for concurrent simulation processing.*
	Model Licensing and Source Code Availability	3	*Model licence is required, and source code is not readily available.*	*Model is open-source and source code is readily available.*

Table 2-2
Candidate model grading results

General Category	Grading Criterion	Importance Weighting	Poor Score (1) Definition	Excellent Score (5) Definition	UBCWM	HBV-EC	WATFLOOD	MIKE SHE	HEC-HMS	VIC	RAVEN	SWAT
Model Design and Complexity	Physical Basis	4	*Excessively conceptual or excessively physical.*	*Appropriately physically comprehensive.*	3	2	3	5	3	5	5	5
	Inclusion of Necessary Natural Hydrologic and Climatological Processes	5	*Major natural hydrologic and climatological processes are represented in basic form.*	*All necessary natural hydrologic and climatological processes are represented in complex form.*	4	3	3	5	4	4	5	4
	Inclusion of Necessary Regulated Hydrologic Processes	5	*No necessary regulated hydrologic processes are represented.*	*All necessary regulated hydrologic processes are represented.*	1	1	3	5	4	1	5	5
	Land Surface Discretization	4	*Excessively lumped or excessively spatially discretized.*	*Appropriately spatially discretized to meet all user needs.*	2	2	5	5	4	3	5	4
	Model Output Discretization	3	*Modelled streamflows are provided at one location.*	*Modelled streamflows are provided at multiple locations across the watershed.*	2	3	5	5	4	5	5	4
	Temporal Discretization	4	*The model operates only on a daily or greater time-step.*	*The model time-step can be varied to sub-daily timesteps.*	5	1	5	5	5	4	5	1
Input Data and Calibration	Availability of Required Input Datasets and Default Parameters	5	*No required input data are available.*	*All required input data already exists. No adaptations are required.*	4	4	3	4	4	2	4	3
	Integration of Existing Water Demand Datasets	5	*The model does not allow for consideration of water demand for domestic, agricultural, and industrial purposes.*	*The model allows for the computation of water demand for domestic, agricultural, and industrial purposes.*	1	1	1	4	2	3	4	4
	Model Calibration	3	*Model calibration procedures are not defined, and model not associated with specific calibration software.*	*Multi-point, multi-variable calibration procedures are well defined and associated with specific calibration software.*	4	3	4	4	5	3	5	5
Model Flexibility	Groundwater complexity	3	*No future upgrades to groundwater simulation capabilities are possible.*	*Groundwater capabilities are highly amenable to future improvement/replacement.*	1	1	2	5	3	2	4	5
	Flexibility to Configure and/or Update Hydrologic Processes	4	*Hydrologic processes cannot be configured, and no future upgrades are possible.*	*Hydrologic processes can be configured and are highly amenable to future improvement/replacement.*	1	1	3	3	4	2	5	4
	Hydraulic Simulation	2	*No hydraulic simulation integration is possible.*	*Fully integrated hydraulic simulation routines exist or can be integrated.*	1	1	1	4	3	1	2	1
	Integration for Basin-wide Hydrologic Model	4	*Once developed, individual modelled spatial extents cannot be linked.*	*Full integration between modelled spatial extents can be achieved.*	1	1	1	3	2	3	5	5
Model Applicability and Usability	Relation to Existing and Future Okanagan Modelling Efforts	4	*The model is not being used in the Okanagan and is not a candidate model for future modelling exercises.*	*The model is actively being, or has been, successfully used in the Okanagan.*	1	1	1	5	5	1	5	1
	Model Developer Support	3	*No formal support and model documentation are not readily available.*	*Extensive model support is available from online and in-person resources, and model documentation is readily available.*	1	1	4	5	4	5	5	5
	Usability and Computational Efficiency	4	*The model is slow to complete simulations and has no ability to process simulations concurrently.*	*The model can be fully automated and is amenable to cloud-based processing for concurrent simulation processing.*	2	2	2	2	3	5	5	5
	Model Licensing and Source Code Availability	3	*Model licence is required, and source code is not readily available.*	*Model is open-source and source code is readily available.*	4	3	3	2	4	5	5	5
				Final Model Score	**148**	**120**	**186**	**273**	**240**	**204**	**306**	**254**

3 OKANAGAN HYDROLOGIC MODELLING ENVIRONMENT (OHME) DEVELOPMENT

This section describes the integration of Raven into a broader platform (i.e., OHME) for flexible and efficient hydrologic analyses of Okanagan Basin watersheds. A comprehensive environment for Okanagan-specific hydrologic modelling, OHME V1 includes:

- Raven Hydrological Modelling Framework, configured for Okanagan usage;
- OSTRICH Optimization Software Toolkit, configured for Okanagan watershed calibration efforts;
- Okanagan-specific and RavenR data management and visualization tools;
- Git version control software, configured to manage and distribute OHME; and
- Cloud computing management scripts and software, configured to run OHME on highly scalable cloud computing architectures.

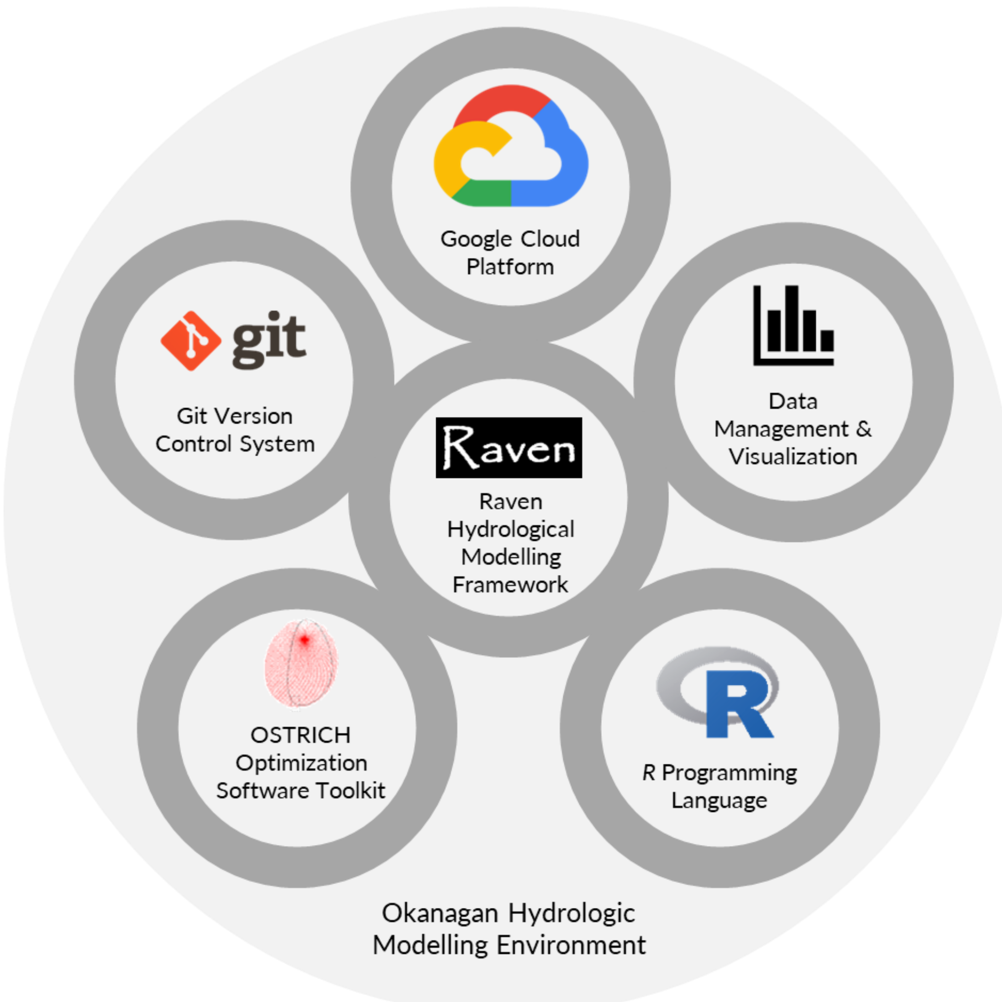


Figure 3-1
Schematic representation of the OHME

These elements of OHME are indicated schematically in Figure 3-1 and described below. Section 4 describes how these aspects are specifically configured for the purposes of OHME V1.

3.1 Raven Hydrological Modelling Framework

Raven (Craig and Raven Development Team 2019) is an open-source hydrologic modelling software developed to provide a flexible framework to support hydrologic modelling applications. Raven is actively developed by a core Raven Development Team of graduate and post-graduate researchers led by Dr. James Craig at the University of Waterloo. Guided by Dr. Craig, Raven development is also supported by external academic, public and private sector collaborators (including Associated) through an open-source model approach. Raven provides a generic discretization approach, allowing it to be operated as a lumped, semi-distributed, or fully-distributed model. Raven is fully customizable by the model developer and natively includes over 80 hydrologic process algorithms and over 40 forcing function generators, which can be used in a modular manner to tailor hydrologic models to different landscapes. The ability to customize Raven process representation and complexity is a key advantage relative to other hydrologic models. It allows Raven-based model exercises carried out within OHME to be quickly and efficiently tailored to scientific and operational/programmatic requirements on a case-by-case basis, including rapid testing and application of different hydrologic model component complexities to satisfy different user needs.

What is a Hydrologic Model?

Hydrologic models are simplified representations of hydrologic systems that allow users to understand how such systems function and respond to environmental changes (e.g., land use, climate, water management). Among the first hydrologic models were miniature physical constructions. With the introduction of computers, these physical models were translated into computer models. A computer-based ('computational') hydrologic model can take a variety of forms depending on its objective. Typically, a hydrologic model consists of mathematical and logical descriptors that describe the movement of water across the landscape and through a hydrologic system.

Computational hydrologic models vary in complexity from simple empirical equations to detailed process-resolving frameworks, with the level of complexity reflecting model user needs. In addition to variation in the complexity of their representation of hydrologic processes, hydrologic models can exhibit diverse spatial complexities, from lumped models that represent an entire watershed as one unit, to fully-distributed models that represent many complex hydrologic processes in a high-resolution gridded model domain. Many hydrologic models exist because these numerous aspects of models can be implemented in unique ways to model a specific type of environment, hydrologic process(es), or certain level of spatial discretization.

At the core of Raven's operation is a model spatial abstraction assumption, which is based on the principle of watersheds comprising sub-basins, and sub-basins comprising Hydrologic Response Units (HRUs). HRUs are defined as areas with hydrologically unique responses to precipitation events and can be contiguous or dis-contiguous areas characterized by a single combination of land use, vegetation cover, and terrain type, and underlain by a defined soil profile. Vertical water and energy balances are solved within each HRU, and water is moved laterally throughout the system via the following routing mechanisms:

- In-catchment routing – Once all vertical water and energy balances are computed within each HRU, remaining water is transferred to the downstream end of the channel within each sub-basin within the respective storage compartment. This process uses a convolution of unit hydrograph approach.
- In-channel routing – For each timestep (i.e., daily or sub-daily), water is moved from sub-basin to sub-basin moving from upstream to downstream via the surface water channel.
- Reservoir/Lake routing – Reservoirs can be modelled within Raven to mediate the outflow from individual sub-basins. Reservoirs can be characterized in several ways, ranging from natural lakes with a conceptual hydraulic weir outflow, to fully regulated reservoirs with integrated operational rules. Reservoir outflows contribute to in-channel routing downstream of the outflow.

- Water Withdrawals and Return Flows/Water Transfers – Water withdrawals and return flows (and water transfers) can be included in Raven by removing water from the inlet or outlet of sub-basins, or directly from reservoirs. Remaining water continues throughout the system by way of in-channel routing.

Within Raven, watershed landscapes can be spatially discretized using methods ranging from entirely lumped through to fully gridded or distributed. In between these two approaches, a semi-distributed discretization is also possible. In a semi-distributed set-up, Raven uses HRUs to identify homogenous areas that have a similar hydrologic response within larger sub-basins, thereby optimizing computational effort. Additionally, HRU groups can be disabled, which allows model execution to be performed only for selected subsets of the full model domain (i.e., individual watersheds). OHME V1 was developed to leverage this aspect of Raven such that the 19 watersheds are included within a single model domain that can be expanded in future to include additional watershed areas. This future-proof approach has significant operational benefits:

- Individual watersheds can be easily targeted for efficient watershed-specific model configuration, calibration, and analysis efforts;
- Multiple watersheds can be jointly targeted for concurrent analysis (e.g., to use observations from one watershed to inform calibrations of an adjacent, ungauged watershed, or to consistently represent water transfers among watersheds);
- All watershed areas could be targeted to provide a comprehensive, detailed, basin-wide model; and
- Global calibration can be completed to develop a base model parameter set in the absence of watershed-specific calibration datasets.

Raven is version-controlled using SVN software (similar in concept to the Git software used to version-control OHME [Section 3.4]). As part of the OHMP, an official SVN-based link to the core Raven source code repository (hosted on the Canadian National Research Council Canadian Hydrologic Model Stewardship 'CHyMS' software management server) was established, with the support of core Raven developers at the University of Waterloo. Because of this version-control software-based link, OHME can rapidly and directly obtain access to emerging Raven developments, improvements, bug-fixes and changes in a manner that is not possible with traditional (e.g., email or FTP-based) model code transfers. It also allows core Raven developers to respond efficiently to specific Okanagan-based Raven model requests and, furthermore, distribute Raven improvements developed during OHME-based Raven modelling back into the broader Raven Hydrologic modelling community.

To support Okanagan-specific naturalized and residual streamflow modelling, the Model Development Team worked extensively with the Raven Development Team to expand existing routines and implement numerous new routines, to improve hydrologic representation within the Okanagan Basin. In addition to many other upgrades, new routines to expand water management capabilities within Raven were implemented as follows:

- Improved representation of water extractions – a new routine was included to extract timeseries of water demand from the outlet of model sub-basins, only if sufficient water exists (i.e., water is not removed from the creek if the extraction would result in zero flows at the sub-basin outlet). This new routine is intended to also account for EFN (and/or other minimum flow) thresholds in future Raven releases.
- Water transfers – two new routines were included to allow the movement of water between model sub-basins to represent water transfers (Section 5.3.2). These routines allow modelled streamflows to be transferred between model sub-basins by specifying a percentage of streamflow or providing a hydraulic relationship (i.e., flow pairs determined from a hydraulic structure, or similar). Both routines can be constrained to occur between specific dates, where required.

- Reservoir release estimates – a new routine was included to allow upland reservoir operations to be estimated based on downstream demand. The 'minimum reservoir release' is adjusted to satisfy a portion of downstream demand within a given model sub-basin(s). If the distribution of water supply between multiple upland reservoirs is unknown, reservoir releases can be estimated based on the maximum capacity of each reservoir, or the contributing area to each reservoir.

Because of these benefits, which stem from explicit design decisions taken early in the OHMP, OHME is well-placed to form the basis for a wide range of future hydrologic simulations and assessments. Integration of Raven into OHME delivers on key OBWB requirements for greater hydrologic model flexibility in terms of watershed-specific model complexity and spatial representation, and the ability to easily update the model as new information and model capabilities arise. Finally, the OHME framework enables sharing of Okanagan-based hydrologic model advances with the broader national hydrologic research and application community (OWSC 2018).

3.2 Ostrich Optimization Software Toolkit

Like other hydrologic models, Raven contains many internal parameters, representing many physical, parameterized and lumped processes, which can be varied by the model user. Effective calibration of Raven requires an automated approach that leverages optimization algorithms and statistics to determine parameter value 'sets' that are both within the range of observational uncertainty and generate model output (e.g., streamflow) that displays reduced bias relative to observations. OSTRICH (Matott 2017) is an open-source, model-agnostic, multi-algorithm, parallelizable parameter optimization/sensitivity estimation tool that implements a wide range of sophisticated numerical and statistical optimization and calibration tools (Matott 2017). While OSTRICH can be applied to many optimization and calibration tasks, it was developed to calibrate hydrologic models and is formally recommended by the Raven Development Team as an appropriate toolkit for Raven calibration (Craig and Raven Development Team 2019). Accordingly, OSTRICH was closely interfaced with Raven within OHME V1 to automate parameter calibration.

Using OSTRICH in combination with multi-core computing platforms, Raven calibration exercises can be performed efficiently. OSTRICH contains a range of optimization methods that can be applied depending on user needs, expertise and resources. In addition, OSTRICH contains a set of parameter sensitivity methods, which can be used to robustly isolate and understand key watershed-specific hydrologic model process uncertainty. Inclusion of OSTRICH optimization and sensitivity methods within OHME allows for a wide range of practical hydrologic model assessments. This capability delivers on a key model requirement for an improved ability to efficiently and effectively calibrate models and understand model uncertainty (OWSC 2018).

3.3 Okanagan-Specific and RavenR Data Management and Visualization Tools

Hydrologic models such as Raven depend on a range of specifically-formatted input data, which drive the model to produce outputs such as simulated streamflow. These input data requirements include:

- climate data (e.g., temperature and precipitation);
- land cover data (e.g., topography, vegetation, and soil type);
- water management data (e.g., reservoir operations and water demand); and
- hydrologic observations (e.g., streamflow and snow depth).

To manage these diverse data inputs within OHME V1, an extensive set of R-based tools was developed to facilitate data access and translation into formats amenable to Raven. These tools interface closely with Raven and OSTRICH as well as Git version control, and cloud compute management OHME components.

RavenR (Craig and Raven Development Team 2019) is an additional open source set of R-based tools developed for streamlining the pre- and post-processing of Raven input and output. RavenR is particularly leveraged within OHME V1 in conjunction with the Okanagan-specific tools described above, in particular to reformat input data and visualize output or initially set up a Raven model by importing meteorological and streamflow data. Together, the combination of RavenR and Okanagan-specific data management and visualization tools allows OHME to flexibly integrate evolving input datasets and rapidly assess Raven output for a variety of hydrologic diagnostics at arbitrary locations within modelled watersheds.

These tools are combined in an R script-driven manner, which when combined with effective Git-based version controlling (Section 3.4) ensures that all aspects of the project (e.g., data pre-processing, Raven configuration, simulation design, calibration methodologies, and data post-processing) are highly automated. This ensures that all OHME applications are, and will continue to be, extremely transparent, easily repeatable, highly robust, and well documented. These capabilities deliver on key OBWB requirements regarding the ability to efficiently access and use best available input data (e.g., evolving climate data) and quickly obtain and understand Raven output data (OWSC 2018). They also ensure that all OHME tools remain fully transparent and adaptable to future user-driven needs.

3.4 Git Version Control

Version control – also known as revision control or source control – refers to the management of changes to computer 'source code' (e.g., the raw text files containing code-based instructions and workflows that define the operation of the program or environment). Version control is a ubiquitous aspect of all successful modelling environments, since it allows for source code backup, shared collaboration, and managed evolution. As source code and other related files evolve within a version-controlled framework, important states that represent a snapshot of the project are tagged with a number or letter code within one or more source code repositories. As a result, past snapshots can be backed up, regenerated, and compared to each other (e.g., to track software development against expected software behaviour). In addition, important milestones in the development pathway can be 'tagged' (e.g., 'Version 1') and released to users in a managed and transparent fashion.

Git is a leading version control software that is extensively used at scales ranging from personal computing to management of the largest software development programs in the world. It is free and open source and is designed to handle everything from small to very large projects with speed and efficiency. It minimizes top-down administration and is therefore well-suited for collaborative web-based development of complex projects. Based on these characteristics, Git was chosen as the version control software for OHME. In addition to user-specific Git-based version control, core OHME project scripts and files are duplicated to Bitbucket.org, a Git-based online source code repository. Via Bitbucket (or a similar service such as Github.com as needed), OHME can be collaboratively developed by OBWB and any number of future additional users in a way that is managed, secure, collaborative and web-based. Git-based version controlling delivers on key model requirements to update the model in the future (OWSC 2018) and to control and manage future updates in a well-governed manner.

3.5 Cloud Computing Management Tools

The Raven model is efficient, with individual watershed-specific simulations taking minutes to complete. However, Raven calibration efforts involving thousands of individual simulations, across multiple watersheds, create a substantial demand for computing power. Traditionally, such demands would be met through either long wait-times while calibrations completed (e.g., as occurred during the previous OWSDP) or through the purchase of expensive, local computing facilities that must be supported through local IT resources. The recent advent of commercial cloud computing has provided an alternative to this approach via the per-minute rental of highly scalable computing resources.

To ensure that the project was not constrained by local computing resources either during development or future use, OHME was developed to capitalize on Canada-located, cloud compute resources using the Google Cloud Platform (GCP[1]). GCP provides scalable compute resources, allowing large, powerful Virtual Machines (VMs) to be created and disposed of as needed. This allows for economical, yet highly efficient model simulation and calibration exercises to proceed in a manner that functionally mirrors the operation of a very expensive local computing cluster. In addition, a fully automated, GCP-based, daily 'snapshot' back-up schedule for the primary modelling VM provides a second layer of model and data security/redundancy above that enabled by Git-based version controlling. The GCP-based OHME framework for the Raven model uses Debian Linux based VMs. However, other operating systems (e.g., Windows Server), tools (e.g., machine learning and large-data analysis methods) and datasets (e.g., via Google Earth Engine) are also available via GCP, allowing future users to substantially expand the breadth of Okanagan-based hydrologic studies. Provision of capabilities within OHME to run on GCP delivers on key model requirements to perform computationally intensive hydrologic simulations and calibrations in a short amount of time (OWSC 2018). It also ensures that OHME remains backed and enables future OHME users to access an array of cutting-edge data and data analysis tools during subsequent Okanagan-based hydrologic assessments.

[1] https://cloud.google.com/

4 OKANAGAN HYDROLOGIC MODELLING ENVIRONMENT CONFIGURATION

This section describes the detailed configuration of the core OHME components for OHME V1 Okanagan watershed simulations, particularly the setup of Raven and OSTRICH and development and application of key input datasets. However, configuration and application of these components to Okanagan watershed simulations was closely supported and enabled by the other core OHME components described in Section 3. The configuration described here is specific to OHME V1 and is intended to form the basis for immediate application of OHME-produced hydrologic model data and provide a key foundation for future watershed-specific and whole-basin hydrologic studies. The latter will likely require case-by-case customization of OHME V1 configuration presented herein (e.g., updates to the Raven model structure or calibration target datasets). As with any other modelling framework, these customizations, when properly version controlled and documented using Git, will result in user-driven OHME evolution into the future, well past the scope of the OHMP.

4.1 Raven Conceptual Design

Based on advice from the Raven Development Team, coupled with information gathered during the recent hydrologic model review (Section 2) and the previous review completed to select a model for use during Phase 2 of the OWSDP, a version of HBV-EC was used as the base hydrologic model configuration within the OHMP. The hydrologic review process completed by WMC (2008) during Phase 2 of the OWSDP focussed on the physical/conceptual nature of select models and their ability to accurately represent the Okanagan landscape. HBV-EC ranked highly in this assessment (however, the MIKE SHE modelling platform was ultimately selected). Implementation of the HBV-EC model configuration within the flexible Raven environment overcomes remaining standalone HBV-EC model limitations, such that while standalone HBV-EC was down-rated in the OHMP model selection process (Section 2), HBV-EC emulation *within Raven* was determined to be the optimal configuration for OHME V1.

Raven can achieve near-perfect emulation of the original HBV-EC model configuration through implementation of it's large library of user-customizable forcing functions and hydrologic processes. Information on the HBV-EC configuration within Raven is provided in the Raven Manual (Craig and Raven Development Team 2019). Appendix B provides a summary of all key processes included in the version of HBV-EC used within the OHMP.

4.2 OHMP Model Watersheds

The 19 watersheds included in the OHMP are shown in Figure 1-1 and listed below:

- Coldstream Creek
- Equesis Creek
- Inkaneep Creek
- McDougall Creek
- McLean Creek
- Mill Creek
- Mission Creek
- Naramata Creek
- Naswhito Creek
- Penticton Creek
- Powers Creek
- Shingle Creek
- Shorts Creek
- Shuttleworth Creek
- Trepanier Creek
- Trout Creek
- Vaseux Creek
- Vernon Creek
- Whiteman Creek

4.3 Temporal Resolution and Model Period of Interest

Raven can generate daily or sub-daily estimates of streamflow, depending on the user needs. For the OHMP, daily streamflow estimates were considered a suitable temporal resolution to adequately satisfy existing (and future) user needs. Accordingly, daily naturalized and residual streamflow estimates are provided at select points-of-interest for all 19 model watersheds. However, if desired, OHME allows users to execute Raven at a sub-daily temporal resolution.

For the purposes of the OHMP, the following temporal extents were defined:

- **Model Period of Interest: 1996-2017** – This represents the period for which daily streamflow estimates are generated by Raven. This period makes optimal use of available input and calibration datasets to provide the longest period of modelled streamflow datasets available. This period was selected for the following reasons:
    - Summit (2009) and Associated (2017) noted that land use, actual water use, and reservoir management information was limited prior to 1996.
    - Associated (2019a) developed mean weekly naturalized and residual streamflow datasets for the period 1996-2010, which support model calibration.
    - Available land use inventory datasets included within the OWDM are representative of conditions in the Okanagan Basin from the early 1990s onwards.
    - Associated (2019b) developed updated gridded climate datasets of daily total precipitation, and minimum and maximum daily air temperature for the period 1950-2017.
- **Model Warm-Up Period: June 1, 1993 to December 31, 1995** – To ensure that a hydrologic model starts with internal stores (e.g., soil moisture, reservoir levels) at an optimal state, a model warm-up period is generally run to set initial starting conditions. A warm-up period from June 1, 1993 to December 31, 1995 was deemed sufficient to set initial starting conditions. Due to the limited information on upland reservoir water levels, a starting date of June 1 was selected for warm-up to reflect reservoir water levels at full-pool (which is generally consistent with the timing of peak natural and residual reservoirs at full-pool).
- **Model Calibration Period: 1996-2010** – This represents the period for which model calibration was completed. This period was selected for the following reasons:
    - Associated (2019a) developed mean weekly naturalized and residual streamflow datasets for the period 1996-2010.
    - Select WSC hydrometric stations have long-term natural and residual streamflow records for the overlapping period, providing suitable calibration datasets for both types of streamflow.
- **Model Validation Period: 2011-2017** – This represents the period for which validation was completed to evaluate the performance of the hydrologic models. It was also completed because model validation was not completed as part of the model development process during the OWSDP. The period of 2011-2017 was selected since it makes full use of all available WSC hydrometric natural and residual streamflow datasets, as well as OWDM estimates.

4.4 Spatial Discretization Approach

The OHMP includes 19 model watersheds within OHME V1. Within Raven, the following spatial components are included:

- **Watersheds** refer to the 19 model watersheds listed in Section 4.2.
- **Sub-basins** refer to sub-basin units defined within each model watershed, which were delineated to provide model output at required locations within each watershed. Further information on the model sub-basin delineations is provided in Section 5.1.5.
- **HRUs** refer to hydrologically similar areas within each model sub-basin.

To support a semi-distributed modelling approach, the definition of HRUs was required to identify hydrologically similar areas. Based on existing understanding and a primary literature review, there are many approaches to define HRUs, depending on the modelling objectives. However, the general principle involves applying a series of spatial overlays to identify sub-basin areas that are hydrologically similar to each other. These are then treated as one area within Raven hydrologic calculations.

For the OHMP, HRUs were defined using an iterative approach to assess the impact of inclusion/exclusion of key identified hydrologic components (e.g., elevation, soils, land use). This process deemed the most appropriate HRU definition was based on unique combinations of the following spatial components (Figure 4-1):

- Sub-basins;
- Elevation band (100 m);
- Aspect class (4 classes); and
- Land use class (11 classes).

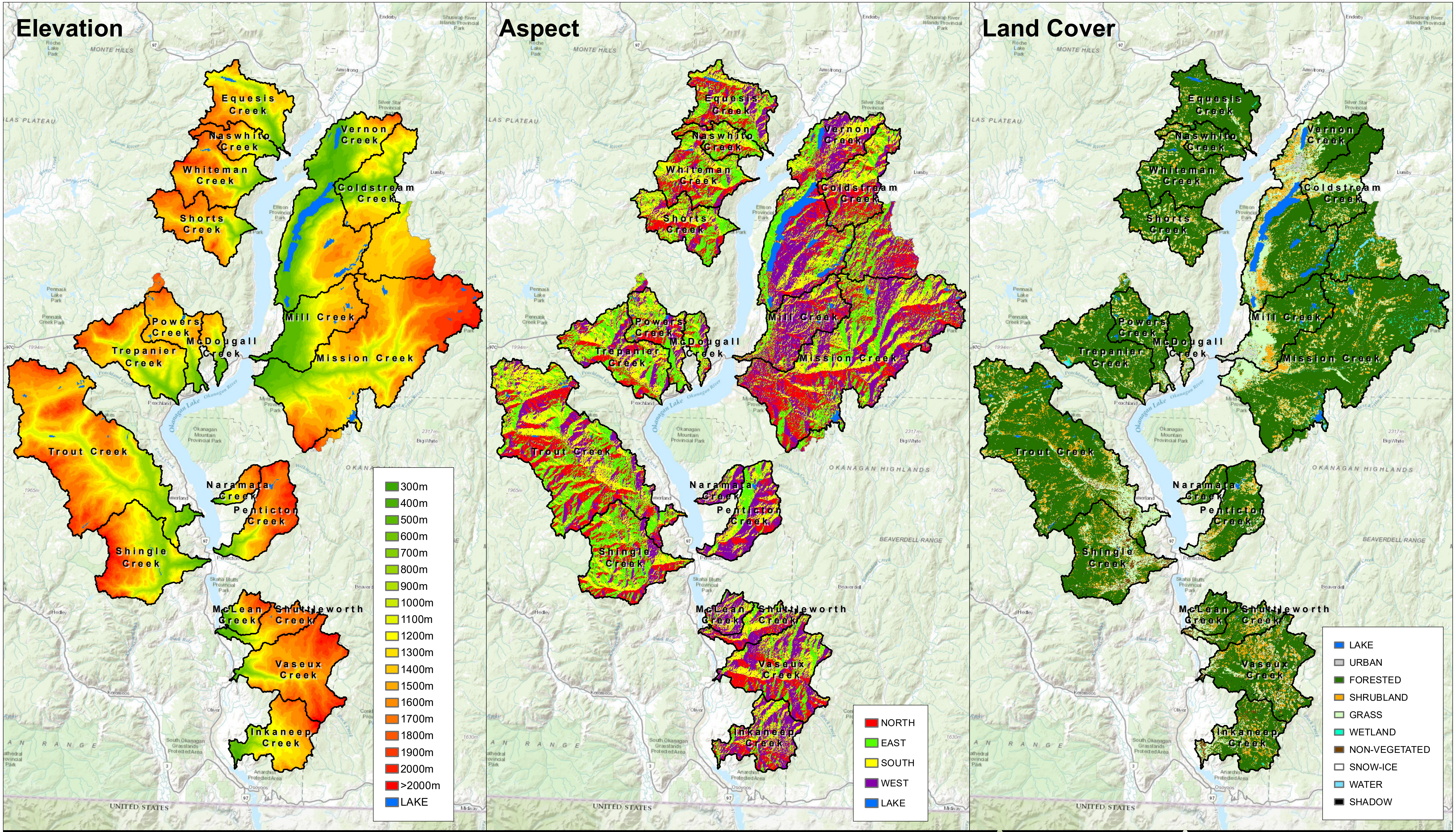
Section 5.1 summarizes how these spatial components were generated and how required aspect and land use classes were defined. If desired, OHME V1 allows the definition of HRUs to be easily adjusted and required Raven input files to be dynamically reproduced for all included watersheds.

In addition to the spatial information used to define HRUs, each HRU requires specific vegetation, soil, and geographic information (Figure 4-2). This information was subsequently assigned to each HRU based on available spatial data (Section 5.1). All spatial data included in the HRU definitions, and subsequently assigned to each HRU, were deemed to represent current conditions in the Okanagan Basin. Accordingly, the default HRU definitions were deemed appropriate for use to model residual streamflows. To appropriately model naturalized streamflows, the default HRUs were adjusted to better represent a historic natural land surface, as follows:

- All Urban land use and vegetation was converted to the most common other land use class / vegetation class by area, within each sub-basin to represent pre-development conditions.
- All Urban soil profiles were converted to the most common other soil profile by area, within each sub-basin to represent pre-development conditions.
- All land use and vegetation classes within the Brenda Mines area (i.e., Trepanier Creek watershed –sub-basin 2709) were converted to 'Forested', and 'Coniferous_Open' (Section 5.1.2) to represent forest conditions prior to the commencement of mining in this area.

In addition, select groups of HRUs are disabled under the following conditions:

- As outlined by Associated (2019a), Lambly Lake and contributing area are not part of the natural watershed area of Powers Creek watershed. Therefore, for naturalized streamflow modelling of Powers Creek watershed, Lambly Lake and contributing area (i.e., sub-basins 2407 and 2408, respectively) are disabled.
- Under both natural and residual conditions, all sub-basins outside of the model watersheds (i.e., out-of-basin diversion extents) are disabled. Sub-basins for these diversions are included in OHME V1 to allow for future build-out of the model(s) once more information on diversion operations becomes available.



Associated Environmental

PROJECT NO.: 2018-8215.000.000
DATE: February 2020
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0 10 20 km

FIGURE 4-1: ELEVATION, ASPECT, AND LANDCOVER CLASSES INCLUDED IN HRU DEFINITIONS ACROSS THE OKANAGAN BASIN

Okanagan Basin Water Board

Okanagan Hydrologic Modelling Project

elev aspect landcover.mxd / 2/13/2020 / 11:09:38 AM

Table 4-1 summarizes the number of sub-basins, reservoirs, and HRUs within each model watershed included in OHME V1. A total of 343 sub-basins, 47 reservoirs, and 29,196 HRUs are included in the current model domain. **The required spatial datasets are available, and the definition of HRUs has been completed for the Okanagan Basin to support future model build-out to additional watersheds in a consistent manner.**

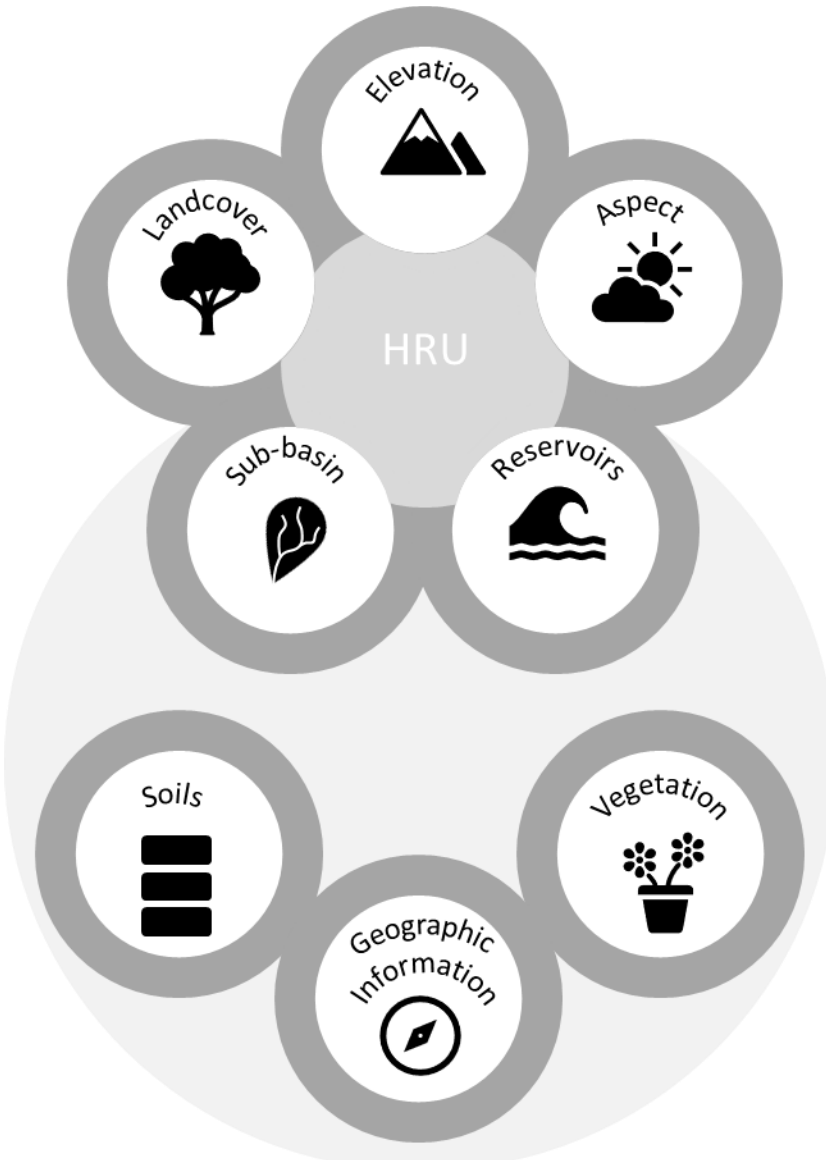


Figure 4-2
Schematic of HRU definition

Table 4-1
Number of sub-basins, reservoirs, and HRUs within each model watershed

Watershed	Number of Sub-basins	Number of Reservoirs	Number of HRUs
Coldstream Creek	21	1	1,768
Equesis Creek	12	1	1,045
Inkaneep Creek	7	0	1,157
McDougall Creek	9	1	574
McLean Creek	3	0	560
Mill Creek	39	4	1,997
Mission Creek	56	9	4,193
Naramata Creek	3	0	362
Naswhito Creek	7	0	660
Penticton Creek	15	1	1,566
Powers Creek	23	7	1,106
Shingle Creek	12	2	1,618
Shorts Creek	12	0	1,387
Shuttleworth Creek	9	2	715
Trepanier Creek	9	0	1,303
Trout Creek	37	11	2,966
Vaseux Creek	8	0	1,509
Vernon Creek	46	7	3,281
Whiteman Creek	15	1	1,429

5 MODEL INPUT DATA

5.1 Spatial Data

Spatial datasets are required to support HRU definition and provide necessary information to allow successful Raven execution. The following spatial attributes are required for all HRUs included in Raven:

- Area (km^2)
- Elevation (m)
- Latitude (decimal degrees)
- Longitude (decimal degrees)
- Sub-basin
- Land Use Class
- Vegetation Class
- Soil Profile
- Aquifer Profile[2]
- Slope (degrees)
- Aspect (degrees)

Table 5-1 summarizes the spatial datasets included in OHME V1. Additional information about each dataset is provided in subsequent sections.

5.1.1 Digital Elevation Model – Elevation, Aspect, Slope, and Geographic Location

The Canadian Digital Elevation Model (CDEM) provided the spatial reference template and topographic data for the model. The CDEM is a gridded data product that has a spatial resolution of 19.8 x 19.8 m; each cell represents an elevation above mean sea level. The Okanagan region was extracted from CDEM and was re-projected to the BC Albers projection, chosen as most suitable for the study area. All other input spatial datasets were rasterized (if not natively in gridded format), projected to the BC Albers projection, and resampled and snapped to match the spatial resolution and alignment of the DEM.

The DEM was classified into 100 m elevation bands and four aspect classes (i.e., North [≥315 <45 degrees], East [≥45 <135 degrees], South [≥135 <255 degrees], and West [≥225 <315 degrees]) to support the definition of HRUs in the Okanagan Basin (Section 4.4). In addition, the CDEM was used to derive the median elevation, mean slope, mean aspect, and mean latitude and longitude for each subsequent HRU.

[2] While Aquifer Profiles are currently included within the model setup, aquifers are not included in the modelling process at this time. Future upgrades of the Raven framework are expected to include a coupled groundwater model in which aquifer characteristics will be included.

Table 5-1
Spatial datasets included in OHME V1

Spatial Component	Data Source	Data Source Link	Native Spatial Resolution
Elevation	Canadian Digital Elevation Model (CDEM)	https://open.canada.ca/data/en/dataset/7f245e4d-76c2-4caa-951a-45d1d2051333	19.8 m
Aspect	Calculated from DEM using *terrain()* function within R *raster* package (version 2.8.19)	N/A	19.8 m
Slope	Calculated from DEM using *terrain()* function within R *raster* package (version 2.8.19)	N/A	19.8 m
Land use	EOSD Landcover Classification	http://tree.pfc.forestry.ca/	25 m
Sub-basin	Manual delineations building upon watershed boundaries from the Province of BC Freshwater Atlas Watersheds layer	https://catalogue.data.gov.bc.ca/dataset	N/A
Reservoirs	Lakes and Reservoirs from the Province of BC Freshwater Atlas layer that include reservoir and lake shapes	https://catalogue.data.gov.bc.ca/dataset	N/A
Vegetation	EOSD Landcover Classification	http://tree.pfc.forestry.ca/	25 m
	Vegetation Resources Inventory	https://catalogue.data.gov.bc.ca/dataset	N/A
Soils	Province of BC Soil Mapping Data Packages	https://catalogue.data.gov.bc.ca/dataset	N/A
Aquifers	Okanagan Basin Phase 2 Water Supply and Demand Study (Summit 2010)	N/A	N/A
Leaf Area Index	MCD15A3H V6 LAI product from Google Earth Engine	https://developers.google.com/earth-engine/datasets/catalog/MODIS_006_MCD15A3H	500 m

5.1.2 Land Use and Vegetation

Land use and vegetation classes were obtained from the Earth Observation for Sustainable Development of Forests (EOSD) landcover dataset (EOSD 2007). The dataset was developed by the Canadian Forest Service using Landsat satellite imagery, developed into a high spatial resolution (i.e., 25 m) gridded landcover map. This dataset was deemed to best represent current landcover (i.e., land use) types within the Okanagan at the required scale. The EOSD dataset was re-projected, resampled, and snapped to match the spatial resolution and alignment of the CDEM. The Agricultural Land Use Inventory was not used to support land use classifications since the spatial scale was not representative of the model requirements, and agricultural water demand is accounted for indirectly through the OWDM under residual streamflow conditions

The EOSD dataset includes several unique landcover classifications (Wulder and Nelson 2003) that cover the whole of Canada. The Okanagan has 36 EOSD landcover classifications. OHME V1 groups similar EOSD landcover classes into 11 unique land use classes (Table 5-2) to support the definition of HRUs. However, not all subsequent land use classes exist within the current model domain (e.g., Agriculture and No Data); information is included for completeness and to allow future model build-out for other areas. In addition, the EOSD dataset provided the vegetation class information required by Raven by including a finer grouping of EOSD landcover classes to capture forest cover types in the Okanagan Basin (e.g., Coniferous and Broadleaf). A total of 17 vegetation classes were defined (Table 5-2).

Table 5-2
Land use and vegetation classes included in the OHMP

EOSD Landcover Type Code	OHME V1 Land Use Class	OHME V1 Vegetation Class
No_Data		No Data
Unclassified	No Data	No Data
Cloud		No Data
Shadow	Shadow	Shadow
Water	Water	Water
Snow_Ice	Snow & Ice	Snow & Ice
Non-Vegetated_Land		Non-vegetated
Rock_Rubble	Non-Vegetated	Non-vegetated
Exposed_Barren_Land		Non-vegetated
Developed		Non-vegetated
Shrubland		Shrubland
Shrub_Tall	Shrubland	Shrubland
Shrub_Low		Shrubland
Wetland		Wetland
Wetland_Treed	Wetland	Wetland
Wetland_Shrub		Wetland
Wetland_Herb		Wetland
Bryoids		Grass
Herbs	Grass	Grass
Grassland		Grass
Agriculture		Agriculture
Agriculture_Cropland	Agriculture	Agriculture
Agriculture_Pasture_Forage		Agriculture
Forest_Trees		Forested
Mixedwood		Forested
Mixedwood_Dense		Forested
Mixedwood_Open		Forested
Mixedwood_Sparse		Forested
Coniferous		Coniferous
Coniferous_Sparse	Forested	Coniferous
Coniferous_Dense		Coniferous - Dense
Coniferous_Open		Coniferous - Open
Broadleaf		Broadleaf
Broadleaf_Sparse		Broadleaf
Broadleaf_Dense		Broadleaf - Dense
Broadleaf_Open		Broadleaf - Open
	Urban[1]	Urban

Notes:

1. The EOSD landcover dataset does not include an “Urban” Landcover classification. Herein, “Urban” was defined as EOSD landcover classification “Exposed Barren Land” within municipal boundaries and within a 50 m right-of-way of major highways. This classification was added to allow a natural landscape to be recreated for modelling natural streamflow conditions.

Several adjustments were made to the native EOSD landcover classes to gap-fill missing data and better define select classes. Prior to definition of HRUs, the following adjustments were made to the raw spatial dataset:

- EOSD landcover classes of “No Data” and “Cloud” were filled by incorporating data from the BC Vegetation Resources Inventory (VRI) dataset, where available. The VRI dataset is a forest inventory geospatial database that includes landcover classifications (e.g., Treed-Coniferous, Treed-Mixed). Where necessary, the VRI landcover classes were assigned to the most similar EOSD landcover class based on species composition (as defined in the VRI) to gap-fill “No Data” and “Cloud” landcover classes within the EOSD dataset. This process was completed prior to definition of HRUs due to the large continuous nature of these areas.
- The EOSD landcover classes were further refined by incorporating an “Urban” landcover class, predominantly to allow distinction between current (i.e., residual) and natural landscapes. Most of the urban landscape was natively defined within the EOSD data as “Exposed Barren Land” (based on visual inspection); however, to differentiate “Urban” areas, municipal boundaries, as well as a 50 m right-of-way on major highways (i.e., Highway 97, 97C, 6), were used to convert “Exposed Barren Land” to a unique “Urban” landcover class. All “Exposed Barren Land” within either municipal boundaries or the highway right-of-way was changed to “Urban” within default (i.e., residual) HRUs. Section 4.4 summarizes how HRUs were adjusted for natural conditions.

While land use classes were included in the definition of HRUs (Section 4.4), vegetation classes were subsequently assigned to each HRU based on the most common vegetation class within each HRU.

