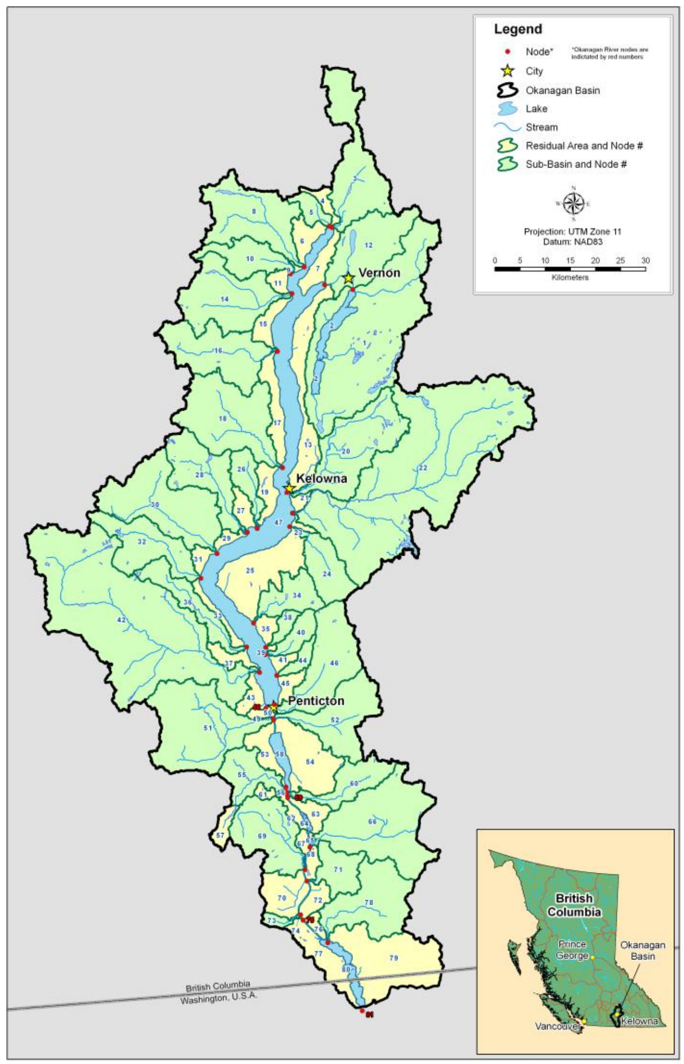
Okanagan Basin Water Accounting Model

Final Report



Prepared for:

Okanagan Basin Water Board

Prepared by:

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May 2010

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Date: 27 May 2010

To:
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RE: Okanagan Basin Water Accounting Model Report

Dear Anna,

Accompanying this letter is the Final Report for Okanagan Basin Water Accounting Model. This document is a compilation of reporting for two separate studies completed under Phase 2 of the Okanagan Basin Water Supply and Demand Project:

1. The first study involved the development and calibration of the Okanagan Basin Hydrology Model that was completed by DHI Water & Environment ULC (DHI) under a subconsulting agreement with Summit Environmental Consultants, Ltd. as part of the Surface Water Hydrology and Hydrologic Modelling Study.
2. The second study involved the development and calibration of the Okanagan Basin Water Accounting Model and running the model under various scenarios to evaluate the potential impacts of climate change, land use changes, population growth and water efficiency programs. This project was completed by DHI as part of the Water Balance Modelling contract (OBWB 08-008).

The model data files and results for the Okanagan Basin Hydrology Model and the Okanagan Basin Water Accounting Model, as well as the input files and results for each scenario are being delivered via an external hard drive.

We have enjoyed working with the Working Group and the other contributing organizations on this challenging and ground-breaking project and we look forward to seeing the results of this work being applied towards meeting the objectives of the Okanagan Basin Water Supply and Demand Project.

If you have any questions or concerns about the report or the model data files, or if you need any additional information, please do not hesitate to contact me.

Yours sincerely
DHI Water & Environment

Pat Delaney

Patrick Delaney
President

LETTER OF TRANSMITTAL

Letters of transmittal are always bound into the report and done on letterhead. This title is in the template so that “Letter of Transmittal” always appears in the Table of contents, but the actual letter replaces this page.

ACKNOWLEDGEMENTS

DHI would like to acknowledge the contributions of the many different teams and people who have participated in the Okanagan Water Supply and Demand Project, and in particular those who contributed directly and indirectly to the development of the Okanagan Basin Water Accounting Model.

Brian Guy from Summit Environmental Consultants acted as the Project Manager and Technical Advisor. Brian provided the high level project vision and understanding required to navigate the complexities of the project from the initial development of the hydrology model through to the delivery of the Okanagan Basin Water Accounting Model and the preparation of this report.

Hugh Hamilton from Summit Environmental Consultants acted as the Project Manager for the Streamflow Naturalization and Hydrology State of the Basin study.

Ron Fretwell from RHF Systems, Ltd. was responsible for developing and running the water demand model that provided the water use data for the calibration period as well as each scenario period.

Clint Alexander and Frank Poulsen from ESSA Technologies designed and operated the OKWater Database where all of the relevant data from the Okanagan Water Supply and Demand Project is stored.

Wenda Mason from BC Ministry of Environment acted as the Project Director and co-Chair of the Working Group.

Denise Neilsen from Agriculture and Agri-Foods Canada was an active member of the Working Group and was a key figure in navigating the issues we experienced with the climate data.

Finally, this project would not have been possible without the vision and financial contributions from the Okanagan Basin Water Board (OBWB), under the direction and leadership of Anna Warwick Sears.

EXECUTIVE SUMMARY

This report consolidates the documentation of two separate studies developed as part of the Okanagan Water Supply and Demand Project. The Surface Water Hydrology and Hydrologic Modelling Study was initially awarded to Summit Environmental Consultants, Ltd. and DHI Water & Environment, and then the Water Balance Modelling project was later awarded to DHI Water & Environment.

The primary objective of the Surface Water Hydrology and Hydrologic Modelling Study was to develop and calibrate a distributed hydrologic model of the Okanagan Basin to simulate naturalized conditions.

The primary objectives of the Water Balance Modelling project were to:

1. Develop and calibrate a hydrology and hydraulic model of the Okanagan Basin that is capable of accurately representing the complex movement and distribution of water within the basin.
2. Use the model to evaluate the potential impacts to the water supply in the basin as a result of climate change, water use changes, population growth, and mountain pine beetle infestation.

The model developed for these projects is referred to as the Okanagan Basin Water Accounting Model (OBWAM) and it was developed using the MIKE SHE integrated watershed modelling system. The OBWAM is a sophisticated, flexible and scalable hydrology model capable of incorporating physical data inputs that represent the spatially and temporally variable hydrologic characteristics of the basin. The model has been successfully calibrated to accurately reproduce a continuous hydrologic response over a wide range of climate conditions from 1996-2006. The OBWAM is also able to accurately represent and reproduce the real-time operational logic of the dams on each of the mainstem lakes in the Okanagan Basin.

The OBWAM was developed to evaluate the basin wide water supply implications of potential changes in climate, land use, water use and mountain pine beetle infestation. This objective was successfully demonstrated by running fifteen different future scenarios to evaluate different combinations of climate change and water use against the recent historical hydrologic response of the basin. The future climate data was generated using the CGCM2-A2 model for one historic period (1996-2006) to establish a baseline, and then for three future periods (2011-2040, 2041-2070, and a three year drought period established using the three driest years from 2010 – 2100). The water use scenarios were assembled to consider three main factors;

(1) Population growth (expected growth rate vs. high growth rate)

(2) Water use efficiency (current trends vs. increased efficiency)

(3) Agricultural land base expansion (present conditions vs. expanded agricultural base)

A comprehensive analysis of the scenario results was prepared and presented in this report. The main conclusions from the scenarios are as follows:

- The total annual precipitation and evapotranspiration do not exhibit any obvious trends in the future scenarios, but the average temperature increases and the number of days with temperatures below zero Celsius decreases significantly.

- As a result of climate change, the maximum snow depth decreases by almost 30% and is occurring almost 3 weeks earlier, while the spring snowmelt runoff hydrograph for most tributaries to the mainstem lakes is shifted 2-4 weeks earlier in the year, and peak flows are consistently lower.
- As a result of the changes to the timing and volume of the spring snowmelt, the upland reservoirs begin emptying earlier and have an average of 10% less storage available at the end of the summer season.
- When measured on an annual basis, Okanagan Basin produces a sufficient volume of water to comfortably meet the annual total water demands for the forseeable future, but due to changes in the timing and volume of the spring snowmelt, the difficulties in meeting increasing demands during the low flow summer season will get worse under current operating conditions.
- Improved water efficiency measures have a measurably positive impact on the water supply during the summer months, and particularly during dry years when water use represents a more significant portion of the available water supply.

The integrated watershed model developed for this study represents the first model of this kind, and at this scale, in Canada. In its current state the model has demonstrated it is capable of producing a very good representation of the major hydrologic responses throughout the Okanagan Basin. However, this project has been a continuous learning process for all members of the team, and as this project has progressed it is clear that there are many ways to improve the performance, reliability, accuracy and calibration of the model, and to broaden the application of the model. This section will discuss the major recommendations for future improvements to the model. The key recommendations follow.

<u>Evaluate More Climate Models</u>

The results of this study are useful and informative in terms of evaluating the potential impacts of climate change and water use considerations, but it must be remembered that this study applied only one of many different global climate models which could be used to generate the future climate conditions. In order to properly bracket the potential impacts of climate change, several additional climate models should be applied and evaluated before any final conclusions regarding climate change can be made.

<u>Obtain More High Elevation Climate Data</u>

The gridded climate data sets provided a much better spatial and temporal resolution of the climate data than is normally available for hydrology studies. However, the under-representation of high elevation stations used to generate the climate data likely resulted in data that is heavily weighted towards the trends occurring at lower elevations. As such, the gridded temperatures may be over-predicted in some cases, which may be causing some of the anomalous runoff events simulated by the model. In order to correct this, at least 2 more meteorological stations should be installed at locations above an elevation of 1500 m, and preferably close to a snow pack measurement station.

<u>Install Additional Flow Monitoring Stations</u>

To improve the calibration of the model, it is recommended to install additional streamflow monitoring gages throughout the basin. In addition to providing valuable calibration data for the model, strategically placed monitoring stations will also help to characterize the surface water and groundwater interactions throughout the year and through different seasonal trends. Ideally, streamflow monitoring stations should be placed at the following locations:

- Immediately upstream of every upland reservoir: These stations will enable a more accurate calibration of the hydrology upstream of the reservoirs in order to make sure the model is generating the correct inflow to each upland reservoir.
- Immediately downstream of each upland reservoir: These stations will establish calibration flows against which the release rules for each reservoir could be calibrated against.
- Upstream of the alluvial fan in the main valley: These stations will help to characterize the lower elevation extractions and any streamflow gains or losses to the alluvial aquifer.
- Immediately upstream of the mouth of the tributary at the the mainstem lake: These stations will help to characterize the extractions and any baseflow losses or gains from the upstream gage.

The model calibration results can also be used to guide the additional data needs for the model. Since the results from the model indicate a good match for most of Natural and High Confidence stations, the locations where the model did not provide a good correlation with the naturalized data may be an indication of flaws in the naturalized data rather than flaws in the model parameters. By collecting more real data at these locations we can determine whether the model needs to be corrected, or whether the naturalized data was flawed. In total there were 7 nodes where the correlation coefficient for the calculated vs. measured streamflows was less than 0.7. These nodes include Vernon Creek at Kalamalka Outlet (N1), Irish Creek (N5), Nashwito Creek (N10), Vernon Creek at mouth (N12), MacDougall Creek (N26), and Testalinden Creek (N76).

Utilize Remote Sensing Data

Although the LAI values were determined largely using raster maps generated from remote sensing, the data quality was generally poor and even after some manual corrections were made to correct obvious flaws, the resultant LAI patterns were inconsistent with expected values for some of the vegetation types. If a more reliable set of remote sensing data is available for LAI it could possibly improve the calibration of the model by providing a more realistic representation of evapotranspiration processes.

Remotely sensed snowpack data could also be used to calibrate the model, particularly in regions where the model is lacking snow stations. In addition, if it is possible to obtain almost real-time estimates of snowpack throughout the basin, this information could be provided to the MIKE SHE model as an initial condition, and the model could be used as a real-time hydrological forecasting tool to help guide the operations of the dams on the mainstem lakes.

Enhance the Groundwater Model

Although the groundwater pumping is implicitly accounted for by the calibrated model, a thorough review of the implementation of groundwater processes is recommended to see if it is possible to find a more integrated approach that will allow the groundwater extraction to be explicitly represented in the baseflow reservoirs while also accounting for the portion of that extracted water than is re-applied on the ground surface for irrigation.

Alternatively, since tapping into the groundwater supply may be one of the strategies used to resolve the water supply problems during the summer months, a fully-distributed, three-dimensional groundwater model would provide a more accurate representation of the groundwater and surface water exchanges and the responses to increased groundwater extractions. However, in order to do this, a more comprehensive hydrogeological characterization of the Okanagan Basin will be required to develop a more detailed, multi-layer conceptual model.

The Geological Survey of Canada will soon be releasing a report entitled "Surficial geology, geochemistry and 3D modeling of the Kelowna-Westbank-Mission Creek area". This information should be used to develop a model of the Mission Creek sub-basin using the OBWAM and substituting a fully 3D groundwater model for the linear reservoir model. This will allow for a more accurate representation of the impacts of groundwater extraction on the groundwater table as well as on surface water and groundwater interactions.

Upland Reservoir Operations

For the future scenarios, some broad assumptions/simplifications were made regarding the operation of the uplands reservoirs, and these assumptions may have a significant impact on the ability of the model to accurately reflect how the system will behave in the future. Since the upland reservoirs seem to play a key role in managing the supply of water to the downstream lakes and water license holders, it is recommended to investigate methods to improve the simple rules used to control the releases from the Upland Reservoirs, or to incorporate the operating logic of the uplands reservoirs in the MIKE 11 model.

Mainstem Lake Operations

Although considerable effort was put into the improving of the operational rules for the mainstem lakes, the operation of the dams by the model is still far more frequent than in practice, and usually results in much larger fluctuations in outflow from the dam. The methods and settings used to control and operate the dams should be carefully reviewed to ensure they are as consistent as possible for all dams, and to minimize unrealistic oscillations in the releases from the dams.

One of the problems encountered with the calibration of the operational rules for Osoyoos Lake was that the lake is actually operated based on predicted flows in the Similkameen River located outside the Okanagan Basin model study area. Since the operation of the dam on Osoyoos Lake controls the release of water out of the Basin, it is important to be as accurate as possible. As such, it is recommended to take steps to incorporate the inflow forecasting used for the Similkameen River, and to properly account for drought condition operations.

Finally, it is recommended that the MOE should record logic for gate change decisions as well as gate levels. By doing so, it would provide some insight into the rules and decision processes that are followed, particularly when they diverge from the published operations plans. This would help to more easily identify periods where the dam should not be expected to behave as indicated in the documents Lake Operation Plans.

Model Verification

The scientific rationale for the model development process adopted in this study has been described in detail in this report and accepted by the Project Working Group. However it is possible that additional comfort with the outcome could be achieved by exposing the model to time periods not used for calibration. To that end, there appears to be several new streamflow monitoring stations installed throughout the basin in 2006 and 2007. Thus, it is recommended to consider the possibility of using the data from these new and previously existing stations to verify the model during the period from 2007-2010. This would involve minimal preparation of the OBWAM itself, but it would require, among other things, assembly and QA/QC of the monitoring data as well as preparation of the water use data and Q_R and Q_T terms at each node.

Improve Performance of the Model

In its current state, the model requires several days to run through a 30 years scenario. Now that all of the major project deadlines have been met, it is recommended to perform a thorough review of the model setup and computations processes to determine which processes are creating the most computational burden and to examine ways of making the model more efficient without sacrificing the quality of the results.

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1 INTRODUCTION

1.1 BACKGROUND AND OVERVIEW

In 2004, the Okanagan Basin Water Board (OBWB) and the Province of B.C., in partnership with Environment Canada, Agriculture Canada, First Nations, and other stakeholders, initiated a basin wide study of surface water and groundwater resources. This project is referenced as the "Okanagan Basin Water Supply and Demand Project". Phase I of the Okanagan Basin Water Supply and Demand Project was completed in May 2005 by Summit Environmental Consultants Ltd. Phase II of this project was initiated in 2007 and consists of several studies as shown in Figure 1-1.

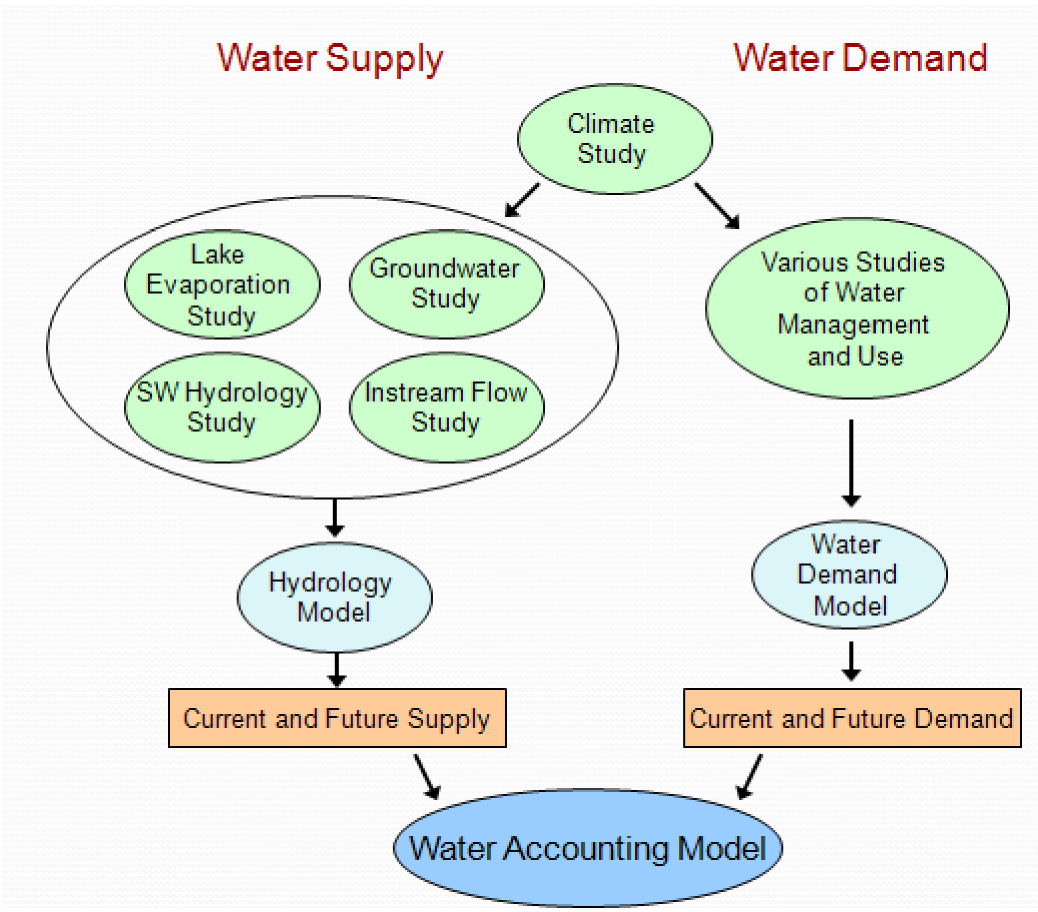


Figure 1-1: Okanagan Basin Water Supply and Demand Project Phase II study components

All technical studies in Phase 2 have been completed under the direction of a Steering Committee of important stakeholders and a Working Group that includes several government agencies and other key stakeholders.

In July 2008, the Okanagan Basin Water Board (OBWB), through the Hydrologic and Water Balance Modeling Committee of the Working Group, issued a Request for Proposal (RFP) for a Surface Water Hydrology and Hydrologic Modeling Study ("the hydrology/modeling study"). A team of consultants including Summit Environmental Consultants Ltd. (Summit), DHI Water & Environment, ULC (DHI), and Polar Geoscience Ltd. (Polar) submitted a proposal and was subsequently awarded the contract to complete the study. The first part of the study involved summarizing existing knowledge of surface water resources in the Basin, developing estimates of natural flows in each of the major tributaries and areas contributing runoff to the main valley lakes and Okanagan River, and preparing a State of the Basin report on surface water hydrology (Summit Environmental Consultants Ltd. and Polar Geoscience Ltd. 2009).

The remaining parts of the hydrology/modeling study included the development and calibration of a surface water hydrology model for the Okanagan Basin. During the course of this work, DHI was awarded a subsequent contract to develop and calibrate a water accounting model, which would provide the framework to analyze tributary streamflows, lake levels, and mainstem river flows under a range of climate-change and land-use scenarios. This report summarizes the development of both the hydrology model and a water accounting model, and summarizes the results of a limited number of future scenarios.

1.2 Project Objectives

The general objective of this study was to develop a distributed hydrologic model of the Okanagan Basin and calibrate it to naturalized conditions, to develop a water accounting model for the Okanagan Basin and calibrate it to existing conditions, and to apply the water accounting model of the Okanagan Basin to analyze future hydrologic conditions under a range of climate-change and land-use scenarios. Specific objectives were to:

- Develop a distributed hydrologic model of the Okanagan Basin to simulate naturalized conditions;
- Calibrate and compare the model results with the results of the related naturalized flow study (Summit and Polar, 2009);
- Estimate naturalized weekly streamflows or lake levels for the period 1996-2006 at 81 surface water nodes (Figure 1-2);
- Incorporate water use data to develop the Okanagan Basin Water Accounting Model;
- Calibrate the Okanagan Basin Water Accounting Model to available measured data;
- Estimate historical weekly streamflows and lake levels for the period 1996-2006 at 81 surface water nodes (Figure 1-2);
- Analyze future streamflows and lake levels under a range of climate-change and land-use scenarios;
- Upload results to the OKWater Database.

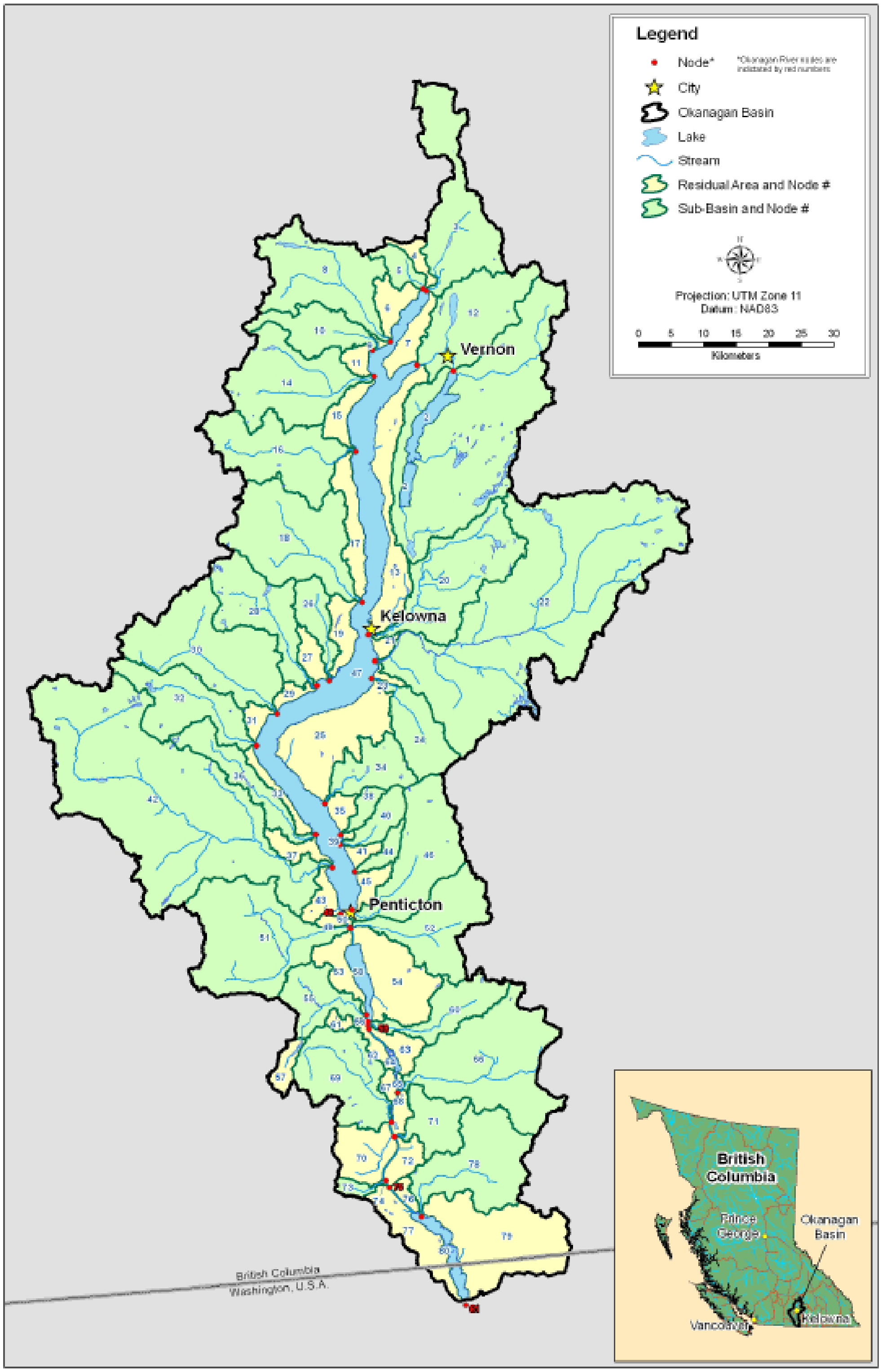


Figure 1-2 Overview map of the Okanagan Basin showing the locations of the 81 surface water nodes (Summit and Polar, 2009)

2 THE OKANAGAN BASIN HYDROLOGY MODEL

2.1 OVERVIEW OF THE HYDROLOGY MODEL

2.1.1 Introduction

The purpose of developing the Okanagan Basin Hydrology Model (OBHM) was to establish a numerical model representing the baseline, naturalized hydrology of the basin (i.e. the hydrology of the basin without human influences) by developing a spatially distributed, integrated surface water and groundwater hydrology model of the basin.

The OBHM was constructed using the MIKE SHE model and MIKE 11 model developed by DHI (DHI, 2009a). MIKE SHE is a numerical hydrologic model that simulates all of the major components of the land-based phases of the hydrologic cycle (Figure 2-1). These components include snowmelt, evapotranspiration (ET), overland flow, unsaturated flow, and groundwater flow. For each of these processes, MIKE SHE offers several different approaches which range from simple, lumped, and conceptual to advanced, distributed, and physically based. Simple and advanced approaches may be combined, enabling the most appropriate model to be constructed in order to meet the demands of a given project while considering computational and data availability constraints. MIKE SHE was used for the modeling study based on the recommendations of Water Management Consultants (2008) in a report prepared for OBWB.

MIKE SHE can be dynamically linked to the one-dimensional hydrodynamic surface water model, MIKE 11, for a complete representation of the hydrologic system. Table 2-1 summarizes the model components used for the OBHM and the method (or governing equation) for each.

Table 2-2 summarizes the model inputs and parameters required for each component. A general explanation of how these components work in MIKE SHE and MIKE 11 is given below and information on data sources follows in Section 2.1.2. A more detailed explanation for all processes is available in the MIKE SHE Technical Reference Guide (DHI, 2009b).

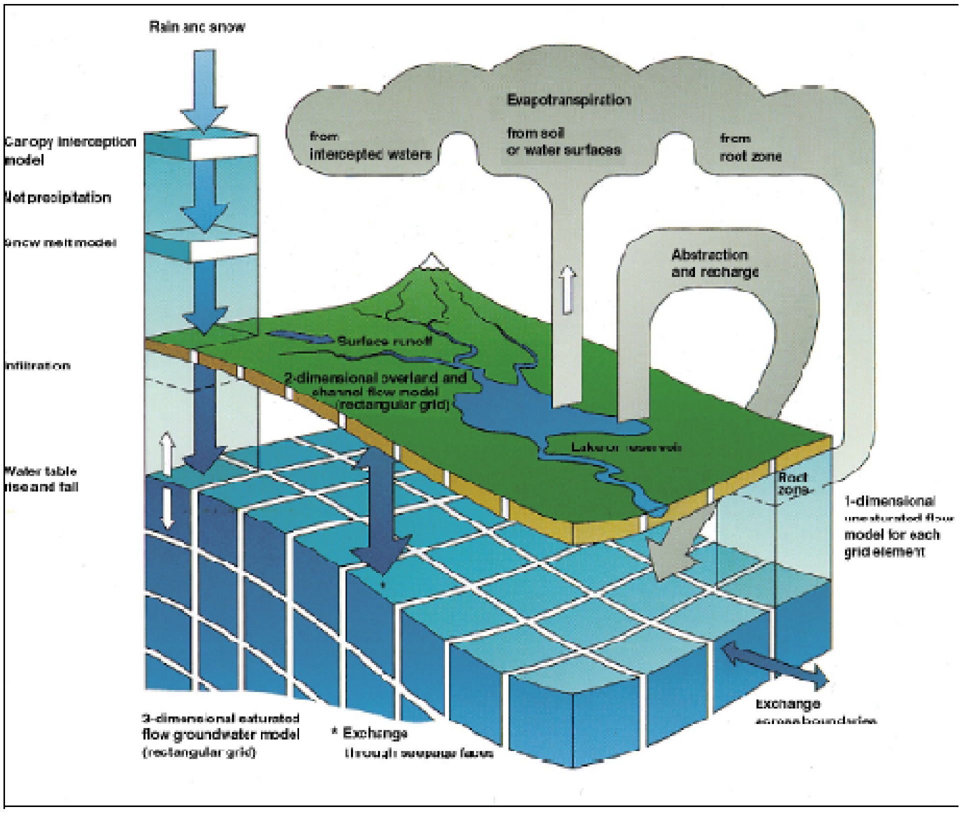


Figure 2-1 Structure of the MIKE SHE/MIKE11 integrated modeling system (DHI, 2009)

Table 2-1 Simulation modules, processes, and methodologies used in the OBHM

Model Component	Processes Simulated	Methodology
MIKE SHE OL	Overland sheet flow. water depths, depression storage	Two-dimensional diffusive wave approximation of the St. Venant equations
MIKE SHE Snowmelt	Snowmelt	Modified degree-day method
MIKE 11	River and lake hydraulics, flows and water-levels for fully dynamic reaches and flows for kinematic reaches	Fully dynamic wave approximation for lakes and valley-bottom reaches, kinematic routing for tributaries
MIKE SHE UZ and ET	Flow and water content in the unsaturated zone, ET, infiltration, groundwater recharge	Two-layer water balance method
MIKE SHE SZ	Groundwater flow, interflow, baseflow	Linear reservoir method

Table 2-2 Required input data for each component of the OBHM

Model Component	Required Input Data
Precipitation	Distribution of precipitation rates
MIKE SHE OL	Topographic map, land use map, distribution of Manning's roughness coefficients, distribution of detention storage, initial water depths
MIKE SHE Snowmelt	Distribution of temperature, reference temperature, degree-day coefficient, minimum snow storage, maximum wet snow fraction, initial total snow storage, initial wet snow storage
MIKE 11	Channel network, cross-section geometries, structure geometries and operational rules, Manning's roughness coefficients, boundary conditions, initial conditions
MIKE SHE UZ and ET	Distribution and rates of potential ET, groundwater table map, soil map, saturated hydraulic conductivities, soil moisture contents at saturation, field capacity, and wilting point, leaf area index, rooting depth
MIKE SHE SZ	Subcatchment boundaries, linear reservoir and baseflow reservoir delineations, reservoir depths, time constants, specific yield

2.1.2 Model Processes

Physical processes included in the OBHM are snowmelt, evapotranspiration (ET), overland flow, unsaturated flow, groundwater flow and channelized flow. This section describes in detail how each process works and the major inputs and parameters for each process.

Snowmelt:

The snowmelt module in MIKE SHE is a modified degree-day method, whereby the rate of melting increases as the air temperature increases. The main input parameters required for the snowmelt process includes:

- Melting Threshold Temperature: The air temperature below which precipitation accumulates as snow.
- Degree Day Coefficient: The amount of snow that melts per day for every degree the Air Temperature is above the Threshold Melting Temperature.
- Minimum Snow Storage for Full Coverage: The minimum snow thickness that covers the entire cell with snow. Snow depths below this value will linearly reduce the snow cover area.
- Maximum Wet Snow Fraction: The amount of wet snow divided by the total amount of snow storage. When the Maximum wet snow fraction is exceeded, any excess melted snow will be converted to ponded water.

Additional parameters exist to simulate melting as a function of incoming solar radiation, to account for the influence of the heat content of rainfall, and to account for sublimation, but these parameters were not applied in this OBHM.

Overland Flow:

The OBHM uses an explicit Finite Difference Method for simulating overland flow. It solves a two-dimensional diffusive wave approximation of the Saint Venant equations to calculate surface flow in the x- and y- directions and water depths for each grid cell of the model domain.

The main inputs to the Overland Flow data category are:

- Manning's Roughness Coefficient (n): A common measure of the resistance of a surface to the flow of water.
- Detention Storage: The depth of water that needs to accumulate before overland flow can initiate.
- Initial Water Depth: The initial depth of water in each grid cell at the start of the simulation period.

The overland flow algorithm interacts with the channel flow, the unsaturated zone, and the saturated zone components of the model. Additionally, an area-inundation option is available which allows flow from the streams in the MIKE 11 model to flood onto the MIKE SHE overland flow plain that is primarily used to represent lakes and reservoirs.

Unsaturated Flow:

The unsaturated flow component of the OBHM uses a Two-Layer Water Balance Method that functions in conjunction with the ET component of the model. This method uses a simple mass-balance approach to represent the unsaturated zone, and accounts for interception storage changes, surface ponding, and water content in the root zone, infiltration, evapotranspiration, and groundwater recharge. The main input data requirements for this method include the following soil properties:

- Volumetric moisture contents at saturation (θ_S): This is the maximum water content of the soil, which is usually approximately equal to the porosity.
- Field capacity (θ_{FC}): This is the water content at which vertical flow becomes negligible.
- Wilting point (θ_{WP}): This is the lowest water content that plants can extract water from the soil.
- Saturated hydraulic conductivity (Kv): This is equal to the maximum infiltration rate of the soil.

All of these terms are required for each soil type included in the model. The first three terms are used to calculate the average moisture content in the soil, which is linearly dependent on the depth of the water table. The difference between the moisture content at saturation and at field capacity (θ_S - θ_{FC}) provides an estimate of the storage capacity of the soil; while the difference between the moisture content at field capacity and at the wilting point (θ_{FC} - θ_{WP}) provides an estimate of the amount of water available for transpiration within the rooting zone.

The saturated hydraulic conductivity is used to control the rate of infiltration of water through the unsaturated zone. This value is uniform across the entire depth of the unsaturated zone, and is not dependent on the soil moisture content. As such, the saturated hydraulic conductivity parameter is effectively a calibration parameter that is initially based on the characteristic Kv and must be sufficient to represent average response of the unsaturated zone for the associated soil type. The actual infiltration to the unsaturated zone is the minimum of the amount of ponded water available, the infiltration rate times the time step, or the available storage volume in the unsaturated zone.

Evapotranspiration (Potential and Actual):

The evapotranspiration (ET) module in MIKE SHE uses meteorological and vegetative data to simulate ET, and includes methods for simulating evaporation from interception storage in the canopy, evaporation from the soil surface, transpiration of water by plant roots based on soil moisture in the unsaturated zone, and transpiration from groundwater if the rooting depth exceeds the thickness of the unsaturated zone (DHI, 2008). The OBHM uses a Two-Layer Water Balance Method for simulating ET which divides the unsaturated zone into an upper rooting zone, from which ET can occur, and a lower zone below the rooting zone, where ET does not occur.

The simulated actual ET is based on the specification of potential ET (PET). For each ET time step, the model tries to meet the PET or determines to what degree the PET can be met from four different storages: the canopy, ponded water, the unsaturated zone, and the saturated zone, and is limited by the available water in each of these storages. The method also allows for upward movement of water from the saturated zone to the rooting zone to occur as a result of rooting zone ET demand. The primary input parameters include PET, Leaf Area Index, and Rooting Depth for the various vegetation types in the model. The Leaf Area Index (LAI) is the ratio of total upper leaf surface of vegetation divided by the surface area of the land on which the vegetation grows. LAI is a dimensionless value, typically ranging from 0 for bare ground to 6 for a dense forest. The Rooting Depth (RD) represents the maximum depth of active roots in the root zone.

Groundwater Flow:

The OBHM uses a Linear Reservoir approach for representing the groundwater system. This approach subdivides the watershed into a series of interdependent, shallow interflow reservoirs, and deeper baseflow reservoirs that contributes to stream baseflow (Figure 2-2). If a stream is present in a given sub-basin, water will be routed through the linear reservoirs as interflow and baseflow and subsequently added as lateral flow to the MIKE 11 component of the model. Thus, the water that recharges from the unsaturated zone may either contribute to the baseflow or move laterally as interflow towards the stream. Additionally, water held in the part of the baseflow reservoirs beneath the lowest interflow zone may be allowed to contribute to the rooting zone when the soil moisture is below field capacity.

Each Interflow reservoir requires a value for:

- Specific Yield: The volume of water released per unit surface area of aquifer per unit decline in head.
- Initial depth: The initial depth of the water table in the reservoir, measured from the ground surface.
- Bottom depth: The depth below the ground surface of the bottom of the reservoir - if the water level drops to the bottom of the reservoir, percolation stops.
- Interflow time constant: A calibration parameter that represents the time it takes for water to flow through the reservoir to the next reservoir.
- Percolation time constant: A calibration parameter that represents the time it takes for water to seep down into the baseflow reservoir.

- Interflow threshold depth: The depth of the interflow reservoir water table below the ground surface when interflow stops.

For each baseflow reservoir pair, there are three items to define:

- Fraction of percolation to reservoir 1: This is used to divide the percolation between each of the two parallel baseflow reservoirs.
- Fraction of pumping from reservoir 1: This is used to divide the pumping (if it exists) between each of the two parallel baseflow reservoirs.
- Use default river links: In most cases the simplified overland flow and the groundwater interflow are linked to all of the river links found in the lowest interflow reservoir in each subcatchment.

The following parameters need to be defined for each of the parallel baseflow reservoirs:

- Specific Yield: The volume of water released per unit surface area of aquifer per unit decline in head.
- Time constant for base flow: A calibration parameter that represents the time it takes for water to flow through the reservoir.
- Dead storage fraction: The fraction of the received percolation that is not added to the reservoir volume but is removed from the available storage in the reservoir.
- UZ feedback fraction: The fraction of base flow to the river that is available to replenish the water deficit in the unsaturated zone adjacent to the river (i.e. the lowest interflow reservoir in the subcatchment).
- Initial depth: The initial depth to the water in the reservoir measured from the ground surface.
- Threshold depth for base flow: The depth below the ground surface when base flow stops.
- Threshold depth for pumping: The depth below the ground surface when pumping is shut off.
- Depth of the bottom of the reservoir: The depth below the ground surface of the bottom of the reservoir.

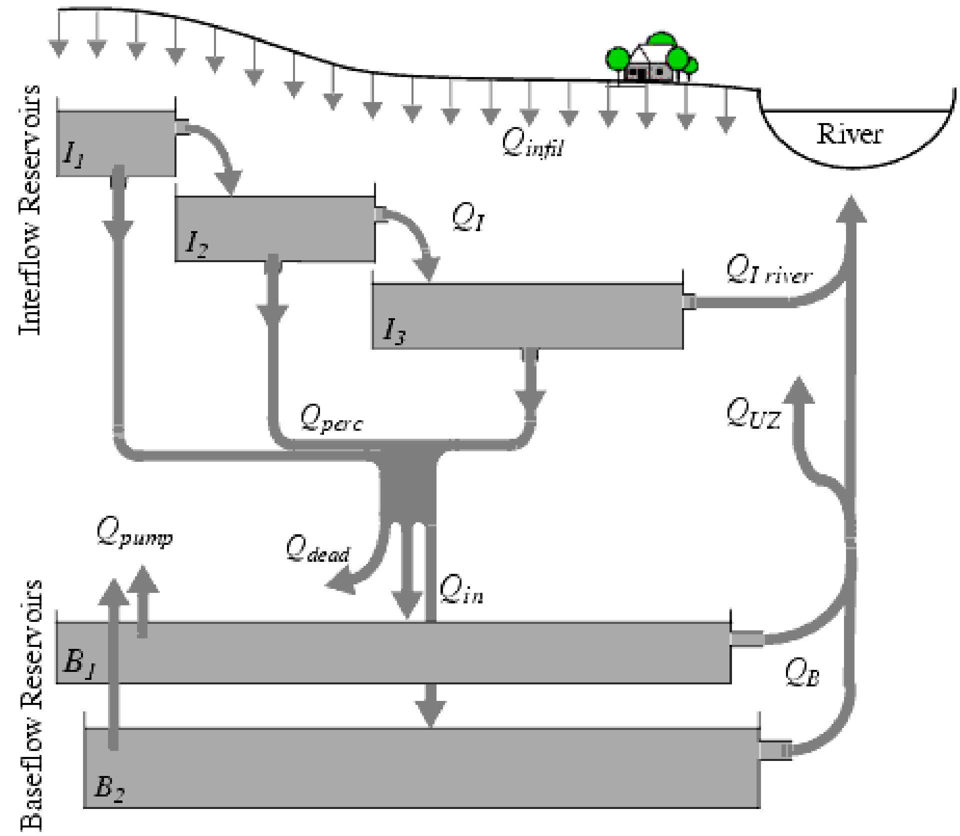


Figure 2-2 Schematic diagram for the subcatchment-based linear reservoir groundwater method

<u>Channelized Flow:</u>

MIKE 11 is a one-dimensional hydrodynamic modeling tool used to analyze water movement in a river network including flow through control structures and other hydraulic features. MIKE 11 has the capability of solving the fully dynamic, diffusive, or kinematic wave approximations of the Saint Venant equations for one-dimensional unsteady flows or the simple Muskingum equations. MIKE 11 can be integrated with the MIKE SHE surface/groundwater model to simulate the routing of runoff conditions (or groundwater return flows) through a river network. MIKE SHE acts as a dynamic boundary condition that exchanges overland flows and groundwater baseflows with MIKE 11. The majority of the surface water system in the OBHM was simulated using the kinematic wave approximation and a simplified routing approach with the exception of the five major lakes included in the model and the connecting rivers in between the lakes which were simulated using a fully-dynamic solution. The fully dynamic solution was used for these features in order to allow for representation of the series of outflow structures which regulate flow through the valley-bottom system.

2.2 HYDROLOGY MODEL CONSTRUCTION

2.2.1 Overview

As described in Section 2.1.2, development of the Okanagan Basin Hydrologic Model (OBHM) requires some essential inputs and parameters for each process based on the selected methods. The MIKE SHE model categorizes the various data input requirements for the OBHM as follows:

- Model Domain and Grid
- Topography
- Climate
- Land Use
- Rivers and Lakes
- Overland Flow
- Unsaturated Flow
- Saturated Flow

This section describes the model setup, conceptualization, development and assignment of the required data inputs for the model construction and discusses the assumptions, strengths and weaknesses in each case. The parameter values presented in these sections represent the parameter values from the calibrated OBHM as it was accepted by the Project Working Group in October 2009.

2.2.2 Model Domain and Grid

The Okanagan Basin Hydrologic Model (OBHM) domain (i.e. the spatial boundary) was set to match the full watershed boundary of the Okanagan River Basin upstream of Zosel Dam near the outlet of Osoyoos Lake (Figure 1-2). The domain represents the ~8,024 km^2 watershed using 500 m by 500 m square grid cells. This grid resolution was selected in order to be consistent with the resolution of the gridded climate datasets provided by OBWB (Duke et al, 2008a) that were used in the model. The overland flow, unsaturated flow, and evapotranspiration calculations are each computed for every 500 m square grid cell. The groundwater calculations occur based on subcatchments rather than at the model grid resolution, and the channel flow calculations occur at discrete computational nodes along the one dimensional representation of the river network. The groundwater subcatchments were developed based on the aquifer delineation performed by Golder Associates (2009) for the groundwater study, while the river model computational node locations are located at intervals along the river network. All spatial data used in the model are based on the BC Albers projection, the NAD 1983 datum, and horizontal and vertical units of meters.

The simulation period used for the OBHM was from September 1, 1995 to December 31, 2006 but the model results are only evaluated for the period from January 1, 1996 to December 31, 2006 (11 years). The last four months of 1995 were included in the simulation as a ‘warm up period’ in order to allow the model a sufficient period of time to adjust from the assumed initial conditions and reach a dynamic equilibrium with the simulated processes and responses. In particular, realistic initial soil moisture and initial snow depth conditions are inherently difficult to estimate. By giving the model this four month “warm-up” period, the model can determine appropriate initial conditions at the beginning of the simulation period based on the simulation results.

2.2.3 Topography

While the vast majority of the OBHM domain is located in Canada, the southern portion of the model includes areas within the United States. Thus, it was necessary to use multiple data sources in order to generate the model topography. A Digital Elevation Model (DEM) with a UTM Zone 11 projection and a 30 m by 30 m cell size was used for the Canadian portion of the basin (Geobase, 2008). For the U.S. portion of the basin, a 100-ft (~30 m) resolution DEM with the same projection was used (Natural Resource, WA, 2002). The two DEMs were merged, re-sampled to a 100 m resolution, and re-projected to the BC Albers projection. The resulting DEM was then used as the topographic input for the model (Figure 2-3). The MIKE SHE engine includes a pre-processing step whereby the input DEM is re-sampled to the model resolution of 500 m, but the 100 m resolution version was retained as the raw model input in case it is desirable to increase the resolution of the model domain at a later date.

Through the calibration process we discovered some deficiencies in the model's representation of the lake bathymetry within the overland flow component of the model. The lake bathymetry generated from the DEM does not sufficiently represent the topography close to the edges of the lakes where fluctuating water levels will inundate or expose some grid cells. However, the bathymetry of the lakes is more accurately represented in the 1D MIKE 11 surface water component of the model using cross-section data. As a result, the bathymetric cross-sections of the lake from the surface water component of the model were used to modify the model topography in order to properly capture the lake bathymetry in the overland flow component of the model.

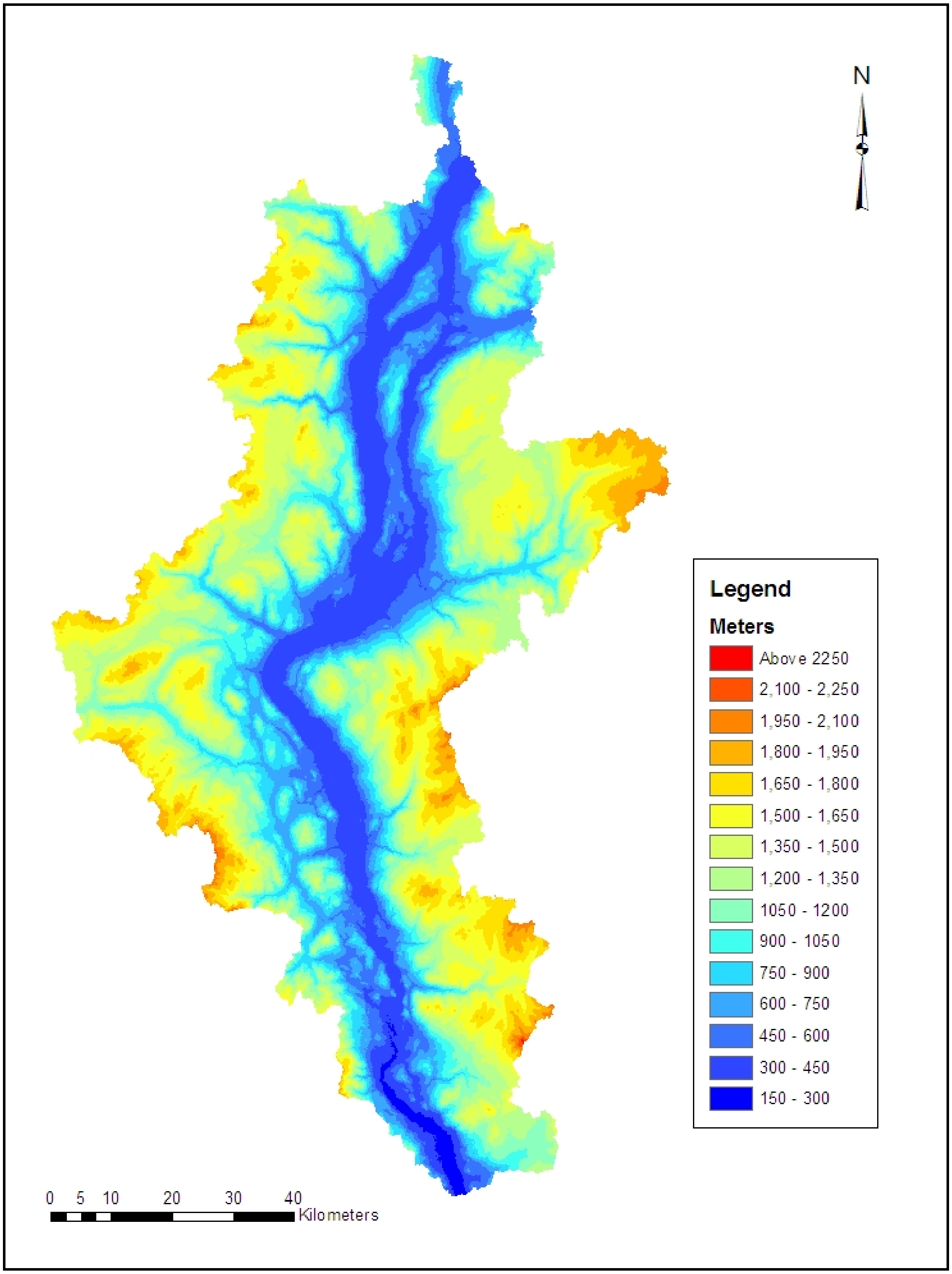


Figure 2-3 Topography of the Okanagan Basin used in the OBHM

2.2.4 Climate

The climate data used in the OBHM is based on an interactive model developed for the basin called the Okanagan Climate Data Interpolator (Duke et al., 2008a; Duke et al., 2008b). This model used GIS interpolation techniques and all available climate station data in the basin to generate basin-wide 500 m by 500 m gridded surfaces of daily minimum and maximum temperature and daily precipitation (Duke et al., 2008b) (Figure 2-4). Additional calculations were performed to generate daily potential evapotranspiration (PET) surfaces using a modified Penman-Monteith formulation. A custom import tool was developed to convert the ASCII files of each daily (and twice daily for the case of temperature) gridded surface into single time-varying grid files in the MIKE SHE .dfs2 format for use in the model.

The original gridded surfaces only cover the Canadian portion of the basin, thus it was necessary to extrapolate the data southwards to the southern boundary of the model domain. This was accomplished by simply copying the southern-most east-west row of cells southwards until the domain boundary was reached. While this approach certainly represents a simplification of the actual variations in climate in this area, the major variations in the climate variables occur across a north-to-south gradient and across an elevation gradient, and given that the valley floor runs roughly north-south in this area, the approach should capture the major patterns of climate variability. Additionally, the area of the model domain that occurs outside of Canada represents a very small percentage of the total basin area, and any misrepresentation of the hydrology in this area occurring as a result of the simplifications in climate variability introduced by the extrapolation is unlikely to have a significant impact to the overall model-simulated hydrologic responses in the basin.

The climatic stations that provided the basis for developing the gridded climate data are unevenly distributed in the basin. There are a total of 11 active climate stations, however only one station, Silver Star Mountain, is located at high elevation, and the other 10 are located at low elevations along the valley floor. There is some uncertainty regarding how well these datasets represent the climatic variations across the basin, particularly at higher elevations.

Having an accurate distribution of air temperature is arguably the most important factor influencing the model's ability to properly simulate snow accumulation and melt processes in the basin, and an accurate simulation of these processes is critical for accurately simulating the spring runoff timing and volume. The use of gridded climate data provides a much better representation than would normally be available with just station based information, but It is important to note that any deficiencies in the gridded temperature data with respect to representing the temperature variations across the basin were carried over to the hydrologic model. It is also important to recognize that daily minimum and maximum temperature values do not fully represent the timing of the fluctuations in temperature that occur throughout the day, and that the model requires that the minimum and maximum grids were set 12-hours apart. While the temporal scale of the model output (weekly hydrographs) is rather coarse, using minimum and maximum temperatures may not allow for an accurate representation of snow accumulation and melt processes in the model because of this limitation.

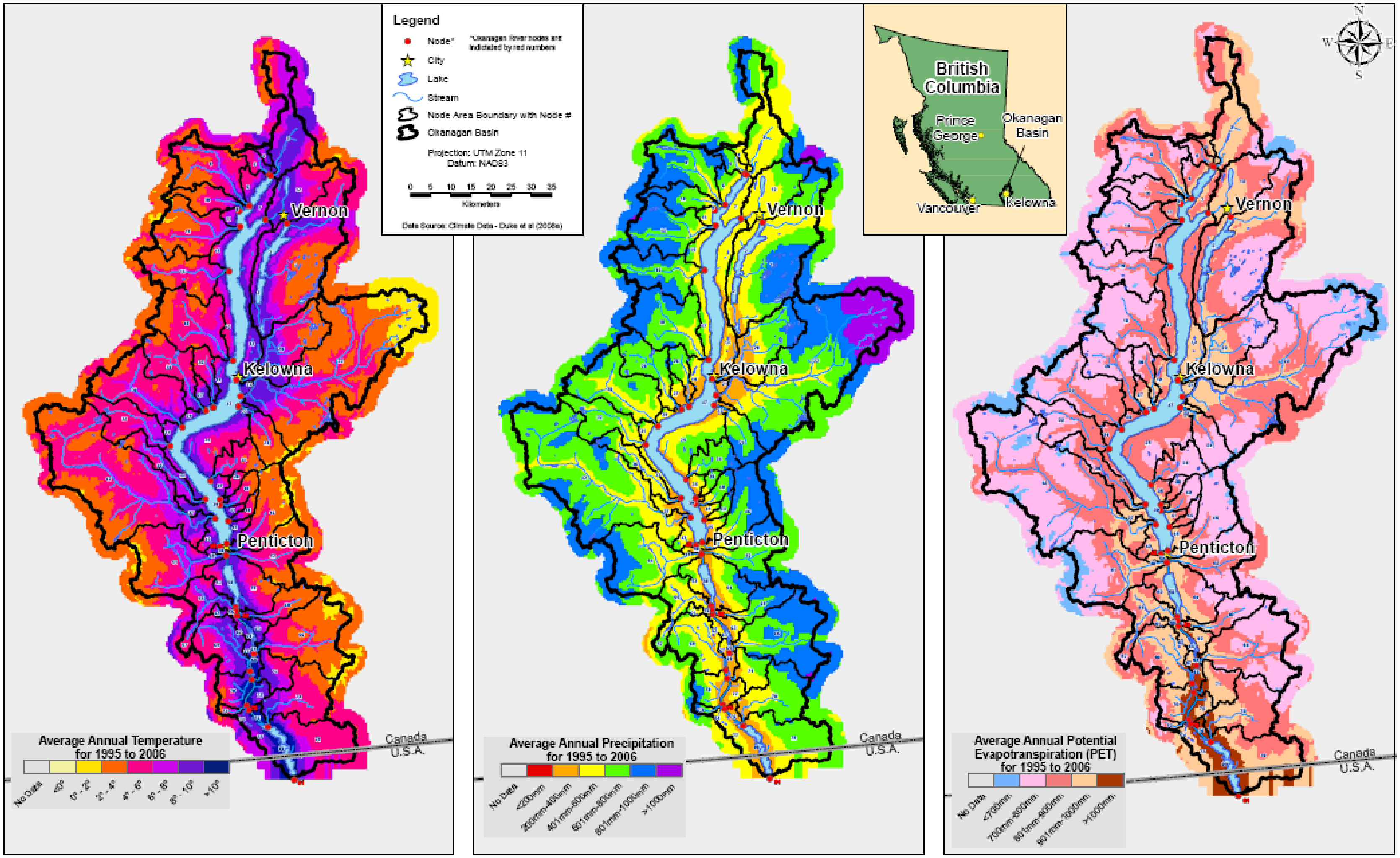


Figure 2-4 Okanagan Basin annual temperature, precipitation and potential evapotranspiration data (Summit and Polar, 2009)

Snowmelt Parameters

Aside from a distribution of air temperature, the primary parameter for the snow component of the model is the degree day coefficient (DDC). This parameter is a key calibration parameter, but typically it is applied as a uniform value throughout the model area and throughout the simulation period. However, some difficulties encountered during the initial calibration led to the investigation of using spatially and temporally varying DDC values. A literature search uncovered some relevant references in support of this approach. Findings by Kuusisto (1980) support using a 45% lower DDC in forested area relative to open area, while research by Haverly et. al (1978) support a 21% lower DDC in forested areas versus open areas.

In order to reflect the spatial variation of DDC associated with land cover and the temporal variation of DDC associated with seasonal change of solar radiation, snowpack density and compaction, and other factors, the Okanagan Basin was divided into three DDC zones consisting of forested area, open area, and a combined logged area and major forest fire area. Each area was assigned a time varying DDC with a sinusoidal pattern of values throughout the year as shown in Figure 2-5. In general, the sinusoidal pattern accounts for more melting during the consistently warmer seasons and less melting during the consistently colder seasons. The lower DDC values in forested areas from late-winter to mid-summer account for the reduced impact of solar radiation and warmer air temperatures within the forested areas.

Additional parameter adjustments included adjusting the minimum snow storage value to 100 mm, and setting the maximum wet snow fraction to 0.01.

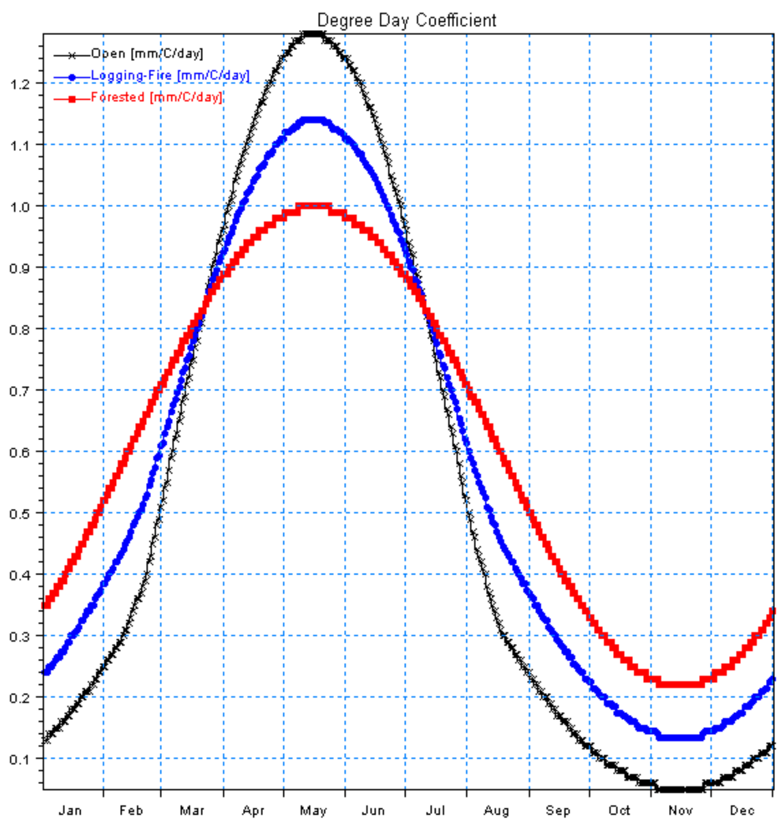


Figure 2-5 Degree day coefficients for open site, logging-fire site and forested site

2.2.5 Land Use

The Land Use category defines the spatial distribution and characterization of different types of vegetation in the model domain. In MIKE SHE, vegetation-based properties like the leaf area index (LAI) and the rooting depth (RD) are assigned based on vegetation types in the land use map. In order to account for the variations in vegetation properties across the basin, several different datasets were used to generate the final land use map used in the model. A base land cover map was defined based on the Vegetation Resources Inventory (VRI) data for the Canadian portion of the basin (VRI, 2005) and the National Land Cover Database (NLCD) for the U.S. portion (NLCD, 2001) of the basin. This base map was further subdivided by a simplified version of the biogeoclimatic zones established for the basin (BECWeb, Ministry of Forests and Range, 2008), and further subdivided again to account for major disturbances resulting from Mountain Pine Beetle (MPB) infestation, wildfires, and timber harvesting. The process used to generate the model land cover map is described in greater detail below.

As indicated above, the land cover classifications (primarily identifying vegetation coverage) were derived from two sets of land cover maps. These maps consisted of land cover polygons with five different classification levels. By studying the criteria used for each level relative to the resolution and needs of the model, the level 4 classification was selected for use in generating the model land cover map (Table 2-3). Some gaps existed in the data which were filled by interpolating based on surrounding land cover polygons. Land cover for the U.S. portion of the basin was based on the 30 m resolution gridded National Land Cover Database data (NLCD, 2001). The land cover categories in the U.S. portion of the basin were matched to categories in the Canadian dataset based on a comparison of the two sets of land cover descriptions. Three categories in the U.S. portion of the basin did not provide a good match with any of the categories in the VRI dataset so they were retained as new categories. The two land cover maps were then merged and re-projected to the BC Albers projection.

Some further subdivision of the land cover map was performed in order to properly represent disturbance areas that are impacted by the Mountain Pine Beetle (MPB). Since the MPB generally only attacks pine trees, and especially Lodgepole Pine, the coniferous forest areas were subdivided into two categories, "pine coniferous forest" and "non-pine coniferous forest". This sub-division was based on the first and second leading species designations which are identified as part of the VRI dataset. If the percentage of pine was greater than or equal to 40% in a given polygon, then the polygon was assigned as pine coniferous forest (Symbol TCP); if the percentage of pine was less than 40% then the polygon was assigned as non-pine coniferous forest (Symbol: TC). Since no detailed information on the percentage of pine was available in the U.S. land cover dataset, this subdivision was only performed for the Canadian portion of the basin. In total, there are 14 categories in the base land cover map (Figure 2-6).

In order to take full advantage of the Leaf Area Index (LAI) raster data in the model, the land cover map was further subdivided based on biogeoclimatic zones that take into account variations in topography, climate, and soil (BECWeb, Ministry of Forests and Range, 2008). The original biogeoclimatic ecosystem classification (BEC) zone map for the basin was simplified from six to four zones by merging two neighboring zones together. The rationale for doing so was to reduce the total number of categories used in the model to a reasonable level but still capture the significant variations in land cover and LAI across the basin. The Montane Spruce (MS) zone was merged with the Englemann Spruce – Subalpine Fir (ESSF) zone and the Interior Douglas Fir (IDF) zone was merged with the Interior Cedar – Hemlock (ICH) zone. The ESSF and ICH zones each cover a relatively small portion of the basin and the variations in land cover are still well-captured by the model using the combination of the 14 original land cover categories subdivided further by the four biogeoclimatic zones. The BEC zone map only covers the Canadian portion of the basin so it was extrapolated southwards to cover the U.S. portion of the basin (Figure 2-7 and Table 2-4). A final land cover/biogeoclimatic zone map was obtained by overlaying the land cover map and the modified bio-climatic zone map. Thus, each of the 14 land cover categories is further sub-divided into four biogeoclimatic zones.

During the 11-year baseline period considered in this study (1996-2006), disturbances such as loss of forest cover due to MPB infestation, forest fires, and timber harvest have occurred which have the potential to significantly alter the basin hydrology. The LAI data provides a means of accounting for the influence of these disturbances in the model. Three disturbance categories were identified: MPB kill, timber harvest, and major wildfires.

Table 2-3 Land cover categories used in the OBHM

Code	Symbol	Description
1	BY	Bryoid: A bryoid polygon with no distinction between mosses and lichens.
2	EL	Exposed Land: Contains all other forms of exposed land identified by a range of subclasses. Urban area
3	HE	Herb: An herb plygon with no distiction between forbs and graminoids.
4	HF	Herb - Forbs: An herb polygon with forbs greater than 50% of the herb cover.
5	HG	Herb - Graminoids: An herb polygon with graminoids greater than 50% of the herb cover.
6	RO	Rock/Rubble: Defined as bedrock or fragmented rock broken away from bedrock surfaces and moved into its present.
7	SL	Shrub Low: A shrub polygon with average shrub height less than two meters.
8	ST	Shrub Tall: A shrub polygon with average shrub height greater than or equal to two meters.
9	TB	Treed - Broadleaf: Defined as those trees classified botanically as Angionspermae in the subclass Dicotyledoneae. These species are commonly referred to as deciduous or hardwoods. The polygon is classified as Broadleaf when the total basal area (expressed as percentage species composition) of broadleaf trees is 75% or more of the total polygon tree basal area, and trees cover a minimum of 10% of the total polygon area, by crown cover.
10	TC	Treed - Coniferous: Defined as those trees found in B.C. within the order Coniferae. These trees are commonly referred to as conifer or softwoods. The polygon is classifed as Coniferous when the total basal area (expressed as percentage species compostion), of coniferous trees is 75% or more of the total polygon tree basal area, and trees cover 10% or more of the total polygon area, by crown cover.
11	TCP	Treed - Coniferous: Defined as those trees found in B.C. within the order Coniferae. These trees are commonly referred to as conifer or softwoods. The polygon is classifed as Coniferous when the total basal area (expressed as percentage species compostion), of coniferous trees is 75% or more of the total polygon tree basal area, and trees cover 10% or more of the total polygon area, by crown cover. More than 40% of the total polygon tree basal area are coverd by Pine including Jack Pine, Limber Pine, Lodgepole Pine, Ponderosa Pine, Shore Pine, Western White Pine, White Bark Pine
12	TM	Treed - Mixed: The polygon is classified as Mixed when neither coniferous nor broadleaf trees account for 75% or more of the total polygon tree basal area, and trees cover a minimum of 10% of the total polygon area, by crown cover.
13	W	Water bodies: including lakes, reservoirs and rivers.

Table 2-4 Biogeoclimatic zones used in the land cover map for the OBHM

Number	Biogeoclimatic Zone
101	BG: Bunchgrass
102	IDF/ICH: Interior Douglas-fir/Interior Cedar - Hemlock
103	MS/ESSF: Montane Spruce/Englemann Spruce – Subalpine Fir
104	PP: Ponderosa Pine

A 400 m resolution gridded data map is available from 1999 to 2007 that shows the severity of attack from MPB (Ministry of Forests and Range, 2008b). The MPB impact severity is classified into five levels indicating the percentage of trees impacted: very severe (>50 %), severe (30%-50%), moderate (11%-30%), low (1%-10%), and light (<1%). The MPB severity data was overlaid with the land cover/bioclimatic zone map, and polygons with very severe, severe and moderate MPB infestation were identified and defined as a separate land cover category.

Annual polygon data showing the locations impacted by major fires were available for 2001 through 2007 (Ministry of Forests and Range, 2008a). The majority of the fires were relatively small in extent, with the exception of the 2003 Kelowna fire which affected a ~256 km^2 area. The area impacted by this fire was used to subdivide the corresponding land cover/biogeoclimatic zones into fire disturbed and undisturbed areas. Timber harvest data was available from the VRI which indicates the logging start date and end date for each polygon. Polygons with a harvest start date of January 1, 1995 or later were used to subdivide the corresponding land cover/biogeoclimatic zones into timber harvest disturbed and undisturbed areas. Areas harvested prior to 1995 were not specifically accounted for. Figure 2-8 shows the disturbed areas divided into MPB kill, large fires, and major timber harvest categories.

The final land cover map used in the model consists of the 14 base land cover categories subdivided by the four biogeoclimatic zones, and then further subdivided into undisturbed areas and the three disturbance categories. The final land cover map has a total of 67 land cover categories as shown in Figure 2-9.

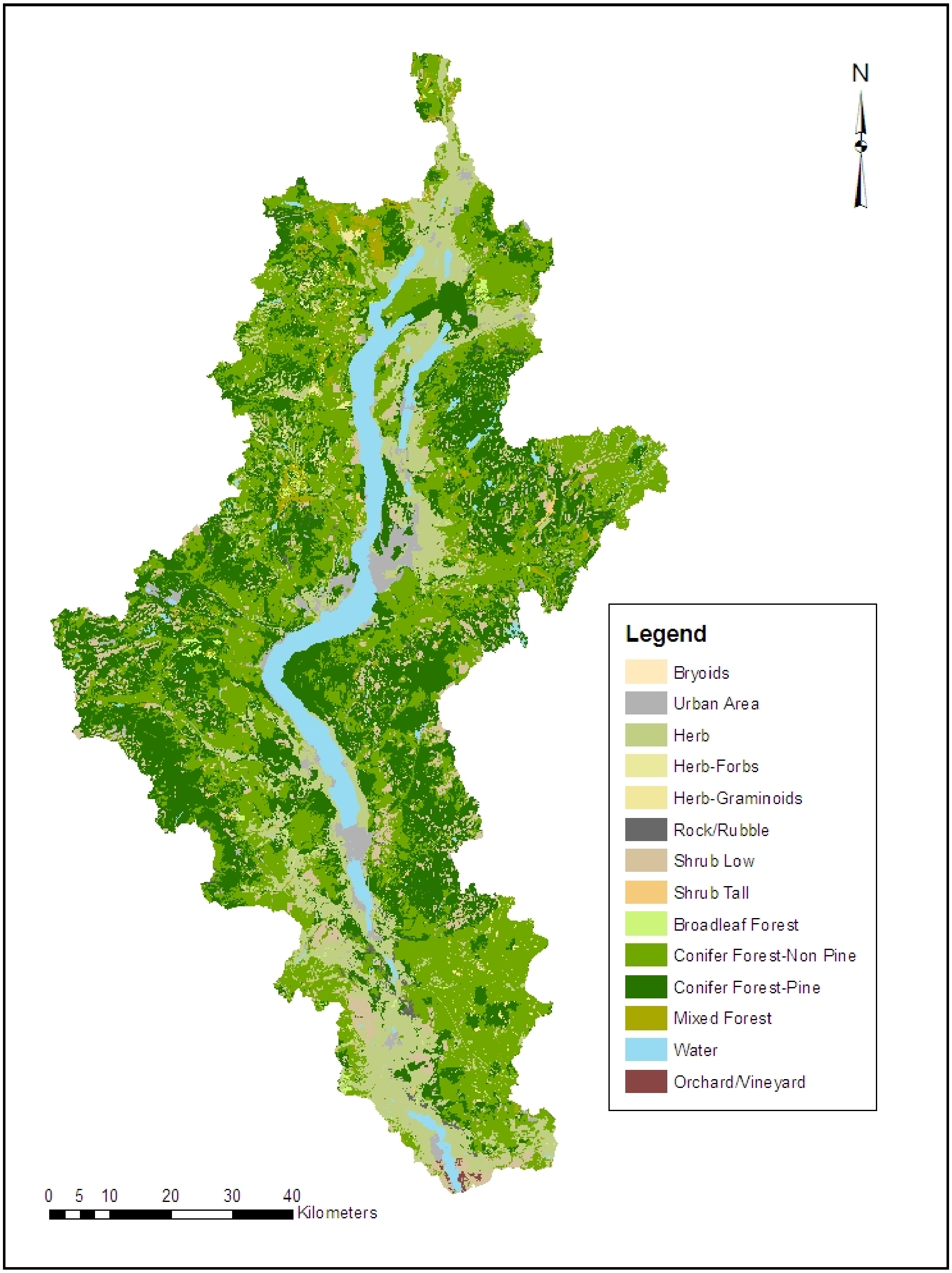


Figure 2-6 Base land cover data used to construct the land cover map used in the OBHM

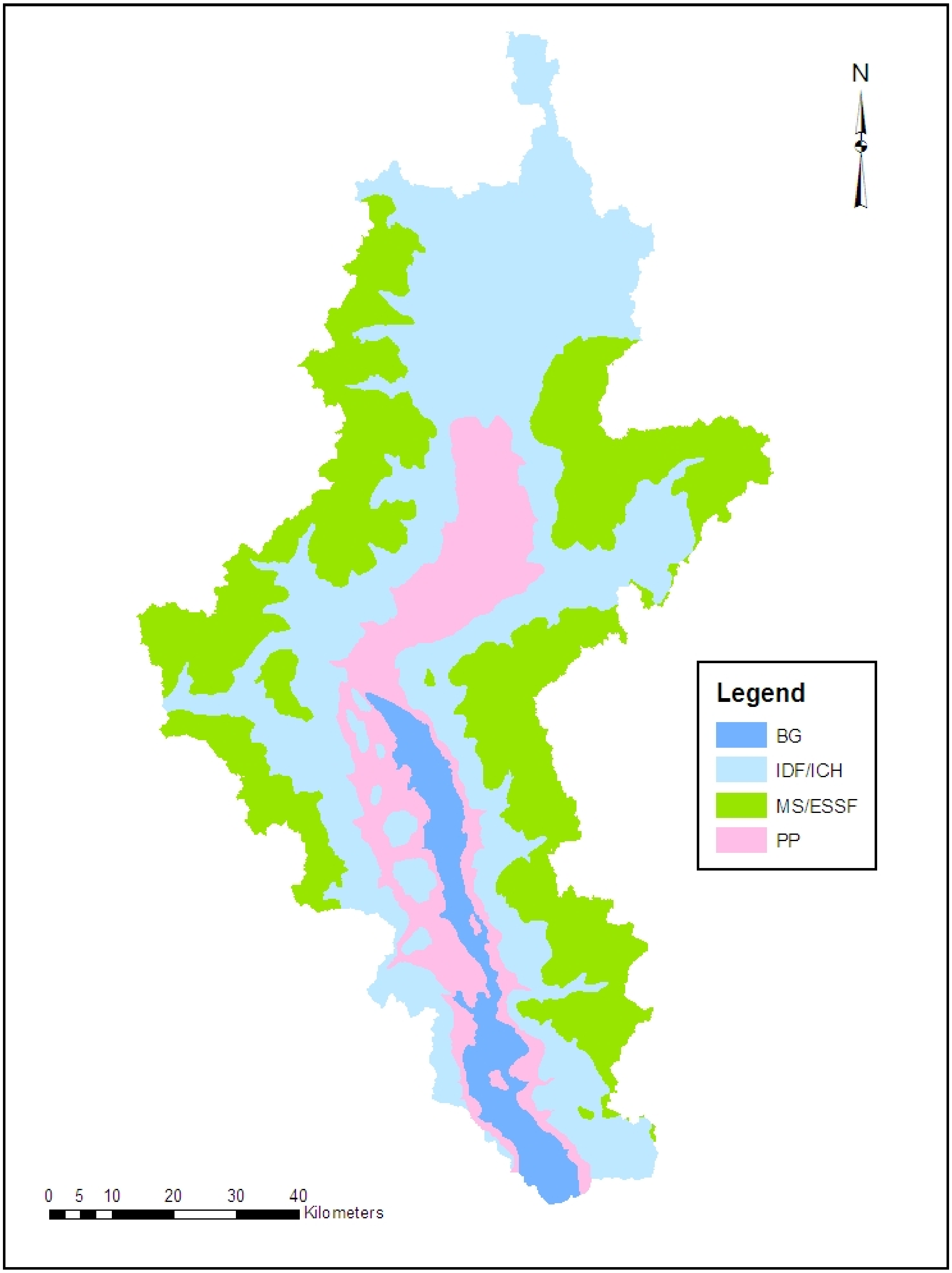


Figure 2-7 Biogeoclimatic zone map used to construct the land cover map used in the OBHM

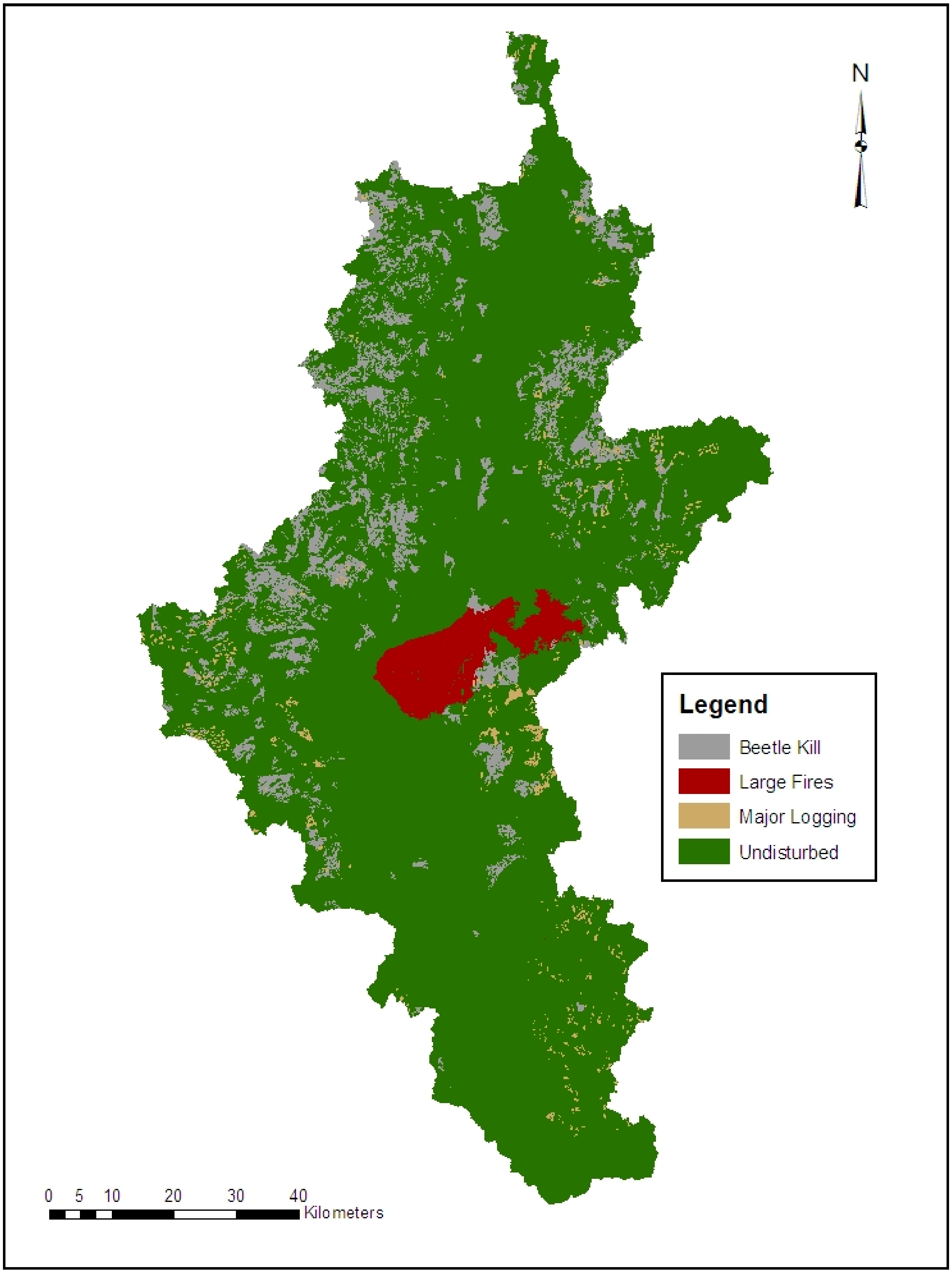


Figure 2-8 Disturbance area map used to construct the land cover map used in the OBHM

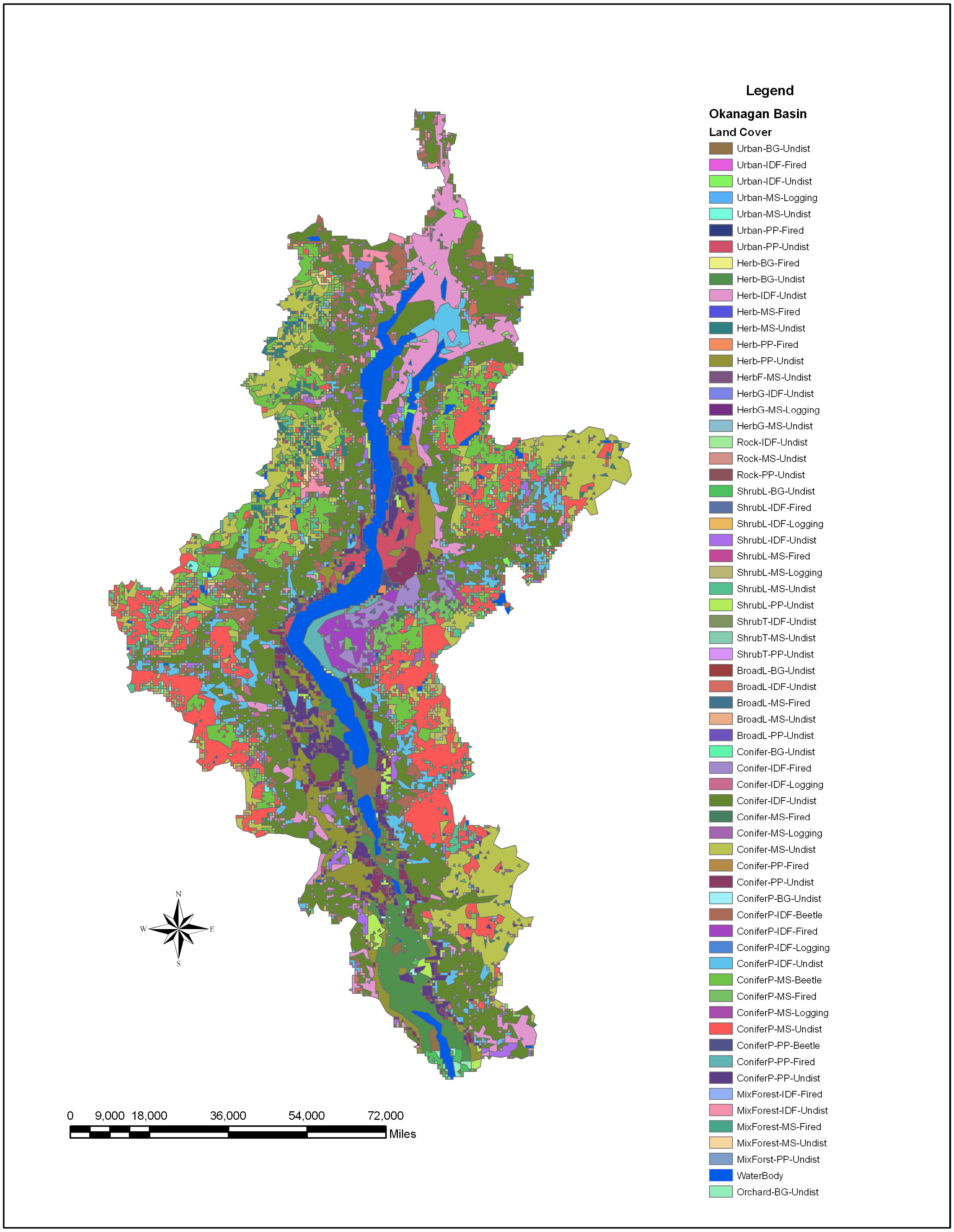


Figure 2-9: Final Land Cover Categories used in Model

Leaf Area Index

The Leaf Area Index (LAI) is the ratio of total upper leaf surface of vegetation divided by the surface area of the land on which the vegetation grows. LAI is a dimensionless value, typically ranging from 0 for bare ground to 6 for a dense forest. In MIKE SHE this parameter influences the rate of evapotranspiration.

LAI values for the basin were available as raster images from 1998 to 2005 (CCRS, NRC, 2006). These images have been provided in one kilometre resolution and collected every 10-days from April 1^{st} to October 31^{st}. In total there are 160 images, an example of which is shown in Figure 2-10. In order to make full use of these 10-day LAI images, a methodology was developed to process the images using an ArcGIS script. The final land cover map described in Section 2.2.5 above was used as a mask to extract the LAI values from each LAI raster image for each land cover polygon, and a zonal average LAI value for each polygon was computed. However, according to the metadata for the 10-day LAI raster images, the LAI values during the growing season have been reasonably well validated but were potentially over-estimated, with low confidence during wet seasons (spring) and for the end of season. As a result the LAI raster images were used to obtain LAI values from May 1^{st} to September 1^{st} while the LAI values for the remaining periods of the year were manually interpolated from the September 1^{st} value to a reasonable winter minimum occurring on December 1^{st}, and then interpolated from the minimum winter value to the next starting value on May 1^{st}. (see example shown in Figure 2-11).

For each undisturbed polygon, the annual average 10-day LAI value from June 1^{st} to September 1^{st} was calculated and repeated for each simulation year. For disturbed polygons, the average 10-day LAI values were calculated from June 1^{st} to September 1^{st} for each year (1998 to 2005). The assumption behind this is that a given undisturbed land cover type has a consistent temporal distribution of LAI from year to year, whereas LAI varies not only within a given year but also between years for disturbed areas. The variations in LAI from year to year also provided a basis for evaluating the impacts of future MPB infestation during the subsequent scenario analysis phase of this project.

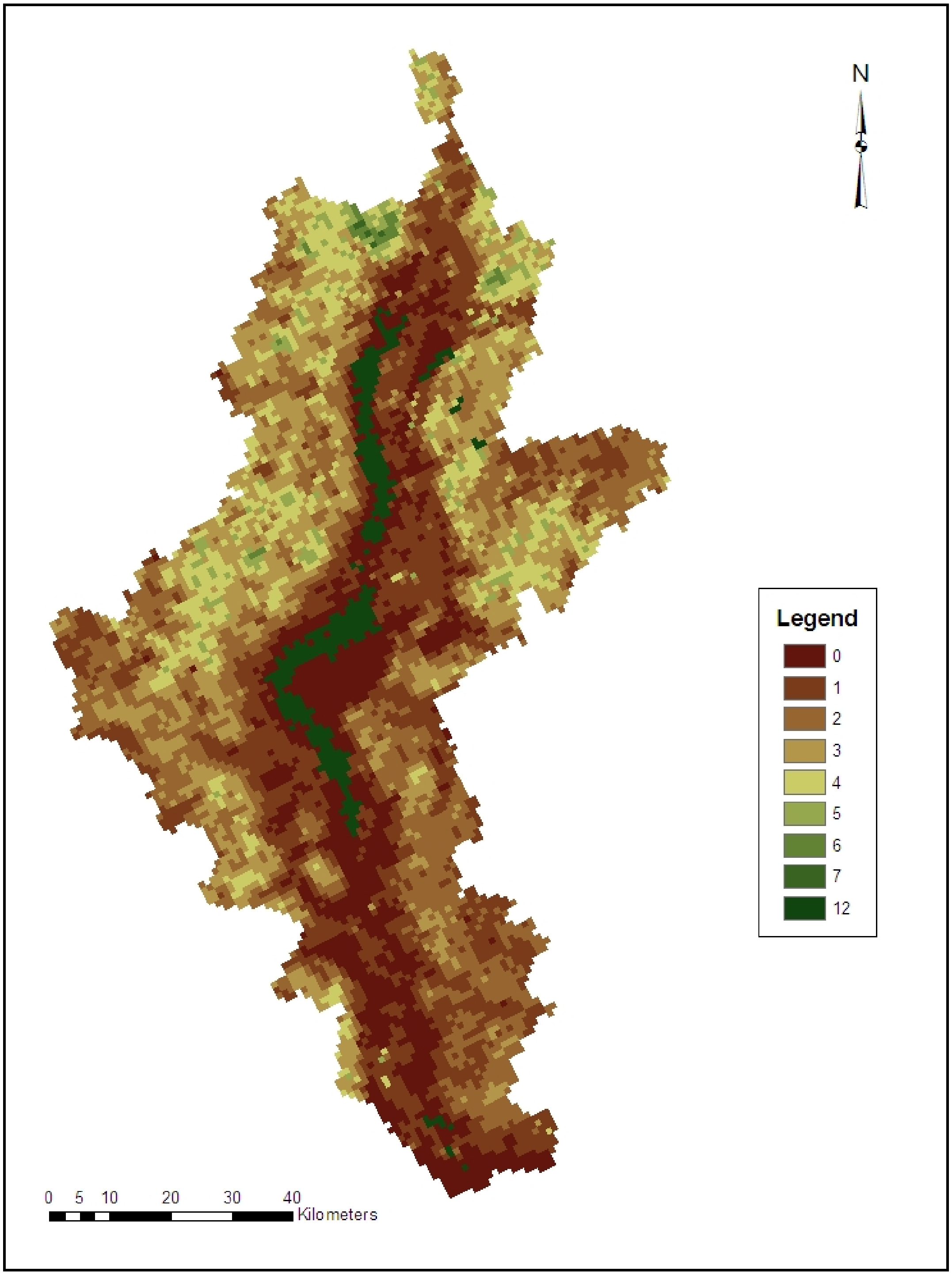


Figure 2-10 Example of a 10-day leaf area index (LAI) raster image used to develop the LAI data for the OBHM

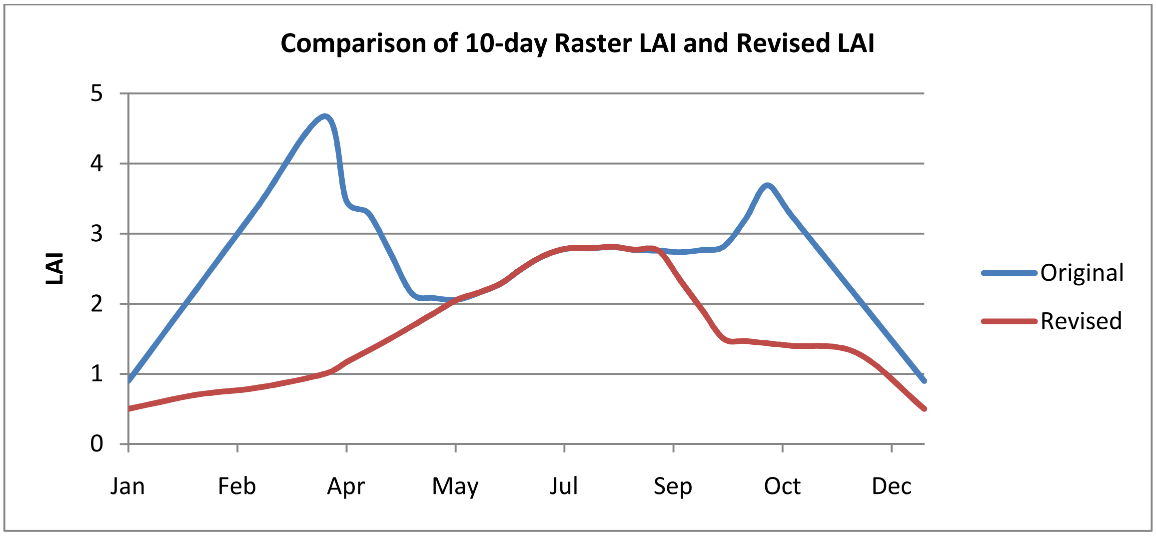


Figure 2-11: Example of Raw vs. Corrected LAI Values

Rooting Depth

In MIKE SHE, the rooting depth represents the maximum depth of active roots in the root zone. Significant seasonal variations in the rooting depth are typical for annual and deciduous plants, whereas for many perennial and evergreen plants, rooting depth values remain relatively constant throughout the year. Two major factors, climate and soil conditions, influence the rooting depth of a given plant assemblage. The primary function of the rooting depth specification in MIKE SHE is in establishing the depth to which plants can remove water through transpiration. Measured rooting depth values were not readily available for the vegetation in the Okanagan Basin, so the values used in the model represent typical literature values for similar vegetation, climate, and soil conditions (Schenk et al., 2003).

2.2.6 Rivers and Lakes

Channel flow was handled by the MIKE 11 model and is dynamically linked to the MIKE SHE model. The primary input data for this model included the river network, boundary conditions, channel and lake geometry, structure geometry and operational rules.

River Network

The river network was generated based on the national hydro-network shape file which was downloaded from the BC TRIM Database (LRDW). The network was developed so as to include a branch running through each of the five main lakes, rivers, and major tributaries. For the residual areas, between one and four branches were included in order to accurately represent the drainage paths in these areas that were not associated with a major tributary (Figure 2-12).

Boundary Conditions

Boundary conditions in MIKE 11 are required for all unconnected ends of branches. In the OBHM, all of the upstream boundaries are closed (i.e. no-flow boundaries). This is because water is introduced to the stream network via overland flow, interflow, and baseflow exchanges with the MIKE SHE overland flow and groundwater flow processes, so it is not necessary to define an upstream inflow hydrograph. The downstream boundary of the model is the Okanagan River near Oroville. This boundary was represented using a discharge vs. stage relationship that was developed by regression of daily measured discharge and stage data from the USGS gage located at this location from the period December 10, 1996 to November 5, 2008 (USGS Water Data, 2008).

River Channels and Lake Geometry

In the OBHM, hydrodynamic calculations were only performed for the Okanagan River, the lower reaches of Vernon Creek, the Oyama Canal, and the five major lakes. All other streams used a kinematic routing approach. Cross-sectional geometry data was only required for the hydrodynamic branches where water-level is computed by the model. In the kinematic routing branches, only discharge is calculated and no cross-sections are needed.

Lake bathymetry data was available in a hard copy format for all five lakes. The bathymetry for Vaseux and Osoyoos Lakes were obtained from BC Ministry of Environment (MOE) Fish and Wildlife Service (FIDQ-MOE, 2009), and the bathymetry for the Okanagan Lake, Skaha Lake and Kalamalka/Wood Lake were obtained from Canadian Hydrographic Services (CHS website, 2009). The data was digitized and merged with a topographic DEM in order to derive accurate bank elevations, and a 20 m DEM for the valley-bottom areas was produced. Lake cross-sections were extracted from this DEM and lake storages from the DEM were verified against published estimates of lake storages (FIDQ-MOE, 2009). In general, the DEM storages agreed closely with the MOE values; however since the bathymetry data for Wood Lake were very coarse, the lake storage obtained from the DEM was significantly smaller than the published estimate (Table 2-5). In order to better reflect the published storage estimate for this lake, additional storage was added at each cross-section on Wood Lake to bring the total storage closer to the published data. A total of 17 cross-sections were used for Kalamalka Lake, 42 for Okanagan Lake, 15 for Skaha Lake, 12 for Vaseux Lake and 30 for Osoyoos Lake.

Cross-sections for the Okanagan River were derived from the Okanagan Flood Control System which was developed for the Okanagan Basin Implementation Program (OFCS, 1983). Cross-sections for Vernon Creek were taken from the Sensitive Habitat Inventory and Mapping (SHIM, 2003). Most reaches of these channels are highly modified for flood management purposes, and channel shapes are mostly trapezoidal and exhibit limited variations along the channel length. Thus, spacing between the cross-sections was relatively large (on the order of 2 to 3-km). No cross-section data were available for Oyama Canal, however given that the canal is very short (~177-m) it is of relatively minor importance to the overall model. The approximate width of the channel was measured from aerial photography and the depth of the canal was estimated based on information from the City of Vernon. A total of 23 cross-sections were used for the Okanagan River, 5 for Vernon Creek, and 2 for the Oyama Canal.

Table 2-5 Comparison of published lake storage and lake storage derived from the bathymetric data used in the OBHM

Lake	Storage from bathymetry (km^3)	Published storage (km^3)	Difference (%)
Okanagan	25.49	25.94	-1.7
Osoyoos	0.32	0.33	-2.1
Skaha	0.54	0.56	-3.6
Kalamalka	1.49	1.50	-1.2
Wood	0.19	0.20	-3.1
Vaseux	0.02	0.02	-0.8

Flood Codes

The MIKE SHE/MIKE 11 coupling allows large water bodies such as lakes, reservoirs, and flooded areas to be simulated in MIKE SHE as 'flooded areas'. If this option is used, MIKE SHE/MIKE 11 applies a simple flood-mapping procedure where MIKE SHE grid points (e.g. grid points in a lake or on a flood plain) are linked to the nearest water level node in MIKE 11. Surface water stages are then calculated in MIKE SHE by comparing the water levels in MIKE 11 with the surface topographic elevations.

The flooded area in MIKE SHE must be delineated by means of integer flood codes, where each coupling reach is assigned a flood code. During the simulation, the flood-mapping procedure calculates the surface water level on top of each MIKE SHE cell with a flood code by comparing the MIKE 11 surface water level to the surface topography in the model grid. A grid cell is flooded when the MIKE 11 surface water level is above the topography. The MIKE 11 water level is then used as the level of ponded surface water and the actual water level in the grid cell is calculated as a distance weighted average of the upstream and downstream MIKE 11 water levels.

Flood codes were used in the OBHM to represent the mainstem lakes whereby all of the grid cells inside polygons representing the lake areas were assigned representative flood codes. For example, Flood Code =1 was assigned to grid cells corresponding to Okanagan Lake, Flood Code = 2 was assigned to grid cells corresponding to Kalamalka Lake, etc. (see Figure 2-13).

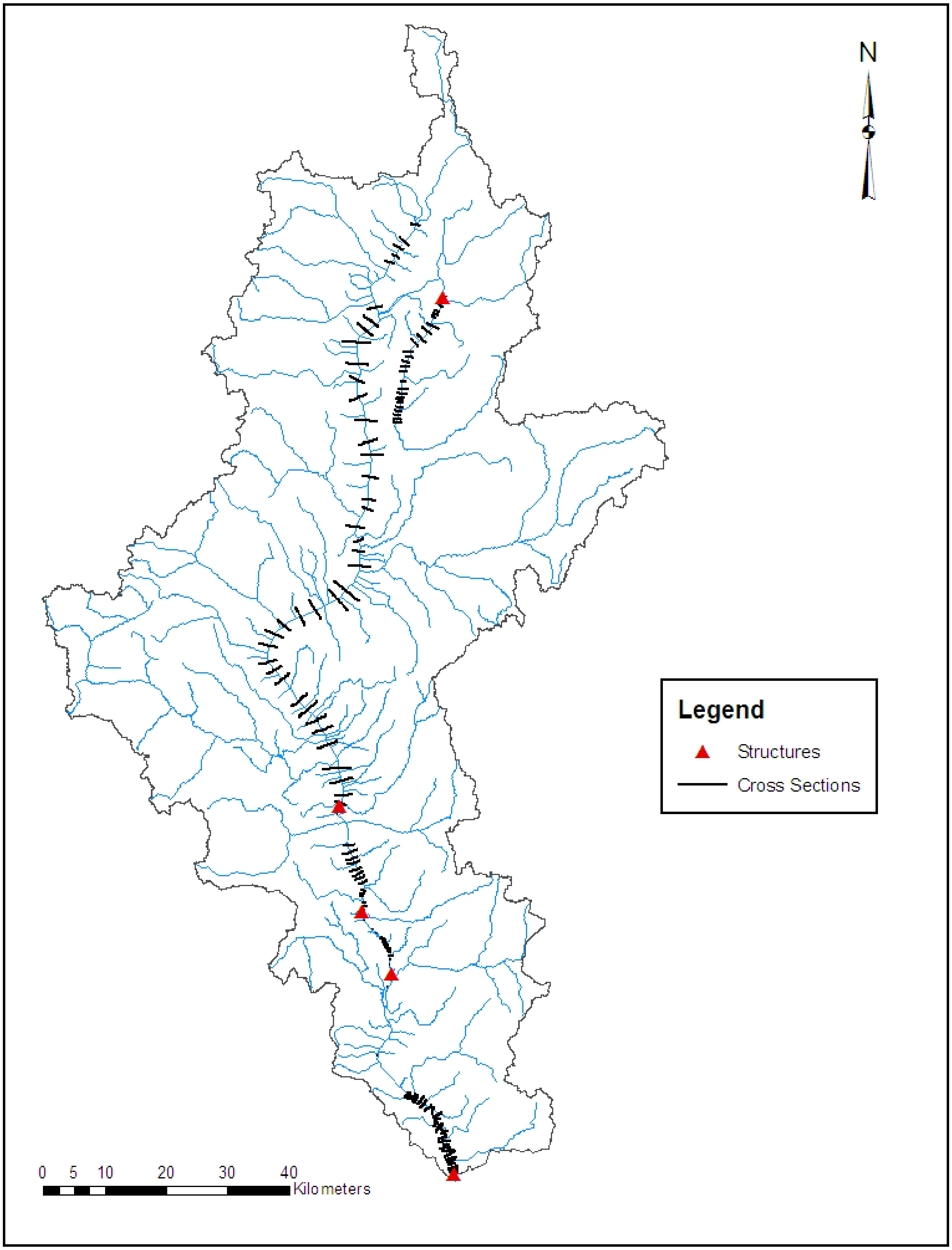


Figure 2-12 River network, cross-sections, and structures used in the OBHM

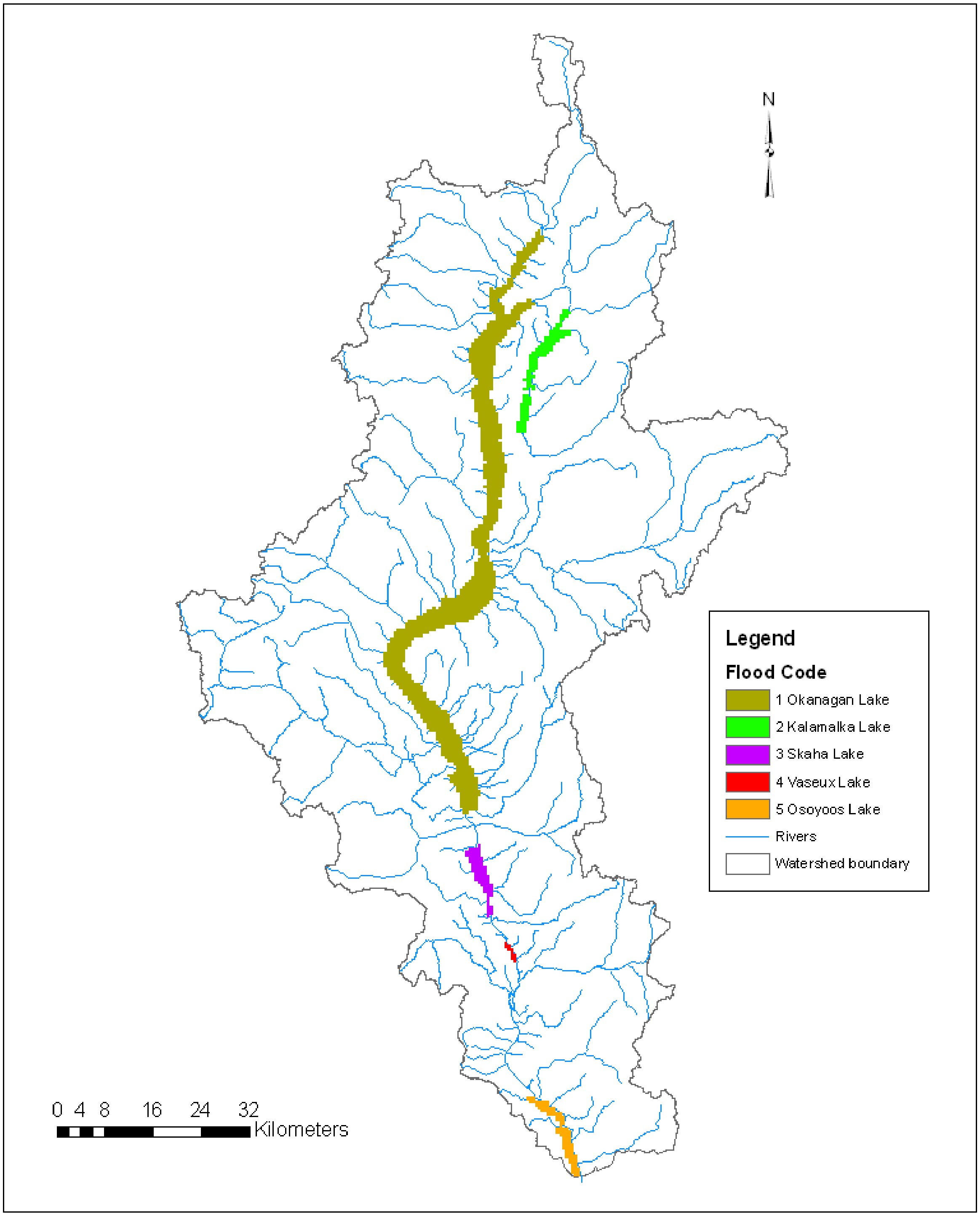


Figure 2-13: Flood Code Assignment

Structures

The five major lakes in the Okanagan Basin are highly regulated by a series of structures which are operated to maintain certain target lake levels and in-stream flow requirements. The MIKE 11 model has the capability to include control structures that allow for the definition of a control strategy using one or more 'if-then statements' to operate moveable gates and attempt to satisfy various target water levels and flows.

The computational burden of control structures is very high relative to the other components of the model, and in order to facilitate running long (11-yr) simulations with this large regional model, it was necessary to simplify the operational rules and structure geometry of the various gates that control outflow from each lake. In reality, multiple gates are present on each lake, and multiple gates may be partially open in order to try and achieve the desired lake levels and river discharges, for reason of icing, public safety, fish passage, etc. In total there are 21 such gates on the five major lakes. In order to achieve reasonable model runtimes, the multiple structures on each lake were combined into one structure with dimensions equal to the sum of the dimensions of each individual structure (see Table 2-6). The combined structures at each location were controlled by a single gate which opens or closes gradually in order to attempt to satisfy the target water levels and flows.

Table 2-6: Specification of combined control structures on the five major lakes in the OBHM

Lake	Gate Width (m)	Gate Height (m)	Sill Level (m)
Kalamalka	4.50	1.47	390.60
Okanagan	30.50	2.57	339.67
Skaha	16.00	2.59	335.76
Vaseux	30.50	1.83	325.82
Osoyoos	30.48	3.05	276.07

Information regarding how the structures at each lake are operated was available from a Lake Operation Plan for each lake (see Appendix A) and from the Fish Water Management Tool (FWMT) (FWMT, 2008). The Lake Operation Plan gave different sets of monthly lake level and Okanagan River discharge targets, whereby the targets in February, March and April were related to the forecast volumes. These operation plans are somewhat outdated and represent an over-simplification of how the lake structures are operated. The FWMT provides better information regarding the current operation of the structures at Okanagan Lake and Vaseux Lake since 2006, and defines a complex strategy for operation of the structures at these two lakes based on multiple objectives including water supply, flood control, and fish habitat requirements. The most important criteria defined in the FWMT in conjunction with the monthly lake level targets in the Lake Operation Plans were used to establish a set of rules for operating the gates on Okanagan Lake and Vaseux Lake. The final set of rules used in the model was determined by testing the performance of the model relative to measured lake levels and discharges for several sets of rules which is discussed in detail in Section 3. The monthly lake level and Okanagan River flow targets from the Lake Operation Plans were used to establish the rules for the other three lakes.

2.2.7 Overland Flow

The main inputs to the Overland Flow data category are Manning's Roughness Coefficient (n), Detention Storage, and Initial Water Depth. The development of these inputs are discussed in this section.

Manning's Roughness Coefficient (n)

A spatial distribution of roughness coefficients was developed based on the land cover map described in Section 2.2.4. No site-specific coefficients were available, so standard literature values and previous modeling experience from other watersheds was used as the basis for determining the initial coefficient values for each land cover category (AASHTO, 2005; DIDM, 2000; HCSS, 2005; McCuen, 2004). It is important to note that while the modeled 'n' values bear some resemblance to typical 'n' values that would be used in, for example floodplain calculations in a surface water model, the choice of values is highly grid-scale dependent. Since the overland flow component of the model operates on a 500 m by 500 m grid, the model representation of the topography is highly generalized. This results in a situation whereby artificial roughness and/or smoothness is introduced by the large flat topographic grid cells, and the larger the cells become the more magnified this effect becomes. The final 'n' values used in the model range from 0.09 for bedrock to 1.43 for broadleaf forest (Table 2-7).

Table 2-7 Overland Manning's roughness coefficients used in the OBHM.

Land cover	Manning's n
Urban area	0.11
Herb	0.14
Herb – Forbs	0.14
Herb - Graminoids	0.14
Rock/Rubble	0.09
Shrub Low	0.17
Shrub Tall	0.18
Treed –Broadleaf	1.43
Treed - Coniferous	1.33
Treed - Coniferous-Pine	1.33
Treed – Mixed	1.38
Open water	0.05
Orchards/Vineyards	0.24

Detention Storage

Detention storage represents a threshold storage depth at the land surface in each cell that must be filled before overland flow is generated. In theory, the natural topographic depressions in the model DEM should reflect topographic depressions that act as small storage areas. In practice, however, many of these depressions are "smoothed" out of the DEM because of the coarse scale of the model grid, and detention storage is a key calibration parameter. The final detention storage values used in the model are 45 mm for forested areas and 10 mm for the other land-cover categories.

2.2.8 Unsaturated Flow

The Two-Layer Unsaturated Zone approach used for the OBHM allows for a spatial distribution of soil types, where the exchange between the overland flow and the saturated groundwater is determined by the soil properties including soil moisture content at saturation (θ_S), field capacity ($\theta_{FC)}$, wilting point (θ_{WP}), and saturated hydraulic conductivity (Ksat).

Four soil maps were used to generate the soil map used in the OBHM. For the Canadian portion of the basin, three individual soil maps were available that cover the valley-bottom area, upland areas, and the Tulameen area in the western portion of the basin (Agriculture and Agri-Food Canada, 2001). For the U.S. portion of the basin, a soil map was taken from the NRCS's Soil Survey Geographic Database (SSURGO, 2008). The four soil maps were merged to develop a continuous map that covers the full model domain. In the raw map, there are a total of 298 soil types identified.

Databases associated with soil maps contained the four soil properties for each soil type and for each soil horizon as well as the thickness of each horizon. The unsaturated flow component of the OBHM uses a depth-averaged approach rather than a definition of individual soil horizons and associated properties. Thus it was necessary to calculate the horizon-thickness weighted average properties for each soil type. This was done for all of the properties except for the saturated hydraulic conductivity, where the harmonic mean of the saturated hydraulic conductivity values from each horizon was calculated. The number of soil types in the raw soil map (298) was much too large to facilitate inclusion on the model. Thus, the soil types were aggregated into 25 classes by lumping soil types with similar properties together (see Figure 2-14 and .

Although the soils maps did not include soil classifications for the mainstem lake areas, the model still requires a soil type to be defined within this area and containing suitable soil properties. A soil type of 'Water' was assigned in these areas with an assumed set of soil properties as indicated in Table 2-8.

Table 2-8). The soils were assigned a number rather than a descriptive name because textural descriptions were not available for all soil types and the final soil map used in the model aggregates multiple soil types together based on similar hydraulic properties.

Although the soils maps did not include soil classifications for the mainstem lake areas, the model still requires a soil type to be defined within this area and containing suitable soil properties. A soil type of 'Water' was assigned in these areas with an assumed set of soil properties as indicated in Table 2-8.

Table 2-8 Soil types and soil properties used in the OBHM

Soil Type	Saturated Hydraulic Conductivity K_{sat} (m/s)	Water Content at Saturation Θ_s	Water Content at Field Capacity Θ_{fc}	Water Content at Wilting Point Θ_{wp}
OK Soil 1	4.32E-07	0.419	0.218	0.095
OK Soil 2	7.81E-07	0.495	0.227	0.099
OK Soil 3	7.88E-07	0.502	0.369	0.240
OK Soil 4	8.52E-07	0.464	0.315	0.158
OK Soil 5	8.91E-07	0.425	0.198	0.087
OK Soil 6	1.22E-06	0.467	0.223	0.094
OK Soil 7	1.91E-06	0.886	0.510	0.247
OK Soil 8	1.20E-06	0.471	0.197	0.075
OK Soil 9	4.57E-06	0.458	0.228	0.107
OK Soil 10	9.96E-06	0.421	0.211	0.098
OK Soil 11	1.47E-05	0.887	0.525	0.281
OK Soil 12	1.52E-05	0.522	0.265	0.119
OK Soil 13	1.73E-05	0.432	0.124	0.050
OK Soil 14	2.15E-05	0.536	0.265	0.119
OK Soil 15	2.22E-05	0.910	0.410	0.170
OK Soil 16	2.83E-05	0.443	0.150	0.066
OK Soil 17	4.08E-05	0.419	0.120	0.055
OK Soil 18	4.73E-05	0.920	0.319	0.130
OK Soil 19	5.26E-05	0.449	0.117	0.051
OK Soil 20	5.83E-05	0.920	0.210	0.140
OK Soil 21	7.76E-05	0.442	0.126	0.058
OK Soil 22	1.08E-04	0.435	0.092	0.038
OK Soil 23	1.38E-04	0.423	0.081	0.033
Bedrock	1.00E-11	0.3	0.3	0.03
Water	1.00E-12	0.4	0.39	0.38

Evapotranspiration Surface Depth

The evapotranspiration (ET) surface depth equals the thickness of the capillary zone. It is used as the water table depth at which the ET starts to decrease. That is, if the water table falls below the ET surface, then the linear function that reduces ET becomes active. In coarse to medium sands, the ET surface depth is typically less than 10 cm. In fine sands and silts, the ET surface depth could be 50 cm or more. For the OBHM the ET Surface Depth was set at 0.1 m for the entire basin and was not adjusted during calibration.

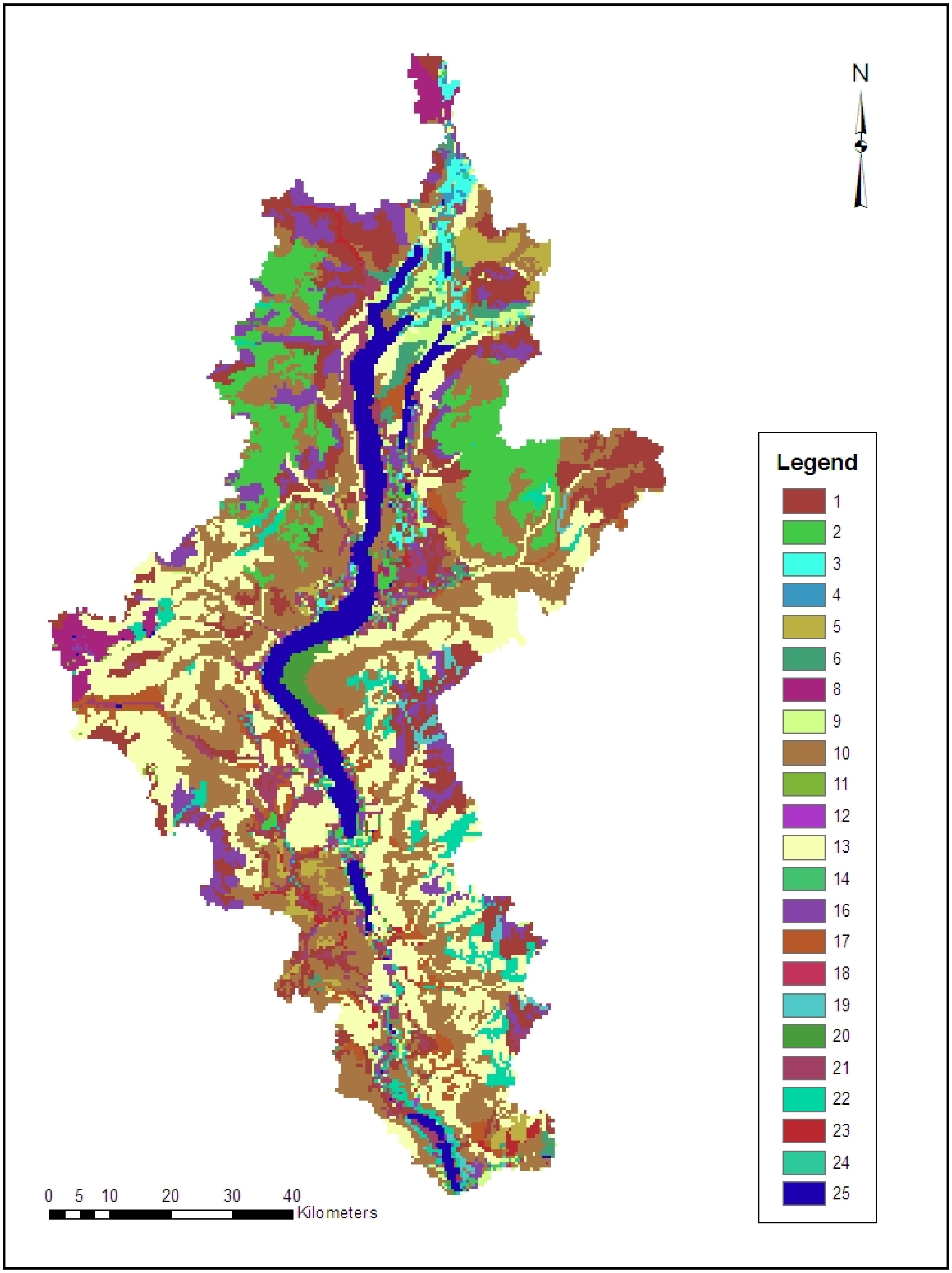


Figure 2-14 Map of the aggregated soil classes used in the OBHM (see Table 2-8)

2.2.9 Saturated Zone

As described in greater detail in Section 2.1.2, the groundwater component of the OBHM represents the groundwater system by dividing the basin into a series of shallow interflow reservoirs and two parallel baseflow reservoirs (a shallow baseflow reservoir and a deep baseflow reservoir). The down-gradient interflow reservoir connected to the MIKE 11 river network in each subcatchment provides interflow to the river network, and the baseflow reservoirs provide baseflow contributions to the river network.

The delineation of the interflow reservoirs and baseflow reservoirs in the model was performed based on a parallel study being conducted by Golder & Associates at the time when the model was being constructed and calibrated. The goal in establishing the groundwater component of the OBHM was to adopt the conceptual groundwater model from the Golder study (Golder, 2008) and utilize the groundwater data provided in that study. In the Golder study, the Okanagan Basin was divided into a series of bedrock and alluvial aquifers (**Error! Reference source not found.**), and a conceptual model was developed describing groundwater flow patterns in the basin. This conceptual model describes how water recharges to the bedrock aquifers in the upper basin, flows laterally through the subsurface towards the alluvial aquifers in the valley-bottom areas, and then discharges as baseflow to streams and the major lakes in the lower basin. According to this study, ~85% of the recharge to bedrock aquifers flow laterally and recharges the down-gradient alluvial aquifers.

Interflow Reservoirs

For modeling purposes, the basin was divided into two interflow reservoirs. An upland reservoir was delineated by merging all of the bedrock aquifers together, and a lower reservoir was delineated by merging all of the alluvial aquifers together (Figure 2-16). Additionally, a small buffer around all of the streams included in the model was added to the lower reservoir in order to allow some interflow to occur in streams overlying bedrock. The final calibrated OBHM utilized the following inputs for both Interflow reservoirs.

- Specific Yield = 0.2
- Initial Depth = Bottom Depth = Interflow Threshold Depth = 5 m
- Interflow Time Constant = 14 days
- Percolation Time Constant = 40 days

The meanings for these parameters are discussed in Section 2.1.2.

Baseflow Reservoirs

The baseflow reservoirs were delineated by merging the bedrock and alluvial aquifers that are shown to be hydraulically connected in the Golder study (Golder, 2009). This merging was necessary because individual baseflow reservoirs in the model are not hydraulically-connected and this merging allowed the concept of upland bedrock aquifers discharging to lowland alluvial aquifers to be included in the model. For the main valley-bottom lakes, no aquifers were delineated in the Golder study, thus it was necessary to extrapolate the surrounding aquifer boundaries into the lake areas in order to provide a continuous map for delineating the baseflow reservoirs. In total, there are 104 baseflow reservoirs included in the model as indicated by the outlined areas in Figure 2-17.

Table 2-9 provides a summary of the Baseflow Reservoir parameters used for the final calibrated OBHM.

Table 2-9: Baseflow Reservoir Parameters

	Baseflow Reservoir 1 (Shallow)	**Baseflow Reservoir 2 (Deep)**
Specific Yield = 0.1	0.1	0.1
Time Constant for baseflow = 100 days	100 days	3650 days
Dead storage fraction = 0	0	0
UZ feedback fraction = 0.1	0.1	0.1
Initial depth = 20 m	20 m	50 m
Threshold depth for baseflow = 20 m	20 m	50 m
Threshold depth for pumping = 20 m	20 m	50 m
Depth to the bottom of the reservoir = 20 m	20 m	50 m

It is important to note that the groundwater component of the OBHM uses a lumped-parameter conceptual approach rather than a physically-based approach. The groundwater table is not simulated; rather the groundwater system is represented volumetrically by these various inter-related storages. The specific yield values, storage depths, and time constants do not necessarily represent real physical attributes of the groundwater system, but instead are parameters that were adjusted during model calibration in order to best match the baseflow component of the measured and derived streamflow hydrographs that were used for calibration. The implications of this approach are discussed in the results section of this report.

Groundwater Table

A map indicating the position of the groundwater table was generated in order to define the lower boundary condition for the unsaturated flow component of the model. The groundwater component of the model (see Section 2.1.2) does not simulate the position of the water table, nor does the model account for variations in the water table through time. It is important to note that while this water table does influence the timing and magnitude of groundwater recharge computed by the model, it does not influence groundwater flow directions or gradients.

Groundwater observation wells are very sparse in the Okanagan Basin; in total there are 25 wells in which four wells are located in bedrock aquifers and the remainder are located in alluvial aquifers. For each alluvial aquifer, a uniform groundwater depth was assigned using the OBWB - Preliminary Alluvial Aquifer Characterization Summary Table provided by Golder prior to the finalization of the Groundwater Study. For the bedrock aquifers there are only four observation wells available, so it was not possible to interpolate a groundwater surface. Thus, the data from these four wells was used as a guide, and an average approximate depth to the water table of 7.6 m was applied globally to all of the bedrock aquifers.

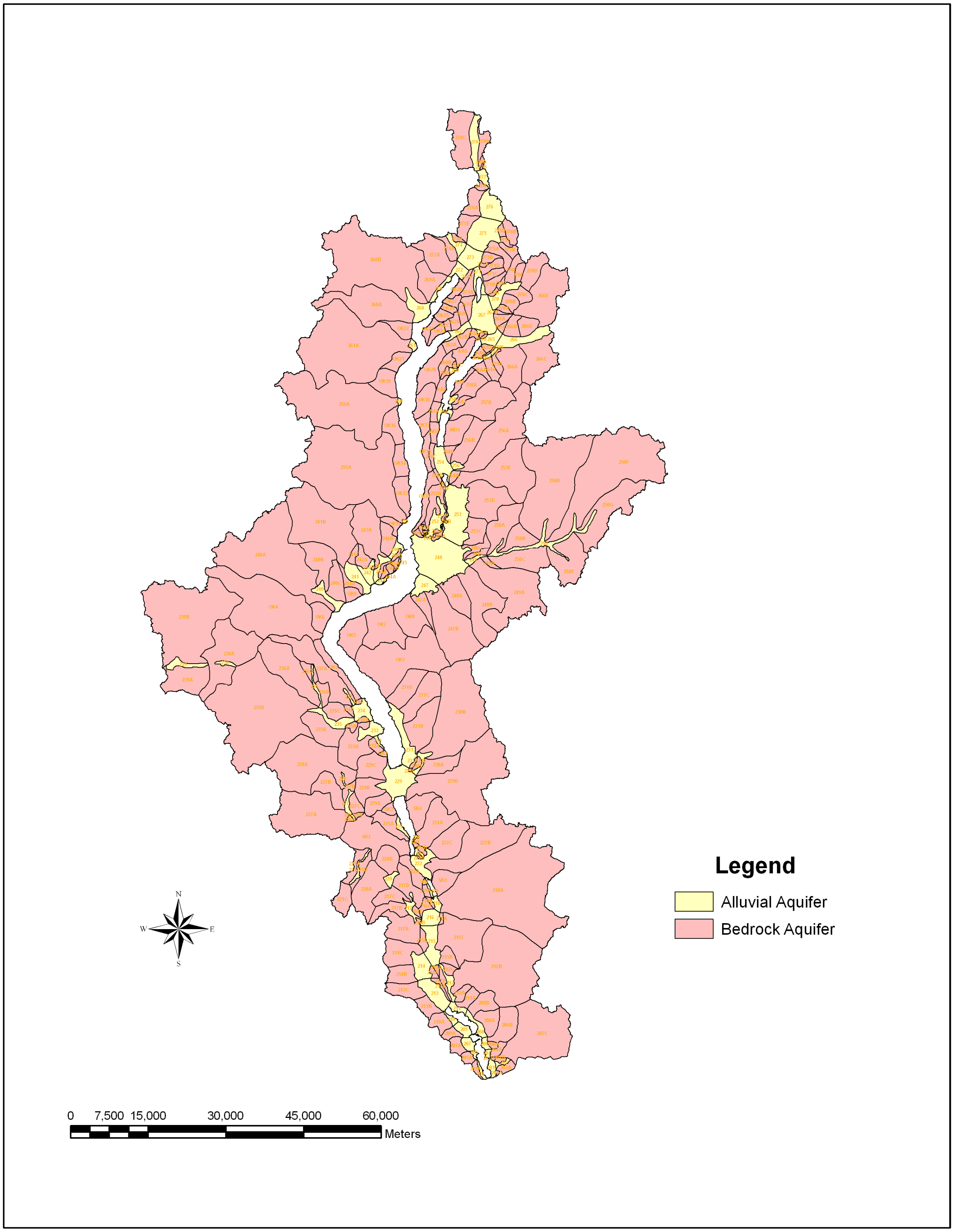


Figure 2-15: Distribution of alluvial and bedrock aquifers from the Groundwater Study

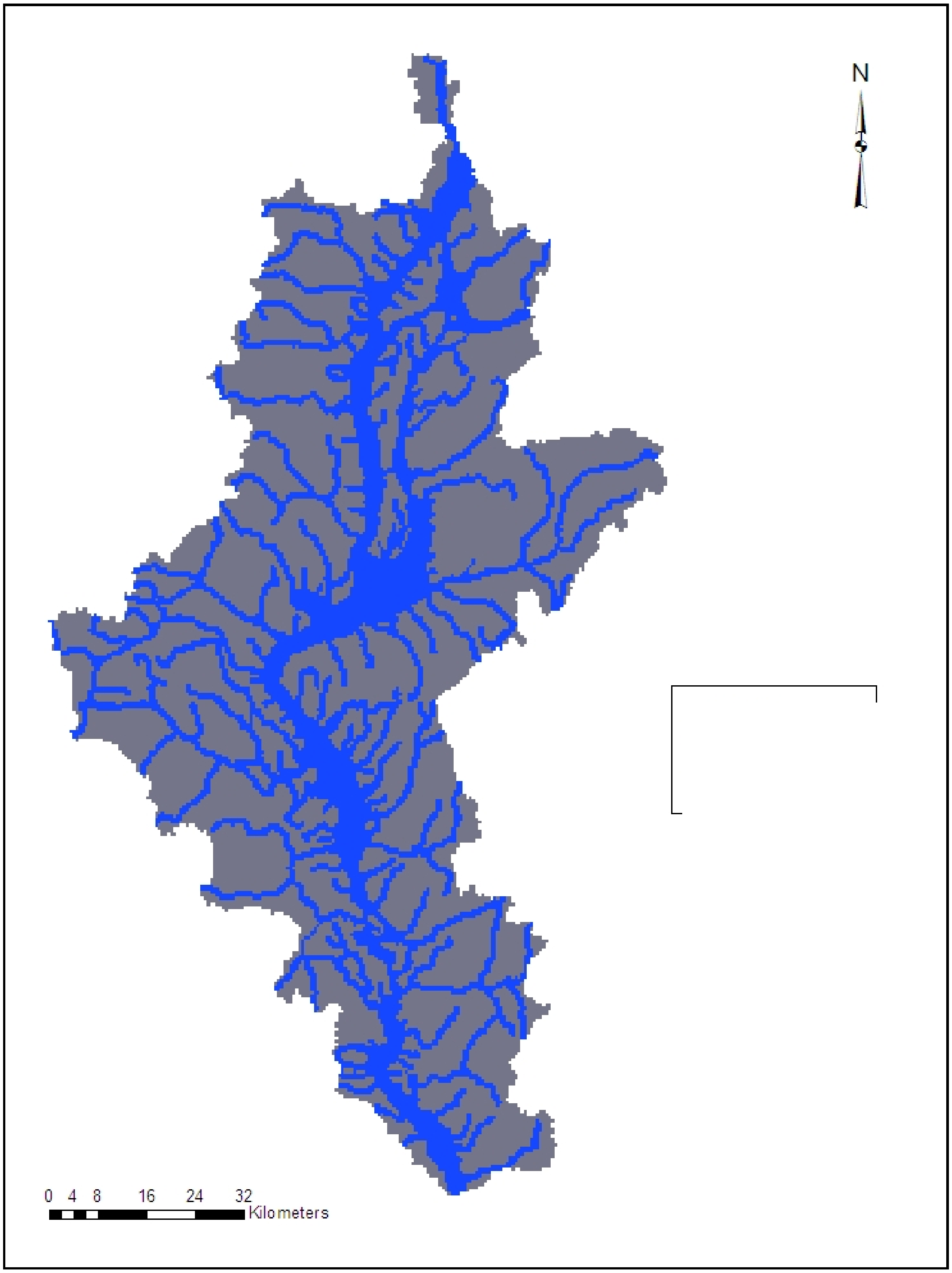


Figure 2-16 Interflow reservoir delineation used in the OBHM (blue area represents interflow reservoir adjacent to tributaries and lakes; gray area represents remaining interflow reservoir area)

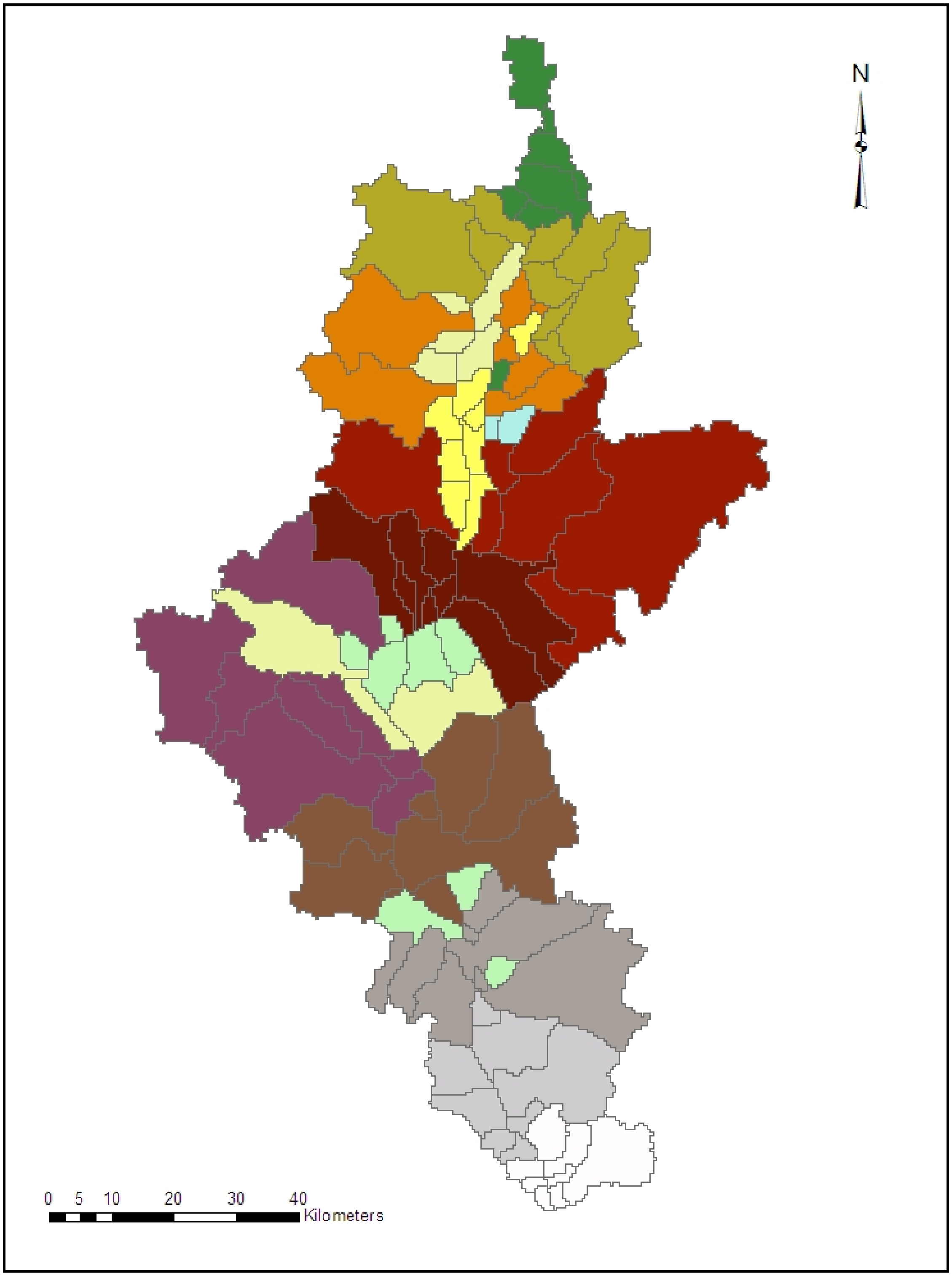


Figure 2-17 Baseflow reservoir delineation used in the OBHM (Baseflow reservoirs are outlined while major catchments are shown with different colors)

2.3 HYDROLOGY MODEL CALIBRATION

2.3.1 Overview of Approach

The goal of the calibration for the OBHM was to compare and calibrate the results of the model against as many different sources and types of data as possible to gain a solid understanding of the model's performance and identify any deficiencies in the model's representation of the hydrology of the basin. The types of data available for calibration and comparison include:

- overall water budgets,
- snow water equivalent data,
- streamflow hydrographs and flow volumes,
- historical inflow data for Okanagan Lake,
- lake level data, and
- lake evaporation estimates from a lake evaporation study conducted for the project by Environment Canada

Calibration vs. Verification

The concept that all models need to be verified is a byproduct of the realization that all complex, highly parameterized models with limited monitoring points have an infinite number of combinations of parameter values that can yield a 'calibrated' model. The process of verifying a model is to take the calibrated model and apply a different set of known „stresses" to the system and see if it can reproduce the measured responses of the system. This verification approach has traditionally been used on models which are calibrated to steady-state, or near steady-state conditions (e.g. most groundwater models), or on models which are calibrated to a single dominant stress on the system (e.g. event-based hydrology models). In these cases, a model verification step is recommended in order to ensure the model will respond accordingly to different stresses or conditions. For example, a hydrology model calibrated to a 5 year 24 hour storm with initial dry conditions could be verified against data from a 2 year 12 hour storm with initially wet conditions. But, a more effective calibration of this model could be achieved by simply running it continuously through many different rainfall events so you can see how it responds under many different conditions and trends in conditions.