Following definition of HRUs, the following adjustments and observations were made:

- Land use and vegetation classes for HRUs dominated by “Shadow” land use and vegetation were redefined based on the most common land use and vegetation classes within each model sub-basin.
- Within the domain, no HRUs were assigned “No Data” or “Agriculture” land use or vegetation classes; however, parameters associated with these classes were included in the model for completeness, and to allow future model build-out. Agricultural areas within the model watersheds are currently captured within the “Grass” land use and vegetation classes.

5.1.3 Soils

The HBV-EC model configuration includes a 3-layer conceptual soil model. Within this soil model, each of the three soil layers can vary in thickness and composition. Due to the conceptual nature of the HBV-EC soil model, middle and lower soil layers are intended to represent ‘fast’ and ‘slow’ groundwater reservoirs, respectively. Accordingly, the thickness of these soil layers has minimal influence on model performance and as such, both soil layers are assigned an arbitrary thickness of 100m to ensure that they do not reach capacity within OHME V1. The top soil layer represents the ‘active’ and effective soil storage component within the HBV-EC model configuration. This top soil layer thickness is included within the calibration and allowed to vary between 0 and 2 m.

Beyond this simple soil representation within OHME V1, OHME maintains built-in capacity for development of more complex soil representations as needed. In particular, ‘physical’ soil profiles and classes are defined based on available soils information contained within the Province of BC Soil Mapping Data Package (Table 5-1). These definitions allow select model parameters to be auto-calculated by Raven based on physical soil characteristics/composition. This ability allows for a more physically based soil model within OHME in future, if desired. The ‘physical’ soil profiles and classes defined within OHME were based on the dominant soil type reported for a given polygon within the Soil Mapping Data Package. Within each model watershed, unique soil profiles were defined based on the dominant soil composition (e.g., SIL [silt], SAN [sand], or CLA [clay]), the degree of dominance (e.g., low [<50%], medium [≥50 <75%], and high [≥75%]), and the depth of the overall soil profile (e.g., shallow [≤0.75 m], medium [>0.75 ≤1.5 m], and deep [>1.5 m]). Model horizon thicknesses were calculated based on the sum of corresponding horizon thicknesses (Table 5-1) (i.e., Modelled Horizon A is the sum of provincially mapped Horizons A, AB, and AC; Modelled Horizon B is the sum of provincially mapped Horizons B, BA, and BC; and Horizon C is the sum of provincially mapped Horizons C, CA, and CB). The fractional soil composition for each horizon reflects the reported composition of each horizon and is used to auto-calculate select physical soil parameters within Raven. Soil types GRAVEL_PIT, DIKE, CUT_FILL, OPEN_WATER, and URBAN have effective soil depths of zero (representing disturbed soils) and are grouped together within OHME to eliminate soil processes in these HRUs. Finally, HRUs identified as lakes or bedrock were assigned special soil profiles (i.e., LAKE and ROCK, respectively) to allow Raven to identify locations where soil-based processes were not relevant. 'Physical' soil composition (i.e., percentage of sand, silt, and clay) defined above was maintained within the conceptual HBV-EC soil model to allow select soil parameters to be auto-calculated by Raven. Only the 'physical' soil thicknesses defined within OHME V1 were excluded within the conceptual soil model.

Soil profiles were assigned to each HRU using a simple spatial overlay, assigning the most common soil profile to each HRU.

5.1.4 Aquifers

Raven currently does not consider aquifer properties; however, "Aquifer Profiles" are assigned to each HRU for completeness and to facilitate future groundwater modelling. Currently, aquifer mapping completed during Phase 2 of the OWSDP (Summit 2010) is used to represent generic aquifer types (i.e., bedrock and alluvial) in the Okanagan Basin. The Phase 2 OWSDP aquifer mapping dataset was rasterized to match the spatial resolution, projection, and alignment of the CDEM. Three aquifer profiles are currently included within the model:

- Bedrock
- Alluvial
- None

Aquifer profiles were assigned to individual HRUs based on the most common aquifer profile within each HRU. Bedrock and alluvial aquifers predominantly cover the Okanagan Basin; however, areas outside of the basin and areas not included in the available aquifer mapping are assigned "none." Currently, this distinction is not important as aquifer properties are not included in the hydrologic processes modelled by Raven; however, future refinements will likely be required when a coupled groundwater model is included in OHME.

5.1.5 Sub-basins

Within Raven, water is moved from individual HRUs to the mouth of a given watershed by combination of in-catchment and in-channel routing (Section 3.1). In-channel routing moves water downstream between user-defined sub-basins. The outlet of all sub-basins represents locations where users can obtain streamflow estimates; therefore, their delineation is critical to ensure that the model supports current (and future) user needs.

Model sub-basin delineations built upon mapped sub-basins from the publicly available BC Freshwater Atlas (DataBC 2019). These sub-basins were defined using BC Terrain Resource Information Management (TRIM) topographic datasets (1:20,000 scale) and are defined, and hydrologically connected, for each stream up to first order watersheds.

The model sub-basins were delineated to align sub-basin outlets with key 'Points-of-Interest' (POIs):

- Major confluences / tributary watersheds;
- Select WSC hydrometric station locations;

- Major water intake / diversion locations;
- Outlet of Major Reservoirs / Lakes (each reservoir/lake is defined as an individual sub-basin that consists of one HRU); and
- Environmental Flow Needs (EFN) Streamflow POI (i.e., apex of the alluvial fan) (Associated 2019a).

In addition, collaboration with ongoing hydraulic modelling efforts within the Mill and Mission Creek watersheds ensured that POIs were included at relevant hydraulic model nodes. Finally, the model domain was extended beyond the Okanagan Basin boundary to include the extent of inter-basin transfers to/from select watersheds (Section 5.3.2). All out-of-basin diversion areas were included as individual sub-basins to facilitate future model buildout and are disabled within OHME V1.

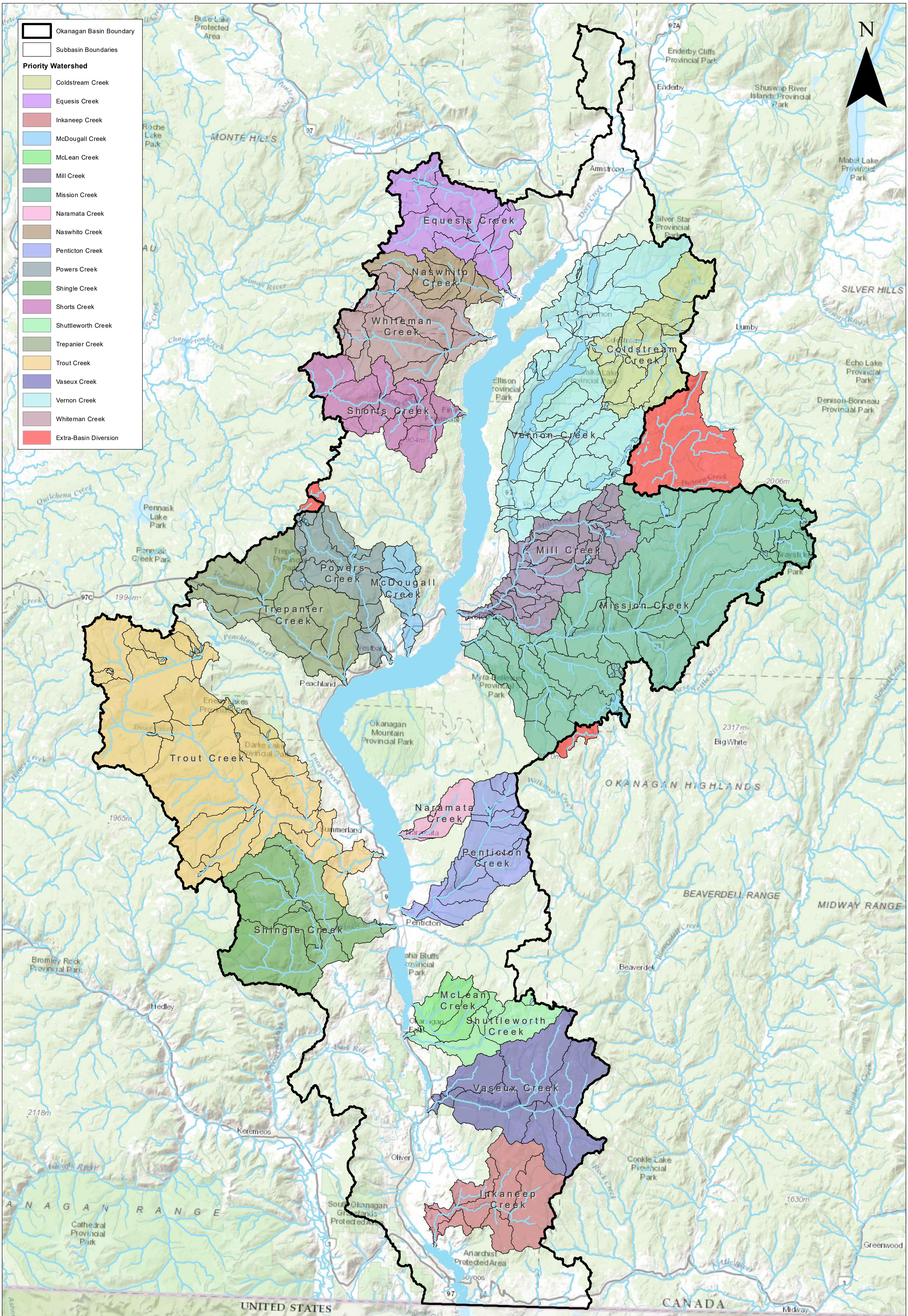
From each POI, existing sub-basin extents (i.e., BC Freshwater Atlas sub-basins) were subdivided as necessary by using 20 m elevation contours. Resultant model sub-basins were rasterized to match the spatial resolution, projection, and alignment of the CDEM. Finally, all sub-basins were hydrologically connected by assigning a downstream sub-basin identifier to each to define in-channel routing within Raven. All model sub-basins are displayed in Figure 5-1.

Sub-basins were incorporated into HRU definitions (Section 3.5) to ensure that HRUs were unique within and between all sub-basins, as required by Raven. Individual watershed maps, including model sub-basins, are provided in Appendix C.

5.1.6 Reservoirs

Within OHME V1, select reservoirs (Section 5.3.3) are included and explicitly modelled. The spatial extent of these reservoirs was obtained from the Lakes and Reservoirs polygon layer within the BC Freshwater Atlas (Table 5-1). Reservoir extents were rasterized, re-projected, resampled, and snapped to match the spatial resolution and alignment of the CDEM. Each reservoir is included as a single model sub-basin, comprising one HRU.

Sub basins Overview WS.mxd / 1/17/2020 / 3:29:46 PM



PROJECT NO.: 2018-8215.000.000
DATE: December 2019
DRAWN BY: DA

0 10 20 km

Associated Environmental

FIGURE 5-1: MODEL SUBBASINS INCLUDED WITHIN THE OKANAGAN HYDROLOGIC MODEL

Okanagan Basin Water Board

Okanagan Hydrologic Modelling Project

5.1.7 Leaf Area Index

The Okanagan Basin is dominated by forested landcover types. Therefore, accurately capturing changes in Leaf Area Index (LAI) is important to ensure that vegetation-driven hydrologic processes (e.g., rain and snow interception) are properly represented in hydrologic modelling. In Raven, multiple approaches exist for representing LAI and relevant processes. Maximum LAI values for vegetation classes included in OHME V1 (Table 5-3) are taken from the Canadian Land Surface Scheme (EC 2012) following a literature review.

Table 5-3
Maximum leaf area index values included in OHME V1

Vegetation Class	Maximum LAI
Broadleaf	
Broadleaf Dense	6
Broadleaf Open	
Coniferous	
Coniferous Dense	2
Coniferous Open	
Forested	4
Grass	3.5
Wetland	1.5
Shrubland	4
Snow / Ice	0
Urban	0
Water	0
Non-vegetated	0

In addition, seasonal (i.e., monthly) LAI adjustments were defined for select vegetation classes (i.e., all Broadleaf forest types, Forested, and Shrubland) to represent the loss of leaves during fall/winter months. Accordingly, 500 m gridded 4-day average LAI datasets (Table 5-1) were obtained from Google Earth Engine (GEE). The GEE dataset is the combined fraction of photosynthetically active radiation and the LAI, from the best available pixel over each 4-day period, as acquired by the MODIS sensors on NASA's Aqua and Terra satellites. The LAI datasets were re-projected, resampled, and snapped to match the spatial resolution and alignment of the CDEM. Monthly average LAI values were calculated for the period 1996-2010 and overlain with the final EOSD landcover dataset to derive monthly LAI values for each vegetation class. Following, monthly correction factors between the maximum monthly average LAI value and individual monthly average values were determined for select vegetation classes to represent monthly changes. Depending on the interception, potential evapotranspiration, and canopy correction routines selected within OHME V1, these monthly correction factors are used by Raven to adjust LAI values throughout the year. These LAI data are available within OHME if it is required by users in the course of key model conceptual development related to land and vegetation processes. However, within HBV-EC, interception is calculated simply as a percentage of precipitation; thus, LAI adjustments based on these data were not used within OHME V1.

5.2 Climate Forcing Data

Hydrologic models require climate information as input to the simulated hydrologic systems. HBV-EC requires temperature and precipitation data. Suitable climate datasets developed in a parallel project (Associated 2019b). The source climate data are gridded daily maximum and minimum temperatures on a 500 m BC Albers (EPSG:3005) grid, encompassing a spatial domain that includes all 19 model watersheds. It was generated using the *monthlyDS* workflow developed by the Pacific Climate Impacts Consortium (Sobie et al. 2017), which is an R-based climate data downscaling methodology (Figure 5-2) that leverages the high spatial resolution of monthly 500 m climatologies produced by the ClimateBC tool (Wang et al. 2016) and the high temporal resolution climate data within the NRCanMet dataset (McKenney et al. 2011). A comprehensive description of the data generation procedure is available by Associated (2019b), and the Okanagan Basin implementation of the *monthlyDS* workflow is available upon request from OBWB. Primary climate data metadata parameters are presented in Table 5-4, and example climate data output is presented in Figure 5-3.

To translate the gridded climate data to the semi-distributed Raven model (discretized by HRUs), a remapping workflow was developed within OHME V1 to calculate average temperature and precipitation conditions based on the spatial overlap between HRUs and the gridded climate data. Based on this remapping, actual climate data ingested into Raven consist of one timeseries of daily maximum and minimum temperatures and daily precipitation per HRU. This approach improves the computational run time of Raven.

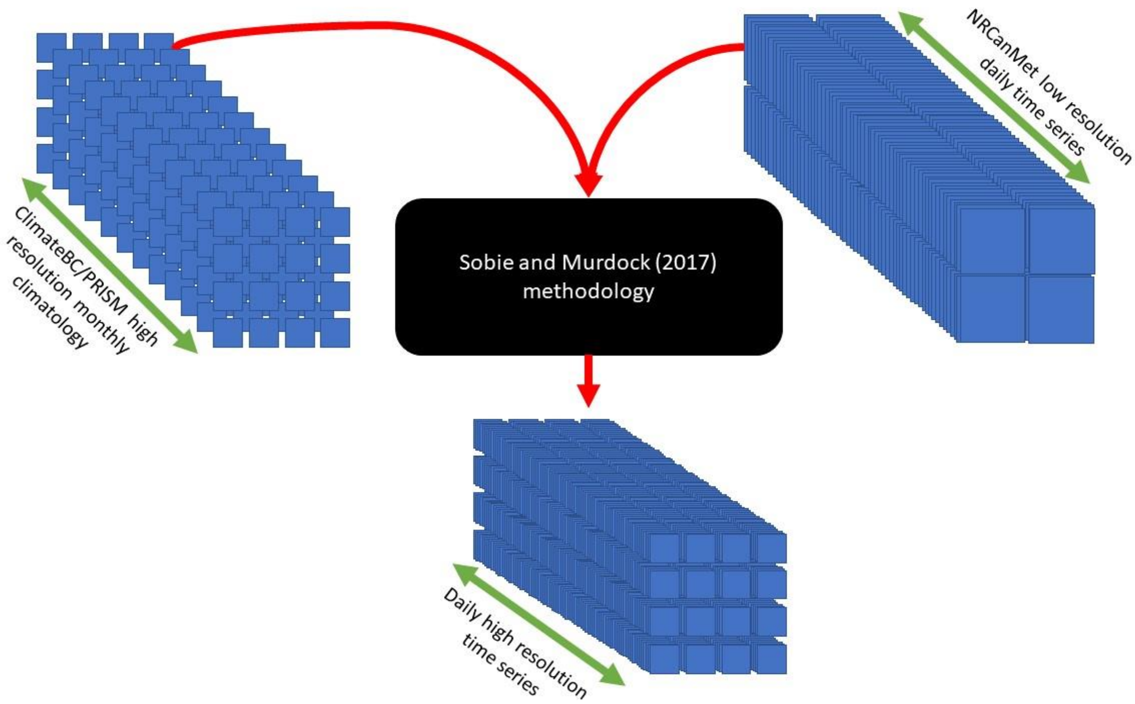


Figure 5-2
***monthlyDS* data processing workflow**

Table 5-4
Primary climate dataset metadata values

Design Parameter	Value
Low resolution daily climate dataset (tasmax, tasmin, precip)	NRCanMet (McKenney, et al., 2011) 300-arc-second (~10 km) data
High resolution monthly climate dataset	500 m ClimateBC (Wang, Hamann, Spittlehouse, & Carroll, 2016) data
Spatial data georeferencing	500m 'OK-NORD' grid (subset of full BC topographic dataset)
Spatial data extent	nx=282; ny=477
Climatological base period	1981-2010
Temporal data extent	January 1, 1950 – December 31, 2017 (nt=24837)
Dataset calendar type	Gregorian
Dataset output format	netCDF4
Dataset precision	float
Dataset volume	36 GB

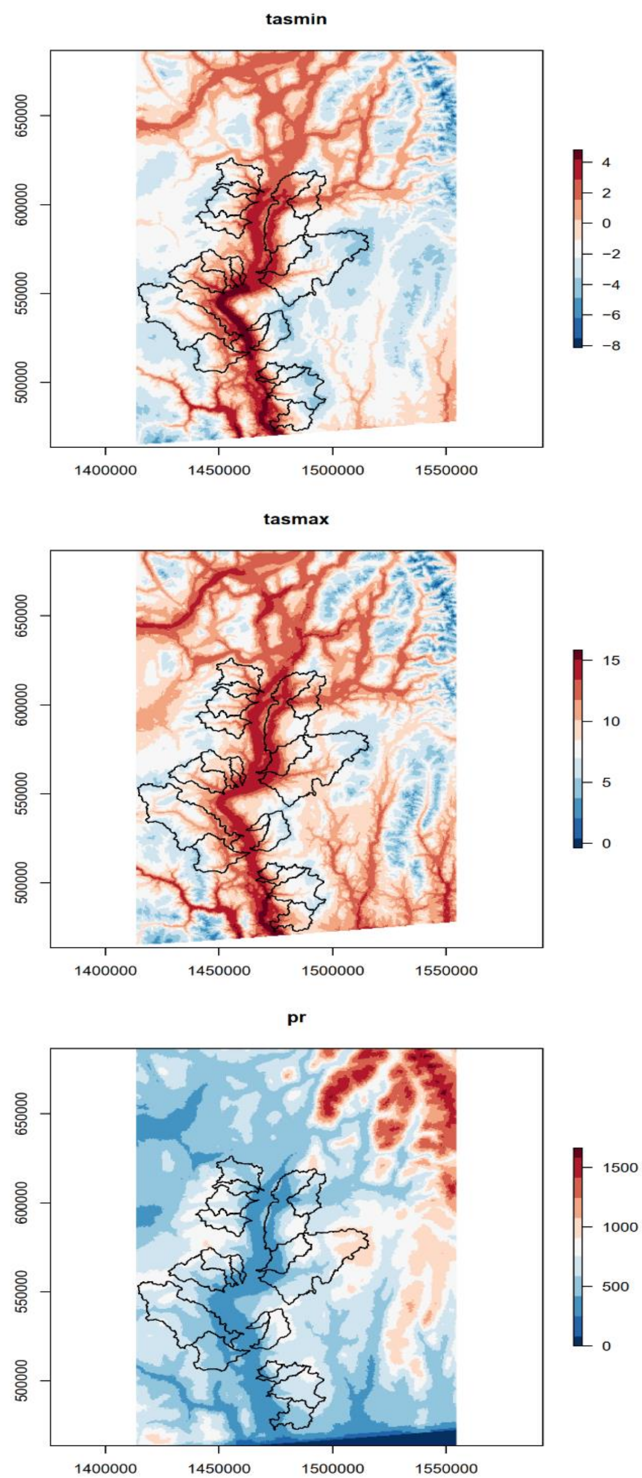


Figure 5-3
1950-2017 annual average maximum/minimum temperature and precipitation spatial distribution (black lines outline model watersheds)

5.3 Water Demand and Water Management

5.3.1 Water Demand Data – Okanagan Water Demand Model

Most water suppliers in the Okanagan Basin have water use records for varying time periods. However, the time periods, the interval (e.g., daily, monthly, annual), and the accuracy (i.e., water metered values versus estimated values) of the records vary. Thus, consistent with the naturalized and residual streamflow datasets to support EFN-setting in the Okanagan Basin (Associated 2019a), the OWDM provides the best available estimate of actual water demand by a water supplier within a watershed and/or the volumes of water withdrawn from a water source. By definition, the OWDM operates over regions where human-related activities occur and does not operate where only natural hydrologic processes are present.

The OWDM estimates current and future water demand for agricultural irrigation, outdoor irrigation (i.e., domestic, municipal, and golf courses), and indoor (i.e., domestic and industrial-commercial-institutional [ICI]) purposes. The OWDM includes an estimate of water supply transmission losses (i.e., 5% of total water demand).

The OWDM is a modified version of the Agriculture Water Demand Model (van der Gulik et al. 2010). The OWDM is based on a Geographic Information System (GIS) database (i.e., Agriculture Land Use Inventory and BC Assessment land parcels) that contains cadastre information (i.e., showing the boundaries of land ownership), land use type, crop type, irrigation system type, soil texture, and climatic data (van der Gulik et al. 2010). This information was assembled from background information, high-resolution orthophotos, BC Assessment records, and GIS, and was confirmed by ground surveys in 2006 and 2014.

For irrigation water demand estimates, the OWDM calculates daily evapotranspiration for each land parcel using a form of the Penman-Monteith equation (van der Gulik et al. 2010). It also computes the existing soil moisture and the daily precipitation. The irrigation water demand is the residual demand that cannot be met from these two sources. The climate dataset outlined in Section 4.2 is the key driver of the evaporation calculations. For indoor water demand estimates, average daily water use values are applied to land parcel types. A detailed description of how the OWDM calculates agricultural and outdoor irrigation and indoor water demands is provided by van der Gulik et al. (2010) and Summit (2010).

Within the OWDM, the estimated water demands have been linked to respective water sources and water suppliers through the delineation of 'water use areas.' These areas match spatial water supplier distribution areas (with private water users grouped as 'other' within a watershed) and provide summaries of total water demand for individual water suppliers (Summit 2010, Polar 2009).

For the 19 watersheds, the OWDM estimated water demand for all water users to support the development of residual streamflow estimates. The following assumptions were included:

- Water demand supplied by surface water was only considered, since groundwater is not specifically modelled within OHME V1.
- Total water demand for a respective water supplier water use area was reduced by the percentage recommended by Summit (2010) to remove estimated groundwater use and/or divide surface water sources within the spatial extent of the water use area. The water demand was then assigned to the sub-basin where the respective water intake was located.
- Total water demand for private water users (i.e., 'other' water use area) was summarized for individual sub-basins within a watershed that included water demand sourced by surface water only.

- For selected years, the OWDM includes a Day 0 to account for field watering by farmers at the end of season to increase soil moisture to field capacity. Thus, water demands estimated for years with Day 0 were assumed to occur evenly for the month of September to consider the end of season watering.

OHME V1 allows users to include additional water demand datasets as they become available in future.

5.3.2 Water Transfers

Within selected watersheds, intra-basin transfers move surface water between watersheds within the Okanagan Basin, and inter-basin transfers move water from out-of-basin watersheds to the Okanagan Basin.

The following water transfers (and spatial domains) are considered within the hydrologic models:

- Alocin Creek Diversion – Inter-basin diversion from Nicola River watershed to Powers Creek watershed;
- Dunswater Creek Diversion – Intra-basin diversion from Dunwaters Creek (a tributary of Shorts Creek) to Lambly Creek watershed;
- MacDonald Creek Diversion – Intra-basin diversion from MacDonald Creek (a tributary of Trepanier Creek) to Peachland Creek watershed;
- Highline Diversion – Intra-basin diversion from Robinson Creek to Naramata Creek watershed that is supplied by upland reservoir storage in Chute and Robinson Creek watersheds;
- Stirling Creek Diversion – Inter-basin diversion from Stirling Creek (a tributary of West Kettle River) to Mission Creek watershed;
- Intra-basin diversion from Kelowna (Mill) Creek to Mission Creek (i.e., flood flow diversion);
- Upper Duteau Creek (located in the Shuswap River watershed) that supplies water to Greater Vernon Water (GVW); and
- Water releases from Brenda Mines into Trepanier Creek.

The location of each water transfer was included within the respective model sub-basin. The inclusion of each water transfer was automated (if available) or calculated time-series datasets were provided. The water transfer datasets included within OHME V1 are as follows:

- Alocin Creek Diversion – Using naturalized streamflow estimates for the Alocin Creek watershed to the point-of-diversion, mean daily diversions were estimated assuming that the City of West Kelowna diverts their total licensed volume over the period of licensed use (i.e., April 1 to June 30). This assumes that the diversion follows the same pattern as the naturalized streamflows over the same period. No diversion records and/or hydraulic capacity of diversion ditch are available.
- Dunswater Creek Diversion – Using naturalized streamflow estimates for Dunswater Creek watershed to the point-of-diversion, mean daily diversions were estimated assuming that the City of West Kelowna diverts their total licensed volume between late May and June 30. This follows the same approach used by Associated (2019a). The diversion wasn't operational until 2009, so is only considered for modelling from 2009 to 2017. No diversion records and/or hydraulic capacity of diversion ditch are available.
- MacDonald Creek Diversion – Using naturalized streamflow estimates for Trepanier Creek, mean daily diversions were estimated assuming that the District of Peachland diverts their total licensed volume from April 1 to June 15. This follows the same approach used by Associated (2019a). The diversion was operational until 2009, so is only considered for modelling from 1996 to 2009. No diversion records for the standard period are available.
- Highline Diversion – No diversion records are available, so following Associated (2019a), it was assumed that the diversion was operational from July 1 to October 31 and that the water diverted was equivalent to the

volume historically withdrawn at the Regional District of Okanagan-Similkameen South Intake (that is no longer operational). Specifically, the median monthly water withdrawals at the South Intake from 1996 to 2005 for the respective months were assumed to reflect the volume of water diverted into Naramata Creek by the highline diversion.

- Stirling Creek Diversion – Using natural streamflow records for Two-Forty-One Creek (WSC No. 08NM241) and limited Stirling Creek diversion records, a relationship was established to use the creek as a surrogate to estimate diversions. This follows the same approach used by Summit (2009). Due to limited actual diversion records available, it was assumed that the diversion was operational from April 1 to October 31.
- Kelowna (Mill) to Mission Creek Diversion – As part of the Kelowna Flood Risk Assessment (Phase 1), Associated (2019c) digitized available rating curves for the Mill Creek flood diversion structure. The rating curve identifies the amount of streamflow diverted to Mission Creek (up to 14.4 m^3/s maximum capacity) based Mill Creek streamflows upstream of the flood diversion structure.
- Upper Duteau Creek watershed – GVW diverts water into their Duteau Creek water distribution system. Although Duteau Creek water is not diverted into an Okanagan basin tributary, the natural watershed area to GVW's intake was included within the Vernon Creek watershed model to allow for the option to complete future water supply investigations.
- Brenda Mines Releases – Brenda Mines operates as a closed system, and all on-site water is captured within ponds. Thus, a portion of the natural watershed area of Trepainer Creek has been removed. However, of the captured water, Brenda Mines releases into Trepanier Creek annually and generally during spring and summer. The releases have occurred from 1998 to present, and actual records are available.

All diversions are spatially linked to the respective model sub-basin (for either removal or gain of water). This allows the diversions to be adjusted if/when additional information becomes available.

5.3.3 Reservoirs

Within the Okanagan, upland storage is heavily used to manage and distribute water for a variety of purposes. In addition, the Okanagan Lake Regulation System (OLRS) consists of a series of dams and control structures that regulate the large mainstem valley bottom lakes and the Okanagan River. For the purposes of the OHMP, consideration of the OLRS was not required. However, OHME V1 could be expanded in future to include the mainstem valley bottom lakes, Okanagan River, and associated regulation. Consideration of reservoir management within each model watershed is included in OHME V1 to support residual streamflow modelling. Accordingly, 46 reservoirs and lakes are explicitly included in OHME V1 (Table 5-5). Other, smaller ponds and lakes are represented as water HRUs, but are not explicitly modelled as reservoirs.

During Phase 2 of the OWSDP (Summit 2010), stage-storage curves were digitized for many of the reservoirs listed in Table 5-5 based on historical design drawings. Accordingly, all available stage-storage curves are included in OHME V1. Where more up-to-date information was available, historical stage-storage curves were updated. Where stage-storage curves were unavailable (i.e., Allendale Lake, Bouleau Lake, and Hayman Lake) the lake was treated as a 'lake-like' reservoir within Raven, which assumes a simple prismatic lake. In all cases, reservoir outflows were constrained by a theoretical overflow weir[3] – weir dimensions were estimated from historic design drawings of reservoir control structures and spillway designs. Due to the uncertainty and simplicity of this approach, the width of the weir was included in model calibration.

[3] Greyback Lake is the only reservoir for which hydraulic equations relating to the outflow structures (i.e., two outflow gates) were available. Accordingly, releases by the City of Penticton from these two control structures were included under residual conditions.

Under natural conditions (i.e., estimation of naturalized streamflows), all reservoirs were operated to ‘fill-and-spill’ and acted as flow-through systems with the absence of reservoir management. This approach was deemed most representative of conditions without current reservoir management.

Under residual streamflow conditions, reservoirs are operated to satisfy a portion of downstream total water demand (Section 6.2.2) due to the absence of reservoir operation records and the general uncertainty of reservoir management in the Okanagan. Under these conditions, a proportion of downstream water demand can be released from reservoirs as a ‘minimum reservoir release.’ This approach can easily be updated within OHME to include consideration of downstream EFN thresholds once they are established for all model watersheds.

Table 5-5
Reservoirs included in the OHMP

Watershed[1]	Reservoir
Coldstream Creek	Kind Edward Lake
Equesis Creek	Pinaus Lake
McDougall Creek	Hayman Lake
Mill Creek	Postill Lake
	South Lake
	James Lake
	Moore Lake
Mission Creek	McCulloch Lake
	Fish Hawk Lake
	Graystoke Lake
	Loch Long Lake
	Long Meadow Lake
	Browne Lake
	Fish Lake
	Ideal Lake
	Mission Lake
Penticton Creek	Greyback Lake
Powers Creek	Tadpole Lake
	Paynter Lake
	West Lake
	Dobbin Lake
	Islaht Lake
	Jackpine Lake
	Lambly Lake

Watershed	Reservoir
Shingle Creek	Brent Lake
	Farleigh Lake
Shuttleworth Creek	Allendale Lake
	Clark Meadows Lake
Trout Creek	Headwater 1 Lake
	Headwater 2 Lake
	Headwater 3 Lake
	Headwater 4 Lake
	Crescent Lake
	Whitehead Lake
	Thirsk Lake
	Tsuh Lake
	Munro Lake
	Darke Lake
	Isintok Lake
Vernon Creek	Crooked Lake
	Swalwell Lake
	Ellison Lake
	Oyama Lake
	Kalamalka / Wood Lake
	Goose Lake
	Swan Lake
Whiteman Creek	Bouleau Lake

Notes:
1. No reservoirs are included within the Inkaneep, McLean, Naramata, Naswhito, Shorts, Trepanier Creek, or Vaseux Creek watersheds. Open water areas within these watersheds are identified by WATER HRUs and no soil processes are included for these HRUs.

5.4 Observation Data

To facilitate model calibration and assess model success, various observation datasets are included in OHME V1. Several goodness-of-fit statistics are automatically generated by Raven to assess the model performance compared to observed data. Within the Okanagan Basin, WSC and privately operated hydrometric stations, previously developed naturalized streamflow estimates (Associated 2019a) and provincial snow survey locations provide some of the best observation datasets to support model calibration and diagnostics.

Observation datasets included in OHME V1 are described below.

5.4.1 Streamflow Datasets – Water Survey of Canada

WSC operates over 2,800 hydrometric gauges across the province, which provide historical and real-time hydrometric data. These data represent some of the best long-term records available for model calibration and validation in the Okanagan Basin.

During the process of model sub-basin delineation, key WSC hydrometric stations were identified and sub-basin delineations were completed to ensure that sub-basin outlets (i.e., POIs) aligned with WSC hydrometric stations. Within OHME V1, all available historic mean daily streamflow records are dynamically retrieved from the WSC HYDAT (version created on January 17, 2019) for each hydrometric station within a given model watershed (or multiple watersheds). This approach allows future updates of the WSC HYDAT database to be easily ingested into OHME to facilitate the inclusion of update hydrometric data to support revised model calibrations. Table 5-6 summarizes all WSC hydrometric stations included in OHME V1.

Although many of the WSC hydrometric stations do not have streamflow records available for the period of interest (i.e., 1996-2017), they were included in sub-basin delineations to allow historic model runs to be completed in future, if required. For each of the WSC hydrometric stations, all available streamflow records within the specified model start and end dates are dynamically retrieved from the WSC HYDAT database allowing users to easily adjust the model period of interest.

Following each model simulation, goodness-of-fit statistics are generated by Raven between all included observed streamflow datasets and modelled streamflow at the corresponding sub-basin outlet. This process is completed regardless of whether natural or residual streamflow estimates are generated; it is at the discretion of the user to consider or disregard the resultant diagnostics accordingly.

Currently, water level records (i.e., lake levels) are not dynamically retrieved from the WSC HYDAT database within OHME V1 due to discrepancies between WSC assumed datum elevations and stage-storage curve elevations (i.e., geodetically referenced) included in OHME V1. However, select water level records can be easily manually included by way of a ‘custom timeseries’ option embedded in OHME. Accordingly, Kalamalka Lake water levels recorded at WSC 08NM143 (Table 5-6) are manually included to provide goodness-of-fit statistics against modelled water levels for Kalamalka Lake and Wood Lake under residual conditions.

Table 5-6
WSC hydrometric stations included in OHME V1

Watershed[1]	ID	WSC Hydrometric Station	Period of Record	Regulated
Coldstream Creek	08NM142	COLDSTREAM CREEK ABOVE MUNICIPAL INTAKE	1967 to 2014	No
	08NM124	COLDSTREAM CREEK NEAR LAVINGTON	1959 to 1979	Yes
	08NM154	COLDSTREAM CREEK AT THE MOUTH	1969 to 1970	Yes
	08NM179	COLDSTREAM CREEK ABOVE KALAVISTA DIVERSION	1970 to 1982	Yes
Equesis Creek	08NM176	EWER CREEK NEAR THE MOUTH	1971 to 1986	No
	08NM024	EQUESIS CREEK NEAR VERNON	1921 to 1926	Yes
Inkaneep Creek	08NM082	INKANEEP CREEK NEAR OLIVER (UPPER STATION)	1941 to 1950	No
	08NM012	INKANEEP CREEK NEAR OLIVER (LOWER STATION)	1919 to 1950	No
	08NM200	INKANEEP CREEK NEAR THE MOUTH	1973 to 2015	Yes
McDougall Creek	08NM014	MCDOUGALL CREEK NEAR WESTBANK	1920 to 1926	Yes
McLean Creek	08NM005	MCLEAN CREEK NEAR OKANAGAN FALLS	1921 to 1926	No
Mill Creek	08NM036	SCOTTY CREEK NEAR RUTLAND	1919 to 1964	No
	08NM234	MOORE LAKE RESERVOIR AT THE DAM	1973 to 1986	Yes
	08NM145	BULMAN CREEK AT THE MOUTH	1968 to 2004	Yes
	08NM026	KELOWNA CREEK NEAR RUTLAND (UPPER STATION)	1920 to 1922	Yes
	08NM117	KELOWNA CREEK AT RUTLAND STATION	1950 to 1975	Yes
	08NM053	KELOWNA CREEK NEAR KELOWNA (LOWER STATION)	1922 to 1996	Yes
Mission Creek	08NM011	HYDRAULIC CREEK AT OUTLET OF MCCULLOCH RESERVOIR	1919 to 1986	Yes
	08NM230	GRAYSTOKE LAKE AT THE OUTLET	1977 to 1998	Yes
	08NM217	LONG MEADOW LAKE RESERVOIR ABOVE THE DAM	1973 to 1977	Yes
	08NM216	BROWNE LAKE RESERVOIR ABOVE THE DAM	1973 to 1977	Yes
	08NM215	FISH LAKE AT THE OUTLET	1973 to 1977	Yes
	08NM210	POOLEY CREEK ABOVE POOLEY DITCH	1973 to 1979	No
	08NM231	IDEAL LAKE NEAR THE OUTLET	1963 to 1980	Yes
	08NM232	BELGO CREEK BELOW HILDA CREEK	1976 to 2016	Yes
	08NM225	BELGO CREEK NEAR THE MOUTH	1976 to 1982	Yes
	08NM137	DAVES CREEK NEAR RUTLAND	1965 to 1986	No
	08NM057	MISSION CREEK RUTLAND DIVERSION	1922 to 1930	Yes
	08NM116	MISSION CREEK NEAR EAST KELOWNA	1949 to 2015	Yes
Naswhito Creek	08NM047	NASWHITO CREEK NEAR EWING'S LANDING	1921 to 1921	No
Penticton Creek	08NM069	REED CREEK NEAR PENTICTON	1930 to 1930	Yes
	08NM240	TWO FORTY CREEK NEAR PENTICTON	1983 to 2014	No
	08NM241	TWO FORTY-ONE CREEK NEAR PENTICTON	1983 to 2014	No
	08NM169	GREYBACK LAKE AT THE OUTLET	1970 to 1987	Yes
	08NM168	PENTICTON CREEK ABOVE DENNIS CREEK	1970 to 1999	Yes
	08NM242	DENNIS CREEK NEAR 1780 METRE CONTOUR	1985 to 2015	No
	08NM170	PENTICTON CREEK BELOW HARRIS CREEK	1970 to 1981	Yes
Powers Creek	08NM136	LAMBLY LAKE DIVERSION TO POWERS CREEK	1965 to 1972	Yes
	08NM033	POWERS CREEK ABOVE WESTBANK DIVERSION	1920 to 1974	No
	08NM034	POWERS CREEK WESTBANK DIVERSION	1920 to 1931	Yes
	08NM157	POWERS CREEK AT THE MOUTH	1969 to 1982	Yes
Shingle Creek	08NM070	RIDDLE CREEK NEAR WEST SUMMERLAND	1930 to 1931	No
	08NM038	SHINGLE CREEK ABOVE KALEDEN DIVERSION	1920 to 1977	No
	08NM037	SHATFORD CREEK NEAR PENTICTON	1919 to 2015	Yes
	08NM150	SHINGLE CREEK AT THE MOUTH	1969 to 1981	Yes

[1] No WSC hydrometric stations are included in the Naramata or Shorts Creek watersheds.

Watershed[1]	ID	WSC Hydrometric Station	Period of Record	Regulated
Shuttleworth Creek	08NM006	SHUTTLEWORTH CREEK NEAR OKANAGAN FALLS	1921 to 1964	Yes
	08NM149	SHUTTLEWORTH CREEK AT THE MOUTH	1969 to 2010	Yes
Trepanier Creek	08NM041	TREPANIER CREEK NEAR PEACHLAND	1919 to 2013	Yes
	08NM013	JACK CREEK AT THE MOUTH	1919 to 1919	Yes
	08NM155	TREPANIER CREEK AT THE MOUTH	1969 to 1981	Yes
Trout Creek	08NM134	CAMP CREEK AT MOUTH NEAR THIRSK	1965 to 2015	No
	08NM055	TROUT CREEK SUMMERLAND DIVERSION	1922 to 1931	No
	08NM238	THIRSK LAKE NEAR THE OUTLET	1979 to 1987	Yes
	08NM237	TROUT CREEK BELOW THIRSK LAKE	1979 to 1986	Yes
	08NM023	DARKE CREEK NORTHWEST FORK	1921 to 1922	No
	08NM025	DARKE CREEK AT MEADOW VALLEY	1921 to 1922	Yes
	08NM133	BULL CREEK NEAR CRUMP	1965 to 1986	No
	08NM054	TROUT CREEK NEAR FAULDER	1922 to 1954	Yes
	08NM158	TROUT CREEK AT THE MOUTH	1969 to 1982	Yes
Vaseux Creek	08NM171	VASEUX CREEK ABOVE SOLCO CREEK	1970 to 2015	No
	08NM015	VASEUX CREEK ABOVE DUTTON CREEK	1919 to 1982	No
	08NM246	VASEUX CREEK NEAR THE MOUTH	2006 to 2010	No
Vernon Creek	08NM020	B.X. CREEK ABOVE VERNON INTAKE	1921 to 1999	Yes
	08NM163	CROOKED LAKE AT THE OUTLET	1970 to 1981	Yes
	08NM022	VERNON CREEK AT OUTLET OF SWALWELL LAKE	1921 to 1996	Yes
	08NM236	VERNON CREEK DIVERSION TO W.O.C.I.D.	Unknown	Yes
	08NM043	VERNON CREEK NEAR OKANAGAN CENTRE	1919 to 1963	Yes
	08NM146	CLARK CREEK NEAR WINFIELD	1968 to 2017	No
	08NM162	VERNON CREEK AT INLET TO ELLISON LAKE	1970 to 1974	Yes
	08NM182	VERNON CREEK AT OUTLET OF ELLISON LAKE	1971 to 1974	Yes
	08NM008	VERNON CREEK ABOVE DIVERSIONS	1919 to 1919	Yes
	08NM181	WINFIELD CREEK AT INLET TO WOOD LAKE	1971 to 1973	Yes
	08NM235	RIBBLEWORTH CREEK NEAR OYAMA	1973 to 1979	No
	08NM183	KALAMALKA LAKE AT OUTLET OF OYAMA CANAL	1971 to 1979	Yes
	08NM224	OYAMA LAKE AT THE OUTLET	1961 to 1986	Yes
	08NM048	OYAMA CREEK ABOVE WOOD LAKE IRRIGATION INTAKE	1921 to 1987	Yes
	08NM065	VERNON CREEK AT OUTLET OF KALAMALKA LAKE	1927 to 2015	Yes
	08NM021	VERNON CREEK AT VERNON	1921 to 1960	Yes
	08NM125	B.X. CREEK ABOVE SWAN LAKE CONTROL DAM	1959 to 1979	Yes
	08NM123	B.X. CREEK BELOW SWAN LAKE CONTROL DAM	1959 to 1978	Yes
	08NM160	VERNON CREEK NEAR THE MOUTH	1969 to 1999	Yes
Whiteman Creek	08NM180	WHITEMAN CREEK AT THE MOUTH	1970 to 1972	Yes
	08NM046	WHITEMAN CREEK NEAR VERNON	1920 to 1970	Yes
	08NM174	WHITEMAN CREEK ABOVE BOULEAU CREEK	1971 to 2014	No

5.4.2 Snowpack Datasets

Understanding that snowpack development and melt drives spring freshet flows, it is important to ensure that the annual snow balance is well represented within Raven. Manual and automated snow survey sites (i.e., snow courses and snow pillows) are maintained and operated by the BC Ministry of Environment and Climate Change, BC Hydro, Roi Tinto Alcan, and Metro Vancouver. Snow Water Equivalent (SWE) (i.e., the amount of water contained within the snowpack) is measured at each site. These data can be compared to SWE estimates generated by Raven to assess the model's representation of snow.

The location of provincial snow survey sites was assigned to corresponding HRUs to allow comparison of modelled and observed snowpack development. When interpreting model diagnostics, model users must understand that Raven provides estimates of HRU-averaged SWE while observation datasets represent SWE at a single location. Within OHME V1, all available historical SWE measurements are dynamically retrieved for each snow survey site within the watershed (or multiple watersheds) of interest. This approach is consistent with the dynamic inclusion of hydrometric records from the WSC and facilitates easy updates as more SWE data become available. Table 5-7 summarizes all snow survey sites included in OHME V1. Prior to mapping snow survey sites to HRUs, their locations were reviewed and those sites just outside of the Okanagan Basin, or those within unmodelled watersheds within the Okanagan Basin, were relocated to representative HRUs within the same elevation band and land use type within model watersheds. This ensured that these datasets were included in Raven.