In the case of the OBHM, the simulation was run for an 11 year period during which the model is exposed to widely varying climatic conditions throughout each year (e.g. snow accumulation, snow melt, wet periods, and dry periods), as well as widely varying annual climate patterns (e.g. wet years, dry years, cold years, and warm years). The model is being run on a continuous basis and the results from the simulations are being compared against different types of measured data (e.g. snow depths, streamflow hydrographs, and lake water levels) throughout the entire simulation period. By running the model continuously throughout the entire simulation period we are able to maintain a continuous representation of the system conditions and responses to the continuous changes in climate and seasonal variations in hydrologic responses.

Breaking the model up into two separate simulation periods, simply for the purpose of calling the second period a 'verification' period, would be counter-productive because it does not subject the model to any dramatically different conditions that would not already be taken into consideration by running the model continuously. In addition, it would require initial conditions to be specified at the beginning of the proposed verification period (i.e. starting parameter values like snow depth, soil moisture, groundwater table, surface storage depth, etc.). The best estimate we could use for these initial conditions would be the conditions at the end of the proposed calibration period. So we would be starting the model from exactly where it finished during the calibration period – thus, in effect, it is essentially the same as running a continuous simulation over the same period.

Given the information above, and in consultation with the Working Group, it was decided that the intended goals of the model verification would be better addressed by calibrating a continuous model over the entire 11 year simulation period rather than breaking it up into the two separate simulation periods in sequence. As noted earlier, the 1996-2006 calibration period includes a good mix of wet, dry, cool, and warm years, and the resulting model is sufficiently robust to respond to the climate and human caused influences on the system.

A description of the available data and how it was used to evaluate or calibrate the model results is discussed in the following text.

2.3.2 Calibration Parameters

When working with a highly parameterized model like MIKE SHE, it is critical to identify which parameters are most sensitive so that the calibration effort can be focused on a subset of the available model parameters. An additional consideration is the degree to which a given parameter is known. For those parameters that are well-constrained by measurements or detailed studies there is less justification for making adjustments. On the other hand, some parameters are based on limited or no site-specific information or are known to have a wide range of reasonable values. For this latter group of parameters, there is significantly more leeway with which to make adjustments. For any parameter, however, it is important to consider the upper and lower bounds of reasonable values to ensure that all model parameter values remain realistic.

In addition, for a basin wide model like this with such a sparse network of monitoring data, it was decided to focus on systematic parameter adjustments which could be made on a system-wide basis. For example, when adjusting the Manning's Surface Roughness Coefficient (n) to achieve a better calibration for a particular monitoring station, we wanted to maintain a consistent 'n' value for the same land use classification throughout the entire model, rather than trying to justify making and isolated change to a value in a specific region simply to achieve a better calibration.

A series of 1-yr test simulations were performed at the beginning of the calibration process where adjustments were made to many of the parameters and we evaluated the sensitivity of the model in terms of the overall water balance. The outcome of this process was a list of parameters that became the focus of the remaining calibration effort. The following parameters were selected:

- **Detention Storage:** This parameter is used to limit the amount of runoff that the model produces as well as control the timing of runoff relative to precipitation. The parameter also has an indirect effect on infiltration and ET.
- **Riverbed Leakage Coefficient:** This parameter regulates the exchange of water between the groundwater and channel flow components of the model.
- **Soil Moisture Contents:** This set of parameters influences the amount of ET, infiltration, and groundwater recharge and indirectly affects the timing and magnitude of runoff.
- **Saturated Hydraulic Conductivity:** This parameter controls the infiltration rate and indirectly affects the rate of groundwater recharge, ET, and runoff.

- **Degree Day Coefficient:** This parameter controls the rate at which snow is melted and converted to runoff.
- **Manning's Coefficient:** This parameter controls the timing and magnitude of runoff.
- **Time Constants for Interflow and Baseflow:** These parameters control the timing and magnitude of interflow and baseflow that discharge to the channel flow component of the model.

The remaining model parameters were either found to have only a limited influence on the model results or are so well constrained that making any significant adjustments is unjustifiable.

The final calibrated model parameter values are described in Section 2.2.

2.3.3 Overall Water Budget

Several previous studies have estimated one or more components of the water budget in all or a portion of the Basin. The 1974 Supply and Demand Study estimated that average annual actual evapotranspiration for the full basin is between 400 and 430 mm/yr or approximately 71% to 77% of incoming precipitation (CBCOBA, 1974). Other estimates exist for sub-areas within the basin including an estimate of 60% of incoming precipitation for the upper Penticton watershed (Spittlehouse, 2002), 60 – 65% for the Joe Rich area (Golder, 2008), 68% for the southern portion of the basin (Golder, 2008), 62 – 67% for the upper Mission Creek watershed (Summit, 2009), 77 – 85% for the Irish Creek watershed (Summit, 2009), and 70 – 76% for the upper Vaseux Creek watershed (Summit, 2009).

The 1974 Supply and Demand Study estimated that average annual runoff for the full basin is approximately 25% of incoming precipitation (CBCOBA, 1974), and the State of the Basin Report completed as part of the current Water Supply and Demand Project estimated a lower percentage of 18% (Summit and Polar, 2009). An estimate of 19% for the southern portion of the basin was also made in a recent study (Golder, 2008).

No estimates of groundwater recharge were found for the full basin, however, several estimates were found for sub-areas within the basin. These estimates include 45 mm/yr or approximately 7% of incoming precipitation for the valley bottom areas in the southern basin (Toews, 2007), 22 mm/yr or 3% of precipitation for the valley bottom areas in the northern basin (Smerdon, 2007), 40 mm/yr or 6% of precipitation for the upland areas in the northern basin (Smerdon, 2007), 13% of precipitation for the southern Okanagan (Golder, 2008), and 10- 15% for the Joe Rich area (Golder, 2008).

Water Budget Calibration Results

Table 2-10 shows the simulated average annual water budget for the full model area over the 11-yr simulation period. The simulated ET is towards the high end of the previous estimates for the basin at 80.9% of the incoming precipitation. The simulated runoff represents 11.9% of the total incoming precipitation, somewhat lower than previous estimates which ranged from 18 to 25% (CBCOBA, 1974; Summit & Polar, 2009). Groundwater recharge accounted for 6.5% of incoming precipitation which is towards the low end of the previous estimates.

Table 2-10 Simulated average annual water budget for the full basin over the 11-yr simulation period

Water Balance Term	Total Depth (mm)	Mean Annual Depth (mm)	Relative to Precipitation (%)
Precipitation	7114	647	
Evapotranspiration	5758	523	81%
Recharge	460	42	7%
Runoff	846	77	12%

2.3.4 Snow Pack

Snow data were obtained from the Ministry of Environment at 19 snow survey stations with data available for the calibration period. The sites range in elevation from 1266 m to 1834 m and the snow data at these sites was generally collected between December and the middle of June, and consisted of both snow depth and snow water equivalent (SWE) data (Figure 2-18 and Table 2-11). In addition, continuous snow pillow data was provided from the Mission Creek and Brenda Mine stations with measured daily snow depth and SWE values throughout the calibration period. The SWE data was compiled and the measured SWE data at each of the 21 stations, including two snow pillow stations, was used to compare and calibrate the simulated SWE values at the corresponding locations in the model.

The calibration statistics for the SWE results are provided in Table 2-12 while Figure 2-19 shows a sample calibration plot comparing the simulated vs. observed snow water equivalent (SWE) data. Appendix B contains all of the calibration plots comparing simulated vs. observed SWE data from 1996-2006. In general, the pattern and timing of snow accumulation and melt is well-captured by the model. At some locations such as Greyback Reservoir and Postill Lake, the overall magnitude and duration of the snow pack matches the observed data very well. At some locations, however, the magnitude and duration of the snowpack is significantly over-predicted (e.g. Vaseux Creek and Similkameen) and significantly under-predicted at others (e.g. Silver Star Mountain and Whiterocks Mountain). Mean errors (ME) range from -165 to 120 mm, with a mean ME of -8 mm (Table 2-12). The low mean ME error indicates that overall the over- and under-predictions tend to balance. Root mean square errors (RMSE) range from 45 to 208 mm, with a mean of 105 mm, and correlation coefficients (R) range from 0.39 to 0.90 with a mean of 0.81 (Table 2-12). In general the calibration is best at the higher elevation stations (Figure 2-20). This is to be expected as any deficiencies in the temperature data are more likely to result in inaccurate predictions of rain versus snow at lower elevation stations where temperatures are expected to be closer to the freezing level for more of the year. There is a weak correlation between the model error and the station elevation and the model tends to over-predict SWE at the lower elevation stations and under-predict SWE at the higher elevation stations (Figure 2-21).

Table 2-11 Snow survey stations used for calibration of the OBHM

Station Name	Elevation (m)
Trout-2F01	1428
Summerland-2F02	1304
Mcculloch-2F03	1266
Graystock-2F04	1818
Mission-2F05, 2F05P	1780
Postill-2F07	1358
Greyback-2F08	1548
Whiterocks-2F09	1789
Silver Star-2F10	1834
Similkameen-2F11	1651
Mount Kobau-2F12	1817
Esperon (upper)-2F13	1634
Esperon (middle)-2F14	1440
Brenda Mine-2F18, 2F18P	1453
Oyama-2F19	1365
Vaseux-2F20	1403
Bouleau-2F21	1405
Macdonald-2F23	1742
Islaht-2F24	1492

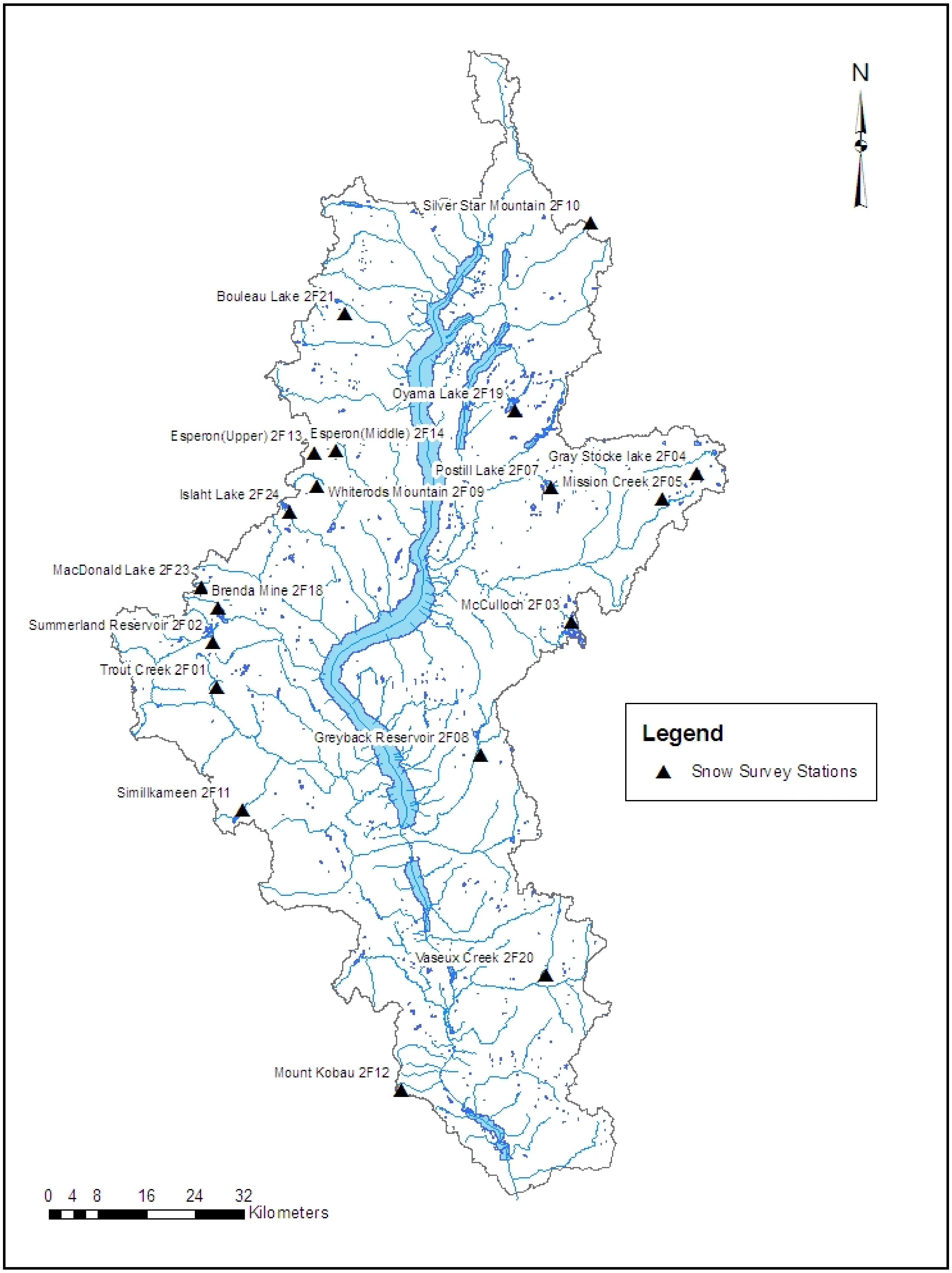


Figure 2-18 Locations of snow survey stations

Table 2-12 Calibration Statistics for SWE Data

Station Name	Mean Error (ME) (mm)	Mean Abs. Error (MAE) (mm)	Root Mean Square Error (RMSE) (mm)	Correl. Coef. (R)
Trout Creek 2F01	47	48	67	0.83
Summerland Reservoir 2F02	102	102	126	0.67
Mcculloch 2F03	28	40	58	0.71
Graystocke Lake 2F04	120	120	133	0.88
Mission Creek 2F05	-15	66	85	0.86
Postill Lake 2F07	35	37	45	0.89
Greyback Reservoir 2F08	21	42	55	0.79
Whiterocks Mountain 2F09	-158	173	208	0.90
Silver Star Mountain 2F10	-165	180	199	0.88
Similkameen 2F11	109	109	121	0.79
Mount Kobau 2F12	-35	54	74	0.84
Esperon(upper) 2F13	-99	101	117	0.88
Esperon(middle) 2F14	-62	88	94	0.89
Brenda Mine 2F18	-104	108	125	0.69
Oyama Lake 2F19	93	108	123	0.39
Vaseux Creek 2F20	101	101	124	0.67
Bouleau Lake 2F21	29	36	47	0.89
Macdonald Lake 2F23	-143	144	159	0.83
Mission Creek (snow pillow)	21	52	92	0.92
Brenda Creek (snow pillow)	-48	57	89	0.90
Islaht Lake 2F24	-43	56	68	0.89
Averages for all 21 Stations	**-8**	**131**	**105**	**0.81**

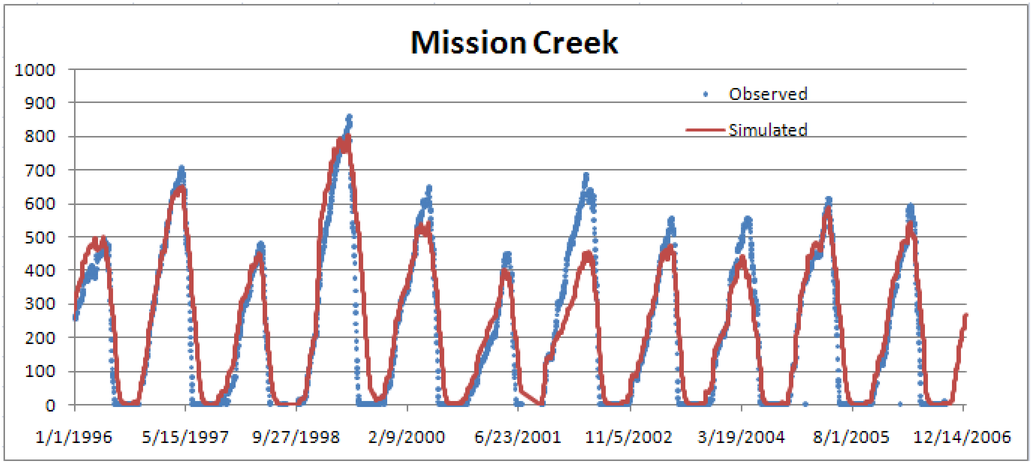


Figure 2-19 Comparison of the simulated SWE with the snow pillow data for the Mission Creek site

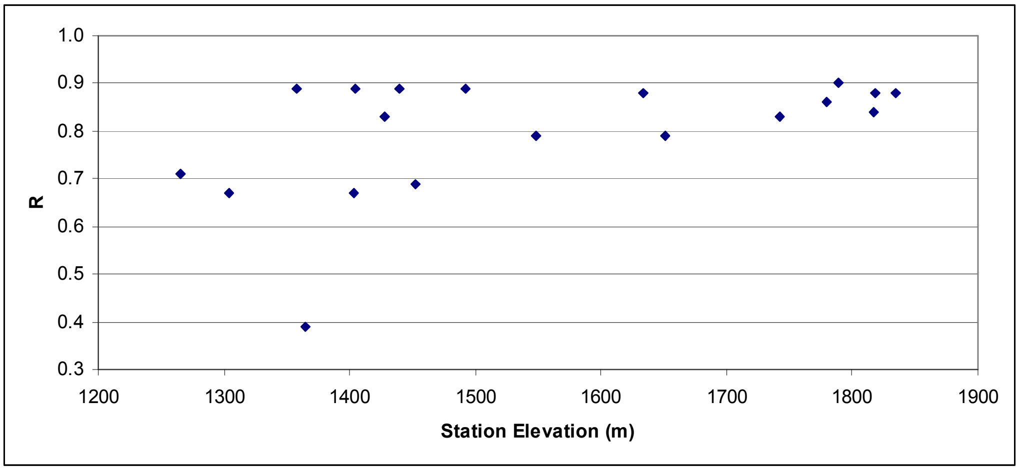


Figure 2-20 Correlation coefficient versus station elevation for the SWE calibration

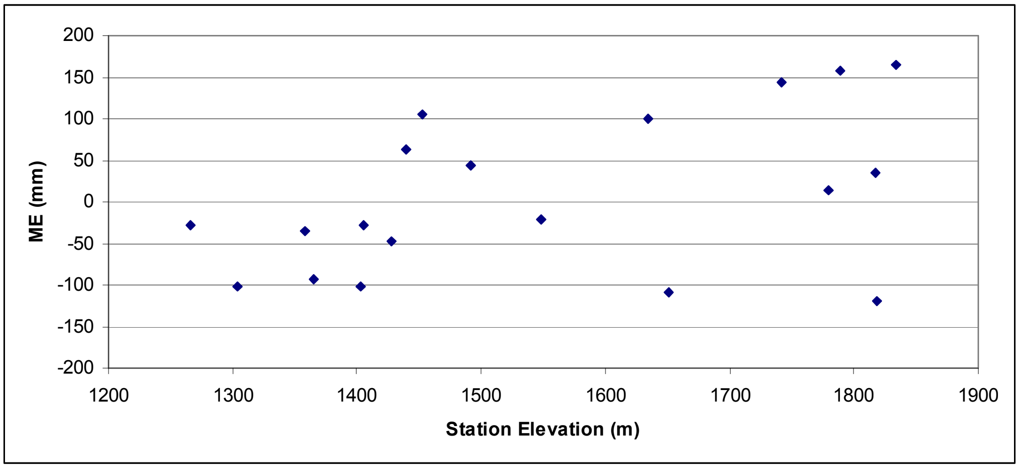


Figure 2-21 Mean error versus station elevation for the SWE calibration

2.3.5 Stream Flow Hydrographs

When calibrating a basin hydrology model, the streamflow hydrographs are usually the primary indicator of the quality of the model calibration. The following objectives are usually considered in the model calibration:

1. A good agreement between the average simulated and observed catchment runoff (i.e. a good water balance)
2. A good overall agreement of the shape of the hydrograph
3. A good agreement of the peak flows with respect to timing, rate and volume
4. A good agreement for low flows

In this respect it is important to note that, in general, trade-offs exist between the different objectives. For instance, one may find a set of parameters that provide a very good simulation of peak flows but a poor simulation of low flows, and vice versa. In the calibration process, the different calibration objectives 1-4 should be taken into account. If the objectives are of equal importance, one should seek to balance all the objectives, whereas in the case of priority to a certain objective this objective should be favoured.

Both graphical and numerical performance measures should be applied in the calibration process. The graphical evaluation includes comparison of the simulated and observed hydrograph, and comparison of the simulated and observed accumulated runoff. The numerical performance measures include the overall water balance error (i.e. the difference between the average simulated and observed runoff), and a measure of the overall shape of the hydrograph based on the coefficient of determination or the Nash-Sutcliffe coefficient (DHI, 2009a).

An exact agreement between simulations and observations must, however, not be expected. The goodness-of-fit of the calibrated model is affected by different error sources, including:

- Errors in meteorological input data
- Errors in recorded observations
- Errors and simplifications inherent in the model structure
- Errors due to the use of non-optimal parameter values

In model calibration only error source (4) should be minimised. In this respect it is important to distinguish between the different error sources since calibration of model parameters may compensate for errors in data and model structure. For catchments with a low quantity or quality of data, less accurate calibration results may have to be accepted.

Evaluating the Calibration Data

As part of the State of the Basin report completed as part of the current Okanagan Water Supply and Demand Project (Summit and Polar, 2009), weekly naturalized hydrographs were generated for 70 node locations in the basin. Nine of these locations had gauging data available at or upstream of the node and are not influenced by upstream water use activities, thus the hydrographs at these locations are considered to be natural and the data to be of very high quality. A confidence level was assigned to each of the remaining hydrographs based on the level of data and information available to support the naturalization process. A high confidence level was assigned to those sub-basin nodes where naturalized streamflows were largely based on high quality hydrometric and/or water use information, usually within or very near the sub-basin. A moderate confidence level was assigned to those sub-basin nodes where the naturalized hydrographs were based on some hydrometric and/or water use information, but where some estimation and professional judgment was required. A low confidence level was assigned to those sub-basin nodes where naturalized hydrograph estimates were based on regional hydrology procedures that required a considerable amount of professional judgment because little or no hydrometric and/or water use information specific to the stream of interest was available. Of the available naturalized hydrograph locations, 8 were considered to have a high level of confidence, 15 were considered to have a moderate level of confidence, and the remaining 49 were considered to have a low level of confidence (Figure 2-22). Of the 49 low confidence stations, 40 were residual areas representing 17% of the total area of the basin and only 5% of the total flow. Note that the confidence ratings only relate to the availability of data with which to derive the estimates, and all estimates were derived using appropriate methods and actual Okanagan Basin streamflow data (Summit and Polar, 2009).

It was of critical importance to recognize the differences between these various confidence levels during the calibration process. In particular, it is important to note that the low and moderate level hydrographs may contain significant deviations from reality and it would be undesirable to calibrate the model to match data developed from another model (e.g. regional relationships). Bearing this in mind, the focus of the calibration was placed on the 9 natural and 8 high confidence level naturalized locations. Once the calibration to these locations was optimized, an effort was made to improve the calibration at the 15 moderate confidence level locations, however, no adjustments that resulted in a deterioration of the calibration at the 9 natural and 8 high confidence level locations was retained. A comparison of the model simulated results at the remaining 49 low confidence locations was also made; however, no attempt was made to calibrate the model to match the hydrographs at these locations. This approach was followed in order to minimize the chances of calibrating the model to erroneous data and because it can be argued that if the model reproduces the higher confidence level data well, the model output may provide as accurate or more accurate estimates of the naturalized hydrographs at the lower confidence level locations. In essence, the modeling can be considered an alternative method for generating naturalized hydrographs to the methods used in the State of the Basin report (Summit and Polar, 2009), and identification of nodes with significant differences will help to set priorities for future data collection during subsequent phases of the OBWSDP.

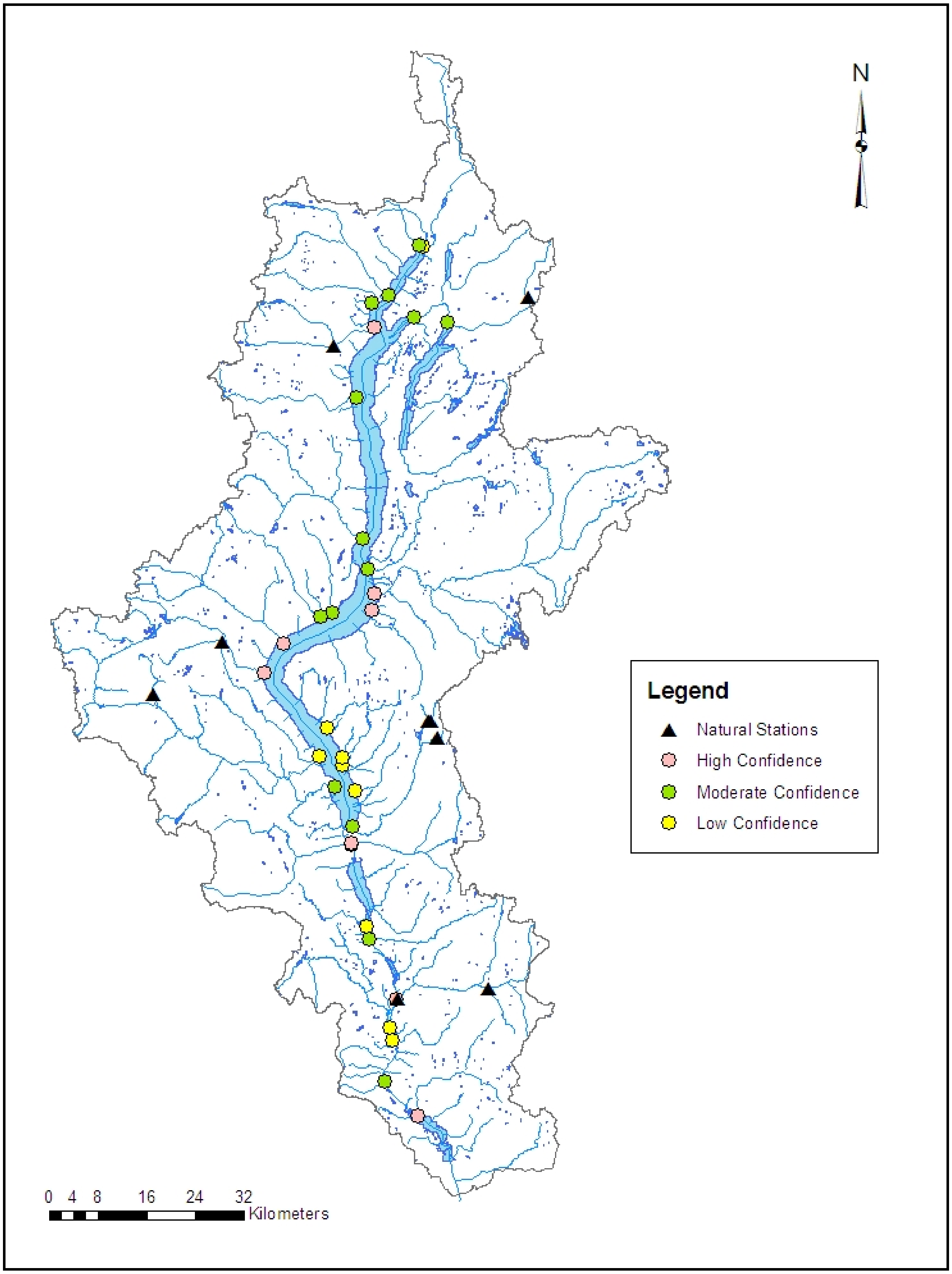


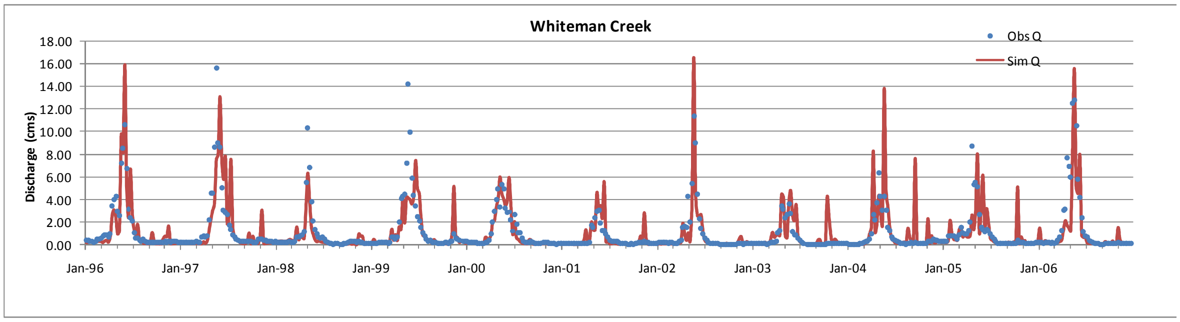
Figure 2-22 Locations of natural and naturalized streamflow stations (residual area nodes are all low confidence locations and are not shown)

As discussed in detail above, the focus of the streamflow calibration was on the natural and high confidence level streamflow stations. In April 2009, the calibration results were first presented to the Project Working Group, and overall results were good in terms of total volume, volume of high flow period and low flow period, timing and calibration statistics. However, it was noted that the model was occasionally predicting late summer and early fall runoff events that were either much smaller or in some cases non-existent in the natural and naturalized data. In most cases, these events occurred when the model simulates significant accumulation and then subsequent rapid melting of snow. In a few cases, the events were not associated with snow melt and are instead driven by runoff generated from rainfall. After the meeting, a careful study was carried out on gridded temperature data, and it was determined these simulated events may be a result of unrealistically high temperatures in the gridded temperature dataset used to drive the snowmelt during these periods. These high temperatures result in melting rates that are too high which in turn results in an over-prediction of runoff. For the cases where the events were not related to snowmelt, the temperature data may still have been unrealistically high and resulted in the model simulating rainfall and subsequent runoff when, in fact, the precipitation should have been accumulating as snow.

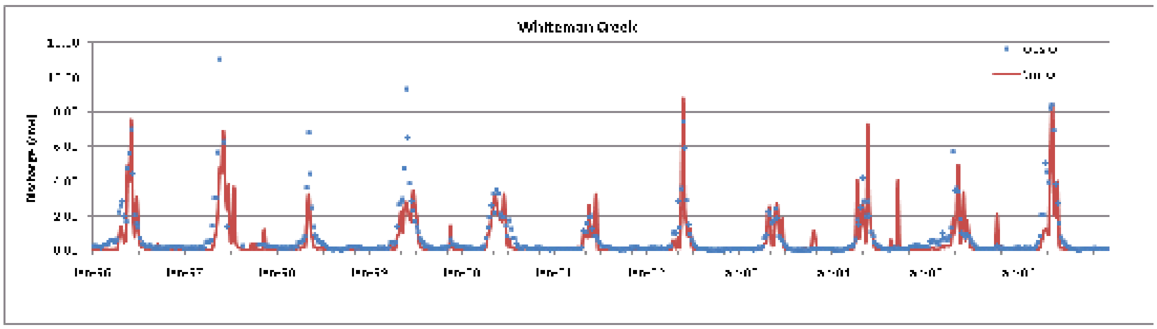
It was suggested that many of the time periods experiencing the peak flows correspond to time periods when a temperature inversion was present in the basin. In order to account for this, a more accurate adjustment to the temperature data may be achieved by experimenting with the inclusion of a lapse rate in the temperature interpolations during inversion periods.

A couple of preliminary tests were made to evaluate the influence of adjusting the temperature data to determine if the adjustments would help to eliminate the anomalous peak flows. The results from the test suggested that a temperature adjustment on the order of 3-degrees would significantly improve the hydrograph calibration during the late summer and fall especially when paired with an adjustment to the minimum snow storage value. The results also suggested that the adjustment should not be made throughout the year but should instead be isolated to the time periods where the model calibration suggested deficiencies.

Based on the results from the tests, a revised temperature dataset was generated to improve the high elevation values and resolve the subsequent minimum/maximum temperature reversals. With the revised temperature plus adjusted minimum snow storage and sinusoidal time varying DDC, the late summer and early fall high runoff issue was improved significantly.



(a) Initial OBHM streamflow calibration



(b) Final OBHM streamflow calibration

Figure 2-23: Comparison of Initial Streamflow Calibration vs. Revised Streamflow Calibration at Whiteman Creek

Natural Stations

The total simulated streamflow volume over the 11-yr simulation period agrees very closely with the measured data at the 8 natural stations, and the simulated volume is 2% higher than the observed or measured volume (Table 2-13). The vast majority of the streamflow volume occurs between April and August during the snowmelt period (high flow period). During the remainder of the year, the primary mechanism for streamflow generation is discharge from groundwater (low flow period). The model closely matches the total high flow volume at the natural stations and the simulated volume is only 2% lower than the observed volume (Table 2-13). The timing of the snowmelt signal is generally well-captured in the model with the exception of a few stations where the simulated runoff is delayed by up to two weeks relative to the observed data. The magnitude of the snow melt runoff signal is well-captured at some stations such as Vaseux Creek, is over-predicted at others such as Coldstream Creek, and under-predicted at others such as Two Forty Creek (Appendix B).

During the low flow period, the model over-predicts streamflow at the natural stations by 27% relative to the observed data (Table 2-13). During the majority of the low flow period, the simulated streamflow matches the observed records quite closely suggesting that the model produces a good representation of baseflow processes (Appendix B). The majority of the over-predicted volume during the low-flow period is caused by the anomalous, late autumn runoff events predicted by the model which are not observed in the monitoring data. Most of these events occur in the autumn and likely represent deficiencies in the model-representation of temperature conditions in the basin. Specifically the model is simulating precipitation occurring as rainfall and subsequent runoff during these periods when in actuality more of this precipitation occurred as snow and did not generate as much runoff.

Table 2-13: Comparison of total simulated streamflow volume with the total volume indicated in the natural and naturalized data (high flow period is from April – August and low flow period is the remainder of the year)

		Natural Stations		High Confidence Stations		All Stations	
		Total Volume (m^3)	Error (%)	Total Volume (m^3)	Error (%)	Total Volume (m^3)	Error (%)
Total	simulated	8.21E+08	2%	4.22E+09	-10%	1.29E+10	18%
	observed	8.07E+08		4.69E+09		1.10E+10	
High Flow Period	simulated	6.89E+08	-2%	3.38E+09	-13%	9.29E+09	4%
	observed	7.03E+08		3.87E+09		8.93E+09	
Low Flow Period	simulated	1.32E+08	27%	8.37E+08	2%	3.61E+09	78%
	observed	1.04E+08		8.22E+08		2.03E+09	

The calibration statistics for the Natural Stations are provided in (Table 2-14). Mean errors (ME) range from -0.18 to 0.10 m^3/s, with an average ME of <0.01 m^3/s. The low mean ME indicates that overall the over- and under-predictions tend to balance.

The root mean square error (RMSE) is used as a measure of the precision of the fit between the model data and the measured data, where lower values indicate a good fit. The RMSE results range from <0.01 to 0.05 m^3/s with an average RMSE of 0.02 m^3/s.

The correlation coefficient (R) is a measure of the overall correlation between the model data and the measured data, where a value of 1.0 indicates a perfect fit. The R values for the Natural hydrographs range from 0.58 to 0.82 with a mean of 0.69.

The Nash-Sutcliffe coefficient (N) provides a measure of the goodness of fit between the shape of the model hydrograph and the observed hydrograph. A value of 1.0 indicates a perfect fit, a value of 0.0 indicates the model predictions are as accurate as the mean of the measured data, and a negative value indicates the observed mean is a better predictor than the model. The N values are above 0.5 for 6 of the 8 Natural Hydrograph locations, with an overall range from -1.01 to 0.79 and an average value of 0.42.

Overall, the model provides a reasonably good fit to the Natural Hydrographs, and it provides a very good fit for Vaseaux Creek and Whiteman Creek which account for more than 70% of the flow at the Natural Hydrograph locations.

Table 2-14 Calibration statistics for natural streamflow stations

Station Name	Mean Error (m^3/s)	Mean Absolute Error (m^3/s)	Root Mean Square Error (m^3/s)	Correl. Coef. R	Nash Sutcliff Coef. N_r	Mean (Obs) (m^3/s)
Camp Creek	0.08	0.10	0.01	0.82	0.79	0.15
ColdStream Creek	0.10	0.18	0.02	0.70	0.67	0.27
Vaseux Creek (Solco)	0.01	0.60	0.05	0.76	0.78	0.98
Greata Creek	0.08	0.11	0.01	0.65	-1.01	0.09
Whiteman Creek	-0.18	0.43	0.04	0.75	0.78	0.70
Two Forty Creek	-0.02	0.04	0.00	0.64	0.54	0.07
Two Forty One Creek	-0.02	0.04	0.00	0.60	0.57	0.06
Dennis Creek	0.00	0.05	0.00	0.58	0.25	0.06
Average	**0.00**	**0.19**	**0.02**	**0.69**	**0.42**	**0.30**

High Confidence Level Naturalized Stations

At the high confidence naturalized stations, the total simulated streamflow volume over the 11-yr simulation period matches the naturalized data reasonably well and represents an under-prediction of 10% (Table 2-13). The majority of this difference can be attributed to the high flow period where the model under-predicts the total high flow volume at the high confidence naturalized stations by 13% (Table 2-13). The timing of the snowmelt signal relative to the naturalized data is similar to what is found for the natural stations (generally well-predicted with a tendency to occur earlier in the model at a few locations). The magnitude of the snow melt runoff signal is very well-captured at the largest tributary locations in this group of stations (Mission Creek), but significantly under-predicted at other stations such as Trepanier Creek (Appendix B).

During the low flow period, the simulated streamflow agrees very well with the naturalized data (2% higher in the model) (Table 2-13). The same phenomenon of simulated runoff events in the autumn that do not appear in the naturalized data occurs here as well although to a lesser degree than was seen for the natural stations. At some locations, such as Vaseux Creek, this phenomenon occurs in some years (particularly 2002-2004) but not in other years (1996 – 2000).

The calibration statistics for the High Confidence Level Naturalized Stations are summarized in Table 2-15. The ME ranges from -2.39 to 0.43 m^3/s, with an average ME of -0.17 m^3/s. The low mean ME indicates that overall the over- and under-predictions tend to balance reasonably well with a slight tendency to under-predict relative to the naturalized estimates. The RMSE ranges from 0.03 to 0.27 m^3/s with a mean of 0.08 m^3/s, and correlation coefficients (R) range from 0.60 to 0.86 with a mean of 0.74 (Table 2-15). The N values are all positive and they range from 0.32 to 0.74 with an average N value of 0.57.

A good indication of the overall quality of the calibration can be taken from Mission Creek (see Figure 2-24), which is one of the largest tributaries in the basin. It demonstrates a very good fit (R = 0.86 and N = 0.57) between the simulated hydrograph and the naturalized observed hydrograph with respect to both baseflow and the timing and magnitude of the spring snowmelt signal. Although the ME, MAE, and RMSE are relatively high compared to the other stations, the flows in Mission Creek are also much higher than at the other locations.

Table 2-15 Calibration statistics for high confidence naturalized streamflow stations

Station Name	Mean Error (m^3/s)	Mean Absolute Error (m^3/s)	Root Mean Square Error (m^3/s)	Correl. Coef. R	Nash Sutcliff Coef. N_r	Mean (Obs) (m^3/s)
Whiteman Creek-N14	0.02	0.64	0.06	0.76	0.74	1.08
Mission Creek (mouth)-N22	-2.39	3.51	0.27	0.86	0.57	7.82
Bellevue Creek-N24	0.10	0.25	0.03	0.80	0.57	0.34
Trepanier Creek-N30	-0.19	0.87	0.07	0.71	0.44	1.22
Peachland Creek-N32	0.11	0.39	0.04	0.60	0.32	0.44
Shingle Creek-N51	0.39	0.65	0.04	0.68	0.53	0.65
Vaseux Creek-N66	0.43	1.12	0.11	0.76	0.62	1.53
Inkaneep Creek-N78	0.16	0.37	0.03	0.72	0.80	0.48
Mean	**-0.17**	**0.98**	**0.08**	**0.74**	**0.57**	**1.70**

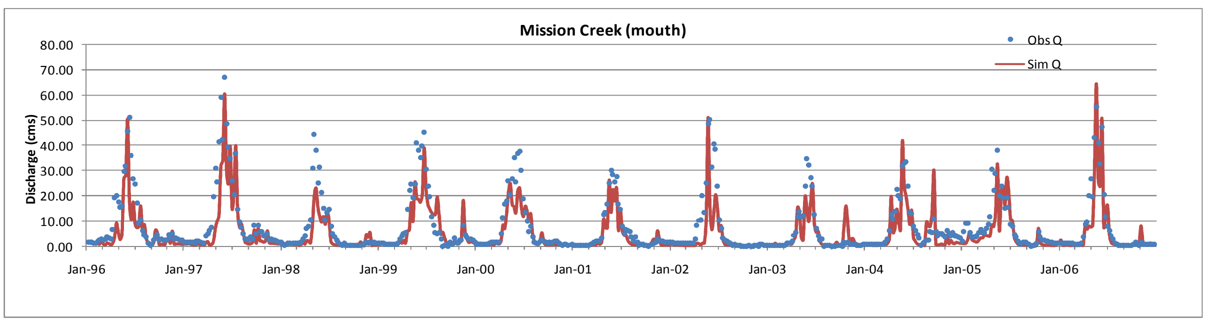


Figure 2-24: Mission Creek Hydrograph Calibration Plot

<u>Moderate and Low Confidence Level Naturalized Stations</u>

When the moderate confidence level and low confidence level stations are included, the model simulates an 18% higher total flow volume then is indicated by the natural and naturalized data (Table 2-13). During the high flow period, the volume difference is relatively small (4% higher in the model) and the majority of the difference is due to differences in the low flow period where the model simulates 78% more volume. A large percentage of this difference can be attributed to the two Vernon Creek stations where the model predicts significantly more flow than the naturalized estimates, particularly during the low flow period and during the period from 2001-2004 where the measured flow rarely exceeded the minimum flows (see Calibration Plots in Appendix Appendix B). When these two stations are excluded, the 18% higher model-simulated total flow volume drops to 8% and the 78% higher low flow period volume drops to 52%. Comparison statistics for the moderate confidence level stations are shown in Table 2-16 for reference. Flow at the two Vernon Creek stations is strongly influenced by the operations of the structures that control the outflow from Kalamalka Lake. Thus the large differences likely reflect differences in the operational strategy used in the model and the strategy assumed during the generation of the naturalized hydrographs rather than differences in the simulated or estimated hydrology.

Table 2-16 Calibration statistics for moderate confidence naturalized streamflow stations

Station Name	**Mean Error (m^3/s)**	**Mean Absolute Error (m^3/s)**	**Root Mean Square Error (m^3/s)**	**Correl. Coef. R**	**Nash Sutcliff Coef. N_r**	**Mean (Obs) (m^3/s)**
Vernon Creek at Kalamalka outlet -N1	1.68	1.88	0.10	0.67	0.45	1.32
Irish Creek-N5	0.08	0.10	0.01	0.67	0.45	0.05
Equesis Creek-N8	0.20	0.55	0.06	0.72	0.51	0.74
Nashwito Creek-N10	0.16	0.31	0.03	0.69	0.47	0.34
Vernon Creek at mouth-N12	1.64	1.93	0.11	0.64	0.41	2.03
Shorts Creek-N16	-0.28	0.77	0.07	0.76	0.58	1.32
Lambly Creek-N18	-0.09	0.80	0.07	0.81	0.65	1.43
Mill Creek-N20	-0.21	0.56	0.04	0.55	0.31	0.84
MacDougall Creek-N26	0.08	0.13	0.01	0.63	0.40	0.09
Powers Creek-N28	-0.14	0.45	0.04	0.81	0.65	0.82
Trout Creek-N42	1.10	1.55	0.14	0.79	0.63	2.08
Penticton Creek-N46	0.56	0.70	0.07	0.76	0.57	0.52
Ellis Creek-N52	0.09	0.48	0.05	0.79	0.63	0.75
Shuttleworth Creek-N60	0.04	0.23	0.02	0.78	0.61	0.36
Testalinden Creek-N76	0.09	0.09	0.01	0.62	0.38	0.00
Mean	**0.33**	**0.70**	**0.06**	**0.71**	**0.51**	**0.85**

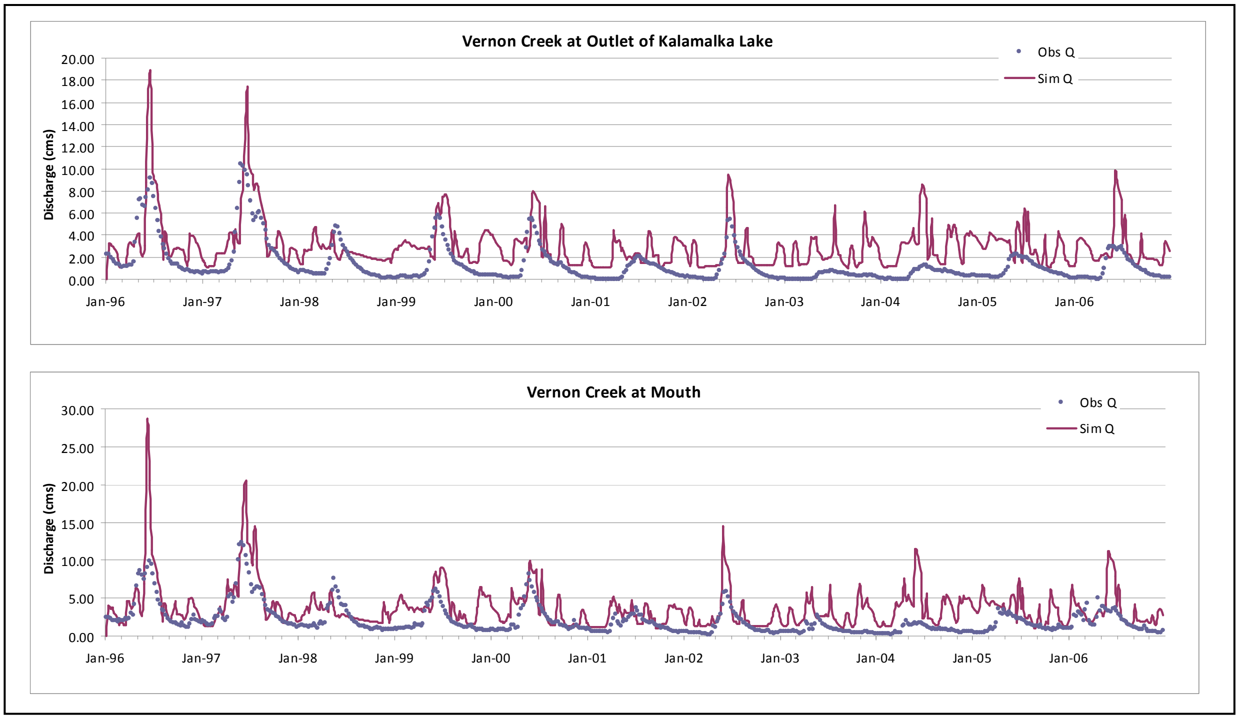


Figure 2-25: Comparison of Simulated vs. Naturalized Observed Discharge at Low Confidence Stations

2.3.6 Historical Lake Inflow Data

The OBHM is designed to simulate naturalized conditions, so no consideration of any human influences on the hydrology are considered for the area of the model above the five major valley-bottom lakes. The only human activities taken into account in the model were the operations of the structures controlling outflow from lakes. The simulated inflows to the lakes are estimates of naturalized lake inflows and not representative of historical inflow conditions during the calibration period except in areas where no human influences existed during the calibration period. Thus, a comparison of the simulated lake levels and Okanagan River discharges with measured data is not meaningful since the measured data is the result of a myriad of other human activities in the watershed in addition to the operation of the lake structures. This reality makes it challenging to evaluate the accuracy of the model's representation of the control structures and consequently lake levels and Okanagan River discharges.

A means for doing so was discovered, however, because estimates of historical net inflows to Okanagan Lake were available from the Fish-Water Management Tool (FWMT) which was derived using a water balance approach in conjunction with measured lake level and lake outflow data. A simplified version of the OBHM was setup to isolate the hydraulics of the Okanagan River and main valley-bottom lakes. The only input to this simplified model was the historical net inflow data to Okanagan Lake as derived from the FWMT. This simplified model was then used to evaluate the model representation of the control structures and operational rules used to regulate flow out of Okanagan Lake. The operational rules were "calibrated" by comparing the simulated and observed lake level and Okanagan River discharge data and modifying the priority of the rules in order to achieve the best match with the observed data.

Historical Lake Inflow Calibration

Figure 2-26 and Figure 2-27 show an example of the calibration achieved using the simplified model. The results showed a very good representation of the lake levels during normal and wet years, but it would under-predict the lake levels during dry years. Similarly, the pattern for the discharge from Okanagan at Penticton showed a generally good agreement with the trends and magnitude of the discharge, but the operation of the structures was much more frequent and the changes in flow were not as gradual as with the observed data. The operational rules for Okanagan Lake and the remaining mainstem lakes were improved during the development and calibration of the Okanagan Basin Water Accounting Model.

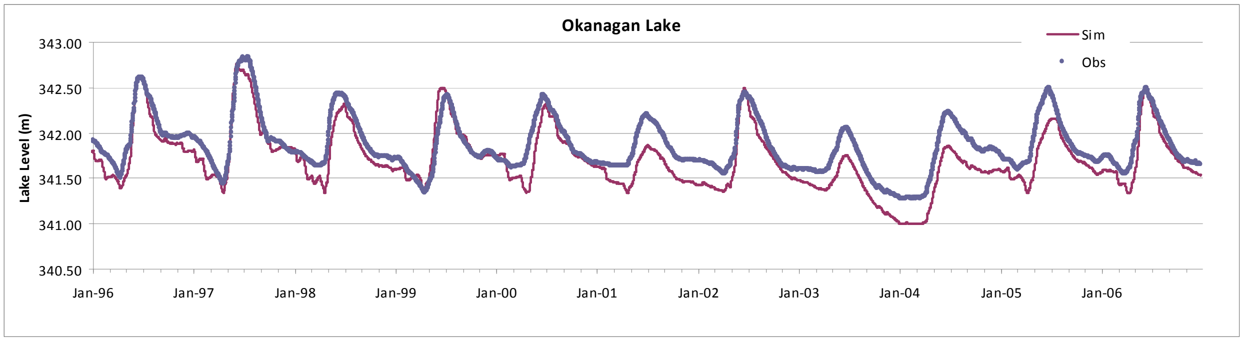


Figure 2-26: Simulated vs. Observed Lake Levels at Okanagan Lake (screening model)

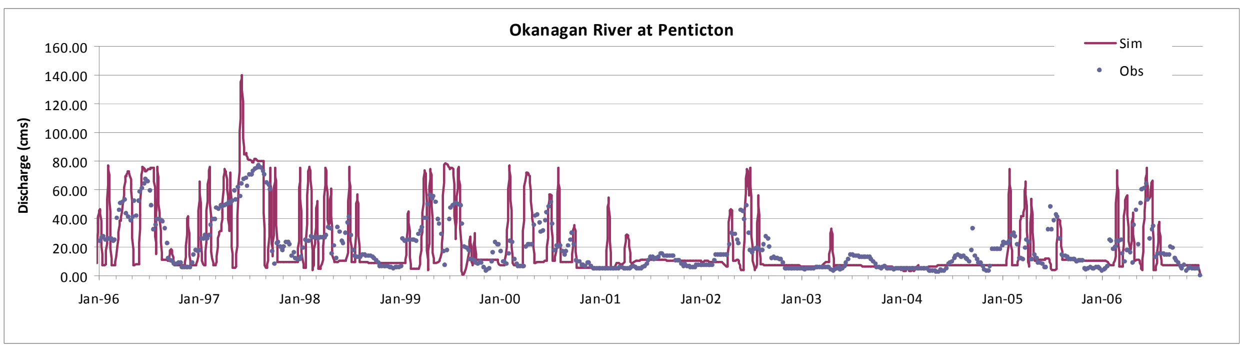


Figure 2-27: Simulated vs. Observed Discharge at Penticton (screening model)

2.3.7 Lake Evaporation Data

In theory, the simulated evaporation from the lakes in the OBWM should match the potential evapotranspiration (PET) because it is a moisture unlimited condition (e.g. on open water bodies like lakes). However, it was discovered that the lake evaporation values modeled by the OBHM under-predicted Potential ET (PET) data that was included in the climate data (as generated from the Okanagan Climate Data Interpolator). The reason for the discrepancy was that some of the model grid cells representing the lakes were drying out during portions of the year, causing ponded water depths of zero. This resulted in simulated lake evaporation values that were noticeably below the input PET values.

This phenomenon was occurring because of deficiencies in the model's representation of the lake bathymetry within the overland flow component of the model. The lake bathymetry is accurately represented in the 1D MIKE 11 surface water component of the model using cross-section data, thus the problem did not have any direct influence on the simulation of lake levels or on any other components of the model and only influenced the simulated lake evaporation. The bathymetric cross-sections of the lake from the surface water component of the model were used to modify the model topography in order to properly capture the lake bathymetry in the overland flow component of the model. These modifications eliminated the majority of the problem of lake cells drying out and resulted in simulated lake evaporation values that are within a few percent of the input PET values. Although some discrepancies are unavoidable due to the large grid cell size, the PET and OBWAM simulated ET were within 2% of each other for all lakes (see Table 2-17 for a summary of the simulated evaporation from each lake).

In addition, daily lake evaporation estimates from the lake evaporation study (Schertzer and Taylor, 2008) were compiled and used to compare with the model simulated lake evaporation for each lake. Table 2-17 provides a comparison between the model simulated lake evaporation for the five mainstem lakes and estimates of lake evaporation from the evaporation study (Schertzer and Taylor, 2008).

It is important to note that the MIKE SHE model does not include a rigorous method for computing evaporation from surface water bodies - given the absence of vegetation and the continuous availability of moisture in the lake areas of the model, the simulated evaporation from the lakes simply occurs at the PET rates provided with the gridded climate data (see Section 2.2.4). On account of the simplified handling of lake evaporation in the model and the uncertainty that exists in the evaporation study estimates, no attempt was made to try and achieve a good match between the model simulated and lake evaporation study estimates of lake evaporation. As such this comparison effectively demonstrates the large variability in potential results that can be obtained using different methods, and it serves to emphasise the importance of gaining a better understanding of the lake evaporation process in order to gain a better understanding of the water budget.

Table 2-17 Comparison of Lake Evaporation Estimates

Lake	MIKE SHE Model Mean Annual Evaporation (mm)	Evaporation Study Mean Annual Evaporation (mm)
Okanagan Lake	918	475
Kalamalka Lake	905	271
Skaha Lake	963	450
Vaseux Lake	1008	363
Osoyoos Lake	1063	369

2.4 UNCERTAINTY ANALYSIS

Due to the time and budget constraints of the project it was not possible to conduct a thorough sensitivity and uncertainty analysis on the calibrated model. However, the deliverables of the project required an assessment of a Data Error Code for the weekly values uploaded to the OKWater Database. The available Data Error Codes are indicated in Table 2-18.

Table 2-18: Data Error Codes

Approximate value of the standard error about the parameter	Model Data Error Code
<= 10%	1
>10% - 25%	2
>25% - 50%	3
>50% - 100%	4
>100%	5

For practical purposes, the assessment of Model Data Error Codes was determined for each node and this value was then assigned to each weekly value reported at this node. The Model Data Error Codes were determined by considering both the quality of the model calibration at each node, and the Error Code of the naturalized data at each node (Summit and Polar, 2009). The methodology used to assess the node Error Code was as follows:

- If the Naturalized Data Error Code = 1 the naturalized data was assumed to be accurate and the Model Data Error Code was determined according to the calibration error at the node.
- If the Naturalized Data Error Code = 4 or 5 then there was no basis to evaluate the model results any differently.
- If the Naturalized Data Error Code = 2 or 3 but the model calibration error is high, then it was assumed the naturalized data is more accurate than the model data, so the Model Data Error Code was assumed to be larger than the Naturalized Data Error Code.
- If the Naturalized Data Error Code = 2 or 3 and the model calibration error is low to moderate, then it was assumed the Model Data Error Code = Naturalized Data Error Code.
- If the model calibration error was small it was assumed that since there is a good agreement between two different approaches, the Model Data Error Code could be estimated as equal or less than the Naturalized Data Error Code.

Table 2-19 below provides a matrix showing the Model Data Error Code value as it relates to the Calibration Error at each node and the Naturalized Data Error Code at each node

Table 2-19: Model Data Error Estimates as a Function of Calculated Model Calibration Error and Naturalized Data Error Estimates

		Calculated Model Calibration Error				
		<10%	**10-25%**	**25-50%**	**50-100%**	**>100%**
Naturalized Data Error	**<10%**	<10%	10-25%	25-50%	50-100%	>100%
	10-25%	<10%	10-25%	25-50%	50-100%	>100%
	25-50%	<10%	10-25%	25-50%	50-100%	50-100%
	50-100%	10-25%	25-50%	50-100%	50-100%	50-100%
	>100%	25-50%	50-100%	>100%	>100%	>100%
	Naturalized Data Error was assumed correct so Model Data Error was set equal to Model Calibration Error					
	Naturalized Data Error and Model Calibration Error were both low to moderate, so Model Data Error set equal to Naturalized Data Error					
	Naturalized Data Error was reduced due to good agreement with modeling results					
	Naturalized Data Error was large so there was no basis for an alternative assessment of Model Data Error					
	Naturalized Data Error is moderate but model calibration error was high so the Model Data Error Code was set larger than the Naturalized Error Code					

The above methodology was used to populate the Error Codes for the Modelled Naturalized Inflow term in the OKWater Database (Q_S + Q_F + D_SN). A summary of the Model Data Error Codes are provided in Table 2-20.

Table 2-20: Summary of Model Data Error Codes for Naturalized Inflow at Each Node

Node	Error Code		Node	Error Code		Node	Error Code
1	4		28	3		55	4
2	5		29	4		56	4
3	2		30	2		57	4
4	4		31	4		58	5
5	4		32	1		59	3
6	4		33	4		60	1
7	4		34	1		61	3
8	2		35	4		62	4
9	4		36	4		63	4
10	3		37	4		64	5
11	4		38	2		65	4
12	3		39	4		66	3
13	4		40	3		67	4
14	1		41	4		68	4
15	4		42	3		69	4
16	2		43	4		70	4
17	4		44	4		71	4
18	2		45	3		72	4
19	4		46	5		73	3
20	4		47	5		74	4
21	4		48	4		75	3
22	3		49	4		73	4
23	4		50	4		77	4
24	3		51	3		78	3
25	2		52	2		79	4
26	4		53	4		80	5
27	4		54	2		81	3

2.5 SUMMARY

An integrated hydrologic model of the Okanagan Basin was constructed and used to simulate naturalized conditions in the basin from 1996 through 2006. The model simulated all of the land-based phases of the hydrologic cycle including evapotranspiration, overland flow, unsaturated flow, groundwater flow, and channel flow. The model was calibrated against eight natural hydrographs, eight high confidence level naturalized hydrographs developed in a parallel study, and snow water equivalent data at 21 locations throughout the basin. Additionally, the model output was compared against moderate and low confidence level naturalized hydrographs, estimates of lake evaporation from a parallel lake evaporation study, and previous estimates of various components of the overall water budget. A simplified version of the model was created in order to evaluate and improve the model representation of operational strategies for the structures that control outflow from the five major valley-bottom lakes.

In general, the pattern and timing of snow accumulation and melt agrees well with the observed snow water equivalent data, but the model has a tendency to over-predict snow accumulations at lower elevations and under-predict snow accumulations at higher elevations. The overall simulated total flow volume agrees well with the natural and high confidence level naturalized hydrographs as does the flow volume simulated during the spring snowmelt period. The model over-predicts flow volumes during the low-flow period, but the majority of this over-prediction can be attributed to runoff events simulated in the model during the autumn months that are either much smaller or in some cases non-existent in the natural and naturalized data. Otherwise, during the majority of the low flow periods, the simulated baseflow generally agrees well with the comparison data.

Simulations conducted with the simplified model constructed to evaluate the lake operations suggested that the operational strategies used in the model to control outflow from Okanagan Lake were able to reproduce historical lake levels in Okanagan Lake and discharges in the Okanagan River reasonably well. No means for evaluating the operational rules used in the model for the other lakes was available for modeling the naturalized conditions, so there was still significant uncertainty regarding lake operations for the other mainstem lakes. This uncertainty likely has some impact on the naturalized hydrographs at two stations along Vernon Creek where steamflows are likely impacted by upstream human operations of the dam on Kalamalka Lake.

For the purposes of this study it was decided that the PET values derived from the gridded climate data provided an acceptable representation of expected ET from the mainstem lakes. If a more reliable means of estimating historical and future lake ET is developed, the new data can easily be incorporated into the gridded climate data set.

While the model appears to be able to accurately reproduce observed snow water equivalent data and it provides a reasonably good representation of natural and naturalized hydrographs, some of the deficiencies in the model calibration point to potential inaccuracies in the temperature data used to drive the snow component of the model. In particular, the over-predicted runoff events in the autumn months suggests the temperature data may be biased towards higher temperatures during these periods, and the errors in the calibration suggest that the temperature data may over-predict temperatures at higher elevations, or under-represent the temperature gradients that occur in the basin between high- and low-elevation locations. These deficiencies, if they exist, may be attributed to the lack of representative temperature stations at elevations above 1000m for the majority of the calibration period. Of the 29 available climate stations, there was only one year (2000) when more than 2 temperature stations were available above an elevation of 1000m.

3 OKANAGAN BASIN WATER ACCOUNTING MODEL

3.1 OVERVIEW OF THE WATER ACCOUNTING MODEL

The purpose of developing and calibrating the Okanagan Water Accounting Model (OBWAM) is to gain a better understanding of the existing hydrology of the Okanagan Basin including human influences, as well as evaluate the changes in the hydrology due to climate change, population growth, water use efficiency, agricultural land base expansion, and mountain pine beetle.

The process of developing the OBWAM involved taking the calibrated OBHM and introducing the impacts of human influences at each node location. The model was then verified against the available monitoring data and subsequent improvements were made to the model to achieve a calibration to the observed lake levels and discharges along the Okanagan River and the mainstem lakes. This involved the following additional calibration efforts;

- Adjusting the gridded topography to match the channel bathymetry around the mainstem lakes,
- Adjusting the temperature in the Gridded Climate Data and modifying the snowmelt parameters to reduce the anamolous spring and fall streamflow peaks, and
- Refining the strategy by which main valley lakes are regulated within the model by gathering more data about their operational strategies and historical operations, reducing the frequency of gate operations, and implementing an inflow volume forecasting option.

The following sections describe the process of integrating human influence water balance terms to the OBHM and the subsequent re-calibration of the model.

3.2 WATER ACCOUNTING MODEL CONSTRUCTION

3.2.1 Incorporating Net Water Use Data

The human influences (hereinafter referred to as the Net Water Use) at each water balance node are described by the water balance terms defined in the document entitled "Water Balance Model – Background Information: Okanagan Phase 2 Water Supply and Demand Project (Version 8)" (OBWB, 2009). The water balance terms used in the model to calculate the human influence at the water balance nodes for the OBWAM are defined as:

- Q_R: Upstream reservoir component of streamflow at node i during time t (positive during reservoir release, negative during reservoir filling)
- RF_S: Surface component of return flow to node i during time t due to human activity (e.g. municipal wastewater discharges)
- RF_G: Return flow due to human activity to node i during time t via groundwater.
- Q_T: Rate of water transfer into streams in node i from streams outside node i
- E_S: Volume extracted from surface sources within node i during time t (end-uses are agriculture, golf courses, parks and open space, domestic indoor, domestic outdoor, institutional, commercial, industrial, and losses).

- E_G: Volume extracted from groundwater sources that would otherwise have discharged to the stream network in node i during time t. This is a component of total groundwater pumping during time interval t from node i (i.e. (SDPj)i,t)

As described in the Water Balance Model document (OBWB, 2009) the formula to calculate the Net Water Use (Q_net) at each node (i) at each weekly time step (t) is dependent on the type/location of the node:

For Tributary and Residual Area nodes the formula is:

$$Q\_net_{,} = (Q\_R + Q\_T)\,\Delta t + RF\_S + RF\_G - E\_S - E\_G$$

For Mainstem Lake Nodes the formula is:

$$Q\_net = RF\_G + RF\_S + Q\_T\,\Delta t - E\_S$$

For Mainstem River Nodes the formula is:

$$Q\_net = RF\_G + RF\_S + Q\_T\,\Delta t - E\_S$$

All of these terms were available from the OK Water Database as weekly values for the duration of the model calibration period from 1996-2006. A weekly time series of the net Water Use Term was extracted from the OK Water Database for each node and was incorporated as an inflow time-series boundary condition on the MIKE 11 river model at the branch location immediately upstream of the model node corresponding to the associated water balance node location.

Note on Groundwater Pumping

The MIKE SHE linear reservoir groundwater model is a lumped, conceptual representation of groundwater in the system – it essentially acts as a volumetric accounting of water as it moves from one hydrologic phase to another. The main purpose of the model is to provide a mechanism to account for groundwater exchanges with surface water bodies. Although it is possible to account for groundwater extraction from the MIKE SHE groundwater baseflow reservoirs, the groundwater pumping term D_P was not directly implemented in the OBWAM model because MIKE SHE can only remove the pumped water from the system - it cannot apply the extracted water as irrigation on the land surface and make it available for infiltration and evapotranspiration.