Table 5-7
Snow survey sites included in OHME V1

Watershed[1]	Station ID	Site	Station Type	Period of Record
Coldstream Creek	1F01A	Aberdeen Lake	Snow Course	1939 to 2019
Equesis Creek	2F06	Bouleau Creek	Snow Course	1947 to 1977
Mill Creek	2F25	Postill Lake (Upper)	Snow Course	2010 to 2019
	2F07	Postill Lake	Snow Course	1950 to 2019
Mission Creek	2F05	Mission Creek	Snow Course	1939 to 2005
	2F04	Graystoke Lake	Snow Course	1935, 1971 to 2019
	2F22	Pearson Creek	Snow Course	1974 to 1993
	2F03	McCulloch	Snow Course	1935 to 2019
	2F05P	Mission Creek	Snow Pillow	1969 to 2018
Penticton Creek	2F08	Greyback Reservoir	Snow Course	1953 to 2019
	2F08P	Greyback Reservoir	Snow Pillow	2016 to 2018
Powers Creek	2F24	Islaht Lake	Snow Course	1982 to 2019
Shorts Creek	2F15	Esperon Cr (Lower)	Snow Course	1966 to 1992
Trepanier Creek	2F23	MacDonald Lake	Snow Course	1976 to 2019
	2F18	Brenda Mine	Snow Course	1969 to 2014
	2F18P	Brenda Mine	Snow Pillow	1992 to 2018
Trout Creek	2F11	Isintok Lake	Snow Course	1965 to 2019
	2F01	Trout Creek	Snow Course	1935 to 2014
	2F01A	Trout Creek (West)	Snow Course	2010 to 2019
	2F02	Summerland Reservoir	Snow Course	1935 to 2019
	2F01AP	Trout Creek West	Snow Pillow	1994 to 2017
Vaseux Creek	2F20	Vaseux Creek	Snow Course	1971 to 2019
Vernon Creek	2F16	Carrs Landing (Lower)	Snow Course	1966 to 1973
	2F17	Carrs Landing (Upper)	Snow Course	1966 to 1979
	2F19	Oyama Lake	Snow Course	1969 to 2019
	2F10P	Silver Star Mountain	Snow Pillow	2015 to 2018
Whiteman Creek	2F21	Bouleau Lake	Snow Course	1971 to 2019

Notes:
1. No snow survey sites are in the Inkaneep, McDougall, McLean, Naramata, Naswhito, Shingle, or Shuttleworth Creek watersheds.

All available snow survey sites were included, regardless of the available period of record. Similarly, as with the WSC hydrometric stations, this allows historic model simulations to be completed in future, and diagnostics for snowpack development to be generated, if required. For each snow survey site, all available records within the specified model start and end dates are dynamically retrieved from publicly available archived snow survey records. This also allows future data releases to be included to provide more recent available snow records.

Following each model simulation, goodness-of-fit statistics are generated by Raven between all included observed snow datasets and modelled snowpack at the corresponding HRU.

5.4.3 Third-Party Hydrometric Records

In addition to WSC, several other organizations collect hydrometric records for various purposes (e.g., reservoir management and EFN setting), which can be used to assess model performance and inform model validation. OHME can ingest these third-party datasets and allow other datasets to be added efficiently in future as more records become available. Currently, OHME V1 can ingest continuous or discontinuous datasets of streamflow, diversion volumes, reservoir levels, and reservoir outflows. In addition, digitized rating curves to control diversion volumes between model sub-basins (e.g., Mill to Mission Creek flood diversion) can also be included. The following third-party hydrometric records are included within OHME V1:

- Okanagan Nation Alliance (ONA) mean daily streamflow datasets – To support the development of naturalized streamflow datasets for EFN-setting using the Okanagan Tenant method, the ONA installed hydrometric stations in select model watersheds. Except for Vernon Creek, all hydrometric stations are located on the alluvial fan to provide field data to inform the consideration of streamflow gains/losses across the alluvial fan. In addition, the ONA operates other hydrometric stations in the Shorts and Vernon Creek watersheds for other purposes. Accordingly, available ONA hydrometric records are included for the following watersheds:
    - Shorts Creek – ONA hydrometric station 08NM151 (October 2014 – December 2018)
    - McDougall Creek – ONA hydrometric station 08NM590 (March 2017 – December 2018)
    - Coldstream Creek – ONA hydrometric station 08NM589 (August 2016 – December 2018)
    - Equesis Creek[4] – ONA hydrometric station 08NM161-HDS (September 2016 – March 2019)
    - Vernon Creek[5] – ONA hydrometric station 08NM588 (September 2016 – December 2017) and 08NM022-HDS (June 2012 – October 2018)
    - Whiteman Creek – ONA hydrometric station 08NM587 (September 2016 – August 2017)
    - Naswhito Creek – ONA hydrometric station 08NM586 (September 2016 – August 2017)
- Mean daily streamflow datasets available from Phil Epp – A hydrometric station on Powers Creek at Gellatly Road (i.e., hydrometric station 08NM570) operated from 2004 to 2009. All available records for 08NM570 are included within OHME V1 for the period July 2004 – October 2009.
- Mean daily streamflow datasets available from Phil Epp – A hydrometric station on Trout Creek at Canyon Mouth (i.e., hydrometric station 08NM042-HDS) operated seasonally from 2004 to 2009. All available records for 08NM042-HDS are included within OHME V1 for the period July 2004 – November 2009.
- Continuous and discontinuous reservoir levels and reservoir releases from the following water suppliers:
    - Black Mountain Irrigation District (BMID) - Continuous estimated reservoir levels and reservoir outflow datasets are available for Fish Hawk, Graystoke, and Ideal Lakes. These datasets provide interpolated water levels and reservoir releases (where available) based on historical operator notes. The frequency and resolution of available manual measurements differ between each location; however, all available records were used to develop a daily timeseries of reservoir levels for the period 1994-2010 and a daily timeseries of reservoir releases for 1996-2010. Note that reservoir level datasets cannot be used for calibration purposes at this time since the assumed elevation datum used to measure water levels is unknown and cannot be referenced to the corresponding stage-storage datum used within Raven.

[4] Two additional ONA hydrometric stations (08NM585 and 08NM707) were located nearby to 08NM161-HDS. While their datasets are available within OHME V1, only data from 08NM161-HDS are ingested into Raven as this station provides the most complete record and all three are attributed to the same model sub-basin.

[5] ONA hydrometric station 08NM588 is located close to the mouth of Vernon Creek. ONA hydrometric station 08NM022-HDS is located just downstream of Swalwell Lake.

  - South East Kelowna Irrigation District (SEKID) – Continuous reservoir releases from McCulloch Reservoir were summarized by Associated (2019a) for the period 1996-2010 and are included in OHME V1.
  - City of West Kelowna – Irregular records of reservoir releases from Lambly Lake are available for the period 2009–2019 and included in OHME V1.
  - City of Penticton – Irregular records of reservoir levels for Greyback Lake are available for the period 2015 – 2019 and included in OHME V1.
  - Greater Vernon Water – Irregular records of reservoir levels for King Edward Lake are available for the period 2015 – 2019 and included in OHME V1.
- Glenmore Ellison Irrigation District (GEID) – Continuous mean daily streamflows recorded at the location of their water intake are available for the period 2010–2017 and included in OHME V1.
- City of Penticton – Continuous mean daily streamflows recorded at Nanaimo Avenue in Penticton are available for the period 2004–2018 and included in OHME V1.

Although not all datasets have available records for the period of interest (i.e., 1996-2017), they are included in OHME V1 for completeness and to allow future model use and development. Also, since all above third-party hydrometric records represent residual streamflow conditions, they are included for comparison against residual streamflow estimates only, not naturalized streamflow estimates.

5.5 Okanagan Environmental Flow Needs Streamflow Datasets

Naturalized and residual streamflow datasets were developed to support the setting of EFNs in Okanagan Basin watersheds (Associated 2019a). Specifically mean weekly streamflows were developed for the period 1996-2010 at two watershed points-of-interest: 1) streamflow points-of-interest (i.e., apex of alluvial fan), and 2) EFN point-of-interest (i.e., mouth or location of an EFN transect). Streamflows were developed for all model watersheds (Section 4.2), except Vernon Creek watershed. Associated (2019a) applied a temporal period adjustment factor to the 1996-2010 period to account for the summer runoff representing a drier period relative to recorded long-term conditions (1971-2014). However, the temporal period adjustment factor can be removed to solely reflect the 1996-2010 period.

Due to limited recent streamflow records available for each model watershed (Table 4-6), sub-basin delineations included the respective Associated (2019a) streamflow points-of-interest. This was completed to support model calibration and validation (Section 6). In addition, due to the differences in temporal resolution between EFN-setting and modelling needs (i.e., mean weekly versus mean daily streamflows), OHME V1 disaggregates weekly EFN streamflows to mean daily values. Streamflows are disaggregated assuming that the weekly to daily ratios for the respective surrogate WSC stations (used to estimate the EFN streamflow datasets) were representative of the watershed. This produced a time series of synthetic (estimated) streamflows for each watershed to be used for watershed-specific calibration.

5.6 Model Parameters

Due to the flexibility of the Raven framework, there are numerous possible model configurations that include many parameters. Within the HBV-EC model configuration, as well as within all other model configurations available within Raven, there are several required and optional model parameters (Craig and Raven Development Team 2019). Select required model parameters (e.g., soil porosity, soil hydroscopic minimum saturation, soil field capacity, wet and dry soil albedo, and sky-view extinction factor), can be auto calculated by Raven (or user-specified) while others must be user-specified. The process of automated calibration aims to identify the 'optimal' value for all user-specified parameters in combination with one another. Table 5-8 provides a summary of the minimum and maximum parameter values included within the automated calibration for each model watershed. Values for each parameter vary between model watersheds. Since many parameters represent conceptual processes and water stores, a literature review was completed to identify reasonable upper and lower calibration bounds. Both the calibration parameter bounds and, by consequence, the final calibrated parameter values are likely to be refined in future calibration efforts. The soil porosity, soil field capacity, soil hydroscopic minimum saturation, and wet and dry soil albedo are auto-calculated by Raven for each soil class based on physical composition of sand, silt, and clay percentages (Section 5.1.3).

Table 5-8
Model parameter calibration bounds

Parameter Type	Parameter	Corresponding Land Use / Vegetation Class	Definition	Lower Calibration Bound	Upper Calibration Bound	Source
Global	SNOW_SWI	-	Maximum liquid content of snow, as percentage of snow water equivalent	0.04	0.07	Craig and Raven Development Team 2019
	RAINSNOW_TEMP	-	The midpoint of RAINSNOW_DELTA	-1	1	Craig and Raven Development Team 2019
	RAINSNOW_DELTA	-	The range of temperatures over which there may be a rain/snow mix when partitioning total precipitation into rain and snow components	0	4	Craig and Raven Development Team 2019
	RESERVOIR_DEMAND_MULT	-	A global correction factor to adjust the percentage of downstream water demand supported by upland reservoirs (included under residual conditions only).	0.5	1.5	Craig and Raven Development Team 2019
Land Use	MELT_FACTOR	-	Snow water equivalent generated per day per degree	1	5	Craig and Raven Development Team 2019; Parajka et al. 2007
	REFREEZE_FACTOR	-	Snow water equivalent frozen per day	1	5	Craig and Raven Development Team 2019
Soil	MAX_CAP_RISE_RATE	A Soil Horizon	HBV maximum capillary rise rate	0	40	Lu and Likos 2007; (Craig, J. personal communication, 2019)
	MAX_PERC_RATE	B Soil Horizon	VIC/ARNO/GAWSER percolation rate	0.01	40	Craig and Raven Development Team 2019; (Craig, J. personal communication, 2019)
	HBV_BETA	A Soil Horizon	HBV soil coefficient	0.1	10	Empirical, as per Bergstrom 1995
	BASEFLOW_N	B Soil Horizon	VIC/ARNO baseflow exponent	1	10	Craig and Raven Development Team 2019
	BASEFLOW_COEFF	B, C Soil Horizons	Linear baseflow storage/routing coefficient	0	10	Raven template parameters file (Craig and Raven Development Team 2019)
	Soil Thickness	A Soil Horizon	Thickness of active soil layer	0	2	Informed by available soils information (Section 5.1.3)
Vegetation	RAIN_ICEPT_FACT	Multiple[1]	Maximum percentage of rain intercepted	0	0.4	Butler 1985; Carlyle-Moses 2011; Ciezkowski et al. 2018; Corbett and Croute 1968; Spittlehouse 1998
	SNOW_ICEPT_FACT	Multiple[1]	Maximum percentage of snow intercepted	0	0.4	McNey 1985; Huerta et al. 2019; Professional estimation
	MAX_CAPACITY	Multiple[1]	Maximum canopy storage of intercepted rainfall	0	10	Couturier and Ripley 1973; Yu et al. 2012; Zou 2015; Garcia-Estringana et al. 2010; Ciezkowski et al. 2018; Vrugt et al. 2003; Llorens and Gallart 2000; Kiem et al. 2006; Fathizadeh 2013; Xiao and McPherson 2016
	MAX_SNOW_CAPACITY	Multiple[1]	Maximum canopy storage of snow	0	20	McNey 1985; Huerta et al. 2019; Professional estimation
	ALBEDO	Multiple[1]	Proportion of incident radiation reflected by the surface	-	-	Kondratyev 1969; Akbari et al. 2009

Notes:
1. Select parameters vary for all vegetation and /or land use classes.
2. Descriptions of parameters including parameter units, are provided in Craig and Raven Development Team (2019).

6 MODEL CALIBRATION AND VALIDATION APPROACH

6.1 Overview of Model Calibration and Validation

The process of developing a reliable hydrologic model requires some form of model calibration and validation. Model calibration is the process of adjusting a parameter, or set of parameters, to provide model results that match an observation dataset(s). Model validation is the process of comparing model results to a different, independent, observation dataset to assess the ability of the model to provide reasonable results. For example, within hydrologic modelling, observed streamflow records are often used to facilitate model calibration and validation by calibrating a model to one time period, or one location, and then validating the model against a different time period, or different location.

Model calibration approaches range from manual trial and error to fully automated calibration that uses sophisticated mathematical, statistical, and computational techniques to automatically find combinations of parameters that reduce model error relative to observations. With hydrologic models, the large number of equations and parameters required to represent physical processes makes it difficult to manually calibrate models due to the equifinality associated with parameter sets. Equifinality refers to the principle that the same results can be achieved by many combinations of parameters or parameter sets. Thus, automated calibration is preferable to reach an adequate calibration of hydrologic models. However, advantages and disadvantages of automated calibration should be considered in hydrologic models that include a large set of parameters (Refsgaard and Storm 1990):

- Advantages:
  - Automated calibration is faster and more efficient than manual trial and error calibration.
  - Automated calibration provides a less subjective outcome than manual trial and error calibration.
- Disadvantages:
  - When more than a few parameters are present, the calibration process likely identifies a local optimum instead of a global one.
  - Most automatic calibration search algorithms assume that all model parameters are mutually independent; however, this is usually not the case with hydrologic models.
  - Since automatic routines lack knowledge of physical processes, automatic calibration can incorrectly compensate for errors in one physical process within another, resulting in parameters being overly constrained or outside of the physical range.

Within OHME, manual trial and error or fully automated calibration can be completed for individual watersheds or any combination of model watersheds. During calibration of OHME V1, a combination of trial and error and multiple automated calibration processes was used to identify an optimal parameter set for each model watershed. Initial parameter values and upper and lower parameter values were identified based on existing knowledge, literature reviews, and advice from the Raven Development Team. OSTRICH was then used to perform several automated calibrations (Section 6.2) to develop optimized parameter sets for each watershed. The resultant parameter set may not be the only combination of parameter values that would yield the same streamflow estimates, and a subsequent calibration could yield a different optimized parameter set and/or better results. The process of calibration is iterative, and results can generally always be improved upon. Figure 6-1 provides a schematic of the automated calibration process included in OHME V1.

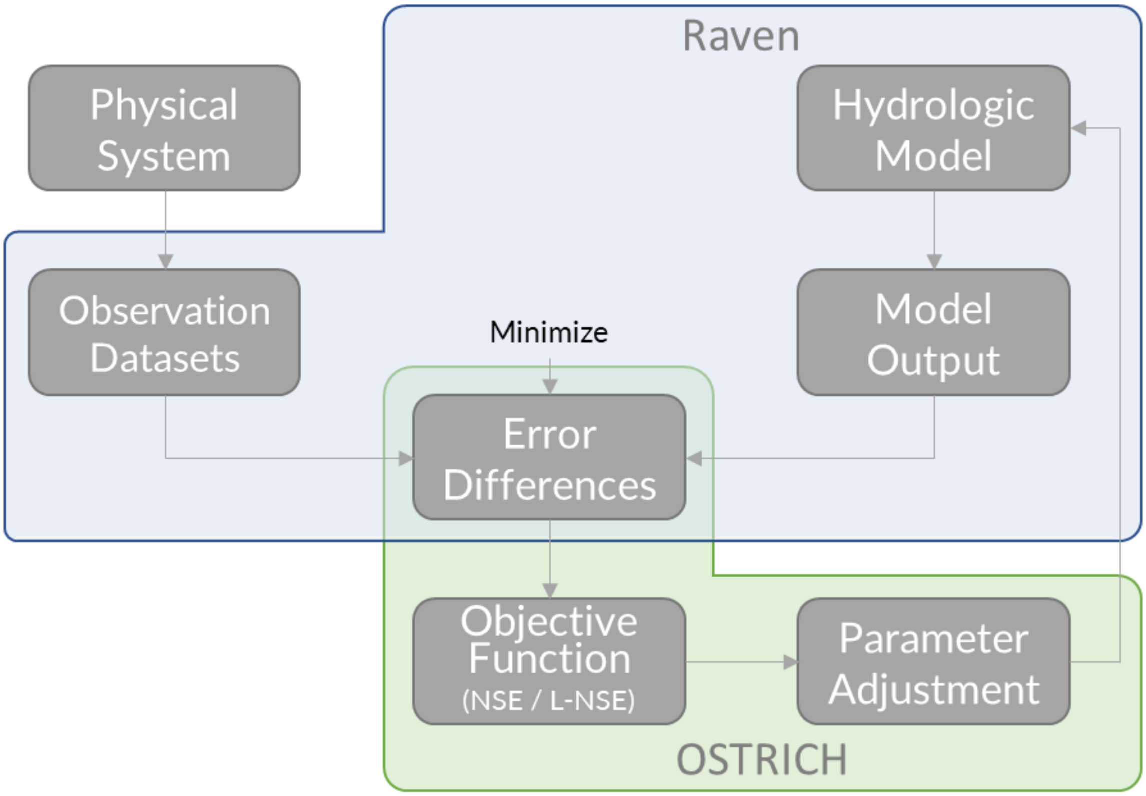


Figure 6-1
Schematic representation of automated calibration process used within OHME V1 (adapted from Refsgaard and Storm [1990])

6.2 Calibration Approach

OHME V1 calibrations for all watersheds are intrinsically coupled with and specific to the HBV-EC model configuration across all model watersheds. Future OHME development, conceptual model changes, emergence of new information and data, and evolving user applications and needs will necessitate new calibrations, using the OHME calibration framework and toolkit.

The flexibility of the calibration approach within OHME makes optimal use of available observation datasets and allows model users to develop unique 'global' (i.e., basin-wide) or watershed specific parameters sets. In addition, all watersheds can be modelled and calibrated in any combination with one another to generate unique parameter sets to satisfy diverse user needs. Based on the limited existing observation-based datasets available to support model calibration, coupled with the need to generate streamflow estimates for both naturalized and residual streamflow conditions, the Model Development Team completed watershed-specific calibration to calibrate physical processes within individual watersheds under natural conditions. Water demand information and reservoir management was then 'superimposed' on natural conditions to develop residual streamflow estimates.

When evaluating hydrologic model performance, the Nash-Sutcliffe model efficiency coefficient (NSE) model diagnostic (as well as other quantitative statistics) is often used (Moriasi et al. 2007). NSE provides a widely used assessment of the match between observed and simulated hydrologic data (intuitively, how close a scatterplot of simulated and observed data for a common location and time period clusters around the 1:1 line). Exceedance of NSE threshold values (e.g., 0.6) is often used as a measure of good model performance. Thus, the optimization of the NSE model diagnostic provides a common calibration target. However, calibrating hydrologic models to optimize the NSE is known to favour high flow periods since the NSE emphasises the fit to peak flows (Lane et al. 2019). Conversely, calibrating hydrologic models to optimize the Nash-Sutcliffe with logarithmic streamflow values (L-NSE) results in a more favourable representation of low flows by flattening streamflow peaks to increase the relative influence of low flow values (Krause et al. 2005). This highlights the need for case-specific calibrations depending on the user need of a given model. Within OHME V1, two calibrations were completed with different calibration targets:

- Calibration 1: NSE – One calibration was completed to optimize only the NSE value between daily disaggregated naturalized streamflow estimates at the apex of the alluvial fan (Associated 2019a) and modelled streamflows at the apex of the fan. This calibration approach focuses on improving representation of peak flows.
- Calibration 2: NSE / L-NSE – One calibration was completed to equally optimize the NSE and L-NSE (i.e., equally weighted sum of NSE and L-NSE) values between daily disaggregated naturalized streamflow estimates at the apex of the alluvial fan (Associated 2019a) and modelled streamflows at the apex of the fan. This calibration approach focuses equally on improving peak and low flows.

Within both calibrations, a ±50% percent bias constraint was included in the calibration process to guide automated calibrations to within the maximum uncertainty associated with some of the naturalized streamflow estimates (Associated 2019a). In addition, although naturalized streamflow estimates at the apex of the alluvial fan (2019a) provided the calibration target, additional observation datasets (e.g., WSC and third-party hydrometric records, and snow survey datasets) informed calibration efforts to ensure results were being achieved for the correct reasons (i.e., snowpack development and modelled streamflows at additional observation locations appeared reasonable).

Due to the diverse user needs outlined by OBWB (2018), the Version 1 calibrations targeted NSE / L-NSE values calculated on year-round streamflows. However, specific user needs and model applications may require a more tailored calibration approach to better target peak or low flow conditions individually. In addition, different weighting of NSE / L-NSE values may yield better calibration results within some model watersheds. Accordingly, additional calibrations are recommended for case-specific applications in the future. When considering Version 1 calibration results for use, if peak flows are largely of interest by a user, Calibration 1 results are recommended, while if low and/or annual flows are of interest, Calibration 2 is recommended.

6.2.1 Naturalized Streamflow Calibration Approach

At the outset of the OHMP, a 'global' model calibration approach was used to identify a suitable basin-wide parameter set based on long-term natural streamflow records from four WSC hydrometric stations (i.e., Whiteman Creek above Bouleau Creek [08NM174]; Vaseux Creek above Solco Creek [08NM171]; Camp Creek at Mouth Near Thirsk [08NM134]; and Coldstream Creek above Municipal Intake [08NM142]). However, due to the interdependency of model parameters and the need to produce 19 individual watershed models, the global calibration approach did not yield favourable results across all watersheds. This was largely a result of the uncertainty in vegetation interception between land use types and the relatively unknown soil characteristics and depths across all model watersheds. In addition, comments received from the OBWB Project Steering Committee favoured the use of naturalized streamflow datasets (Associated 2019a) to develop watershed-specific calibrations.

Accordingly, the following approach was implemented to determine watershed-specific Version 1 calibrations for naturalized streamflows:

- Watershed-specific calibrations that focussed on optimizing the NSE between naturalized streamflow estimates (Associated 2019a)[6] and modelled streamflows at the apex of the alluvial fan were completed (i.e., Calibration 1).
- Watershed-specific calibrations that focussed on optimizing the equal weighting of NSE and L-NSE values between naturalized streamflow estimates (Associated 2019a)[6] and modelled streamflows at the apex of the alluvial fan were completed (i.e., Calibration 2).

During calibration, the model was run for the period model warm-up period and the calibration period (i.e., June 1, 1993 – December 31, 2010), with model diagnostics being computed for only the calibration period (i.e., January 1, 1996 – December 31, 2010) (Section 4.3). The following model parameters were included in the calibration process for each watershed:

- Rain and snow vegetation interception percentages;
- Snow melt and refreeze parameters;
- Reservoir crest widths (and maximum depth for simple 'lake-like' reservoirs);
- Rain/snow temperature partitioning parameters;
- All soil parameters (e.g., baseflow, capillary rise, percolation and PET correction coefficients); and
- Topsoil thicknesses.

OHME V1 allows users to develop custom calibration approaches by including/excluding any model parameters, as well as including or excluding reservoir dimensions or soil thicknesses from the calibration process. Different (or multiple) calibration targets can also be easily selected within OHME V1.

Regardless of the calibration target, Raven generates model diagnostics (e.g., NSE, L-NSE, percent bias, R^2 values) at all coincident observation locations (e.g., WSC hydrometric stations and snow survey locations) allowing model users to assess the adequacy of the Version 1 calibration at select locations within a given model watershed (where appropriate observation datasets exist). However, due to the limited observation datasets of natural streamflow conditions within respective watersheds, it is currently difficult to assess model performance at the sub-basin scale within individual watersheds.

6.2.2 Residual Streamflow Calibration Approach

Following watershed-specific naturalized streamflow calibration, residual streamflows were modelled by incorporating water demand and, where possible, reservoir management. Water demand estimates from the OWDM (Section 5.3.1) were used to represent the best available estimates of water demand for all model watersheds within Version 1 model results. Under residual streamflow conditions, no water demand was included during the model warm-up period (i.e., June 1, 1993 – December 31, 1995). Within OHME V1, Version 1 residual streamflows were modelled based on three main scenarios:

1. **Watersheds with no reservoirs present, or reservoirs with no known storage licences or operations to support downstream water demand** – for these watersheds, it is assumed that OWDM data is representative

[6] Naturalized streamflow estimates were not generated for Vernon Creek by Associated (2019a). Therefore, naturalized streamflow estimates previously developed by Summit (2009) were used to guide calibrations in the Vernon Creek watershed. Understanding that Kalamalka-Wood Lake outflows largely drive streamflows within lower Vernon Creek, naturalized streamflow estimates at the outlet of Kalamalka Lake were used as the calibration target in Vernon Creek.

of actual water demand and that all extractions are direct from the creek (or reservoir, where appropriate). Within OHME V1, sub-basin total water demand is extracted from the outlet of each sub-basin at the end of each timestep, if sufficient water is available to maintain positive streamflows. Where appropriate, water transfers were estimated (Section 5.3.2) and included in residual streamflow models.

2. **Watersheds with managed reservoirs and no residual streamflow calibration targets** – several different approaches were applied as follows:
   - For all watersheds, it was assumed that the OWDM data represents actual demand. However, since not all demand is fully supported by reservoir storage in some watersheds, available water licence information was used to estimate the percentage of water demand supported by storage.
   - In watersheds with major water intakes (i.e., extraction locations for water use areas within the OWDM), it was assumed that reservoirs were operated to support 100% of water demand at the intake location, and no water demand within "other" water use areas is supported by upland reservoir storage.
   - In watersheds without major water intakes, the percentage of water demand supported by upland storage was estimated based on the amount of licensed water supported by licensed storage.
   - When multiple upland reservoirs were present, total water demand from each downstream model sub-basin was distributed by Raven automatically, based on the maximum capacity of each reservoir (i.e., the maximum live storage value taken from available stage-storage curves, or the product of the lake area and calibrated maximum depth for natural reservoirs where no stage-storage curve was available).
   - When appropriate, water transfers were estimated (Section 5.3.2) and included.

3. **Watersheds with managed reservoirs and residual streamflow calibration targets** – for these watersheds, reservoir operations were adjusted through calibration based on available residual streamflow records. Under this approach, it was assumed that reservoirs are operated to supply water demand only at major water intake locations, and no water demand within "other" water use areas is supported by upland storage. To account for the uncertainty in reservoir operations and water demand estimates from the OWDM, the percentage of water demand supported by upland reservoirs was adjusted through calibration. The percentage of water demand supported by upland reservoirs was varied between 50% - 150% of the OWDM water demand estimates within calibration. Where appropriate, water transfers were estimated (Section 5.3.2) and included. When multiple upland reservoirs were present, total demand from each downstream model sub-basin was distributed by Raven automatically, based on the maximum capacity of each reservoir. This residual calibration approach may result in reservoir releases higher or lower then implemented in practice. This is a result of the calibration accounting for and distributing the uncertainty in reservoir operations, water demand, and modelled naturalized streamflows. However, without detailed reservoir release records, this calibration was deemed suitable for OHME V1 and can be updated/refined in the future.

A summary of residual streamflow modelling scenarios used within each model watershed is provided below:

- Coldstream Creek:
  - Greater Vernon Water (GVW) operates King Edward Lake to support irrigation demand at a water intake located in the Deer Creek sub-basin. GVW's water demand represents 100% of total water demand within the Deer Creek sub-basin; therefore, it was assumed that King Edward Lake operates to satisfy 100% of water demand at GVW's Deer Creek intake, that supplies water to Coldstream Ranch during the irrigation season. All other sub-basins and water users within Coldstream Creek

watershed are unsupported by reservoir storage and water demand is extracted directly from the creek.

- Equesis Creek:
    - A review of water licences within the Equesis Creek watershed suggest that 65% of all licensed water demand is supported by upland storage; therefore, it was assumed that Pinaus Lake operates to satisfy 65% of all water demand within downstream sub-basins. All other water demand is unsupported by upland storage.
- Inkaneep Creek:
    - There are no reservoirs or diversions within the Inkaneep Creek watershed to support water demand. All water demand is extracted directly from the creek.
- McLean Creek:
    - There are no reservoirs or diversions within the McLean Creek watershed to support water demand. All water demand is extracted directly from the creek.
- Mill and Mission Creeks:
    - Under residual conditions, Mill and Mission Creek watersheds must be modelled in combination to allow for the Mill-Mission flood diversion in the lower reaches to be appropriately considered. Accordingly, a coupled Mill-Mission natural calibration was first completed to obtain an optimized parameter set for both watersheds. Stirling Creek diversion estimates from the Stirling Creek watershed to the Mission Creek watershed were estimated (Section 5.3.2) and included under residual streamflow conditions. Subsequently, reservoir operations in each watershed were estimated as follows:
        - Mission Creek reservoir operations were estimated by calibrating the percentage of demand at the BMID and SEKID water supply system intake locations on the mainstem of Mission Creek and Hydraulic Creek, respectively, to observed residual streamflow records at WSC 08NM116 downstream. Since WSC 08NM116 is downstream of both intake locations, it was deemed an appropriate calibration target to adequately capture operations on both the BMID and SEKID water supply systems, since detailed reservoir release records or management strategies were not available. In addition, calibration at WSC 08NM116 also helps to account for any minimum streamflow releases implemented (above water demand) at each upstream intake. All other sub-basins and water uses within Mission Creek were considered unsupported by upland storage.
        - Mill Creek reservoir operations were estimated by calibrating the percentage of demand at the GEID water intake location on the Mill Creek to residual streamflow records from GEID just below the intake. No residual streamflow records exist below the BMID water intake on Scotty Creek; therefore, James Lake reservoir operations by BMID were assumed consistent with those used by GEID on their reservoirs. All other sub-basins and water uses are unsupported by upland storage.
        - Following concurrent watershed-independent calibrations, one coupled model run was completed (based on a coupled naturalized streamflow calibration for the two watersheds) to distribute the necessary percentage of water demand (at each intake location) within each watershed between upland reservoirs. This approach was to account for the percentage of water demand supported by upland reservoir storage in each watershed.
- Naramata Creek:
    - There are no reservoirs within the Naramata Creek watershed to support water demand. All water demand is extracted directly from the creek. Highline Diversion estimates from the Chute-Robinson

Creek watersheds into the Naramata Creek were estimated (Section 5.3.2) and included under residual streamflow conditions.

- Naswhito Creek:
    - There are no reservoirs or diversions within the Naswhito Creek watershed to support water demand. All water demand is extracted directly from the creek.
- Penticton Creek:
    - The City of Penticton (COP) operates Greyback Lake to support downstream water withdrawals at its Campbell Mountain Diversion (for irrigation) and at its Water Treatment Plant (WTP). Under normal conditions, Greyback Lake is managed under two settings: (1) winter and (2) summer. The two settings are summarized by the COP (2014) as follows:
        - Winter Setting (mid-November to mid-April) – gate (i.e., 8" gate) is set to provide enough water within Penticton Creek for potable usage, WTP operations, and fall Kokanee Salmon spawning.
        - Summer Setting (mid-April to mid-November) – gate (i.e., 24" gate open and 8" gate closed, or 24" and 8" gates open proportionally) is set to provide enough water in Penticton Creek for potable and irrigation usage, WTP operations, and minimum flows past the WTP.
    - Following the above, hydraulic equations were included for both gate settings for the noted time periods. Manual Greyback Lake records are available for 2015 – 2019 (Section 5.4.3) and were used to visually assess modelled reservoir management.
    - Daily residual streamflow records collected by the City of Penticton at Nanaimo Avenue (Section 5.4.3) are available for the period 2004 – 2018 and provide the most complete calibration dataset. However, data between 2004 and 2010 include periods of sustained zero flow, which is likely erroneous due to the COP's implementation of minimum streamflows at its WTP. Therefore, since the accuracy of the zero flow records is unknown, these data were excluded. Subsequently, residual streamflow records at Nanaimo Avenue (for 2011-2017) were used within calibration to estimate Greyback Lake operations by adjusting the percentage of COP water demand (at both intake locations) that is satisfied by releases from Greyback Lake. All other sub-basins and water uses are unsupported by upland storage.
- Powers Creek:
    - The City of West Kelowna (CWK) maintains an intake in the middle portion of Powers Creek watershed to support water demand. Upland reservoir operations within the Powers Creek watershed are largely unknown; however, a summary of water licenses suggest that CWK water licenses are fully supported by upland storage. Therefore, all upland reservoirs were operated to support water demand at the CWK intake. The percentage of demand supported by reservoirs was determined via calibration to residual streamflow records collected at Gellatly Road (Section 5.4.3) from July 2004 to October 2009. Under residual conditions, Lambly Lake was included as part of Powers Creek watershed and is managed by CWK – naturally Lambly Lake was part of Lambly Creek watershed until the lake was dammed in the early to mid 1900s. All other sub-basins and water uses are unsupported by upland storage. Alocin Creek diversion estimates from the Nicole River watershed to the Powers Creek watershed were estimated (Section 5.3.2) and included under residual streamflow conditions.
- Shingle Creek:
    - Reservoirs within the Shingle Creek watershed are operated by the Farleigh Lake Water Users Community (FLWUC) and Bobtail Ranch. Reservoir operations are largely unknown; however, Associated (2019a) summarized the following water management activities within the Shingle Creek watershed:

    - Water from the Upper Shingle Creek sub-basin is diverted into Brent Lake to supplement lake levels. Diversion rates are assumed to be approximately 0.143 m^3/s and occur between May 15 and June 15 (C. Purton, personal communication, 2018). Brent Lake is operated to support water demand to Bobtail Ranch and Farleigh Lake.
    - Farleigh Lake is operated to have no reservoir surface outflow. However, the lake is managed to support the FLWUC and members of the Penticton Indian Band (PIB) who reside immediately downstream of the lake. It is understood that FLWUC removes water directly from the lake and the PIB members are supplied by a 12-inch pipe from the lake (C. Purton, personal communication, 2018). FLWUC water demand is included through OWDM estimates, while PIB water demand was assumed to be 0.160 m^3/s (i.e., maximum capacity of outflow pipe) between July and September, since no actual records were available.
  - Within OHME V1, the above noted reservoir management strategies were implemented as follows:
    - Under Calibration 1 and 2, the 0.143 m^3/s diversion rate into Brent Lake represents 19% and 11% of streamflow (on average) in the Upper Shingle Creek sub-basin between May 15 – June 15, respectively. Accordingly, 19% and 11% of streamflow from the Upper Shingle Creek sub-basin was diverted into Brent Lake between May 15 – June 15 each year under Calibration 1 and 2, respectively.
    - In the absence of water demand records for PIB from Farleigh Lake, the 12-inch pipe releases were assumed to be 0.160 m^3/s between July and September annually, to support downstream irrigation. To represent this within OHME V1, reservoir outflows were overridden with a timeseries of estimated releases of 0.160 m^3/s between July and September, and 0 m^3/s at all other times of the year.
- Shorts Creek:
  - There are no reservoirs within the Shorts Creek watershed to support water demand. All water demand is extracted directly from the creek. Dunwaters diversion estimates from the Dunwaters Creek sub-basin to the Lambly Creek watershed were estimated (Section 5.3.2) and included under residual streamflow conditions.
- Shuttleworth Creek
  - There are no major water supplier intakes within the Shuttleworth Creek watershed. A summary of water licences suggests that 95% of licensed water demand within the watershed is supported by upland storage. Therefore, it was assumed that Allendale and Clark Meadows Lakes operate to satisfy 95% of water demand within all downstream sub-basins, and the remaining 5% is obtained through natural streamflows.
- Trepanier Creek
  - There are no reservoirs within the Trepanier Creek watershed. All water demand is extracted directly from the creek. The MacDonald Creek Diversion (to unmodelled Peachland Creek watershed) was estimated (Section 5.3.2) and included under residual streamflow conditions. This diversion was considered until 2009, after which it was no longer in use. In addition to the MacDonald Creek Diversion, Brenda Mines releases (Section 5.3.2) were also included.
- Trout Creek:
  - Mountain View Irrigation District (MVID) and the District of Summerland (DOS) both operate water intakes within the Trout Creek watershed to support water demand within their water use areas. Residual streamflow records at the Canyon Mouth (08NM042-HDS) (Section 5.4.3) provide the only available residual streamflow calibration dataset within the Trout Creek watershed. The percentage of demand supported by reservoirs was determined via calibration to residual streamflow records

collected at the 08NM042-HDS between 2004-2009. Residual streamflows collected at 08NM042-HDS are below both MVID and DOS water intakes and are therefore representative of operations on both water systems. All other sub-basins and water uses are unsupported by upland storage.

- Vaseux Creek
  - There are no reservoirs or water diversions within the Vaseux Creek watershed to support water demand. All water demand is extracted directly from the creek.
- Vernon Creek:
  - Due to the complex water management that occurs within Vernon Creek watershed and the lack of historic natural outflows records from Kalamalka Lake, the naturalized streamflow estimates within OHME V1 are not considered representative of natural conditions. Therefore, as residual streamflow estimates within OHME V1 build upon the naturalized model configuration, discussions with the OBWB determined that it was not appropriate to model residual streamflow conditions for Vernon Creek at this time.
- Whiteman Creek:
  - Bouleau Lake is the only reservoir within the Whiteman Creek watershed. No known lake management exists; thus, no reservoir operations were included under residual conditions. All water demand is extracted directly from the creek.

Due to the inconsistency of residual streamflow datasets, a consistent calibration / validation approach was not possible under residual conditions. Table 6-1 summarizes the residual streamflow datasets used to assess model performance within each watershed, for which model diagnostics could be computed.

Table 6-1
Summary of calibration and validation datasets and periods for Version 1 residual streamflow models

Watershed	Calibration Dataset and Period	Validation Dataset and Period
Coldstream Creek	None	ONA hydrometric station 08NM589 (August 2016 – December 2017)
Equesis Creek	None	ONA hydrometric station 08NM161-HDS (September 2016 – December 2017)
Inkaneep Creek	None	WSC 08NM200 (2006 – 2017)
McDougall Creek	None	ONA hydrometric station 08NM590 (March 2017 – December 2017)
McLean Creek	None	None
Mill and Mission Creeks	• Mission Creek: WSC 08NM116 (1996 – 2010) • Mill Creek: GEID Mill Creek records below intake (2010-2017)	• Mission Creek: WSC 08NM116 (2011 – 2015) and WSC 08NM232 (2011 – 2016) • Mill Creek: None
Naramata Creek	None	None
Naswhito Creek	None	ONA hydrometric station 08NM586 (September 2016 – August 2017)
Penticton Creek	COP residual streamflow records (2010-2017)	WSC 08NM168 (1996 – 1999)
Powers Creek	Powers Creek at Gellatly Road (Private hydrometric station 08NM570) (2004-2009)	Irregular, instantaneous reservoir releases from Lambly Lake (July 2009 – December 2017)
Shingle Creek	None	08NM037 (1996 – 2015)
Shorts Creek	None	ONA hydrometric station 08NM151 (November 2014 – December 2017)
Shuttleworth Creek	None	WSC 08NM149 (2006 – 2010)
Trepanier Creek	None	WSC 08NM041 (1996 – 2013)
Trout Creek	Trout Creek at Canyon Mouth (Private hydrometric station (08NM042-HDS) (2004-2009)	None
Vaseux Creek	None	WSC 08NM246 (2006 – 2010)
Vernon Creek	N/A[1]	N/A
Whiteman Creek	None	ONA hydrometric station 08NM587 (September 2016 – August 2017)

Notes:

1. Residual streamflow modelling was not completed for Vernon Creek.

6.3 Validation Approach

For natural streamflow conditions, model validation involved simply extending the period for which the models were run (i.e., model warm-up period, plus the full model period of interest [1996-2017]), and comparing modelled streamflow values against appropriate observation datasets for the model validation period (i.e., 2011-2017) (Section 5.4) at all locations within each watershed with available observation data. This validation approach assesses the ability of the model(s) to be used to provide naturalized streamflow estimates outside of the model calibration period (1996-2010).

Since naturalized streamflow estimates (Associated 2019a) are only available for the 1996-2010 calibration period, model validation of naturalized streamflows relies on natural streamflow records from WSC. Accordingly, naturalized streamflow model validation is only possible for those watersheds with WSC natural streamflow records (i.e., Whiteman, Coldstream, Trout, Vaseux, and Penticton Creek watersheds). However, adequate model validation within one watershed is not necessarily representative of adequate model validation within another watershed. This is largely a result of the variability in parameter values obtained through automated calibration between different watersheds. As a result, the model diagnostics computed during the calibration period provide the best assessment of model performance within each model watershed.

Under residual streamflow conditions, model validation was only possible for select watersheds where available residual streamflow records exist (Table 6-1). The period for model validation varies between watersheds and is dependant on the period of available residual streamflow datasets (Table 6-1).

7 MODEL RESULTS

Within OHME V1, the following model diagnostics are computed for all observation datasets within a given watershed during every model run:

- Nash-Sutcliffe model efficiency coefficient (NSE);
- Logarithmic Nash-Sutcliffe model efficiency coefficient (L-NSE);
- Root-mean-squared Error (RMSE);
- Percent Bias (PB); and
- R-squared (R^2).

The following sections summarize the naturalized and residual modelled streamflow results for the model watersheds. As outlined in Section 6.2.2, the naturalized streamflow modelling of Vernon Creek produced unrealistic results due to the complexity of the watershed and the lack of available naturalized streamflow calibration records. Thus, residual streamflow modelling for Vernon Creek is not reported herein and further model refinement (outside the scope of this project) is required to improve naturalized and residual streamflow results.

7.1 Naturalized Streamflow Model Results

Version 1 model calibrations obtained using OHME V1 focussed on calibrating modelled naturalized streamflows to match naturalized streamflow estimates at the apex of the alluvial fan (Associated 2019a). The calibrations were completed using OSTRICH to optimize the NSE (Calibration 1) and NSE / L-NSE (Calibration 2) model diagnostics calculated on year-round streamflows. During each model run, model diagnostics were also generated for all available WSC hydrometric records, and available SWE data records from snow course and snow pillow locations within the given model extent. While Raven generates all above diagnostics for each observation location, regardless of observation type (i.e., streamflow records or snow survey information), not all model diagnostics are useful for assessing model performance of different processes (e.g., NSE values are only particularly useful for assessing hydrographs).

Tables 7-1 and 7-2 summarize all useful model diagnostics for each model watershed under calibration and subsequent validation runs (where applicable) for Calibration 1 and Calibration 2, respectively. Streamflow diagnostics are reported for naturalized streamflow estimates at the apex of the alluvial fan (i.e., the calibration target) and for available WSC hydrometric stations (where applicable). In addition, SWE diagnostics are provided between HRU-average snowpack and observed snowpack at snow course or snow pillow locations (where applicable). OHME V1 diagnostics are provided for both the calibration period (i.e., 1996-2010) and the validation period (i.e., 2011-2017) at all relevant observation locations within the Coldstream, Penticton, Trout, Vaseux, and Whiteman Creek watersheds.

Table 7-1
OHME V1 model diagnostics for naturalized streamflow Calibration 1

Model Watershed	Diagnostic Period	Streamflow Diagnostics										SWE Diagnostics (Model Diagnostics Only)		
		Apex of the Alluvial Fan (Calibration Target)[1]					WSC Natural Hydrometric Station (Model Diagnostics Only)							
		NSE	L-NSE	RMSE	PB	R2	NSE	L-NSE	RMSE	PB	R^2	RMSE	PB	R^2
Coldstream Creek	Calibration	0.74	-3.71	0.57	-19.18	0.77	0.65 (08NM142)	-1.01 (08NM142)	0.24 (08NM142)	10.32 (08NM142)	0.76 (08NM142)	-	-	-
	Validation	-	-	-	-	-	0.68 (08NM142)	-0.67 (08NM142)	0.24 (08NM142)	7.47 (08NM142)	0.78 (08NM142)			
Equesis Creek	Calibration	0.69	0.49	0.74	-18.79	0.70	-		-	-	-	-	-	-
Inkaneep Creek	Calibration	0.70	-0.91	0.30	-15.28	0.72	-		-	-	-	-	-	-
McDougall Creek	Calibration	0.62	-18.4	0.14	-26.95	0.66	-		-	-	-	-	-	-
McLean Creek	Calibration	0.80	-0.43	0.14	-5.09	0.80	-		-	-	-	-	-	-
Mill Creek	Calibration	0.64	-48.09	0.62	-27.49	0.68	-		-	-	-	76.89 (SC 2F07)	40.53 (SC 2F07)	0.74 (SC 2F07)
Mission Creek	Calibration	0.86	0.36	3.46	-8.32	0.87	-		-	-	-	37.81 (SC 2F03)	-20.91 (SC 2F03)	0.77 (SC 2F03)
												49.50 (SC 2F04)	0.02 (SC 2F04)	0.81 (SC 2F04)
												103.22 (SP 2F05)	-26.85 (SP 2F05)	0.88 (SP 2F05)
Naramata Creek	Calibration	0.73	-5.07	0.20	-13.13	0.74	-		-	-	-	-	-	-
Naswhito Creek	Calibration	0.74	-5.31	0.37	-14.21	0.75	-		-	-	-	-	-	-
Penticton Creek	Calibration	0.80	-0.27	1.09	-10.06	0.80	0.70 (08NM240)	-16.18 (08NM240)	0.08 (08NM240)	-34.38 (08NM240)	0.74 (08NM240)	56.59 (SC 2F08)	-2.31 (SC 2F08)	0.62 (SC 2F08)
							0.61 (08NM241)	-14.04 (08NM241)	0.09 (08NM241)	-32.71 (08NM241)	0.64 (08NM241)	-	-	-
	Validation	-	-	-	-	-	0.75 (08NM240)	-15.09 (08NM240)	0.09 (08NM240)	-36.66 (08NM240)	0.81 (08NM240)	79.08 (SC 2F08)	-23.75 (SC 2F08)	0.61 (SC 2F08)
							0.66 (08NM241)	-19.21 (08NM241)	0.11 (08NM241)	-34.65 (08NM241)	0.72 (08NM241)	-	-	-
Powers Creek	Calibration	0.82	-2.03	0.48	-14.93	0.83	-		-	-	-	-	-	-
Shingle Creek	Calibration	0.82	-6.04	0.48	-12.06	0.83	-		-	-	-	-	-	-
Shorts Creek	Calibration	0.73	-2.02	1.38	-4.38	0.73	-		-	-	-	-	-	-
Shuttleworth Creek	Calibration	0.78	-0.60	0.43	-9.55	0.79	-		-	-	-	-	-	-
Trepanier Creek	Calibration	0.82	-5.29	0.97	-15.24	0.83	-	-	-	-	-	53.15 (SC 2F18)	-3.84 (SC 2F18)	0.67 (SC 2F18)
												105.39 (SC 2F23)	-18.23 (SC 2F23)	0.62 (SC 2F23)
												54.73 (SP 2F18)	-22.49 (SP 2F18)	0.92 (SP 2F18)
Trout Creek	Calibration	0.90	-1.42	1.22	-10.14	0.90	0.67 (08NM134)	-7.44 (08NM134)	0.14 (08NM134)	18.88 (08NM134)	0.81 (08NM134)	28.03 (SC 2F01)	-0.72 (SC 2F01)	0.88 (SC 2F01)
												31.69 (SC 2F02)	-15.80 (SC 2F02)	0.93 (SC 2F02)
												36.05 (SC 2F11)	15.83 (SC 2F11)	0.70 (SC 2F11)
	Validation	-	-	-	-	-	0.37 (08NM134)	-6.93 (08NM134)	0.19 (08NM134)	41.34 (08NM134)	0.79 (08NM134)	46.09 (SC 2F01)	-22.33 (SC 2F01)	0.88 (SC 2F01)
												41.41 (SC 2F02)	-5.47 (SC 2F02)	0.82 (SC 2F02)
												54.80 (SC 2F11)	21.43 (SC 2F11)	0.56 (SC 2F11)
Vaseux Creek	Calibration	0.80	-0.66	1.20	-5.37	0.80	0.73 (08NM171)	-2.01 (08NM171)	0.91 (08NM171)	-23.79 (08NM171)	0.77 (08NM171)	67.40 (SC 2F20)	87.66 (SC 2F20)	0.79 (SC 2F20)
	Validation	-	-	-	-	-	0.72 (08NM171)	-0.60 (08NM171)	1.05 (08NM171)	-26.35 (08NM171)	0.80 (08NM171)	81.47 (SC 2F20)	55.22 (SC 2F20)	0.50 (SC 2F20)
Vernon Creek	Calibration	-0.05	0.01	1.99	0.93	0.10	-	-	-	-	-	85.73 (SC 2F19)	-0.98 (SC 2F19)	0.32 (SC 2F19)
Whiteman Creek	Calibration	0.75	-3.00	1.18	-12.19	0.76	0.75 (08NM174)	-5.32 (08NM174)	0.66 (08NM174)	-17.34 (08NM174)	0.76 (08NM174)	65.32 (SC 2F21)	-18.80 (SC 2F21)	0.71 (SC 2F21)
	Validation	-	-	-	-	-	0.82 (08NM174)	-6.25 (08NM174)	0.48 (08NM174)	-14.63 (08NM174)	0.83 (08NM174)	64.01 (SC 2F21)	-11.22 (SC 2F21)	0.58 (SC 2F21)

Notes:

1. Model diagnostics for Vernon Creek are provided at the apex of the alluvial fan for consistency with all other model diagnostics; however, naturalized streamflow estimates at the outlet of Kalamalka Lake provided the calibration target for the Vernon Creek watershed.

Table 7-2
OHME V1 model diagnostics for naturalized streamflow Calibration 2

Model Watershed	Diagnostic Period	Streamflow Diagnostics										SWE Diagnostics (Model Diagnostics Only)		
		Apex of the Alluvial Fan[1] (Calibration Target)					WSC Natural Hydrometric Station (Model Diagnostics Only)							
		NSE	L-NSE	RMSE	PB	R^2	NSE	L-NSE	RMSE	PB	R^2	RMSE	PB	R^2
Coldstream Creek	Calibration	0.71	0.48	0.59	3.56	0.71	0.65 (08NM142)	0.46 (08NM142)	0.24 (08NM142)	39.35 (08NM142)	0.74 (08NM142)	-	-	-
	Validation	-		-	-	-	0.67 (08NM142)	0.61 (08NM142)	0.24 (08NM142)	34.05 (08NM142)	0.75 (08NM142)			
Equesis Creek	Calibration	0.72	0.76	0.71	-5.74	0.72	-		-	-	-	-	-	-
Inkaneep Creek	Calibration	0.68	0.57	0.31	-5.59	0.68	-		-	-	-	-	-	-
McDougall Creek	Calibration	0.69	0.62	0.12	-5.49	0.70	-		-	-	-	-	-	-
McLean Creek	Calibration	0.71	0.67	0.17	-13.79	0.72	-		-	-	-	-	-	-
Mill Creek	Calibration	0.65	0.67	0.61	-6.13	0.67	-		-	-	-	89.73 (SC 2F07)	47.77 (SC 2F07)	0.75 (SC 2F07)
Mission Creek	Calibration	0.86	0.80	3.54	-4.43	0.86	-	-	-	-	-	40.65 (SC 2F03) 56.40 (SC 2F04) 110.06 (SP 2F05)	-25.97 (SC 2F03) -3.06 (SC 2F04) -29.92 (SP 2F05)	0.77 (SC 2F03) 0.77 (SC 2F04) 0.86 (SP 2F05)
Naramata Creek	Calibration	0.71	0.69	0.20	-2.78	0.71	-		-	-	-	-	-	-
Naswhito Creek	Calibration	0.72	0.79	0.38	-0.69	0.73	-	-	-	-	-	-	-	-
Penticton Creek	Calibration	0.78	0.70	1.15	-3.67	0.78	0.65 (08NM240)	-0.21 (08NM240)	0.09 (08NM240)	-45.29 (08NM240)	0.71 (08NM240)	54.55 (SC 2F08)	-16.74 (SC 2F08)	0.62 (SC 2F08)
							0.55 (08NM241)	-0.29 (08NM241)	0.09 (08NM241)	-34.46 (08NM241)	0.58 (08NM241)	-	-	-
	Validation	-		-	-	-	0.68 (08NM240)	0.17 (08NM240)	0.10 (08NM240)	-44.76 (08NM240)	0.77 (08NM240)	85.78 (SC 2F08)	-33.97 (SC 2F08)	0.63 (SC 2F08)
							0.69 (08NM241)	-0.28 (08NM241)	0.10 (08NM241)	-34.74 (08NM241)	0.74 (08NM241)	-	-	-
Powers Creek	Calibration	0.75	0.76	0.57	-14.61	0.75	-	-	-	-	-	-	-	-
Shingle Creek	Calibration	0.75	0.77	0.58	-6.08	0.75	-	-	-	-	-	-	-	-
Shorts Creek	Calibration	0.73	0.85	1.38	-4.30	0.73	-	-	-	-	-	-	-	-
Shuttleworth Creek	Calibration	0.69	0.65	0.51	-10.86	0.71	-	-	-	-	-	-	-	-
Trepanier Creek	Calibration	0.78	0.61	1.08	-0.48	0.79	-	-	-	-	-	59.47 (SC 2F18) 85.49 (SC 2F23) 52.98 (SP 2F18)	-1.42 (SC 2F18) -10.37 (SC 2F23) -22.16 (SP 2F18)	0.67 (SC 2F18) 0.62 (SC 2F23) 0.91 (SP 2F18)
Trout Creek	Calibration	0.86	0.81	1.44	-5.16	0.86	0.64 (08NM134)	-1.17 (08NM134)	0.15 (08NM134)	-15.10 (08NM134)	0.72 (08NM134)	30.07 (SC 2F01) 38.37 (SC 2F02) 33.60 (SC 2F11)	-6.22 (SC 2F01) -21.93 (SC 2F02) 8.39 (SC 2F11)	0.87 (SC 2F01) 0.92 (SC 2F02) 0.69 (SC 2F11)
	Validation	-	-	-	-	-	0.41 (08NM134)	-1.12 (08NM134)	0.18 (08NM134)	-0.37 (08NM134)	0.68 (08NM134)	56.46 (SC 2F01) 45.91 (SC 2F02) 50.07 (SC 2F11)	-28.35 (SC 2F01) -14.24 (SC 2F02) 15.57 (SC 2F11)	0.85 (SC 2F01) 0.80 (SC 2F02) 0.57 (SC 2F11)
Vaseux Creek	Calibration	0.72	0.61	1.42	-8.90	0.72	0.64 (08NM171)	0.54 (08NM171)	1.05 (08NM171)	-26.98 (08NM171)	0.69 (08NM171)	98.81 (SC 2F20)	133.19 (SC 2F20)	0.79 (SC 2F20)
	Validation	-		-	-	-	0.59 (08NM171)	0.69 (08NM171)	1.27 (08NM171)	-28.43 (08NM171)	0.64 (08NM171)	114.48 (SC 2F20)	91.78 (SC 2F20)	0.49 (SC 2F20)
Vernon Creek	Calibration	-0.14	-0.15	2.08	-33.63	0.08	-	-	-	-	-	83.66 (SC 2F19)	-14.67 (SC 2F19)	0.29 (SC 2F19)
Whiteman Creek	Calibration	0.75	0.797651	1.20	-1.37	0.75	0.75 (08NM174)	-2.54 (08NM174)	0.67 (08NM174)	-18.65 (08NM174)	0.76 (08NM174)	69.74 (SC 2F21)	-21.05 (SC 2F21)	0.70 (SC 2F21)
	Validation	-	-	-	-	-	0.84 (08NM174)	-3.55 (08NM174)	0.46 (08NM174)	-17.72 (08NM174)	0.84 (08NM174)	69.96 (SC 2F21)	-15.42 (SC 2F21)	0.54 (SC 2F21)

Notes:

1. Model diagnostics for Vernon Creek are provided at the apex of the alluvial fan for consistency with all other model diagnostics; however, naturalized streamflow estimates at the outlet of Kalamalka Lake provided the calibration target for the Vernon Creek watershed.

Figures provided in Appendix D present daily and weekly timeseries of modelled naturalized streamflows at the apex of the alluvial fan for the model watersheds. Based on Version 1 naturalized streamflow results, the following observations are made:

- The timing and magnitude of peak streamflows are generally well represented in most model watersheds within Calibration 1 results. This is consistent in both calibration and validation periods.
- There is large daily streamflow variability, particularly during low flow periods, in most model watersheds within Calibrations 1 and 2.
- Low flow periods are typically underestimated in all model watersheds within Calibration 1. This is consistent in both calibration and validation periods.
- Low flow periods are generally better represented within Calibration 2. This is consistent in both calibration and validation periods.
- While many of the NSE values reported for the 19 model watersheds may be considered reasonable, the limited calibration datasets within each watershed prevent model performance in smaller upland sub-basins to be assessed.

Model results presented herein largely focus on the ability of the model to represent streamflows at the apex of the alluvial fan. Model users can request additional output from the model to represent various other processes within a given model watershed(s) (e.g., evaporation, soil water movement, climate data summaries). Due to the variety of custom output, these summaries are not included herein but can be requested by model users within OHME V1 depending on the user need.

7.2 Residual Streamflow Model Results

Version 1 modelled residual streamflows built upon Version 1 modelled naturalized streamflows obtained for Calibration 1 and Calibration 2 (Section 7.1). Where applicable, upstream reservoir operations were adjusted via automated calibration to match available residual streamflow records (Section 6.2.2). Subsequently, model validation was completed for watersheds with available residual streamflow records. Modelled residual streamflow datasets were generated based on both Calibrations 1 and 2.

Tables 7-3 and 7-4 summarize all useful model diagnostics for each model watershed under calibration and subsequent validation runs (where applicable) for Calibration 1 and 2, respectively. Streamflow diagnostics are reported for locations with available residual streamflow records, as summarized in Table 6-1. No SWE diagnostics are reported herein under residual streamflow conditions, since physical processes and parameter values remain unchanged from natural conditions at all snow course and snow pillow locations.

Table 7-3
OHME V1 model diagnostics for residual streamflow Calibration 1

Model Watershed	Diagnostic Period	Residual Hydrometric Station				
		NSE	L-NSE	RMSE	PB	R^2
Coldstream Creek	Validation (2016 - 2017)	0.40 (ONA 08NM589)	-7.00 (ONA 08NM589)	0.99 (ONA 08NM589)	19.49 (ONA 08NM589)	0.78 (ONA 08NM589)
Equesis Creek	Validation (2016 - 2017)	-1.83 (ONA 08NM161-HDS)	-6.44 (ONA 08NM161-HDS)	1.40 (ONA 08NM161-HDS)	18.68 (ONA 08NM161-HDS)	0.60 (ONA 08NM161-HDS)
Inkaneep Creek	Validation (2006 - 2017)	0.67 (WSC 08NM200)	-0.66 (WSC 08NM200)	0.39 (WSC 08NM200)	-13.72 (WSC 08NM200)	0.68 (WSC 08NM200)
McDougall Creek	Validation (2017)	0.66 (ONA 08NM590)	-1.25 (ONA 08NM590)	0.49 (ONA 08NM590)	-1.79 (ONA 08NM590)	0.66 (ONA 08NM590)
McLean Creek	No diagnostics available	-	-	-	-	-
Mill Creek[1]	Calibration (2010 - 2017)	0.43 (GEID Mill Creek)	-0.24 (GEID Mill Creek)	0.56 (GEID Mill Creek)	-30.30 (GEID Mill Creek)	0.46 (GEID Mill Creek)
Mission Creek[1]	Calibration (1996 - 2010)	0.87 (WSC 08NM116)	-0.72 (WSC 08NM116)	3.48 (WSC 08NM116)	-13.31 (WSC 08NM116)	0.88 (WSC 08NM116)
	Validation (2011-2017)	0.84 (WSC 08NM116)	-6.91 (WSC 08NM116)	4.62 (WSC 08NM116)	-26.41 (WSC 08NM116)	0.87 (WSC 08NM116)
		0.61 (WSC 08NM232)	0.38 (WSC 08NM232)	0.68 (WSC 08NM232)	-7.85 (WSC 08NM232)	0.63 (WSC 08NM232)
Naramata Creek	No diagnostics available	-	-	-	-	-
Naswhito Creek	Validation (2016 - 2017)	0.56 (ONA 08NM586)	-2.27 (ONA 08NM586)	0.93 (ONA 08NM586)	19.59 (ONA 08NM586)	0.67 (ONA 08NM586)
Penticton Creek	Calibration (2010 - 2017)	0.54 (COP Residuals)	-0.14 (COP Residuals)	1.34 (COP Residuals)	8.09 (COP Residuals)	0.69 (COP Residuals)
	Validation (1996-1999)	0.18 (WSC 08NM168)	-0.80 (WSC 08NM168)	0.41 (WSC 08NM168)	-18.59 (WSC 08NM168)	0.23 (WSC 08NM168)
Powers Creek	Calibration (2004-2009)	0.60 (08NM570)	-0.52 (08NM570)	0.27 (08NM570)	25.55 (08NM570)	0.75 (08NM570)
	Validation (2009 - 2017)	-11.79 (Lambly Lake Releases)	-2.89 (Lambly Lake Releases)	0.35 (Lambly Lake Releases)	27.11 (Lambly Lake Releases)	0.04 (Lambly Lake Releases)
Shingle Creek	Validation (1996-2015)	0.83 (WSC 08NM037)	-3.12 (WSC 08NM037)	0.48 (WSC 08NM037)	-14.13 (WSC 08NM037)	0.83 (WSC 08NM037)
Shorts Creek	Validation (2014 - 2017)	-0.17 (ONA 08NM151)	-3.26 (ONA 08NM151)	1.83 (ONA 08NM151)	45.17 (ONA 08NM151)	0.62 (ONA 08NM151)
Shuttleworth Creek	Validation (2006 - 2010)	0.70 (WSC 08NM149)	-0.20 (WSC 08NM149)	0.46 (WSC 08NM149)	-2.92 (WSC 08NM149)	0.70 (WSC 08NM149)
Trepanier Creek	Validation (1996 - 2013)	0.80 (WSC 08NM041)	-1.95 (WSC 08NM041)	0.87 (WSC 08NM041)	-8.84 (WSC 08NM041)	0.82 (WSC 08NM041)
Trout Creek	Calibration (2004 – 2009)	0.53 (08NM042-HDS)	-7.55 (08NM042-HDS)	0.87 (08NM042-HDS)	-16.84 (08NM042-HDS)	0.73 (08NM042-HDS)
Vaseux Creek	Validation (2006 - 2010)	0.45 (WSC 08NM246)	0.44 (WSC 08NM246)	1.40 (WSC 08NM246)	57.57 (WSC 08NM246)	0.76 (WSC 08NM246)
Vernon Creek	Residual streamflow modelling not completed					
Whiteman Creek	Validation (2016 - 2017)	-1.79 (ONA 08NM587)	-16.72 (ONA 08NM587)	2.56 (ONA 08NM587)	94.22 (ONA 08NM587)	0.75 (ONA 08NM587)

Notes:
1. Calibration diagnostics for Mill and Mission Creek watersheds represent the watershed-specific calibrations that were completed to determine the percentage of downstream demand supported by upland reservoirs. The validation diagnostics presented for Mission Creek represent the Mill and Mission Creek coupled validation run (based on a separate coupled naturalized calibrations) that was completed to ensure the Mill-Mission flood diversion is accurately represented.

Table 7-4
OHME V1 model diagnostics for residual streamflow Calibration 2

Model Watershed	Diagnostic Period	Residual Hydrometric Station				
		NSE	L-NSE	RMSE	PB	R^2
Coldstream Creek	Validation (2016 - 2017)	0.33 (ONA 08NM589)	-1.50 (ONA 08NM589)	1.04 (ONA 08NM589)	46.35 (ONA 08NM589)	0.80 (ONA 08NM589)
Equesis Creek	Validation (2016 - 2017)	-2.52 (ONA 08NM161-HDS)	0.25 (ONA 08NM161-HDS)	1.56 (ONA 08NM161-HDS)	66.40 (ONA 08NM161-HDS)	0.66 (ONA 08NM161-HDS)
Inkaneep Creek	Validation (2006 - 2017)	0.60 (WSC 08NM200)	0.52 (WSC 08NM200)	0.43 (WSC 08NM200)	-6.90 (WSC 08NM200)	0.65 (WSC 08NM200)
McDougall Creek	Validation (2017)	0.84 (ONA 08NM590)	0.14 (ONA 08NM590)	0.33 (ONA 08NM590)	30.83 (ONA 08NM590)	0.87 (ONA 08NM590)
McLean Creek	No diagnostics available	-	-	-	-	-
Mill Creek[1]	Calibration (2010 - 2017)	0.40 (GEID Mill Creek)	0.34 (GEID Mill Creek)	0.58 (GEID Mill Creek)	-36.51 (GEID Mill Creek)	0.44 (GEID Mill Creek)
Mission Creek[1]	Calibration (1996 - 2010)	0.85 (WSC 08NM116)	0.78 (WSC 08NM116)	3.81 (WSC 08NM116)	-10.32 (WSC 08NM116)	0.85 (WSC 08NM116)
	Validation (2011-2017)	0.82 (WSC 08NM116)	0.74 (WSC 08NM116)	4.93 (WSC 08NM116)	-13.10 (WSC 08NM116)	0.83 (WSC 08NM116)
		0.65 (WSC 08NM232)	0.48 (WSC 08NM232)	0.64 (WSC 08NM232)	11.97 (WSC 08NM232)	0.66 (WSC 08NM232)
Naramata Creek	No diagnostics available	-	-	-	-	-
Naswhito Creek	Validation (2016 - 2017)	0.53 (ONA 08NM586)	0.70 (ONA 08NM586)	0.96 (ONA 08NM586)	45.84 (ONA 08NM586)	0.76 (ONA 08NM586)
Penticton Creek	Calibration (2010 - 2017)	0.49 (COP Residuals)	0.38 (COP Residuals)	1.41 (COP Residuals)	17.21 (COP Residuals)	0.66 (COP Residuals)
	Validation (1996-1999)	0.17 (WSC 08NM168)	-1.39 (WSC 08NM168)	0.42 (WSC 08NM168)	-31.77 (WSC 08NM168)	0.28 (WSC 08NM168)
Powers Creek	Calibration (2004-2009)	0.63 (08NM570)	0.16 (08NM570)	0.26 (08NM570)	24.30 (08NM570)	0.74 (08NM570)
	Validation (2009 - 2017)	-10.74 (Lambly Lake Releases)	-2.08 (Lambly Lake Releases)	0.34 (Lambly Lake Releases)	35.63 (Lambly Lake Releases)	0.03 (Lambly Lake Releases)
Shingle Creek	Validation (1996-2015)	0.61 (WSC 08NM037)	-0.85 (WSC 08NM037)	0.47 (WSC 08NM037)	-40.95 (WSC 08NM037)	0.66 (WSC 08NM037)
Shorts Creek	Validation (2014 - 2017)	-0.04 (ONA 08NM151)	0.44 (ONA 08NM151)	1.72 (ONA 08NM151)	38.06 (ONA 08NM151)	0.63 (ONA 08NM151)
Shuttleworth Creek	Validation (2006 - 2010)	-1.76 (WSC 08NM149)	0.29 (WSC 08NM149)	0.69 (WSC 08NM149)	99.20 (WSC 08NM149)	0.43 (WSC 08NM149)
Trepanier Creek	Validation (1996 - 2013)	0.77 (WSC 08NM041)	0.57 (WSC 08NM041)	0.93 (WSC 08NM041)	0.51 (WSC 08NM041)	0.77 (WSC 08NM041)
Trout Creek	Calibration (2004 – 2009)	-10.74 (08NM042-HDS)	-2.08 (08NM042-HDS)	0.34 (08NM042-HDS)	35.63 (08NM042-HDS)	0.03 (08NM042-HDS)
Vaseux Creek	Validation (2006 - 2010)	0.47 (WSC 08NM246)	0.15 (WSC 08NM246)	1.37 (WSC 08NM246)	54.09 (WSC 08NM246)	0.70 (WSC 08NM246)

Notes:
1. Calibration diagnostics for Mill and Mission Creek watersheds represent the watershed-specific calibrations that were completed to determine the percentage of downstream demand supported by upland reservoirs. The validation diagnostics presented for Mission Creek represent the Mill and Mission Creek coupled validation run (based on a separate coupled naturalized calibrations) that was completed to ensure the Mill-Mission flood diversion is accurately represented.

Figures provided in Appendix E present daily and weekly timeseries of modelled residual streamflows at the apex of the alluvial fan, compared to weekly modelled naturalized streamflows at the corresponding location for 18 of the model watersheds[7]. Based on these Version 1 residual streamflow results, the following observations are made:

- Model diagnostics presented in Tables 7-3 and 7-4 are generally less favourable than comparable diagnostics for modelled naturalized streamflow datasets. This is largely due to the small period of record available at many of the third-party hydrometric stations used to generate model diagnostics for residual streamflow conditions. In addition, most third-party records are only available for the 2016-2017 period, which represents unusual climatic and hydrologic conditions within the Okanagan (i.e., extreme floods and droughts).
- The general timing and magnitude of residual streamflows is consistent with Version 1 naturalized streamflow results, since these provide the basis for residual streamflow modelling. However, water withdrawals, reservoir releases, and water transfers result in slight differences to the hydrologic regime.
- To model reservoir releases, calibration with actual streamflow datasets resulted in the percentage of downstream water demands being increased in most watersheds by approximately 50%. This percentage accounts for uncertainty in the naturalized streamflows, the OWDM water demand estimates, and any streamflow loses and/or minimum streamflow requirements.
- For some watersheds, reservoir water levels were drawn down below expected minimum (invert) elevations. This is a result of reservoir constraint priorities implemented in Raven and/or the lack of detailed reservoir management information. However, modelled reservoir stage in other watersheds appears to generally follow operational activities.

7.3 General Model Result Limitations

Due to the various calibration datasets used (or lack of for some watersheds) for the naturalized and residual streamflow modelling, as well as the uncertainty in some model parameters and processes (e.g., vegetation interception, soil model), this section provides a qualitative summary of the Version 1 model results. This summary is intended to highlight model functionality limitations to make model users aware of existing limitations. Most of the model functionality limitations identified here have recommendations for improvement outlined in Section 9. It is expected that overall improvements to OHME and subsequent model functionality will be completed as future updates to Raven are released and/or improved, or as additional calibration datasets become available.

As outlined in Sections 7.1 and 7.2, the general model functionality of OHME V1 produces reasonable results under naturalized and residual streamflow conditions for all watersheds, and resultant low and high streamflows are generally within expected ranges. However, some general comments about OHME V1 functionality and resultant Version 1 modelled streamflow datasets are as follows:

- With the limited calibration information available per watershed, naturalized streamflow datasets produced by Associated (2019a) were used to support individual watershed calibrations. Although the datasets cover the modelling period of interest, they were produced using regional analysis and other scaling techniques. Thus, Associated (2019a) assigned a resultant data error rating to each dataset. For modelled naturalized streamflow datasets, at a minimum, the uncertainty would be equivalent to that reported by Associated (2019a).
- Large variability between modelled and observed SWE records exists in some watersheds. SWE is calculated by Raven and is largely dependent upon vegetation interception and the climate forcing data. Also, Raven calculates SWE as an HRU-averaged value, rather than a point measurement. Due to the spatial discretization of model watersheds within Raven, direct comparisons of HRU-averaged SWE and observed point SWE measurement are unlikely to match. This is largely due to uncertainty in the mapped location of snow courses

[7] No residual streamflow estimates were generated for Vernon Creek.

/ snow pillows within a watershed and its corresponding vegetation influence (i.e., open area versus under canopy). In addition, uncertainty in the climate forcing data can heavily influence the amount and timing of snowpack development and melt, particularly at lower elevations. Although the results for some SWE comparisons indicate simulated SWE magnitudes are less than measured values, the general timing of snowpack development and melt are consistent with observation datasets, which is critical to accurately represent the hydrologic regime in the model watersheds.

- The high daily variability of modelled streamflows observed in Calibrations 1 and 2 is likely a result of the conceptual nature of the HBV-EC model configuration, the uncertainty in vegetation interception, and soil representation within each watershed. Within the HBV-EC model configuration used within the OHMP, the top (i.e., active) soil thickness is calibrated to achieve an 'optimal' thickness. However, soil thickness influences the HBV-EC infiltration routine, subsequently influencing other soil parameters, and affecting the movement of water through the water column. The current upper and lower parameter bounds may require refinement to better represent soil water behaviour. In addition, due to the interdependency of model parameters and the automated calibration approach, rain and snow percentage interception values are currently allowed to vary up to 40%. While previous studies have reported interception values in this range (Carlyle and Moses 2011), it is expected that further refinement of other model components, and a better understanding of interception effects of different vegetation types, will help refine these parameters.
- The conceptual nature of the soil model (included within OHME V1), plus the lack of a groundwater module within Raven, results in a challenging physical representation of regional (valley floor) baseflow contribution in some watersheds (i.e., Mill and Coldstream Creeks). In addition, with limited calibration datasets at critical locations (e.g., upland and lowland areas), unique watershed characteristics may be oversimplified during calibration. It is expected that when groundwater representation is improved in Raven, the re-structuring of the conceptual soil and groundwater model(s) for select watersheds may be required to adequately improve streamflow representation under low flow conditions (when baseflow contribution is at its highest).
- Poor representation of low flow periods in Calibration 1 may be a result of focusing Calibration 1 to optimize the NSE based on year-round streamflows. This calibration approach tends to favour high flow periods, since the NSE emphasises the fit to peaks (Lane et al. 2019). Accordingly, model performance under this calibration may be sacrificed during low flow periods.
- Better representation of low flow periods in Calibration 2 is consistent with the understanding that the inclusion of both the NSE and L-NSE model diagnostics in calibration favours high and low flows more equally. However, further investigation and testing of the required weighting between NSE and L-NSE model diagnostics within the calibration for each model watershed, may yield better overall model calibration.
- For naturalized streamflow modelling, limited information about natural lake/reservoir outlet channel dimensions and sill elevations was available. It was assumed that existing spillway crest elevations for reservoirs were similar to historic natural sill elevations. Using existing spillway dimensions as initial crest width dimensions, the outflow crest widths were auto-calibrated by Raven to support meeting calibration targets downstream. Therefore, without knowing natural lake/reservoir dimensions, annual water level ranges, and/or outlet dimensions, the calibrated crest widths are considered reasonable for the naturalized conditions. Subsequently, since the calibration of crest widths was constrained by existing spillway dimensions, it was appropriate to carry forward calibrated crest widths to support residual streamflow modelling. Overall, the resultant reservoir water level fluctuations and releases under naturalized streamflow conditions are considered a reasonable estimate. These may be improved upon in the future, if historic bathymetric (or topographic) surveys used to support dam construction are located/available.
- Under residual streamflow conditions, upland reservoirs in some watersheds are being drawn down below established minimum (invert) water level elevations. This is a result of reservoir constraint priorities implemented in Raven. To operate reservoirs to support downstream demand in some watersheds (Section

6.2.2), Raven dynamically adjusts the 'minimum reservoir flow' for a given reservoir. This constraint is given priority over the 'minimum reservoir stage' for a given reservoir, which is used to define the invert elevation. Thus, downstream demand is supplied from reservoirs regardless of the reservoirs stage, until the reservoir is completely emptied. It is expected that future updates to Raven will improve the representation of automated reservoir operations, to ensure that the 'minimum reservoir stage' (i.e., invert elevation) is respected for these situations and prevent reservoirs being drawn down below this elevation.

- In some watersheds, minimum streamflow releases are implemented in practice at water supplier intakes (e.g., BMID – Mission Creek, DOS – Trout Creek); however, the current version of Raven does not have the functionality to implement and prioritize releases from upland reservoirs to meet downstream minimum flow needs. To accommodate for this, reservoir operations within Version 1 models were calibrated to available residual streamflow records below respective minimum flow locations in appropriate watersheds (e.g., Mission and Trout Creeks). This ensures that additional reservoir releases (i.e., minimum flows), in addition to downstream water demand, are considered. It is expected that future implementation of this functionality in Raven will improve reservoir modelling and allow for minimum flow release and/or EFN scenario modelling.
- There is little to no reservoir operation information for many upland reservoirs within the model watersheds. Thus, different modelling scenarios were outlined within Section 6.2.2 to account for the difference in available information. Several of the modelling scenarios let Raven auto-calibrate to downstream water demands and/or calibration targets. It is expected that future modelling can and will improve upon reservoir modelling, once Raven updates are implemented and additional calibration and reservoir management information becomes available.

8 CONCLUSIONS

OHME V1 was developed as a hydrologic modelling framework for the Okanagan Basin based on Raven. The development and application of OHME V1 was carried out as the key activity of the OHMP, and satisfies the need for a hydrologic modelling system that improves upon previous regional hydrologic model efforts, provides the basis for continued hydrologic assessments in support of regional water management and planning, and can be calibrated and run for 18[8] OBWB-selected watersheds. OHME embeds the open source Raven and the OSTRICH Optimization Software Toolkit within a flexible modelling environment. It is designed to be easily reconfigured to varying degrees of hydrologic complexity and spatial extents and accepts a wide range of evolving climate, geophysical, and land use inputs, allowing OHME to be applied to a wide variety of studies, assessments and reporting. It can be efficiently calibrated using highly scalable and economical cloud computing infrastructure and a range of sophisticated hydrologic model calibration methodologies. Finally, governance of OHME is facilitated via open source licensing and a structured version control and distribution model. Together, these characteristics of OHME directly satisfy the OBWB technical specifications (OWSC 2018) for the model developed as part of the OHMP. Specifically, the following requirements are addressed by OHME:

- **Ability to easily simulate both individual Okanagan watersheds, and combined watershed systems:** The implementation of Raven within OHME easily allows for simulations ranging from single watershed, to combined watershed systems, to every watershed defined within the OHME environment. Additional watersheds or watershed areas can easily be added, beyond the 19 model watersheds.
- **Ability to vary the spatial and temporal model complexity/resolution on a per-watershed basis:** OHME model construction workflows are designed to accommodate configuration of Raven models for a wide range of spatial and temporal resolutions. Therefore, Raven can be individually configured on a per-watershed basis to best represent watershed-specific spatial processes and temporal scales.
- **Use of best available climate forcing data:** OHME makes use of recent updated climate forcing data (Associated 2019b). OHME contains script-based tools to efficiently preprocess the full suite of necessary Raven and OSTRICH input datasets on an as-needed basis. This capability ensures that future OHME versions will stay abreast of rapidly evolving climate, land use, and other datasets, with minimal effort.
- **Better incorporation of an approach for representing groundwater:** While OHME V1 contains a Raven version that does not yet demonstrate a full groundwater component, ongoing work to develop this is underway by the Raven Development Team. Given OHME-based version-controlled linkage to Raven development activities, it will be possible to easily implement a more detailed groundwater routine once it is available from the Raven Development Team, and perform configuration and calibration OHME V1 steps with the updated integrated Raven model.
- **Ability to link with the OWDM:** OHME workflows can quickly and efficiently ingest OWDM model output into Raven simulations.
- **Ability to update the model in the future:** OHME includes a comprehensive Git-based version control system, and SVN-based version-control linkages to the core Raven development repository. Thus, OHME is explicitly designed for ease of upgrading as new Raven capabilities and user-based OHME developments emerge.
- **Ability to access output at user-selectable locations:** Raven can provide output from all spatial units of the model. Thus, users can access simulated streamflow and other information from any Raven simulation on an individual HRU-by-HRU basis (as well as broader integrated measures across sub-basins or whole watersheds).

[8] The spatial extent included within OHME V1 includes 19 key Okanagan watersheds. However, due to the complexity of the Vernon Creek watershed and the lack of available naturalized streamflow calibration records, the naturalized streamflow modelling produced unrealistic results and was not investigated further within Version 1 naturalized or residual streamflow calibrations.

- **Ability to easily run future climate scenarios on a watershed-specific basis:** Although not currently available within OHME V1, the capability to perform watershed-specific simulations, coupled with establishment of robust, script-based input data workflows and cloud-based workflows, means that cutting-edge, ensemble-based OHME-based hydrology/climate change assessments will be technically straightforward to implement.
- **Ability to intuitively and easily develop input data, initiate a model run, and analyze output data:** The automated, script-based nature of OHME is directly intended to support rapid, transparent, and reproducible model setup, run, and analysis. As a result, Okanagan-based Raven simulations using OHME can be developed efficiently, with a minimum of repetitive or manual input.
- **Internal process models must reflect the relative importance of watershed-specific hydrologic cycle elements:** Raven is designed for maximum flexibility in watershed process representation, via the inclusion of a wide variety of hydrologic process representations. OHME V1 includes a Raven configuration with a set of process representations that is intended to best capture the processes present across all model watersheds. Future OHME versions, especially those designed for user-driven investigations of specific watershed characteristics or hydrologic trends, can be easily adapted from the OHME V1 base configuration on a per-user basis.

These characteristics of OHME represent a significant upgrade from previous modelling efforts, particularly the OBHM developed as part of the OWSDP. Together, they ensure that the OHME framework is suitable for the range of Okanagan-specific hydrologic applications and purposes identified by OBWB (OWSC 2018). In addition, they are designed so that OHME remains future-proofed as input datasets, Raven capabilities, and computing frameworks rapidly evolve. They also ensure that Okanagan-based advances in hydrologic modelling are well-placed to contribute to broader provincial and national hydrologic initiatives.

OHME V1 usage has currently been demonstrated for 18 of the model watersheds by way of implementing two calibration approaches (i.e., Calibration 1 [NSE focused] and Calibration 2 [NSE / L-NSE focused]). Based on these calibrations, the following conclusions are made:

- **Watershed-specific calibrations focussed on reflecting naturalized streamflows at the apex of the alluvial fan were completed:** Naturalized streamflow estimates developed by Associated (2019a) provide the only calibration datasets representative of natural streamflow conditions in most of the key Okanagan watersheds, while only four long-term WSC hydrometric stations measuring natural streamflows are present in the Okanagan Basin. Thus, due to the sparsity and geographic separation of long-term WSC hydrometric stations in the Okanagan Basin, a 'global' calibration using the WSC hydrometric stations alone did not yield adequate results. Therefore, watershed-specific calibrations were completed. However, in the future adjustments to the model configuration, model parameters included in calibration, and/or improvement in input data may allow select model parameter representation to be better constrained. OHME V1 allows all model watersheds to be simulated in unison to determine a 'global' parameter set(s).
- **The conceptual HBV-EC model configuration yields reasonable streamflow results at the apex of the alluvial fan within most of the model watersheds based on Version 1 calibrations:** Calibration 1 results generally represent the timing and magnitude of peak flows, while low flows are typically underestimated in most model watersheds. Conversely, Calibration 2 results generally provide better representation of low flows at the slight expense of model performance during high flow periods.
- **Version 1 calibrations highlight the need for case-specific calibrations:** The effect of different calibration targets is critical to appropriate model use. The results of Calibration 1 and Calibration 2 are achieved based on the same model configuration and same model parameter bounds within calibration yet yield different results because of the model diagnostic value(s) targeted during calibration.

- **Calibrations/model results can generally be improved by way of additional calibration runs:** The process of calibration is iterative and can generally always be improved upon. The Version 1 calibrations provide reasonable Version 1 model results. However, additional calibrations – ideally facilitated by expanded observational hydrologic data collection efforts - would likely further refine and constrain streamflow estimates, for example at the apex of alluvial fans.
- **Residual streamflows are consistent with Version 1 naturalized streamflows, but reservoir management representation can likely be improved upon:** Reservoir operations are challenging to replicate and/or automate without actual information/datasets. Within the model watersheds there is limited information available. Thus, several reservoir management scenarios were established in OHME V1 to account for different operating strategies. However, in some watersheds under residual streamflow conditions, reservoir water levels were drawn down below expected minimum (invert) elevations. It is expected that as Raven updates are implemented, and additional calibration information becomes available, reservoir operations will be improved upon.

9 RECOMMENDATIONS

OHME is a comprehensive, Okanagan-based hydrologic model framework that provides Okanagan users with an open-source Raven-based hydrologic modelling capability that is integrated into a broader environment that includes robust data management, pre- and post-processing, version control, and cloud computing. These capabilities allow the potential for extensive further OHME development and adaptation in support of new OHME versions (beyond OHME V1) and diverse array of operational and research applications. The following actions are considered priorities for future OHME development and use:

- **Develop a web-based user interface, basic training and a customized user-specific training framework:** OHME is a full-featured modelling system that will require investment by new users to access, use, and develop. OHME is web-hosted via Bitbucket, and this hosting allows for easy public distribution of OHME, as well as web-based documentation. Beyond this capability, there is additional potential to develop a web-based graphic user interface (e.g., to configure and run full-featured cloud-based Raven simulations and OSTRICH calibrations directly from the web). This approach is emerging as a mechanism to engage water professionals with no modelling experience but who are nonetheless interested in OHME application. A robust web-based presence would facilitate widespread OHME use within and beyond the Okanagan Basin. Beyond web-based OHME access, OBWB should expect that different applications of OHME will require different training levels and training targets. A plan should be established to support customized OHME training across the spectrum of potential training needs, as these needs develop and evolve.
- **Improve the quantity and quality of input data:** Successful hydrologic modelling depends on the quality of input datasets. There is room for improvement in many Okanagan-specific input datasets used within OHME, for example:
    - Soils and gridded climate data are poorly constrained by in-situ measurements, especially at high elevations.
    - Okanagan-specific physical vegetation information (e.g., leaf-area index) is poorly constrained by in-situ measurements.
    - Water management data (e.g., reservoir operations) are sparse or inadequate in many locations.
    - Direct streamflow observations from hydrometric stations, used to calibrate Raven simulations, are extremely limited in the Okanagan.

  Improvement across these fronts should continue, as this has the potential to greatly improve the quality of OSTRICH-calibrated Raven output. This recommendation mirrors similar recommendations related to regional data quality (Associated 2010; Associated 2017b).
- **Monitor and apply Raven modelling advances using version controlling:** Raven will continue to rapidly evolve as new hydrologic processes are included (e.g., full groundwater representation), new input data becomes available, new calibration methods emerge, obsolete model code is removed, and software bugs are identified and fixed. For OHME to leverage this development, OHME should retain an operational version-controlled link to the Raven source code repository, and maintain steady personal communication between OHME administrators and users and the Raven Development Team.
- **Further develop watershed-specific and application-specific Raven conceptual designs for user needs:** The OHMP scope involved development of 19 watershed models within a unified hydrologic modelling environment. This approach, which was carried out successfully as part of OHME V1 development, forms the basis for development of focussed watershed-specific and application-specific future Raven configurations. Such configurations will almost certainly involve custom conceptual designs, tailored specifically to maximize model fidelity for unique watershed characteristics and applications (e.g., detailed watershed-specific land use change or watershed management analyses). Users interested in watershed-specific and application-specific

analyses should acquire OHME V1 for the watershed of interest and modify the Raven conceptual design from this proven baseline to address specific analysis needs.

- **Further refine watershed-specific parameter sets and develop a global parameter set appropriate for use in Okanagan watersheds where no appropriate calibration datasets exist:** Version 1 model results and resultant parameters sets provide a reasonable naturalized and residual streamflow datasets and corresponding parameter sets for 18 of the 19 model watersheds. However, further refinement of parameter values and bounds included within calibration may provide improved results. In addition, using watershed-specific calibrations completed within the OHMP as a starting point, a 'global' calibration approach should be developed to provide an optimal parameter set for use within watersheds outside of the current 19 model watersheds that may not have appropriate datasets available to support watershed-specific calibrations. To support 'global' calibrations, OHME V1 allows land use, vegetation, and soil parameters to be 'grouped' in order to reduce the overall number of parameters included within a calibration.
- **Further develop watershed-specific and application-specific OSTRICH calibration and parameter sensitivity procedures for user needs:** The OHMP scope involved the calibration of 19 watershed models within OHME, using a common OSTRICH calibration methodology applied to the entire (annual) streamflow time series in each watershed for a common calibration period. While this produces calibration results that are intended to generate a reasonable fit across all seasons and watersheds, future applied hydrologic assessments using OHME could require calibration approaches tailored to maximize watershed-specific calibration over other specific time periods, against different metrics, and using different OSTRICH-hosted calibration methodologies. Users interested in watershed-specific and application-specific analyses should acquire OHME V1 model results for the watershed of interest, and subsequently modify the default OHME V1 OSTRICH-based calibration design and add OSTRICH-based parameter sensitivity assessments as needed to address specific analysis needs.
- **Develop robust software support mechanisms to support OHME maintenance, distribution, and governance:** As with other complex open source software intended for ongoing collaborative use and development, OHME requires active and robust software support mechanisms to be maintained, distributed, and effectively governed. Without ongoing support, there is a high likelihood that OHME-based Raven and OSTRICH components will become outdated, the overall OHME structure will drift out of consistency with evolving computing platforms and techniques, and OHME input data will be rendered obsolete by rapidly evolving data sources. To remedy decreased user confidence, the OBWB should develop a plan to support the OHME software environment in a consistent and ongoing manner via web-based Git version control and establishment of a responsive in-house, virtual, or model community-based on-demand software expertise.
- **Develop robust scientific support mechanisms to support OHME use and development:** Raven is a complex and full-featured, research-grade hydrologic model. As a result, non-expert users may be challenged to understand the full breadth of (rapidly evolving) Raven capabilities, as well as the capabilities of other OHME components such as OSTRICH, version control, or cloud-based computing workflows. This may impede their ability to quickly and/or correctly apply OHME to real-world applications. To ensure that users are adequately informed as to OHME usage, and underlying hydrologic modeling and physical fundamentals, the OBWB should develop a plan to facilitate expert level hydrologic expertise and assistance for OHME users. This would be greatly aided by active OBWB participation in established regional, provincial, and federal-level hydrologic modelling forums. Aside from strengthening the OHME scientific user support community, such participation will strengthen OBWB links to the broader hydrologic modelling community, with expected clear benefits for the Okanagan-based hydrologic knowledge base.
- **Integrate OWDM algorithms directly into Raven:** Currently, the OWDM is a separate modelling framework, which is run prior to Raven simulations to develop required water demand data. While this approach is feasible in practice, as demonstrated by its use in the 19 watershed model simulations, a more streamlined

workflow would involve either the recoding of all OWDM algorithms directly into the Raven source code or recoding of the OWDM into an amenable script-based format that could be called within the broader automated OHME workflow. It is recommended that this work to recode the OWDM be undertaken.