Rather than explicitly accounting for groundwater extraction from the aquifers, the model handles the impacts of groundwater pumping implicitly via the calibration of the baseflow contributions to the tributaries. However, in future phases of this project a thorough review of the implementation of groundwater processes is recommended to see if it is possible to find a more integrated approach that will allow the groundwater extraction to be explicitly represented while also accounting for the application of that water for irrigation.

3.2.2 Structure Operations

As indicated previously, the calibration of the OBHM did not include a rigorous calibration against the water levels of the major valley-bottom lakes or the discharge in the Okanagan River because the historical inflows, water levels and river discharge are highly influenced by human decisions. Once the Net Water Use terms were included in the OBWAM an intensive structure operations calibration phase was initiated for modeling the mainstem lake levels and the river discharge using the full integrated model. Since the OBHM provided the calibrated hydrology of the basin, the primary method to calibrate the lake levels and discharges along the mainstem lakes was to adjust the operational rules of the structures at the outlet of each lake.

The calibration of the water levels for Okanagan Lake, and to a lesser degree the other major valley-bottom lakes, proved to be the single biggest challenge in finalizing the OBWAM. Although the initial calibration provided by the OBHM provided an acceptable representation of Okanagan Lake water levels during wet and normal years, it under-predicted the water levels during dry years by up to 0.75 m. A closer inspection of the operational logic used to control the structures in the model revealed that the gates were frequently being adjusted in the spring to achieve target Okanagan Lake water levels associated with a normal snow accumulation. As a result the model was letting too much water out of Okanagan Lake early in the year and the lake levels were unable to recover through the summer months because there was insufficient snowmelt in late spring.

In reality, the Penticton Dam is operated differently in years where there is a greater than average snowpack versus years when there is a lower than average snowpack. In general terms, if the snow stations in the basin above Penticton show higher than normal accumulations of snow, the target lake levels in the spring are set lower than normal to accommodate an expected large volume of inflow generated by the snowmelt. If there is less than normal accumulations of snow then the target lake levels in the spring are set higher than normal to preserve water in Okanagan Lake for meeting downstream flow requirements and desired lake levels throughout the summer. The target lake levels are determined using inflow volume forecasts provided by BC Ministry of Environment on February 1, March 1 and April 1, and are used to determine the target lake level at the end of each month.

Unfortunately, the model was unable to adjust the rules during dry years because it has no way of getting real-time feedback of the modeled SWE results. Although the OBWAM could be calibrated by adjusting the operational targets using the historic records of inflow volume forecasts for the calibration period, this would not be useful for the future scenarios when forecasted inflow volumes are not available. In order to use this model for the future scenarios, we needed to find a way to generate future snow cover and then use that future snow cover to generate the inflow volume forecasts on February 1, March 1 and April 1.

It was determined that this could be accomplished by running the hydrologic part of the OBHM to generate the snow water equivalent data for the simulation period, and then using that data to generate the inflow volumes forecast time series. Although the actual inflow volume forecast model has a wide selection of equations to choose from depending on the conditions and availability of data, we needed to define a relatively simple and consistent relationship between the modeled snow water equivalent data and the actual inflow volume forecast. After testing and evaluating several different approaches we settled on a separate linear regression for each month of the historical inflow volume forecast vs. the average simulated SWE value in the Basin above Okanagan Lake at Penticton and above an elevation of 1000 m. The regression analysis results are provided in Appendix C.

Additional modifications made to the rules of the operational structures include:

- Introducing a lower update frequency to prevent the gates from operating every time step
- Introducing an absolute Max Flow value of 78 m^3/s at Penticton Dam at the outlet of Okanagan Lake to prevent unrealistic peak discharge values
- Introducing an upstream water level control at the outlet of Kalamalka Lake to try and improve the discharge and water levels at Kalamalka Lake

A summary of the key operation settings for each dam is provided in Appendix E.

3.3 WATER ACCOUNTING MODEL CALIBRATION

3.3.1 Overview of Approach

The goal of the calibration for the OKWAM was to verify the hydrology of the OBHM and to calibrate the operational strategies of the mainstem lakes to achieve a good fit between the simulated and observed mainstem lake levels and discharges along the Okanagan River.

3.3.2 Tributary Streamflow Hydrographs

Once the Net Water Use terms were accounted for in the model, the hydrology of the OBHM was verified against the measured streamflows from regulated tributaries. In the OBHM, the measured data from the regulated tributaries was used to generate naturalized steamflow hydrographs at the downstream water balance nodes. However, since the OBWAM accounts for the impacts of water use and regulated releases from the upland reservoirs, it was possible to utilize the 'real' measured streamflows from the regulated stations to verify the hydrology from the OBHM.

Unfortunately, the streamflow data for the regulated tributaries is sparse at best, with only Mission Creek providing continuous streamflow data for the entire calibration period (1996-2006). A list of the regulated monitoring stations and the period of record is provided in below while a map of the monitoring locations is shown in Figure 3-1.

Table 3-1: Regulated Streamflow Monitoring Stations Used for Calibration of the OBWAM

Regulated Station Name	Station ID	Longitude	Latitude	Period of Record
Vernon Creek at mouth-N12	08NM160	-119.31	50.26	Nov. – May from 1996 -1999
Lambly Creek-N18	08NM165	-119.61	49.99	1/1/1996 – 7/8/1996
Mill Creek-N20	08NM116	-119.41	49.88	1/1/1996 – 7/1/1996
Mission Creek-N22	08NM041	-119.79	49.83	1/1/1996 – 12/31/2006
Shuttleworth Creek-N60	08NM050	-119.62	49.50	3/4/2006 – 12/31/2006
Vaseux Creek-N66	08NM002	-119.58	49.34	3/25/2006 – 12/31/2006
Inkaneep Creek-N78	08NM149	-119.58	49.34	3/4/2006 – 12/31/2006

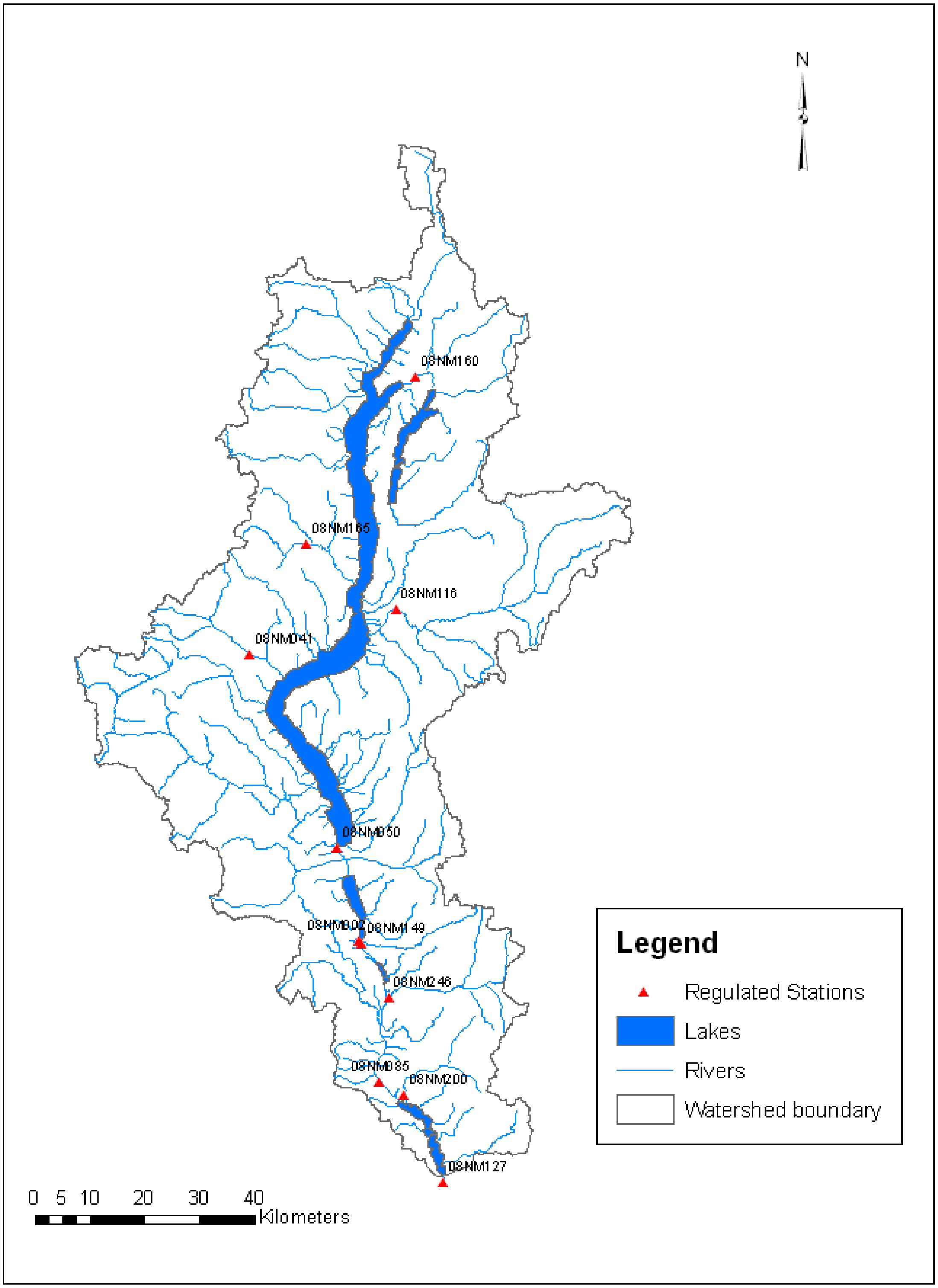


Figure 3-1: Map of Regulated Tributary Stream Monitoring Stations

Table 3-3 presents a summary of the calibration statistics for the regulated stations. The Correlation Coefficient indicated a good to very good fit for all of the regulated tributary stations except Vernon Creek at the mouth of Okanagan. The reason for the discrepancy at Vernon could be attributed to the fact that a significant portion of the flow at this location is controlled by releases from Kalamalka Lake.

Table 3-2: Streamflow Calibration Statistics for Regulated Monitoring Stations Used for Calibration

Streamflow Monitoring Station	Mean Error (m^3/s)	Mean Absolute Error (m^3/s)	Root Mean Square Error (m^3/s)	Standard Deviation (m^3/s)	Correl. Coef. R
Vernon Creek at mouth-N12	-1.8	2.0	0.1	2.5	0.67
Lambly Creek-N18	-1.1	1.2	0.1	2.5	0.84
Mill Creek-N20	-0.4	0.5	0.1	1.0	0.78
Mission Creek-N22	1.8	3.1	0.2	5.3	0.85
Shuttleworth Creek-N60	-0.4	0.4	0.0	0.8	0.82
Vaseux Creek-N66	-1.8	1.8	0.2	3.8	0.74
Inkaneep Creek-N78	-0.6	0.6	0.1	1.1	0.86

Figure 3-2 provides a plot comparing the simulated vs. observed flows at the Mission Creek-N22 station while a complete series of calibration plots for all the Regulated Tributary Stations is included in Appendix B. Since Mission Creek is the most significant tributary in the basin, it is also the most important indicator of how well the OBWAM hydrology is calibrated. As shown in the plot, the simulated response at Mission Creek provides a very good representation of the observed response including both peak flow and low flow conditions.

These results serve to reasonable verify the hydrology from the OBHM.

Table 3-3: Streamflow Calibration Statistics for Regulated Monitoring Stations Used for Calibration

Streamflow Monitoring Station	Mean Error (m^3/s)	Mean Absolute Error (m^3/s)	Root Mean Square Error (m^3/s)	Standard Deviation (m^3/s)	Correl. Coef. R
Vernon Creek at mouth-N12	-1.8	2.0	0.1	2.5	0.67
Lambly Creek-N18	-1.1	1.2	0.1	2.5	0.84
Mill Creek-N20	-0.4	0.5	0.1	1.0	0.78
Mission Creek-N22	1.8	3.1	0.2	5.3	0.85
Shuttleworth Creek-N60	-0.4	0.4	0.0	0.8	0.82
Vaseux Creek-N66	-1.8	1.8	0.2	3.8	0.74
Inkaneep Creek-N78	-0.6	0.6	0.1	1.1	0.86

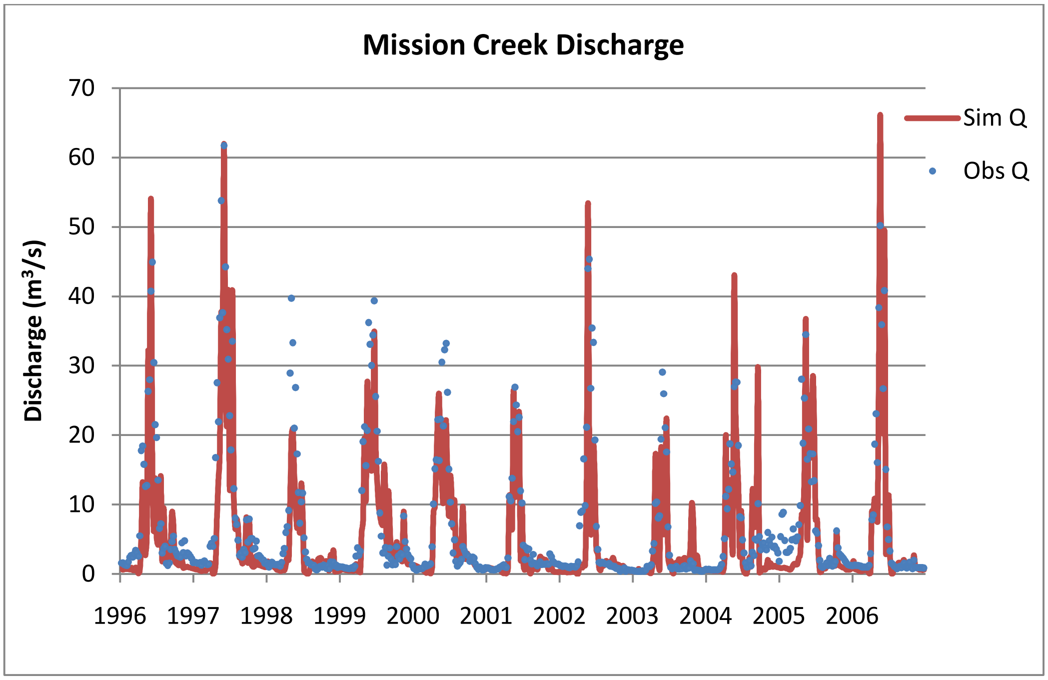


Figure 3-2: Simulated vs. Observed Streamflows at Mission Creek

3.3.3 Lake Levels and Outflows

As discussed previously, the calibration of the model to the mainstem lake levels and discharges proved to be the most difficult aspect of this project. The data quality of the lake levels and discharges is quite good, and the operational rules are well documented, but implementation of the rules is at the discretion of the dam operator. As a result, there are some observed responses of the mainstem lakes which could simply not be reproduced by the model because the response contradicts the way in which the lakes are supposed to be operated.

In addition, there are some limitations with the way the model permits the rules to be described and the way the model tests for the rules during run-time. For example, although the gates appear to be adjusted by a relatively consistent amount each time, they are not adjusted at a regular frequency (e.g. every two days), but rather they are adjusted when the dam operator thinks it is necessary based on current vs. target lake levels (i.e. more frequently in the late winter and spring and less frequently in the summer, fall and early winter). The model, on the other hand, needs to test for the rule criteria at a fixed time interval, and if the rule is not satisfied at this time, the model makes an adjustment in the gate level according to either a fixed adjustment, or a fixed rate of adjustment.

In the case of a fixed adjustment, the magnitude of the adjustment is fixed for each rule for the entire simulation. If the adjustment is too small or too large, the next adjustment will not be made until the rules are tested again.

In the case of a fixed rate of adjustment, the rate of adjustment is fixed for each rule for the entire simulation. If the rate of adjustment is too small the gates will not be able to open or close fast enough. If the rate of adjustment is too large the gate will not be able to reverse the adjustment until the next time the rules are adjusted.

The calibration of the operational rules was largely a trial-and-error exercise in finding the right combination of rule priorities, testing frequency and gate level increment schemes.

Table 3-4 and Table 3-5 provide a summary of the calibration statistics for the lake levels and discharges for each of the mainstem lakes in the OBWAM, while the individual calibration plots for each lake are provided and discussed in the following sections. In general, the results show a good fit between the simulated and observed lake levels, and a reasonable fit for the discharge. The variability in the discharge is a reflection of the limitations of the way in which the operational strategies can be described in the model. As a result, in the model the rules are tested and the gates are adjusted far more frequently than in reality, and this leads to more frequent oscillations of the discharge from the lakes than occurs in reality.

Table 3-4: Lake Level Calibration Statistics for OBWAM

Lake	Mean Error (m)	Mean Absolute Error (m)	Root Mean Square Error (m)	Standard Deviation (m)	Correl. Coef. R
Kalamalka Lake-N2	0.01	0.15	0.01	0.19	0.75
Okanagan Lake-N47	0.07	0.14	0.01	0.16	0.84
Skaha Lake-N58	0.04	0.07	0.00	0.08	0.28
Vaseux Lake-N64	0.02	0.08	0.00	0.10	0.60
Osoyoos Lake-N80	0.02	0.17	0.01	0.23	0.66

Table 3-5: Lake Discharge Calibration Statistics for OBWAM

Streamflow Monitoring Station	Mean Error (m^3/s)	Mean Absolute Error (m^3/s)	Root Mean Square Error (m^3/s)	Standard Deviation (m^3/s)	Nash Sutcliff N_r
Vernon Creek at outlet of Kalamalka Lake-N1	1.68	1.88	0.10	0.67	0.45
Okanagan River at Penticton N48	0.08	0.10	0.01	0.67	0.45
Okanagan River at Falls N59	0.20	0.55	0.06	0.72	0.51
Okanagan River Near Oliver N75	0.16	0.31	0.03	0.69	0.47
Okanagan River at Oroville-N81	1.64	1.93	0.11	0.64	0.41

Since the releases from Okanagan Lake are the main source of flows for the Okanagan River and downstream mainstem lakes, the majority of the lake operations calibration effort was spent on getting a good fit between the simulated and observed water levels and discharge from Okanagan Lake. Figure 3-3 shows a plot of the simulated vs. observed water levels at Okanagan Lake, while Figure 3-4 shows a plot of the simulated vs. observed discharges from Okanagan Lake at Penticton.

Calibration plots for lake levels and discharge from the other mainstem lakes (Kalamalka, Skaha, Vaseux, and Osoyoos) are included in Appendix D.

For Okanagan Lake, the lake level shows a very good fit during normal and wet years, but it tends to under-predict lake levels during dry years. Many attempts were made to correct this behaviour in the model and some success was achieved by adjusting the operational rules and settings, as well as incorporating inflow volume forecasting. However, a closer examination of the observed response vs. the documented operational rules indicated that, during dry years, the operation of the dam diverged from the operational rules. Since the logic used to operate the dams during these times was not specifically documented, it was not possible to incorporate it into the model.

Although the simulated discharge from Okanagan Lake captures many of the major seasonal trends in the discharge, the high frequency of activity with the structures in the model causes short term oscillations in discharge as the model tries to strictly meet the operational rules. We were unable to overcome this limitation in this phase of the study, but this may require more investigation in future phases of the project.

For Kalamalka Lake the OBWAM achieved a generally good fit for the lake levels, with most of the seasonal trends being well represented, but also under-predicting lake levels during dry years. The discharge calibration plot also shows a good fit in the first half of the simulation until the year 2002. From 2002 to 2004 the measured flows indicate no response from the spring snow melt. Unfortunately, there is no indication of what happened during these years to make it respond differently than it did during the first half of the simulation.

For Skaha Lake, the calibration statistics indicate that the OBWAM achieved a generally poor fit for the lake levels and a reasonable fit for the discharge. However, if you consider the relatively narrow range of operating levels for Skaha (between 337.8 and 338 m) and the influence of the high-frequency, large inflow from simulated operations of Okanagan Lake, the model provides a satisfactory representation of seasonal trends, with the exception of the dry years where it consistently under-predicts the levels. This may be something that requires a closer examination in future phases of this project.

For Vaseux Lake, the OBWAM model achieved a reasonable fit for both the lake levels and the discharge. All of the major seasonal trends were well represented by the simulated lake levels with the exception of the dry years in 2001 and 2003 where lake levels are under-predicted. Since Vaseux Lake is downstream of Skaha, most of the effects of the highly-variable discharge from Okanagan are dampened out by the time it reaches Vaseux Lake. The discharge from Vaseux Lake is also relatively well represented by the model with the exception of 2004 where the model significantly over-predicted outflow from Vaseux Lake. We were unable to resolve these issues during this phase of the project.

For Osoyoos Lake, the OBWAM model achieved a very good fit for lake levels from March to November in most years, with the exception of 1998, 2004 and 2005. The operation of Osoyoos Lake is influenced by inflow volume forecasts from the Similkameen River and Okanagan River. If low inflows are expected, a drought condition is declared and the target lake levels are raised during summer.

In 1998 a drought was declared on April 7, 1998 based on the inflow volume forecast for the Similkameen River. Due to high precipitation in late May, the drought declaration was rescinded. In 2004 a similar condition occurred and the drought declaration was later rescinded. This information was acquired in the late stages of the OBWAM calibration so there was not sufficient time to properly investigate the methodology used to calculate the inflow volume forecast or determine a way to incorporate it in the operational rules for Osoyoos Lake.

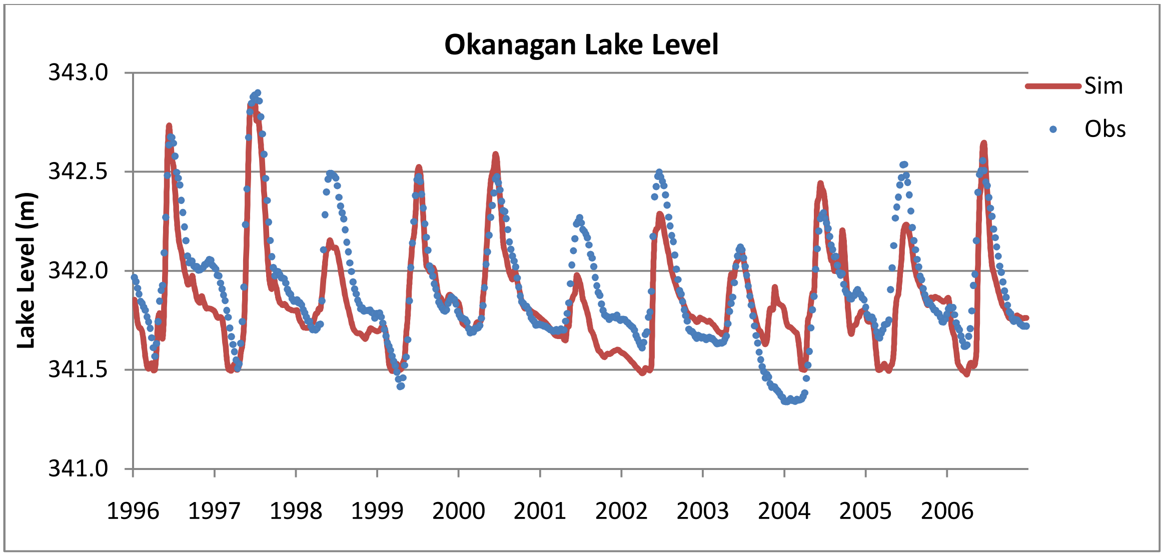


Figure 3-3: Simulated vs. Observed Lake Levels at Okanagan Lake

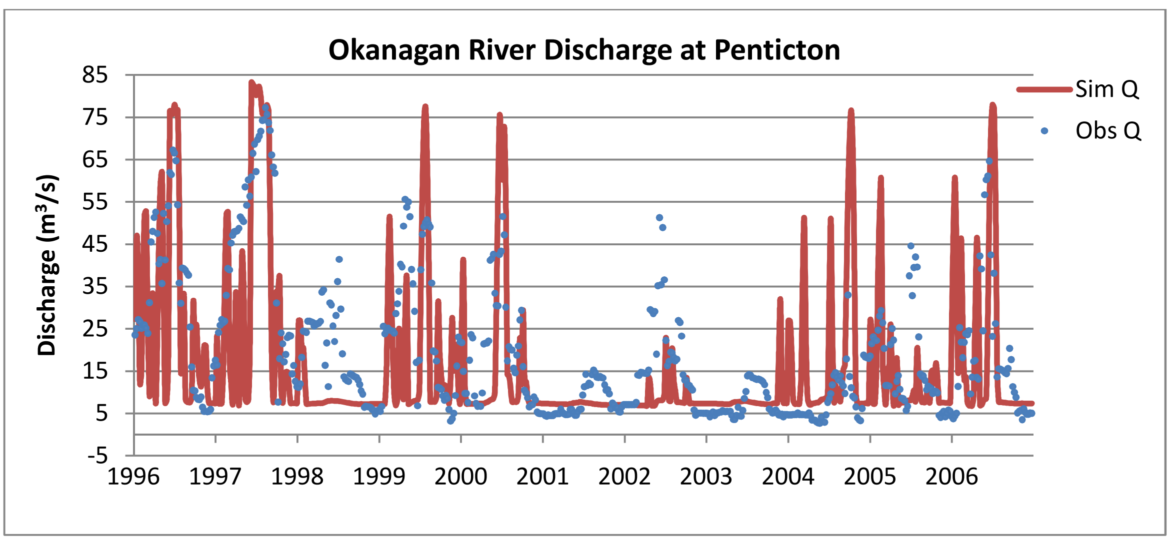


Figure 3-4: Simulated vs. Observed Discharge from Okanagan Lake at Penticton

In general, the calibration process was driven largely by the ability of the OBWAM to accurately represent the basin hydrology (as measured by flows in the main tributaries) and the lake levels for Okanagan Lake. In its currently state, the OBWAM provides a very good representation of both the hydrology and the lake levels at Okanagan Lake, and a good fit for the lake levels for Kalamalka Lake, Skaha Lake, Vaseux Lake, and Osoyoos Lake. The discharge along the mainstem was reasonable well represented, but it was strongly influenced by the frequent gate adjustments as the model attempted to meet the specified operational criteria.

3.4 OKWATER DATABASE UPLOAD

Following approval of the OBHM, the results of the model were processed to extract the data for required water balance terms including:

- **P_L:** Precipitation onto lake during time t (used for the 5 main lake nodes only)
- **E_L:** Evaporation from lake during time t (used for the 5 main lake nodes only)
- **Q_out:** Residual streamflow (after storage and withdrawal effects) from node i during time period t. Also equivalent to net streamflow after anthropogenic influences.
- **Q_in:** Net inflow to mainstem lake (node i) during time t (incoming streamflow from all sources (mainstem river, tributary and miscellaneous surface flow)) plus direct precipitation onto the lake, less evaporation from the lake, plus human additions and subtractions from the lake itself.
- **L_Elev:** Lake elevation (node i) at start of time t, in meters above mean sea level. E.g., first day of day 1 in week t, and last day in week t. (Not an average value).
- **Q_S:** Natural direct runoff component of streamflow at node i during time t. Also called overland flow.
- **Q_F:** Interflow to streams in node i, during time t. (MikeSHE)
- **SigmaD_SN:** Naturally-occurring baseflow component of streamflow at node i during time t (the sum of natural groundwater discharge from one or more groundwater aquifers)
- **Q_S&SigmaD_SN&Q_F:** Natural streamflow at node i during time t

The P_L values were extracted as area average values directly from the gridded climate data for the area occupied by each main lake and processed to weekly values.

The E_L values was extracted as area average values from the gridded evapotranspiration results for the area occupied by each main lake, but as indicated in Section 2.3.7 these values are essentially the same as the PET values from the gridded climate data used as input for the model.

The Q_out values were extracted from Q-point of the MIKE 11 model corresponding to the associated water balance node location and the results were processed to weekly values.

The Q_in values were obtained by summing the baseflow contributions to each calculation point of each MIKE 11 river branch representing each lake, and then processing the time series to weekly values. The weekly Q_in value was then calculated as the sum of weekly baseflow for each lake + weekly Q_out for all tributaries to the lake + weekly P_L values for each lake - weekly E_L for each lake.

The L_Elev values were obtained from the calculated water level results at the H-point in the MIKE 11 branch immediately upstream of the dam at each lake.

The Q_S values were obtained by summing the overland flow contribution to each calculation point of each MIKE 11 river branch of each tributary upstream of each water balance node and processed to weekly values. The resultant time series was then processed to weekly values.

The Q_F values were obtained by summing the interflow flow contribution to each calculation point of each MIKE 11 river branch of each tributary upstream of each water balance node and processed to weekly values. The resultant time series was then processed to weekly values.

The SigmaD_SN values were obtained by summing the baseflow flow contribution to each calculation point of each MIKE 11 river branch of each tributary upstream of each water balance node. The resultant time series was then processed to weekly values.

The Q_S&SigmaD_SN&Q_F values were obtained by summing the Q_S, Q_F, and SigmaD_SN weekly values.

The weekly values for these water balance terms were then assembled in a format compatible with the OKWater Database and were uploaded to the database.

3.5 SUMMARY

The OBWAM developed for this project is a sophisticated, flexible and scalable hydrology model capable of incorporating physical data inputs that represent the spatially and temporally variable hydrologic characteristics of the basin. The model has been successfully calibrated to accurately reproduce a continuous hydrologic response over a wide range of climate conditions from 1996-2006, and it accurately accounts for human influences including mainstem dam operations, upland reservoir operations, water consumption, and irrigation. The OBWAM is able to accurately represent and reproduce the real-time operational logic of the dams on each of the mainstem lakes in the Okanagan Basin in order to achieve a very good representation of lake levels and a reasonable representation of discharge from each dam. In addition, by accounting for water use impacts, and still achieving an effective hydrologic calibration, the OBWAM acts as a surrogate verification of the calibrated OBHM.

As such, this model may be applied as a decision support tool to help evaluate the impacts of potential climate change and water use considerations on the basin wide water supply. The following section describes how the model was modified to account for climate change, water use considerations, and mountain pine beetle infestation, and presents some of the key findings from the scenario results.

4 SCENARIO MODELLING

4.1 OVERVIEW OF THE PHASE 2 SCENARIOS

A limited range of 15 possible future conditions were modeled to demonstrate the utility of the model as a scenario tool. Specifically, we evaluated changes in the hydrology, streamflows, lake levels and water budget due to climate change, population growth, water use efficiency, agricultural land base expansion, and mountain pine beetle through 15 scenarios. For the purposes of this study we chose one of the six available global climate models (CGCM2-A2) and we assumed that the main influences on climate (global emissions of greenhouse gases) were well predicted by the latest International panel on climate change. Although this limits the range of outcomes that can be generated, it still provides an excellent demonstration of the capability of the model to be used for a more extensive evaluation of potential climate change impacts. The scenarios also examined the impact of other factors including:

- two possible rates of population growth (the expected rate and a high rate);
- two possible future agricultural conditions (the current amount of land under cultivation, and a larger cultivated area derived by including all reasonably irrigable land); and
- two possible trends in water use efficiency (current trends, and a new trend represented by the Provincial Living Water Smart guideline of achieving 33% efficiency improvements by 2020).

Finally, recognizing the historic significance of the 1929-1931 drought sequence in the Okanagan, a possible future three year drought scenario was estimated by examining the bias-corrected climate data during the period from 2010 – 2100 and choosing the three driest years (2076, 2033, and 2026) and assembling them as though they occurred in succession. This scenario is referred to as the Drought scenario. However, it should be noted that the climate model was not able to produce any years with the same severity of drought as what has been observed several times in the last 80 years. This is discussed further in Section 4.3.2. A summary of all the scenarios run for Phase 2 of this project is presented in Table 4-1.

Scenarios 1-4 were run for the 2011-2040 period using the future climate data with the expected CO_2 emissions, expected progression of Mountain Pine Beetle infestation, and current trends of gradually reducing per capita water consumption. Using these conditions as a base, these scenarios examine the impacts of increased water usage due to increasing the population growth rate, and expanding the agricultural land base to all reasonably irrigable lands.

Scenario 4-8 were run for the 2011-2040 period using the future climate data with the expected CO_2 emissions, expected progression of Mountain Pine Beetle infestation, and an accelerated implementation of water efficiency measures with 33% efficiency achieved by 2020. Using these conditions as a base, these scenarios examine the impacts of increased water usage due to increasing the population growth rate, and expanding the agricultural land base to all reasonably irrigable lands.

Scenarios 17-20 were run for the Drought period using the future climate data with the expected CO_2 emissions, expected progression of Mountain Pine Beetle infestation, and current trends of gradually reducing per capita water consumption. Using these conditions as a base, these scenarios examine the impacts of increased water usage due to increasing the population growth rate, and expanding the agricultural land base to all reasonably irrigable lands.

Table 4-1: Summary of Phase 2 Model Scenarios*

Scenario number	Time Period	CO2 Emission scenario	Mountain Pine Beetle	Efficiency	Agricultural Land Base	Population growth
1	2011-2040	Expected	Expected	Current use patterns and current trends	Present conditions	Expected rate
2	2011-2040	Expected	Expected	Current use patterns and current trends	Present conditions	High rate
3	2011-2040	Expected	Expected	Current use patterns and current trends	Irrigate all	Expected rate
4	2011-2040	Expected	Expected	Current use patterns and current trends	Irrigate all	High rate
5	2011-2040	Expected	Expected	33% Efficiency gains by 2020	Present conditions	Expected rate
6	2011-2040	Expected	Expected	33% Efficiency gains by 2020	Present conditions	High rate
7	2011-2040	Expected	Expected	33% Efficiency gains by 2020	Irrigate all	Expected rate
8	2011-2040	Expected	Expected	33% Efficiency gains by 2020	Irrigate all	High rate
17	3 driest years 2011-2100	Expected	Expected	Current use patterns and current trends	Present conditions	Expected rate
18	3 driest years 2011-2100	Expected	Expected	Current use patterns and current trends	Present conditions	High rate
19	3 driest years 2011-2100	Expected	Expected	Current use patterns and current trends	Irrigate all	Expected rate
20	3 driest years 2011-2100	Expected	Expected	Current use patterns and current trends	Irrigate all	High rate
25	2011-2040	Expected	Expected	Present conditions	Present conditions	Present conditions
26	2041-2070	Expected	Expected	Present conditions	Present conditions	Present conditions
27	3 driest years 2011-2100	Expected	Present	Present conditions	Present conditions	Present conditions

*The numbering scheme for the scenarios is not continuous because this represents a subset of the scenarios that were originally planned to be evaluated.

Scenario 25 was run for the 2011-2040 period using the future climate data with the expected CO_2 emissions, expected progression of Mountain Pine Beetle infestation, present conditions of water consumption, present conditions of irrigation, and the present population. This scenario served as the 'do nothing' scenario demonstrating the impacts of climate change alone, and was used to compare against the results of Scenarios 1-8.

Scenario 26 was run for the 2041-2070 period using the future climate data with the expected CO_2 emissions, expected progression of Mountain Pine Beetle infestation, present conditions of water consumption, present conditions of irrigation, and the present population. This scenario was used to evaluate the impacts of climate change between the 2011-2040 period and the 2041-2070 period.

Scenario 27 was run for the Drought period with expected CO_2 emissions, present levels of Mountain Pine Beetle infestation, present conditions of water consumption, present conditions of irrigation, and present population. This scenario is referred to in this report as the Drought scenario and was used to evaluate the relative impacts of three successive dry years as compared to Scenario 25 and Scenario 26.

In addition, in order to evaluate the impacts of future climate change against historical conditions, it was necessary to run the OBWAM using climate data generated by the same model that was used to generate the future climate data. This provided a consistent baseline set of modeling results generated using the same climate model with the same biases and trends. This model is hereinafter referred to as the Baseline model.

4.2 Scenario Model Construction

4.2.1 Climate Data

The climate data for each of the three future scenario periods, and the baseline scenario period, were provided by Environment Canada and were generated using the Canadian Global Climate Model referred to in this report as CGCM2 A2. An examination of the 1996-2006 CGCM2 A2 climate data vs. the recorded precipitation from 1996-2006 indicated the CGCM2 A2 climate data was producing an average of 100 mm per year less precipitation throughout the Okanagan Basin. As a result, Environment Canada re-evaluated the original CGCM2 A2 climate data and applied a correction factor to eliminate the precipitation and temperature bias during the Baseline model period (1996-2006), as well as the future scenario periods. The bias-corrected climate data provided a gridded climate data set on 500 m x 500 m grid resolution containing daily precipitation, daily minimum and maximum temperature, and daily PET.

For the Drought scenarios, the study team selected three of the driest years from the bias-corrected CGCM2 A2 climate data, as measured by total annual precipitation throughout the basin. The years selected were identified as being 2076, 2033, and 2026 with total annual precipitation of 482 mm, 545 mm and 490 mm respectively. In order to run these as three successive years in the model, the climate data for these years was extracted and the data from these years (hydrologic years from September to August) was arranged in succession in the same gridded climate data file containing daily precipitation, daily minimum and maximum temperature, and daily PET.

4.2.2 Water Use Data

The water use projections for the future scenarios were calculated using the Okanagan Water Demand Model developed by B.C. Ministry of Agriculture and Lands. The following is a summary of how the Water Demand model was applied to generate water use data for the scenarios. A more detailed description of the Water Demand Model is provided in the Summary Report for Phase 2 Okanagan Water Supply and Demand Project (Summit, 2010).

The water use data for the future scenarios included three separate water use considerations:

- Population growth (expected growth rate vs. high growth rate)
- Water use efficiency (current trends vs. increased efficiency)
- Agricultural land base expansion (present conditions vs. expanded agricultural base)

For Population growth, the Expected rate scenarios incorporated urban planning projections to predict the location and amount of population growth throughout the basin. The High rate scenarios used the same approach as with the Expected rate and then used a multiplication factor to account for a higher population density.

For Water Use Efficiency, the Current trends scenarios apply a 33% decrease in per capita use between 2011 and 2040. The 33% efficiency scenarios include the same improvements as for the current trends, but at a faster pace where it all takes place over the 2010 – 2020 period instead of the 2010 – 2040 period. In addition, the irrigation management practices for agricultural crops improves from *average* to *good* over the same 2010 – 2020 period.

For Agricultural land base expansion, the Present conditions scenarios use existing conditions. The Expanded agricultural base scenarios use mapped out areas suitable for agricultural expansion. Using a similar process to the urban growth phase-in, the agricultural polygons were assigned random years between 2010 and 2040 and brought on stream accordingly over the modeling period.

The resultant water use data from the Water Demand Model was incorporated into the OBWAM the same as described in Section 3.2.1.

4.2.3 Q_R and Q_T Terms

There are 32 upland reservoirs which are generally operated to capture water during the freshet period from April to June and release water to meet downstream water demand and maintain in-stream flow for fish. Table 4-2 summarizes the major upland reservoirs with their storages in the Okanagan Basin.

Table 4-2: Major Upland Storage Reservoirs in the Basin

Water Supplier No.	Water Supplier	Reservoir	Sub-basin	Developed storage capacity (ML)
2	Greater Vernon Water	Grizzly	Duteau Creek*	5,280
		Aberdeen	Duteau Creek*	11,150
		Haddo	Duteau Creek*	2,730
		King Edward	Node 1: Vernon Creek	1,356
3	City of Penticton	Grayback	Node 46: Penticton Creek	12,330
		Ellis	Node 52: Ellis Creek	1,230
4	Black Mountain Irrigation District	Ideal	Node 22: Mission Creek	6,780
		Greystoke	Node 22: Mission Creek	5,103
		Fish Hawk	Node 22: Mission Creek	1,850
		James	Node 20: Mill Creek	1,825
5	Westbank Irrigation District	Tadpole	Node 18: Lambly Creek	3,601
		Horseshoe/Dobbin	Node 28: Powers Creek	1,724
		Jackpine	Node 28: Powers Creek	1,233
		Lambly	Node 28: Powers Creek	3,490
6	District of Summerland	Headwaters	Node 42: Trout Creek	4,472
		Tsuh, Canyon, Isintok, Cresent, Whitehead	Node 42: Trout Creek	3,673
		Thirsk	Node 42: Trout Creek	6,490
		Eneas, Garnet	Node 36: Eneas Creek	2,360
7	Glenmore Ellison Improvement District	Posthill, Bulman, South	Node 20: Mill Creek	7,869
8	Lakeview Irrigation District	Big Horn	Node 18: Lambly Creek	3,454
		Rose Valley	Node W7	4,922
10	District of Lake Country	Oyama	Node 1: Vernon Creek	7,137
		Crooked	Node 1: Vernon Creek	2,383
		Swallwell	Node 1: Vernon Creek	11,880
11	District of Peachland	MacDonald	Node 32: Peachland Creek	5,303
13	Southeast Kelowna Irrigation District	McCulloch, Browne, Fish, Long Meadow	Node 22: Mission Creek	17,545
Total:				132,589

*Flows from Duteau Creek, a tributary to Shuswap River, are imported to the Okanagan Basin.

By definition, Q_R is the upstream reservoir component of streamflow at a node (positive during reservoir release, negative during reservoir filling) and Q_T is the rate of water transfer into a particular node (into a surface water body) from outside the natural contributing area. There are 11 nodes with Q_R terms and 5 nodes with Q_T terms. Table 4-3 summarizes the nodes with these two terms.

Table 4-3: Summary of nodes with Q_R and Q_T terms

Nodes	Terms
Vernon Creek at Outlet-Node1	Q_R
Lambly Creek Mouth-Node18	Q_R, Q_T
Residual Area W-7-Node19	Q_R
Kelowna(Mill) Creek Mouth-Node20	Q_R, Q_T
Mission Creek Mouth-Node22	Q_R, Q_T
Powers Creek Mouth-Node28	Q_R
Trepanier Creek (mouth)-Node30	Q_T
Peachland Creek Mouth-Node32	Q_R, Q_T
Eneas Creek Mouth-Node36	Q_R
Trout Creek Mouth-Node42	Q_R
Penticton Creek Mouth-Node46	Q_R
Ellis Creek Mouth-Node52	Q_R

For the purposes of the OBHM, the historical Q_R and Q_T terms during the calibration period (1996-2006) were provided to DHI from the results of a previous study. However, these two terms were not available for the future scenario periods, so DHI was required to develop a methodology to derive these two terms for each scenario period.

The methodology used to develop Q_T was to follow the same seasonal pattern and amount of weekly inter-basin diversions used during the calibration period as described in "Q_T and RF_S Term Updates" (Summit, 2010). In the development of Q_T, the following watershed transfers within the Okanagan Basin were considered:

- Lambly Creek watershed to Powers Creek watershed (the Alocin Creek diversion);
- Trepanier Creek watershed to Peachland Creek watershed (the MacDonald Creek diversion);
- Chute Creek watershed to Robinson Creek watershed;
- Robinson Creek watershed to Naramata Creek watershed;
- Kelowna (Mill) Creek watershed to Mission Creek watershed (flood flow diversion);
- Duteau Creek watershed to Vernon Creek watershed;
- Okanagan Lake to Vernon Creek watershed;
- Kettle River watershed to Mission Creek watershed (Stirling Creek diversion); and
- Fortune Creek watershed to Deep Creek watershed.

Duteau Creek diversion, the Okanagan Lake diversion, and the Fortune Creek diversion listed above are not included in the Q_T development as all three diversions are added directly into their respective water supplier's distribution system which does not meet the criteria of Q_T. Additionally, the Stirling Creek diversion is not included as a Q_T term for Mission Creek, as water is directly imported into McCulloch Reservoir and the volume was included within Mission Creek watershed's Q_R term; since the Alocin Creek diversion flows directly into Dobbin Lake within Powers Creek watershed, no Q_T values are included for the Powers Creek watershed and the volume was included in the Powers Creek watershed Q_R term.

The methodology used for Q_R development can be summarized as described in the following steps:

- Run the model with naturalized condition for each climate scenario;
- Extract inflows to each upland reservoir and inflows at each 11 nodes with Q_R term;
- Calculate reservoir inflows based on simulation inflows under naturalized conditions;
- Calculate reservoir outflows based on residual downstream demand which is demand plus minimum flow (minimum simulated flow during calibration period at each of the 11 nodes) that is not met from flow generated below reservoirs or from Q_T;
- Track storage in reservoir that will not be less than minimum storage (15% of available storage) and fill the reservoir storage up to 100% of available storage from the second week of March to last week of October, and not higher than 80% of available storage from the first week of November to the first week of March the following year.

This methodology was accepted by the Working Group as an acceptable approach given the time and budget constraints of the project. However, given the significant influence the reservoir operations have on the tributary flows, a closer examination and refinement of this approach is recommended for future phases of the project.

A spreadsheet model was developed for tracking reservoir storages and developing Q_R time series. The calculated Q_R values were verified against values for the calibration period and they matched reasonably well in terms of timing and quantity.

4.2.4 Mountain Pine Beetle Development

The mountain pine beetle (MPB) infestation and associated salvage harvesting has the potential to affect the amount, timing and quality of water originating from the forest upland watersheds. In order to reflect impact of MPB on watershed hydrology during the scenario period from 2010 - 2076, MPB Impact Mapping for years 2009 – 2013 (2008, NRCAN) was used to capture the distribution and timing of MPB attack, which shows the percentage of infested pine each year. Figure 4-1 shows the MPB progression and distribution.

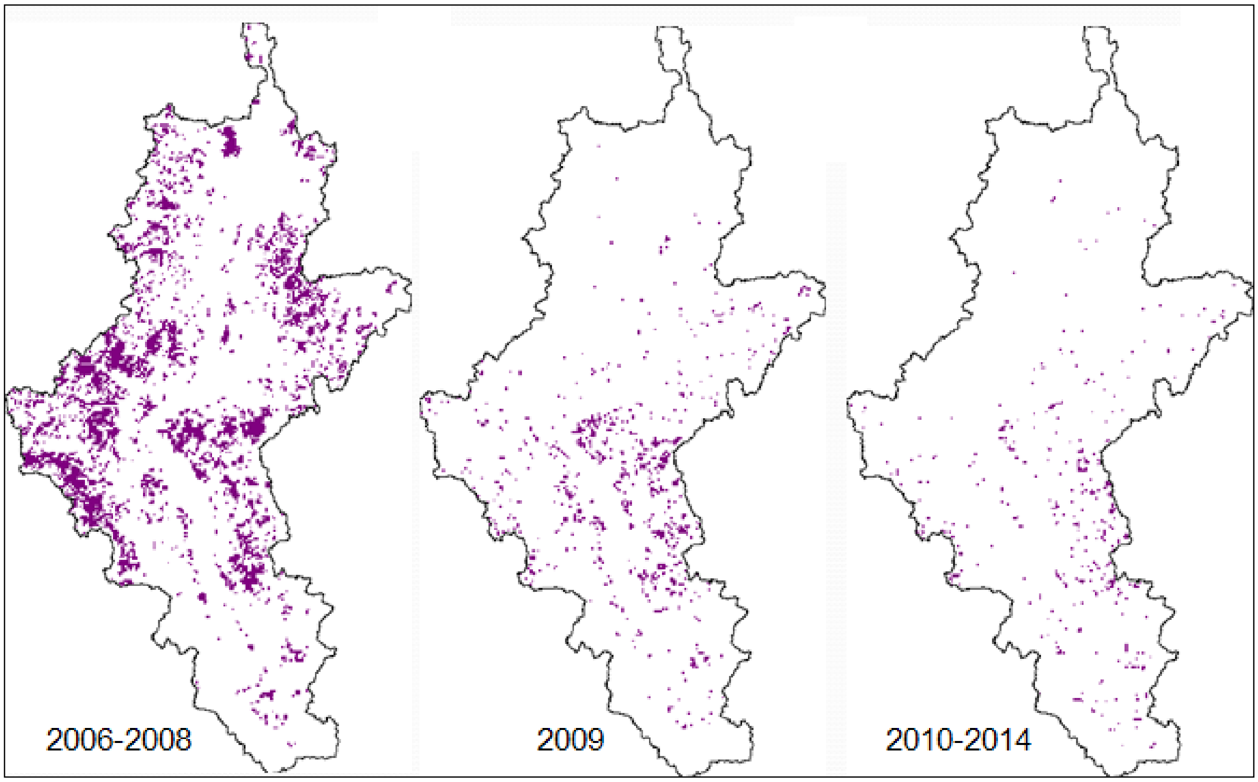


Figure 4-1: MPB progression and distribution used for scenarios

The approach is to identify the initial attack of MPB and then apply a progression of attack and recovery since initial attack based on Huggard & Lewis (2007), which gives a synthesis of available local data on the effects of salvaging vs. not salvaging stands killed by MPB (Figure 4-2). This figure shows that for un-salvaged area which would die and recover naturally, the Equivalent Clearcut Area (ECA) starts from near zero % at the time of initial attack, reaches a peak about 40-60% after 15-20 years, and then declines gradually and finally reaches 0% after about 50 years; for salvaged and planted areas, the ECA starts from 100%, then declines sharply and finally reaches 0% after about 35 years.

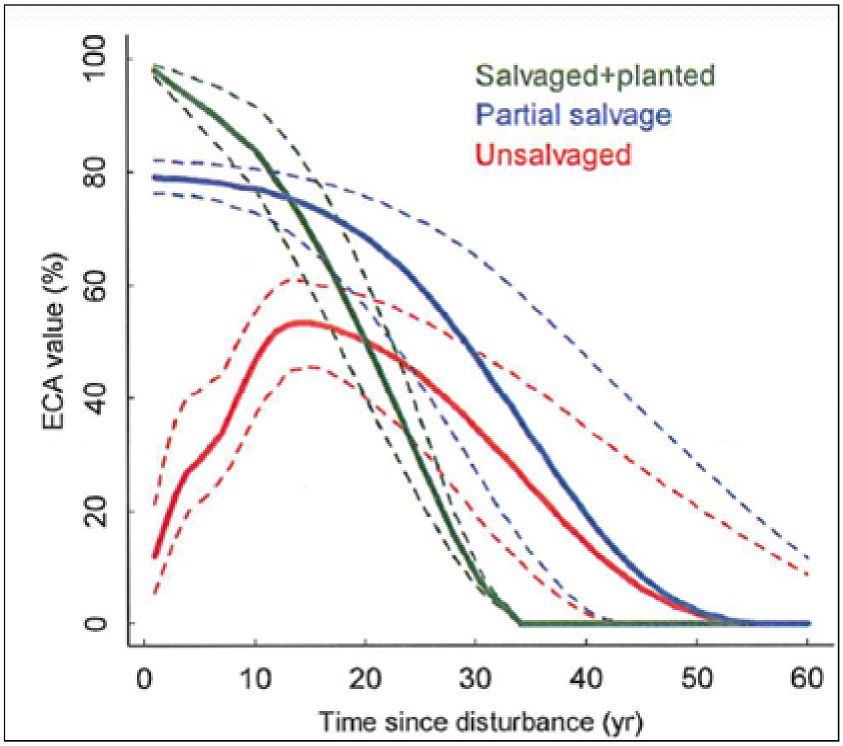


Figure 4-2: Time series of Equivalent Clearcut Area for MPB under Different Harvesting Methods

A couple of assumptions were made in order to implement the progression of MPB attack and recovery in the model. Basic assumptions were used as follows:

- Assuming that 30% of the attacked pine will be salvaged logged and re-planted the first year of attack; the remaining 70% will die and recover naturally; they were randomly selected across the whole basin.
- ECA was used as the basis for perturbing model parameter values to reflect progression of MPB impact (see Table 4-4).
- 500 m grid resolution required simplification of the distribution provide in the map of potential MPB progression (NRCAN, 2008), so 5 classes were used based on the percentage of the pine attacked in 2008. The classes used were 5-20%, 20-40%, 40-60%, 60-80% and 80-100%.

Table 4-4: ECA Progression for Clearcut and Natural Conditions for Different MPB Infestation Levels

Infestation	5-20%		20-40%		40-60%		60-80%		80-100%	
	Clearcut	Natural	Clearcut	Natural	Clearcut	Natural	Clearcut	Natural	Clearcut	Natural
Years from Start	ECA (%)		ECA (%)		ECA (%)		ECA (%)		ECA (%)	
0	0.13	0.00	0.32	0.00	0.53	0.00	0.74	0.00	0.95	0.00
1	0.13	0.01	0.31	0.02	0.51	0.03	0.72	0.04	0.93	0.05
2	0.13	0.01	0.30	0.04	0.50	0.06	0.71	0.08	0.91	0.11
3	0.12	0.02	0.30	0.05	0.49	0.09	0.69	0.13	0.89	0.16
4	0.12	0.03	0.29	0.07	0.48	0.12	0.68	0.17	0.87	0.22
5	0.12	0.04	0.28	0.09	0.47	0.15	0.66	0.21	0.85	0.27
6	0.12	0.04	0.28	0.10	0.46	0.17	0.64	0.23	0.83	0.30
7	0.11	0.05	0.27	0.11	0.45	0.19	0.63	0.26	0.81	0.33
8	0.11	0.05	0.26	0.12	0.44	0.20	0.61	0.28	0.79	0.37
9	0.11	0.06	0.26	0.13	0.43	0.22	0.60	0.31	0.77	0.40
10	0.10	0.06	0.25	0.14	0.41	0.24	0.58	0.33	0.74	0.43
11	0.10	0.06	0.23	0.15	0.39	0.25	0.55	0.34	0.70	0.44
12	0.09	0.06	0.22	0.15	0.37	0.25	0.51	0.35	0.66	0.45
13	0.09	0.06	0.21	0.16	0.34	0.26	0.48	0.36	0.62	0.47
14	0.08	0.07	0.19	0.16	0.32	0.27	0.45	0.37	0.57	0.48
15	0.07	0.07	0.18	0.16	0.30	0.27	0.41	0.38	0.53	0.49
45	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Based on the above assumptions and classifications, in total 27 MPB infected areas were identified with initial attack time, and then each classification were further divided into two zones, Clearcut and Natural recovery, thus a total of 54 final MPB infected zones were identified.

The hydrologic changes resulting from MPB mortality and harvesting are primarily related to the loss of canopy cover, which in turn affects hydrological processes such as interception and transpiration, snow accumulation and melt. The result is generally higher snow accumulation and more water reaching the ground surface and increased stream flow. In the model basic parameters used to reflect the impact of MPB are leaf area index (LAI), rooting depth (RD) and degree day coefficient (DDC). Scenario parameter values were computed using the following equation as:

$S_{par} = U_{par} – ((U_{par} – CC_{par}) * ECA)$

Where:

S_{par} – final parameter value

U_{par} – Undisturbed parameter value

CC_{par} – Clearcut parameter value

ECA – Equivalent Clearcut Area

4.2.5 Leaf Area Index and Rooting Depth

The Leaf Area Index (LAI) and Rooting Depth (RD) are parameters which influence the interception and evaportranspiration of the vegetation in the model.

For LAI, large contiguous clearcut areas harvested between 1995-1998 were identified from the VRI logging maps were used to calculate and compare representative LAI values for clearcut areas (see the gray lines in Figure 4-3). An average LAI value of 1.05 was used as an estimate for the clearcut area. The LAI for the disturbed areas was reduced to a value of 1.05 but limited to a minimum of 0.2 which is the minimum value for herbs (http://www.uni-giessen.de/~gh1461/plapada/lai/lai.html). Figure 4-4 shows the final LAI time series for undisturbed pine and clearcut pine.

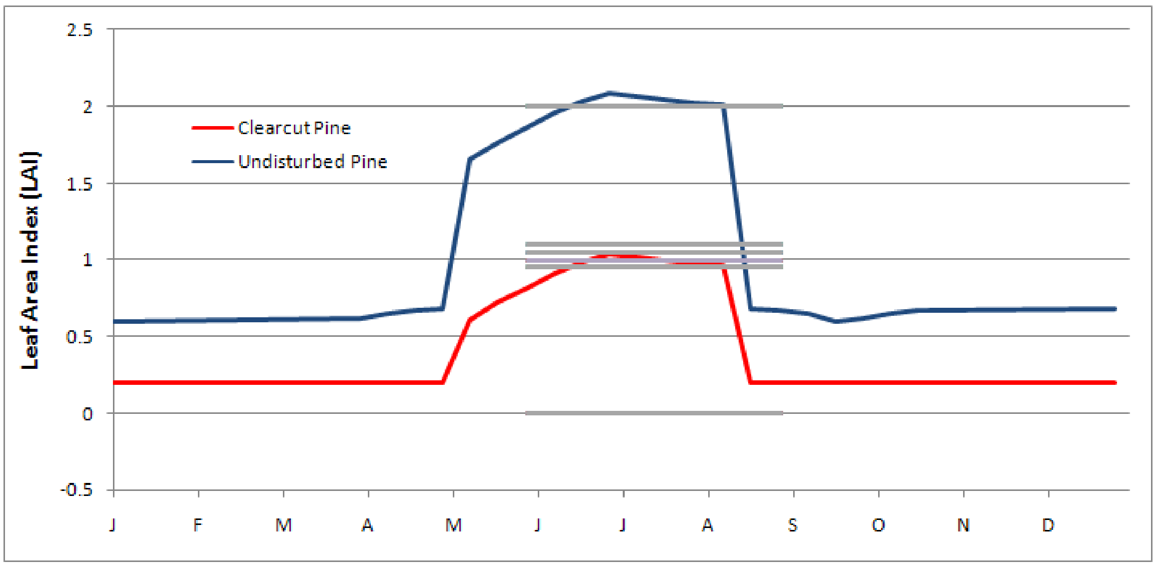


Figure 4-3: LAIs for clearcut pine and undisturbed pine

Discussions undertaken late in this phase of the project indicate that regional LAI values for the main vegetation types may be available, and there was some question about the use of such a large amount of seasonal variability for a largely coniferous forest. As a result, a closer evaluation of the LAI values and patterns used by the model is recommended in future phases of the project.

For RD, due to the lack of local measured data, values from literature and previous projects were used. The time series developed for herbaceous vegetation was used to represent the remaining understory vegetation in clearcut areas. Figure 4-4 shows an example of final RD time series for undisturbed pine and clearcut pine.

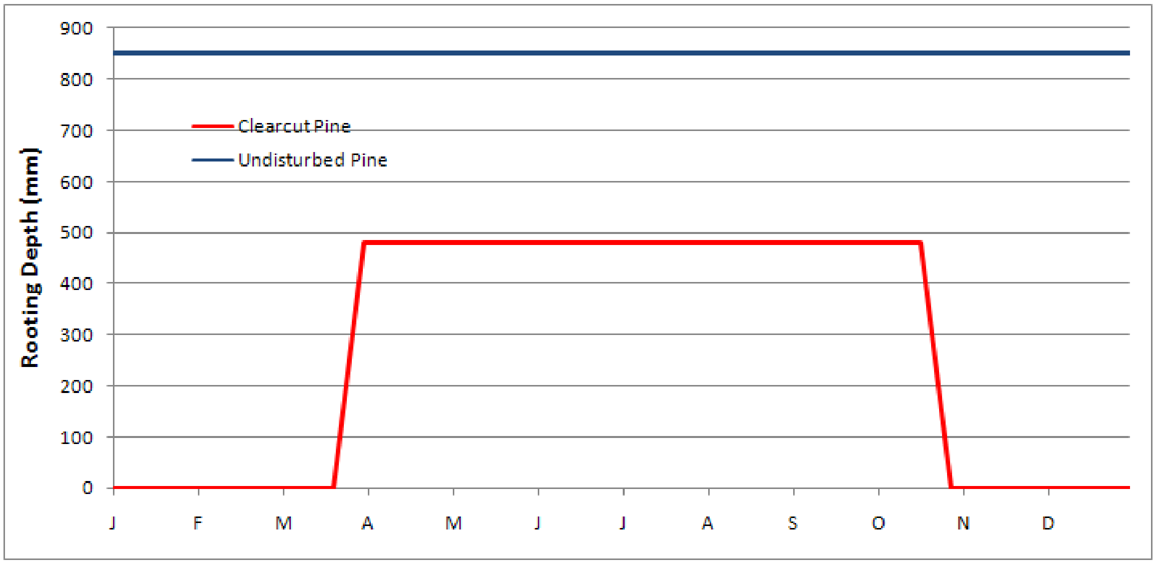


Figure 4-4: Figure: Rooting depths for clearcut pine and undisturbed pine

4.2.6 DDC

MIKE SHE uses a modified degree-day method for simulating snow accumulation and melt, and the primary parameter influencing the melting rate and timing of snowmelt is the degree day coefficient (DDC). As discussed above, the big impact of MPB kill is changing the distribution of snow accumulation as well as the rate and timing of snow melt. It is big challenge to reflect this impact using a single snow parameter in the model. A lot of literature research work has been done in order to estimate the expected impact of a clearcut on DDC and snow water equivalent (SWE). Kuusisto (1980) suggested 18% lower SWE in forested sites relative to open sites and 45% lower DDC relative to open; Haverly et. al (1978) suggested 21% lower DDC relative to open sites; and Winkler & Boon, 2009 suggested on green/red attack sites 25% lower SWE relative to open sites, on grey attack site 13% lower SWE and 31% lower ablation relative to open sites, on forested sites 2 – 12 days later depletion in forested sites relative to open sites. Based on the above references, the DDC time series for the clearcut area was estimated using the same approach as with the LAI and RD and then it was calibrated to yield the expected trends in snow accumulation and melt (i.e. increased solar radiation in clearcuts generates more rapid melting during the freshet and increased compaction & liquid water content generates less melting and higher SWE during the winter months (see Figure 4-5). Examples of the variability of DDC throughout the scenario period for natural recovery vs. clearcutting are provided in Figure 4-6 and Figure 4-7, respectively.

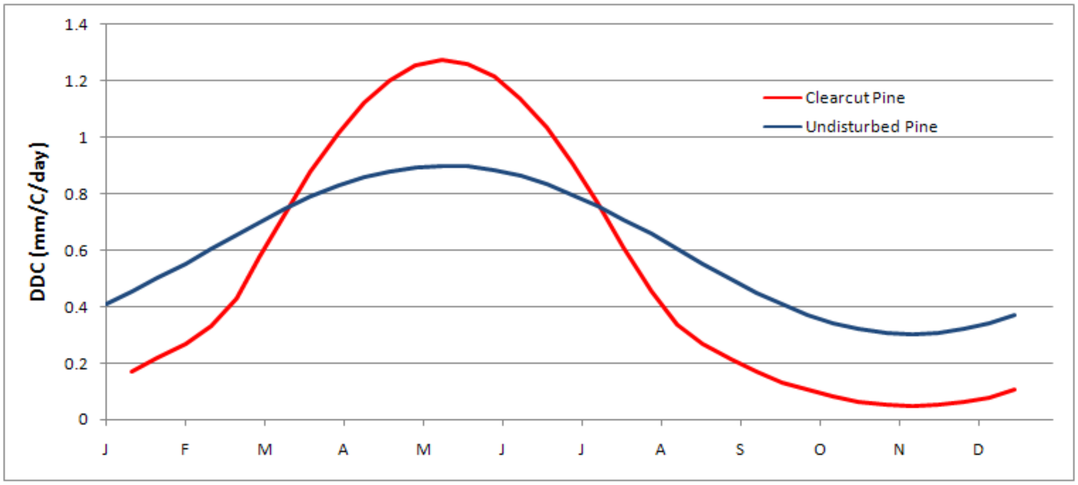


Figure 4-5: Example of DDC for Clearcut pine and undisturbed pine

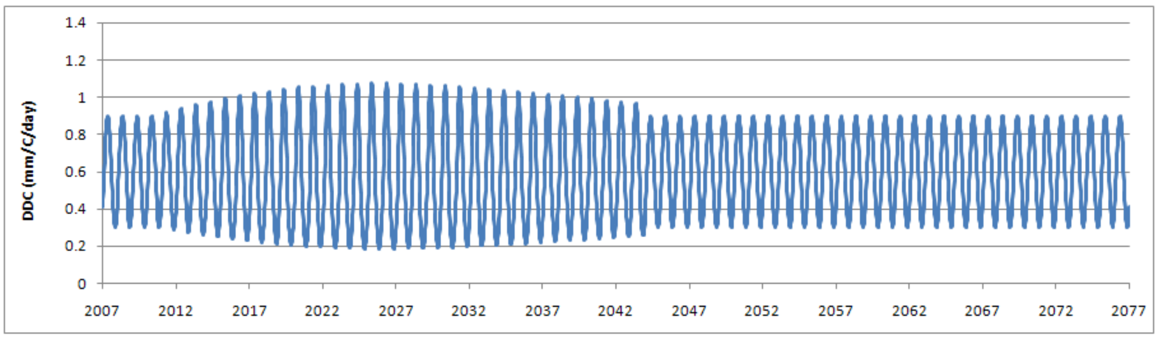


Figure 4-6: Example of DDC for attacked in 2010 – natural kill & recovery

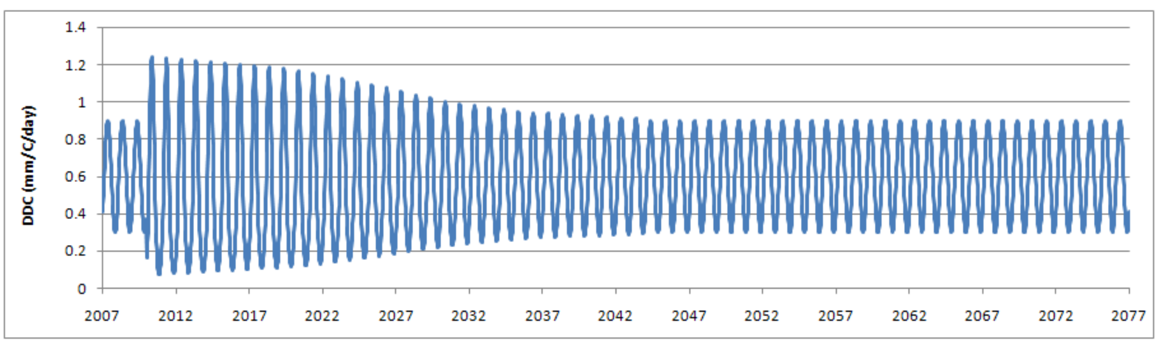


Figure 4-7: Example of DDC for attacked in 2010 – clearcut

4.3 Scenario Results

4.3.1 Overview of Analysis

The results of the scenarios are presented in two sections; the first section presents the results of climate change impacts on the basin hydrology; and the second section presents the results comparing the impacts of different water use scenarios. Unfortunately, it was not possible to directly determine the influence of the mountain pine beetle infestation on the hydrology because there was no effective reference scenario against which to compare it.

Since all of the simulations were evaluated against the backdrop of climate change, it is important to first clarify the purpose of evaluating climate change. Climate change scenarios are not intended to predict what the climate will be like in the future, but rather to facilitate an understanding of the consequences of climate change on related processes. For the purposes of this project we have prepared the OBWAM in order to examine the impact of climate change on water supply and demand in the Okanagan Basin. The results from the model can have many applications including, but not limited to, the following (Environment Canada, 2010):

- Providing data for Vulnerability, Impacts and Adaptation (VIA) assessment studies;
- Acting as an awareness-raising device;
- Aiding strategic planning and/or policy formation;
- Scoping the range of plausible futures;
- Summarizing our knowledge (or ignorance) of the future;
- Exploring the implications of policy decisions.