In addition to OHME-focused recommendations above, Version 1 model results highlighted some further refinements to Raven routines that are recommended to improve model results, particularly under residual streamflow conditions:

- **Determine unmet water demand:** Within Raven, water demand is only extracted if positive streamflows can be maintained at the sub-basin outlet (Section 3.1). It is possible that not all water demand is being satisfied by modelled streamflows. It is recommended that the volume of "unmet" demand be determined and reported by Raven. This would provide model users more information on how water demand is affecting modelled streamflows and may help to better inform reservoir management within Raven.
- **Include temporal constraints on estimated reservoir releases:** The current iteration of the routine included to estimate reservoir releases based on downstream demand allows downstream demand to be supplied year-round by adjusting the minimum reservoir releases of upstream reservoirs. However, in practice, upland reservoirs are typically operated primarily to support downstream demand during irrigation season (i.e., April – September) Therefore, it is recommended that this new routine be further refined in Raven to allow temporal constraints (e.g., julian day) on when reservoirs are available to support downstream demand within the model.
- **Minimum reservoir stage should be respected by estimated reservoir releases:** The current iteration of the routine to estimate reservoir releases based on downstream demand does not consider the minimum reservoir stage constraint of each reservoir. As a result, the downstream demand is met regardless of the reservoir stage. Within Version 1 model results, this caused many reservoirs to be drawn below the known invert elevation of the outlet, and subsequently to the bottom of the reservoir in some cases. In practice, reservoirs cannot be operated to provide releases below their outlet. Thus, reservoir releases should be zero when the reservoir stage reaches this elevation. It is recommended that this new routine in Raven be further refined to ensure that reservoir minimum stage constraints are considered to prevent reservoirs being drawn down below this elevation.
- **Water system- or watershed-specific reservoir demand adjustment:** The current iteration of the routine to estimate reservoir releases based on downstream demand allows the downstream demand supported by reservoirs to be adjusted using a global multiplier. However, within the Okanagan, water purveyors often operate systems differently within and between model watersheds. It is not currently possible to assign different demand adjustments to different watersheds to facilitate multi-watershed calibration of this parameter. It is possible to manually distribute demand requirements for each sub-basin/reservoir (as completed in Mill and Mission Creeks within the OHMP); however, specifying watershed-specific global multiplier parameters would allow for more streamlined calibration when watersheds are calibrated in unison.

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APPENDIX A – MODEL SELECTION FOR USE WITHIN THE OKANAGAN BASIN

Date:	January 9, 2019 **File:** 2018-8215.000.003
To:	OBWB Hydrologic Modelling Project Steering Committee
From:	Project Model Selection Team
Project:	Okanagan Hydrologic Modelling
Subject:	Model selection for use within the Okanagan Basin

MEMO

1 INTRODUCTION

The Okanagan Basin Water Board (OBWB) is looking to improve and expand upon the hydrologic modelling that was completed during Phase 2 of the Okanagan Water Supply and Demand Project (OWSDP). Specifically, updated hydrologic modelling is required within 19 Okanagan Basin watersheds to address user needs (now and in the future), as well as to allow for the following (in the future):

1. Further enhancements when additional information becomes available (e.g., confined/unconfined aquifer representation, alluvial fan complexes);
2. Changes in spatial scales (e.g., tributary watershed versus entire Okanagan Basin);
3. Changes in unique watershed features (e.g., reservoir storage increases, new water licences, environmental flow needs); and
4. Future scenario investigations (e.g., climate change, population growth, land use/infrastructure changes).

The first step to improve hydrologic modelling within the Okanagan Basin is to identify an appropriate model software/framework that meets current user needs and addresses the limitations of the OWSDP models. To select the most appropriate model software/framework, model grading criteria were developed by the Project Model Selection Team (Associated 2018) and agreed upon by the OBWB Hydrologic Modelling Project Steering Committee (PSC). Herein, the model grading criteria are applied to selected candidate models to identify the most appropriate model for use within the Okanagan Basin to meet existing user needs.

2 MODEL GRADING CRITERIA

Based on the user needs summarized by Associated (2018), 17 grading criteria were established to assess the applicability of selected candidate models for use within the Okanagan Basin. The grading criteria and their associated importance weighting, as agreed upon by the PSC, are summarized in Table 2-1[1]. Definitions for each of the model grading criteria (by category) are provided following Table 2-1 for improved clarity.

[1] Some criteria and/or importance weightings have been updated slightly from those originally reported by Associated (2018) to incorporate comments from the Project Model Selection Team members and the PSC.

Table 2-1 Model grading criteria

General Category	Grading Criterion	Importance Weighting	Poor Score (1) Definition	Excellent Score (5) Definition
Model Design and Complexity	Physical Basis	4	*Excessively conceptual or excessively physical.*	*Appropriately physically comprehensive.*
	Inclusion of Necessary Natural Watershed and Climatological Processes	5	*Major natural hydrological and climatological processes represented in basic form.*	*All necessary natural hydrological and climatological processes represented in complex form.*
	Inclusion of Necessary Regulated Hydrological Processes	5	*No necessary regulated hydrological processes represented.*	*All necessary regulated hydrological processes represented.*
	Land Surface Discretization	4	*Excessively lumped or excessively spatially discretized.*	*Appropriately spatially discretized to meet all user needs.*
	Model Output Discretization	3	*Modelled streamflows are provided at one location.*	*Modelled streamflows are provided at multiple locations across the watershed.*
	Temporal Discretization	4	*The model operates only on a daily or greater time-step.*	*The model time-step can be varied.*
Input Data and Calibration	Availability of Required Input Datasets and Default Parameters	5	*No required input data is available.*	*All required input data already exists. No adaptations are required.*
	Integration of Existing Water Demand Datasets	5	*The model does not allow for consideration of water demand for domestic, agricultural, and industrial purposes.*	*The model allows for the computation of water demand for domestic, agricultural, and industrial purposes.*
	Model Calibration	3	*Model calibration procedures are not defined, and model not associated with specific calibration software.*	*Multi-point, multi-variable calibration procedures are well defined and associated with specific calibration software.*
Model Flexibility	Groundwater complexity	3	*No future upgrades to groundwater simulation capabilities are possible.*	*Groundwater capabilities are highly amenable to future improvement/replacement.*
	Flexibility to Configure and/or Update Hydrological Processes	4	*Hydrological processes cannot be configured, and no future upgrades are possible.*	*Hydrological processes can be configured and are highly amenable to future improvement/replacement.*
	Hydraulic Simulation	2	*No hydraulic simulation integration is possible.*	*Fully integrated hydraulic simulation routines exist or can be integrated.*
	Integration for Basin-wide Hydrologic Model	4	*Once developed, individual modelled spatial extents cannot be linked.*	*Full integration between modelled spatial extents can be achieved.*
Model Applicability and Usability	Relation to Existing and Future Okanagan Modelling Efforts	4	*The model is not being used in the Okanagan and is not a candidate model for future modelling exercises.*	*The model is actively being, or has been, successfully used in the Okanagan.*
	Model Developer Support	3	*No formal support and model documentation is not readily available.*	*Extensive model support is available from online and in-person resources, and model documentation is readily available.*
	Usability and Computational Efficiency	4	*The model is slow to complete simulations and has no ability to process simulations concurrently.*	*The model can be fully automated and is amenable to cloud-based processing for concurrent simulation processing.*
	Model Licensing and Source Code Availability	3	*Model licence is required, and source code is not readily available.*	*Model is open-source and source code is readily available.*

Model Design and Complexity

1. **Physical Basis** – Hydrologic models can be based on detailed descriptions of physical processes, or primarily conceptual. To correctly represent hydrologic processes within the Okanagan Basin, an appropriately physically based model is required that sufficiently represents all important processes identified as part of the user needs survey (Associated 2018).
2. **Inclusion of Necessary Natural Watershed and Climatological Processes** – The selected model must be able to represent (in sufficient detail) the important natural controls on hydrology and hydrogeology that impact the Okanagan Basin. These include interactions with meteorological conditions, snow accumulation and melt (e.g., degree day or energy balance approach), evaporation (e.g., FAO Penman Monteith approach), heterogenous natural land type descriptions, shallow and deep groundwater, surface/groundwater interactions, and stream routing.
3. **Inclusion of Necessary Regulated Hydrological Processes** – The selected model must be able to represent (in sufficient detail) the important human controls on hydrology that impact the Okanagan Basin. These include reservoirs, dams, transfers, and water licences for various water use purposes.
4. **Land Surface Discretization** – Spatial distribution can vary from lumped models (i.e., one value for climate forcing over the entire domain) to fully distributed (i.e., climate forcing data distributed across the model domain based on grid cells, or hydrological response units). To appropriately represent hydrologic processes within the Okanagan Basin, an appropriate spatial discretization is required that captures a level of spatial resolution that is sufficient for all users.
5. **Model Output Discretization** – Understanding that some models generate streamflow estimates at a different spatial resolution to input data, the ability of the model to generate streamflow estimates at selected locations must be considered.
6. **Temporal Discretization** – Since the selected model is intended to support a variety of users for different purposes (particularly users concerned with shorter-time scale hydrological processes [e.g., flood hazard assessments and water allocation decisions]), the selected model must initially be capable of operating at a daily time-step. However, the ability to model at a sub-daily time-step in future (dependant on future data availability) is desirable and should be considered.

Input Data and Calibration

7. **Availability of Required Input Datasets and Default Parameters** – Input data requirements (i.e., spatial and temporal) will vary depending on the degree of watershed discretization and model process representation. The degree of effort to develop or alter existing required spatial and temporal datasets to satisfy model requirements must be considered. For example, the ability of the model to use gridded climate data is desired.
8. **Integration of Existing Water Demand Datasets** – Based on information provided in the user needs survey (Associated 2018), the selected model must be able to incorporate water demand data and spatial datasets (i.e., agricultural land use inventory, soils) from the existing OWDM.
9. **Model Calibration** – The selected model should be closely associated with well-developed secondary model calibration software (e.g., OSTRICH, SWAT-CUP) to facilitate sensitivity analyses and model calibration of streamflow and other important modelling parameters against available data at multiple locations.

Model Flexibility

10. **Groundwater complexity** – Currently, the Okanagan Basin has limited information available on shallow and deep groundwater systems within respective watersheds and/or on alluvial fans. Similarly, well record availability can be limited; thereby limiting development of two (2D) or three-dimensional (3D) groundwater models (e.g., MODFLOW[2]). However, recent and ongoing groundwater investigations within the Okanagan Basin (e.g., Mission Creek Groundwater / Surface Water Interaction Study) are improving the understanding of groundwater interactions within select sub-basins. Accordingly, the selected model should allow for immediate groundwater system representation, but should be flexible to allow for more complex groundwater representation (i.e., 2D/3D models) to be integrated in the future.
11. **Flexibility to Configure and/or Update Hydrological Processes** – Improvements or adjustments to physical processes within the model framework may become necessary as understanding of Okanagan Basin hydrological controls and hydrological process modelling capabilities (e.g., surface/groundwater interactions) improve. In addition, it may be necessary to migrate agricultural aspects of the Agricultural/OWDM into the hydrological model. Accordingly, the selected model should allow hydrological process representation to be varied by the user, and more complex consideration of hydrological components to be integrated in the future.
12. **Hydraulic Simulation** – The ability of modelled streamflow datasets to support floodplain mapping in urban centres (e.g., Kelowna, Vernon, Penticton) within the Okanagan Basin is desired. Accordingly, the ability of the selected model to link with, or have integrated, a hydraulic analyses component to simplify the transition between watershed hydrologic modelling and site-specific hydraulic simulation to support floodplain mapping would be useful.
13. **Integration for Basin-wide Hydrologic Model** – Understanding that a basin-wide hydrologic model may be desired in future, the ability of the selected model to be able to perform simulations that span watersheds, as well as reasonably simulate the characteristics of the large mainstem lakes, must be considered.

Model Applicability and Usability

14. **Relation to Existing and Future Okanagan Modelling Efforts** – Understanding that existing modelling projects are underway within the Okanagan Basin (e.g., development of inflow model for Okanagan Lake) and additional modelling efforts are expected in future (e.g., Okanagan mainstem lake floodplain mapping), the ability of the selected model to interface and/or integrate with these modelling efforts must be considered. In addition, proven successful model implementation in similar BC interior environments should be considered.
15. **Model Developer Support**– Understanding that the selected model is intended to be used by multiple users, user support from the model developer and the availability of source code must be considered. Support from the model developer should be considered to include user manuals, workshops, and online forums, at a minimum.
16. **Usability and Computational Efficiency** – Understanding that the selected model must be applied to various Okanagan Basin tributaries to develop streamflow datasets for multiple locations over a multi-year period, computational efficiency must be considered. Computational efficiencies can be obtained through cloud-based computing (e.g., Google Cloud Platform) and the ability to process to multiple model runs concurrently.

[2] MODFLOW is a sophisticated groundwater model developed by the US Geological Survey.

17. **Model Licensing and Source Code Availability** – Understanding that some hydrologic models are open-source and based upon a community development framework, whilst others are offered for purchase from proprietary sources, model licensing costs must be considered. In addition, the availability of source code to allow custom configuration of hydrological processes must be considered.

3 SELECTED CANDIDATE MODELS

3.1 Existing Hydrologic Model Reviews

Understanding that there are many different hydrologic models in use across Canada and worldwide, it is unreasonable to assess the applicability of all of them for use within the Okanagan Basin. Accordingly, previous relevant model reviews are drawn upon to identify candidate models that have previously been considered for use within the Okanagan Basin, or within similar BC interior and North American environments. The following reviews and comparisons of hydrologic models have been used to identify and evaluate candidate models:

- **WMC (2008)**: During Phase 2 of the OWSDP, WMC (2008) completed a similar process to select the most applicable hydrological model to develop an Okanagan Basin wide water balance model. The objective of the Phase 2 model was primarily intended to evaluate future water supply and demand scenarios resulting from a changing climate and land use types. To this end, the model was calibrated at a tributary level for the period 1996-2006 (i.e., the period with the most available information on streamflows and actual water use). Accordingly, many of the user needs identified during the Phase 2 model selection process still remain valid for this current modelling scope; therefore, the model descriptions and selection criteria included in WMC (2008) provided a starting point for the model selection process completed herein.
- **Cunderlik et al. (2013)**: BC Hydro commissioned a model comparison and selection process to assist with the selection of a (potentially) new hydrological model to be used for operational purposes throughout BC. A rigorous evaluation framework was established to compare four candidate models' performance across three test basins within BC. Within the study, a detailed overview of model structure, computational strategies, and model parameterization was provided.
- **Alberta WaterSMART (2015)**: To support assessment of the past and potential future changes to water quantity and water quality within the Athabasca River Basin (ARB), Alberta WaterSMART (2015) completed a review of candidate models applicable for use within the ARB. Whilst the ARB exhibits a different hydrological regime to the Okanagan Basin, many of the grading criteria and model descriptions remain applicable.
- **Gayathri et al. (2015)**: Providing a high-level description of fundamental differences between hydrological model types, as well as brief descriptions for select models, this review provides context for some of the differences observed between select candidate models.
- **Beckers et al. (2009)**: Although dated, this review of 27 hydrological models provides a valuable comprehensive review of many of the candidate models. The extensive model summaries provide many of the key features/limitations of each model and provide a baseline for the model grading completed herein. This review focused on the application of hydrologic models to forest management and climate change application in BC, providing many relevant criteria to meet the user needs of this current review.

3.2 Candidate Models

Eight candidate models have been identified as appropriate for use within the Okanagan Basin. The models were selected from those previously identified by WMC (2008), the Project Model Selection Team's experience using the models, as well as the current and historic use of hydrologic models within the Okanagan Basin. The eight candidate models are identified as follows:

- **University of British Columbia Watershed Model (UBCWM):** Developed in the 1970's, UBCWM was originally intended to provide runoff estimates from mountainous watersheds within BC (Quick and Pipes 1976). The model centres on operating in areas of sparse climatic data and thus, can interpolate climate data from discreet points across the entire watershed, if required. UBCWM has an integrated optimization routine for precipitation distribution, and routing constants (WMC 2008); as well, it has been successfully coupled with multiple optimization and/or uncertainty estimation tools (Cunderlik et al. 2013). UBCWM has been successfully applied and calibrated to many watersheds in different physiographic and climatic zones of BC, including the Alouette, Finlay, and Mica River watersheds as part of the BC Hydro intercomparison study (Cunderlik et al. 2013). Furthermore, the UBCWM was historically used by BC Hydro for operational forecasting.
- **Environment Canada modification of the Hydrologiska Bryåns Vattenbalansavdelning Model (HBV-EC):** The HBV model is a conceptual hydrological model originally developed for use in Scandinavia in the early 1970's. The HBV model has been modified and applied in over 40 countries around the world. Environment Canada and the University of British Columbia (UBC) modified the original HBV model for use within Canada in the mid-1980's (i.e., HBV-EC). HBV-EC has been incorporated into the Green Kenue software developed by the National Research Council Canada (NRC) to provide enhanced data processing, analysis, and visualization capabilities for the model (Cunderlik et al. 2013). HBV-EC has previously been applied in the Okanagan Basin (e.g., climate change studies [Merritt and Alila 2003], Mission Creek Water Use Plan [WMC 2010]).
- **WATFLOOD:** WATFLOOD is a distributed hydrological model developed in the 1970's by the University of Waterloo's Department of Civil and Environmental Engineering. WATFLOOD is optimized to make use of remotely sensed data (e.g., LANDSAT, SPOT land use/cover, radar rainfall data) to perform flood forecasting and long-term hydrologic simulation. WATFLOOD has been applied in many watersheds in BC, including two large mountainous snowmelt-dominated watersheds (i.e., Columbia and Peace Rivers) (Beckers et al. 2009).
- **MIKE SHE:** MIKE SHE is a fully distributed hydrological model originally developed in the 1970's and is currently distributed by the Danish Hydrological Institute (DHI). MIKE SHE has previously been used within the Okanagan Basin during Phase 2 of the OWSDP. MIKE SHE is a surface water / groundwater coupled model with the ability to complete full three-dimensional groundwater modelling. MIKE SHE is developed within the MIKE suite of hydrologic and hydraulic models; accordingly, MIKE SHE can be interfaced with other MIKE modelling softwares to complete additional analyses.
- **Hydrologic Engineering Centre – Hydrologic Modeling System (HEC-HMS):** HEC-HMS is a semi-distributed model developed by the US Army Corps of Engineers to support modelling of natural and urban runoff. Further development of HEC-HMS now allows for sediment transport modelling, water quality modelling, flow forecasting, and depth-area analysis (Alberta WaterSMART 2015). HEC-HMS has been successfully applied worldwide, including northwestern USA (e.g., forest fire impact studies [Kinoshita et al., 2014] and extreme flood investigations [Tripathi et al., 2014]) and within Shuttleworth Creek (within the Okanagan Basin) to simulate pre- and post-dam decommission streamflows (SNCL 2015).
- **Variable Infiltration Capacity (VIC) Macroscale Hydrologic Model:** VIC is a coarse-scale, semi-distributed hydrological model developed by the University of Washington. VIC can be coupled with global circulation models

to solve full water and energy balance equations to assess the effects of climate change on a macroscale. VIC discretizes the land surface into large, uniform cells of at least 4 km^2 and performs vertical energy and water transfer within each cell. VIC does not consider lateral transfers between grid cells; streamflow routing must be completed by integrating a separate routing model (e.g., Lohmann et al. 1996; 1998).

- **Raven Hydrological Modelling Framework (Raven):** Raven is a universal, flexible hydrological modelling framework. Spatial discretization within Raven can be user defined, ranging from lumped to fully distributed. Centred on providing the user complete transparency to model development, Raven can integrate select parameter algorithms from other, well established hydrological models (e.g., UBCWM, HBV-EC). Raven is open-source with a large community user group across Canada and the US. Raven has proven successful integration with the OSTRICH model calibration platform and is amenable to full automation due to its command-line execution and text file input/output structure. In addition, Raven is currently being used to develop an inflow forecasting model for Okanagan Lake, and is proposed to be used to support floodplain mapping of the Okanagan mainstem lakes.
- **Soil and Water Assessment Tool (SWAT):** SWAT is an established semi-distributed open-source hydrological model developed by the Texas A&M University and US Department of Agriculture - Agriculture Research Service. SWAT was primarily developed to assess the impacts of land management practices on water resources, pollution, and climate change at a watershed-scale. Spatial discretization occurs via sub-basins, within which hydrologic response units (HRUs) representing discrete land types can also be applied. SWAT has been applied recently in Alberta to assess combined impacts of natural and regulated hydrological processes. A version of SWAT can also be coupled to MODFLOW to represent the coupled surface/groundwater system and related interactions. SWAT also has an associated calibration software package (i.e., SWAT-CUP).

4 MODEL GRADING

Based on the model reviews completed above, as well as the experience of the Project Model Selection Team, relevant components of each candidate model are summarized in Table 4-1. Using the information from Table 4-1, each model was graded using an importance-weighted sum of all model grading criteria to identify the most applicable candidate model for the current modelling scope. The grading was completed using a census approach by the Project Model Selection Team. A summary of the model grading and results is provided in Table 4-2.

Based on the model grading criteria results (Table 4-2), the Raven hydrological modelling framework achieved the highest score, followed by MIKE SHE (2nd place) and SWAT (3rd place). Raven achieved a grading value (306) of more than one standard deviation above the average model grading (216), and approximately 10% above the grading value of 2nd place MIKE SHE (273). Following the model grading criteria results, **the Raven hydrological modelling framework is recommended to support the current modelling scope.**

Table 4-1
Candidate model summaries

General Category	Grading Criterion	Importance Weighting	Poor Score (1) Definition	Excellent Score (5) Definition	UBCWM	HBV-EC	WATFLOOD	MIKE SHE	HEC-HMS	VIC	RAVEN	SWAT
Model Design and Complexity	Physical Basis	4	Excessively conceptual or excessively physical.	Appropriately physically comprehensive.	Predominantly Empirical; Selected Physically based processes	Predominantly Empirical	Predominantly Empirical	Variable	Predominantly Empirical	Physically based	Variable	Physically based
	Inclusion of Necessary Natural Hydrological and Climatological Processes	5	Major natural hydrological and climatological processes represented in basic form.	All necessary natural hydrological and climatological processes represented in complex form.	**Evaporation/Evapotranspiration:** Empirical evapotranspiration **Snow Accumulation:** Elevation & Temperature dependent **Snowmelt:** Energy balance method **Groundwater Flow:** Linear reservoir method (slow or very slow reservoirs) **Subsurface Runoff:** Linear reservoir method **Lakes:** Included **Streamflow Routing:** Linear reservoirs	**Evaporation/Evapotranspiration:** Empirical evapotranspiration **Snow Accumulation:** Temperature threshold **Snowmelt:** Temperature Index **Groundwater Flow:** Linear reservoir method (fast and slow reservoirs) **Subsurface Runoff:** Linear reservoir method **Lakes:** Not included **Streamflow Routing:** Linear reservoirs	**Evaporation/Evapotranspiration:** Preiestley-Taylor or Hargreaves **Snow Accumulation:** Percent of snow-covered area **Snowmelt:** Temperature Index or Radiation-Temperature algorithms **Groundwater Flow:** Not included - baseflow calculated using power function of drainage to lower zone **Subsurface Runoff:** Storage-discharge relationship **Lakes:** Included **Streamflow Routing:** Storage routing technique	**Evaporation/Evapotranspiration:** Kritensen and Jensen (1975) method **Snow Accumulation:** User specified threshold **Snowmelt:** Degree-day method **Groundwater Flow:** 3D Saturated Flow or Linear Reservoirs (fast and slow) **Subsurface Runoff:** 3D Saturated Flow or Linear Reservoirs (fast and slow) **Lakes:** Included **Streamflow Routing:** Forced by stream network file	**Evaporation/Evapotranspiration:** Preistley Taylor (calculated at monthly timestep) **Snow Accumulation:** Temperature threshold **Snowmelt:** Tempraure Index or distributed by elevation band **Groundwater Flow:** Multiple reservoirs **Subsurface Runoff:** Multiple methods **Lakes:** Included **Streamflow Routing:** Multiple methods	**Evaporation/Evapotranspiration:** Energy-budget approach **Snow Accumulation:** Temperature threshold **Snowmelt:** Snow accumulation and melt based on energy-budget approach **Groundwater Flow:** Not included **Subsurface Runoff:** Linear reservoir method **Lakes:** Included **Streamflow Routing:** Routed to edge of grid cell - intercell routing completed using stream network	Raven allows the user to select from a list of over 80 hydrological process algorithms and over 40 forcing function generators to customize the model as needed. Near-exact emulation has been completed for HBV-EC, GR4J and UBCWM hydrologic models	**Evaporation/Evapotranspiration:** Multiple methods **Snow Accumulation:** Temperature threshold **Snowmelt:** Temperature threshold of air and snowpack, areal coverage of snow, and melt rate **Groundwater Flow:** Reservoir **Subsurface Flow:** Reservoir **Lakes:** Included **Streamflow Routing:** Multiple methods
	Inclusion of Necessary Regulated Hydrological Processes	5	No necessary regulated hydrological processes represented.	All necessary regulated hydrological processes represented.	Primarily targeted at mountainous natural watersheds; little evidence found for previous integration of regulated hydrological processes, which may be difficult to implement given elevation-band approach to discretization	Little evidence found of inclusion of regulated hydrological processes into model design/use. Empirical/conceptual nature of model may make such inclusion difficult.	Reservoir operating rules can be integrated into routing. Ability to 'nudge' streamflows may be adaptable to prescibing extraction, but evidence for explicit operational water demand capability not found	Upland reservoir operations can be handled using generic stage-discharge rules or explicit representation of gate structures with water level dependent operational rules. Interbasin transfers can also be implicitly or explicitly accounted for.	Reservoirs, lakes and impoundsments can be represented. Diversion instrastructures such as weirs and pumphouses can be included.	Reservoirs and water withdrawals can be incorprated using modified source code	Reservoir release rules and stage-storage curves can be used to define reservoir operations; Interbasin transfers can be accounted for	All necessary regulated hydrological processes represented
	Land Surface Discretization	4	Excessively lumped or excessively spatially discretized.	Appropriately spatially discretized to meet all user needs.	Elevation band (values weighted by semi-distributed land cover classes)	Semi-distributed; Grouped Response Units (GRUs) - limited land cover classes	Fully distributed	Fully distributed	Semi-distibuted; discrete location meterologcal inputs	Semi-distributed (>4 km^2 grid); Potential to further discretize grid cells into HRUs	Flexible distribution; Hydrologic Respone Units (HRUs)	Semi-distributed
	Model Output Discretization	3	Modelled streamflows are provided at one location.	Modelled streamflows are provided at multiple locations across the watershed.	Elevation band	Watershed (lumped); Selected calculations returned at Group Response Units (GRUs)	Grouped Response Units (GRUs)	Flexible (Gridded, Lumped, Linear or Time-Series)	Sub-basin	Gridded	Sub-basin	Grouped Response Units (GRUs)
	Temporal Discretization	4	The model operates only on a daily or greater time-step.	The model time-step can be varied.	Hourly to Daily	Daily	Hourly to Daily; WATFLOOD centres around event-based scenarios, but can produce estimates of continuous simulations by linking up to 100 annual events at an hourly time step	Variable	Hourly or Greater	Hourly	Hourly or Greater	Daily
Input Data and Calibration	Availability of Required Input Datasets and Default Parameters	5	No required input data is available.	All required input data already exists. No adaptations are required.	**Required Datasets:** DEM, land classification (4 groups), daily precipitation, mean daily temperature, daily PET **Required Default Parameters:** Correction factors for elevation and gauge erros, overstorey crown closure, Empirical soil reservoir parameters, soil field capacity, lower limit for ET, linear reservoir parameters	**Required Datasets:** DEM, land classification (4 groups), daily precipitation, mean daily temperature, daily PET **Required Default Parameters:** Correction factors for elevation and gauge errors, canopy factors for sunlight blocked, interception factor, snowmelt ratios, empirical soil reservoir parameters, soil field capacity, lower limit for ET, linear reservoir parameters	**Required Datasets:** DEM, hourly air temperature, hourly precipitation and snowfall (radar data possible), radiation **Required Default Parameters:** Forest vegetation coefficient, Interception factors, Empirical soil paramaters, Soil moisture and temperature coefficients, Depth and resistance of interflow layer, Channel roughness, Bankfull vs. drainage table	**Required Datasets:** Flexible depending on the approach taken (i.e. physically based or lumped conceptual) for each hydrological process. The choice of the modelling approach can be tailored to the availability of data. Basic requirements include slope, land use (roughness), soil type (infiltration), and vegetation cover (ET) plus climate data including temperature, precipitation, and PET. More rigorous process descriptions may require a DEM, surficial soil properties, and hydrogeological layering and properties **Required Default Parameters:** Rain/snow temperature thresholds, ground roughness, Leaf Area Index, field capacity, wilting point, interception value, root zone depth, soil hydraulic conductivity, specific storage, porosity, anisotrophy ratio	**Required Datasets:** precipitation, evapotranspiration, radiation, snow melt, sub-basin characteristics (slope, area), maximum temperature **Required Default Parameters:** sub-basin soil properties, infiltration/loss parameters, lag time and peaking coefficient, routing/flow lag parameters	**Required Datasets:** DEM, land cover, soil type, temperature (to match model timestep), precipitation (to match model timestep), flow direction file, flow velocity file, flow diffusion file, grid cell contributing factors **Required Default Parameters:** Rain/snow temperature thresholds, fractional vegetation cover by grid cell, number of root zones, root zone thickness, root fraction in each zone, Leaf Area Index, overstorey presence, architectural resistance, minimum stomatal resistance, shortwave albedo, roughness length, displacement height, shortwave radition evapotranspiration threshold, radiation attenuation factor, wind attenuation, trunk ratio, variable infiltration curve parameter, meximum velocity of baseflow, fraction of maximum velocity where non-linear baseflow begins, fraction of maximum soil moisture where non-linear baseflow occurs, baseflow exponent, saturated hydraulic conductivity, exponent for variation of conductivity with soil moisture, soil moisture diffusion parameter, initial moisture content, average soil temperature, soil thermal damping depth, bulk density, field capacity, wilting point, residual moisture content, soil roughness	**Required Datasets:** HRUs and sub-basins (Spatial discretization definitions), daily precipitation, daily minimum and daily maximum temperature **Required Default Parameters:** required parameters depend highly on chosen representation of hydrological processes	**Required Datasets:** DEM, landuse/land cover, daily precipitation, daily minimum and maximum temperature, daily solar radiation **Required Default Parameters:** Leaf Area Index, canopy height, root depth, stomatal conductances, nitrogen uptake parameters, deep aquifer percolation fraction, specific yield, groundwater delay time, recharge delay time, baseflow recession constant, soil hydrologic group, root depth, water capacity, hydraulic conductivity, soil composition and texture, channel dimensions, channel roughness
	Integration of Existing Water Demand Datasets	5	The model does not allow for consideration of water demand for domestic, agricultural, and industrial purposes.	The model allows for the computation of water demand for domestic, agricultural, and industrial purposes.	Likely difficult given apparent lack of regulated hydrological process inclusion	Likely difficult given apparent lack of regulated hydrological process inclusion	Likely difficult given apparent lack of regulated hydrological process inclusion	Water demand information can be added at defined points of diversion	Capbility to integrate existing water demand datasets may be limited due to the GUI structure of the model design	VIC can incorporate water withdrawals. However, existing water demand datasets exist at a more detailed spatial scale than the land surface discretization withi VIC and thus require coupling to a routing model, which VIC does not include internally	Water demand information can be added at a sub-basin scale	Water demand information can be added at the GRU scale
	Model Calibration	3	Model calibration procedures are not defined, and model not associated with specific calibration software.	Multi-point, multi-variable calibration procedures are well defined and associated with specific calibration software.	Integrated optimization routie for select parameters (i.e., precipitation distribution, water distribution, and routing constants)	No model calibration procedures are integrated; Manual or external model calibration is required	Integrated de-bug and calibration modes allow for streamlined model calibration. Up to 100 parameters can be optimized using model calibration mode	No internal model calibration utilities - model calibration can be completed using AutoCal (a MIKE Calibration utility)	Automated model calibration is integrated in the model software	No internal model calibration utilies; Manual or external automated procedure required - MOCOM-UA is a well established clibration tool for VIC	Model calibration can be completed using OSTRICH or similar external calibration tools	Model calibration can be completed using the SWAT-CUP interface
Model Flexibility	Groundwater complexity	3	No future upgrades to groundwater simulation capabilities are possible.	Groundwater capabilities are highly amenable to future improvement/replacement.	Groundwater is limited to linear reservoirs, delinated by elevation band. Future improvements are likely challenging due to predominantly empirical nature of the model	Groundwater is limited to fast and slow reservoirs. Future improvements are likely challenging due to predominatly empirical nature of the model	Simple groundwater leakage/recharge scheme. WATFLOOD can produce output in MODFLOW format, but is not currently coupled to a full groundwater model. Future improvements are likely challenging due to predominantly empirical nature of the model	Groundwater considerations can be handled using a linear reservoir approximation of exhanges between near surface and deeper groundwater storages and to account for event-based and seasonal exchanges with surface water. Alternatively, groundwater can be represented using a fully-integrated 2D or 3D saturated groundwater flow model. Future improvements are unlikely required given the present complexity of modelled groundwater representation	Groundwater is currently reprsented by multiple reservoirs. Future improvements are likely challenging due to the lack of source code and support for non-COPRS users	A shallow groundwater component is incorporated within VIC. A deep groundwater module may be available for integration in future	Coupled MODFLOW/RAVEN model has been developed, but has not be pushed to the main distribution yet. Expected within the next few years	Coupled SWAT/MODFLOW model developed and operational. Simpler groundwater options also available
	Flexibility to Configure and/or Update Hydrological Processes	4	Hydrological processes cannot be configured, and no future upgrades are possible.	Hydrological processes can be configured and are highly amenable to future improvement/replacement.	Hydrological processes cannot be readily configured within the model; updates may be available within future releases	Hydrological processes cannot be readily configured within the model; updates may be available within future releases	Select hydrological processes have the potential to be configured with support from the model development team (e.g., Snowmelt [Radiation-Temperature Index Algorithm is not yet available to users])	Selected hydrological processes can be configured within the model	Hydrological processes can be readily configured at the sub-basin scale	VIC source code is open source and undergoes frequent development. Future upgrades would be possible, if needed	Hydrological processes can be readily configured at the HRU scale	SWAT+ code is now object based and the input files are relational based to increase ability update hydrological processes
	Hydraulic Simulation	2	No hydraulic simulation integration is possible.	Fully integrated hydraulic simulation routines exist or can be integrated.	Hydraulic simulation integration is not possible	Hydraulic simulation integration is not possible	Hydraulic simulation integration is not possible	MIKE SHE can use simple 1D routing of water through a river network or it can use fully hydrodynamic routing of flows through a network with consideration of hydraulic structures and operational strategies	HEC-HMS output can be used as initial boundary conditions within HEC-RAS; however, full coupling of the two is not supported	Model is coarse-scale by default, and is not intended for easy support of hydraulic modelling	Hydraulic simulation integration is not possible by default; however, could likely be added if necessary	Hydraulic simulation integration is not possible by default
	Integration for Basin-wide Hydrologic Model	4	Once developed, individual modelled spatial extents cannot be linked.	Full integration between modelled spatial extents can be achieved.	Model is primarily designed for individual watersheds in mountainous terrain and does not appear widely used for wider (multi-watershed) basins	Unlikely to be amenable to basin-wide modelling due to conceptual nature of model resulting in poor representation of mainstem lakes	Appears to target individual watersheds, not basin-wide mainstem lake applications. Likely would require significant effort to construct basin-wide domain from multiple individual watersheds	Outflows from individual basin models can be cumulatively added to a hydraulic model of the mainstem lakes; however, it is impractical to try to merge multiple basin models together into a single large model	Model set-up appears to be restricted to connected sub-basins only and maybe restrictive for basin-wide hydrologic modelling of mainstem lake-connected system consisting of many sub-basins	An offline routing model is available which could possibly be modified to allow for future integrations	Integration between sub-basins is possible. Recalibration will be required	Integration between GRUs is possible. Recalibration will be required.
Model Applicability and Usability	Relation to Existing and Future Okanagan Modelling Efforts	4	The model is not being used in the Okanagan and is not a candidate model for future modelling exercises.	The model is actively being, or has been, successfully used in the Okanagan.	UBCWM was applied to the Finlay, Alouette, and Mica River watersheds as part of the BC Hydro Model Intercomparison study	Model has been used extensively in glacerized catchments within BC, as well to assess impacts of forest cover change in smaller watersheds within central and southern BC. In addition, HBV-EC was applied to the Finlay, Alouette, and Mica River watersheds as part of the BC Hydro Model Intercomparison study	WATFLOOD has been applied to the Columbia and Peace Rivers in BC. In addition WATFLOOD was applied to the Finlay, Alouette, and Mica River watersheds as part of the BC Hydro Model Intercomparison study	MIKE SHE was used during Phase 2 of the OWSDP; an existing model domain has been established	HEC-HMS has previously been applied to the Shuttleworth Creek watershed to simulate pre- and post-dam decommision streamflows	No uses of VIC within the Okanagan or similar southern BC waterheds are known	RAVEN is currently being used to develop a forecasting model for Okanagan Lake inflows and is proposed to be used to develop floodplain maps for large valley bottom Okanagan Lakes	SWAT has been applied in the Nechako River and Salmon River watersheds in BC to support climate change and nutrient loading investigations
	Model Developer Support	3	No formal support and model documentation is not readily available.	Extensive model support is available from online and in-person resources, and model documentation is readily available.	Manual not readily available; User support likely available due to large number of previous users	Manual not readily available; User support likely available from model development team directly	User manual is readily available; demonstration/training datasets are readily available; Model development and support is ongoing	User manual is readily available; model support and training courses are available from distributor	Quick start guides, manuals, and release notes are readily available online. HEC will not provide user assistance or support for this software to non-Corps users	User manual is readily available; tutorials and example files are readily available	User manual is readily available; turorials and example files are readily available; active user community currently exists	User manual is readily available, tutorials and example files are readily available; active user community currently exists
	Usability and Computational Efficiency	4	The model is slow to complete simulations and has no ability to process simulations concurrently.	The model can be fully automated and is amenable to cloud-based processing for concurrent simulation processing.	The model can be coupled with the Green Kenue data management software for ease of model simulations	The model can be coupled with the Green Kenue data management software for ease of model simulations	The model can be coupled with the Green Kenue data management software for ease of model simulations	The GUI for MIKE SHE is user-friendly and facilitates the processing and visualization of spatially distributed input data and results. But the degree of flexibility available for model setup requires a steep learning curve to understand the implications of each option. Given the spatially distributed nature of MIKE SHE models they do require more time to run than a lumped model treating each catchment as a uniform HRU. The ability to generate more granularity and water balance details comes at the cost of computational time	Model input data is stored in HEC-DSS file format which allows multiple records for hydrologic data. In addition, the model can be executed from command line, allowing ensemble simulations. Finally, the model can be integrated with HEC-GeoHMS, a GIS platform for integrated mapping capabilities	Model is designed for parallel processing, by each independent grid cell (since no routing included, all grid cells are entirely independent). C code requires compiling, but would be amenable to script-based cloud usage	The model is coded is C++ and driven by *.txt files; accordingly, simulations could be compiled, automated and hosted on the cloud	The model is coded is FORTRAN and driven by *.txt files; accordingly, simulations could be compiled, automated and hosted on the cloud
	Model Licensing and Source Code Availability	3	Model licence is required, and source code is not readily available.	Model is open-source and source code is readily available.	No usage fee, Source code is available	Model licence required; No usage fee; Source code can be requested from model development team	Model executables freely available, but source code is not available	Model licence required; Usage fee required; Source code unavilable	Model licence required; No usage fee. Source code appears unavailable (only executables available via US Corp of Engineer website. There is 'very limited' ability control model via script-based command line control	Open-source; No usage fee; source code is available	Open-source; No usage fee; source code is available	Open-source; No usage fee; source code is available

Table 4-2
Candidate model grading results

General Category	Grading Criterion	Importance Weighting	Poor Score (1) Definition	Excellent Score (5) Definition	UBCWM	HBV-EC	WATFLOOD	MIKE SHE	HEC-HMS	VIC	RAVEN	SWAT
Model Design and Complexity	Physical Basis	4	*Excessively conceptual or excessively physical.*	*Appropriately physically comprehensive.*	3	2	3	5	3	5	5	5
	Inclusion of Necessary Natural Hydrological and Climatological Processes	5	*Major natural hydrological and climatological processes represented in basic form.*	*All necessary natural hydrological and climatological processes represented in complex form.*	4	3	3	5	4	4	5	4
	Inclusion of Necessary Regulated Hydrological Processes	5	*No necessary regulated hydrological processes represented.*	*All necessary regulated hydrological processes represented.*	1	1	3	5	4	1	5	5
	Land Surface Discretization	4	*Excessively lumped or excessively spatially discretized.*	*Appropriately spatially discretized to meet all user needs.*	2	2	5	5	4	3	5	4
	Model Output Discretization	3	*Modelled streamflows are provided at one location.*	*Modelled streamflows are provided at multiple locations across the watershed.*	2	3	5	5	4	5	5	4
	Temporal Discretization	4	*The model operates only on a daily or greater time-step.*	*The model time-step can be varied to sub-daily timesteps.*	5	1	5	5	5	4	5	1
Input Data and Calibration	Availability of Required Input Datasets and Default Parameters	5	*No required input data is available.*	*All required input data already exists. No adaptations are required.*	4	4	3	4	4	2	4	3
	Integration of Existing Water Demand Datasets	5	*The model does not allow for consideration of water demand for domestic, agricultural, and industrial purposes.*	*The model allows for the computation of water demand for domestic, agricultural, and industrial purposes.*	1	1	1	4	2	3	4	4
	Model Calibration	3	*Model calibration procedures are not defined, and model not associated with specific calibration software.*	*Multi-point, multi-variable calibration procedures are well defined and associated with specific calibration software.*	4	3	4	4	5	3	5	5
Model Flexibility	Groundwater complexity	3	*No future upgrades to groundwater simulation capabilities are possible.*	*Groundwater capabilities are highly amenable to future improvement/replacement.*	1	1	2	5	3	2	4	5
	Flexibility to Configure and/or Update Hydrological Processes	4	*Hydrological processes cannot be configured, and no future upgrades are possible.*	*Hydrological processes can be configured and are highly amenable to future improvement/replacement.*	1	1	3	3	4	2	5	4
	Hydraulic Simulation	2	*No hydraulic simulation integration is possible.*	*Fully integrated hydraulic simulation routines exist or can be integrated.*	1	1	1	4	3	1	2	1
	Integration for Basin-wide Hydrologic Model	4	*Once developed, individual modelled spatial extents cannot be linked.*	*Full integration between modelled spatial extents can be achieved.*	1	1	1	3	2	3	5	5
Model Applicability and Usability	Relation to Existing and Future Okanagan Modelling Efforts	4	*The model is not being used in the Okanagan and is not a candidate model for future modelling exercises.*	*The model is actively being, or has been, successfully used in the Okanagan.*	1	1	1	5	5	1	5	1
	Model Developer Support	3	*No formal support and model documentation is not readily available.*	*Extensive model support is available from online and in-person resources, and model documentation is readily available.*	1	1	4	5	4	5	5	5
	Usability and Computational Efficiency	4	*The model is slow to complete simulations and has no ability to process simulations concurrently.*	*The model can be fully automated and is amenable to cloud-based processing for concurrent simulation processing.*	2	2	2	2	3	5	5	5
	Model Licensing and Source Code Availability	3	*Model licence is required, and source code is not readily available.*	*Model is open-source and source code is readily available.*	4	3	3	2	4	5	5	5
				Final Model Score	**148**	**120**	**186**	**273**	**240**	**204**	**306**	**254**

5 SUMMARY

Based on the results of the model grading process completed herein, the Raven hydrological modelling framework is recommended for use to complete the existing modelling scope. The existing scope of work includes the development of a hydrological model for two pilot watersheds (i.e., Whiteman Creek and Mission Creek) to ensure the selected model is appropriate. This memo is intended to provide the PSC an opportunity to review the model grading process and results and to ensure that there is census agreement on the recommended model before model development begins.

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APPENDIX B – HBV-EC MODEL CONFIGURATION USED IN THE OHMP

Table B-1 summarizes all key processes included within the HBV-EC model configuration used within the OHMP. Details on all processes is provided in the Raven user's and developer's manual (Craig and Raven Development Team 2019).

Table B-1
Summary of process algorithms used in OHMP

Algorithm Type	Process	Algorithm
Routing	In-catchment routing	ROUTE_TRI_CONVULTION
	In-channel routing	ROUTE_DIFFUSIVE_WAVE
Forcing Functions	Evaporation	PET_HARGREAVES_1985
	Open Water Evaporation	PET_HARGREAVES_1985
	Shortwave Radiation	SW_RAD_DEFAULT
	Shortwave Cloud Correction	SW_CLOUD_CORR_NONE
	Shortwave Canopy Correction	SW_CANOPY_CORR_NONE
	Longwave Radiation	LW_RAD_DEFAULT
	Rain Snow Partitioning	RAINSNOW_HBV
	Potential Melt	POTMELT_HBV
	Cloud Cover Correction	CLOUDCOV_NONE
	Canopy Interception	PRECIP_ICEPT_USER
General	Monthly Interpolation Method	MONTH_INT_LINEAR_21
	Soil model	SOIL_MULTILAYER (3)
	Reservoir Demand Allocation	DEMANDBY_MAX_CAPACITY
Hydrologic Processes	Snow Refreeze	FREEZE_DEGREE_DAY
	Precipitation	PRECIP_RAVEN
	Canopy Evaporation	CANEVP_ALL
	Canopy Snow Evaporation	CANEVP_ALL
	Snow Balance	SNOBAL_SIMPLE_MELT
	Infiltration	INF_HBV
	Soil Evaporation	SOILEVAP_HBV
	Capillary Rise	RISE_HBV
	Percolation	PERC_CONSTANT
	Baseflow	BASE_POWER_LAW (Soil [1]) BASE_LINEAR (Soil [2])

APPENDIX C - MODEL SUB-BASINS INCLUDED IN OHME V1

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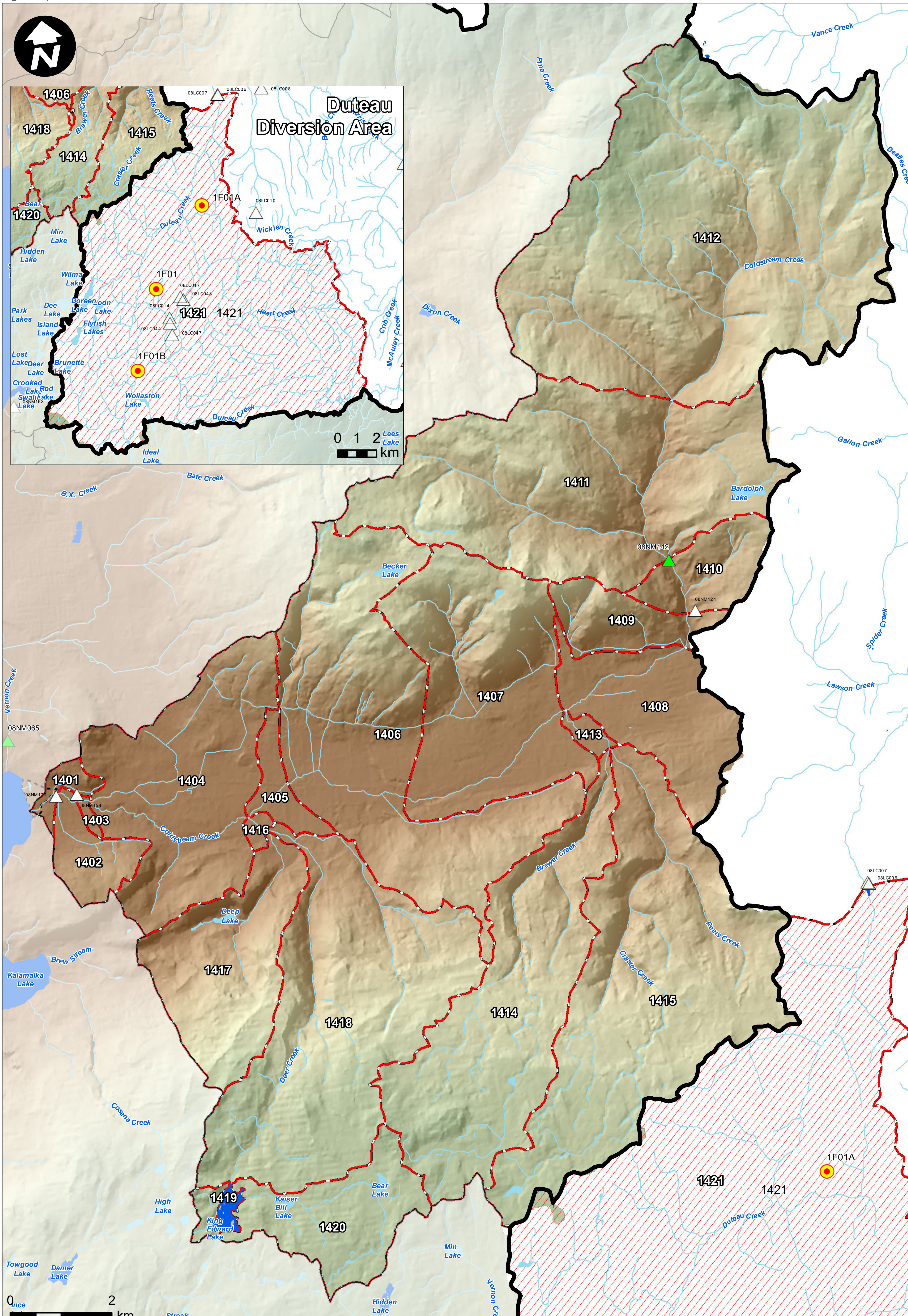

Snow Pillow

Snow Course

Major Water Intake / Diversion

Active WSC Hydrometric Station

Discontinued WSC Hydrometric Station

230 Sub-Basin Boundary with Basin ID

Extra Basin Diversion Area

Reservoirs

Alluvial Fan

Associated Environmental

PROJECT NO.: 2016-8067.040.000

DATE: January 2020

DRAWN BY: DA

APPENDIX C-1: MAP OF COLDSTREAM CREEK WATERSHED

Okanagan Basin Water Board

Okanagan Hydrologic Modelling Project

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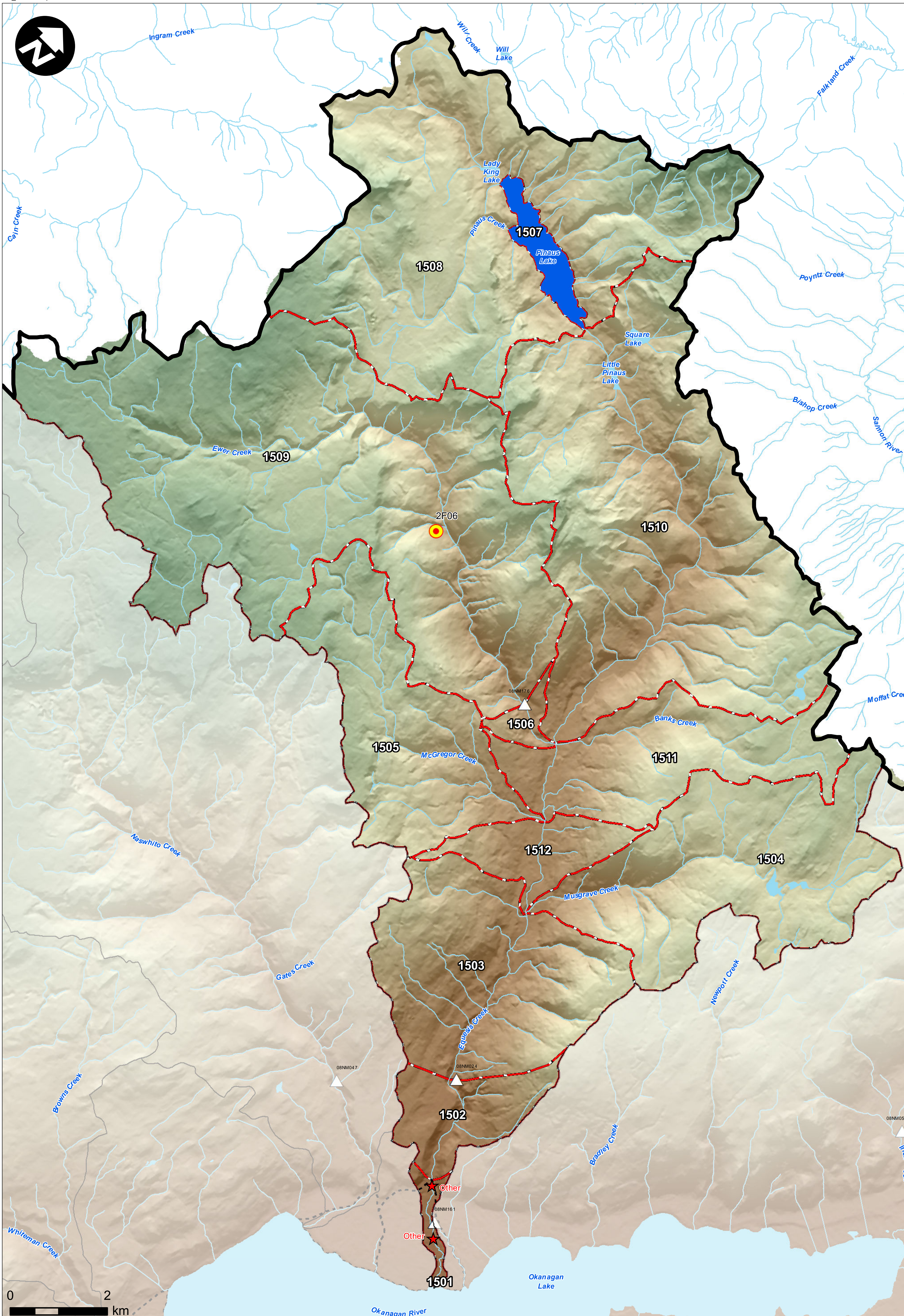

Associated Environmental

Snow Pillow
Snow Course
Major Water Intake / Diversion
Active WSC Hydrometric Station
Discontinued WSC Hydrometric Station

230 Sub-Basin Boundary with Basin ID
Extra Basin Diversion Area
Reservoirs
Alluvial Fan

PROJECT NO.: 2016-8067.040.000
DATE: January 2020
DRAWN BY: DA

APPENDIX C-2: MAP OF EQUESIS CREEK WATERSHED

Okanagan Basin Water Board

Okanagan Hydrologic Modelling Project

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Associated Environmental

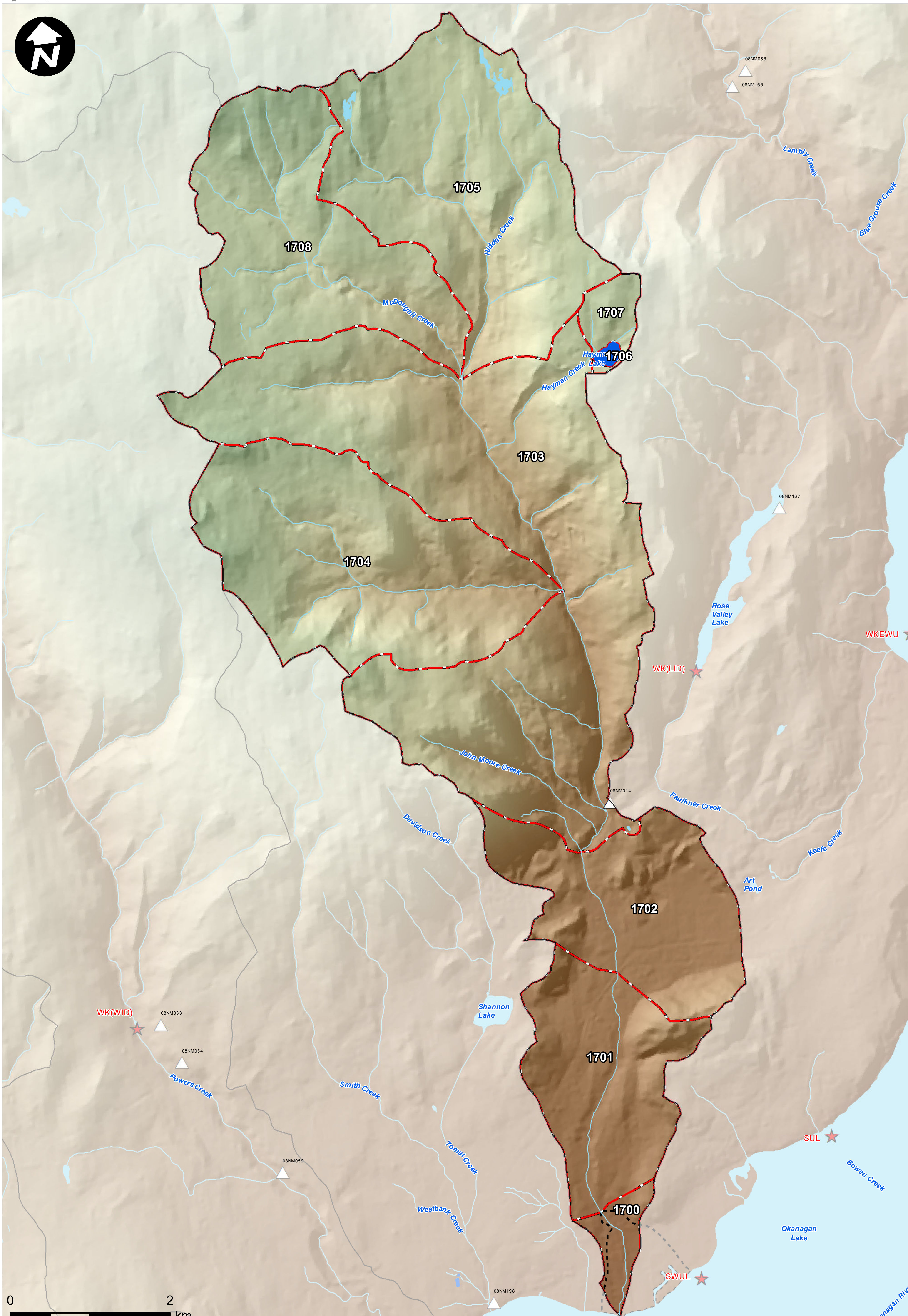
Snow Pillow
Snow Course
Major Water Intake / Diversion
Active WSC Hydrometric Station
Discontinued WSC Hydrometric Station
230 Sub-Basin Boundary with Basin ID
Extra Basin Diversion Area
Reservoirs
Alluvial Fan

PROJECT NO.:	2016-8067.040.000
DATE:	January 2020
DRAWN BY:	DA

APPENDIX C-3: MAP OF INKANEEP CREEK WATERSHED

Okanagan Basin Water Board

Okanagan Hydrologic Modelling Project



Snow Pillow

Snow Course

Major Water Intake / Diversion

Active WSC Hydrometric Station

Discontinued WSC Hydrometric Station

230 Sub-Basin Boundary with Basin ID

Extra Basin Diversion Area

Reservoirs

Alluvial Fan

Associated Environmental

PROJECT NO.: 2016-8067.040.000

DATE: January 2020

DRAWN BY: DA

APPENDIX C-4: MAP OF MCDOUGALL CREEK WATERSHED

Okanagan Basin Water Board

Okanagan Hydrologic Modelling Project

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Snow Pillow
Snow Course
Major Water Intake / Diversion
Active WSC Hydrometric Station
Discontinued WSC Hydrometric Station
230 Sub-Basin Boundary with Basin ID
Extra Basin Diversion Area
Reservoirs
Alluvial Fan

Associated Environmental

PROJECT NO.: 2016-8067.040.000
DATE: January 2020
DRAWN BY: DA

APPENDIX C-5: MAP OF MCLEAN CREEK WATERSHED

Okanagan Basin Water Board

Okanagan Hydrologic Modelling Project

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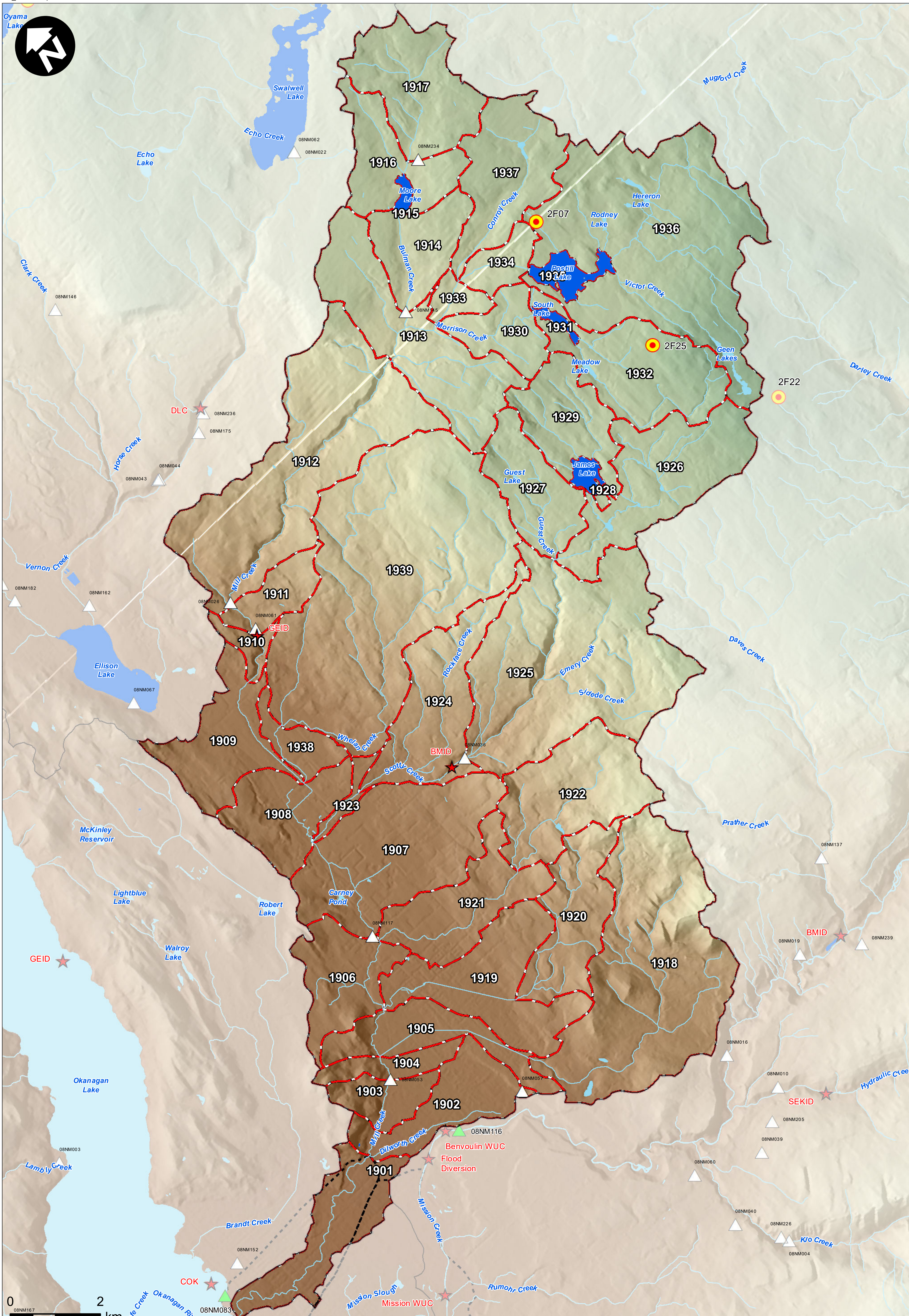

Snow Pillow
Snow Course
Major Water Intake / Diversion
Active WSC Hydrometric Station
Discontinued WSC Hydrometric Station

230 Sub-Basin Boundary with Basin ID
Extra Basin Diversion Area
Reservoirs
Alluvial Fan

Associated Environmental

PROJECT NO.:	2016-8067.040.000
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APPENDIX C-6: MAP OF MILL CREEK WATERSHED

Okanagan Basin Water Board

Okanagan Hydrologic Modelling Project

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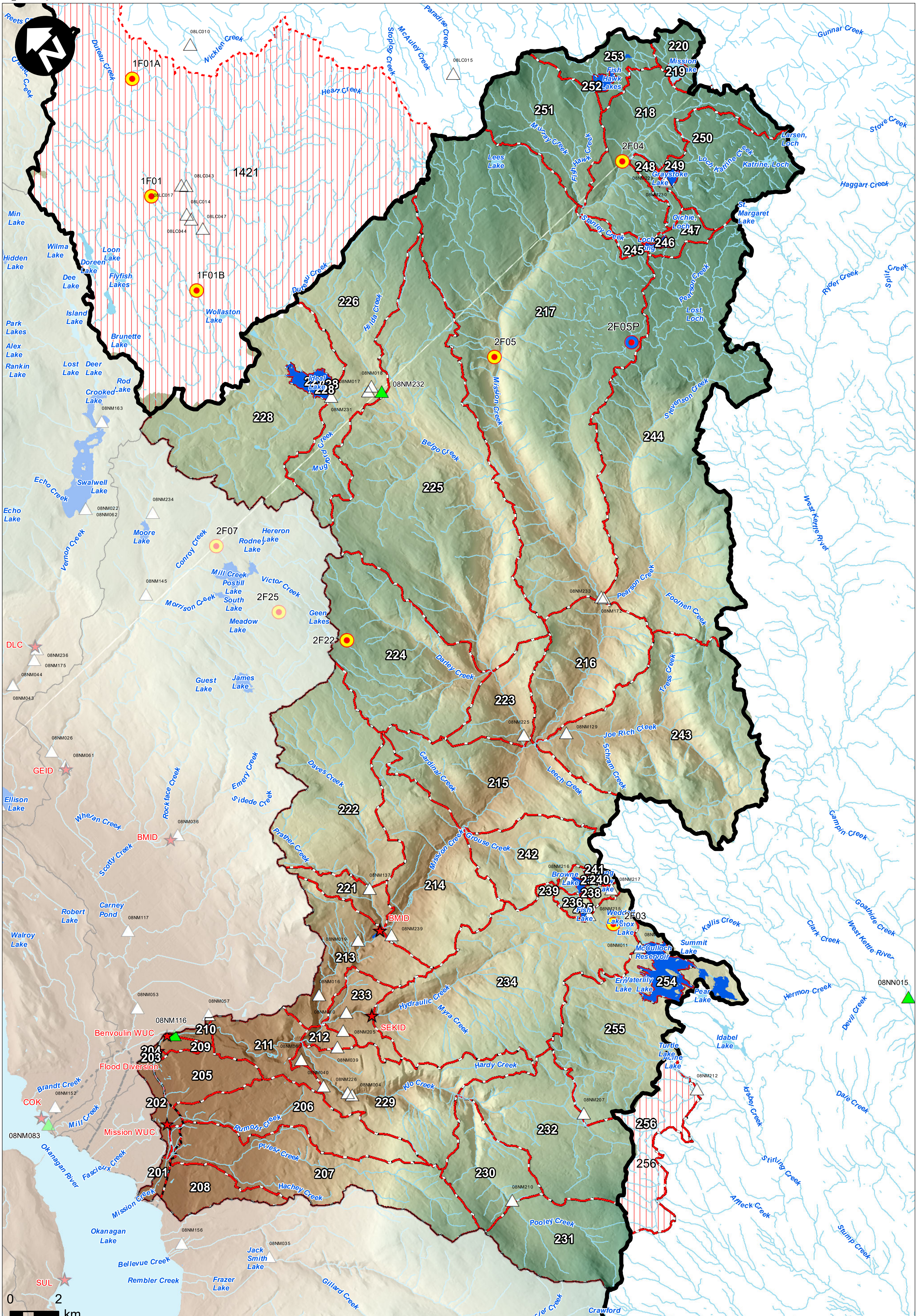

Snow Pillow

Snow Course

Major Water Intake / Diversion

Active WSC Hydrometric Station

Discontinued WSC Hydrometric Station

230 Sub-Basin Boundary with Basin ID

Extra Basin Diversion Area

Reservoirs

Alluvial Fan

Associated Environmental

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APPENDIX C-7: MAP OF MISSION CREEK WATERSHED

Okanagan Basin Water Board

Okanagan Hydrologic Modelling Project

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Snow Pillow
Snow Course
Major Water Intake / Diversion
Active WSC Hydrometric Station
Discontinued WSC Hydrometric Station
230 Sub-Basin Boundary with Basin ID
Extra Basin Diversion Area
Reservoirs
Alluvial Fan

Associated Environmental

PROJECT NO.: 2016-8067.040.000
DATE: January 2020
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APPENDIX C-8: MAP OF NARAMATA CREEK WATERSHED

Okanagan Basin Water Board

Okanagan Hydrologic Modelling Project

Snow Pillow
Snow Course
Major Water Intake / Diversion
Active WSC Hydrometric Station
Discontinued WSC Hydrometric Station
230 Sub-Basin Boundary with Basin ID
Extra Basin Diversion Area
Reservoirs
Alluvial Fan

Associated Environmental

PROJECT NO.:	2016-8067.040.000
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APPENDIX C-9: MAP OF NASWHITO CREEK WATERSHED

Okanagan Basin Water Board

Okanagan Hydrologic Modelling Project

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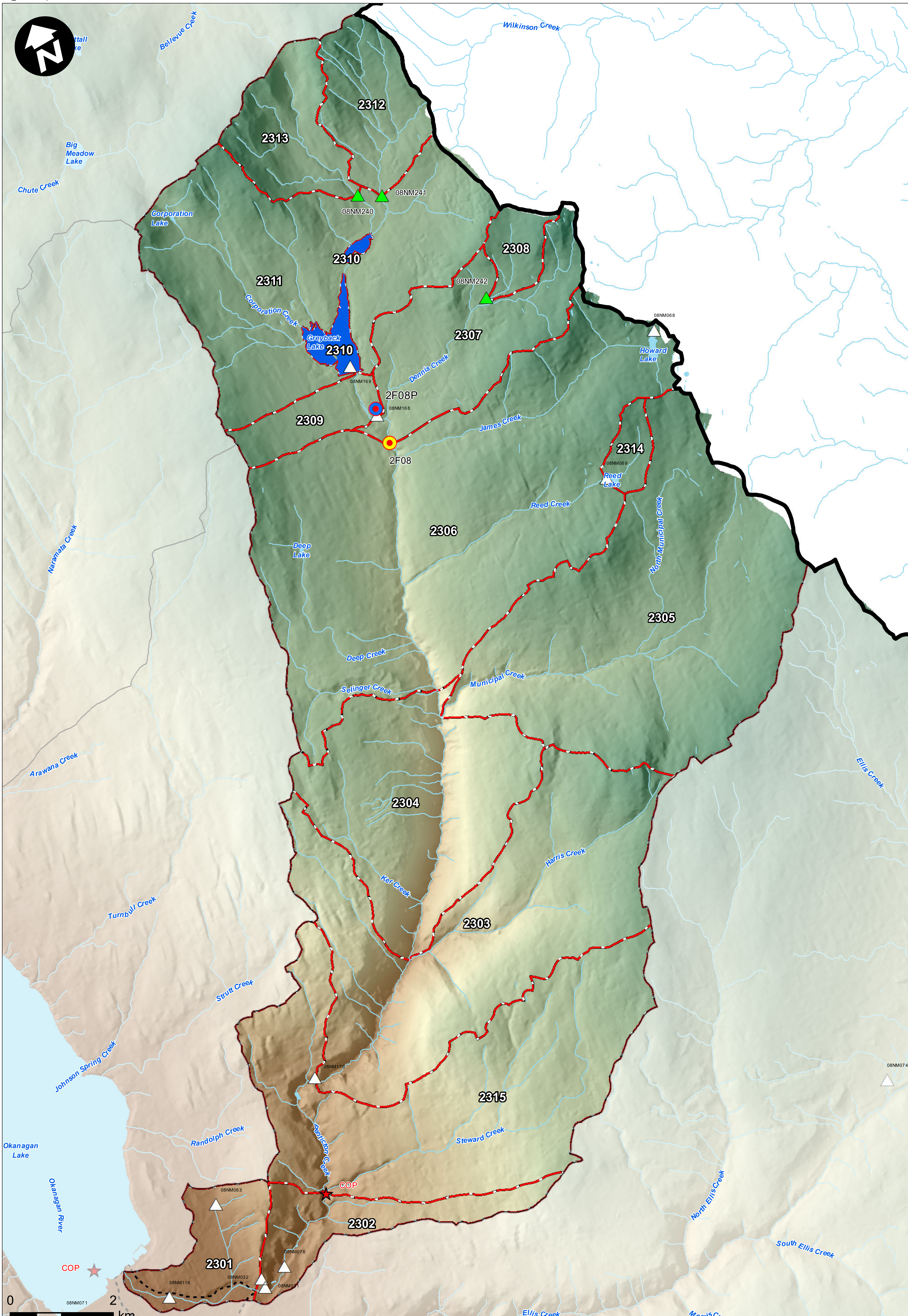

Associated Environmental

Snow Pillow

Snow Course

Major Water Intake / Diversion

Active WSC Hydrometric Station

Discontinued WSC Hydrometric Station

230 Sub-Basin Boundary with Basin ID

Extra Basin Diversion Area

Reservoirs

Alluvial Fan

PROJECT NO.: 2016-8067.040.000

DATE: January 2020

DRAWN BY: DA

APPENDIX C-10: MAP OF PENTICTON CREEK WATERSHED

Okanagan Basin Water Board

Okanagan Hydrologic Modelling Project

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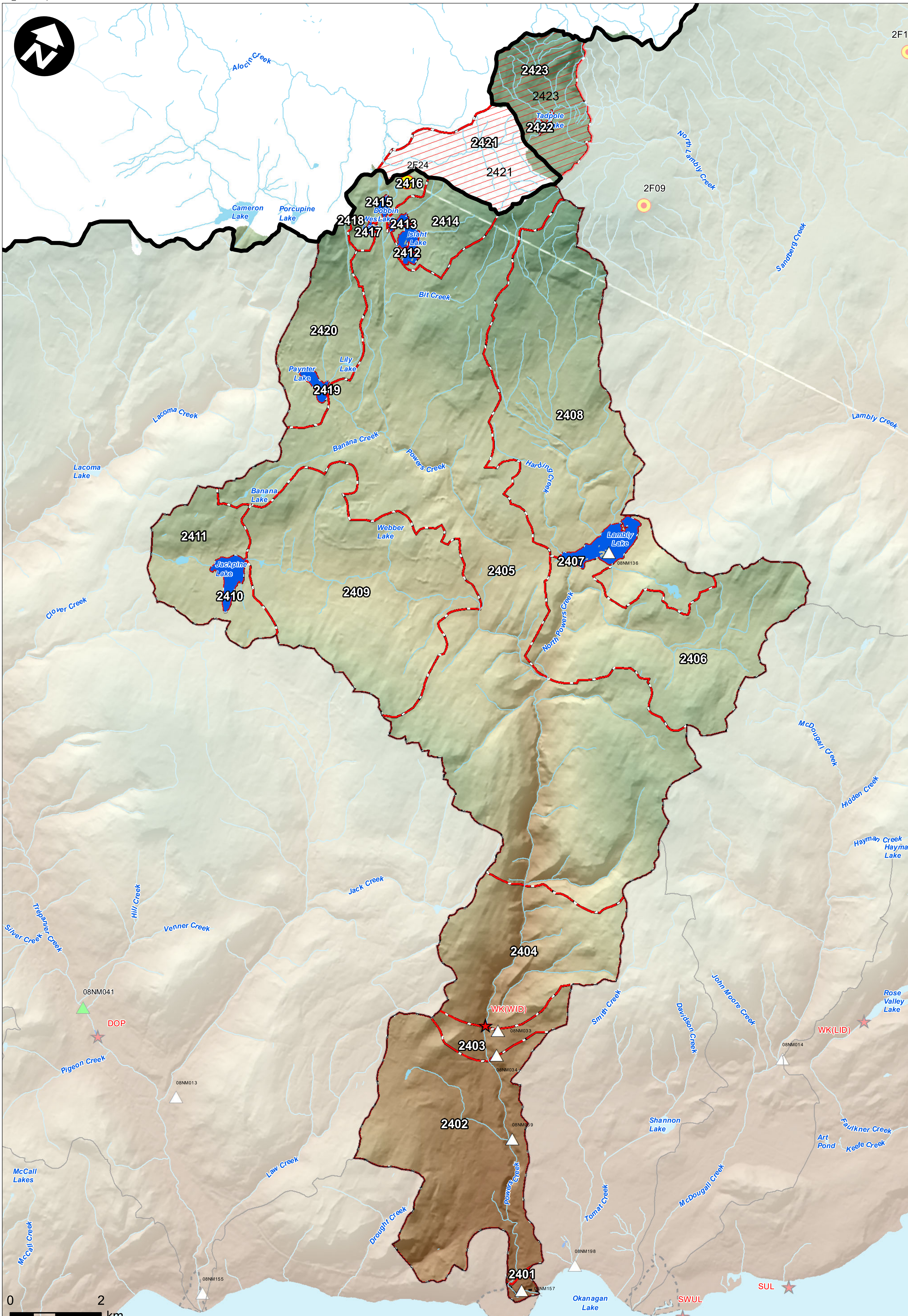

Snow Pillow
Snow Course
Major Water Intake / Diversion
Active WSC Hydrometric Station
Discontinued WSC Hydrometric Station

230 Sub-Basin Boundary with Basin ID
Extra Basin Diversion Area
Reservoirs
Alluvial Fan

Associated Environmental

PROJECT NO.:	2016-8067.040.000
DATE:	January 2020
DRAWN BY:	DA

APPENDIX C-11: MAP OF POWERS CREEK WATERSHED

Okanagan Basin Water Board

Okanagan Hydrologic Modelling Project

Associated Environmental

Snow Pillow

Snow Course

Major Water Intake / Diversion

Active WSC Hydrometric Station

Discontinued WSC Hydrometric Station

230 Sub-Basin Boundary with Basin ID

Extra Basin Diversion Area

Reservoirs

Alluvial Fan

PROJECT NO.:	2016-8067.040.000
DATE:	January 2020
DRAWN BY:	DA

APPENDIX C-12: MAP OF SHINGLE CREEK WATERSHED

Okanagan Basin Water Board

Okanagan Hydrologic Modelling Project

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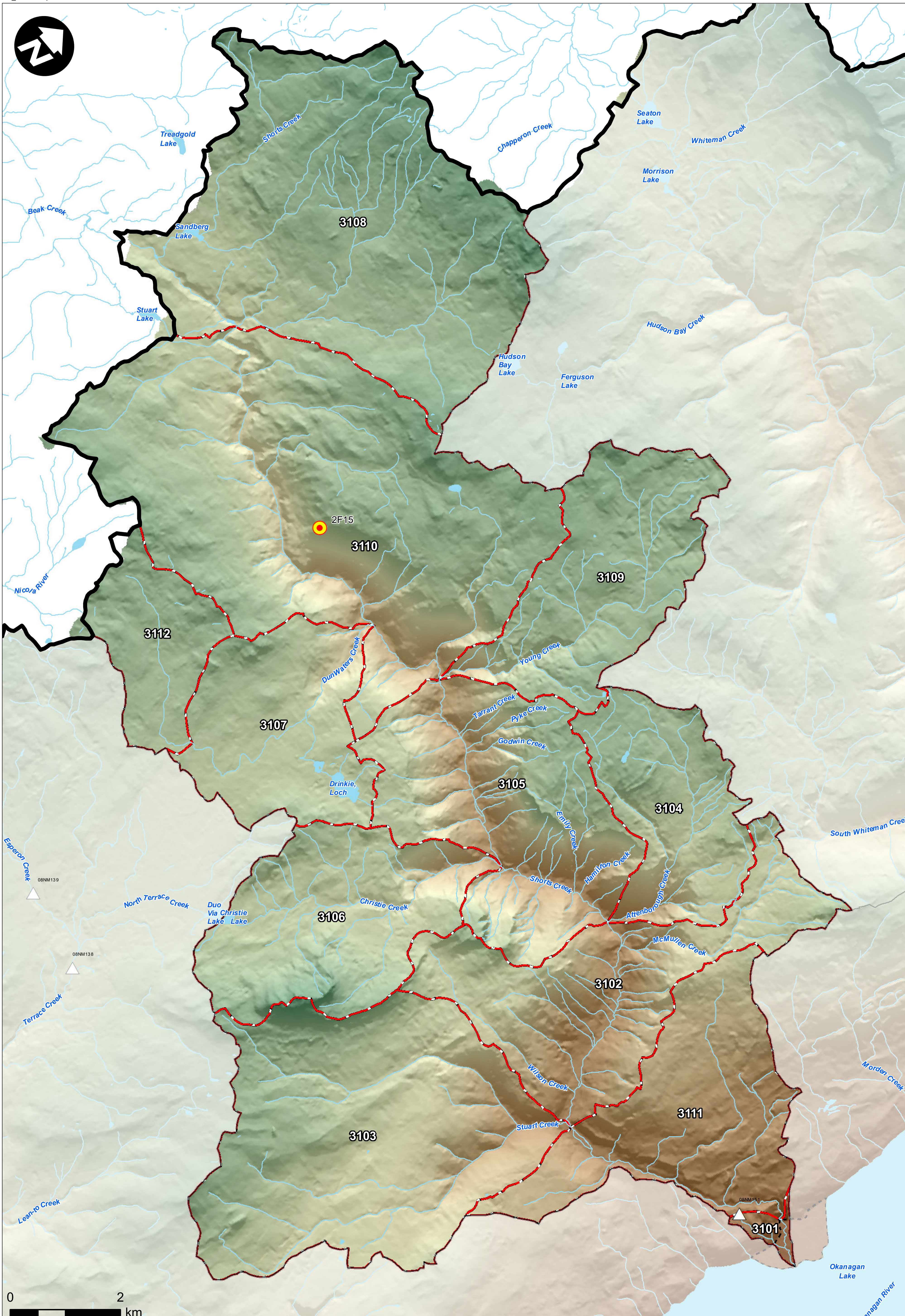


Snow Pillow
Snow Course
Major Water Intake / Diversion
Active WSC Hydrometric Station
Discontinued WSC Hydrometric Station

230 Sub-Basin Boundary with Basin ID
Extra Basin Diversion Area
Reservoirs
Alluvial Fan

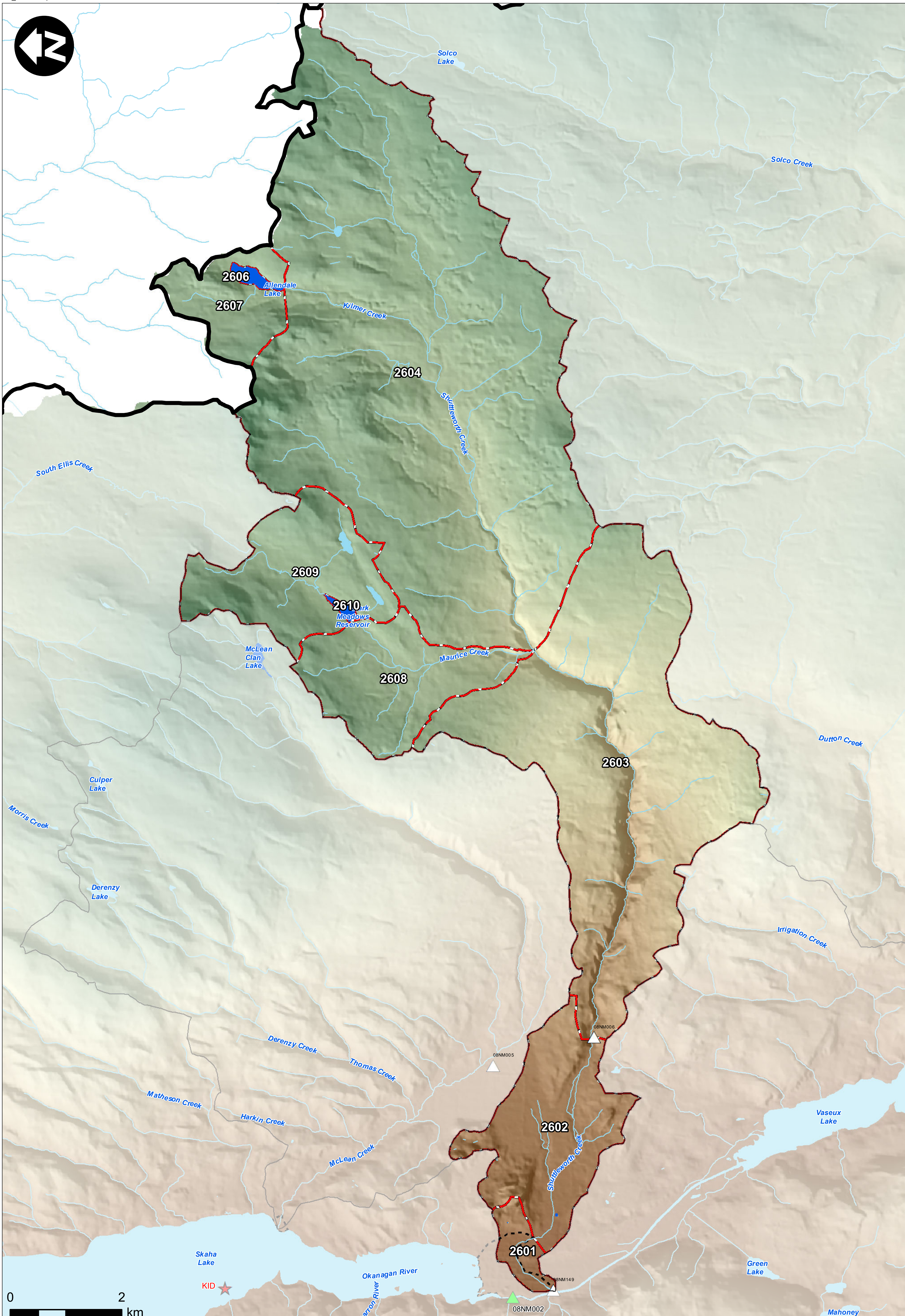
Associated Environmental

PROJECT NO.: 2016-8067.040.000
DATE: January 2020
DRAWN BY: DA

APPENDIX C-13: MAP OF SHORTS CREEK WATERSHED

Okanagan Basin Water Board

Okanagan Hydrologic Modelling Project



Associated Environmental

Snow Pillow
Snow Course
Major Water Intake / Diversion
Active WSC Hydrometric Station
Discontinued WSC Hydrometric Station
230 Sub-Basin Boundary with Basin ID
Extra Basin Diversion Area
Reservoirs
Alluvial Fan

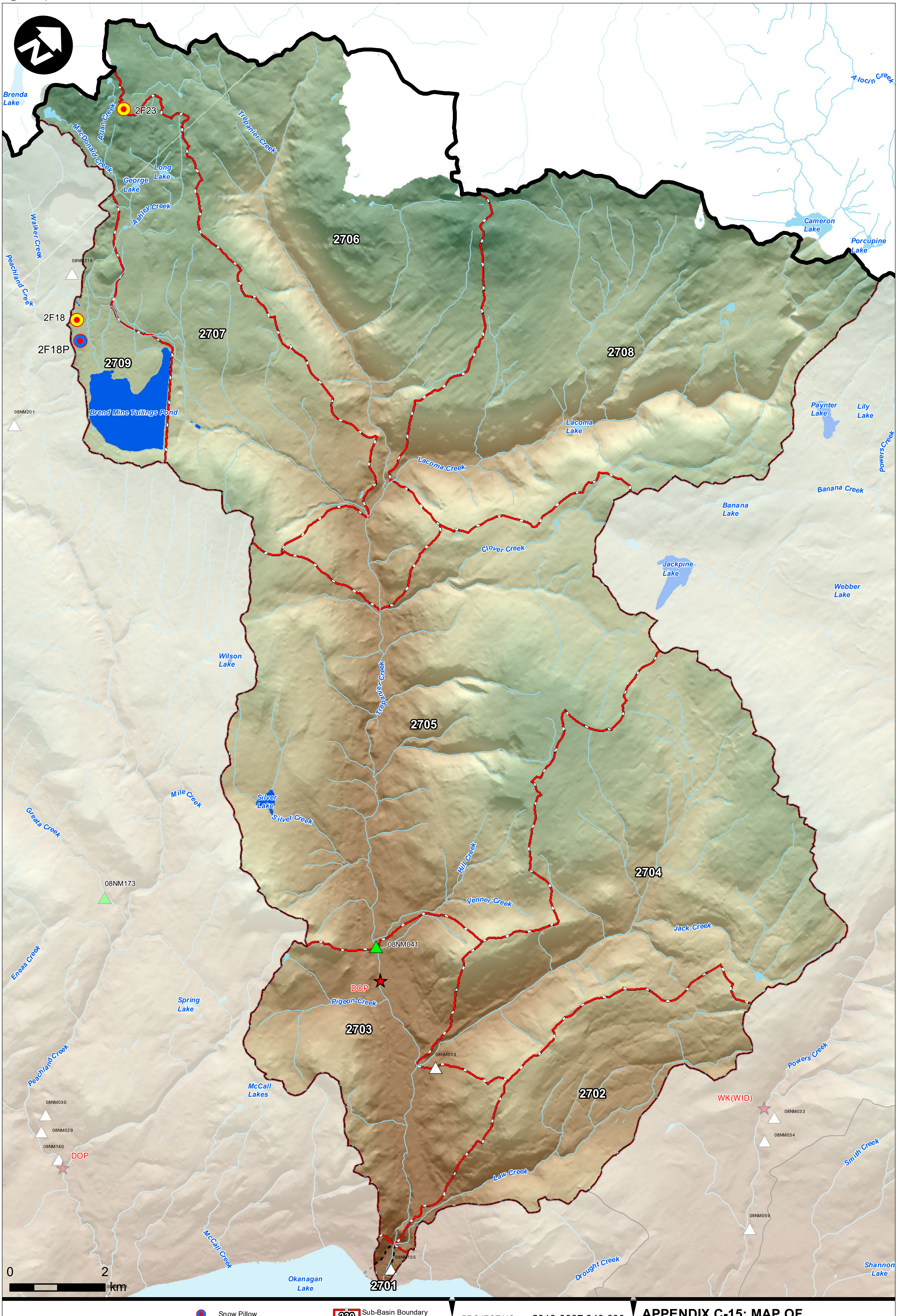
PROJECT NO.: 2016-8067.040.000
DATE: January 2020
DRAWN BY: DA