The purpose of this section of the report is to present, summarize and interpret the results in such a way as they may be useful for some or all of the above applications.

In order to evaluate the consequences of the scenarios it was decided to focus on the identification and interpretation of long term trends in the results rather than evaluating specific results at selected locations and times. As such, this report primarily uses three different ways of analysing and presenting the results:

(1) A summary table of average quarterly values and differences with the baseline scenario

(2) A plot of average weekly values for a typical year

(3) A matrix of the % change in values between scenarios

These analysis methods are described in more detail in the following sections.

Summary Table of Average Quarterly Values

The summary table will present a summary of the average values of the item of interest (e.g. cumulative precipitation, cumulative inflow volume, weekly average streamflows) occurring during each quarter for the entire simulation period. In this case:

- Quarter 1 (Q1) refers to the period from January to March
- Quarter 2 (Q2) refers to the period from April to June
- Quarter 3 (Q3) refers to the period from July to September
- Quarter 4 (Q4) refers to the period from October to December.

For example, if the item of interest is cumulative precipitation, the average quarterly value would be calculated as:

$$Pq,avg = \frac{1}{n \times m}\sum_{j=1}^{n}(\sum_{i=1}^{m} Pw_i)$$

Where

Pq, avg is the average quarterly precipitation

n is the number of years for the scenario

m is the number of weeks in the quarter

Pw_i is the weekly precipitation in week *i*

See Table 4-5 for an example of an Average Quarterly Summary table.

Table 4-5: Sample Average Quarterly Summary Table

		Baseline 1996-2006	**2011-2040**	**2041-2070**	**Drought**
Quarter 1	Value	157	152	153	117
	Difference (%)		-3.2	-2.5	-25.5
Quarter 2	Value	177	189	178	145
	Difference (%)		6.6	0.4	-17.8
Quarter 3	Value	132	115	127	63
	Difference (%)		-9.6	-2.3	-38.5
Quarter 4	Value	186	198	197	184
	Difference (%)		6.8	6.4	-0.8
Annual	Value	651	653	655	510
	Difference (%)		0.3	0.6	-21.7

The Value represents the average quarterly value of the parameter of interest (e.g. Precipitation) while the Difference represents the % difference between the average quarterly value for the scenario vs. the baseline condition.

Plot of Average Weekly Values for a Typical Year

Another useful way of examining trends in the scenario results is to plot a time series of the average weekly value of the item of interest as it occurs during that week for each year of the simulation. For example, if the item of interest is weekly streamflows, the average weekly value would be calculated as:

$$Qw_i, avg = \frac{1}{n}\sum_{j=1}^{n} Qw_{i,j}$$

Where

Q*w,avg* is the average weekly flow during week *i* for the entire simulation period

n is the number of years for the scenario

Q$w_{i,j}$ is the weekly flow for week *i* during year *j*

When the average weekly values time series for each scenario period are plotted together it provides an effective way to identify trends in the timing and magnitude of the item of interest (see Figure 4-8).

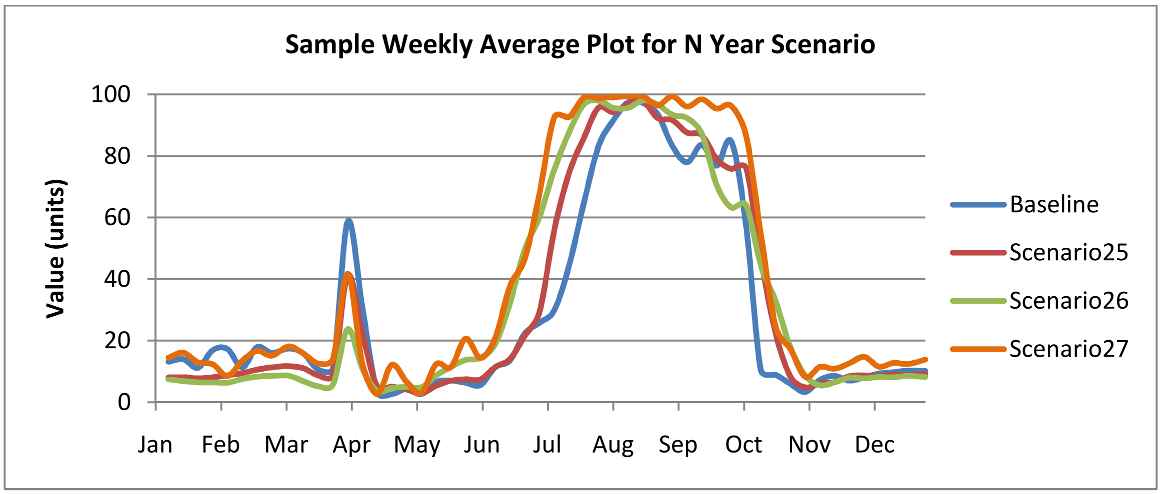


Figure 4-8: Sample Weekly Average Plot

<u>Matrix Analysis of % Change in Results</u>

Finally, in order to effectively compare the impacts and influence of the various water use scenarios against each other, a matrix of relative changes in results was used. The matrix includes one column for each scenario, and one row for each scenario as shown in the table below.

	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S25**
S1		0.02	-1.08	-11.26	1.28	0.98	-0.03	-0.30	-0.56
S2	-0.02		-1.10	-11.28	1.26	0.96	-0.05	-0.32	-0.58
S3	1.09	1.11		-10.29	2.39	2.09	1.06	0.79	0.53
S4	12.69	12.72	11.48		14.13	13.80	12.66	12.36	12.06
S5	-1.26	-1.24	-2.33	-12.38		-0.29	-1.29	-1.56	-1.81
S6	-0.97	-0.95	-2.04	-12.13	0.29		-1.00	-1.27	-1.53
S7	0.03	0.05	-1.05	-11.24	1.31	1.01		-0.27	-0.53
S8	0.30	0.32	-0.78	-11.00	1.58	1.28	0.27		-0.26
S25	0.56	0.58	-0.53	-10.77	1.85	1.55	0.53	0.26	

The values in the matrix represent the % change in the value relative to the reference scenario. The values in the top right-hand side of the matrix use the scenarios at the top of the column as the reference scenario, while the values in the bottom left-hand side of the matrix use the row as the reference scenario. For example, the value at Column S3, Row S6 is calculated as:

$$\%\,Change = \frac{S6 - S3}{S6} \times 100$$

Where;

S6 is the value of the result for Scenario 6

S3 is the value of the result for Scenario 3

Similarly, the value at Column S7, Row S4 is calculated as:

$$\%\,Change = \frac{S7 - S4}{S7} \times 100$$

4.3.2 Effects of Climate Change

The effects of climate change on the basin hydrology are examined by comparing the changes in the results for the three future scenarios (2011-2040, 2041-2070, and Drought) against the Baseline scenario (1996-2006). This section will examine the impacts of climate change by first examining the changes in the climate (precipitation and temperature), and then evaluating the impacts of these changes on snowmelt, net inflow to Okanagan Lake, lake levels, streamflows, and storage in uplands reservoirs.

Precipitation and Evapotranspiration

Table 4-6 and Table 4-7 provide a summary comparison of the average annual precipitation and actual evapotranspiration (as calculated by the OBWAM) for the Baseline scenario vs. the future scenarios, while Figure 4-9 shows a plot of the same data (plots comparing annual precipitation and evapotranspiration for each scenario period are provided in Appendix F). Based on this analysis the bias-corrected CGCM2-A2 climate data shows no appreciable long term changes in the average precipitation and evapotranspiration occurring in Okanagan Basin.

However, a subsequent analysis of the average annual potential evapotranspiration reveals a very clear trend of increasing PET in future scenarios. The average annual PET increases steadily from 853 mm for the Baseline scenario, to 877 mm for the 2011-2040 scenario, and to 909 mm for the 2041-2070 scenario. These results indicate that actual evapotranspiration is generally limited by the availability of moisture throughout the basin, particularly during the second and third quarter of the year when PET is the highest.

Figure 4-10 shows a plot of the average weekly precipitation for each scenario period while Table 4-8 summarizes the average quarterly precipitation for each scenario period. This analysis shows that precipitation trends are relatively consistent between the Baseline scenario period and the future scenario periods from 2011-2040, and from 2041-2070, with no consistent trends developing.

Even the Drought scenario showed a relatively good fit with the timing and magnitude of precipitation throughout the year, with only a few periods (January, March, May and September) where significantly less precipitation occurred. However, the Drought scenario included only three years so it is difficult to draw any firm conclusions about the precipitation trends in these years.

Table 4-6: Average Annual Precipitation

	Baseline	A2-Expected		
	1996-2006	2011-2040	2041-2070	Drought
Maximum (mm)	916	939	863	545
Minimum (mm)	501	491	533	483
Average (mm)	665	649	654	506
% Change*		-2.4	-1.6	-23.9

*% Change is relative to Baseline Average

Table 4-7: Average Annual Actual Evapotranspiration (as calculated by OBWAM)

	Baseline	A2-Expected		
	1996-2006	2011-2040	2041-2070	Drought
Maximum	651	614	631	489
Minimum	492	481	483	481
Average	559	552	553	485
% Change		-1.3	-1.0	-13.3

*% Change is relative to Baseline Average

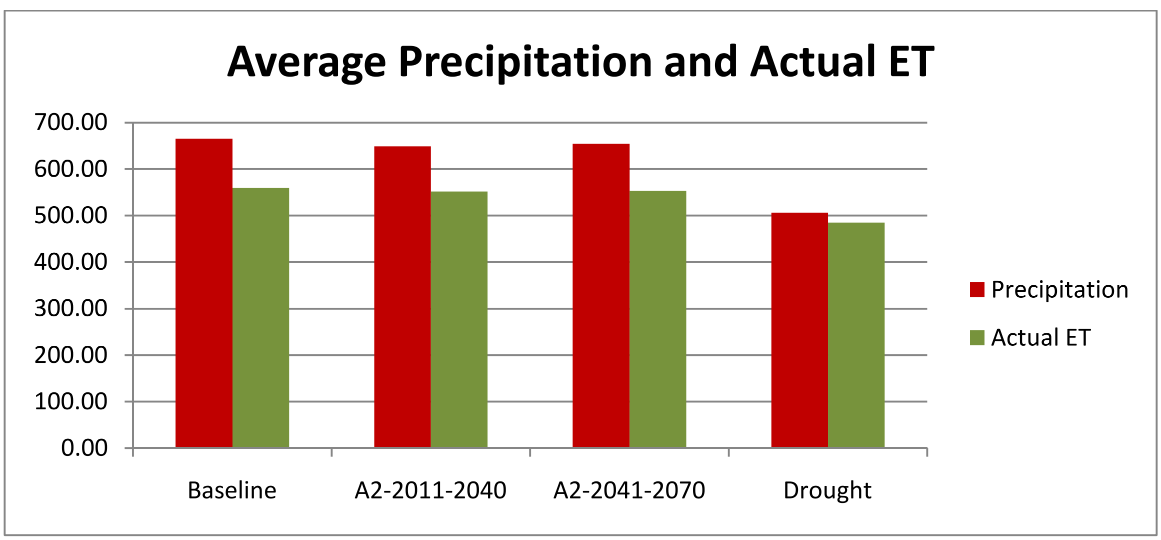


Figure 4-9: Average Annual Precipitation and Actual Evapotranspiration for Okanagan Basin

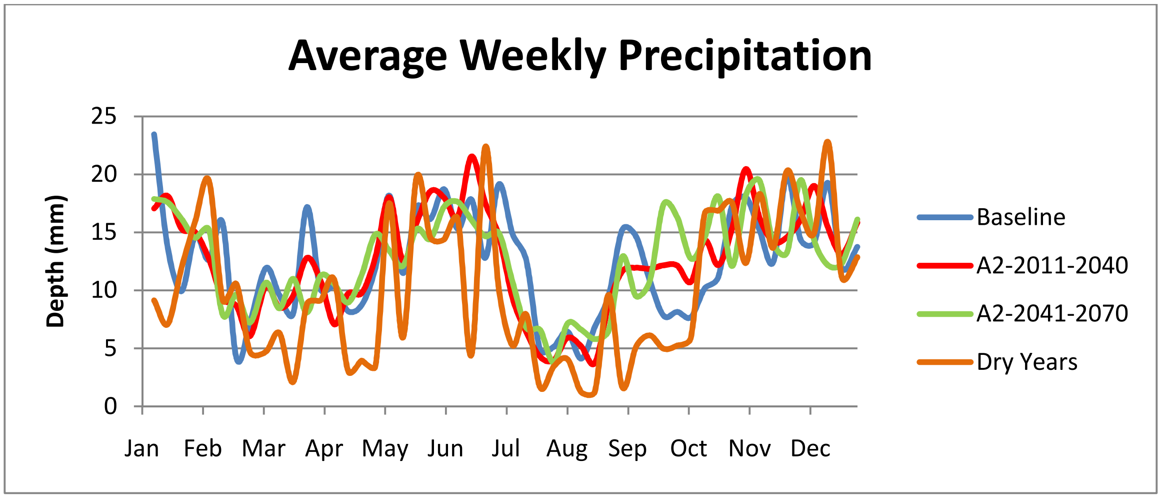


Figure 4-10: Average Weekly Precipitation in Okanagan Basin

Table 4-8: Summary of Average Quarterly Precipitation

		Baseline 1996-2006	2011-2040	2041-2070	Drought
Quarter 1	Depth(mm)	157	152	153	117
	Difference (%)		-3.2	-2.5	-25.5
Quarter 2	Depth(mm)	177	189	178	145
	Difference (%)		6.6	0.4	-17.8
Quarter 3	Depth(mm)	132	115	127	63
	Difference (%)		-9.6	-2.3	-38.5
Quarter 4	Depth(mm)	186	198	197	184
	Difference (%)		6.8	6.4	-0.8
Annual	Depth(mm)	651	653	655	510
	Difference (%)		0.3	0.6	-21.7

Temperature

Table 4-9 provides a summary of the average number of days per year where the average daily temperature[1] was below 0 degrees Celsius for the Baseline scenario and the three future scenario

[1] The average daily temperature is calculated based on the average of the daily minimum and daily maximum for each day. This data was derived from a spatial data set extracted from a subset of the Okanagan Basin study area and is comprised of only the area above 1000m from the basins above Penticton.

periods. The data clearly shows a consistent declining trend in the number of days where the average temperature is below zero. In addition, there is a good indication of increases in both the maximum temperature and the minimum temperature, and some indication of an increase in the average temperature.

This trend is important because it supports the observation of declining snow accumulations discussed in the next section.

Table 4-9: Analysis of Average Daily Temperature

	Baseline		A2-Expected	
	1996-2006	2011-2040	2041-2070	Drought
Count (Days <0^{o}C)	1454	3576	3070	317
Avg. (Days/Yr < 0^{o}C)	132	119	102	106
Avg. Max Temp. (^{o}C)	23	25	27	25
Avg. Min Temp. (^{o}C)	-28	-24	-22	-17
Avg. Temp. (^{o}C)	4	5	6	6

Snowmelt

The following tables summarize the average accumulated SWE value above 1000 m as measured on the first day of February, March and April. These SWE values are used as the basis for forecasting the inflow volume to Okanagan Lake, and the forecasts are used to control the lake level during the freshet period. These tables show a consistent trend of a small decline in SWE values for the 2011-2040 scenario, and a much larger decline in the SWE values for the 2041-2070 scenario. Interestingly, the 2041-2070 scenario shows a consistently smaller average SWE value than the Drought scenario in all three months. Given the significantly lower precipitation during the Drought years, it was expected that these years would also have the lowest SWE values, but given the small sampling of Drought years it is not possible to say if this is a consistent trend or an artifact of a small sample.

Table 4-11 provides a summary of the maximum annual SWE and the date of occurrence while Figure 4-11 is a plot showing the date of occurrence of the maximum SWE vs. time, where the size of the 'bubbles' indicates the relative value of the maximum SWE in that year. The red markers represent the Baseline Scenario (1996-2006), the blue markers represent the 2011-2040 scenario, and the green markers represent the 2041-2070 scenario. This table and graph effectively identifies two distinct trends:

- The date of occurrence of the maximum SWE value is getting earlier
- The maximum SWE value is getting smaller

These trends are very important because they indicate that the snowmelt runoff contributions to the lakes will be peaking earlier in the year, and the spring snowmelt process will be providing a smaller amount of water.

Table 4-10: Analysis of SWE on February 1, March 1, and April 1

SWE (in mm) as of February 1st

	Baseline	**Scenario 25**	**Scenario 26**	**Scenario 27**
Maximum	314	286	273	233
Minimum	163	115	117	135
Average	218	206	174	189
% Change		-6	-20	-13

SWE (in mm) as of March 1st

	Baseline	**Scenario 25**	**Scenario 26**	**Scenario 27**
Maximum	350	330	277	263
Minimum	192	156	129	137
Average	255	236	196	211
% Change		-7	-23	-17

SWE (in mm) as of April 1st

	Baseline	**Scenario 25**	**Scenario 26**	**Scenario 27**
Maximum	392	339	243	261
Minimum	162	128	81	94
Average	270	228	162	178
% Change		-16	-40	-34

Table 4-11: Average Max. SWE and Date of Occurence

	Baseline	**Scenario 25**	**Scenario 26**
Avg. Date of Max SWE	March 20	March 16	March 1
Avg. Max. SWE (mm)	281	248	202

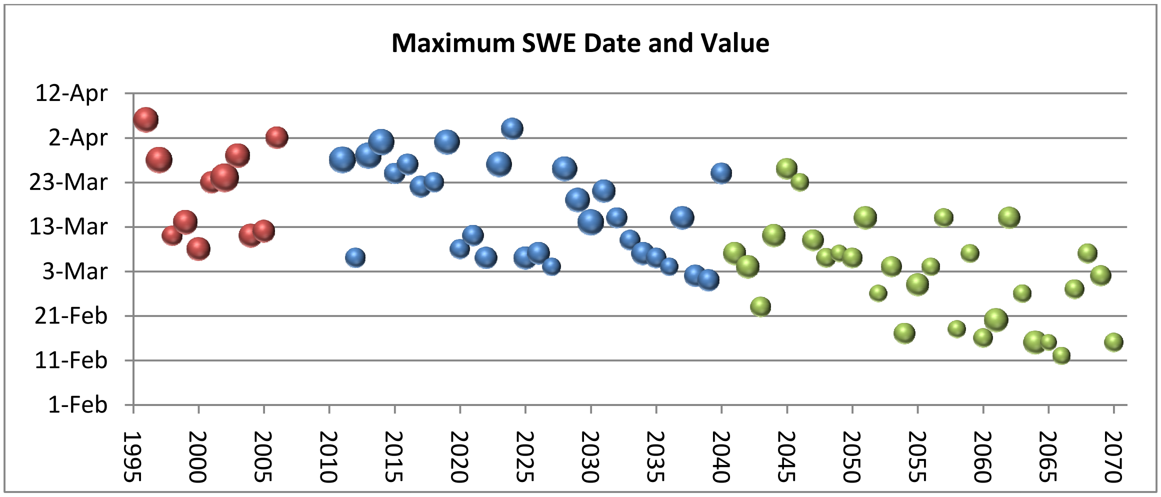


Figure 4-11: Maximum SWE value and date of occurrence

__Net Inflows to Okanagan Lake__

A summary of the average quarterly net inflows to Okanagan Lake is provided in Table 4-12 while a plot of the average weekly inflows to Okanagan Lake is presented in Figure 4-12. Although this analysis indicates there will be little change in the Annual Net Inflow to Okanagan Lake, it does present a clear shift in the timing and magnitude of the Net Inflows to Okanagan Lake.

In Q1 the reduced number of snow accumulation days (i.e. days with the average temperature below zero) causes more of the winter precipitation to be released as inflow. In Scenario 25 there is a moderate increase in the inflow, while in Scenario 26 there is a dramatic increase in the inflow. This can be easily seen in Figure 4-12 where the inflow for Scenario 26 is consistently higher than the Baseline scenario and Scenario 25.

In Q2 there is little difference between the Baseline scenario and Scenario 25, but as shown in Figure 4-12 the peak inflow for Scenario 25 is occurring earlier in Q2. In Scenario 26 the peak inflow in Q2 has continued to shift to an earlier time of the year, and the magnitude of the peak inflow is significantly reduced (likely due to less snow accumulation during Q1).

In Q3 it can be seen that negative Net Inflow is occurring earlier in the future scenarios, by approximately two weeks in Scenario 26. The quarterly summary table indicates a larger decline in Net Inflows in Scenario 25, relative to the Baseline, than in Scenario 26, but this is likely an artefact of the relatively low magnitude of the inflow values occurring during Q3 (see Figure 4-12).

For the Drought scenario, the average annual net inflows to Okanagan Lake are approximately one-half of the normal net inflows as measured against the Baseline scenario. Although this could be considered to be an extended drought when compared against the Baseline data, it is interesting to note that the average net inflows during the simulated drought are more than 3 times greater than during the severe drought recorded from 1929-1931 (Summit and Polar, 2009). During the 1929-1931 drought years the net annual inflows to Okanagan Lake were estimated to range from approximately 80,000 – 110, 000 ML.

Table 4-12: Summary of Average Quarterly Net Inflows to Okanagan Lake

		Baseline	Scenario 25	Scenario 26	Scenario 27
Quarter 1	Volume (ML)	62,906	84,756	139,030	39,978
	Difference (%)		35	121	-36
Quarter 2	Volume (ML)	458,293	466,512	367,476	168,410
	Difference (%)		2	-20	-63
Quarter 3	Volume (ML)	47,752	13,332	21,274	1,947
	Difference (%)		-72	-56	-96
Quarter 4	Volume (ML)	97,188	114,437	159,676	96,135
	Difference (%)		18	64	-1
Annual	Volume (ML)	666,139	679,037	687,456	306,470
	Difference (%)		2	3	-54

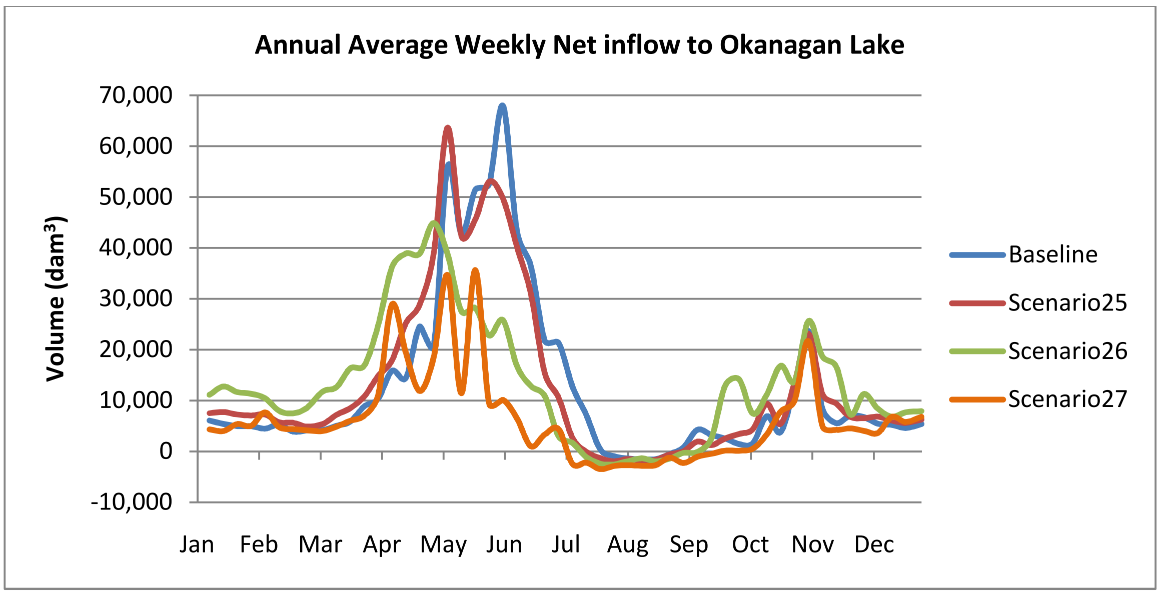


Figure 4-12: Average Weekly Net Inflows to Okanagan Lake

The surface water extractions from Okanagan Lake were also evaluated as a percentage of the Net Inflow to Okanagan Lake (using the E_S term from the OkWater Database). The average quarterly results are summarized in Table 4-13 while a plot of the average weekly values is presented in Figure 4-13. These results also indicate the summer period during which the Extractions exceed Net Inflow is occurring approximately 2 weeks earlier in Scenario 26, and the amount by which the Extractions exceed the Net Inflow is increasing by approximately 20% over the Baseline period.

This analysis is important because it demonstrates that although the Average Annual Net Inflow to Okanagan is not significantly changing in future scenarios, the period during which water supply is a potential problem is occurring earlier and the amount by which the Extraction exceeds Net Inflow during this period is increasing.

It should be noted that the % Difference values represent an average of the % Difference each week, rather than the % Difference between the Quarterly Average Net Inflow and the Quarterly Average Extraction. This was done for the sake of maintaining consistency with how the Net Inflow and Extraction values were calculated from the weekly data.

Table 4-13: Summary of Quarterly Average of Net Inflow vs. Extractions at Okanagan Lake

		Baseline	Scenario25	Scenario26	Scenario27
Quarter 1	Net Inflow (ML)	68,347	90,862	145,178	67,972
	Extraction (ML)	5,441	6,106	6,149	6,160
	Difference (%)	9	9	7	10
Quarter 2	Net Inflow (ML)	496,085	508,208	416,567	246,044
	Extraction (ML)	37,791	41,696	49,091	44,246
	Difference (%)	15	16	25	34
Quarter 3	Net Inflow (ML)	121,391	91,826	101,611	64,688
	Extraction (ML)	73,639	78,495	80,337	84,453
	Difference (%)	96	109	119	142
Quarter 4	Net Inflow (ML)	104,539	125,113	170,763	89,640
	Extraction (ML)	7,351	10,676	11,086	10,737
	Difference (%)	12	16	16	20
Annual	Net Inflow (ML)	790,361	816,010	834,120	468,343
	Extraction (ML)	124,222	136,973	146,664	145,597
	Difference (%)	33	38	42	52

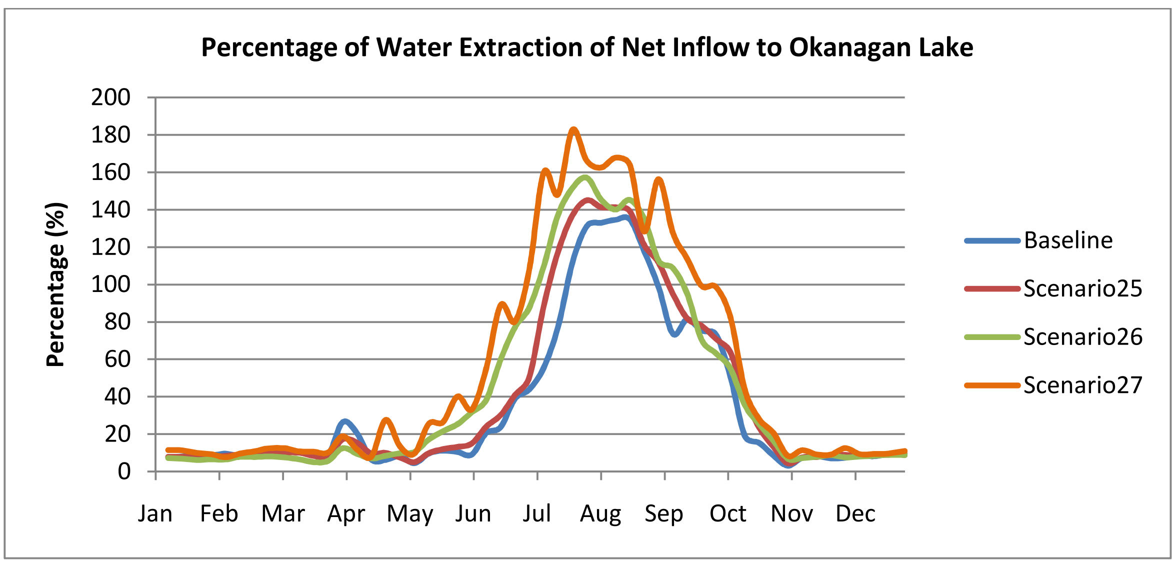


Figure 4-13: Weekly Average of % Extraction of Net Inflow to Okanagan Lake

Lake Levels

Plots of the lake levels for Okanagan Lake for each future scenario period are provided in Figure 4-14 to Figure 4-16, including the minimum and maximum operating levels for Okanagan Lake during the Baseline scenario from 1996-2006. These plots show that Okanagan Lake is likely to operate within the 'normal' ranges of lake levels for the majority of the time for Scenario 25 and Scenario 26, and as expected, it operates near or below the 'normal' range for the majority of the Drought scenario, but it never gets less than 0.8 m above the sill of the gates (339.7 m). It is interesting to note that the Scenario 25 climate data showed drought conditions for 4 successive years from 2014 to 2018 and during this time the response of the simulated lake level for Okanagan Lake was similar to the Drought scenario. However, given the apparent inability of the climate model to predict representative drought years, it is recommended that a more extreme drought scenario be evaluated in future phases of the project in order to properly evaluate the impacts and determine appropriate responses.

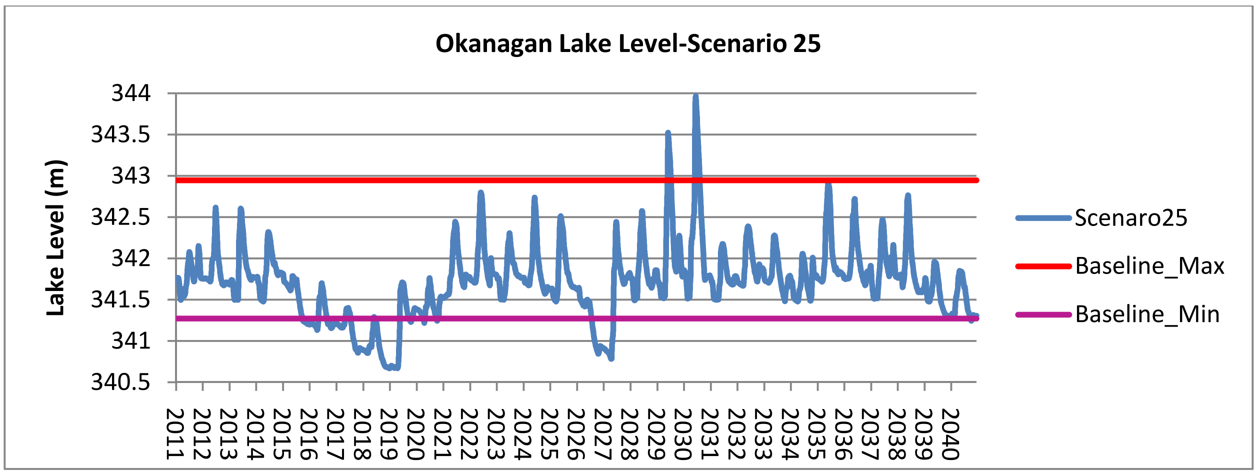


Figure 4-14: Okanagan Lake Level - Scenario 25

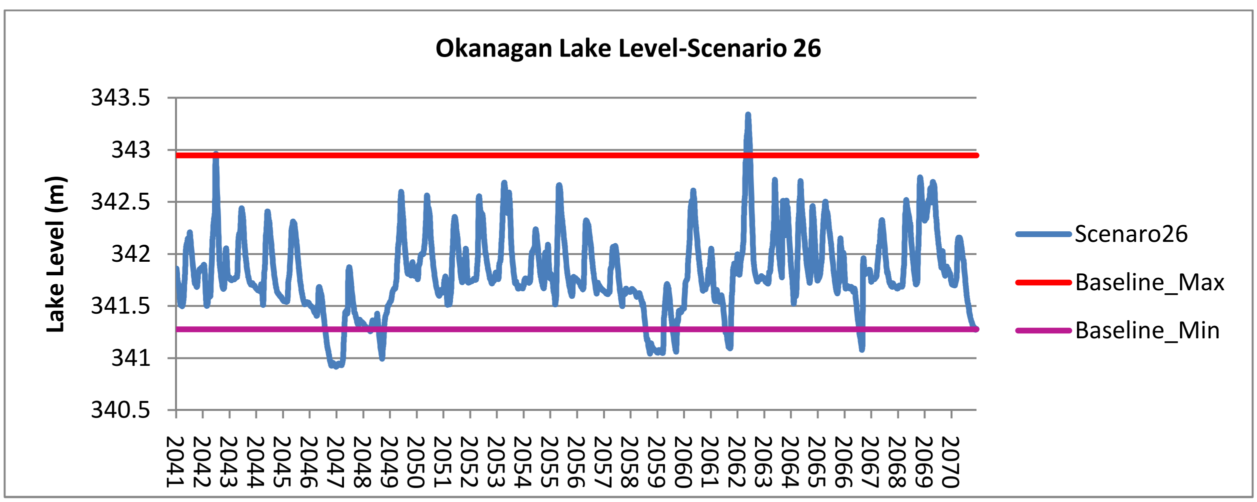


Figure 4-15: Okanagan Lake Level - Scenario 26

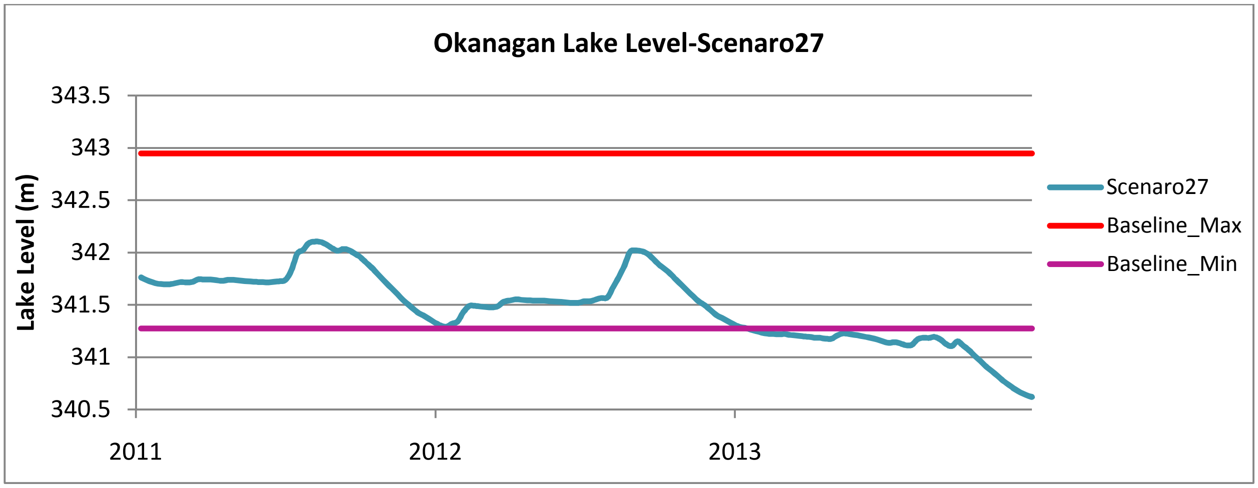


Figure 4-16: Okanagan Lake Level - Scenario 27

The average weekly lake levels for each climate change scenario are shown in Figure 4-17. This plot clearly shows the shift in seasonal trends for Scenario 26 where the lake levels begin to rise approximately one month earlier in the year (at the beginning of April) compared to the Baseline scenario and Scenario 25. But they also begin to decline in June – also approximately one month earlier than the Baseline scenario and Scenario 25.

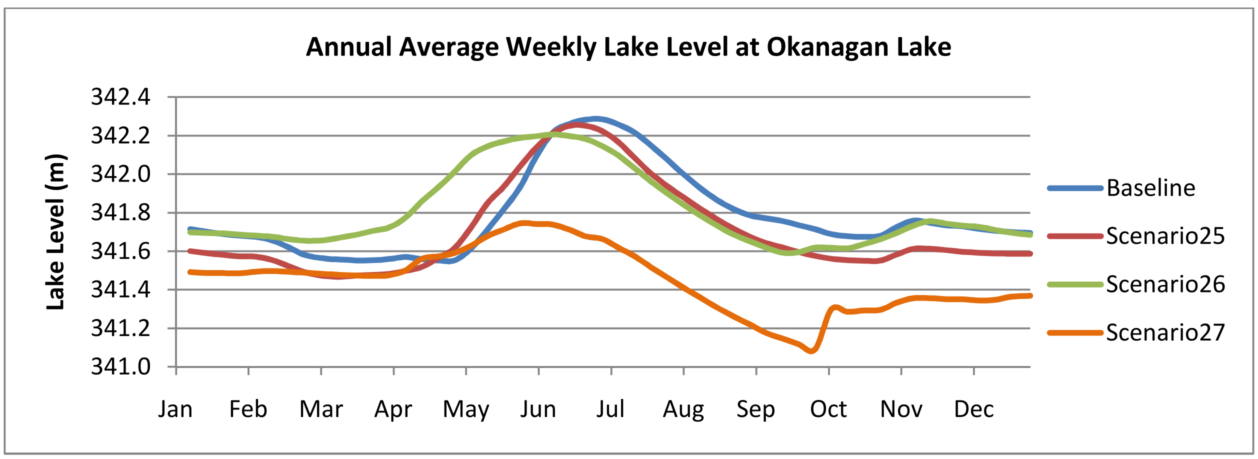


Figure 4-17: Average Weekly Lake Level at Okanagan Lake

<u>Tributary Flows</u>

This section examines the impact of climate change on the flows in selected tributares to the mainstem lakes of the Okanagan Basin. The tributaries examined in this section include Vernon Creek, Mission Creek, Trout Creek and Vaseux Creek.

Table 4-14 provides a summary of the average quarterly flows in Mission Creek for each future scenario, compared against the Baseline scenario. Figure 4-18 presents a plot of the average weekly flows in Mission Creek for each of the four scenario periods. Similar tables and plots for Vernon Creek, Trout Creek and Vaseux Creek are provided in Appendix F. In general, all of the tributaries examined in detail exhibit the same response to climate change as previously described in this report:

- Higher flows throughout the winter months, likely due to a higher number of melting days
- An earlier start to the spring snowmelt runoff, likely due to an earlier onset of spring temperatures
- A lower peak flow during the spring snowmelt runoff, likely due to less snow accumulation

In Q1 each tributary experienced increasing average flows from the Baseline to Scenario 25 to Scenario 26. As indicated above, this is likely due to the higher average temperature predicted in the future scenario climate data.

In Q2 there was no consistent trend for Scenario 25 compared against the Baseline scenario. In some cases the average simulated flow for Scenario 25 was higher, and in some cases it was lower but in general there was little overall change. Only Vernon Creek showed more than a 10% difference (+13%) from the Baseline to Scenario 25, but a significant portion of these flows are controlled releases from Kalamalka Lake, so this may have some influence as well.

In Q3 there is a consistent indication of lower flows in all tributaries, but in each case the flows in Scenario 25 are lower than the flows in Scenario 26. An examination of the plots of average weekly flows for each tributary shows increased flows in September and October during Scenario 26. An examination of the average weekly precipitation data indicates this is likely due to trends showing increased precipitation during this period.

In Q4 there is a consistent trend indicating increasing flows in all tributaries from the Baseline scenario to Scenario 25 to Scenario 26. This is attributable to the increased temperatures during the winter causing more precipitation runoff than snow accumulation. The higher flows in later Q3 and early Q4 in Scenario 26 correlate with the increased precipitation observed for that scenario during this time of the year. The increased flows during late October and early November are related to upland reservoir releases required to bring storage down to 80% of available capacity prior to the winter.

Table 4-14: Summary of Average Quarterly Flows in Mission Creek

		Baseline	Scenario 25	Scenario 26	Scenario 27
Quarter 1	Discharge(cms)	0.48	0.81	1.69	0.45
	Difference (%)		67	249	-8
Quarter 2	Discharge(cms)	13.63	15.44	13.36	8.37
	Difference (%)		13	-2	-39
Quarter 3	Discharge(cms)	2.64	1.28	1.08	0.41
	Difference (%)		-51	-59	-84
Quarter 4	Discharge(cms)	1.45	1.73	2.93	1.09
	Difference (%)		19	102	-25
Annual	Discharge(cms)	4.59	4.82	4.75	2.58
	Difference (%)		5	3	-44

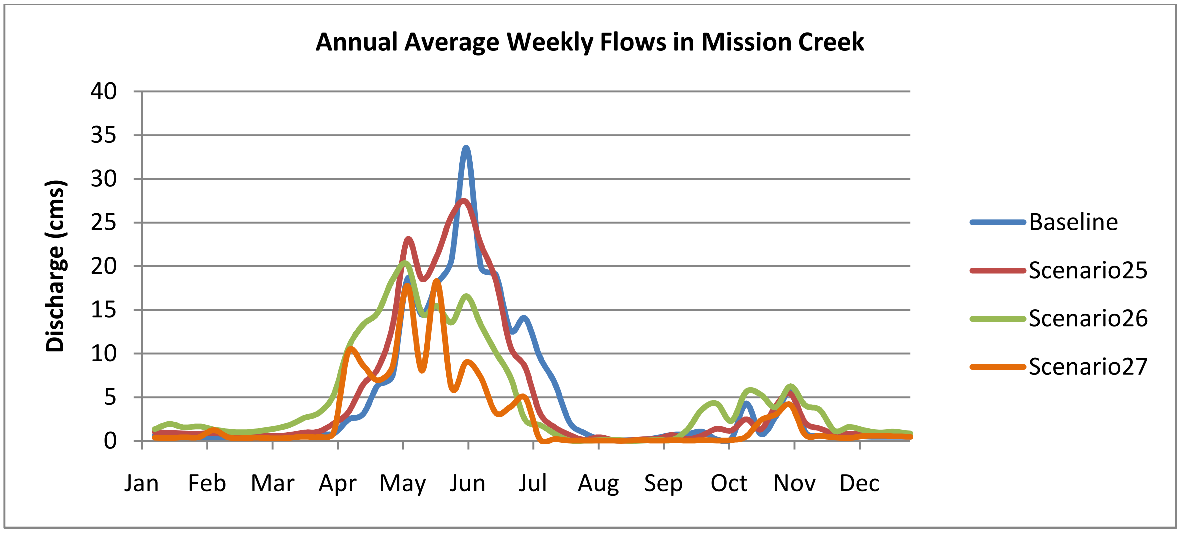


Figure 4-18: Average Weekly Flows at Mission Creek

The discharges (Q_OUT) in Mission Creek, Vernon Creek, Trout Creek and Vaseux Creek were also evaluated against the surface water extractions taken from each tributary to determine the relative amount of water being extracted vs. the discharge in each tributary. This analysis is important because it provides a clear indication of how delicate the water supply is during the summer months when discharge in the tributaries is generally low and water demand is generally high. Table 4-15 below presents a summary of the average quarterly discharge in Mission Creek vs. extraction rates while Figure 4-19 presents a plot of the average weekly extraction from Mission Creek (as % discharge). Quarterly summaries and plots for Vernon Creek, Trout Creek and Vaseux Creek are included in Appendix D.

It should be noted that the assumptions made about the operation of the upland reservoirs will have a significant impact on the available flows in the tributaries. Recall that the rules governing the releases from the uplands reservoirs are such that it tries to meet minimum flow requirements after extractions, baseflow, interflow, overland flow and return flows are taken into consideration for the section of the tributary downstream of the reservoir. The operational assumptions prevent the downstream tributaries from going dry unless the storage in the upload reservoir drops below 15% of available storage volume (see explanation in Section 3.2.1). This means there are some broad assumptions that go into the determination of flows in the tributaries, particularly during the summer months, so these analyses should be interpreted accordingly.

It is interesting to note that the average annual extraction from Mission Creek is relatively steady for all scenarios at around 30-33%, but the period during which the extraction is almost equivalent to the available flow in Mission Creek is getting longer and occurring earlier in the future scenarios, and of course, with the Drought scenario as well.

Table 4-15: Summary of Average Quarterly Discharge vs. Extraction for Mission Creek

		Baseline	Scenario25	Scenario26	Scenario27
Quarter 1	Discharge (cms)	0.54	0.87	1.75	0.50
	Extraction (cms)	0.05	0.06	0.06	0.06
	Difference (%)	14	9	7	14
Quarter 2	Discharge (cms)	14.46	16.35	14.48	9.32
	Extraction (cms)	0.83	0.91	1.12	0.95
	Difference (%)	13	12	16	19
Quarter 3	Discharge (cms)	4.56	3.32	3.19	2.62
	Extraction (cms)	1.92	2.03	2.10	2.21
	Difference (%)	74	82	87	95
Quarter 4	Extraction (cms)	1.52	1.89	3.10	1.24
	Extraction (cms)	0.07	0.16	0.17	0.15
	Difference (%)	12	17	18	22
Annual	Discharge (cms)	5.35	5.65	5.66	3.46
	Extraction (cms)	0.83	0.91	1.12	0.95
	Difference (%)	30	31	33	39

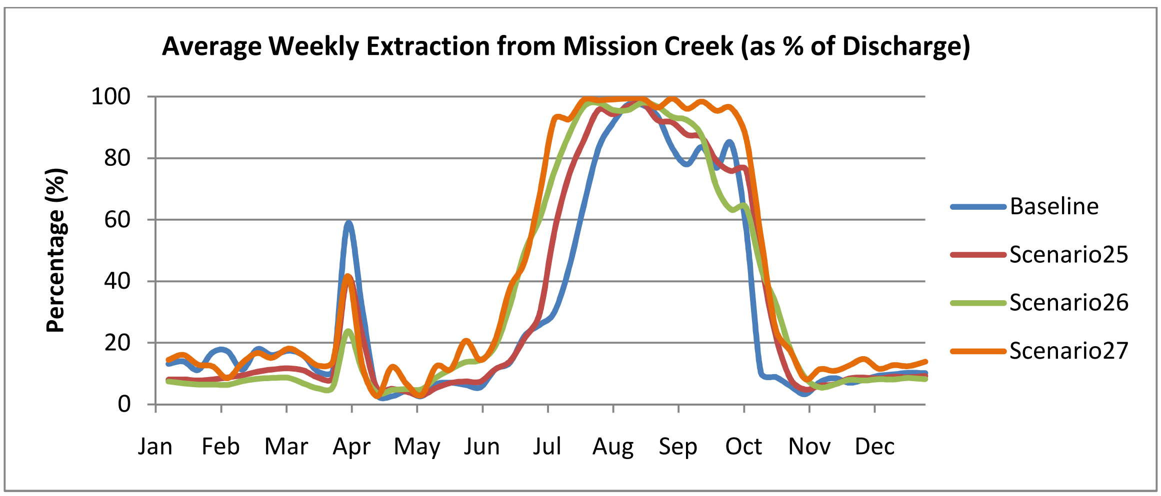


Figure 4-19: Average Weekly Extraction from Mission Creek (as % of Discharge)

Okanagan River Flows

This section examines the impact of climate change on the flows in Okanagan River at Penticton (immediately downstream of Okanagan Lake) and at Oliver (immediately downstream of Vaseux Lake).

Table 4-16 provides a summary of the average quarterly flows in the Okanagan River at Penticton for each future scenario, compared against the Baseline scenario. Figure 4-20 presents a plot of the average weekly flows in Okanagan River at Penticton for each of the four scenario periods. Similar tables and plots for the flows at Oliver are provided in Appendix F. In general, both of the locations examined in detail exhibit the same response to climate change as supported by the previous findings in this report:

- Higher flows throughout the winter months, likely due to a higher number of melting days
- An earlier start to the spring snowmelt runoff, likely due to an earlier onset of spring temperatures
- A lower peak flow during the spring snowmelt runoff, likely due to less snow accumulation

In Q1 each location experienced increasing average flows from the Baseline to Scenario 25 to Scenario 26 (in ascending order). As indicated above, this is likely due to the higher average temperature predicted in the future scenario climate data.

In Q2 each location experienced decreasing average flows from the Baseline to Scenario 25 to Scenario 26 (in decending order). These changes are relative small so it is difficult to determine if there is a consistent trend, but it is likely a result of the earlier spring snowmelt causing earlier flood control releases from Okanagan Lake.

In Q3 each location experienced decreasing average flows from the Baseline to Scenario 25 to Scenario 26 (in decending order). This is likely a result of the earlier spring snowmelt. In the Baseline and Scenario 25, the spring snowmelt runoff can be seen to extend well into Q3, but in Scenario 26 the spring snowmelt has mostly completed by the end of Q2.

In Q4 there is a trend indicating increasing flows at each location from the Baseline scenario to Scenario 25 to Scenario 26 (in ascending order). The higher flows observed in the early part of Q4 are likely attributable to the increase in precipitation during this period, while the slightly higher flows observed late in Q4 are attributable to higher temperatures causing more runoff than snow accumulation during this period. The peaks observed in early November are attributable to released from the uplands reservoir required to reduce storage to 80% of capacity prior to winter.

Table 4-16: Summary of Average Quarterly Flows in Okanagan River at Penticton

		Baseline	Scenario 25	Scenario 26	Scenario 27
	Discharge(cms)	14.63	16.35	18.26	6.80
Quarter 1	Difference (%)		12	25	-54
	Discharge(cms)	19.41	18.56	17.87	7.05
Quarter 2	Difference (%)		-4.4	-7.9	-63.6
	Discharge(cms)	16.74	15.70	11.75	6.47
Quarter 3	Difference (%)		-6	-30	-61
	Discharge(cms)	10.77	12.21	16.70	6.75
Quarter 4	Difference (%)		13	55	-37
	Discharge(cms)	15.44	15.69	16.02	6.78
Annual	Difference (%)		2	4	-56

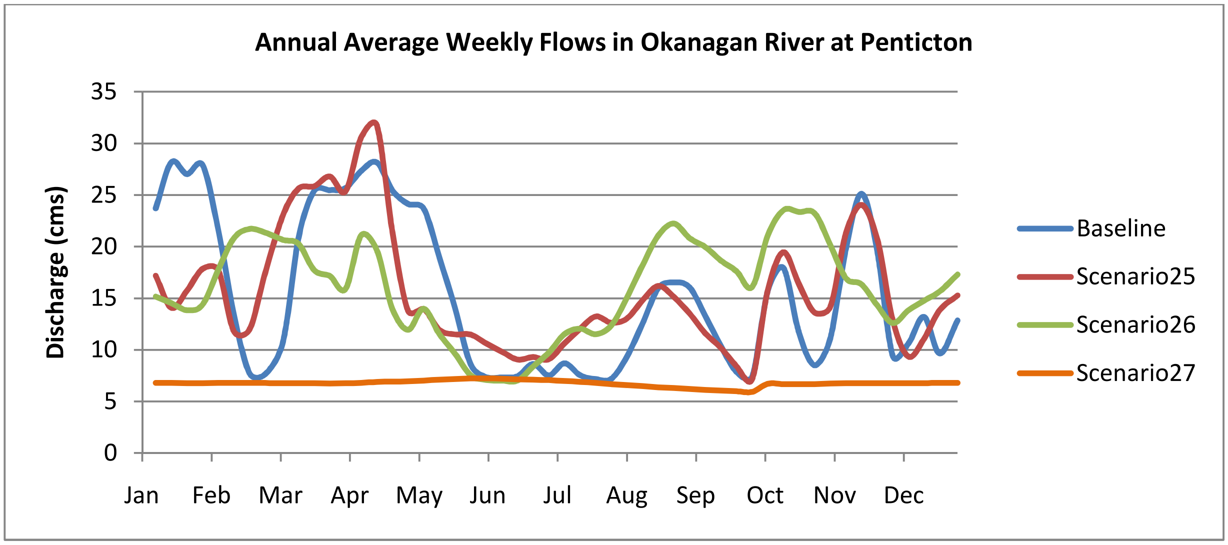


Figure 4-20: Average Weekly Flows in Okanagan River at Penticton

Upland Reservoir Storage

This section examines the impact of climate change on the total storage in the upland reservoirs in the Okanagan Basin.

Table 4-17 provides a summary of the average quarterly total storage in the uplands reservoirs for each future scenario, compared against the Baseline scenario. Figure 4-21 presents a plot of the average weekly storage available in the uplands reservoirs for each of the four scenario periods. Appendix F contains plots of the weekly total storage in the uplands reservoirs for each scenario period. In general, the annual trends seen in upland reservoir storage show the same response to climate change as previously indicated in this report:

- Earlier increases in storage, likely due to an earlier onset of spring temperatures
- A lower peak storage, likely due to lower snow accumulation
- Earlier drawdown of storage, likely due to small spring snowmelt runoff volumes
- Significantly lower storage available in the late summer due to a longer summer season

In Q1 the total storage remained relatively constant with all of the scenarios.

In Q2 there is a slight increase in the total storage from the Baseline scenario to Scenario 25 to Scenario 26 (in ascending order). These changes are relative small so it is difficult to determine if there is a consistent trend, but it is likely a result of the earlier spring snowmelt resulting in more accumulation during this period.

In Q3 there is a consistent trend towards decreasing storage from the Baseline to Scenario 25 to Scenario 26 (in decending order). This is also likely a result of the earlier spring snowmelt. In the Baseline and Scenario 25, the spring snowmelt runoff can be seen to extend well into Q3, but in Scenario 26 the spring snowmelt has mostly completed by the end of Q2. This requires the upland reservoirs to begin releasing flows earlier in the year in order to meet downstream demands and low flow requirements in the tributaries.

In Q4 there is a trend towards a slightly increasing rate of accumulation of total storage. The amount of total storage is still less in Scenario 25 and Scenario 26, but they is recovering at a faster rate than the Baseline. The large decline in storage at the beginning of November occurs because the reservoirs reduce storage to 80% of available capacity prior to the onset of winter in order to prepare for the spring freshet. This is done because ice build-up around the gates will often prevent operation of the dams in later winter and early spring.

Table 4-17: Summary of Average Quarterly Storage in Uplands Reservoirs

		Baseline	Scenario25	Scenario26	Scenario27
Quarter 1	Storage (dam^3)	84,916	85,313	85,309	79,888
	Difference (%)		0.5	0.5	-5.9
Quarter 2	Storage (dam^3)	100,359	102,814	104,802	95,392
	Difference (%)		2.4	4.4	-4.9
Quarter 3	Storage (dam^3)	103,794	100,526	95,071	84,390
	Difference (%)		-3.1	-8.4	-18.7
Quarter 4	Storage (dam^3)	91,074	88,236	86,389	79,751
	Difference (%)		-3.1	-5.1	-12.4
Annual	Storage (dam^3)	100,359	102,814	104,802	95,392
	Difference (%)		2.4	4.4	-4.9

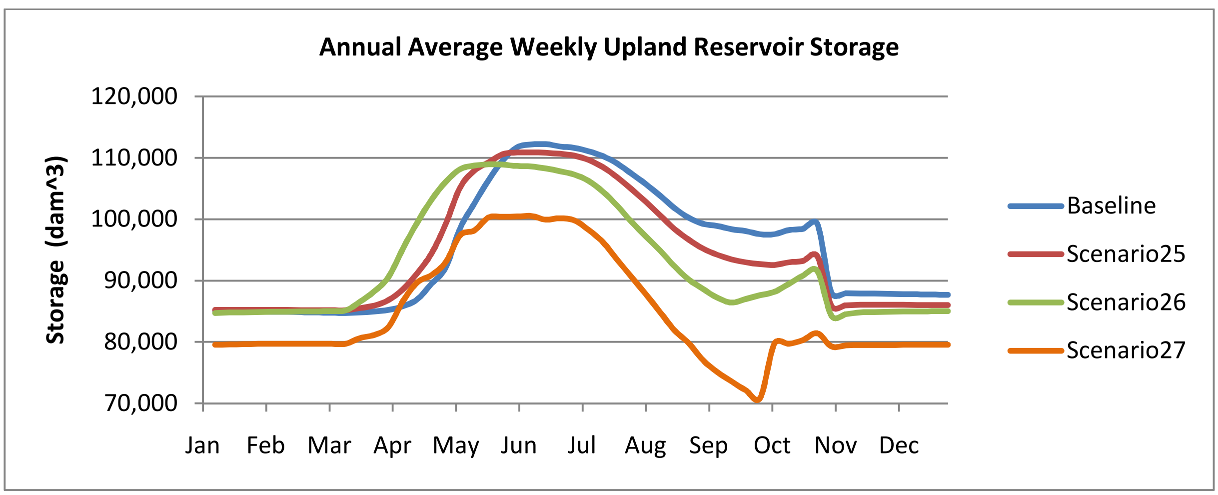


Figure 4-21: Average Weekly Storage in Upland Reservoirs

4.3.3 Effects of Water Use

The effects of the different combinations of Water Use considerations was examined by comparing the relative change in results for scenarios 1-8 and 25 against each other using selected plots of annual and seasonal results, as well as using a matrix as described above. This section will examine the impacts of the various water use scenarios described by examining the impacts of each scenario on the Net Inflow to Okanagan Lake as well as the discharge in selected tributaries.

Net Inflows to Okanagan Lake

This section examines the impact of the various Water Use scenarios on the Net Inflows to Okanagan Lake. Figure 4-22 shows a plot of the annual Net Inflows to Okanagan Lake for each of Scenarios 1-8 and Scenario 25. This figure demonstrates that the changes in the water use between Scenarios 1-8 have very little positive or negative impact on the annual net inflows.

Figure 4-23 shows a plot of the % change in the annual net inflow to Okanagan Lake for each scenario relative to Scenario 25. This plot shows consistent trends from each set of Water Use scenarios. As expected, Scenario 4 demonstrates the most significant negative impact on the current conditions because it has the highest population, the most irrigable lands, and the highest per capita consumption. However, even during the worst conditions, Scenario 4 had less than a 10% negative impact on the net inflows to Okanagan Lake.

Figure 4-23 clearly shows the positive impact of the accelerated implementation of the 33% water efficiency for Scenarios 5-8 during the first 10 years. However, even for Scenario 5, with the most optimistic outlook (lowest population, lowest irrigable lands, and lowest per capita water consumption) the best improvement that is made after 10 years is approximately 2% savings over the present conditions.

Finally, Table 4-18 provides a matrix of the % change in average annual net inflows to Okanagan Lake for each scenario.

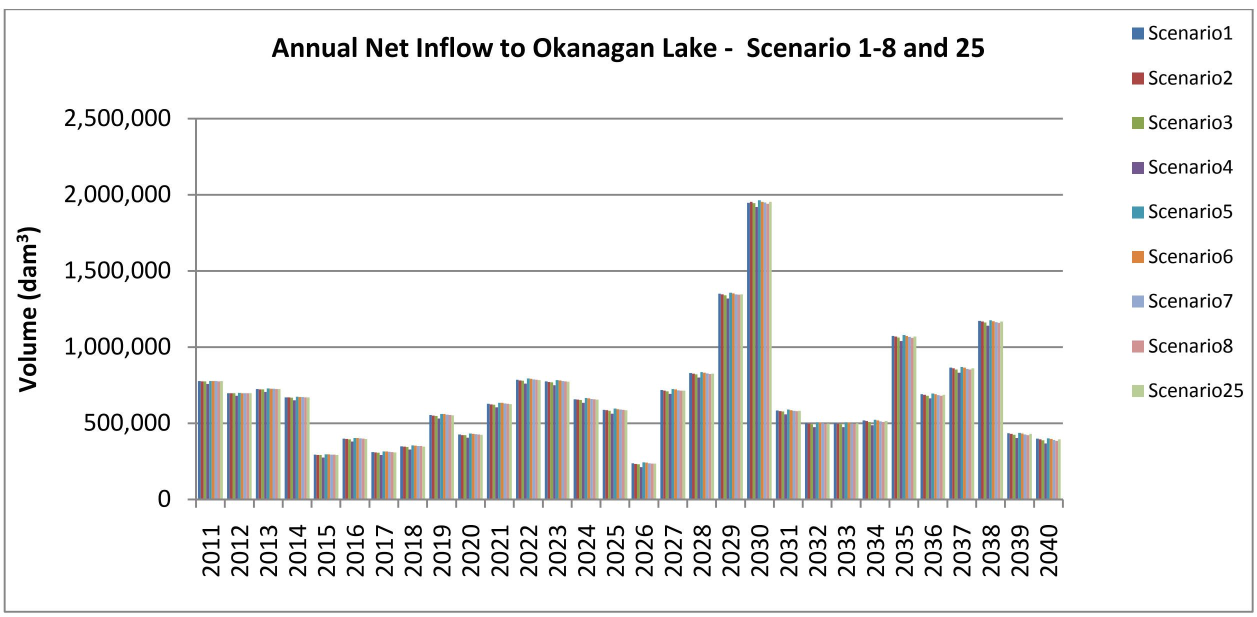


Figure 4-22: Annual Net Inflow to Okanagan Lake - Scenarios 1-8 and 25

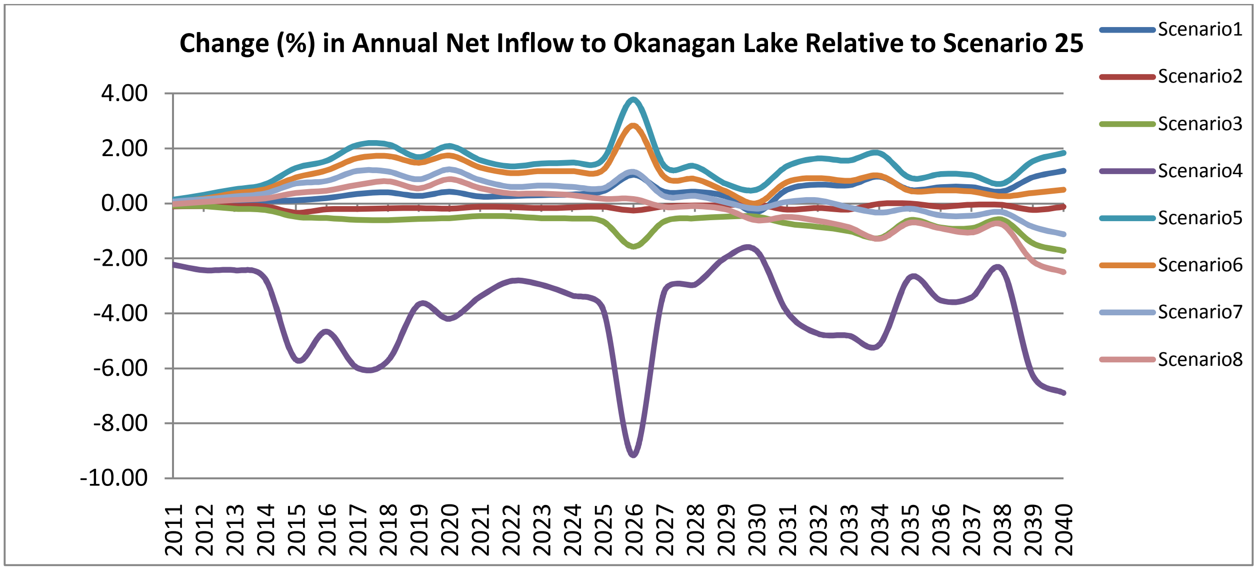


Figure 4-23: Change (%) in Net Inflow to Okanagan Lake Relative to Scenario 25

Table 4-18: Change (%) in the Average Annual Net Inflow to Okanagan Lake

	S1	S2	S3	S4	S5	S6	S7	S8	S25
S1		-0.45	-0.96	-3.70	0.82	0.38	-0.19	-0.63	-0.34
S2	0.45		-0.51	-3.27	1.28	0.83	0.26	-0.19	0.11
S3	0.97	0.52		-2.77	1.80	1.35	0.78	0.33	0.63
S4	3.85	3.38	2.85		4.70	4.24	3.65	3.19	3.49
S5	-0.81	-1.26	-1.77	-4.49		-0.44	-1.00	-1.44	-1.15
S6	-0.37	-0.82	-1.33	-4.06	0.44		-0.56	-1.01	-0.71
S7	0.19	-0.26	-0.77	-3.52	1.01	0.57		-0.44	-0.15
S8	0.64	0.19	-0.33	-3.09	1.46	1.02	0.45		0.30
S25	0.34	-0.11	-0.62	-3.38	1.16	0.72	0.15	-0.30	

Based on the above analyses it is clear that, on an annual basis, the water use efficiency measures will not have a significant impact on the annual net inflows to Okanagan Lake. These analyses also demonstrate there is sufficient water supply in the basin to meet water demands now and well into the future. However, although this is surely good news for water supply in the Okanagan Basin, it is not the whole story because the problems with water supply occur mostly during the summer periods of the year when the supply is low and the demand is high.

Figure 4-24 presents a comparison of the seasonal net inflow to Okanagan Lake for each scenario during the period from June to September each year, while Figure 4-25 presents a plot of the change in the average seasonal net inflow for each scenario relative to Scenario 25. These plots show that the water efficiency measures have a much more significant impact on the net inflow during the summer months when the net inflow is usually low and demand is usually high.

In Figure 4-24 it can be seen that during the predicted drought from 2015-2018 the accelerated water efficiency measures in Scenario 8 indicate it will require 20% less of the available net inflow to Okanagan Lake than the worst case represented by Scenario 4.

Similarly, during the dry year in 2026 the accelerated water efficiency measures in Scenario 8 indicate it will require almost 35% less of the available net inflows to Okanagan Lake than the worst case represented by Scenario 4.

The results for 2033 were difficult to interpret with this type of analysis because the net inflows were close to zero for Scenario 25. In this case even the small changes in net inflow between scenarios had a very large impact on the net inflows relative to Scenario 25.

In general, it is clear that the water use considerations have a much more significant impact on the net inflows to Okanagan Lake when only seasonal flows are evaluated during the summer months, and they are particularly valuable during drought periods when total inflows are lower than normal and water demands are higher than normal.