APPENDIX C-14: MAP OF SHUTTLEWORTH CREEK WATERSHED

Okanagan Basin Water Board

Okanagan Hydrologic Modelling Project

sub_Basin maps.mxd / 2/14/2020 / 12:19:52 PM



Associated Environmental

Snow Pillow

Snow Course

Major Water Intake / Diversion

Active WSC Hydrometric Station

Discontinued WSC Hydrometric Station

230 Sub-Basin Boundary with Basin ID

Extra Basin Diversion Area

Reservoirs

Alluvial Fan

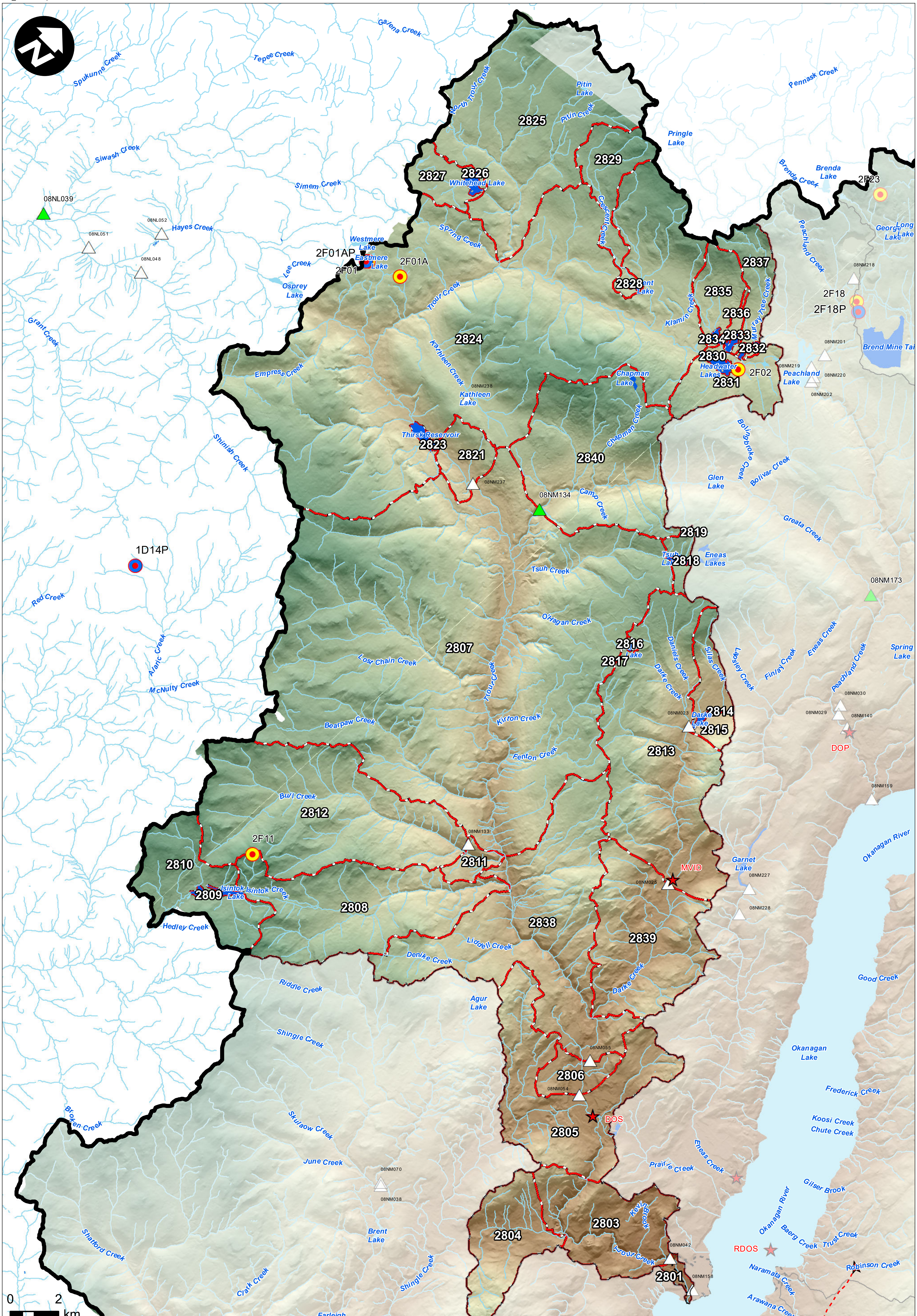
PROJECT NO.:	2016-8067.040.000
DATE:	January 2020
DRAWN BY:	DA

APPENDIX C-15: MAP OF TREPANIER CREEK WATERSHED

Okanagan Basin Water Board

Okanagan Hydrologic Modelling Project

sub_Basin maps.mxd / 2/14/2020 / 12:20:08 PM



Snow Pillow
Snow Course
Major Water Intake / Diversion
Active WSC Hydrometric Station
Discontinued WSC Hydrometric Station

230 Sub-Basin Boundary with Basin ID
Extra Basin Diversion Area
Reservoirs
Alluvial Fan

Associated Environmental

PROJECT NO.:	2016-8067.040.000
DATE:	January 2020
DRAWN BY:	DA

APPENDIX C-16: MAP OF TROUT CREEK WATERSHED

Okanagan Basin Water Board

Okanagan Hydrologic Modelling Project

sub_Basin maps.mxd / 2/14/2020 / 12:20:22 PM

Associated Environmental

- Snow Pillow
- Snow Course
- Major Water Intake / Diversion
- Active WSC Hydrometric Station
- Discontinued WSC Hydrometric Station
- 230 Sub-Basin Boundary with Basin ID
- Extra Basin Diversion Area
- Reservoirs
- Alluvial Fan

PROJECT NO.:	2016-8067.040.000
DATE:	January 2020
DRAWN BY:	DA

APPENDIX C-17: MAP OF VASEUX CREEK WATERSHED

Okanagan Basin Water Board

Okanagan Hydrologic Modelling Project

sub_Basin maps.mxd / 2/14/2020 / 12:20:33 PM

Snow Pillow
Snow Course
Major Water Intake / Diversion
Active WSC Hydrometric Station
Discontinued WSC Hydrometric Station

230 Sub-Basin Boundary with Basin ID
Extra Basin Diversion Area
Reservoirs
Alluvial Fan

Associated Environmental

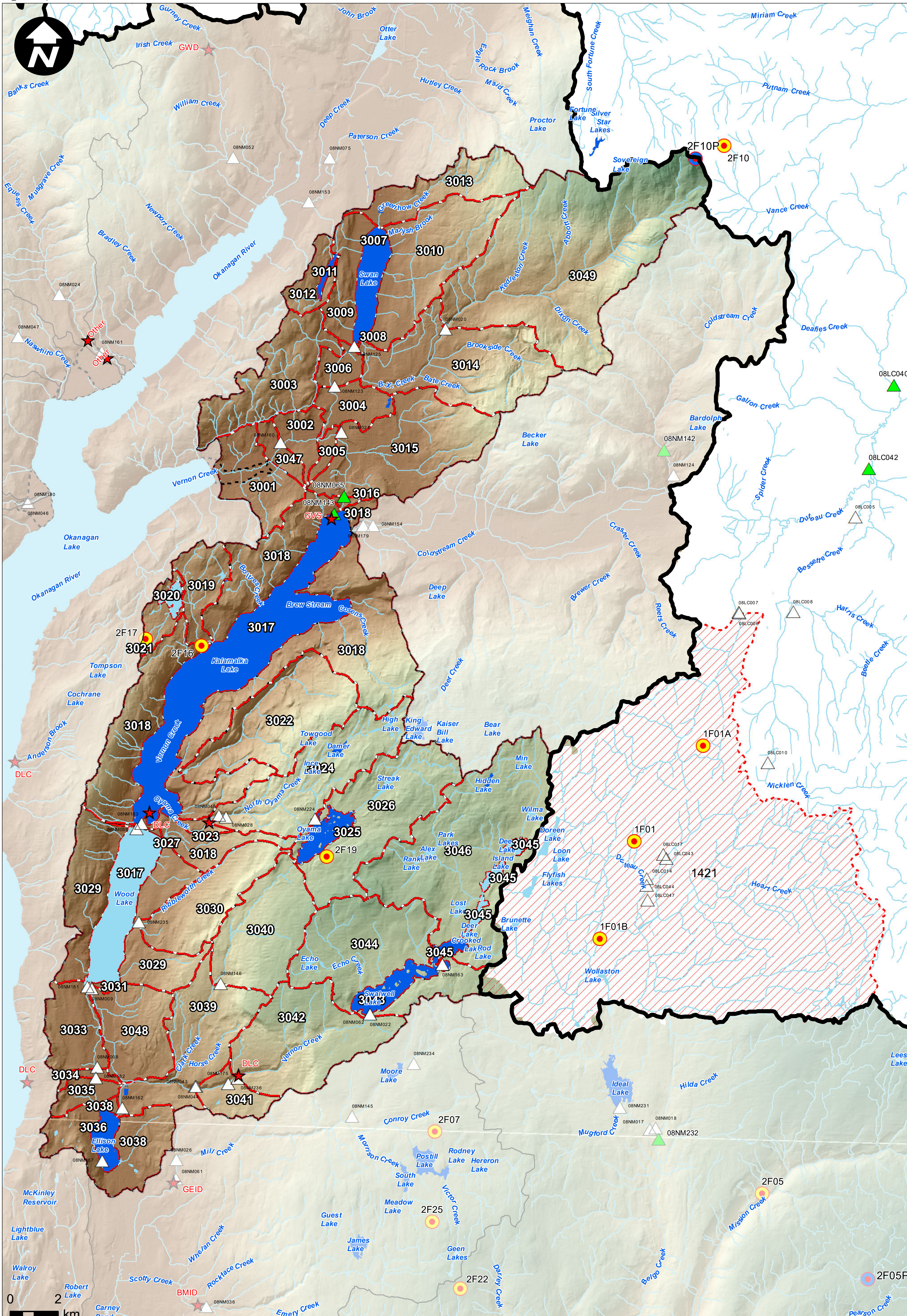
PROJECT NO.:	2016-8067.040.000
DATE:	January 2020
DRAWN BY:	DA

APPENDIX C-18: MAP OF WHITEMAN CREEK WATERSHED

Okanagan Basin Water Board

Okanagan Hydrologic Modelling Project

sub_Basin maps.mxd / 2/14/2020 / 12:20:44 PM



Snow Pillow
Snow Course
Major Water Intake / Diversion
Active WSC Hydrometric Station
Discontinued WSC Hydrometric Station

230 Sub-Basin Boundary with Basin ID
Extra Basin Diversion Area
Reservoirs
Alluvial Fan

Associated Environmental

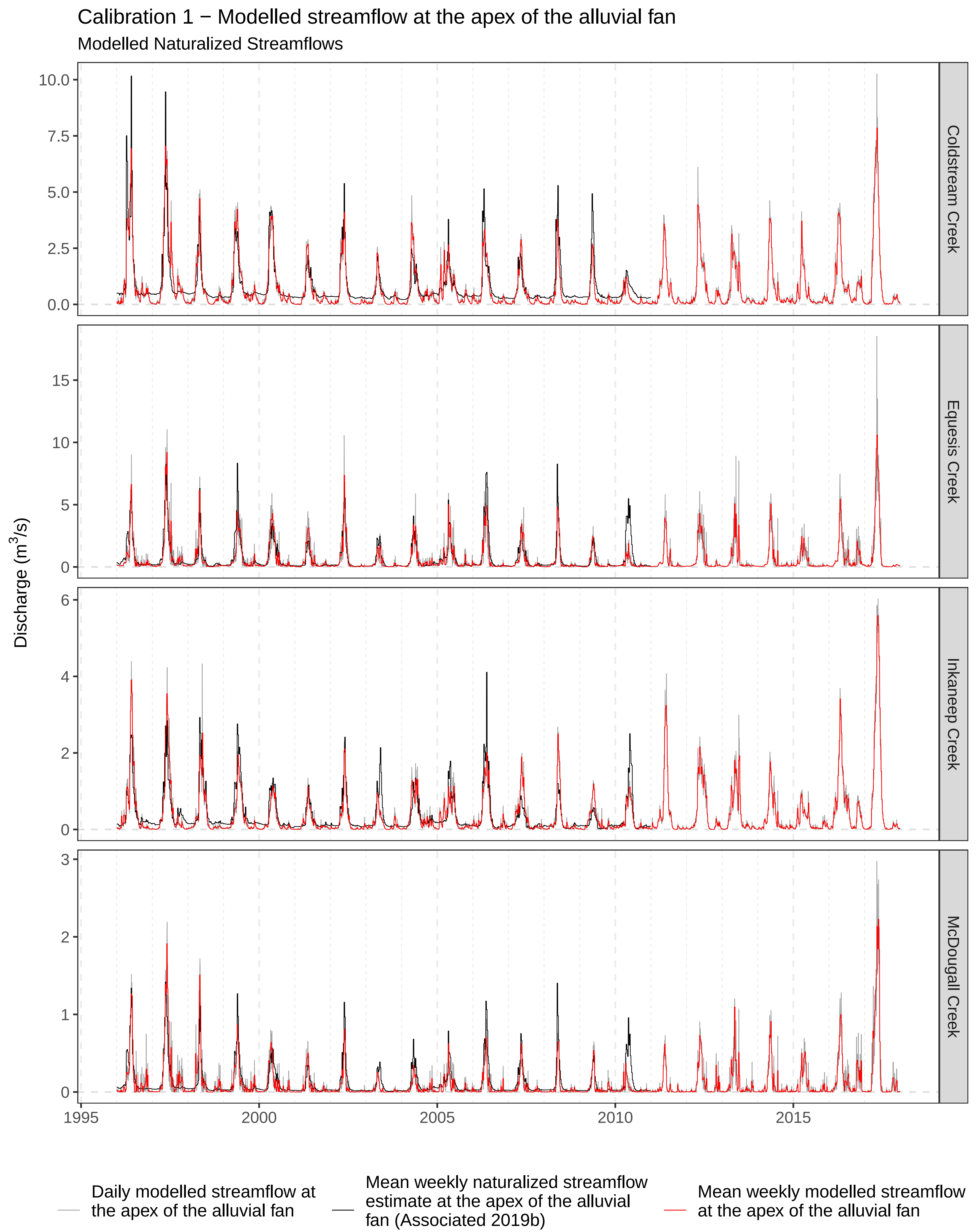
PROJECT NO.:	2016-8067.040.000
DATE:	January 2020
DRAWN BY:	DA

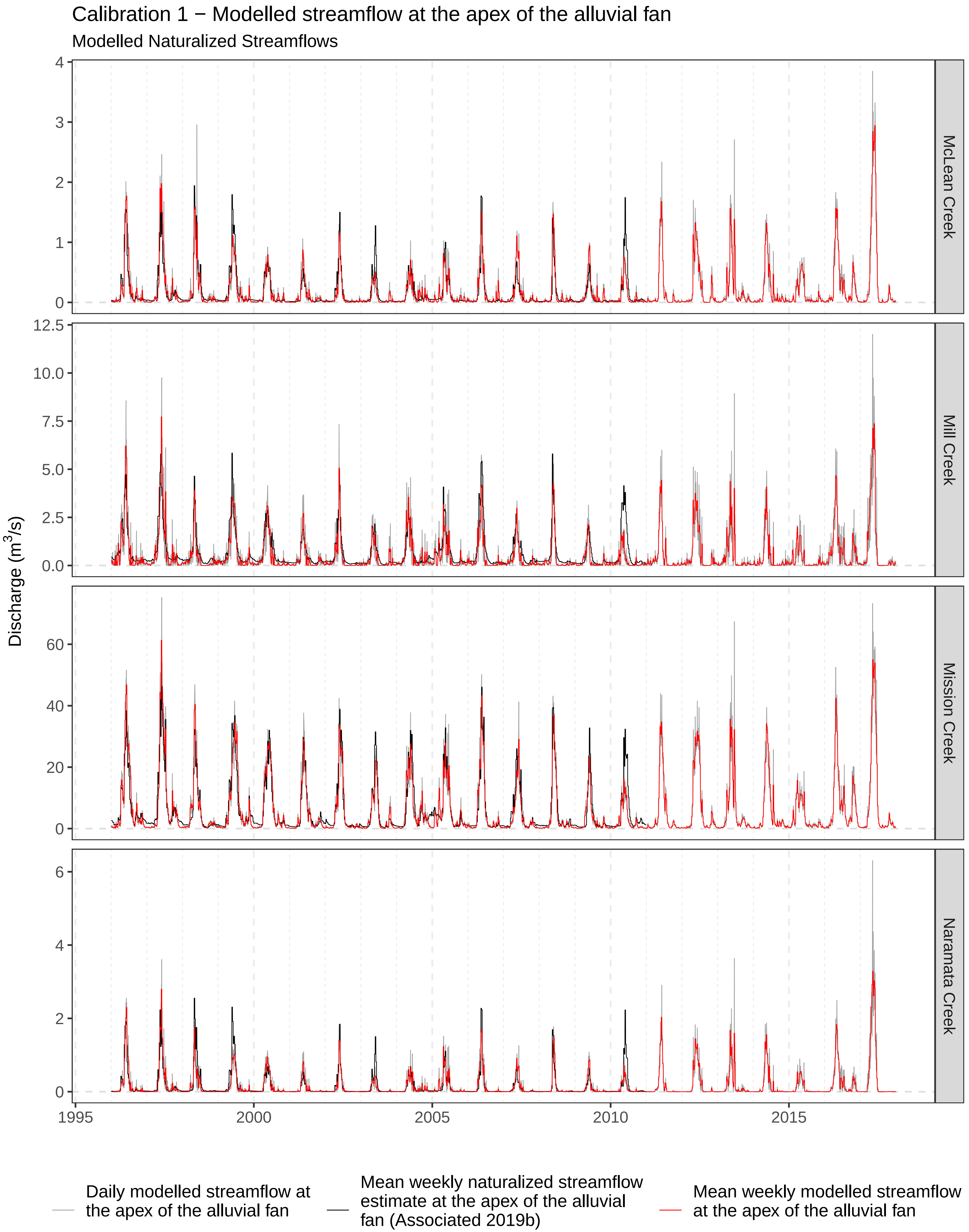
APPENDIX C-19: MAP OF VERNON CREEK WATERSHED

Okanagan Basin Water Board

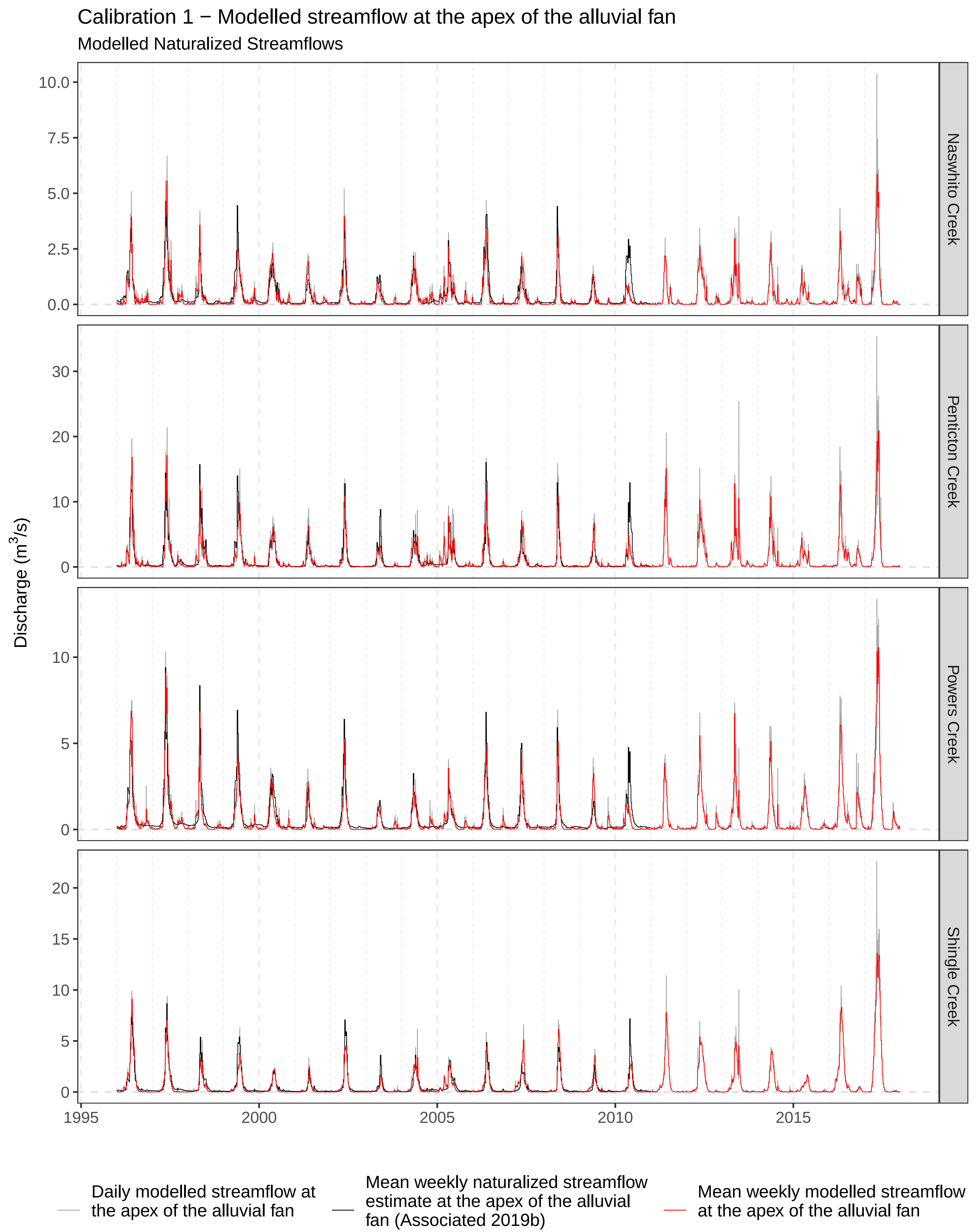
Okanagan Hydrologic Modelling Project

APPENDIX D - OHME V1 NATURALIZED STREAMFLOW MODEL RESULTS (VERSION 1)


Calibration 1 − Modelled streamflow at the apex of the alluvial fan
Modelled Naturalized Streamflows
Coldstream Creek
Equesis Creek
Inkaneep Creek
McDougall Creek
Discharge (m3/s)
1995
2000
2005
2010
2015
Daily modelled streamflow at the apex of the alluvial fan
Mean weekly naturalized streamflow estimate at the apex of the alluvial fan (Associated 2019b)
Mean weekly modelled streamflow at the apex of the alluvial fan



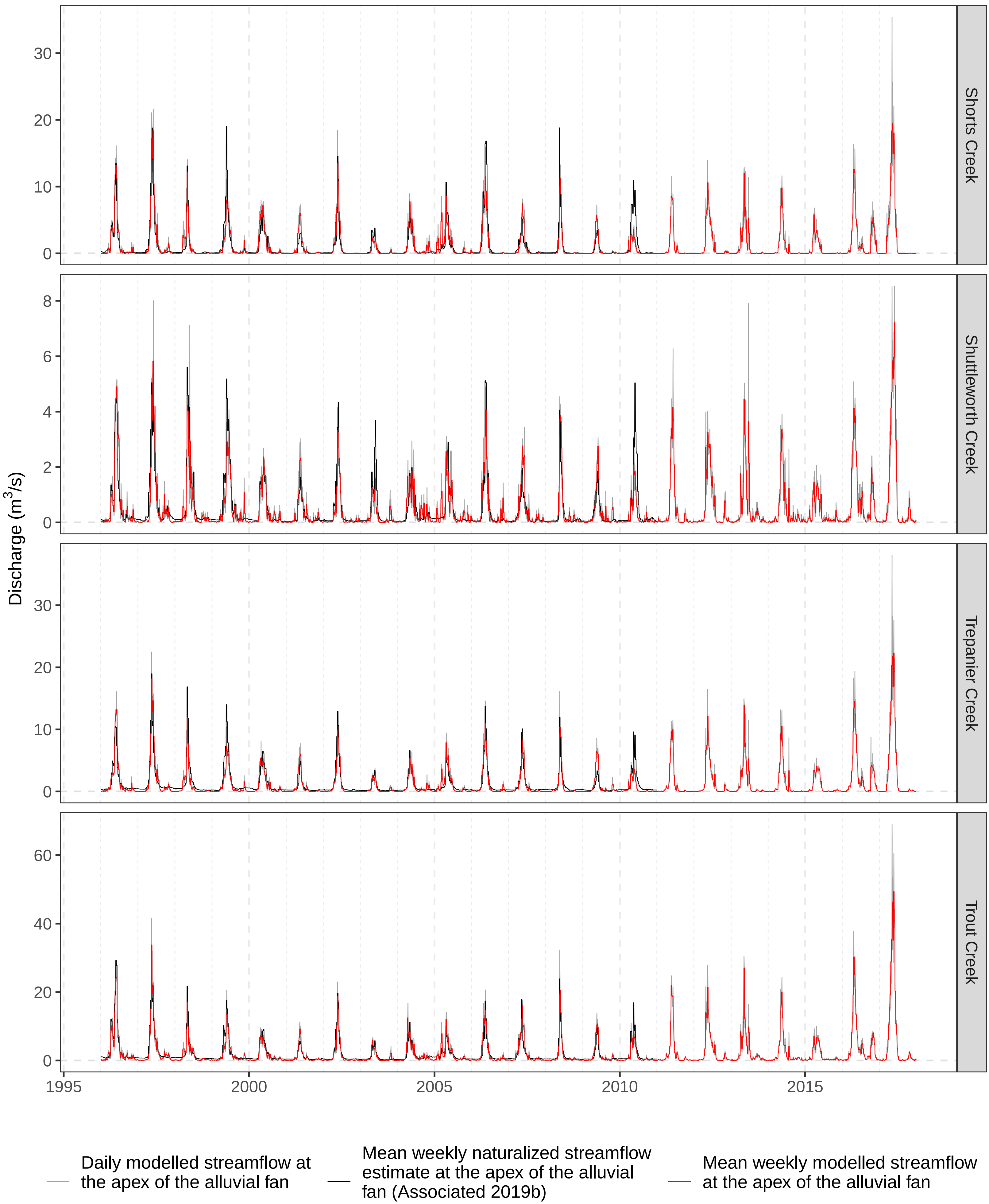
Calibration 1 − Modelled streamflow at the apex of the alluvial fan
Modelled Naturalized Streamflows
McLean Creek
Mill Creek
Mission Creek
Naramata Creek
Discharge (m3/s)
1995
2000
2005
2010
2015
Daily modelled streamflow at the apex of the alluvial fan
Mean weekly naturalized streamflow estimate at the apex of the alluvial fan (Associated 2019b)
Mean weekly modelled streamflow at the apex of the alluvial fan

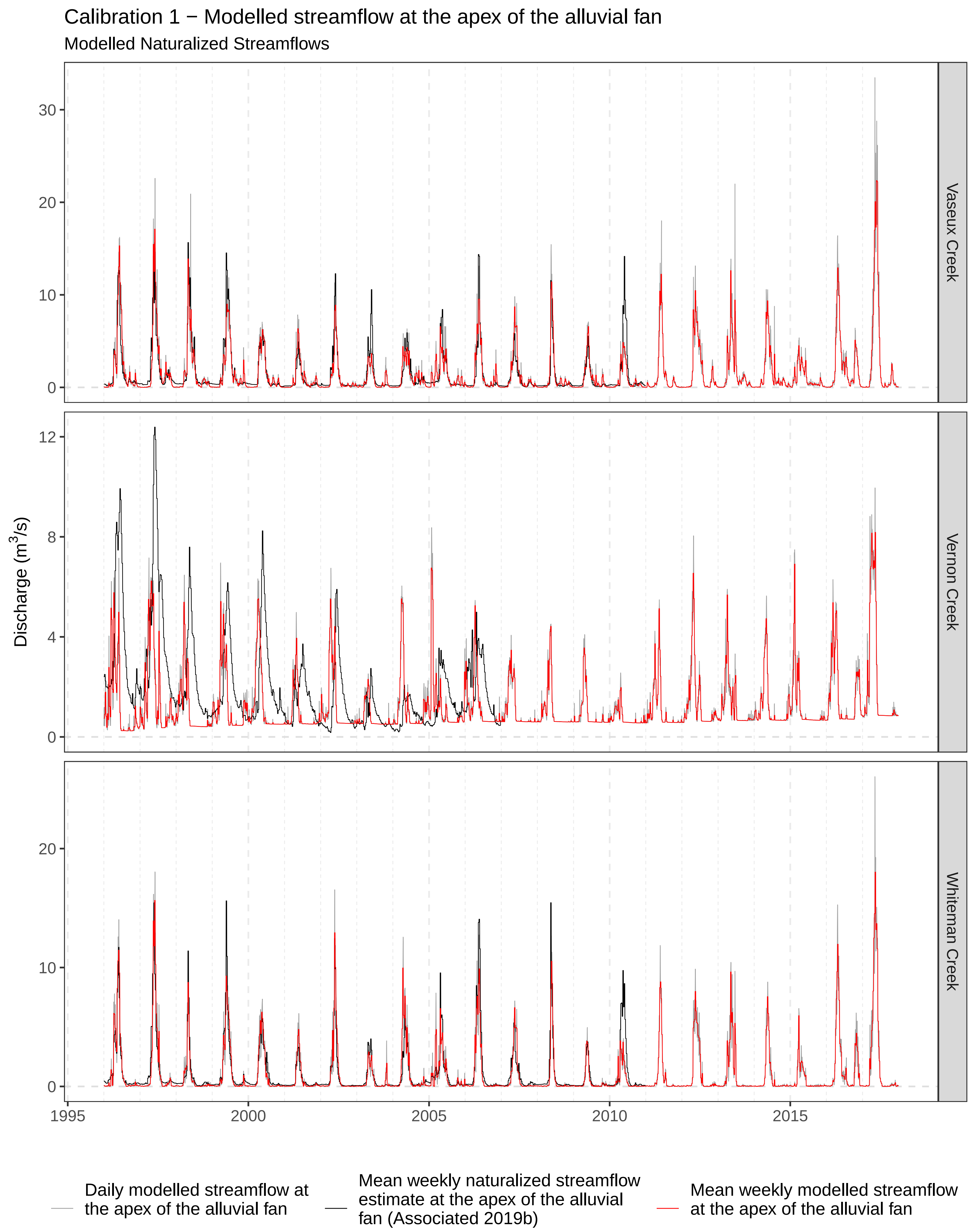


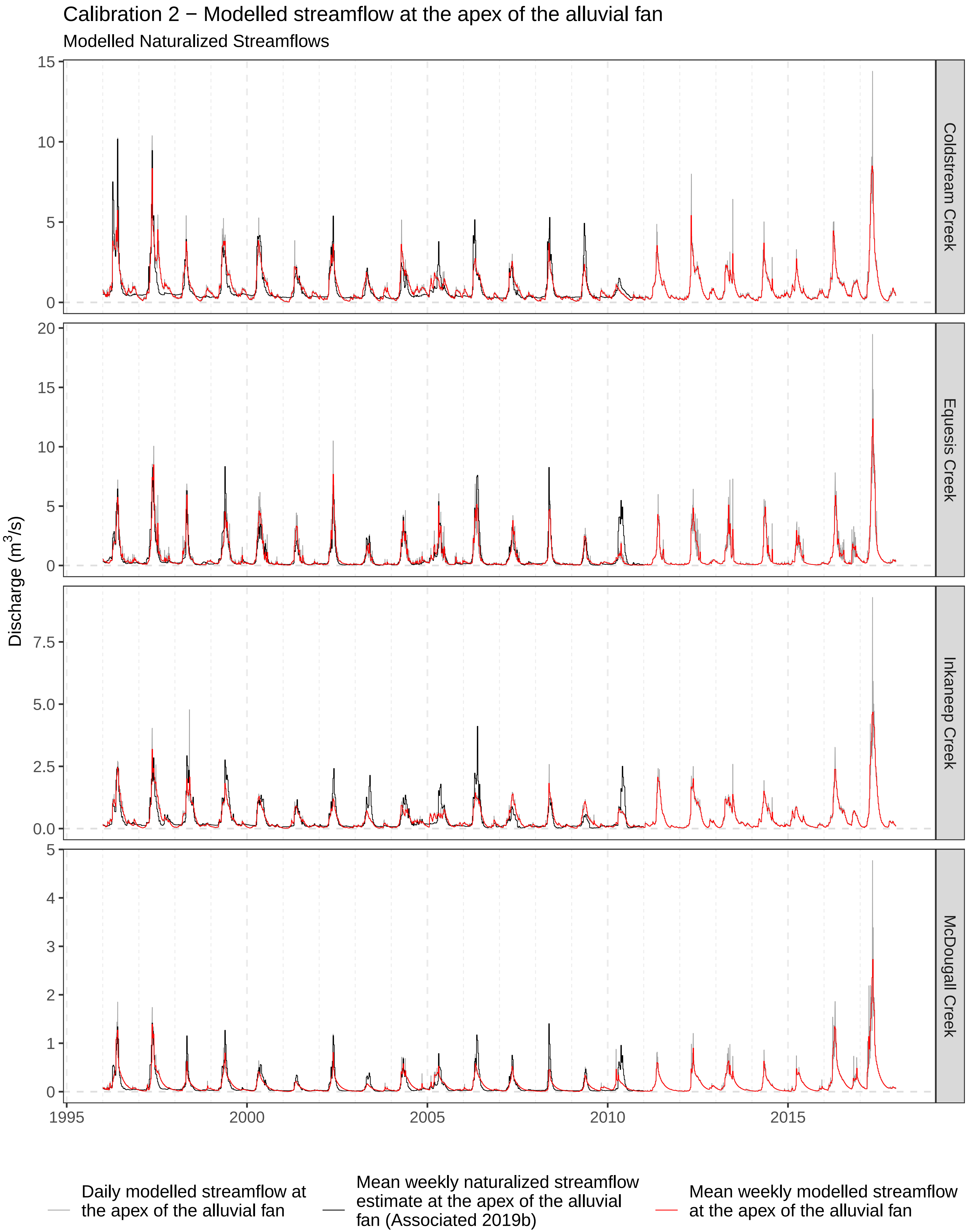
Calibration 1 − Modelled streamflow at the apex of the alluvial fan
Modelled Naturalized Streamflows
Naswhito Creek
Penticton Creek
Powers Creek
Shingle Creek
Discharge (m3/s)
0.0
2.5
5.0
7.5
10.0
0
10
20
30
0
5
10
0
5
10
15
20
1995
2000
2005
2010
2015
Daily modelled streamflow at the apex of the alluvial fan
Mean weekly naturalized streamflow estimate at the apex of the alluvial fan (Associated 2019b)
Mean weekly modelled streamflow at the apex of the alluvial fan

Calibration 1 − Modelled streamflow at the apex of the alluvial fan

Modelled Naturalized Streamflows



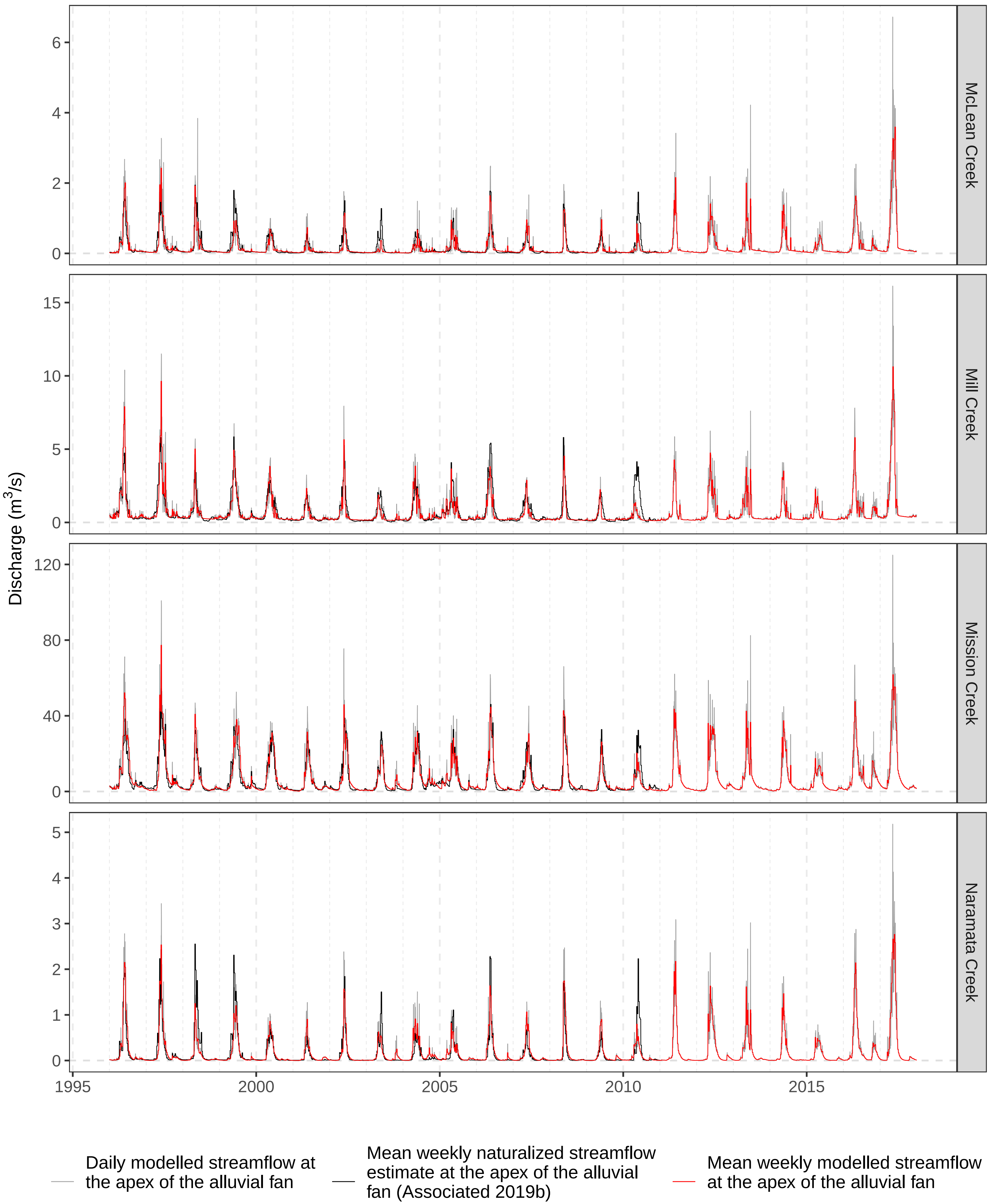

Calibration 1 − Modelled streamflow at the apex of the alluvial fan
Modelled Naturalized Streamflows
Discharge (m3/s)
Vaseux Creek
Vernon Creek
Whiteman Creek
0
10
20
30
0
4
8
12
0
10
20
1995
2000
2005
2010
2015
Daily modelled streamflow at the apex of the alluvial fan
Mean weekly naturalized streamflow estimate at the apex of the alluvial fan (Associated 2019b)
Mean weekly modelled streamflow at the apex of the alluvial fan

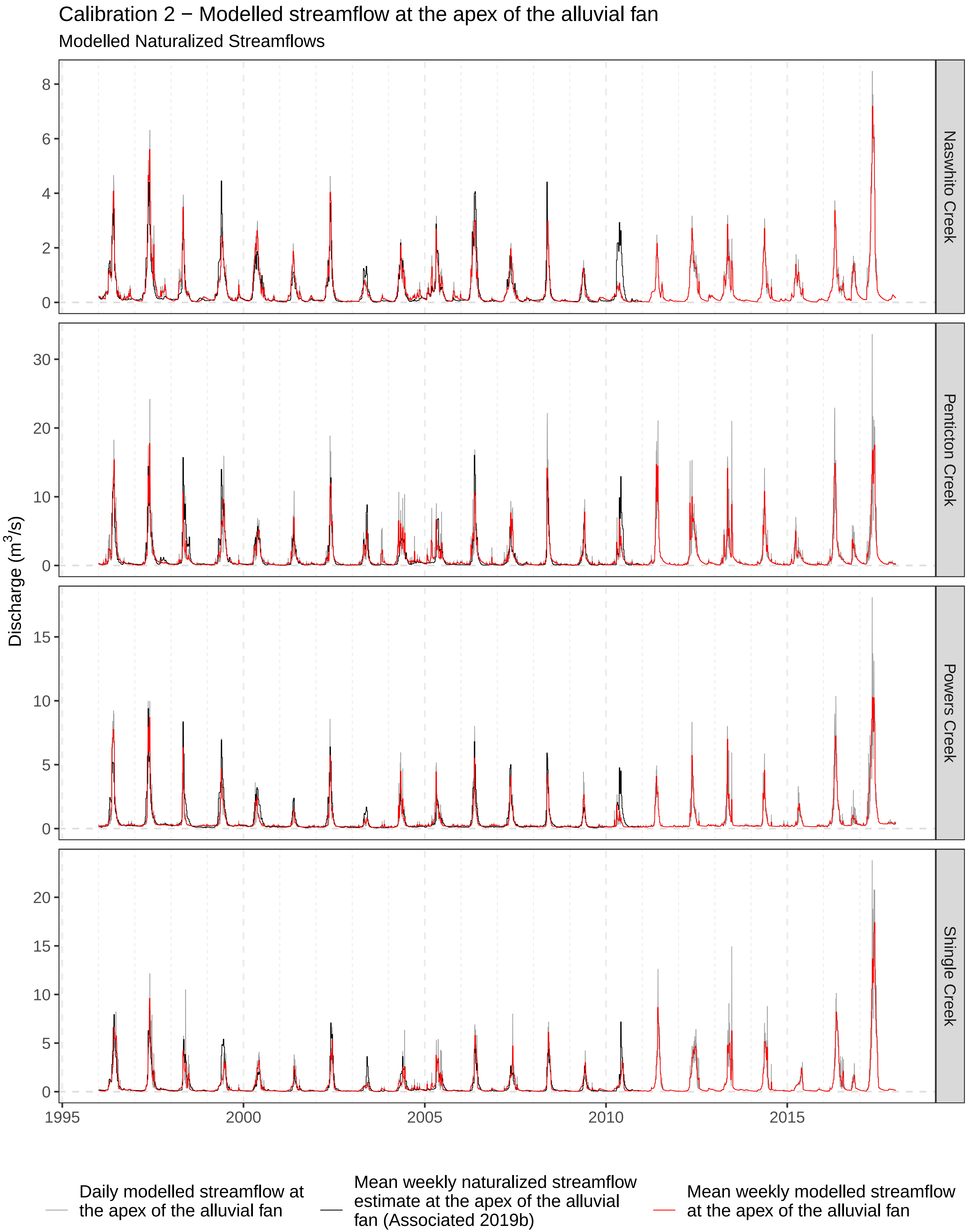


Calibration 2 − Modelled streamflow at the apex of the alluvial fan
Modelled Naturalized Streamflows
Coldstream Creek
Equesis Creek
Inkaneep Creek
McDougall Creek
Discharge (m3/s)
1995
2000
2005
2010
2015
Daily modelled streamflow at the apex of the alluvial fan
Mean weekly naturalized streamflow estimate at the apex of the alluvial fan (Associated 2019b)
Mean weekly modelled streamflow at the apex of the alluvial fan

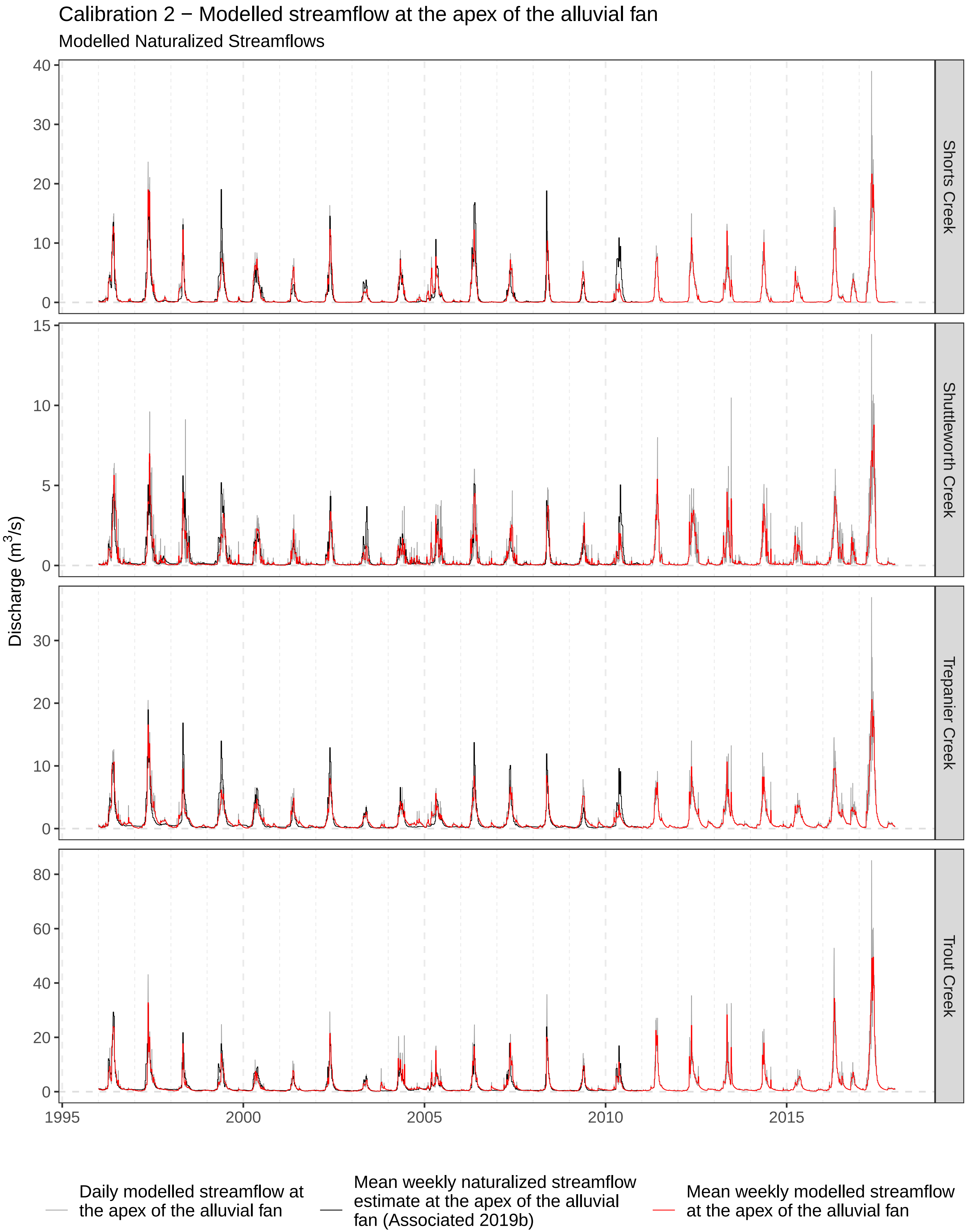
Calibration 2 − Modelled streamflow at the apex of the alluvial fan

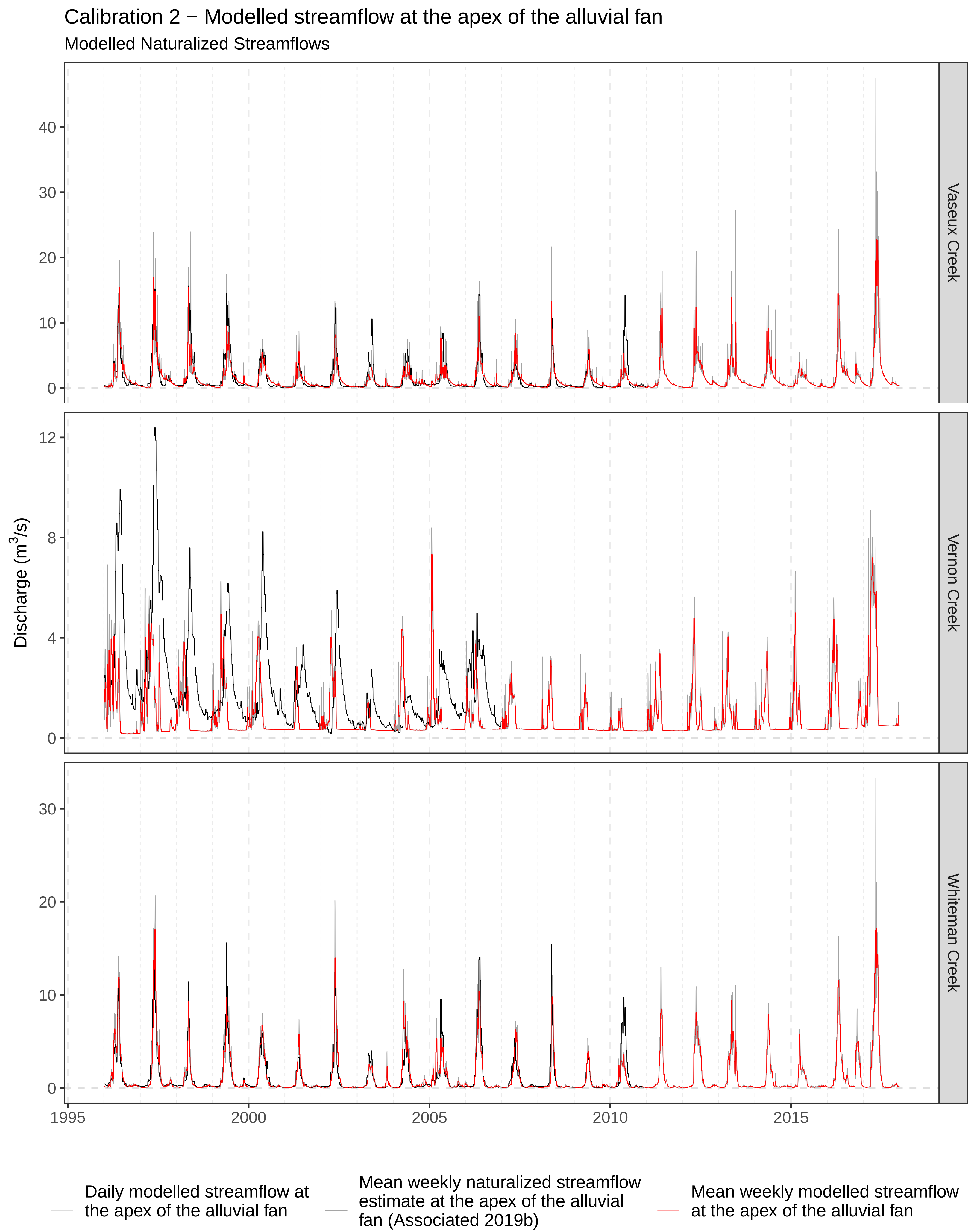
Modelled Naturalized Streamflows





Calibration 2 − Modelled streamflow at the apex of the alluvial fan
Modelled Naturalized Streamflows
Naswhito Creek
Penticton Creek
Powers Creek
Shingle Creek
Discharge (m3/s)
1995
2000
2005
2010
2015
Daily modelled streamflow at the apex of the alluvial fan
Mean weekly naturalized streamflow estimate at the apex of the alluvial fan (Associated 2019b)
Mean weekly modelled streamflow at the apex of the alluvial fan

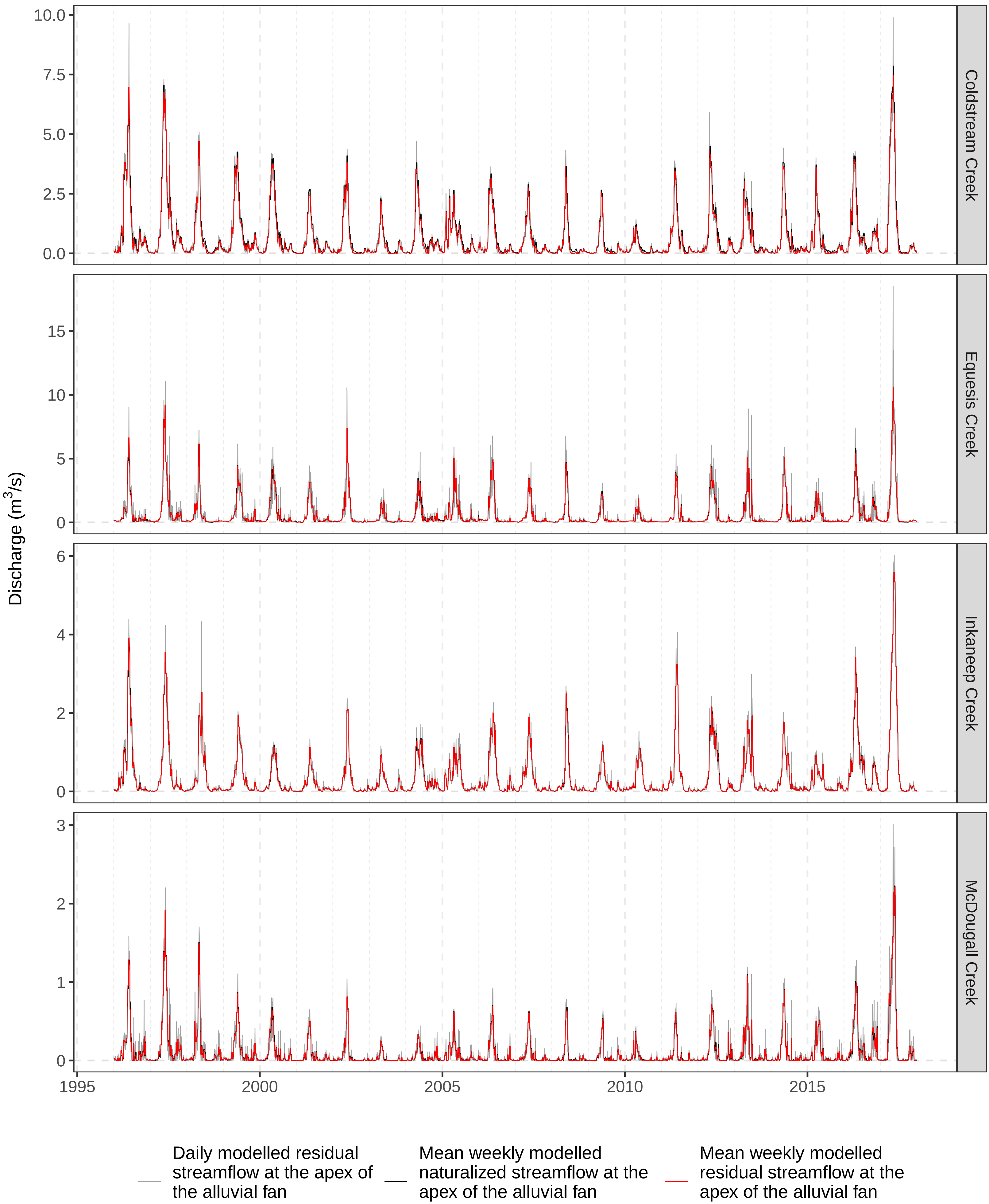

Calibration 2 − Modelled streamflow at the apex of the alluvial fan
Modelled Naturalized Streamflows
Discharge (m3/s)
Shorts Creek
Shuttleworth Creek
Trepanier Creek
Trout Creek
0
10
20
30
40
0
5
10
15
0
10
20
30
0
20
40
60
80
1995
2000
2005
2010
2015
Daily modelled streamflow at the apex of the alluvial fan
Mean weekly naturalized streamflow estimate at the apex of the alluvial fan (Associated 2019b)
Mean weekly modelled streamflow at the apex of the alluvial fan


Calibration 2 − Modelled streamflow at the apex of the alluvial fan
Modelled Naturalized Streamflows
Discharge (m3/s)
Vaseux Creek
Vernon Creek
Whiteman Creek
0
10
20
30
40
0
4
8
12
0
10
20
30
1995
2000
2005
2010
2015
Daily modelled streamflow at the apex of the alluvial fan
Mean weekly naturalized streamflow estimate at the apex of the alluvial fan (Associated 2019b)
Mean weekly modelled streamflow at the apex of the alluvial fan

APPENDIX E - OHME V1 RESIDUAL STREAMFLOW MODEL RESULTS (VERSION 1)

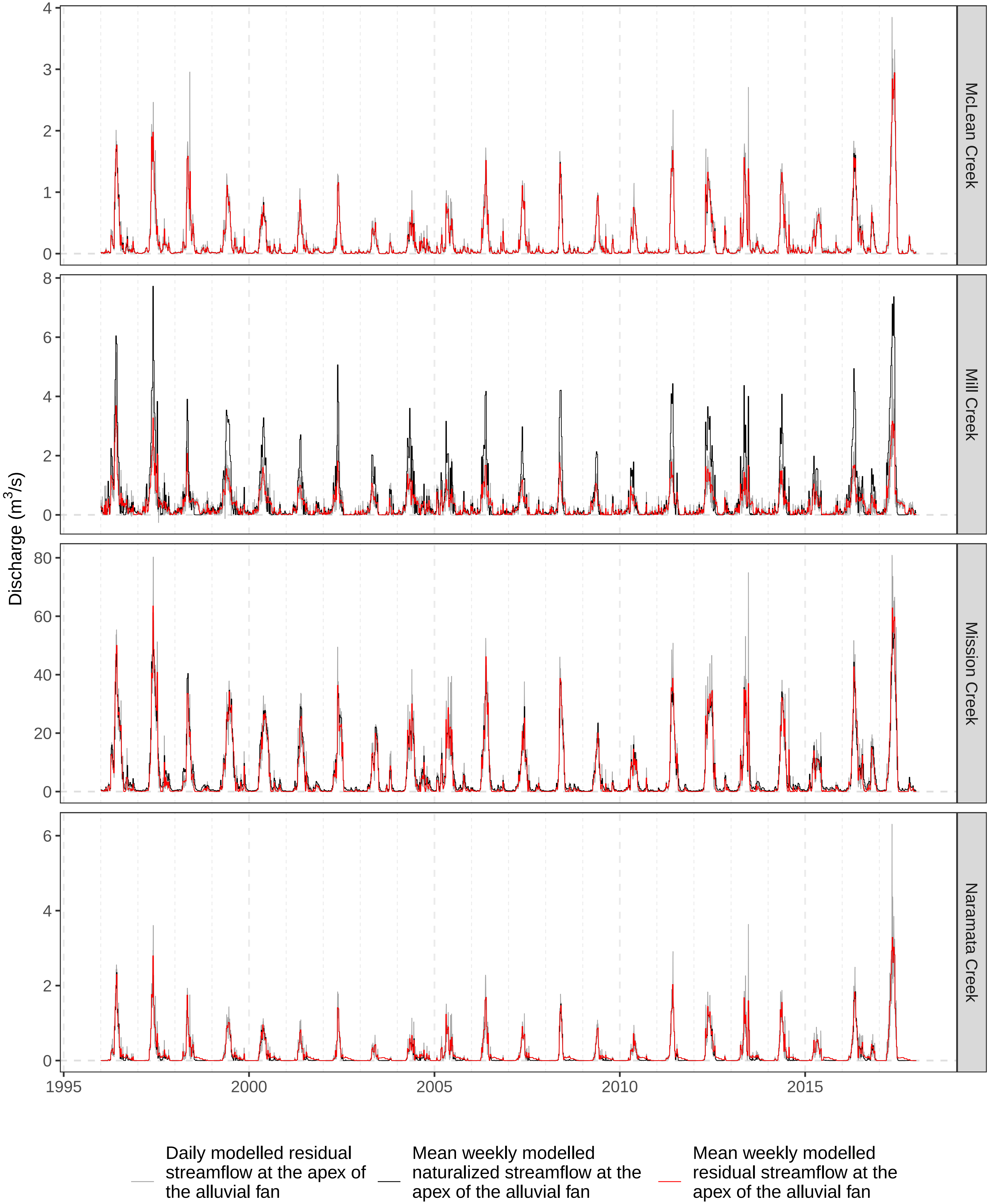
Calibration 1 − Modelled streamflow at the apex of the alluvial fan

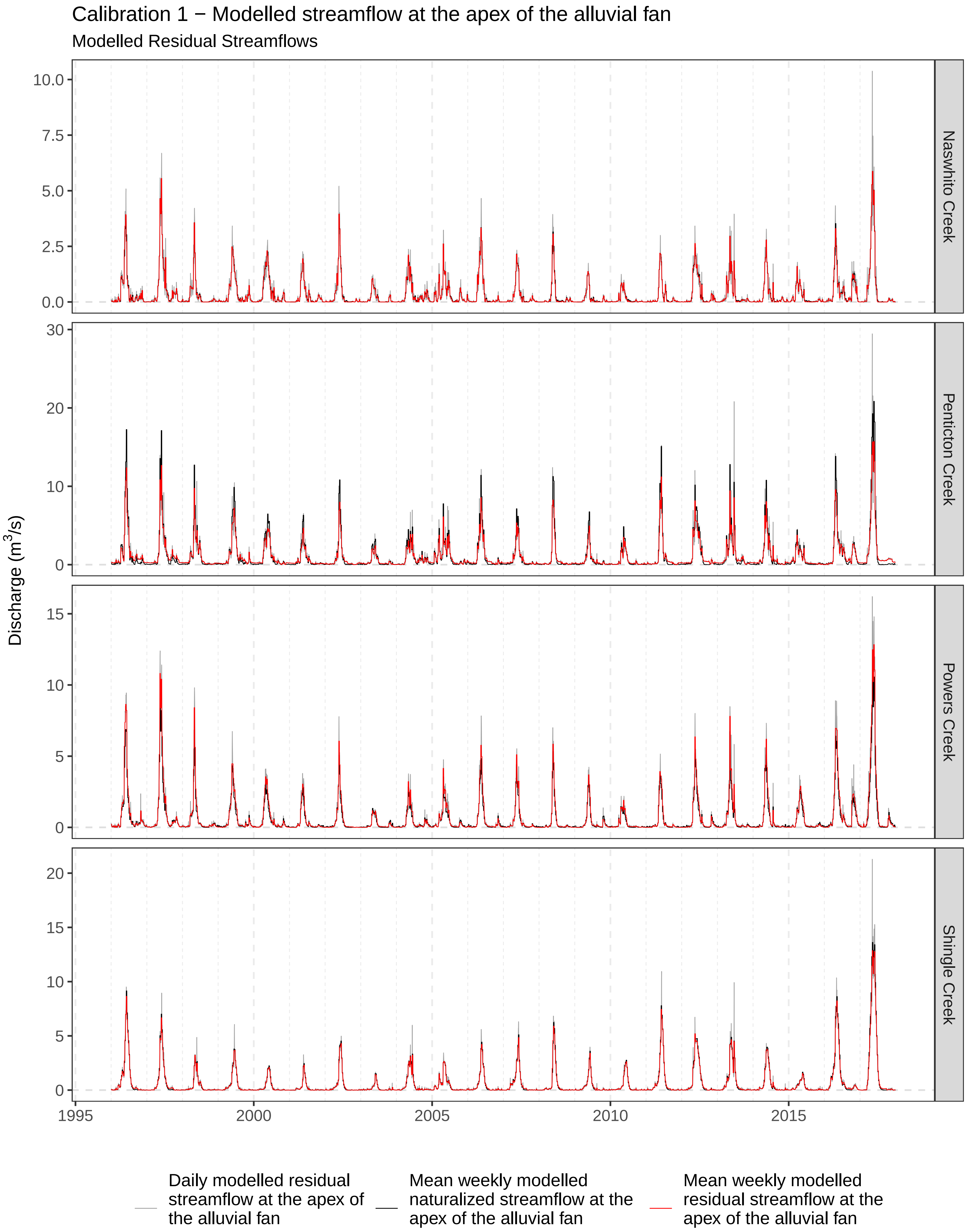
Modelled Residual Streamflows



Calibration 1 − Modelled streamflow at the apex of the alluvial fan

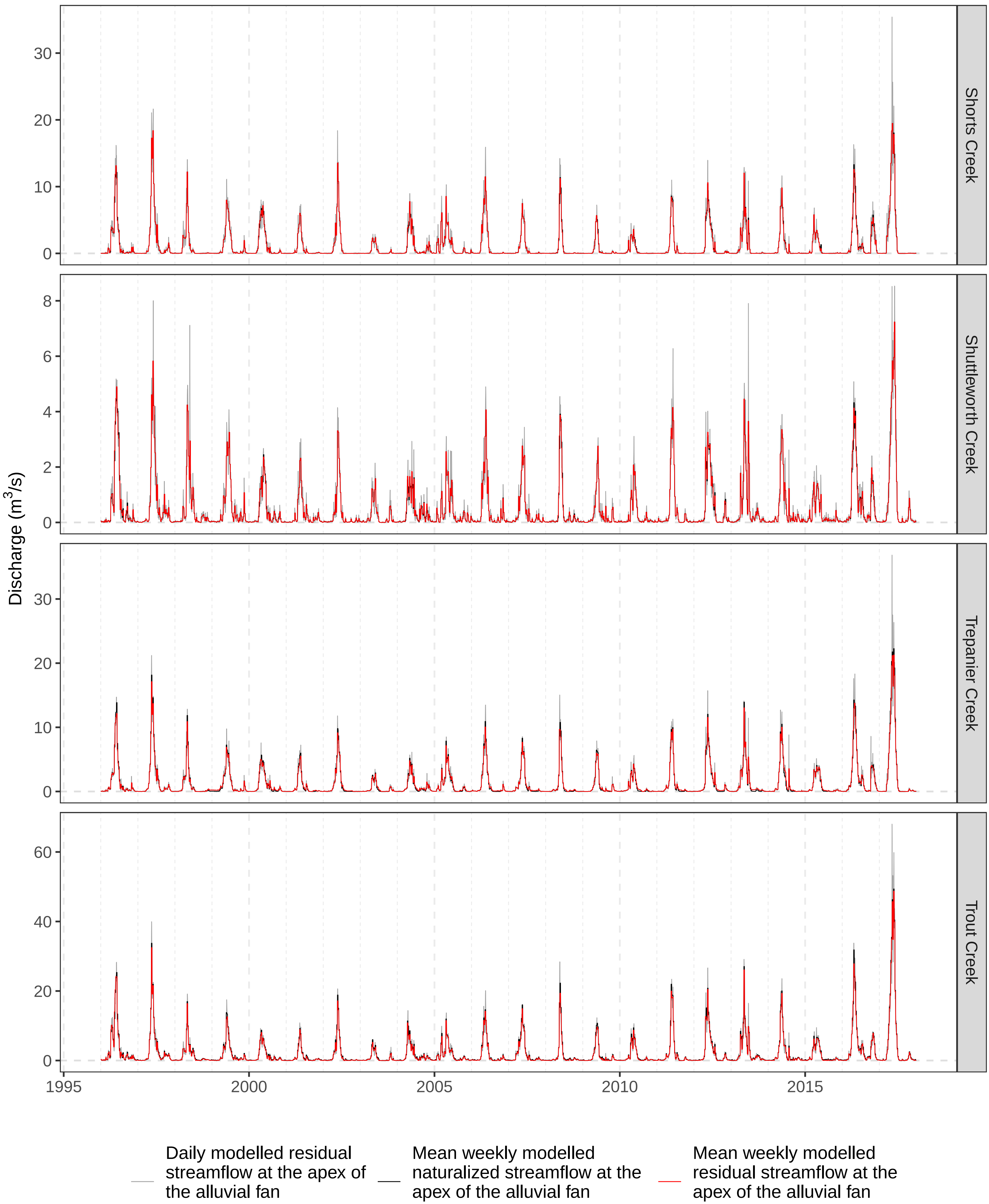
Modelled Residual Streamflows

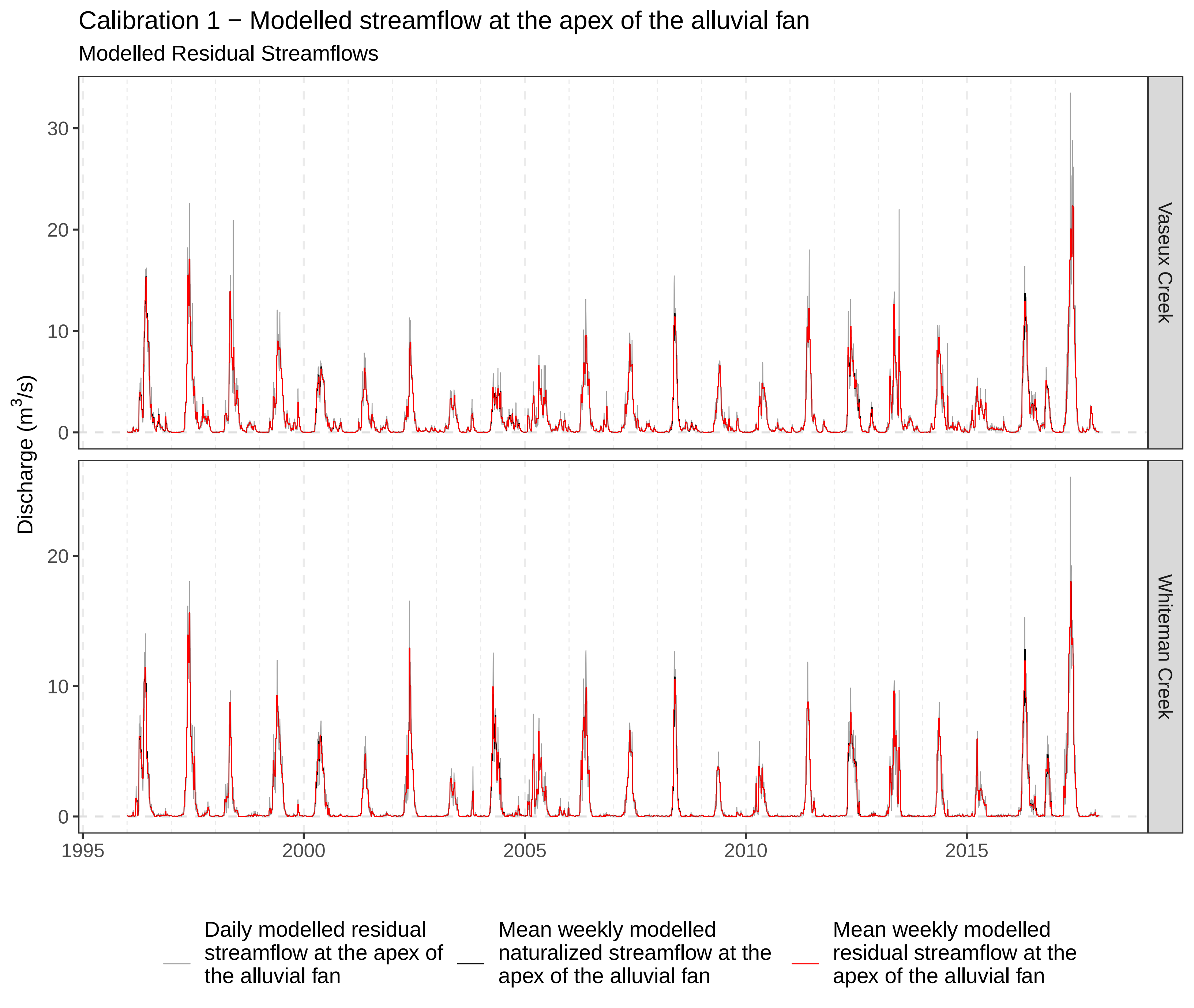


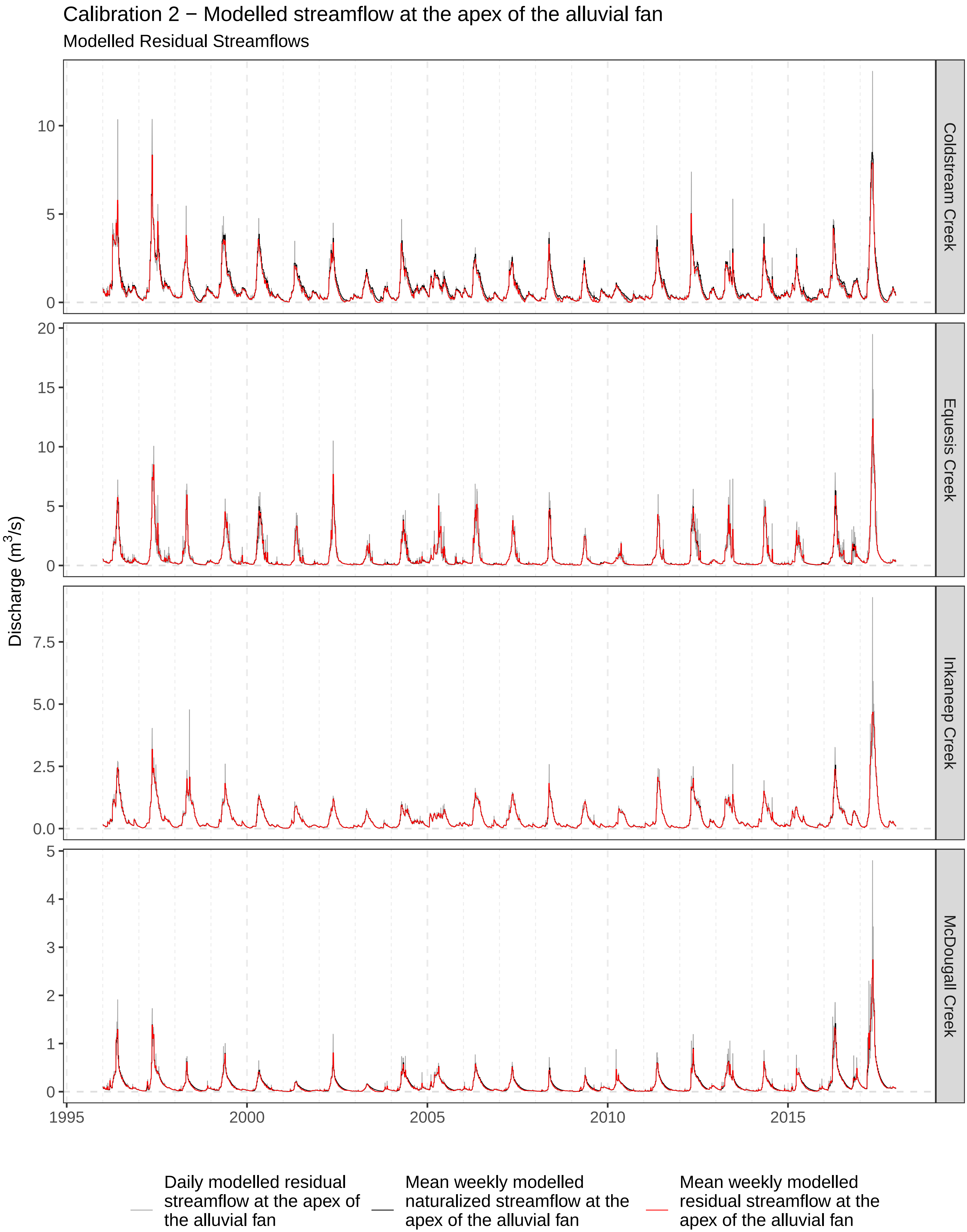

Calibration 1 − Modelled streamflow at the apex of the alluvial fan
Modelled Residual Streamflows
Discharge (m³/s)
Naswhito Creek
Penticton Creek
Powers Creek
Shingle Creek
0.0
2.5
5.0
7.5
10.0
0
10
20
30
0
5
10
15
0
5
10
15
20
1995
2000
2005
2010
2015
Daily modelled residual streamflow at the apex of the alluvial fan
Mean weekly modelled naturalized streamflow at the apex of the alluvial fan
Mean weekly modelled residual streamflow at the apex of the alluvial fan

Calibration 1 − Modelled streamflow at the apex of the alluvial fan

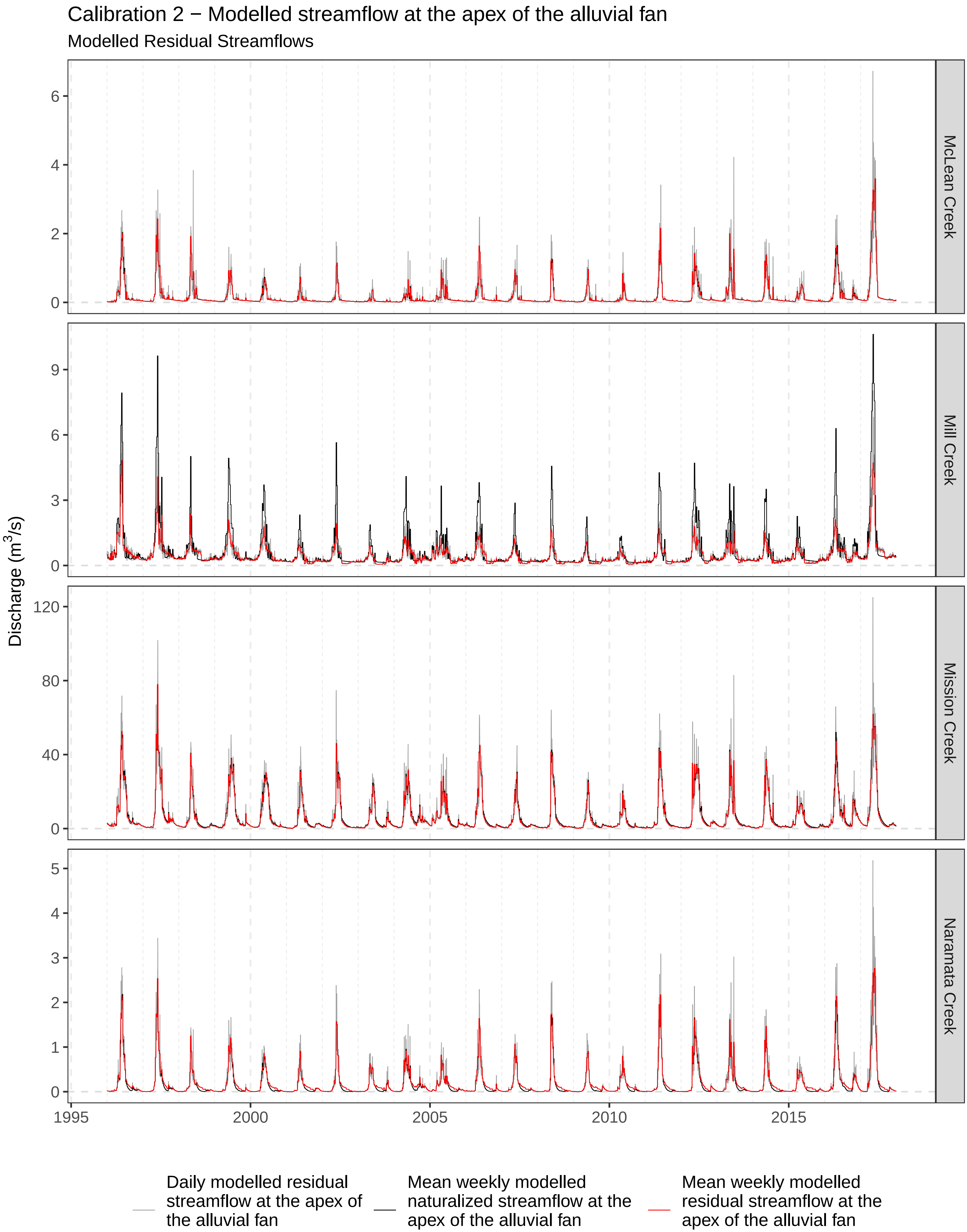
Modelled Residual Streamflows




Calibration 1 − Modelled streamflow at the apex of the alluvial fan
Modelled Residual Streamflows
Discharge (m3/s)
Vaseux Creek
Whiteman Creek
0
10
20
30
1995
2000
2005
2010
2015
Daily modelled residual streamflow at the apex of the alluvial fan
Mean weekly modelled naturalized streamflow at the apex of the alluvial fan
Mean weekly modelled residual streamflow at the apex of the alluvial fan



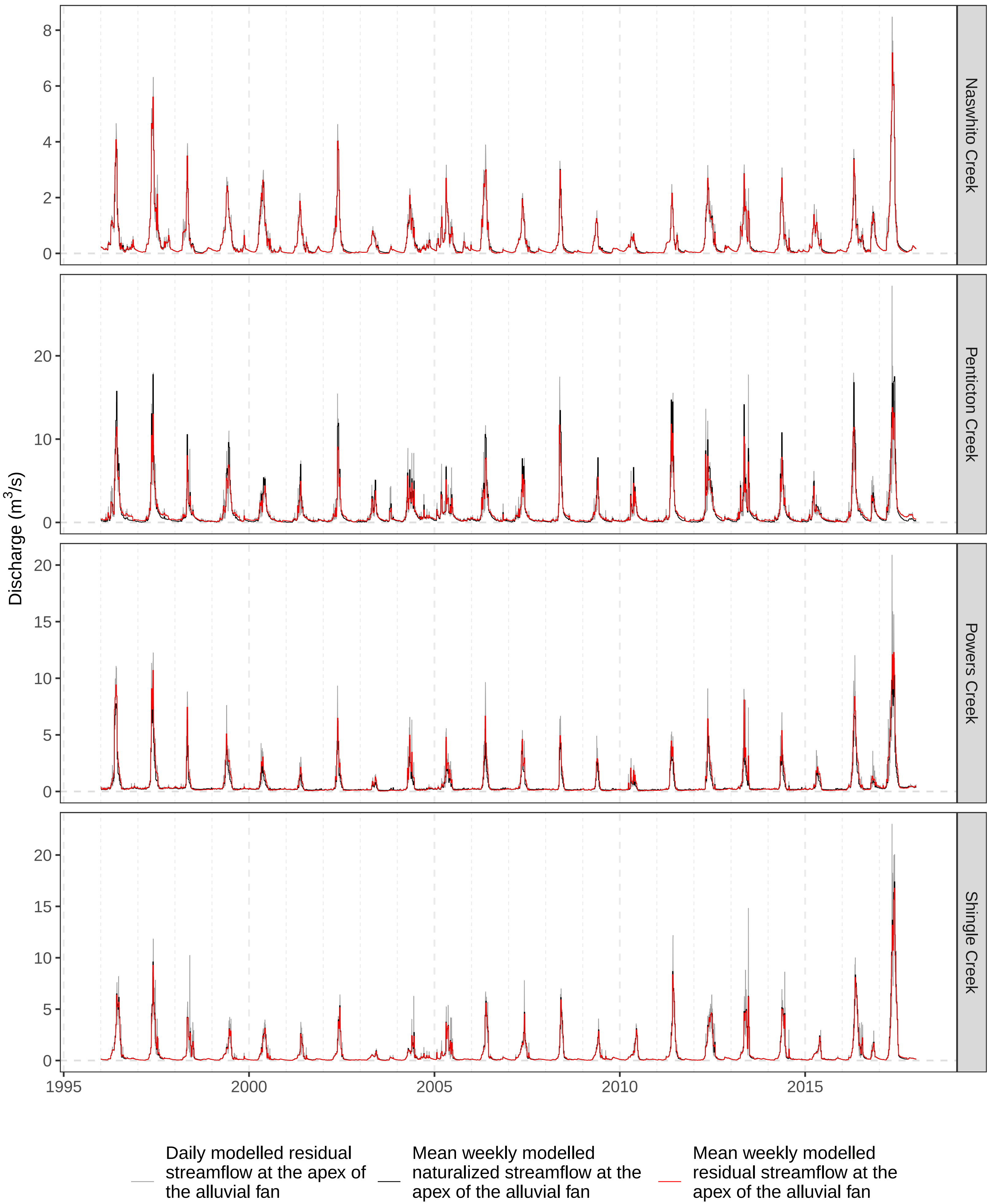
Calibration 2 − Modelled streamflow at the apex of the alluvial fan
Modelled Residual Streamflows
Discharge (m³/s)
Coldstream Creek
Equesis Creek
Inkaneep Creek
McDougall Creek
0
5
10
15
20
0.0
2.5
5.0
7.5
1
2
3
4
1995
2000
2005
2010
2015
Daily modelled residual streamflow at the apex of the alluvial fan
Mean weekly modelled naturalized streamflow at the apex of the alluvial fan
Mean weekly modelled residual streamflow at the apex of the alluvial fan

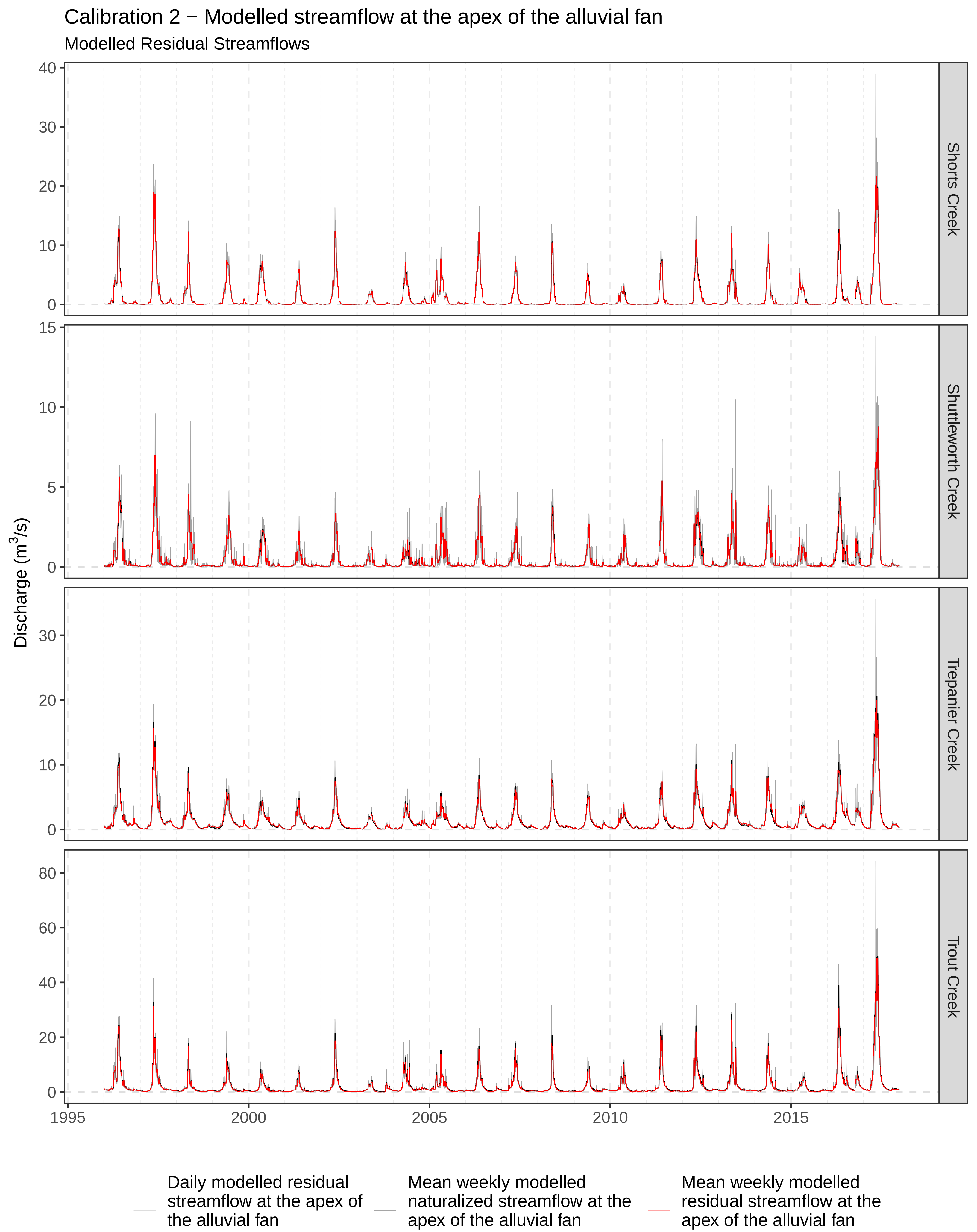


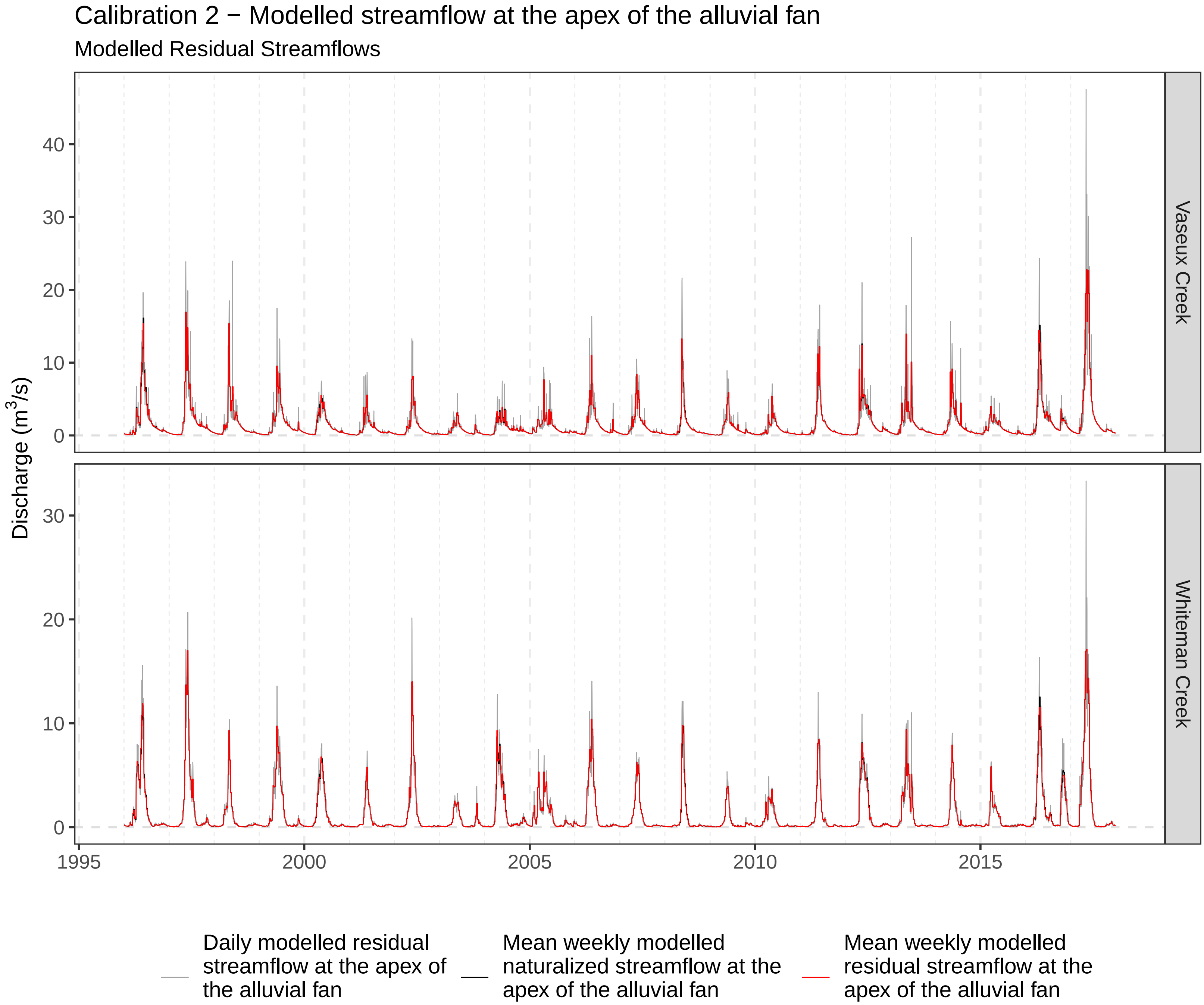
Calibration 2 − Modelled streamflow at the apex of the alluvial fan
Modelled Residual Streamflows
Discharge (m3/s)
McLean Creek
Mill Creek
Mission Creek
Naramata Creek
0
2
4
6
3
9
40
80
120
1
5
1995
2000
2005
2010
2015
Daily modelled residual streamflow at the apex of the alluvial fan
Mean weekly modelled naturalized streamflow at the apex of the alluvial fan
Mean weekly modelled residual streamflow at the apex of the alluvial fan

Calibration 2 − Modelled streamflow at the apex of the alluvial fan

Modelled Residual Streamflows




Calibration 2 − Modelled streamflow at the apex of the alluvial fan
Modelled Residual Streamflows
Discharge (m3/s)
Shorts Creek
Shuttleworth Creek
Trepanier Creek
Trout Creek
1995
2000
2005
2010
2015
Daily modelled residual streamflow at the apex of the alluvial fan
Mean weekly modelled naturalized streamflow at the apex of the alluvial fan
Mean weekly modelled residual streamflow at the apex of the alluvial fan



Calibration 2 − Modelled streamflow at the apex of the alluvial fan
Modelled Residual Streamflows
Discharge (m3/s)
Vaseux Creek
Whiteman Creek
0
10
20
30
40
1995
2000
2005
2010
2015
Daily modelled residual streamflow at the apex of the alluvial fan
Mean weekly modelled naturalized streamflow at the apex of the alluvial fan
Mean weekly modelled residual streamflow at the apex of the alluvial fan