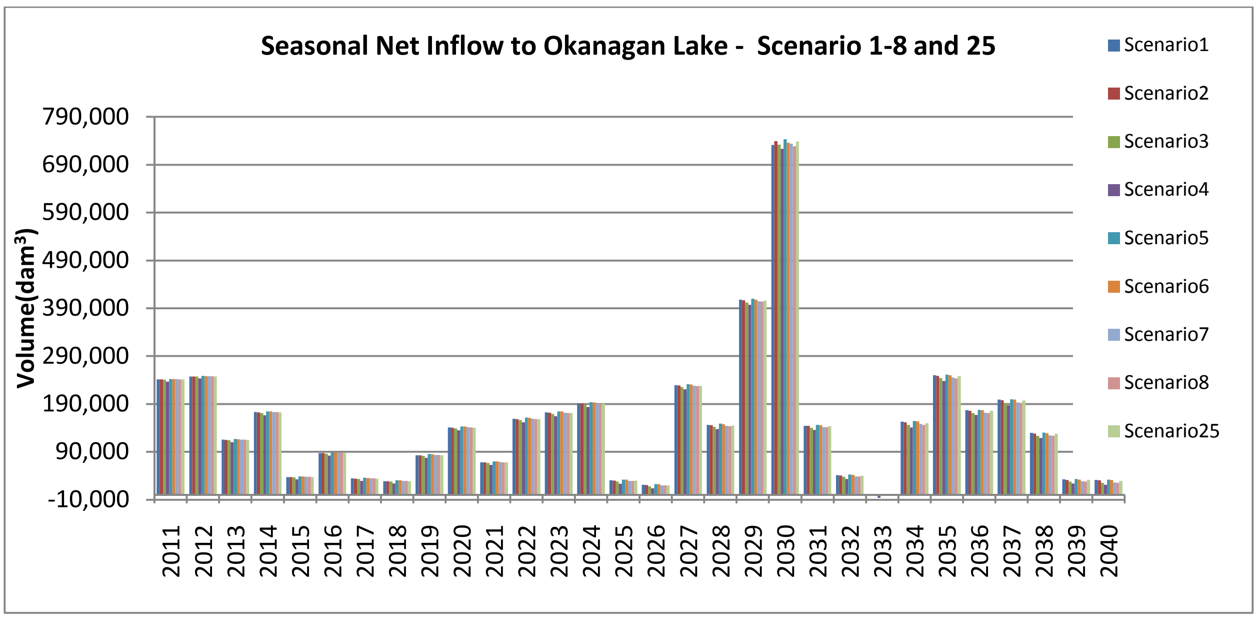


Figure 4-24: Seasonal (Jun – Sep) Net Inflow to Okanagan Lake for Scenarios 1-8 and 25

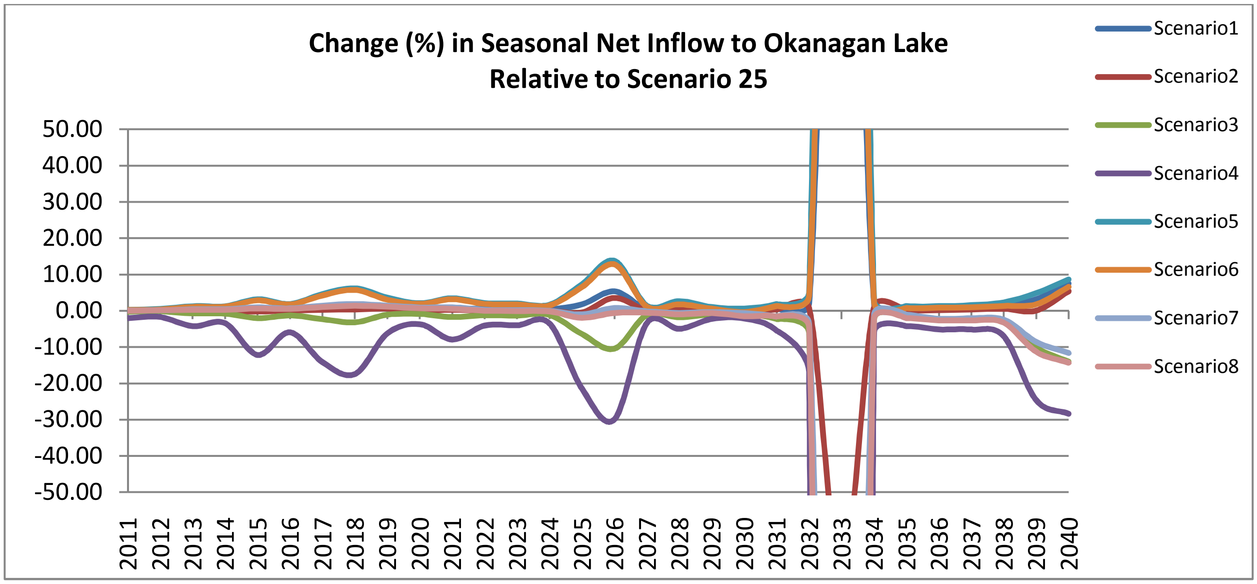


Figure 4-25: Change in Seasonal (Jun – Sep) Net Inflow to Okanagan Lake Relative to Scenario 25

Tributary Flows

This section examines the impact of water use considerations on the flows in selected tributaries to the mainstem lakes of the Okanagan Basin. The tributaries examined in this section include Vernon Creek, Mission Creek, Trout Creek and Vaseux Creek.

Table 4-19 provides a matrix of the change in average annual flow volumes at Mission Creek for each scenario. These results are consistent with the results presented above where the various water use scenarios show, at best, a 14% increase in the average annual flow in Mission Creek could be achieved by Scenario 5 vs. Scenario 4 through various planning, policy and water use efficiency measures.

Figure 4-26 shows a summary of the seasonal flow volumes at Mission Creek from June to September each year, while Figure 4-27 presents a plot of the change in the average seasonal flow volumes for Scenarios 1-8 relative to Scenario 25. These plots show that the seasonal flow in Mission Creek is usually much larger than the impact of the water use considerations, but during periods of drought the water efficiency measures do have a measurably positive impact (up to 25%) on the summer season flows in Mission Creek. This result is particularly important because it demonstrates a significantly positive impact of water efficiency measures during critical times of the year when water supply issues are most relevant. As demonstrated previously the flows in the tributaries will begin declining earlier in the year, and the extraction will be almost equivalent to the available flows for longer periods of the summer. As such, even moderate reductions in the required extractions will make a significant difference in either the available flows in the tributaries, or the amount of water required to be released from the upland reservoirs.

A similar analysis was completed on Vernon Creek, Trout Creek and Vaseux Creek (see Appendix F). Vernon Creek and Trout Creek demonstrated very similar results as Mission Creek, while Vaseux Creek did not demonstrate any significant impact from the water use scenarios. The lack of response of Vaseux is likely due to the relatively low levels of water use in this catchment.

Table 4-19: Change (%) in the Average Annual Flow Volumes in Mission Creek

	S1	S2	S3	S4	S5	S6	S7	S8	S25
S1		0.02	-1.08	-11.26	1.28	0.98	-0.03	-0.30	-0.56
S2	-0.02		-1.10	-11.28	1.26	0.96	-0.05	-0.32	-0.58
S3	1.09	1.11		-10.29	2.39	2.09	1.06	0.79	0.53
S4	12.69	12.72	11.48		14.13	13.80	12.66	12.36	12.06
S5	-1.26	-1.24	-2.33	-12.38		-0.29	-1.29	-1.56	-1.81
S6	-0.97	-0.95	-2.04	-12.13	0.29		-1.00	-1.27	-1.53
S7	0.03	0.05	-1.05	-11.24	1.31	1.01		-0.27	-0.53
S8	0.30	0.32	-0.78	-11.00	1.58	1.28	0.27		-0.26
S25	0.56	0.58	-0.53	-10.77	1.85	1.55	0.53	0.26	

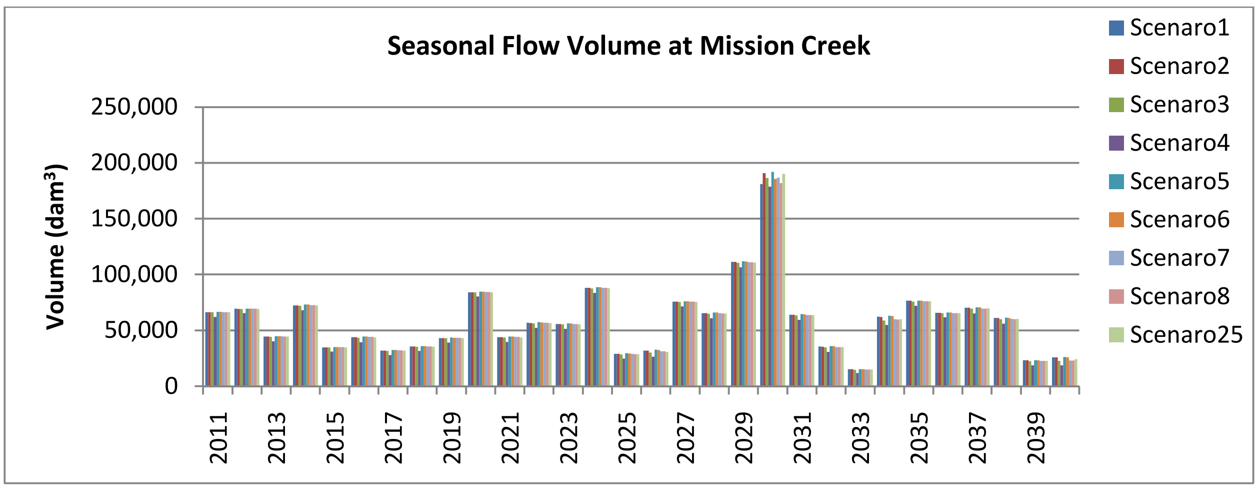


Figure 4-26: Seasonal (Jun – Sep) Flow Volumes at Mission Creek - Scenarios 1-8 and 25

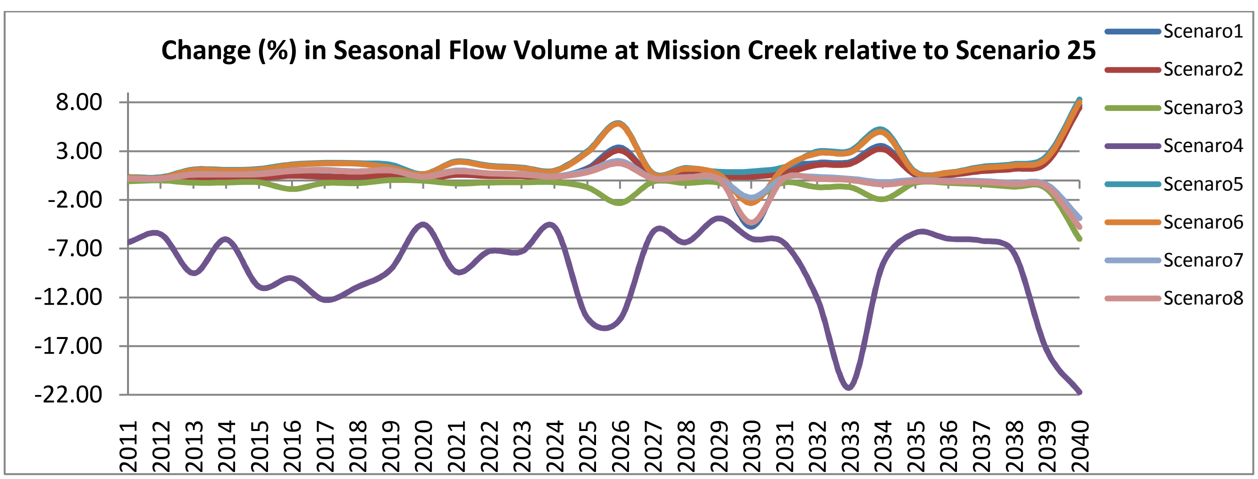


Figure 4-27: Change in Average Seasonal (Jun - Sep) Flow Volumes Relative to Scenario 25

4.4 OKWATER DATABASE UPLOAD

After running the 15 scenarios, the results were processed to extract the data for required water balance terms as described in Section 3.4 for the calibration period.

- **P_L:** Precipitation onto lake during time t (used for the 5 main lake nodes only)
- **E_L:** Evaporation from lake during time t (used for the 5 main lake nodes only)
- **Q_out:** Residual streamflow (after storage and withdrawal effects) from node i during time period t. Also equivalent to net streamflow after anthropogenic influences.
- **Q_in:** Net inflow to mainstem lake (node i) during time t (incoming streamflow from all sources (mainstem river, tributary and miscellaneous surface flow)) plus direct precipitation onto the lake, less evaporation from the lake, plus human additions and subtractions from the lake itself.
- **L_Elev:** Lake elevation (node i) at start of time t, in meters above mean sea level. E.g., first day of day 1 in week t, and last day in week t. (Not an average value).
- **Q_S:** Natural direct runoff component of streamflow at node i during time t. Also called overland flow.
- **Q_F:** Interflow to streams in node i, during time t. (MikeSHE)
- **SigmaD_SN:** Naturally-occurring baseflow component of streamflow at node i during time t (the sum of natural groundwater discharge from one or more groundwater aquifers)
- **Q_S&SigmaD_SN&Q_F:** Natural streamflow at node i during time t

The P_L values were extracted as area average values directly from the gridded climate data for the area occupied by each main lake and processed to weekly values.

The E_L values were extracted as area average values from the gridded evapotranspiration results for the area occupied by each main lake, but as indicated in Section 2.3.7 these values are essentially the same as the PET values from the gridded climate data used as input for the model.

The Q_out values were extracted from Q-point of the MIKE 11 model corresponding to the associated water balance node location and the results were processed to weekly values.

The Q_in values were obtained by summing the baseflow contributions to each calculation point of each MIKE 11 river branch representing each lake, and then processing the time series to weekly values. The weekly Q_in value was then calculated as the sum of weekly baseflow for each lake + weekly Q_out for all tributaries to the lake + weekly P_L values for each lake - weekly E_L for each lake.

The L_Elev values were obtained from the calculated water level results at the H-point in the MIKE 11 branch immediately upstream of the dam at each lake.

The Q_S values were obtained by summing the overland flow contribution to each calculation point of each MIKE 11 river branch of each tributary upstream of each water balance node and processed to weekly values. The resultant time series was then processed to weekly values.

The Q_F values were obtained by summing the interflow flow contribution to each calculation point of each MIKE 11 river branch of each tributary upstream of each water balance node and processed to weekly values. The resultant time series was then processed to weekly values.

The SigmaD_SN values were obtained by summing the baseflow flow contribution to each calculation point of each MIKE 11 river branch of each tributary upstream of each water balance node. The resultant time series was then processed to weekly values.

The Q_S&SigmaD_SN&Q_F values were obtained by summing the Q_S, Q_F, and SigmaD_SN weekly values.

The weekly values for these water balance terms were then assembled in a format compatible for upload to the OKWater Database and provided to ESSA.

5 CONCLUSIONS AND RECOMMENDATIONS

The Okanagan Basin Hydrology Model (OBHM) was successfully developed using the MIKE SHE integrated watershed modelling system incorporating physical data inputs that represent the spatially and temporally variable hydrologic characteristics of the basin. The model was calibrated to accurately represent the naturalized hydrologic response of the basin as measured against available snow pack data, streamflows, lake water levels, and discharge from the dams along the mainstem.

The OBHM was then used to develop the Okanagan Basin Water Accounting Model (OBWAM). The OBWAM is a sophisticated, flexible and scalable hydrology model capable of accurately reproducing a continuous hydrologic response over a wide range of climate conditions from 1996-2006. The model is also able to accurately represent and reproduce the real-time operational logic of the dams on each of the mainstem lakes in the Okanagan Basin.

The purpose of developing the OBWAM was to evaluate the basin wide water supply implications due to potential changes in climate, land use, water use and mountain pine beetle infestation. This objective was successfully demonstrated by running fifteen different future scenarios to evaluate different combinations of climate change and water use against the recent historical hydrologic response of the basin. The future climate data was generated using the CGCM2-A2 model for one historic period (1996-2006) to establish a baseline, and then for three future periods (2011-2040, 2041-2070, and a three year drought period established using the three driest years from 2010 – 2100). The water use scenarios were assembled to consider three main factors;

(4) Population growth (expected growth rate vs. high growth rate)

(5) Water use efficiency (current trends vs. increased efficiency)

(6) Agricultural land base expansion (present conditions vs. expanded agricultural base)

A comprehensive analysis of the scenario results was prepared and presented in this report. The main conclusions from comparing the Baseline Scenario to the future scenarios are as follows:

- The total annual precipitation and evapotranspiration do not exhibit any obvious trends in the future scenarios, but the average temperature increases and the number of freezing days (i.e. days with average temperatures below zero degrees Celsius) decreases significantly.
- As a result of climate change reducing the number of freezing days, the maximum snow water equivalent decreases by almost 30% and is occurring almost 3 weeks earlier
- As a result of climate change the spring snowmelt runoff hydrograph for most tributaries to the mainstem lakes is shifted 2-4 weeks earlier in the year, and peak flows are consistently lower.
- As a result of the changes to the timing and volume of the spring snowmelt, the upland reservoirs begin emptying earlier and have an average of 10% less storage available at the end of the summer season.
- The mainstem lakes all operate within normal ranges of water levels during the majority of the future scenario periods, and at no time did the water level drop below the level required to maintain minimum flows in the Okanagan River.
- When measured on an annual basis, Okanagan Basin produces a sufficient volume of water to comfortably meet water use demands for the forseeable future, but due to changes in the timing and volume of the spring snowmelt, the difficulties in meeting increasing demands during the low flow summer season will get worse under current operating conditions.

- Improved water efficiency measures have a measurably positive impact on the water supply during the summer months, and particularly during dry years when water use represents a more significant portion of the available water supply.
- In the Drought scenario the net inflow to Okanagan Lake will be approximately one half of the normal inflows. This will result in the levels for Okanagan Lake dropping well below the normal operating range but still maintaining minimum flows in the Okanagan River.

5.1 RECOMMENDATIONS

The integrated watershed model developed for this study represents the first model of this kind, and at this scale, in Canada. In its current state the model has demonstrated it is capable of producing a very good representation of the major hydrologic responses throughout the Okanagan Basin. However, this project has been a continuous learning process for all members of the team, and as this project has progressed it is clear that there are many ways to improve the performance, reliability, accuracy and calibration of the model, and to broaden the application of the model. This section will discuss the major recommendations for future improvements to the model.

Evaluate More Climate Models

The results of this study are useful and informative in terms of evaluating the potential impacts of climate change and water use considerations, but it must be remembered that this study applied only one of many different global climate models which could be used to generate the future climate conditions. In order to properly bracket the potential impacts of climate change, several additional climate models should be applied and evaluated before any final conclusions regarding climate change can be made.

More High Elevation Climate Stations

The gridded climate data sets provided a much better spatial and temporal resolution of the climate data than is normally available for hydrology studies. However, the under-representation of high elevation stations used to generate the climate data likely resulted in data that is heavily weighted towards the trends occurring at lower elevations. As such, the gridded temperatures may be over-predicted in some cases, which may be causing some of the anomalous runoff events simulated by the model. In order to correct this, at least 2 more meteorological stations should be installed at locations above an elevation of 1500 m, and preferably close to a snow pack measurement station.

Install Additional Flow Monitoring Stations

To improve the calibration of the model, it is recommended to install additional streamflow monitoring gages throughout the basin. In addition to providing valuable calibration data for the model, strategically placed monitoring stations will also help to characterize the surface water and groundwater interactions throughout the year and through different seasonal trends. Ideally, streamflow monitoring stations should be placed at the following locations:

- Immediately upstream of every upland reservoir: These stations will enable a more accurate calibration of the hydrology upstream of the reservoirs in order to make sure the model is generating the correct inflow to each upland reservoir.
- Immediately downstream of each upland reservoir: These stations will establish calibration flows against which the release rules for each reservoir could be calibrated against.

- Upstream of the alluvial fan in the main valley: These stations will help to characterize the lower elevation extractions and any streamflow gains or losses to the alluvial aquifer.
- Immediately upstream of the mouth of the tributary at the the mainstem lake: These stations will help to characterize the extractions and any baseflow losses or gains from the upstream gage.

The model calibration results can also be used to guide the additional data needs for the model. Since the results from the model indicate a good match for most of Natural and High Confidence stations, the locations where the model did not provide a good correlation with the naturalized data may be an indication of flaws in the naturalized data rather than flaws in the model parameters. By collecting more real data at these locations we can determine whether the model needs to be corrected, or whether the naturalized data was flawed. In total there were 7 nodes where the correlation coefficient for the calculated vs. measured streamflows was less than 0.7. These nodes include Vernon Creek at Kalamalka Outlet (N1), Irish Creek (N5), Nashwito Creek (N10), Vernon Creek at mouth (N12), MacDougall Creek (N26), and Testalinden Creek (N76).

Remote Sensing Data

Although the LAI values were determined largely using raster maps generated from remote sensing, the data quality was generally poor and even after some manual corrections were made to correct obvious flaws, the resultant LAI patterns were inconsistent with expected values for some of the vegetation types. If a more reliable set of remote sensing data is available for LAI it could possibly improve the calibration of the model by providing a more realistic representation of evapotranspiration processes.

Remotely sensed snowpack data could also be used to calibrate the model, particularly in regions where the model is lacking snow stations. In addition, if it is possible to obtain almost real-time estimates of snowpack throughout the basin, this information could be provided to the MIKE SHE model as an initial condition, and the model could be used as a real-time hydrological forecasting tool to help guide the operations of the dams on the mainstem lakes.

Groundwater Modelling

Although the groundwater pumping is implicitly accounted for with the calibrated model, a thorough review of the implementation of groundwater processes is recommended to see if it is possible to find a more integrated approach that will allow the groundwater extraction to be explicitly represented in the baseflow reservoirs while also accounting for the portion of that extracted water than is re-applied on the ground surface for irrigation.

Alternatively, since tapping into the groundwater supply may be one of the keys to resolving the water supply problems during the summer months, a fully-distributed, three-dimensional groundwater model would provide a more accurate representation of the groundwater and surface water exchanges and the responses to increased groundwater extractions. However, in order to do this, a more comprehensive hydrogeological characterization of the Okanagan Basin will be required to develop a more detailed, multi-layer conceptual model.

Upland Reservoir Operations

For the future scenarios, some broad assumptions/simplifications were made regarding the operation of the uplands reservoirs, and these assumptions may have a significant impact on the ability of the model to accurately reflect how the system will behave in the future. Since the upland reservoirs seem to play a key role in managing the supply of water to the downstream lakes and water license holders, it is recommended to investigate methods to improve the simple rules used to control the releases from the Upland Reservoirs, or to incorporate the operating logic of the uplands reservoirs in the MIKE 11 model.

Mainstem Lake Operations

Although considerable effort was put into the improving of the operational rules for the mainstem lakes, the operation of the dams by the model is still far more frequent than in practice, and usually results in much larger fluctuations in outflow from the dam. The methods and settings used to control and operate the dams should be carefully reviewed to ensure they are as consistent as possible for all dams, and to minimize unrealistic oscillations in the releases from the dams.

One of the problems encountered with the calibration of the operational rules for Osoyoos Lake was that the lake is actually operated based on predicted flows in the Similkameen River located outside the Okanagan Basin model study area. Since the operation of the dam on Osoyoos Lake controls the release of water out of the Basin, it is important to be as accurate as possible. As such, it is recommended to take steps to incorporate the inflow forecasting used for the Similkameen River, and to properly account for drought condition operations.

Finally, it is recommended that the MOE should record logic for gate change decisions as well as gate levels. By doing so, it would provide some insight into the rules and decision processes that are followed, particularly when they diverge from the published operations plans. This would help to more easily identify periods where the dam should not be expected to behave as indicated in the documents Lake Operation Plans.

Model Verification

The scientific rationale for the model development process adopted in this study has been described in detail in this report and accepted by the Project Working Group. However it is possible that additional comfort with the outcome could be achieved by exposing the model to time periods not used for calibration. To that end, there appears to be several new streamflow monitoring stations installed throughout the basin in 2006 and 2007. Thus, it is recommended to consider the possibility of using the data from these new and previously existing stations to verify the model during the period from 2007-2010. This would involve minimal preparation of the OBWAM itself, but it would require, among other things, assembly and QA/QC of the monitoring data as well as preparation of the water use data and Q_R and Q_T terms at each node.

Improve Performance of the Model

In its current state, the model requires several days to run through a 30 years scenario. Now that all of the major project deadlines have been met, it is recommended to perform a thorough review of the model setup and computations processes to determine which processes are creating the most computational burden and to examine ways of making the model more efficient without sacrificing the quality of the results.

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Appendix A

Lake Operations Plans

Okanagan Lake Regulation System Operating Plan

MONTH	VOLUME FORECAST (million cu. m.)	OKANAGAN LAKE ELEVATION (metres)	SKAHA LAKE ELEVATION (metres)	VASEUX LAKE ELEVATION (metres)	FLOW AT OLIVER (cu. m./sec)
Jan.		341.74 by month end	337.80	327.40	5.0 to 28.3
Feb	< 430	As High as Possible	337.80	327.40	5.0 to 28.3
	> 430	341.54 by month end			5.0 to 28.3
Mar.	< 620	As High as Possible	337.80	327.40	5.0 to 28.3
	> 620	341.49 by month end			5.0 to 28.3
Apr.	<260	As High as Possible	337.80	327.40	5.0 to 28.3
	370 to 500	341.44 by month end			5.0 to 28.3
	> 620	341.04 by month end (major flooding expected)			> 45.0
May	Lake Filling	342.48 by month end	337.85	327.50	> 6.5
June		342.44 by month end	337.90	327.[illegible]	> 6.6
July		342.24 by month end	337.90	327.60	> 8.2
Aug		342.04 by month end	337.30	327.60	10.6 to 28.5
Sep.		342.04 on Sep 1st	337.85	327.50	9.2 to 28.3
		341.94 by Sep. 15th			9.9 to 15.6
		341.69 by Sep 30th			
Oct.		341.64 by Oct.15th	337.80	327.40	9.9 to 15.6
Nov.		341.84 by month end	337.60	327.40	5.0 to 28.3
Dec.		341.64 by month end	337.80	327.40	5.0 to 28.3

NOTES . Lake elevations are targeted for the end of the month unless otherwise noted.
Flows at Oliver are targeted for the beginning of the month unless otherwise noted.
Max. flows at Oliver may be exceeded in August and September due to extreme flood conditions.
Lake levels may be exceeded due to extreme flood conditions.
Okanagan Lake levels may not be attained due to extreme drought conditions.
Okanagan River flows at Penticton and Okanagan Falls are "as required to obtain lake levels"
Flows at Oliver from Nov. 1 to April 30 not less than 50% of the Sept. 15 to Oct. 31 flow.

****** New datum for Okanagan Lake = 340.236m GSC (July 2007) ******
results in new water level targets.

Kalamalka Lake Operating Plan

Surface Area	3520 ha
Normal Operating Range	391.2m – 391.7m
Normal Discharge Range	0.085cms – 5.7cms
FV = Forecast Volume	

Targets

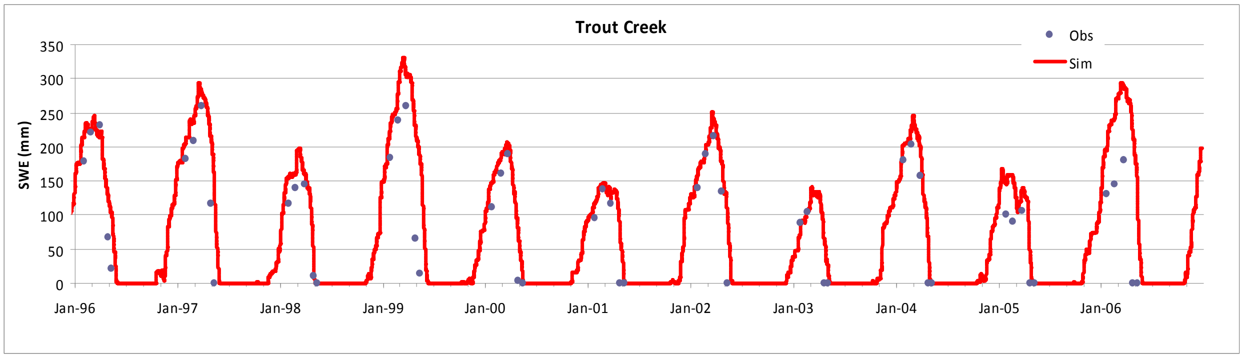
Month	Lake Level(LL) *	Discharge(Q)
January	391.2	0.085 (minimum fishery flow)
February	391.2	FV < 15 $(10)^6$: Q = 0.085 FV > 15 $(10)^6$: Set Q to maintain LL = 391.2
March	391.2	FV < 15 $(10)^6$: Q = 0.085 FV > 15 $(10)^6$: Set Q to maintain LL = 391.2
April	391.4	FV < 30 $(10)^6$: Set Q to achieve LL = 391.5 FV > 30 $(10)^6$: Set Q to achieve LL = 391.4
May	391.6	Set Q to achieve LL = 391.6
June	391.7 391.67	Set Q to achieve LL = 391.7
July	391.6	Set Q to achieve LL = 391.6
August	391.5	Set Q to achieve LL = 391.5
September	391.4	Set Q to achieve LL = 391.4
October	391.35	Set Q to achieve LL = 391.35
November	391.3	Set Q to achieve LL = 391.3
December	391.25	Set Q to achieve LL = 391.25

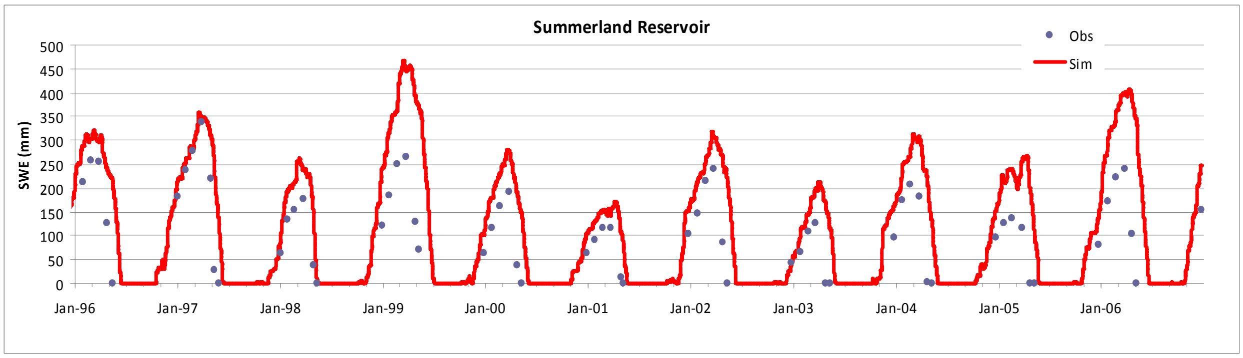
* Month-end targets

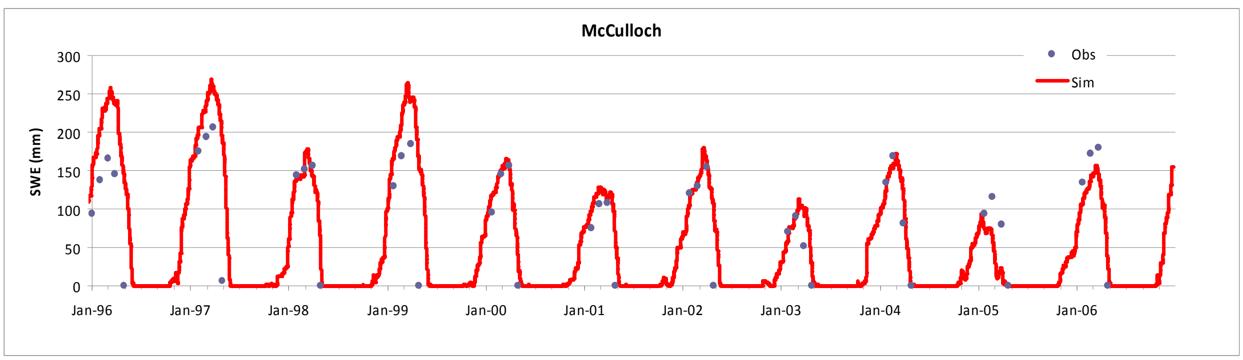
Ray Jibb May/01

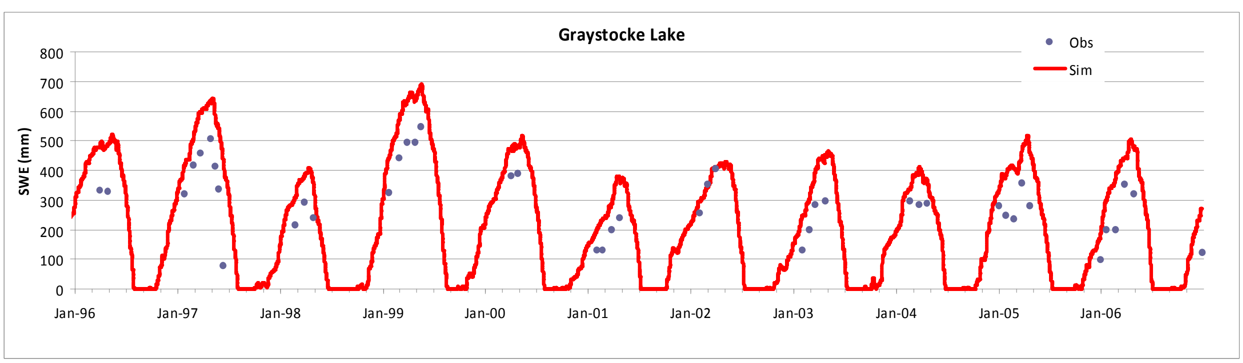
Appendix B
Okanagan Basin Hydrology Model Calibration Plots

Comparison of Simulated SWE with Observed SWE

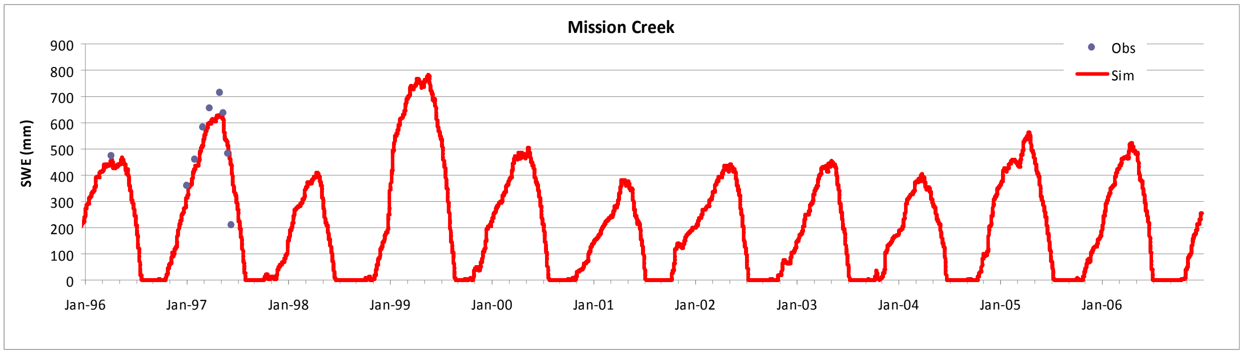


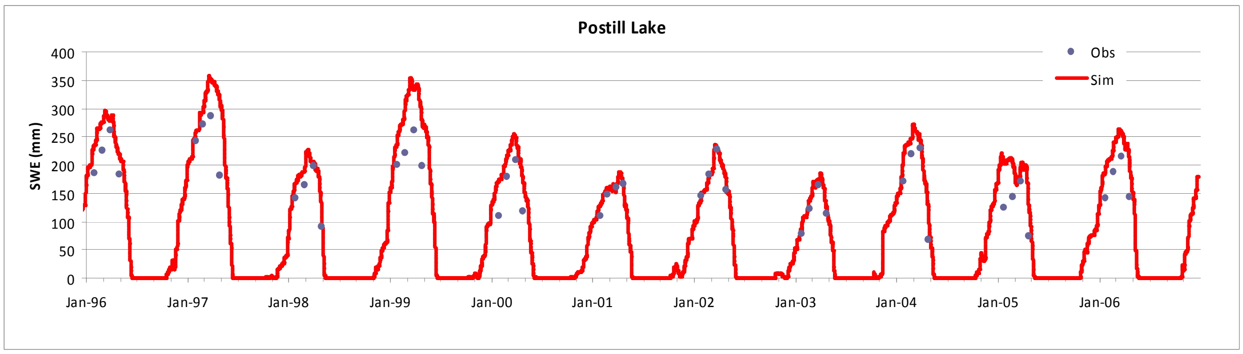


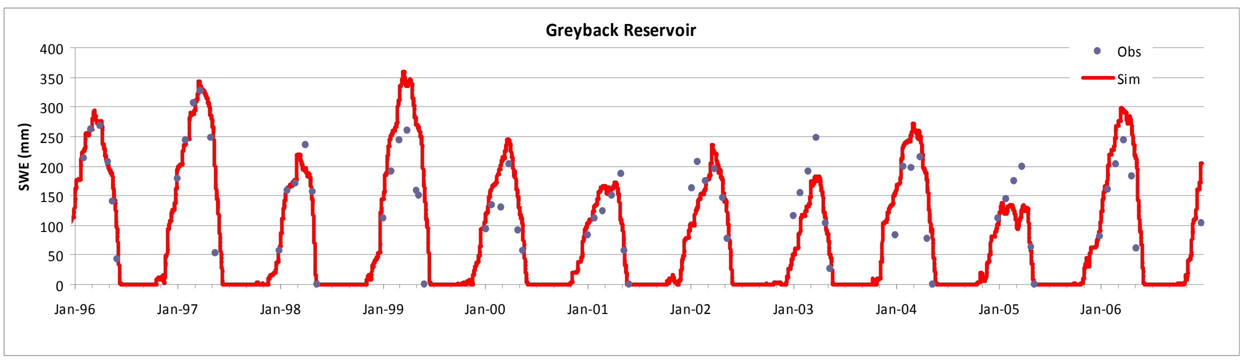


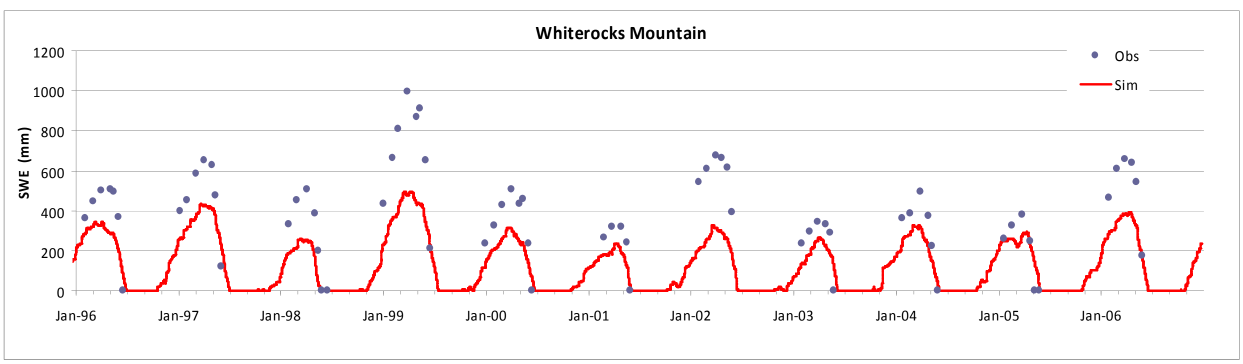


Comparison of Simulated SWE with Observed SWE

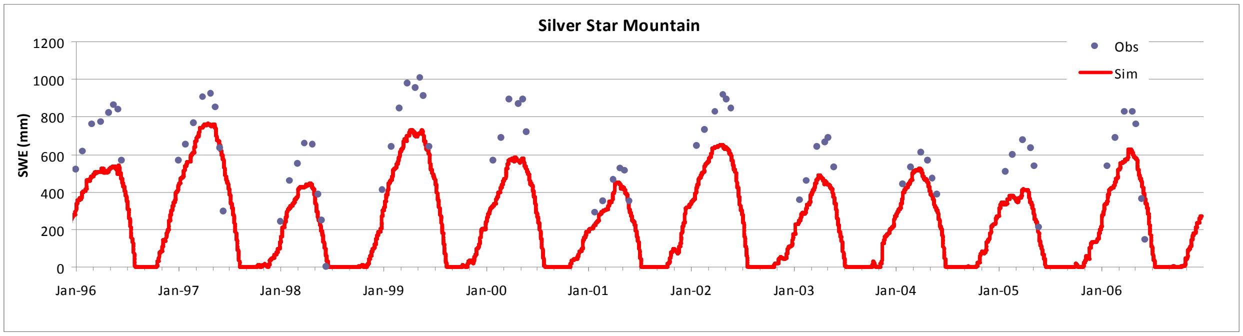


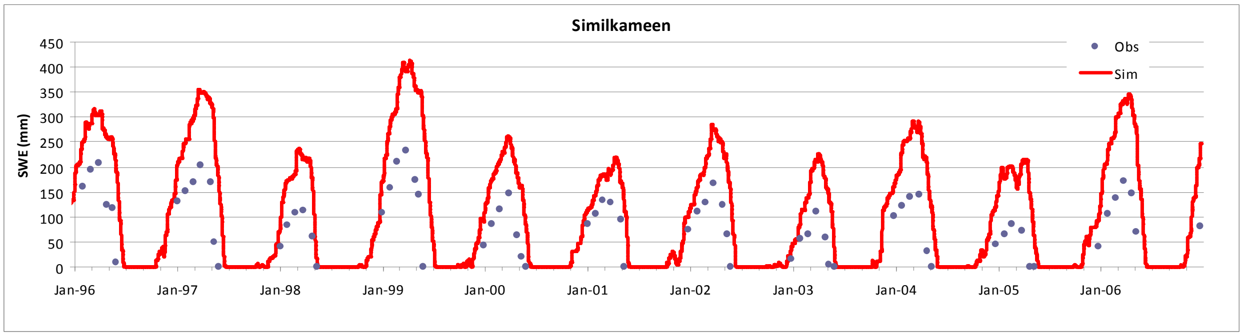


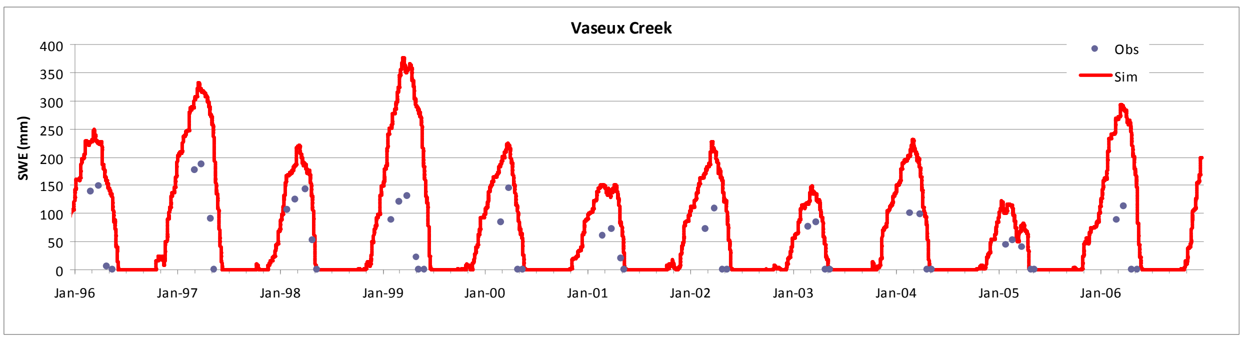


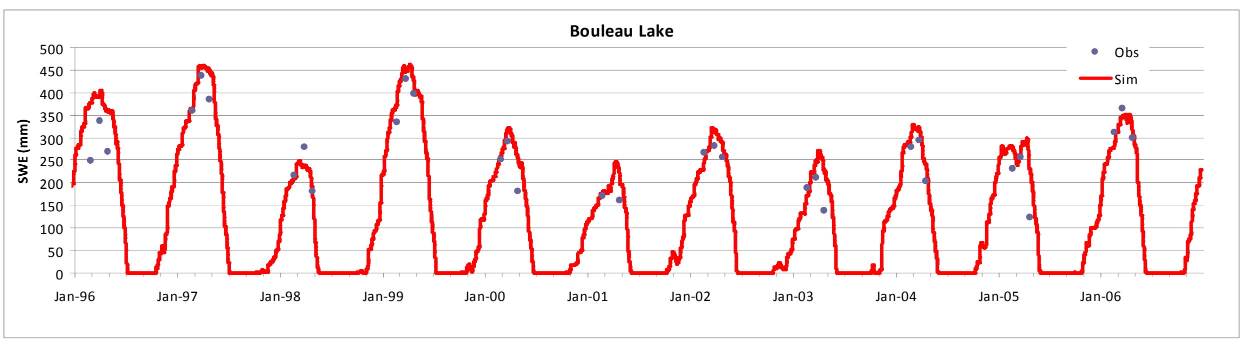


Comparison of Simulated SWE with Observed SWE

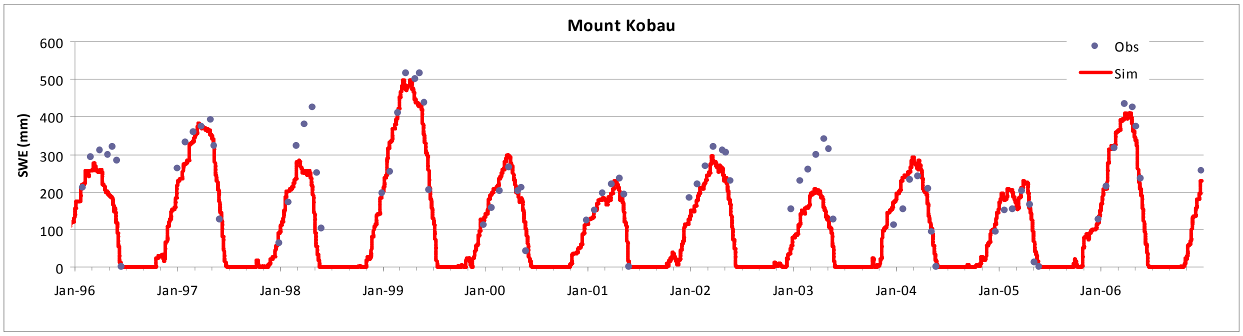


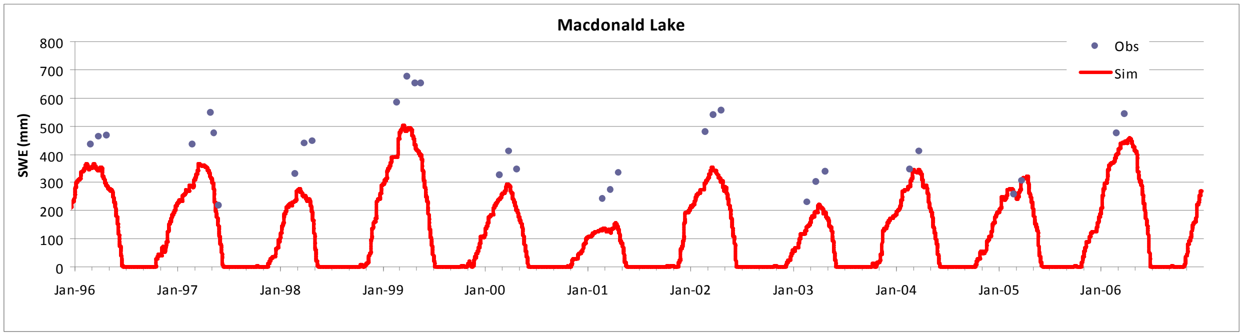


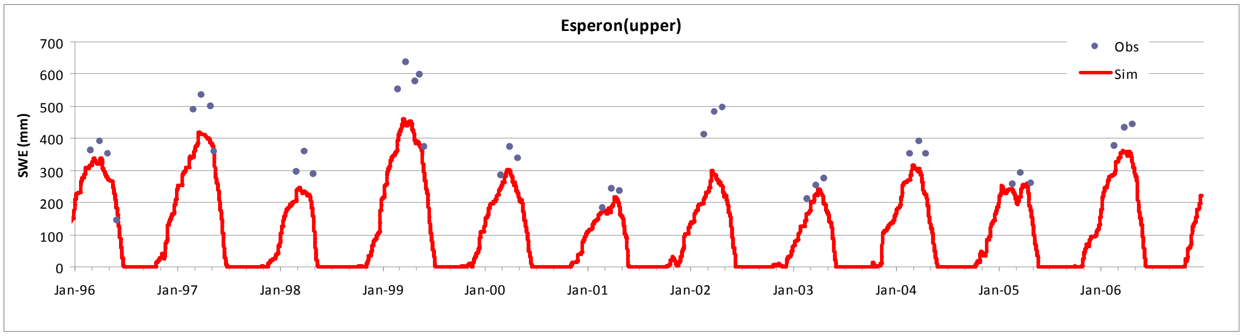


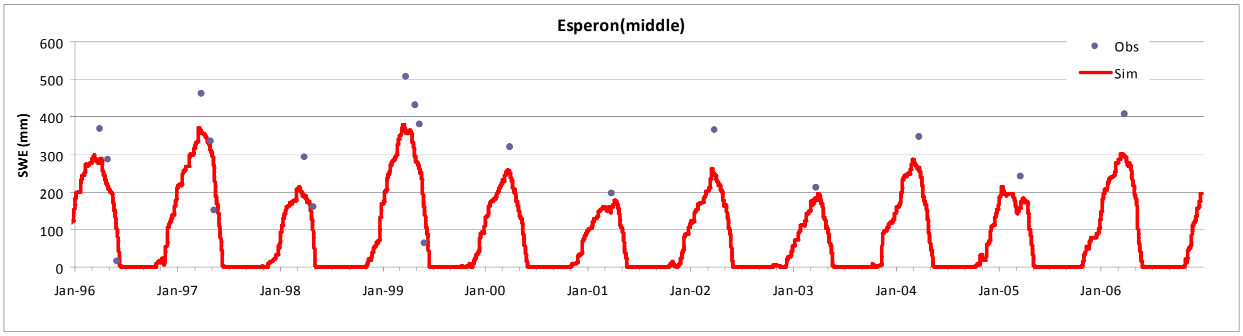


Comparison of Simulated SWE with Observed SWE

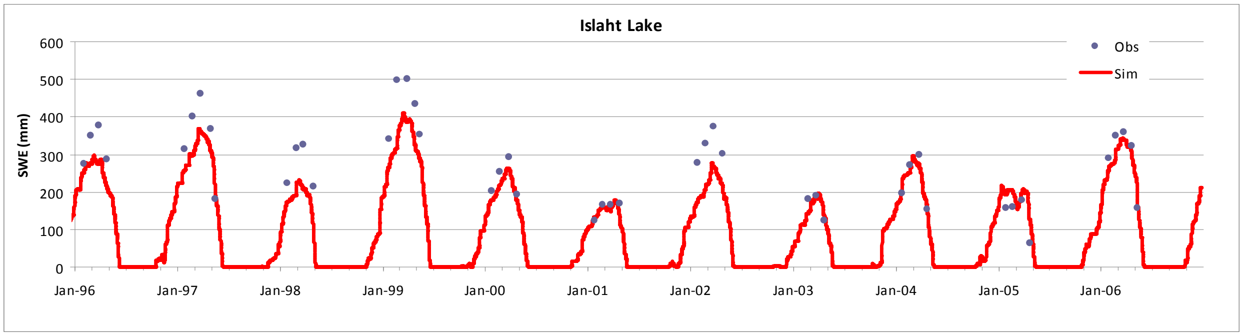


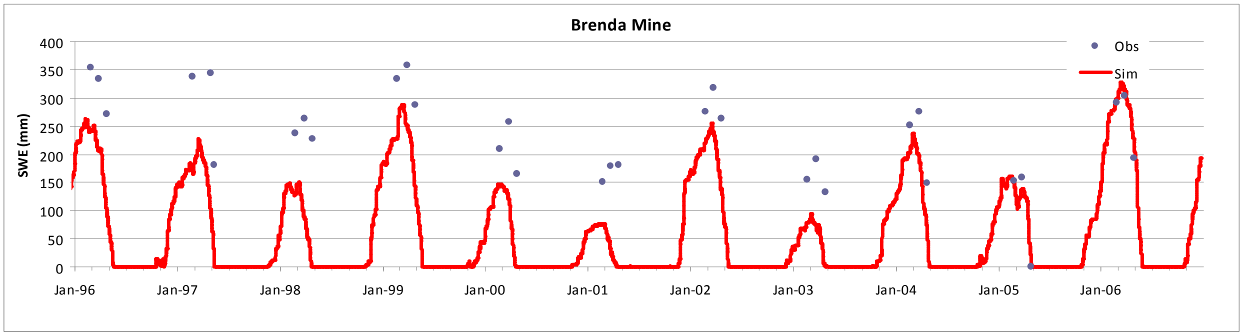


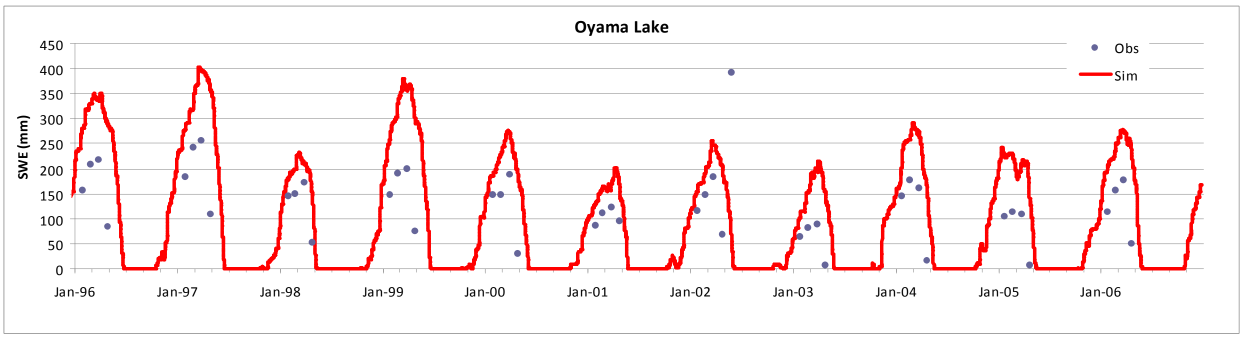




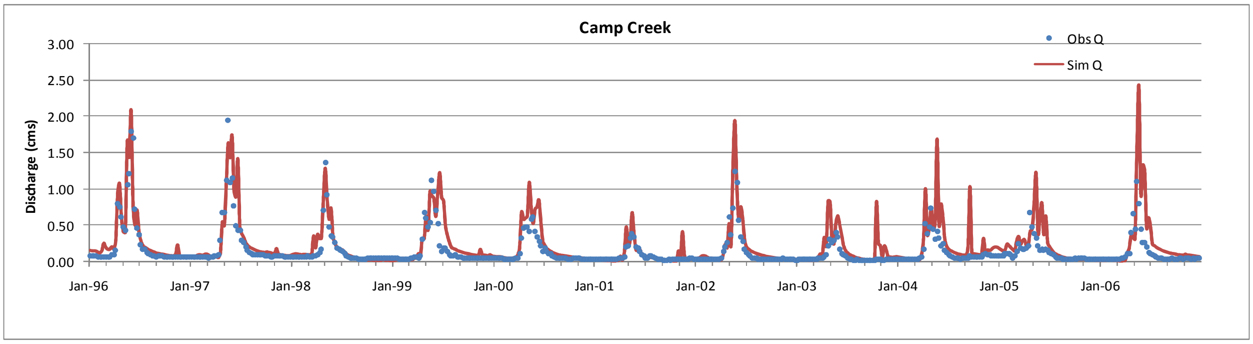
Comparison of Simulated SWE with Observed SWE

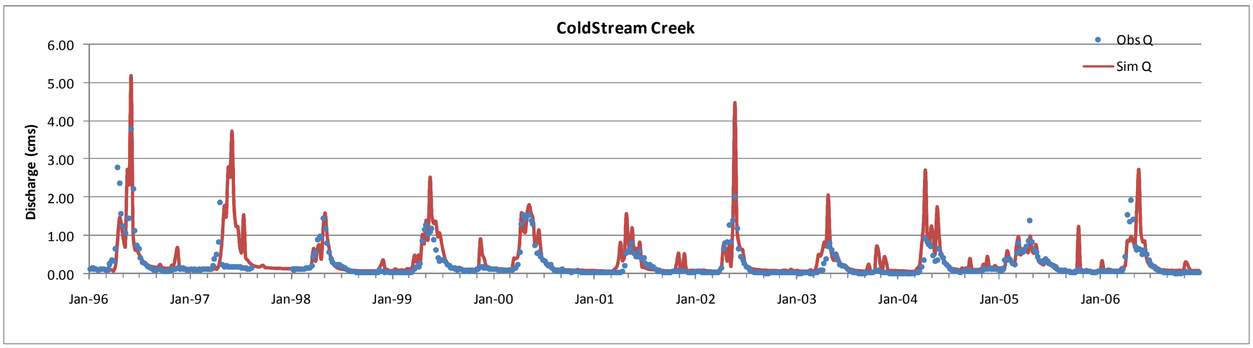


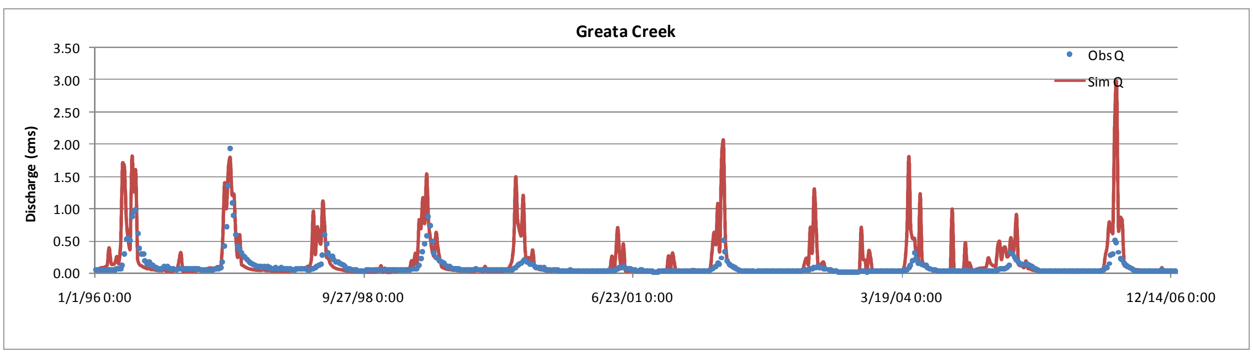


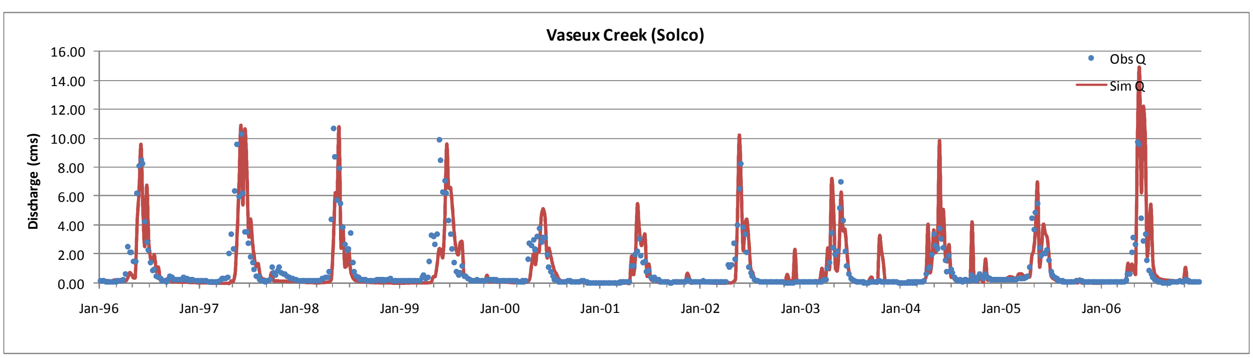


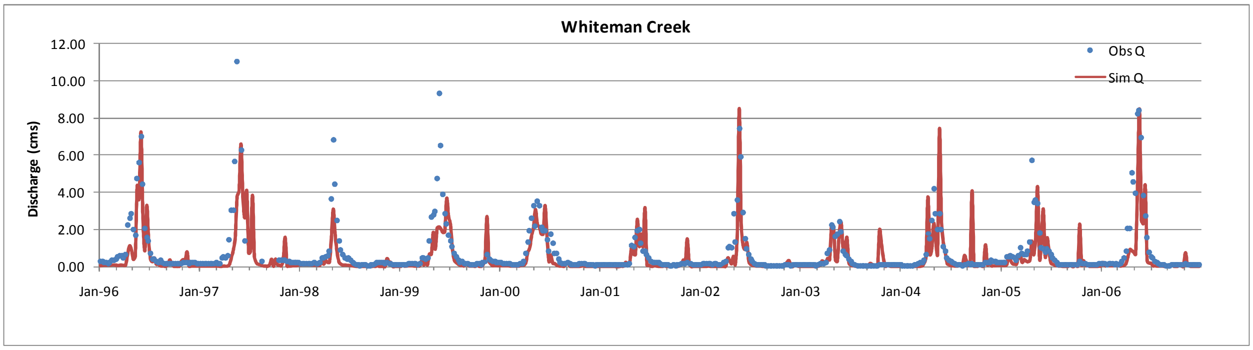
Comparison of simulated hydrographs with hydrographs from the natural streamflow stations

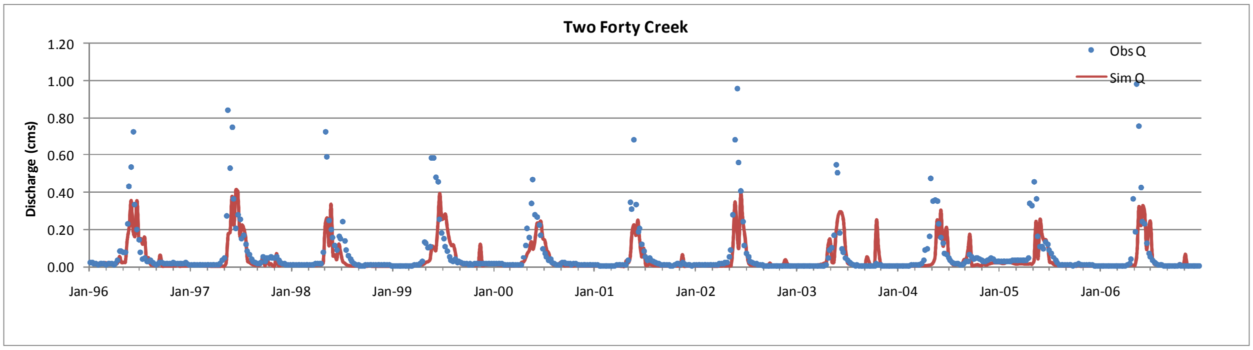


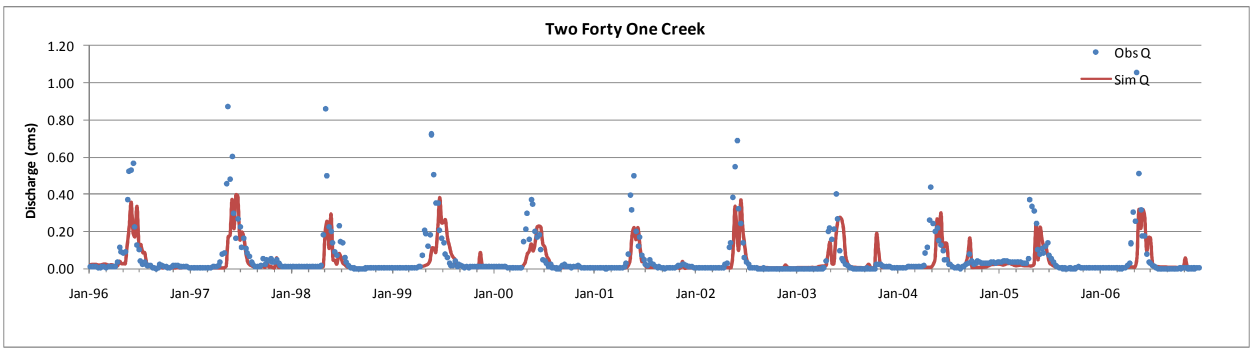


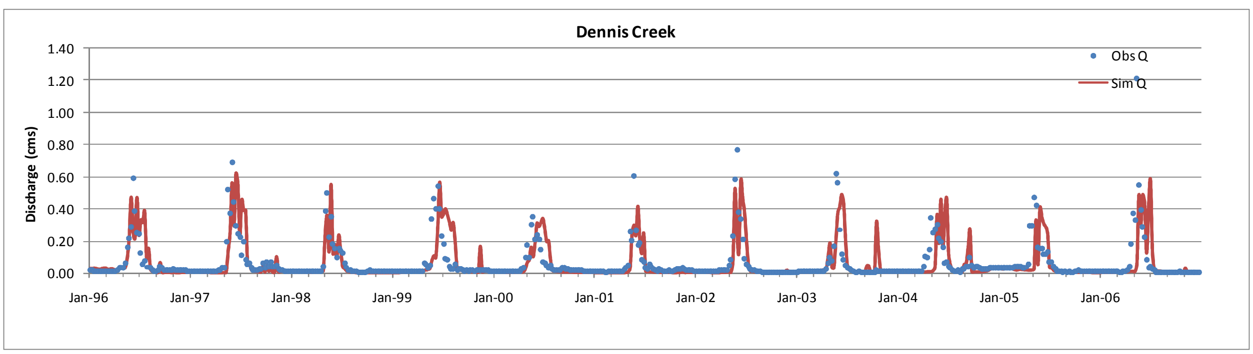




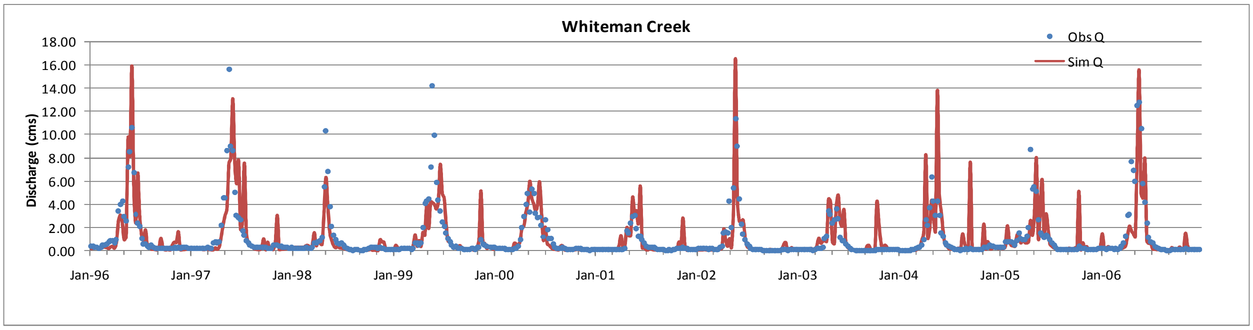

Whiteman Creek
Discharge (cms)
12.00
10.00
8.00
6.00
4.00
2.00
0.00
Jan-96
Jan-97
Jan-98
Jan-99
Jan-00
Jan-01
Jan-02
Jan-03
Jan-04
Jan-05
Jan-06
Obs Q
Sim Q

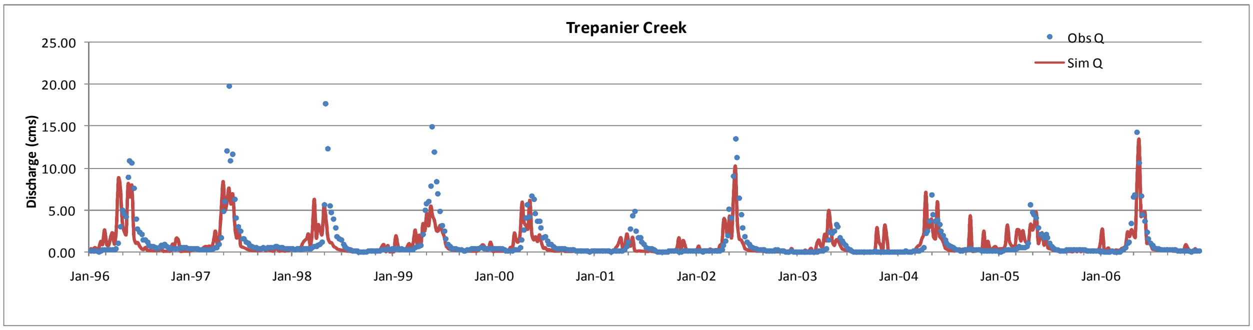

Two Forty Creek
Discharge (cms)
1.20
1.00
0.80
0.60
0.40
0.20
0.00
Jan-96
Jan-97
Jan-98
Jan-99
Jan-00
Jan-01
Jan-02
Jan-03
Jan-04
Jan-05
Jan-06
Obs Q
Sim Q

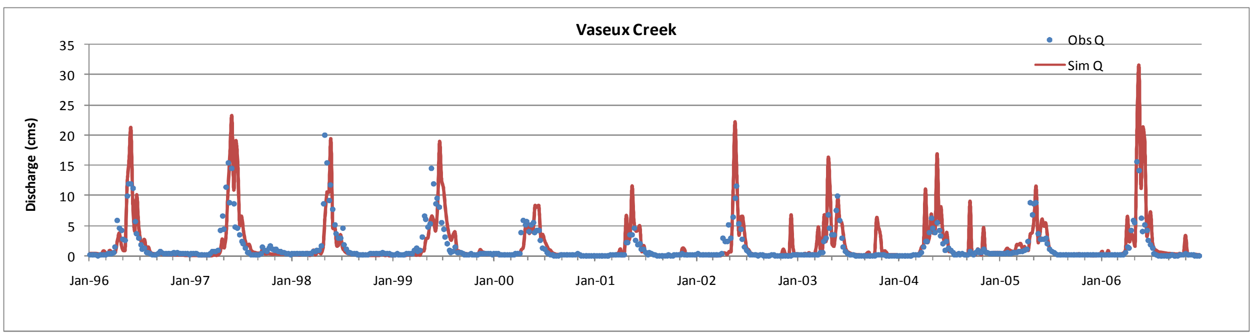

Two Forty One Creek
Discharge (cms)
1.20
1.00
0.80
0.60
0.40
0.20
0.00
Jan-96
Jan-97
Jan-98
Jan-99
Jan-00
Jan-01
Jan-02
Jan-03
Jan-04
Jan-05
Jan-06
Obs Q
Sim Q

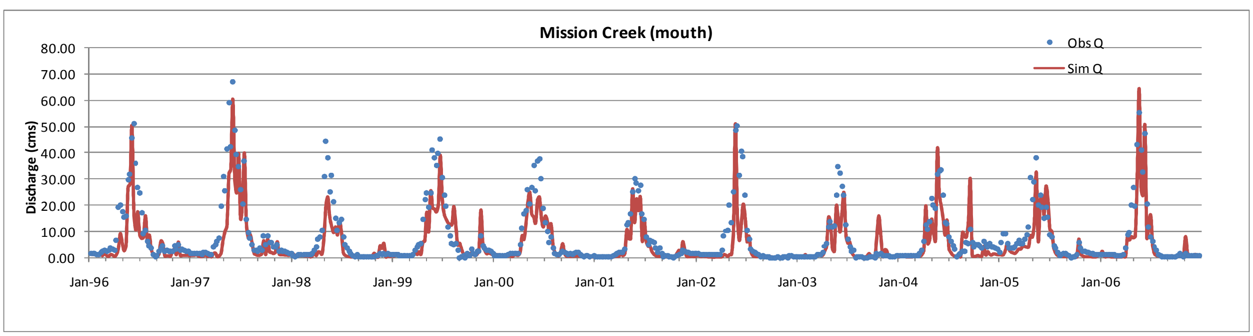

Dennis Creek
Discharge (cms)
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
Jan-96
Jan-97
Jan-98
Jan-99
Jan-00
Jan-01
Jan-02
Jan-03
Jan-04
Jan-05
Jan-06
Obs Q
Sim Q

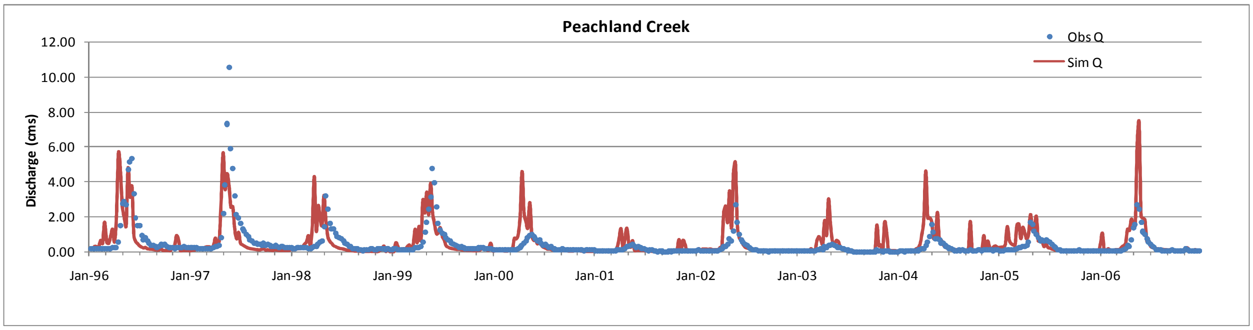
Comparison of simulated hydrographs with hydrographs from the high confidence level naturalized streamflow stations










Peachland Creek
Obs Q
Sim Q
Discharge (cms)
12.00
10.00
8.00
6.00
4.00
2.00
0.00
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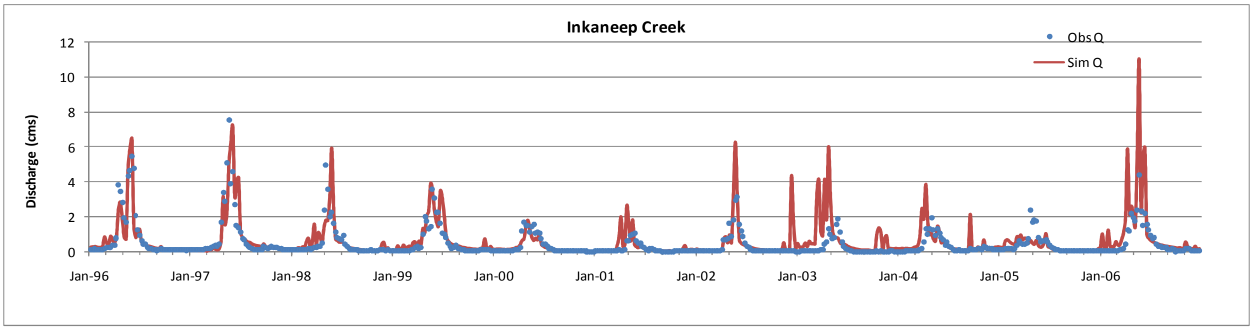
Jan-04
Jan-05
Jan-06


Inkaneep Creek
Obs Q
Sim Q
Discharge (cms)
12
10
8
6
4
2
0
Jan-96
Jan-97
Jan-98
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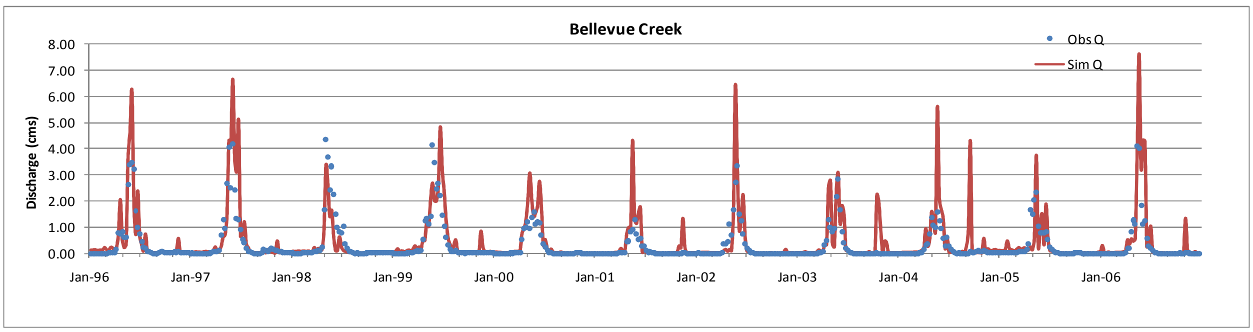
Jan-04
Jan-05
Jan-06


Bellevue Creek
Obs Q
Sim Q
Discharge (cms)
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
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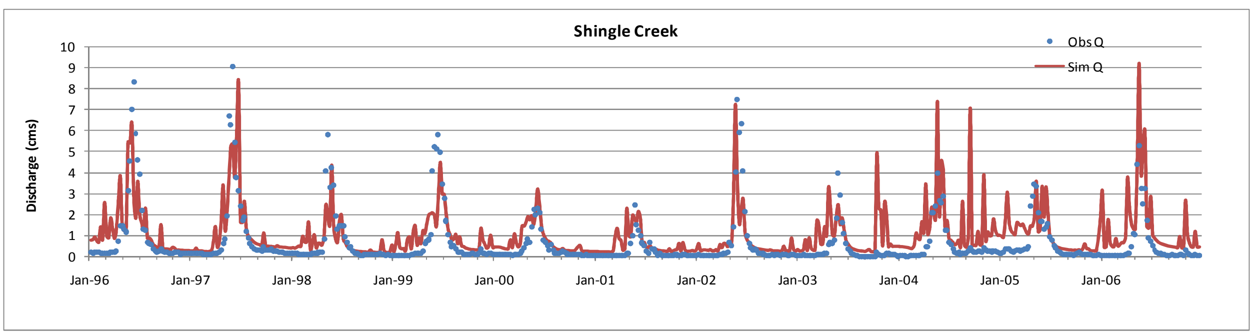
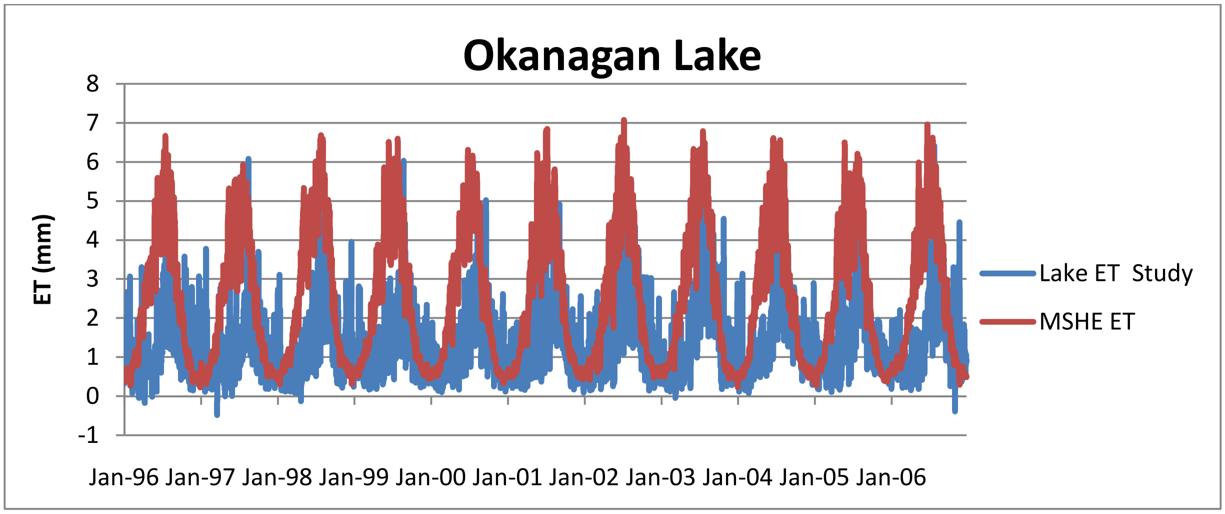
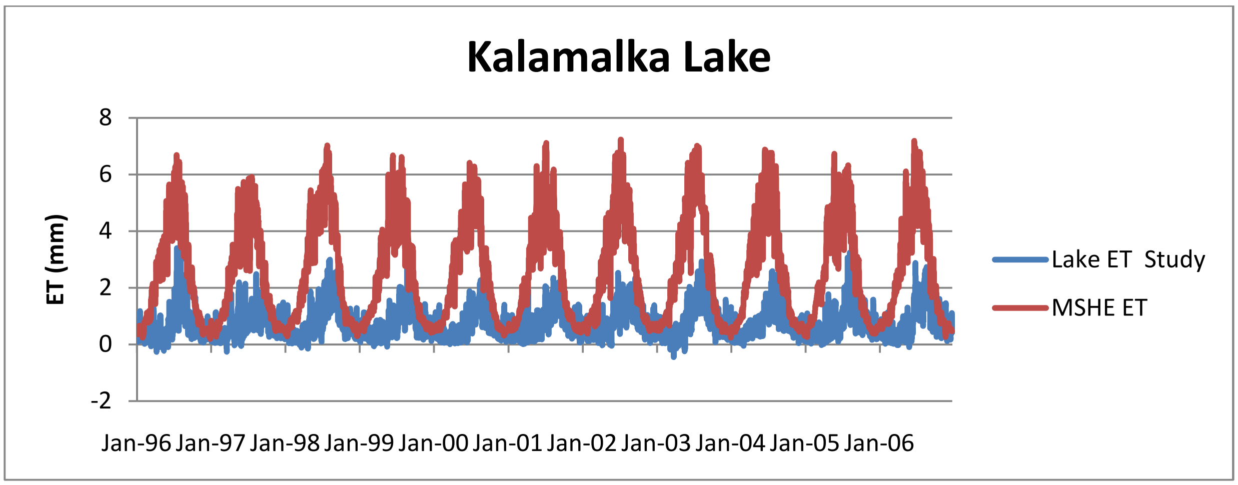
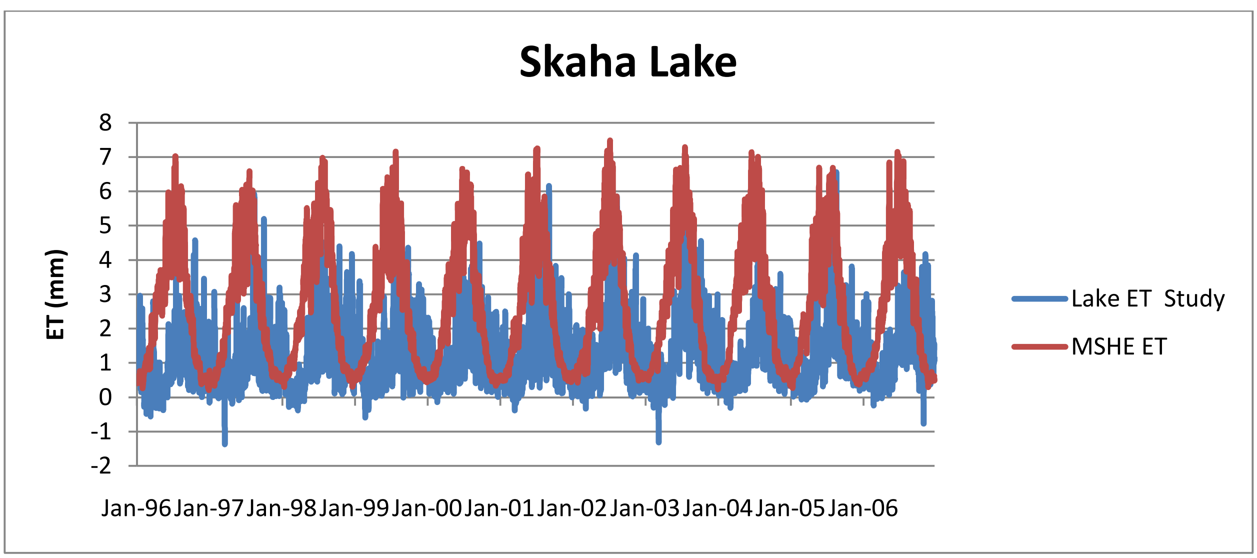
Jan-04
Jan-05
Jan-06

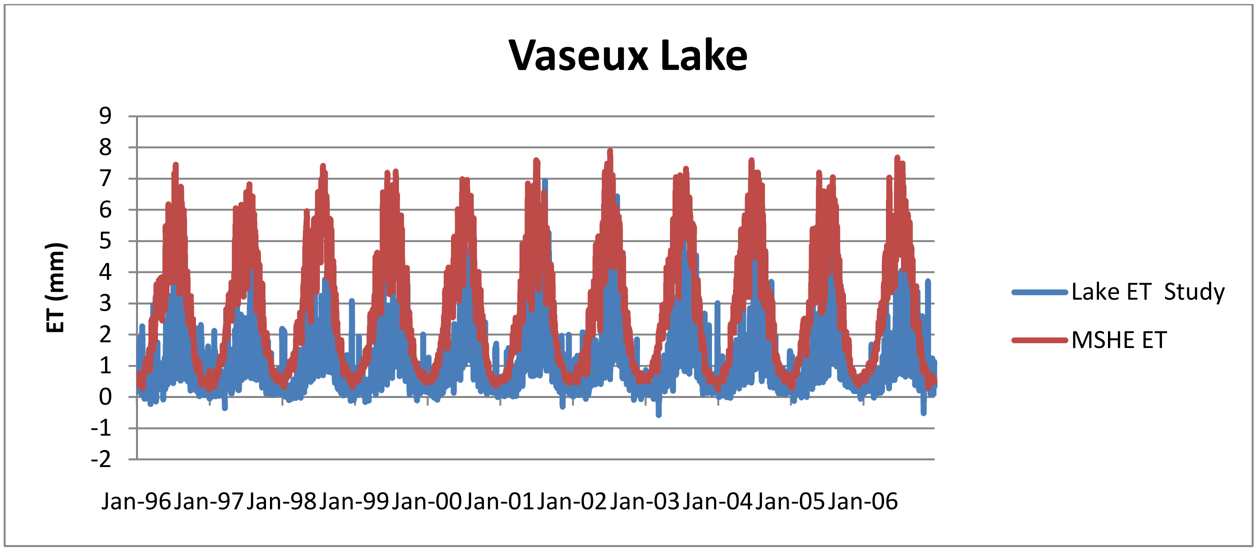

Shingle Creek
Obs Q
Sim Q
Discharge (cms)
10
9
8
7
6
5
4
3
2
1
0
Jan-96
Jan-97
Jan-98
Jan-99
Jan-00
Jan-01
Jan-02
Jan-03
Jan-04
Jan-05
Jan-06

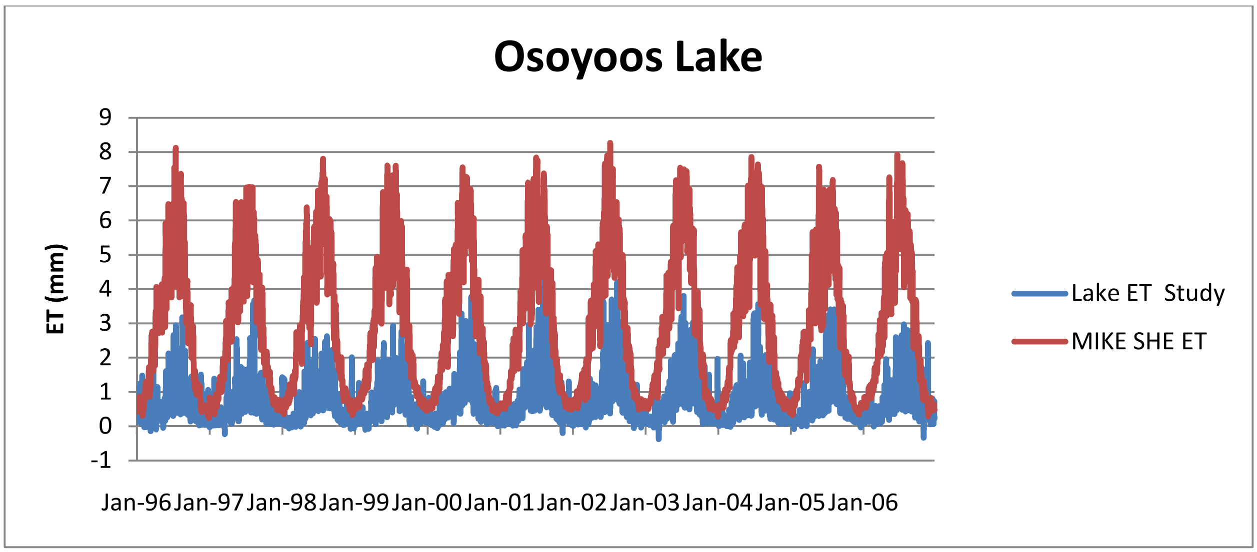
Comparison of model simulated lake evaporation data with estimates from the Lake Evaporation Study





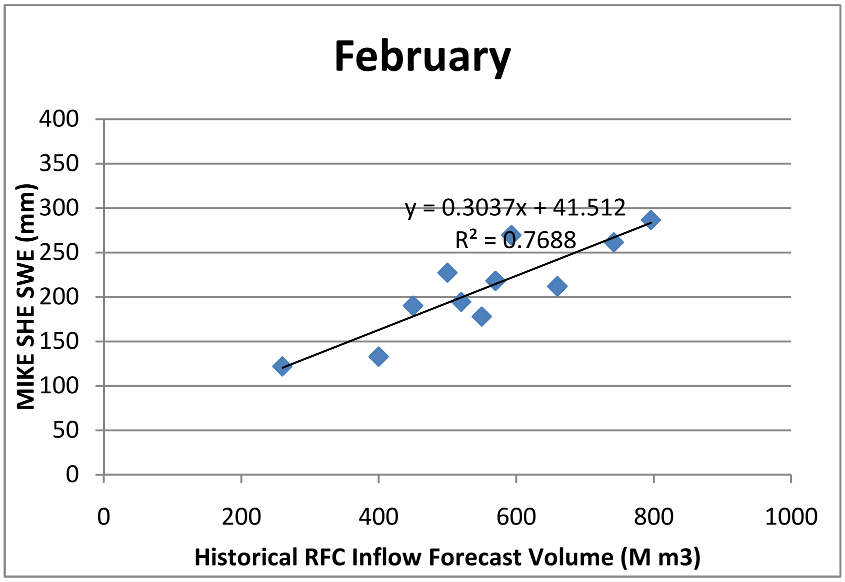


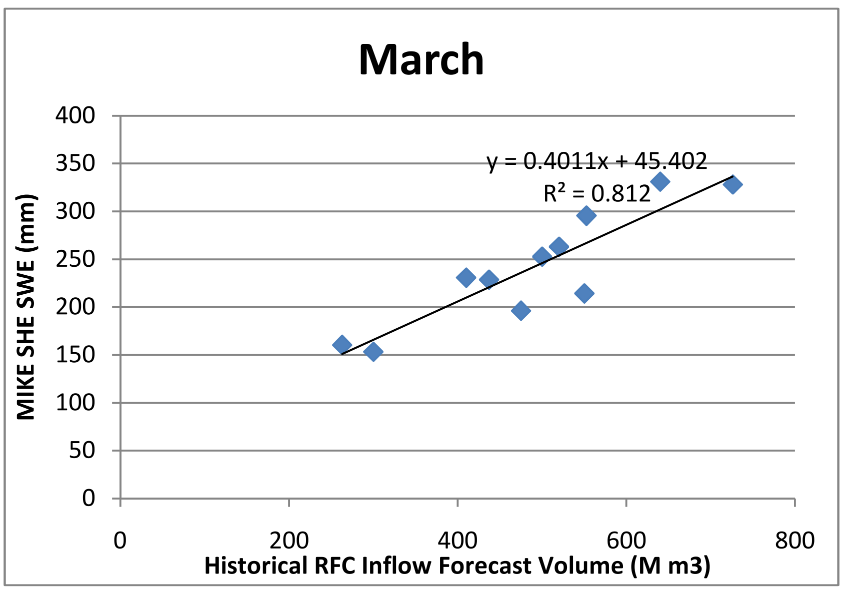

Vaseux Lake
ET (mm)
9
8
7
6
5
4
3
2
1
0
-1
-2
Jan-96 Jan-97 Jan-98 Jan-99 Jan-00 Jan-01 Jan-02 Jan-03 Jan-04 Jan-05 Jan-06
Lake ET Study
MSHE ET

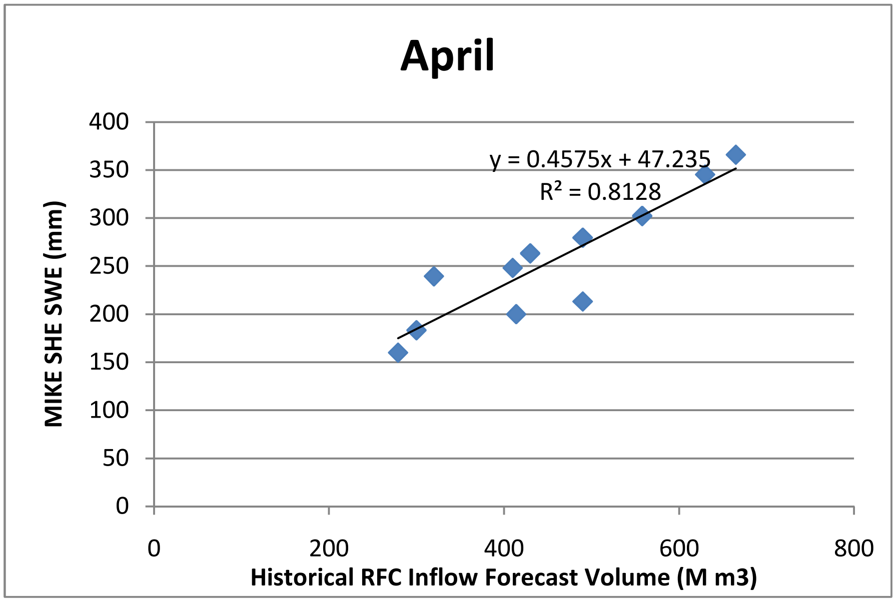

Osoyoos Lake
ET (mm)
9
8
7
6
5
4
3
2
1
0
-1
Jan-96 Jan-97 Jan-98 Jan-99 Jan-00 Jan-01 Jan-02 Jan-03 Jan-04 Jan-05 Jan-06
Lake ET Study
MIKE SHE ET

Appendix C

Regression Analysis of Historical Inflow Volume Forecast vs. Simulated SWE

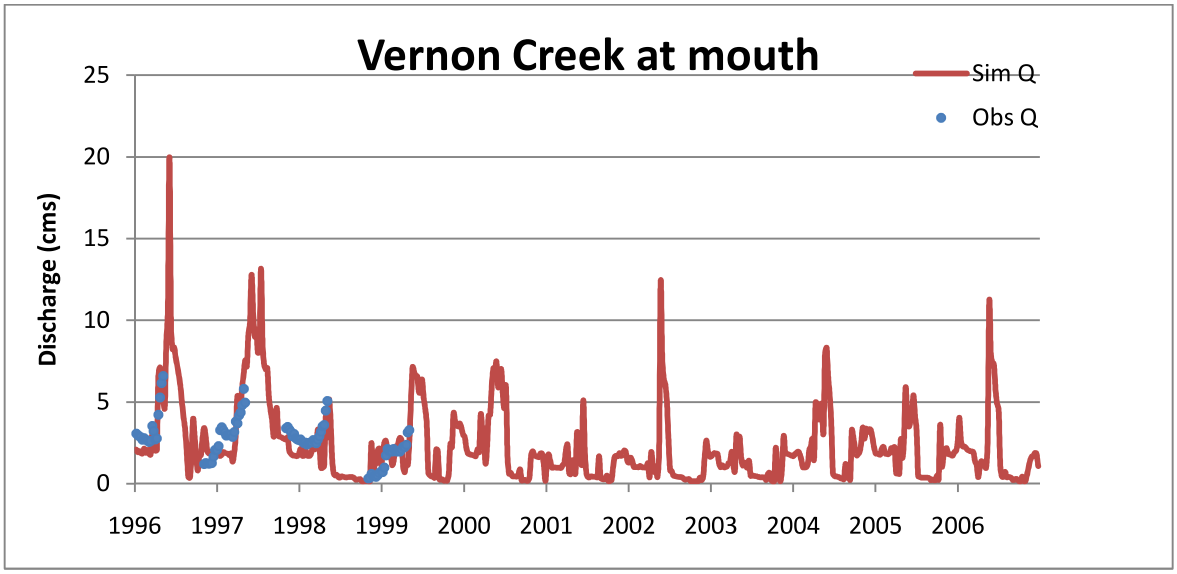

February
MIKE SHE SWE (mm)
Historical RFC Inflow Forecast Volume (M m3)
y = 0.3037x + 41.512
R² = 0.7688
0
50
100
150
200
250
300
350
400
0
200
400
600
800
1000

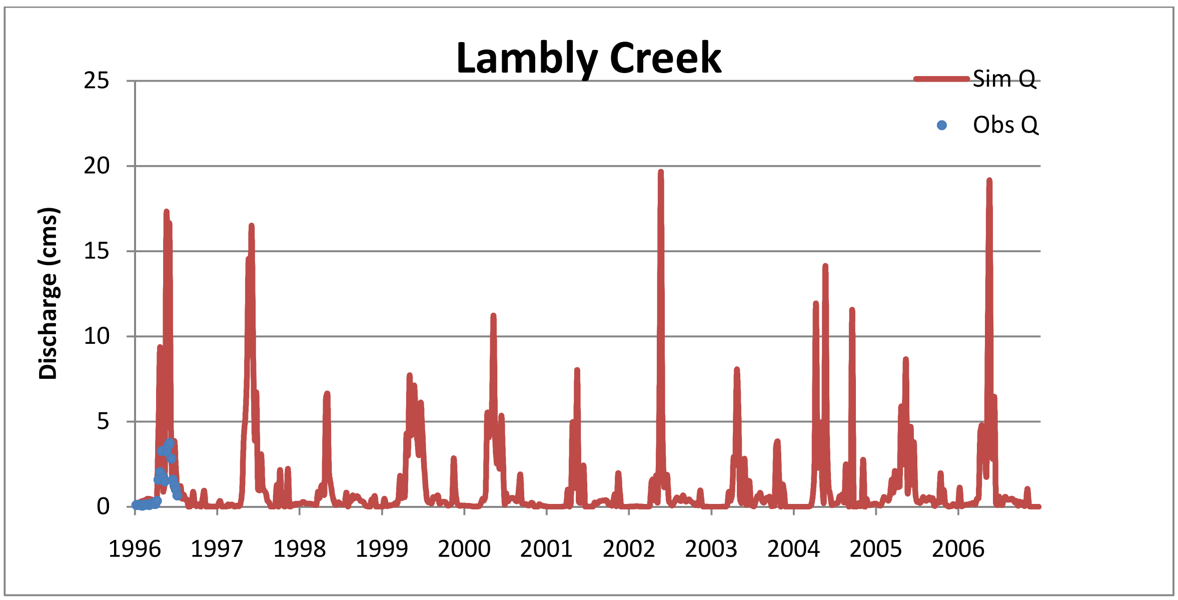

March
MIKE SHE SWE (mm)
Historical RFC Inflow Forecast Volume (M m3)
y = 0.4011x + 45.402
R² = 0.812
0
50
100
150
200
250
300
350
400
0
200
400
600
800


April
y = 0.4575x + 47.235
R^2 = 0.8128
MIKE SHE SWE (mm)
Historical RFC Inflow Forecast Volume (M m3)
0
50
100
150
200
250
300
350
400
0
200
400
600
800

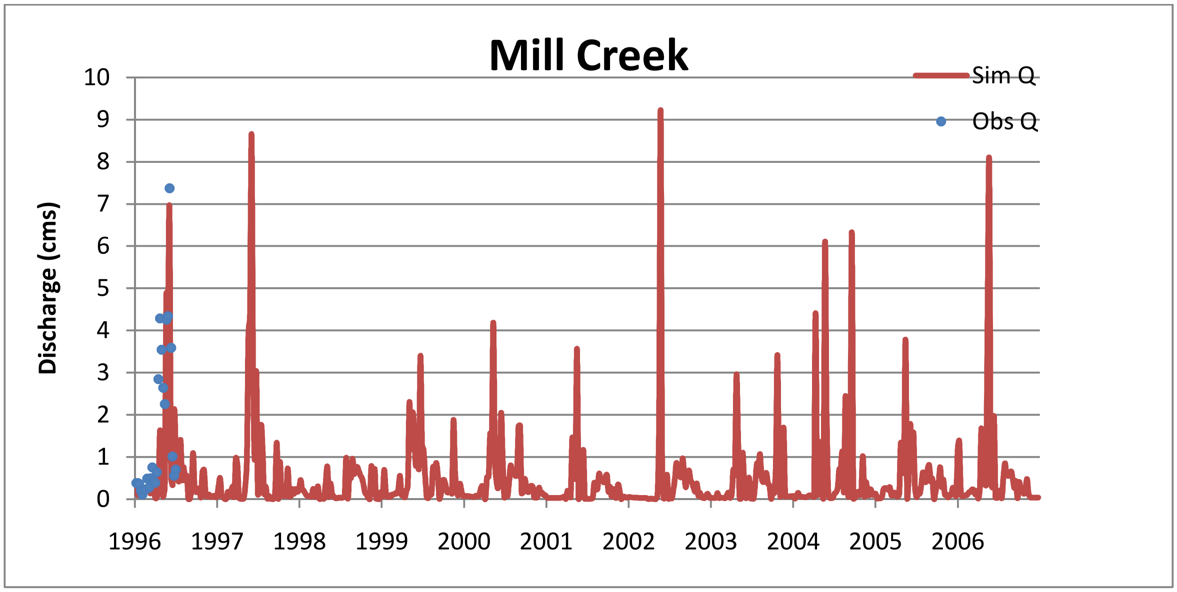
Appendix D
Okanagan Basin Water Accounting Model Calibration Plots

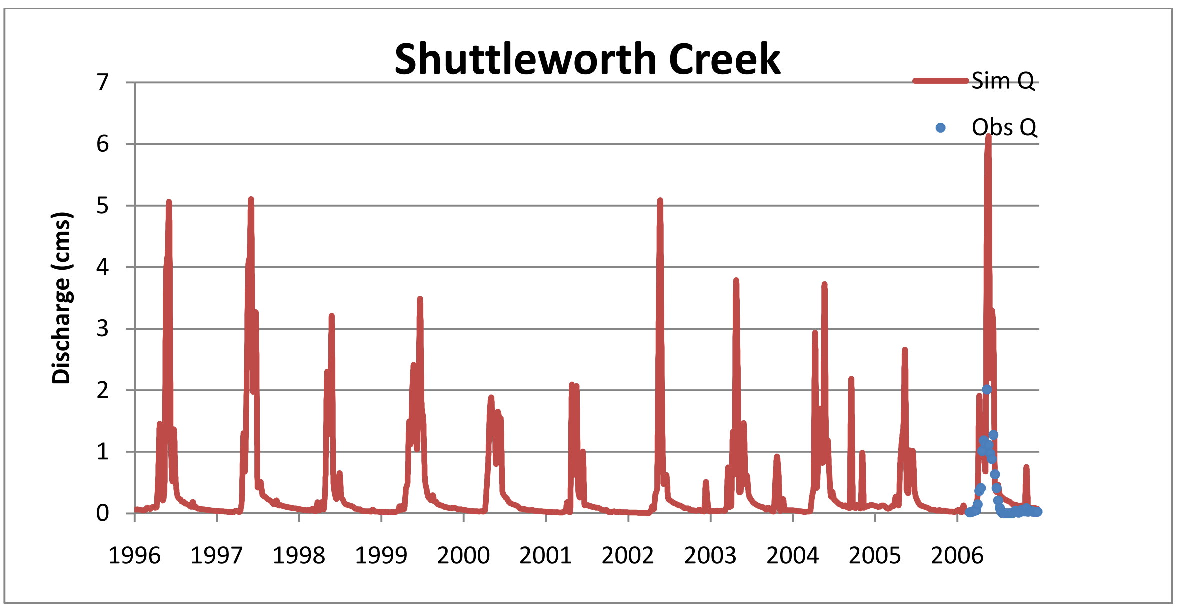
Simulated vs. Observed Discharge at Regulated Stations



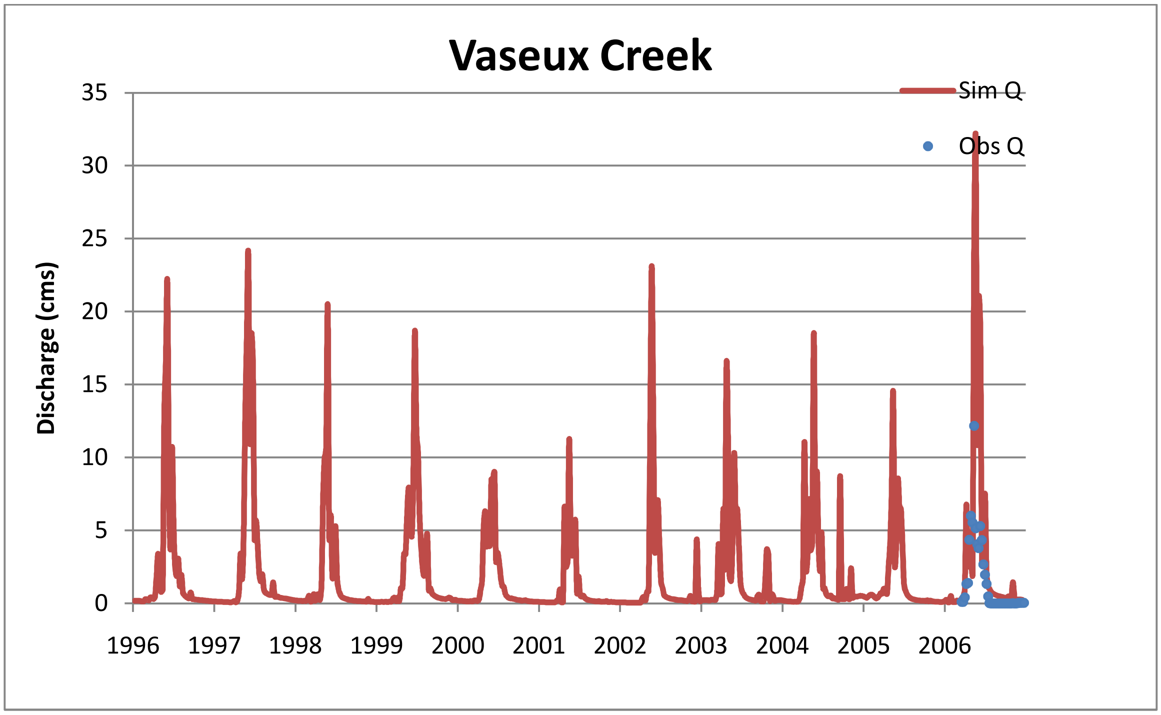


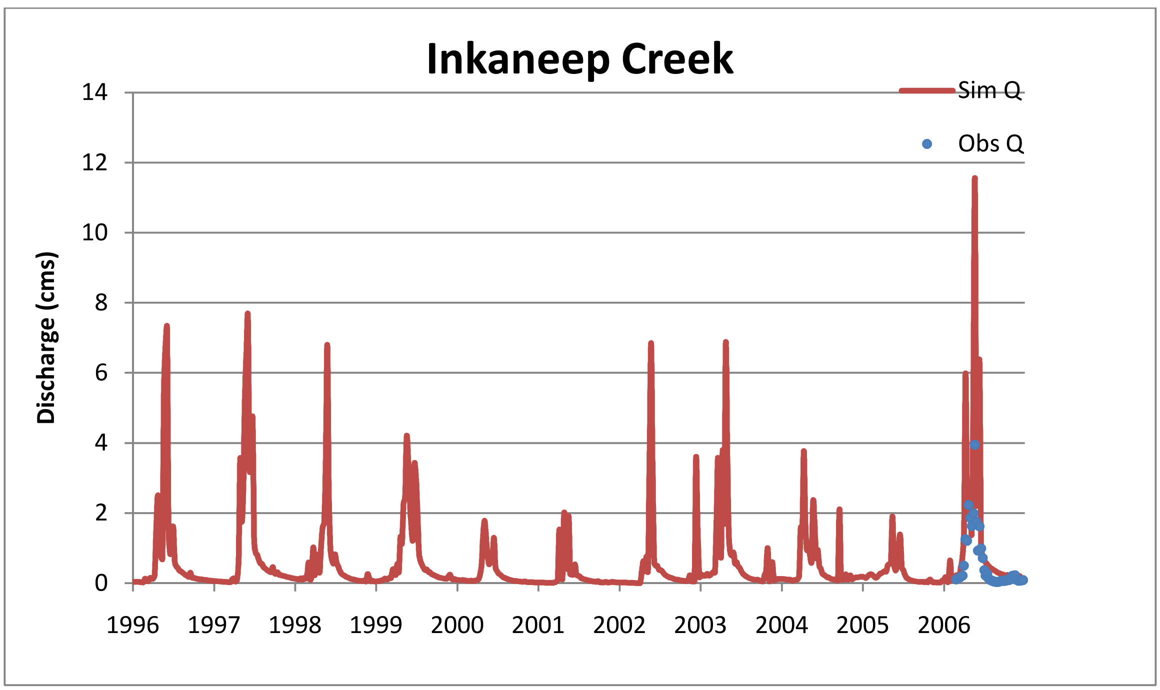
Simulated vs. Observed Discharge at Regulated Stations



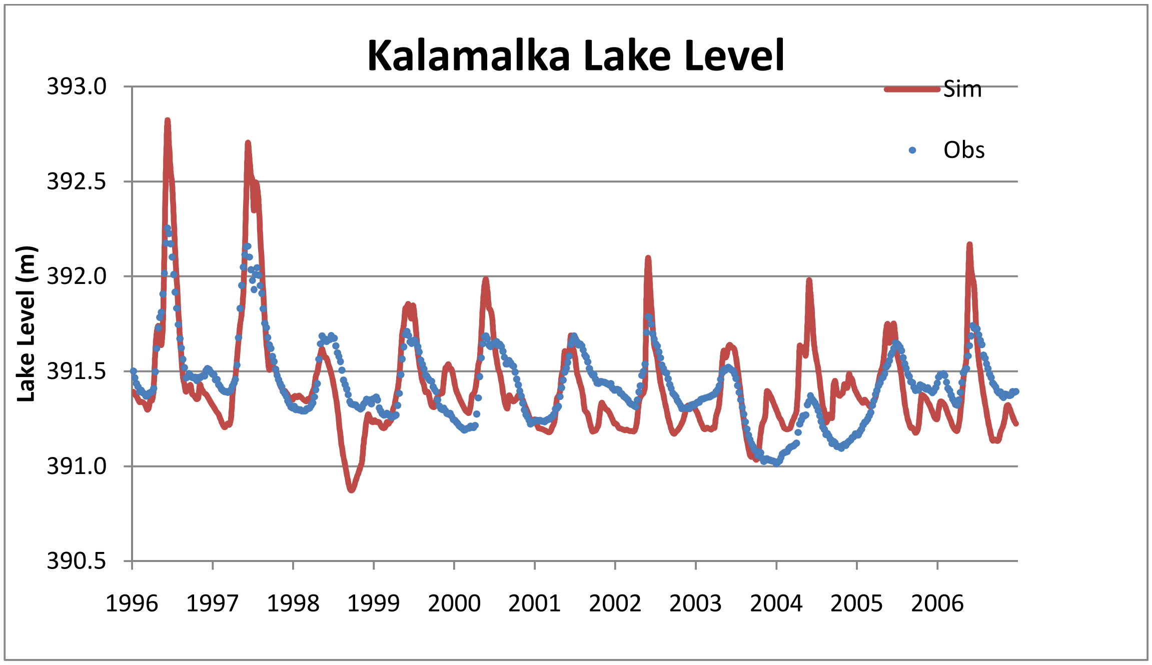


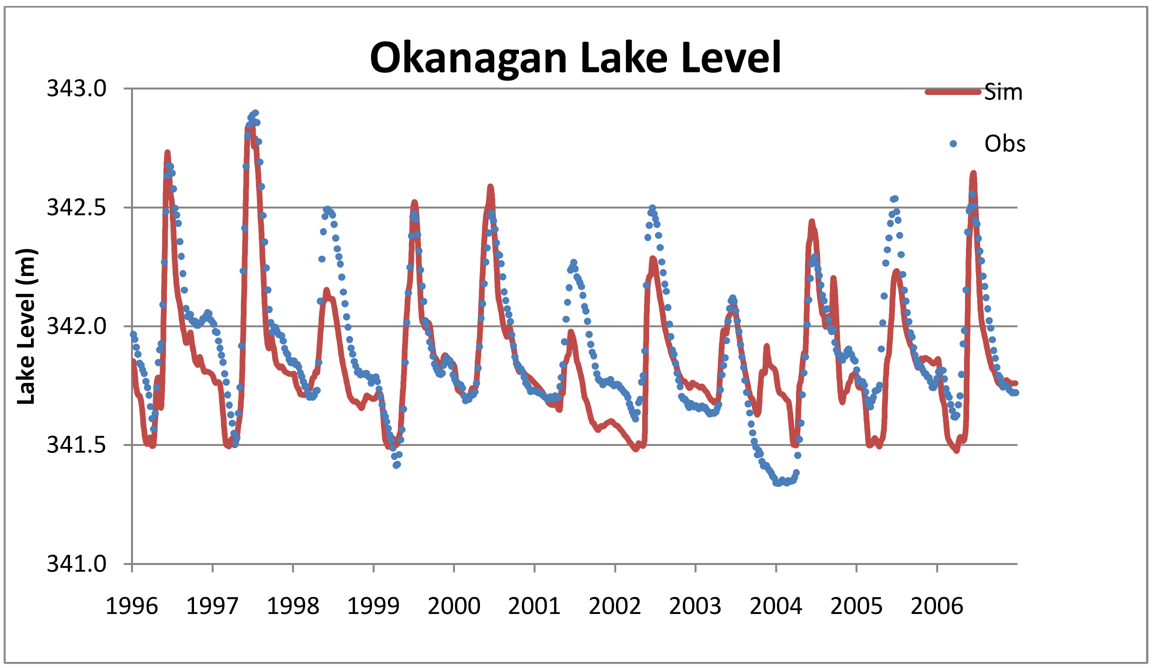
Simulated vs. Observed Discharge at Regulated Stations



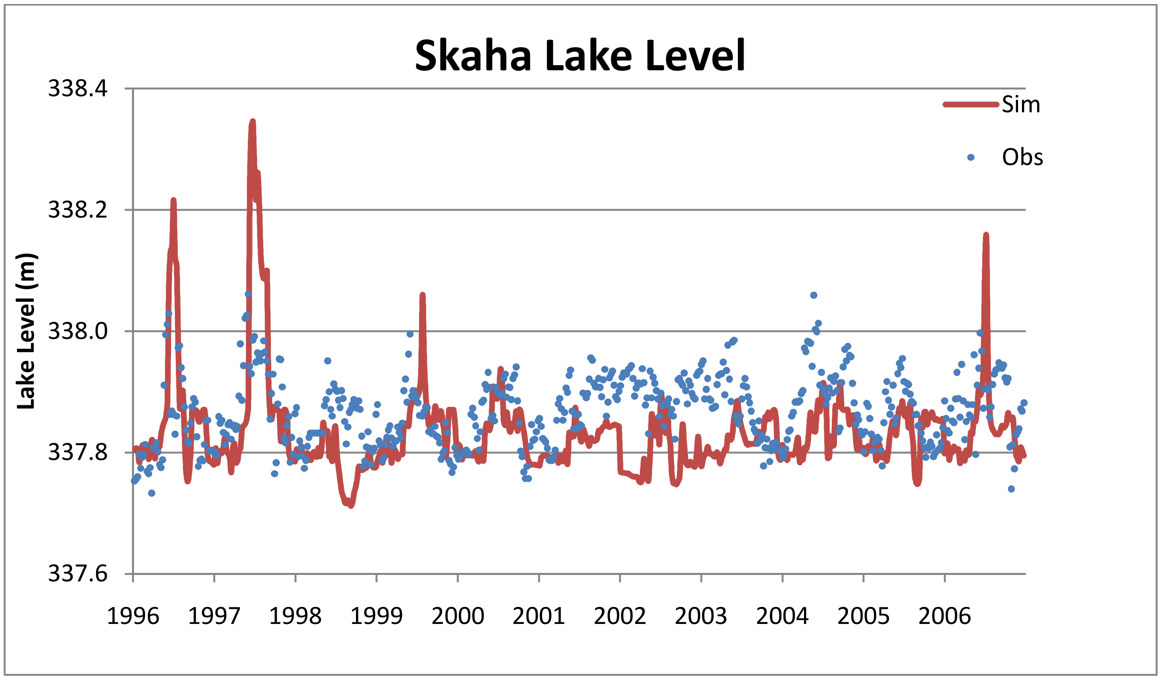


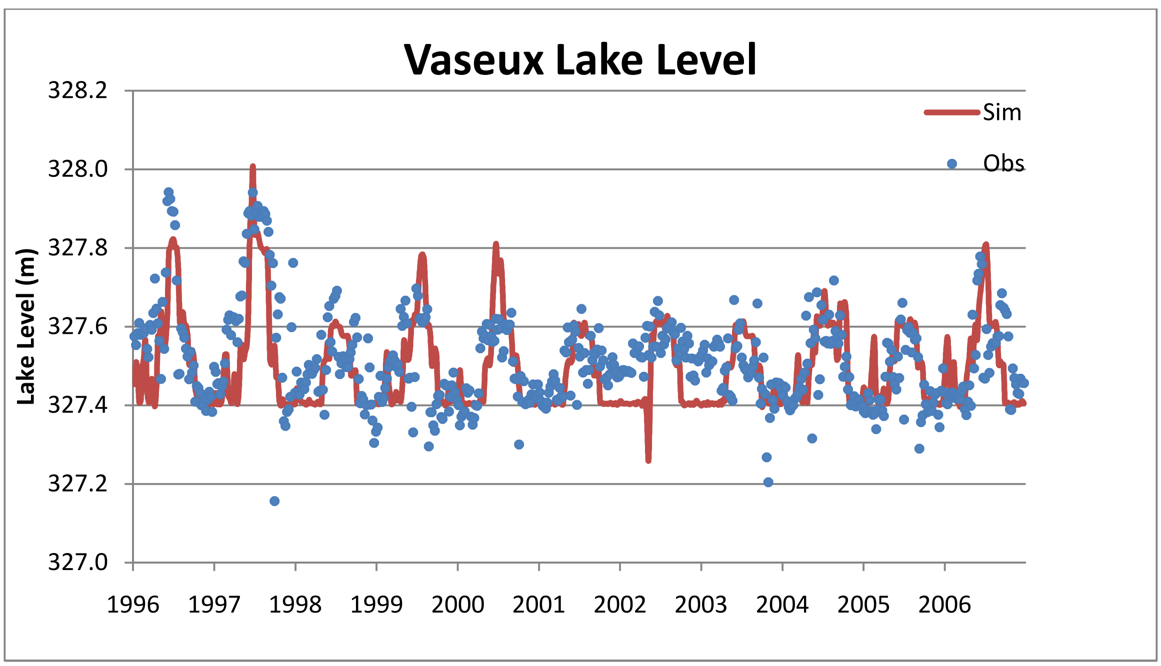
Simulated vs. Observed Lake Levels



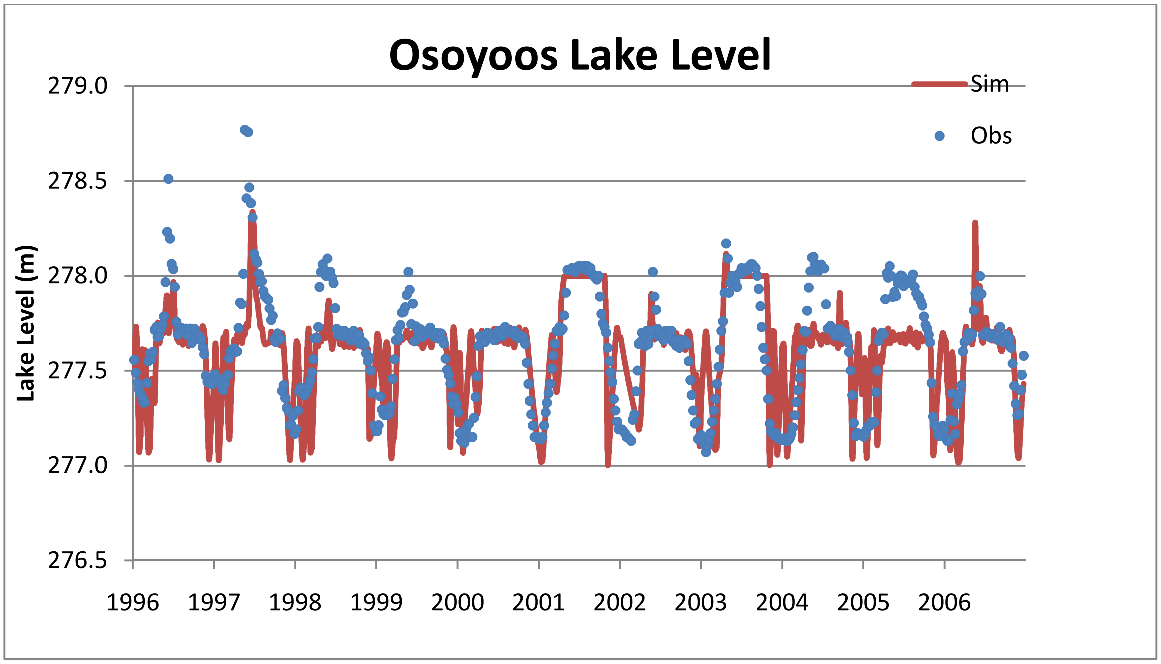


Simulated vs. Observed Lake Levels

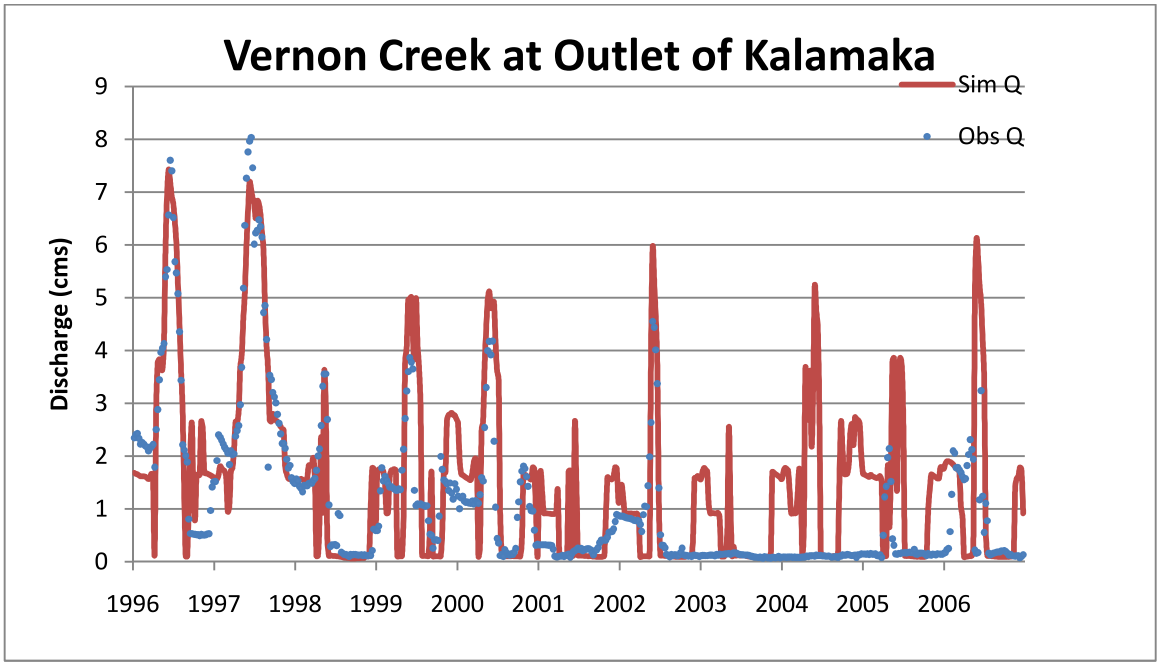


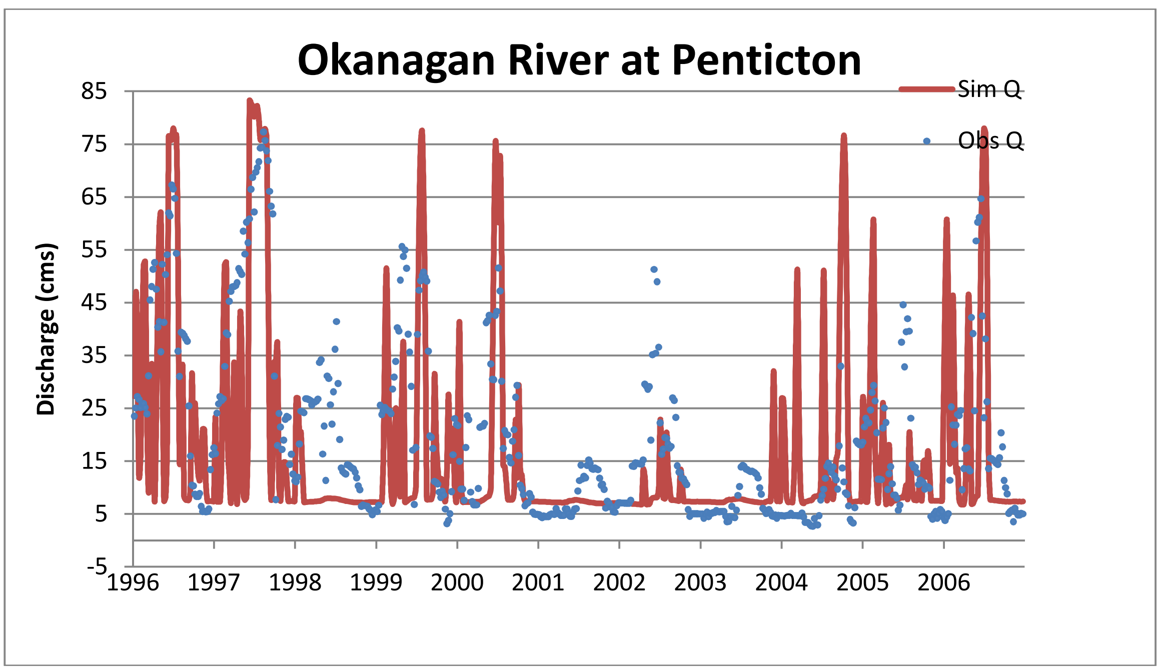


Simulated vs. Observed Lake Levels

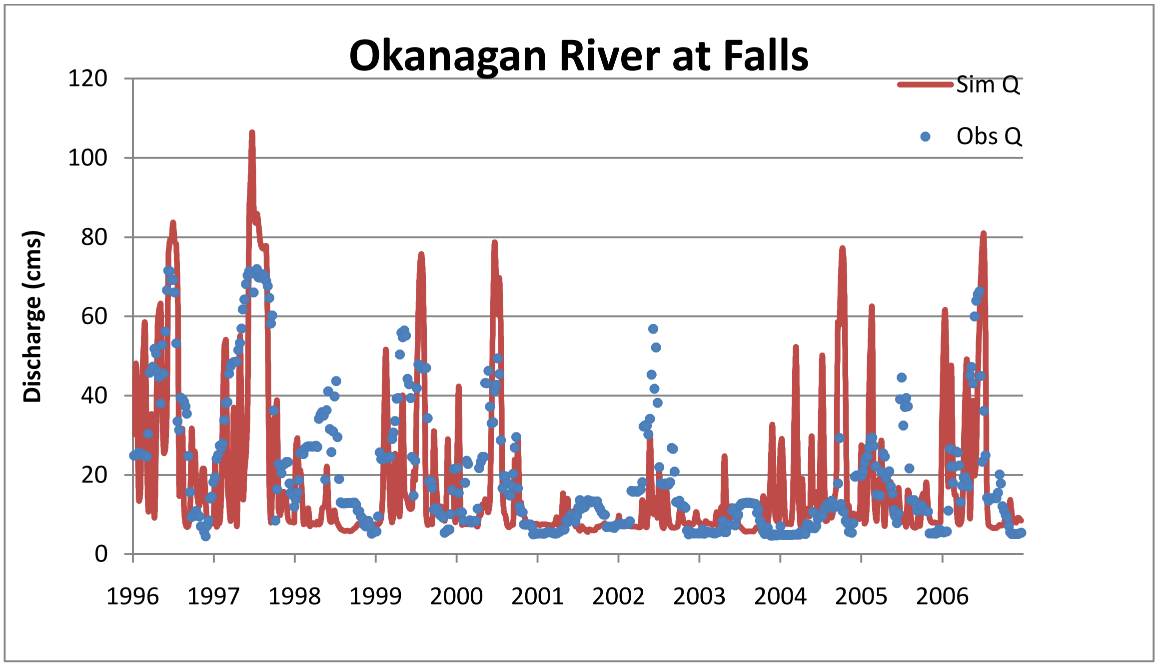


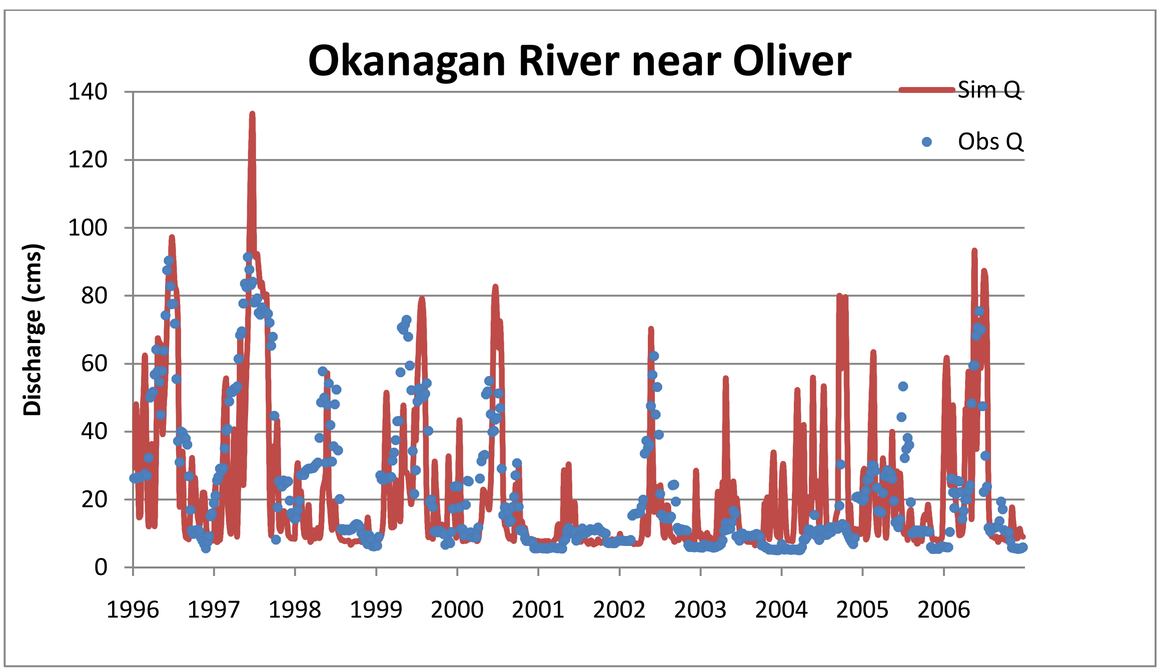
Simulated vs. Observed Discharge



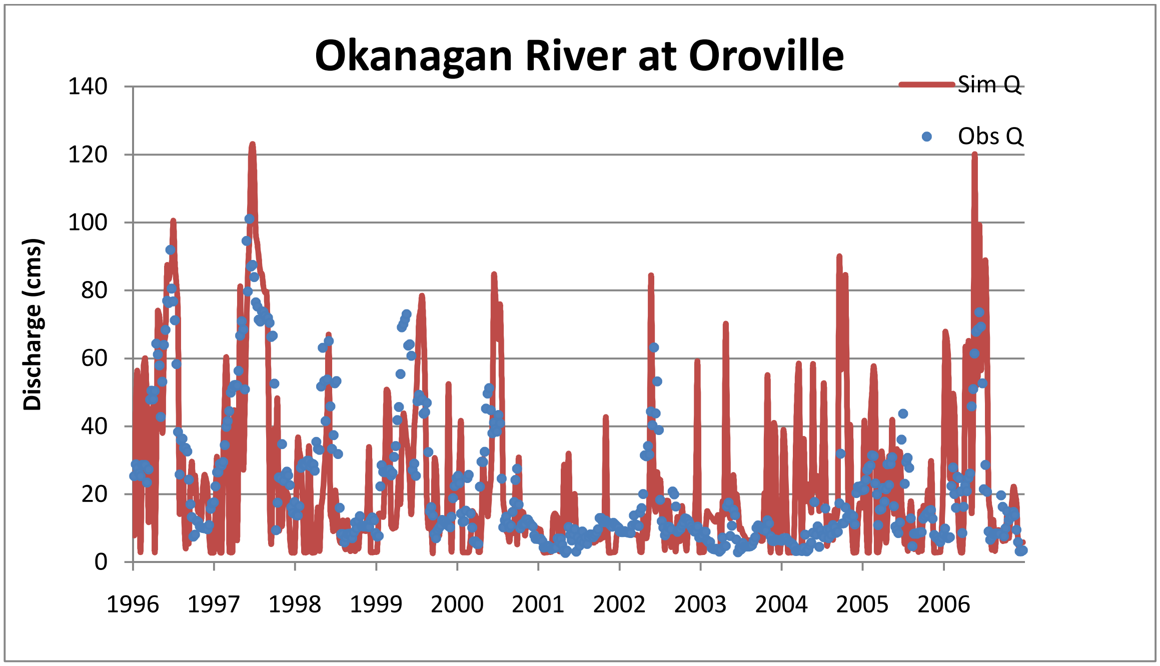


Simulated vs. Observed Discharge





Simulated vs. Observed Discharge



Appendix E

Summary of Structure Operations Logic and Settings for Mainstem Lakes

Okanagan Lake Operational Logic and Settings

Operational rules	Source	Priority
Maximum lake level	FWMT	3
Minimum lake level	FWMT	4
Minimum flow requirement downstream	FWMT	1
Maximum flow capacity	FWMT	2
Monthly lake level targets (Feb 1st, Mar 1st, April 1st targets vary based on forecasted inflow)	operation plan	5
Monthly flow requirement at Oliver (Feb 1st, Mar 1st, April 1st targets vary based on forecasted inflow)	operation plan	6

Gate update frequency: 72hours

Gate level change:

Opening: 0.06 m

Closing: 0.12m

Min. gate opening: 0.06 m

Max. gate opening: 1.83m

Real max. gate opening: 2.565m

Kalamalka Lake Operational Logic and Settings

Operational rules	Source	Priority
Maximum lake level	Observed	2
Minimum lake level	Observed	3
Minimum flow requirement downstream	Operation plan	1
Maximum flow capacity	Observed	4
Monthly lake level targets	Operation plan	5

Gate update frequency: 3 hours

Gate level change: 0.06 m

Min. gate opening: 0.03 m

Max. gate opening: 0.42m

Real max. gate opening: 1.473m

Vaseux Lake and Skaha Lake Operational Logic and Settings

Operational rules	Source	Priority
Minimum flow requirement downstream	FWMT	1
Monthly lake level targets	operation plan	2
Monthly flow requirement at Oliver	operation plan	3

Gate update frequency: every time step (5 min)

Gate level change: 0.03 m

Min. gate opening: 0.03 m

Max. gate opening: 2.59m (Skaha) and 1.83m (Vaseux)

Real max. gate opening: 2.59m (Skaha) and 1.83m (Vaseux)

Osoyoos Lake Operational Logic and Settings

Operational rules	Source	Priority
Minimum flow requirement downstream	FWMT	1
Lake level targets from April to October (based on April 1st forecasted inflow)	operation plan (Drought condition)	2
Monthly lake level targets	operation plan (Normal condition)	3

Gate update frequency: every time step (5 min)

Gate level change: 0.03 m

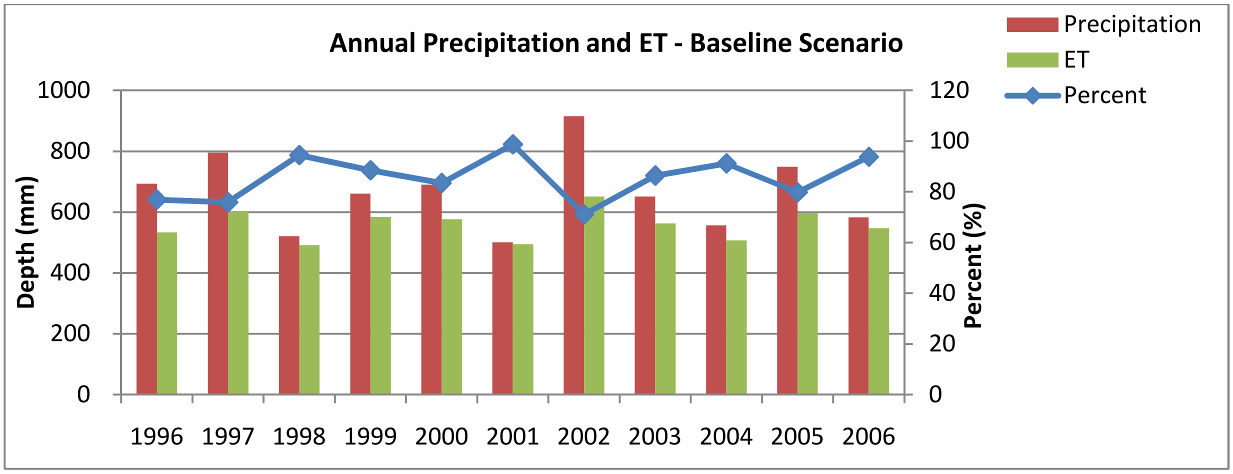
Min. gate opening: 0.03 m

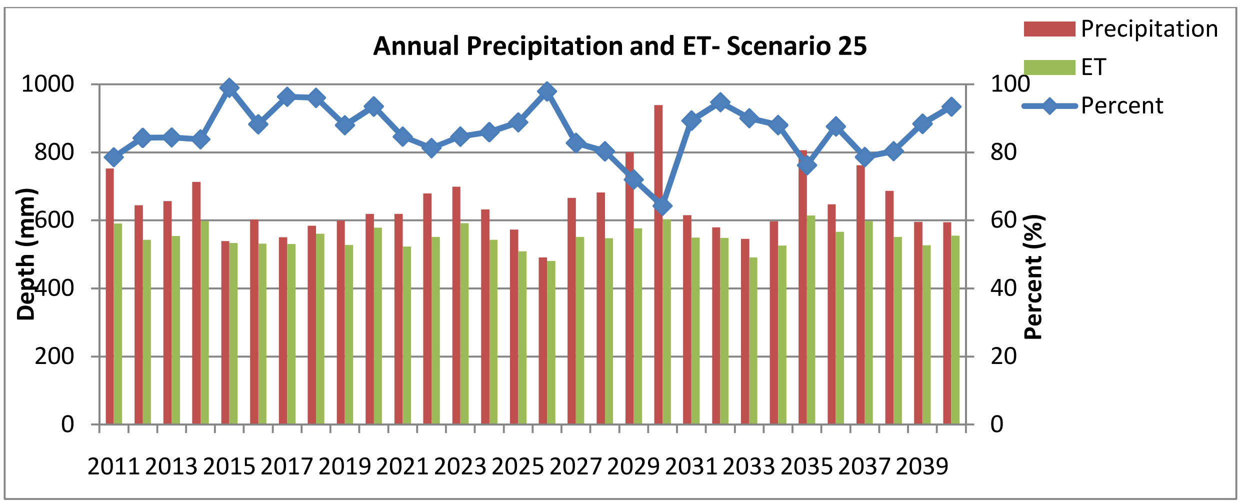
Max. gate opening: 3.05m

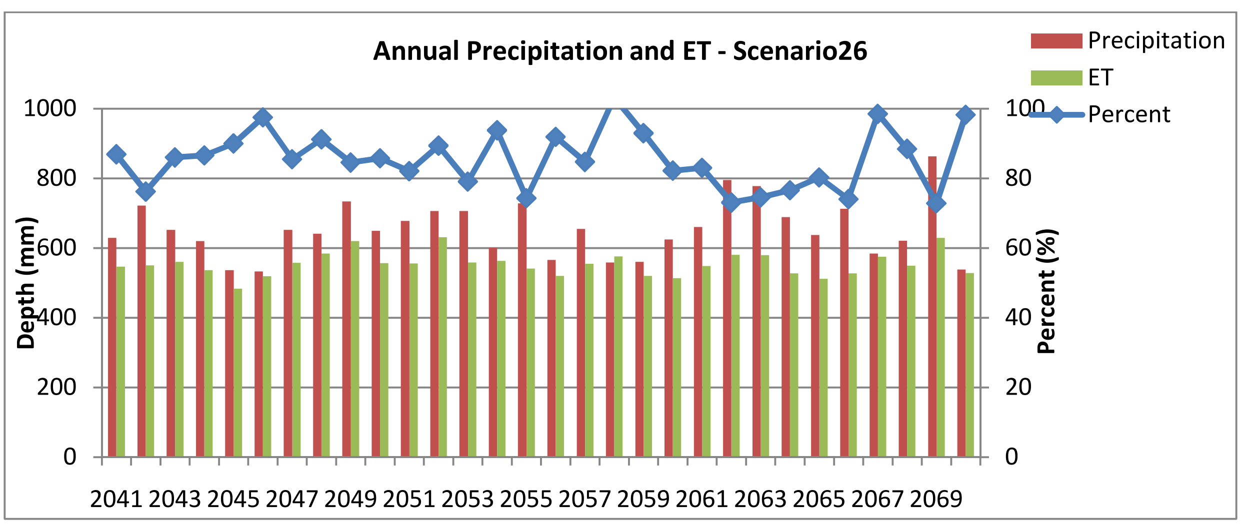
Real max. gate opening: 3.05m

Appendix F
Climate Change Scenarios Results

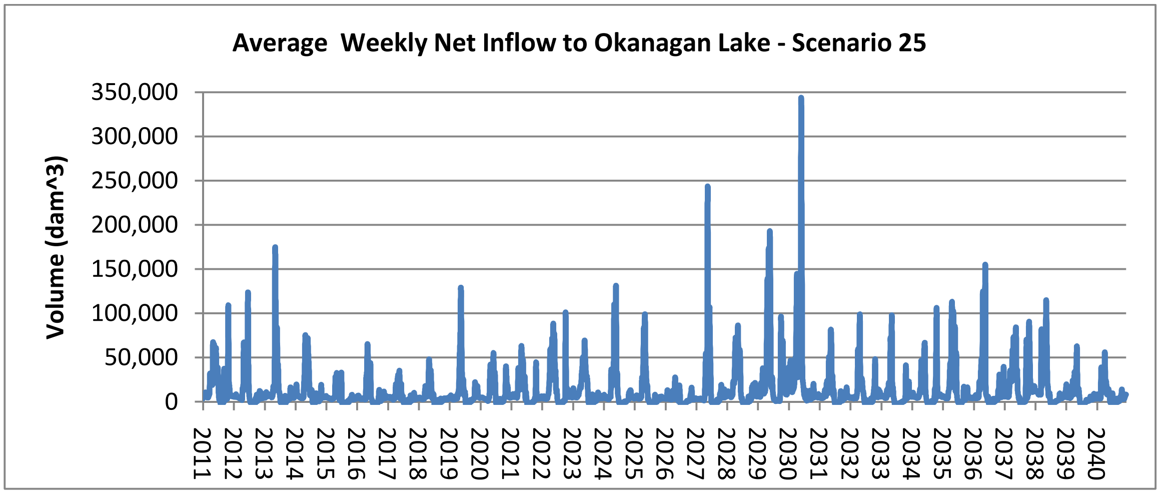
Summary of Precipitation and Evapotranspiration for Scenario Periods

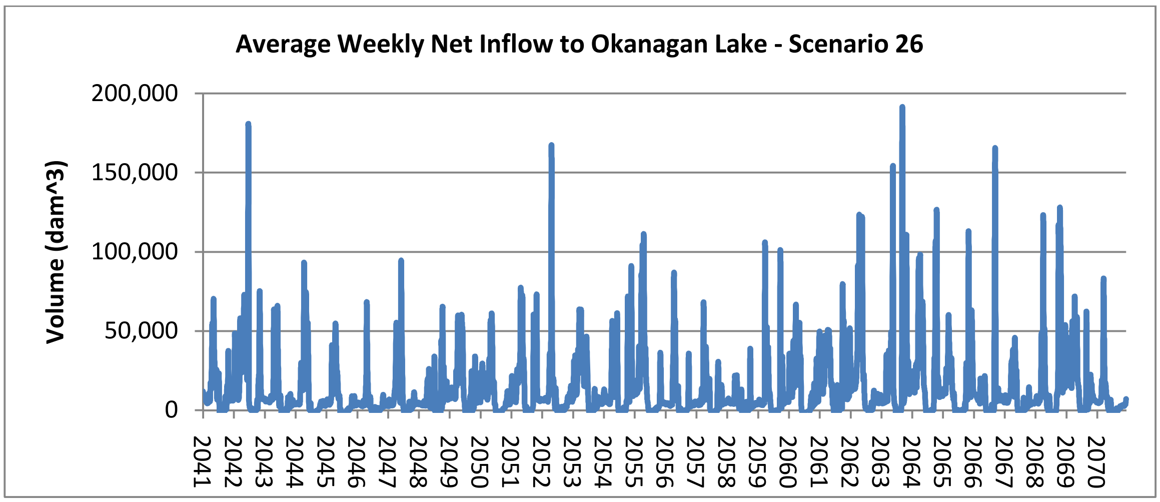


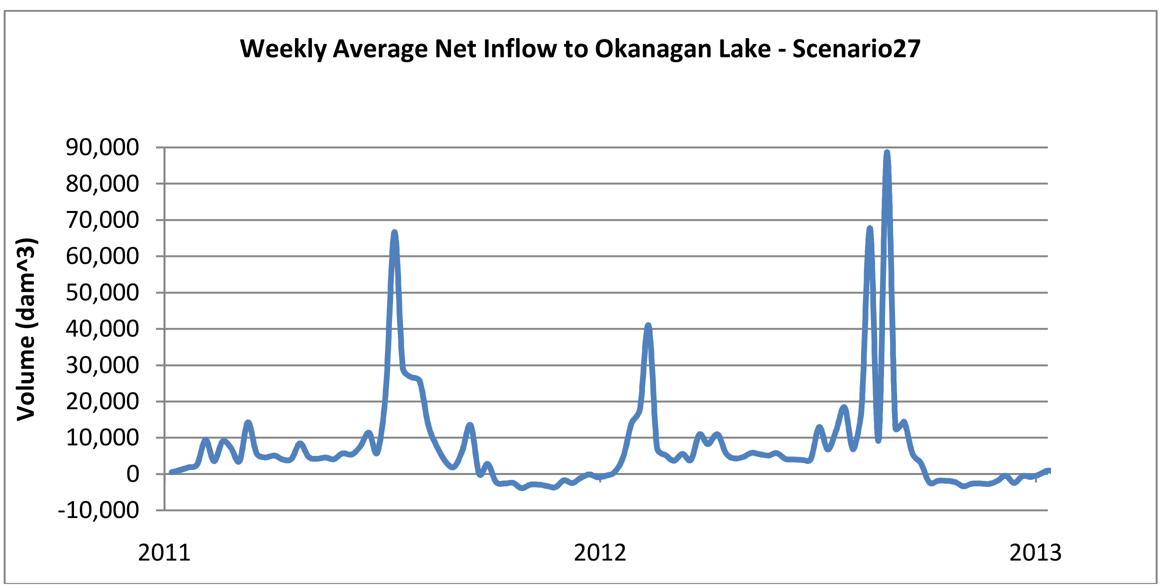




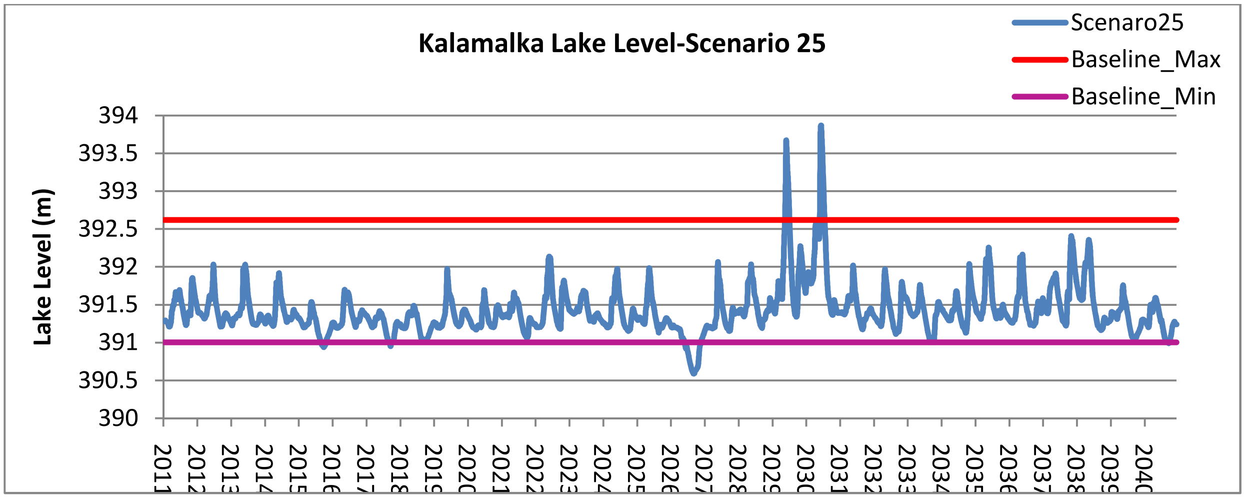
Average Weekly Net Inflows to Okanagan Lake

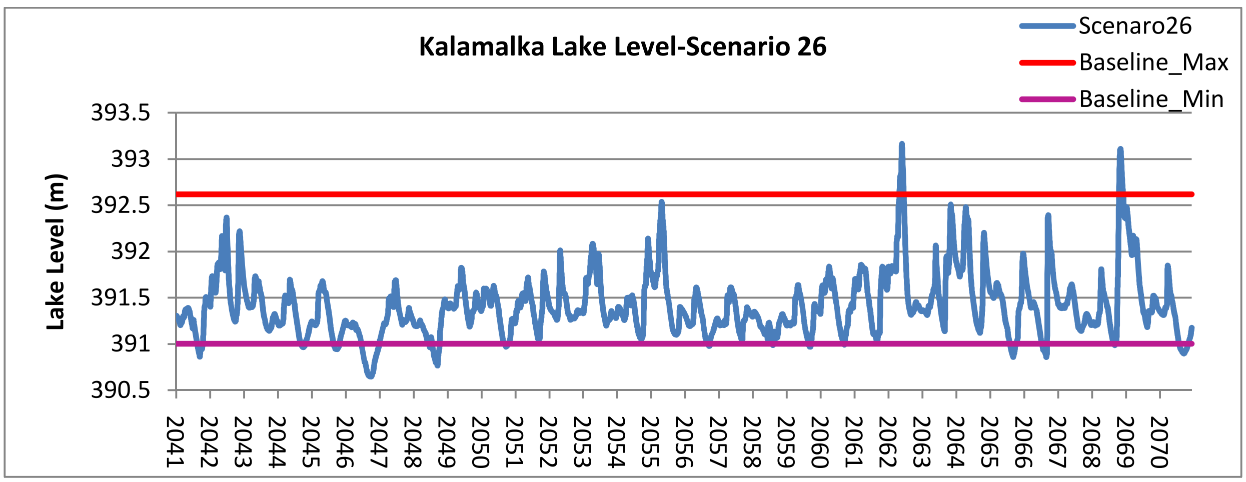


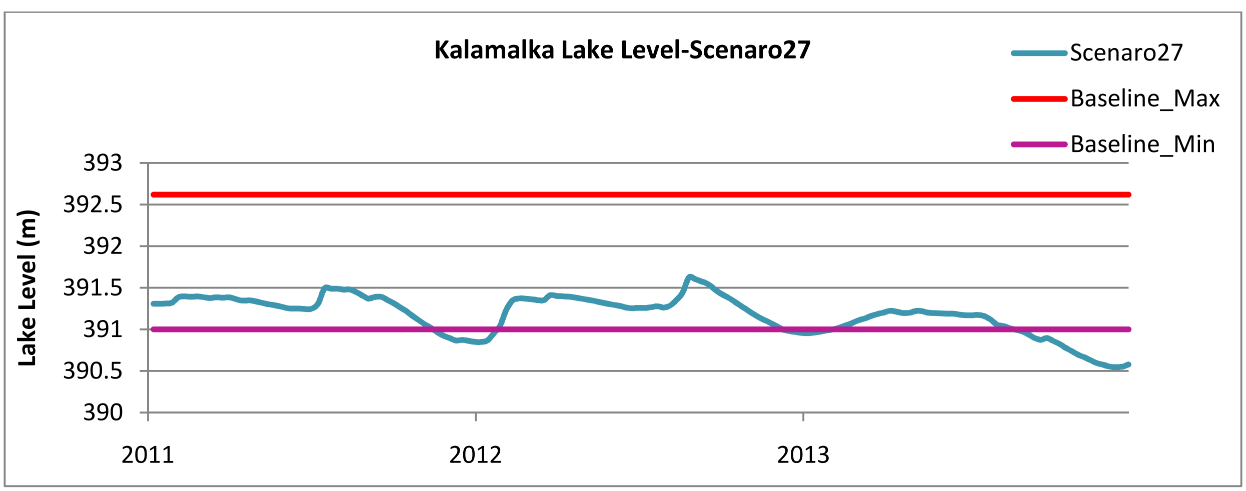




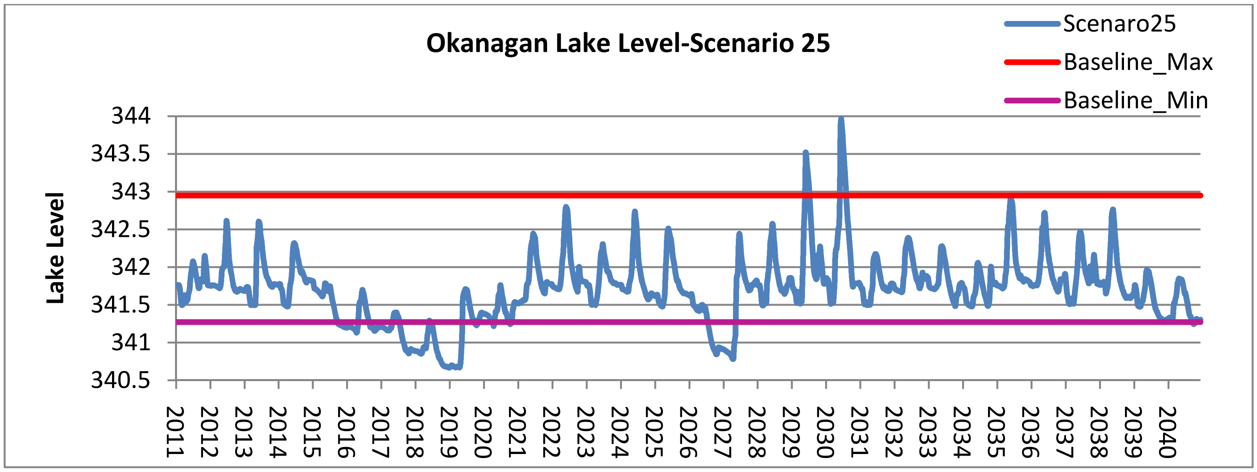
Lake Levels – Kalamalka Lake

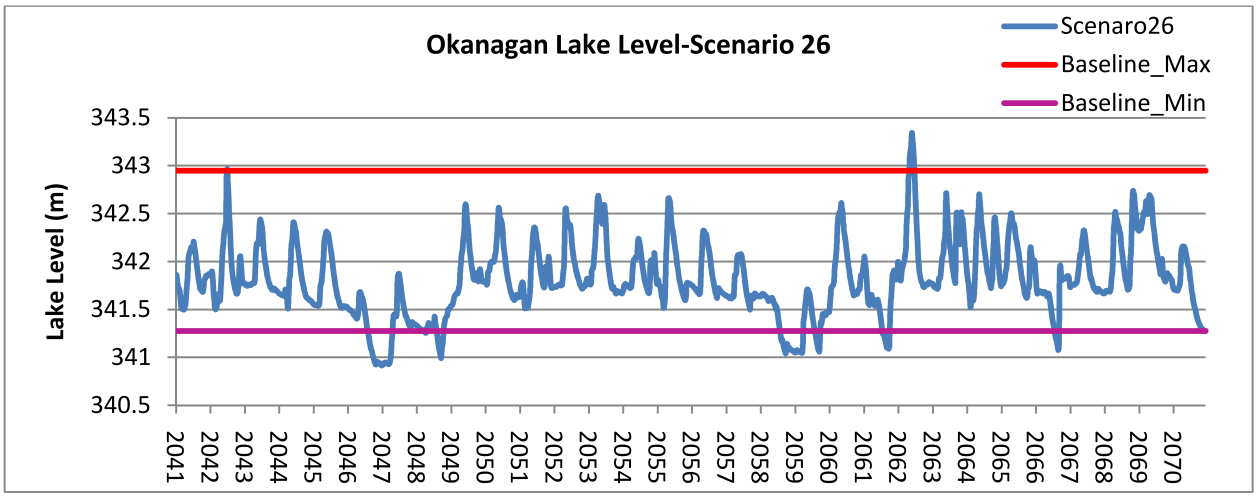


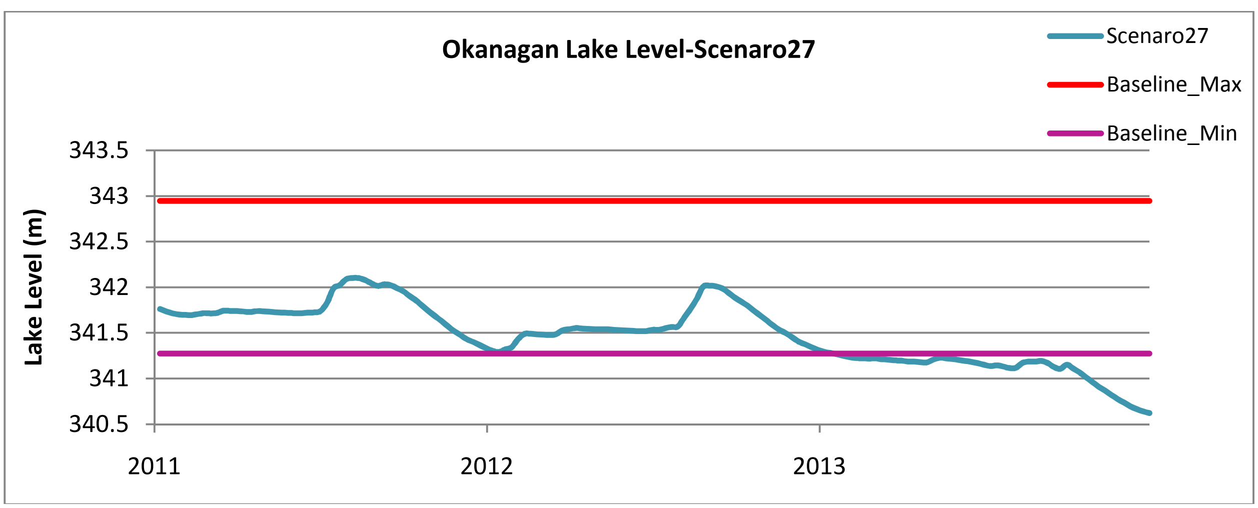




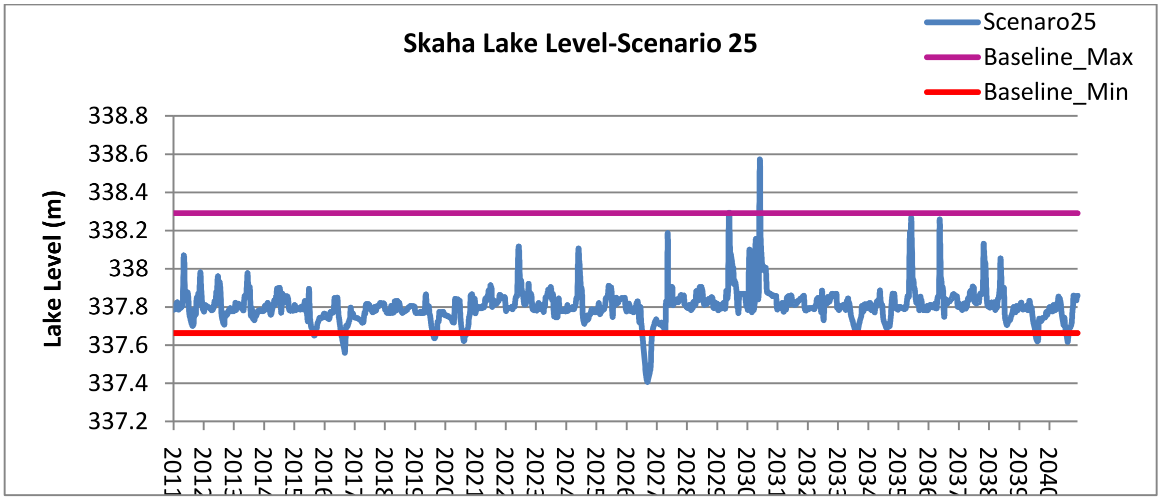
Lake Levels – Okanagan Lake

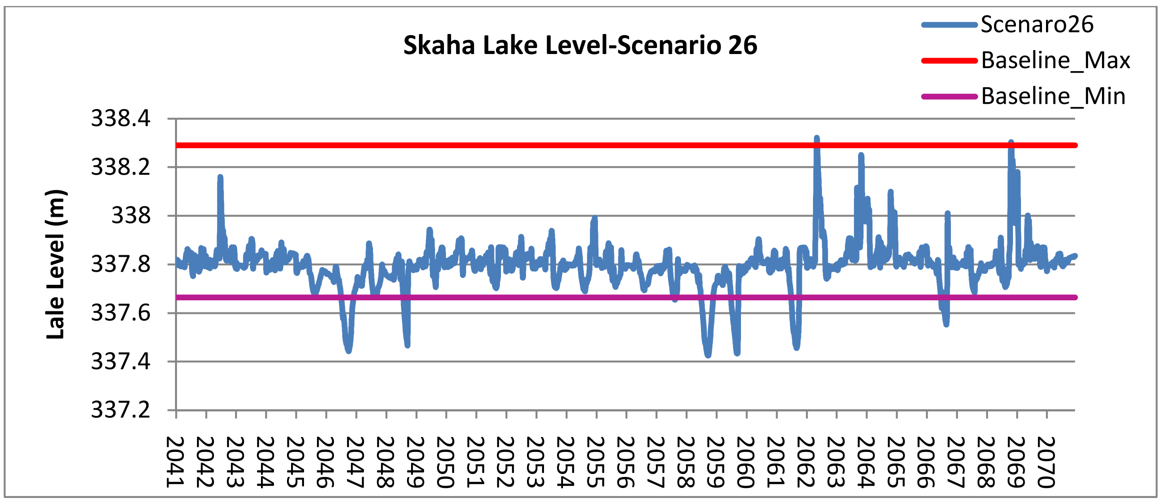


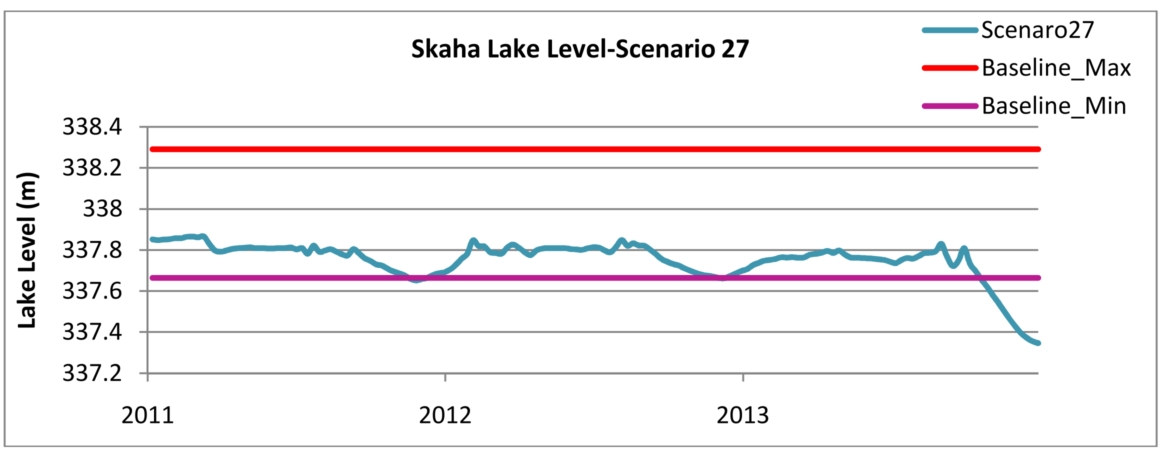




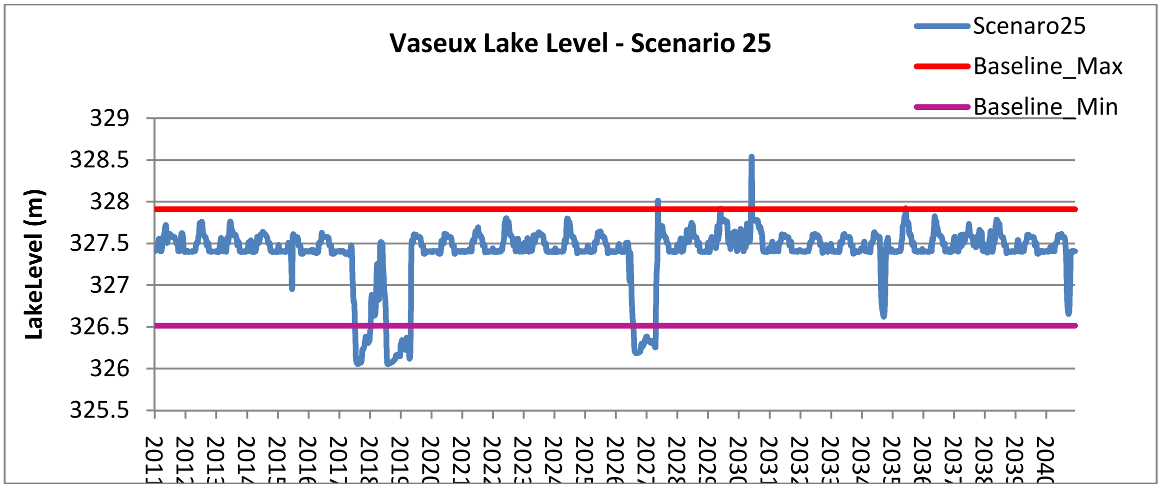
Lake Levels – Skaha Lake

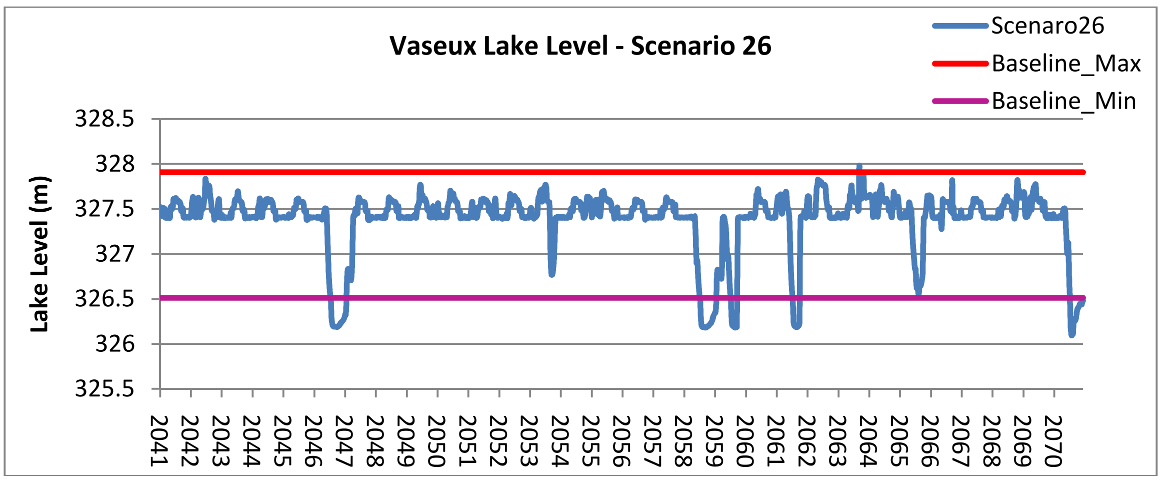


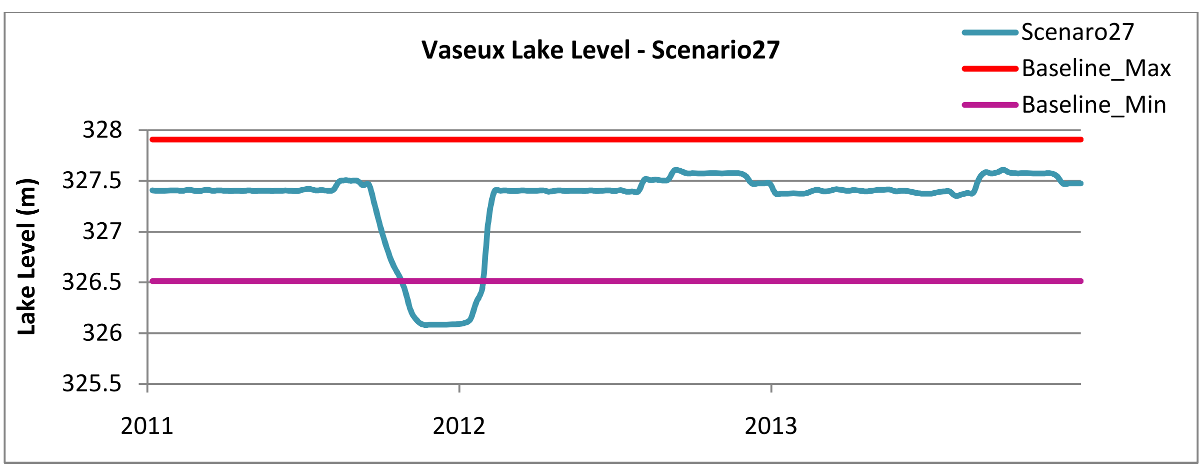




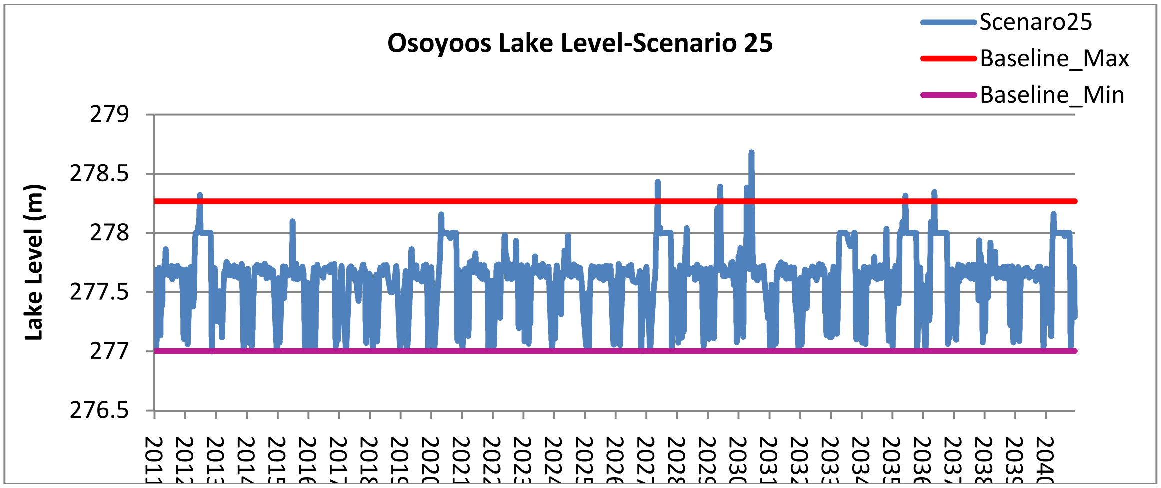
Lake Levels – Vaseux Lake

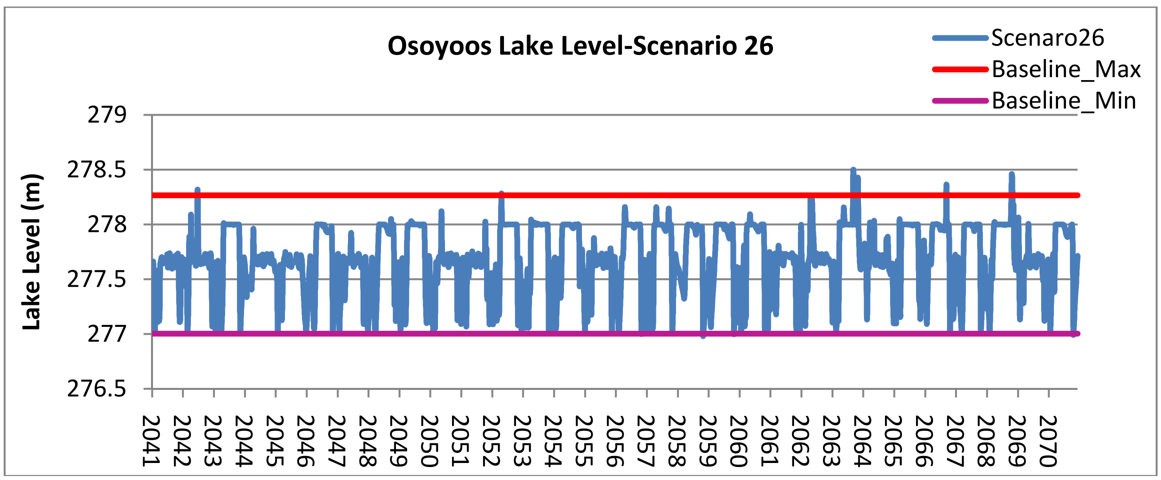


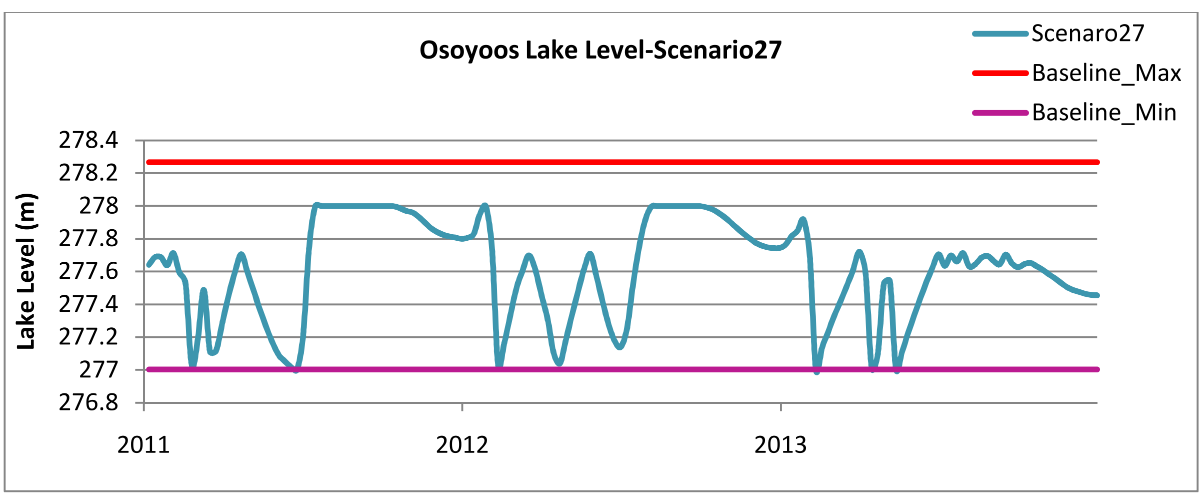




Lake Levels – Osoyoos Lake



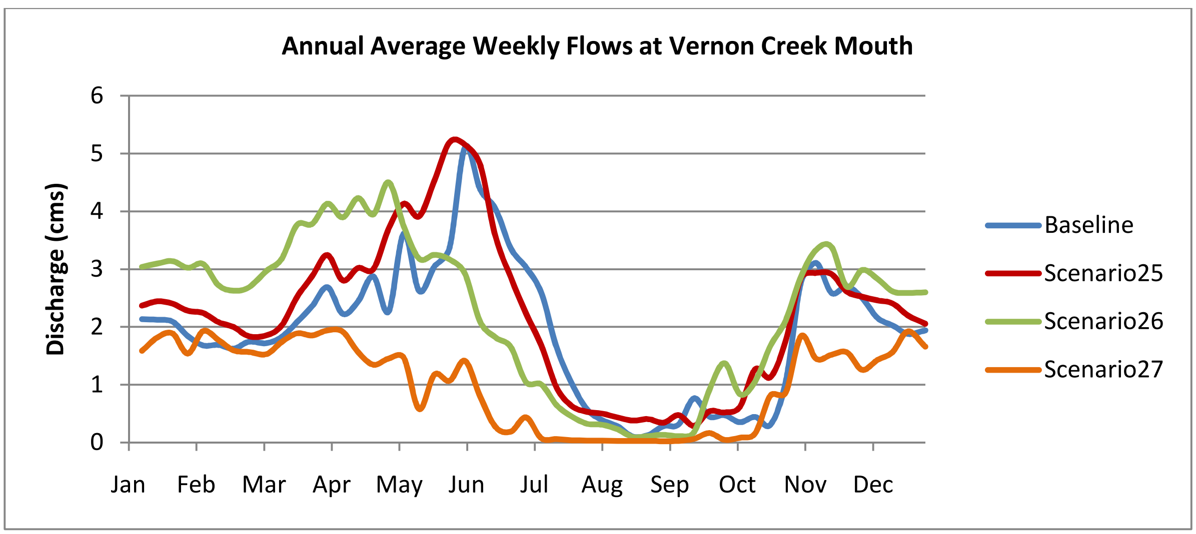




Tributary Flows – Vernon Creek

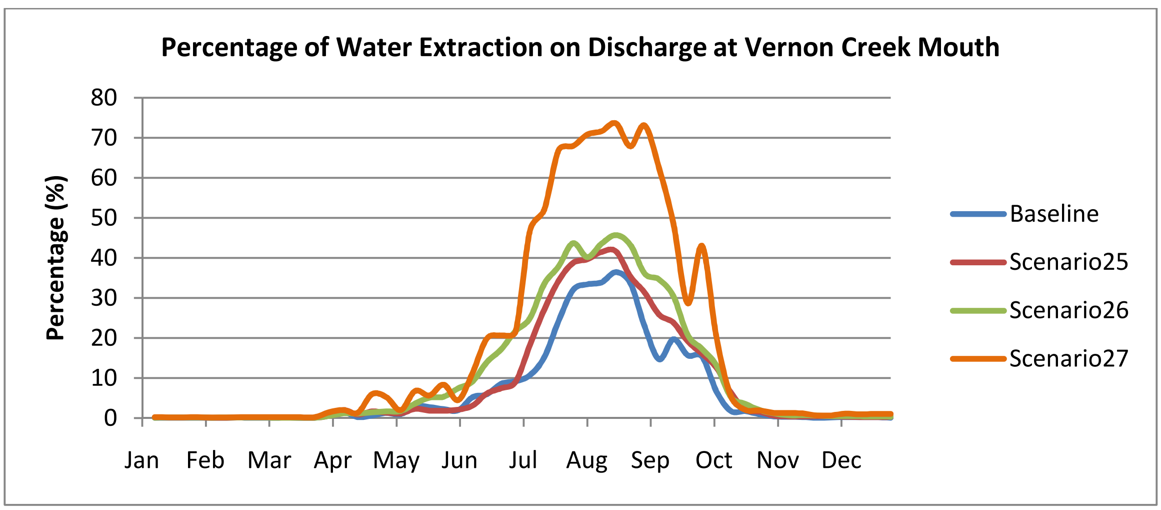
Summary of Average Quarterly Flow in Vernon Creek at Mouth

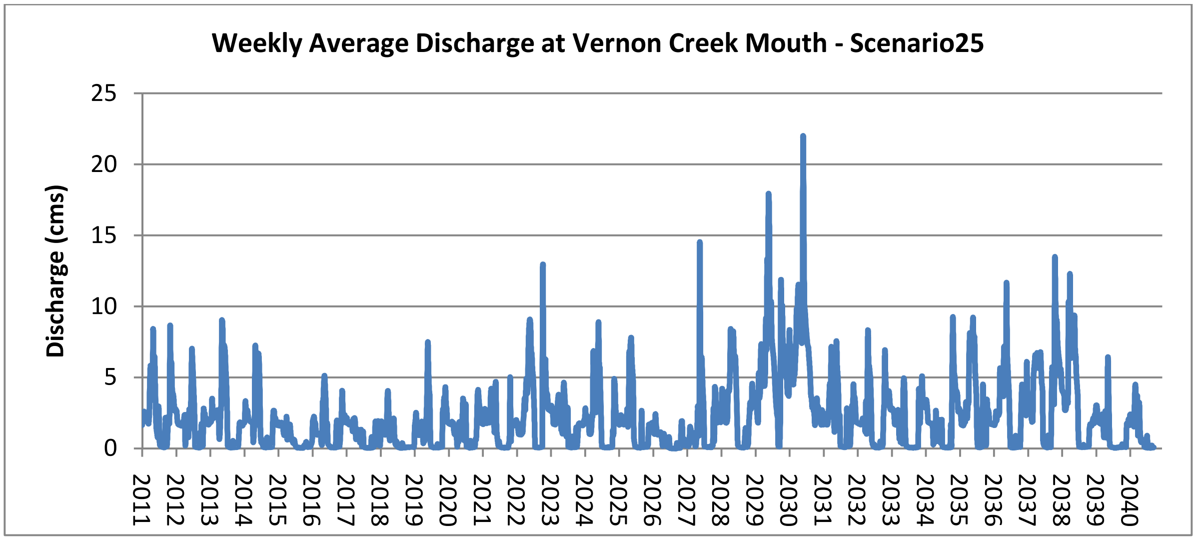
		Baseline	Scenario 25	Scenario 26	Scenario 27
Quarter 1	Discharge(cms)	1.91	2.24	3.09	1.73
	Difference (%)		18	62	-10
Quarter 2	Discharge(cms)	3.23	3.84	3.27	1.17
	Difference (%)		18.8	1.2	-63.9
Quarter 3	Discharge(cms)	0.86	0.71	0.49	0.08
	Difference (%)		-18	-43	-91
Quarter 4	Discharge(cms)	1.83	2.13	2.43	1.24
	Difference (%)		16	33	-32
Annual	Discharge(cms)	1.94	2.20	2.27	1.02
	Difference (%)		14	17	-47

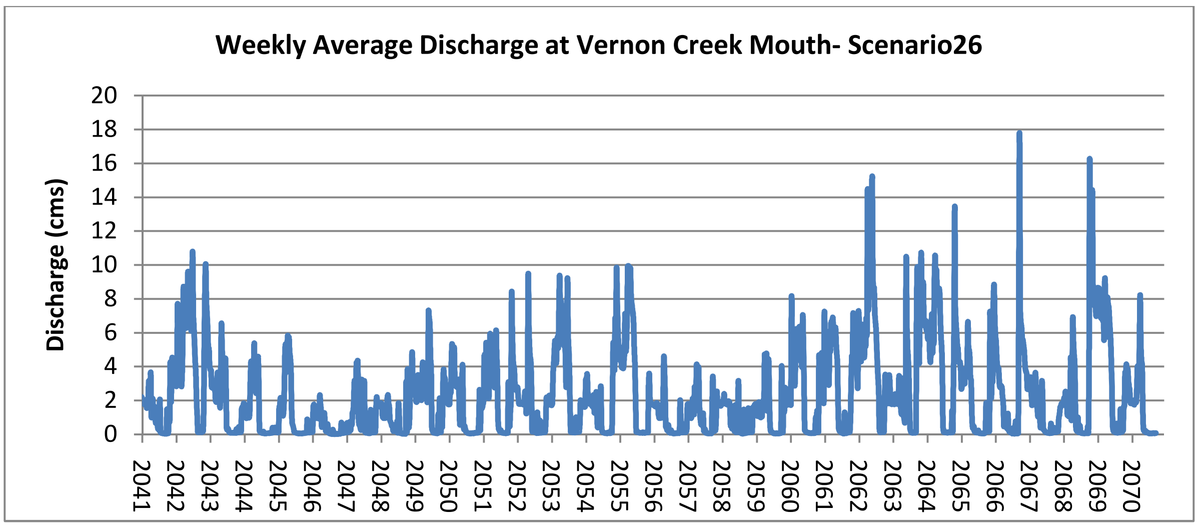


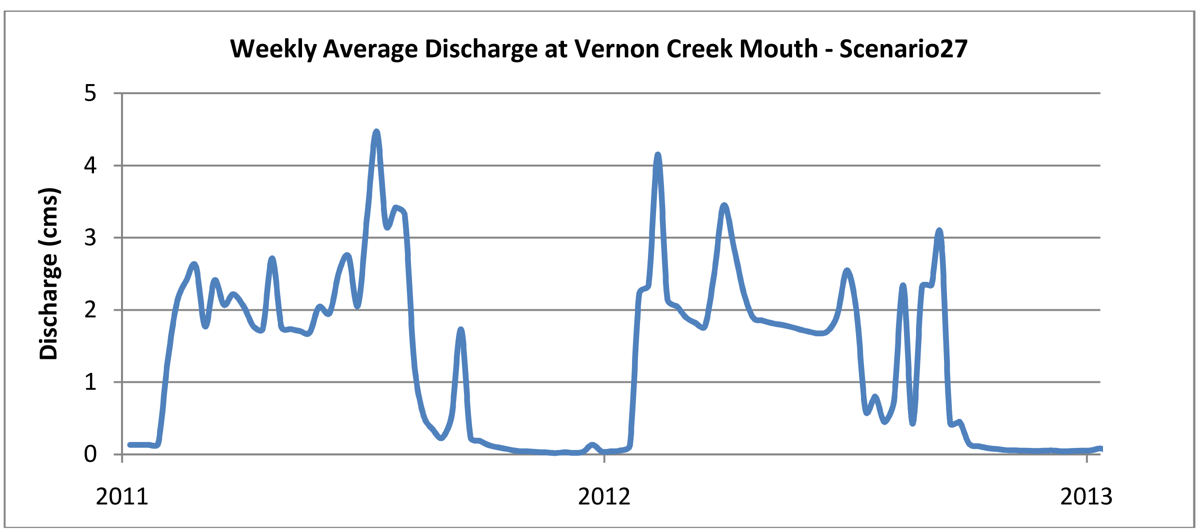
Summary of Average Quarterly Extraction from Vernon Creek (as % Discharge)

		Baseline	Scenario25	Scenario26	Scenario27
Quarter 1	Discharge (cms)	1.91	2.25	3.10	1.71
	Extraction (cms)	0.003	0.003	0.003	0.003
	Difference (%)	0.15	0.19	0.16	0.27
Quarter 2	Discharge (cms)	3.26	3.87	3.31	1.20
	Extraction (cms)	0.03	0.03	0.04	0.03
	Difference (%)	2.74	2.55	5.37	7.31
Quarter 3	Discharge (cms)	0.90	0.75	0.54	0.12
	Extraction (cms)	0.04	0.05	0.05	0.05
	Difference (%)	22.71	28.72	33.83	56.78
Quarter 4	Extraction (cms)	1.84	2.14	2.44	1.24
	Extraction (cms)	0.003	0.005	0.005	0.005
	Difference (%)	1.07	2.08	2.30	2.99
Annual	Discharge (cms)	1.96	2.22	2.30	1.04
	Extraction (cms)	0.03	0.03	0.04	0.03
	Difference (%)	7.10	8.93	11.06	17.91




Weekly Average Discharge at Vernon Creek Mouth - Scenario25
Discharge (cms)
25
20
15
10
5
0
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
2031
2032
2033
2034
2035
2036
2037
2038
2039
2040

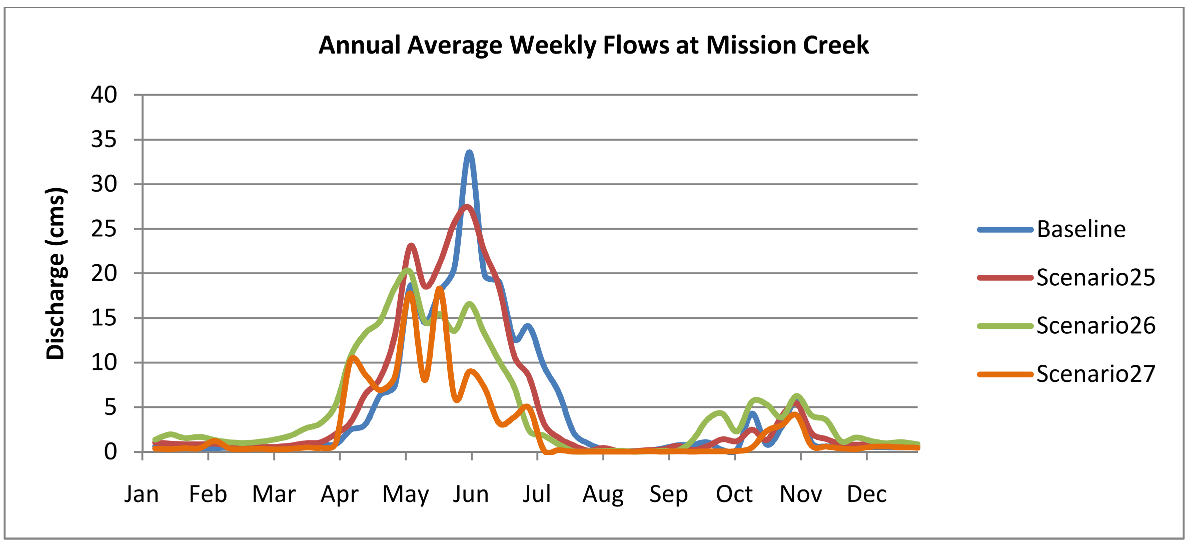

Weekly Average Discharge at Vernon Creek Mouth- Scenario26
Discharge (cms)
20
18
16
14
12
10
8
6
4
2
0
2041
2042
2043
2044
2045
2046
2047
2048
2049
2050
2051
2052
2053
2054
2055
2056
2057
2058
2059
2060
2061
2062
2063
2064
2065
2066
2067
2068
2069
2070


Weekly Average Discharge at Vernon Creek Mouth - Scenario27
Discharge (cms)
5
4
3
2
1
0
2011
2012
2013

Tributary Flows – Mission Creek

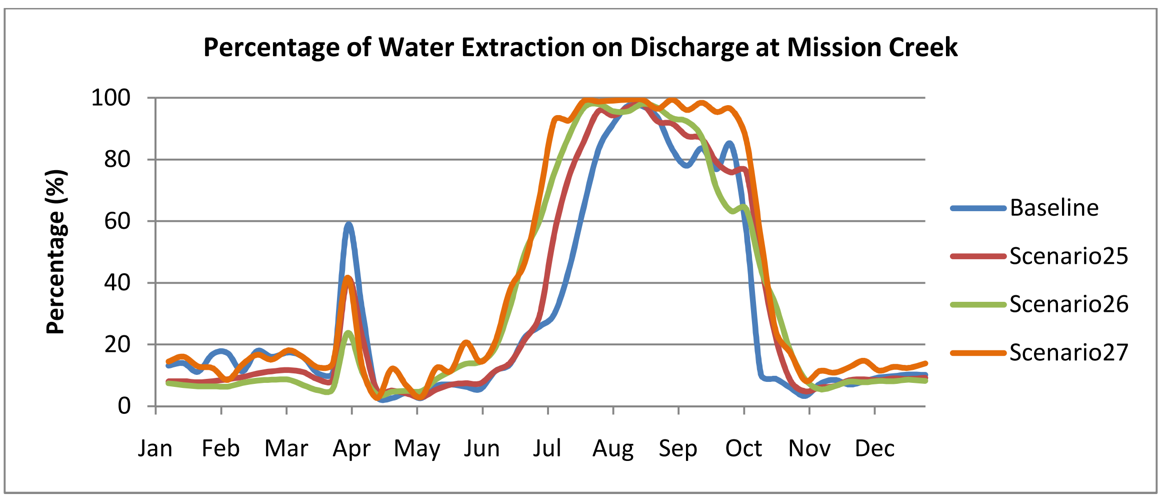
Summary of Average Quarterly Flow in Mission Creek

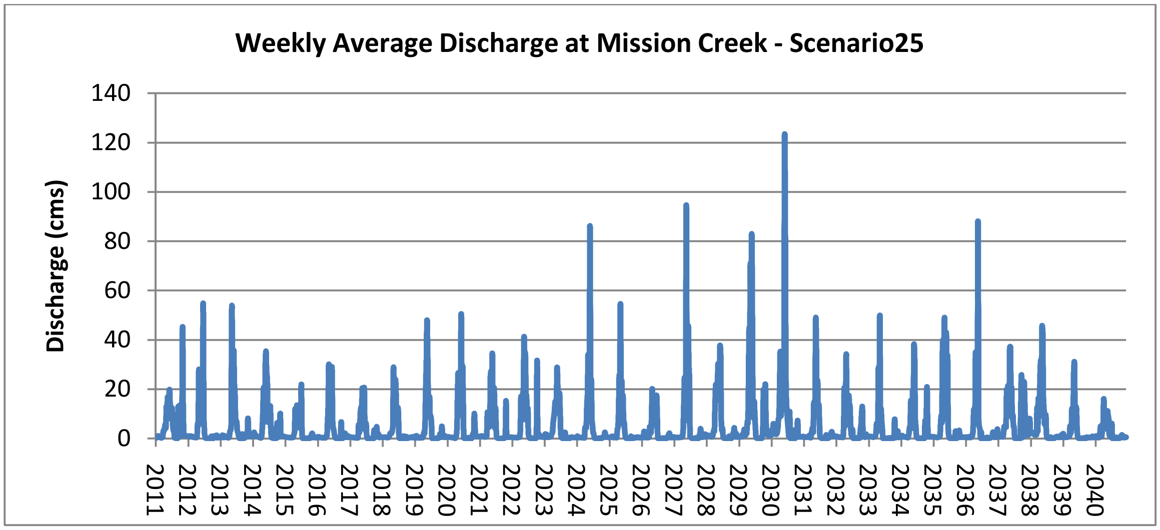
		Baseline	Scenario 25	Scenario 26	Scenario 27
Quarter 1	Discharge(cms)	0.48	0.81	1.69	0.45
	Difference (%)		67	249	-8
Quarter 2	Discharge(cms)	13.63	15.44	13.36	8.37
	Difference (%)		13	-2	-39
Quarter 3	Discharge(cms)	2.64	1.28	1.08	0.41
	Difference (%)		-51	-59	-84
Quarter 4	Discharge(cms)	1.45	1.73	2.93	1.09
	Difference (%)		19	102	-25
Annual	Discharge(cms)	4.59	4.82	4.75	2.58
	Difference (%)		5	3	-44

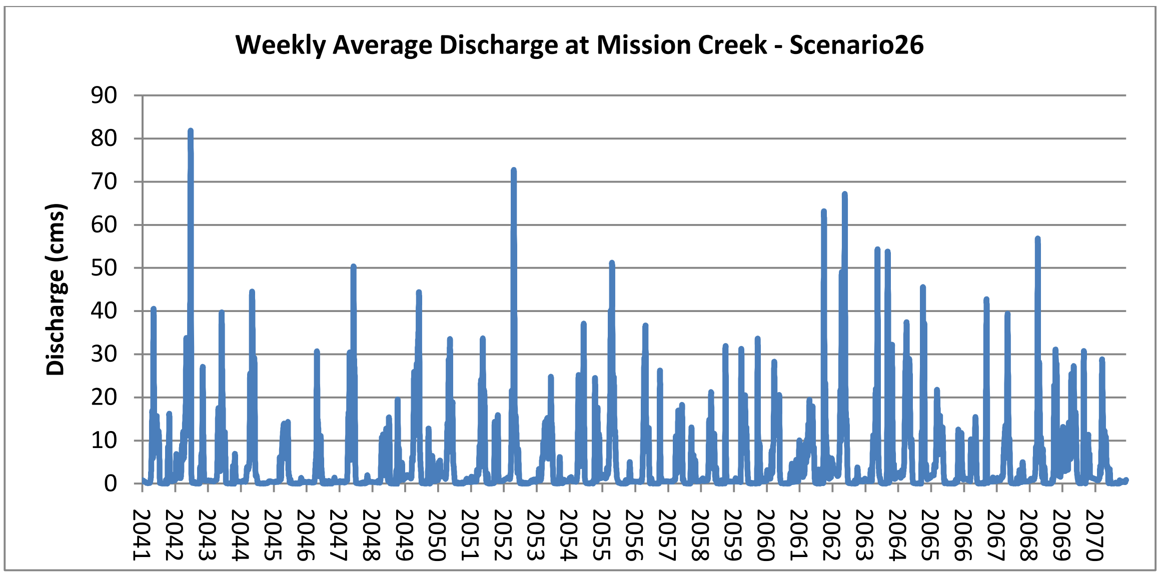


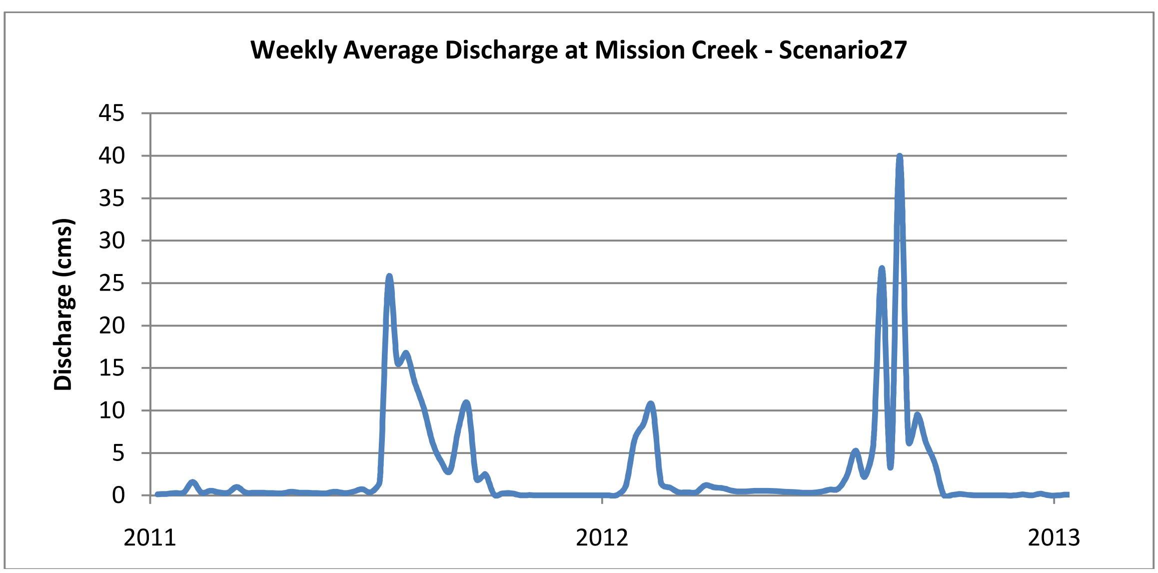
Summary of Average Quarterly Extraction from Mission Creek (as % Discharge)

		Baseline	Scenario25	Scenario26	Scenario27
Quarter 1	Discharge (cms)	0.54	0.87	1.75	0.50
	Extraction (cms)	0.05	0.06	0.06	0.06
	Difference (%)	14	9	7	14
Quarter 2	Discharge (cms)	14.46	16.35	14.48	9.32
	Extraction (cms)	0.83	0.91	1.12	0.95
	Difference (%)	13	12	16	19
Quarter 3	Discharge (cms)	4.56	3.32	3.19	2.62
	Extraction (cms)	1.92	2.03	2.10	2.21
	Difference (%)	74	82	87	95
Quarter 4	Extraction (cms)	1.52	1.89	3.10	1.24
	Extraction (cms)	0.07	0.16	0.17	0.15
	Difference (%)	12	17	18	22
Annual	Discharge (cms)	5.35	5.65	5.66	3.46
	Extraction (cms)	0.83	0.91	1.12	0.95
	Difference (%)	30	31	33	39




Weekly Average Discharge at Mission Creek - Scenario25
Discharge (cms)
140
120
100
80
60
40
20
0
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
2031
2032
2033
2034
2035
2036
2037
2038
2039
2040

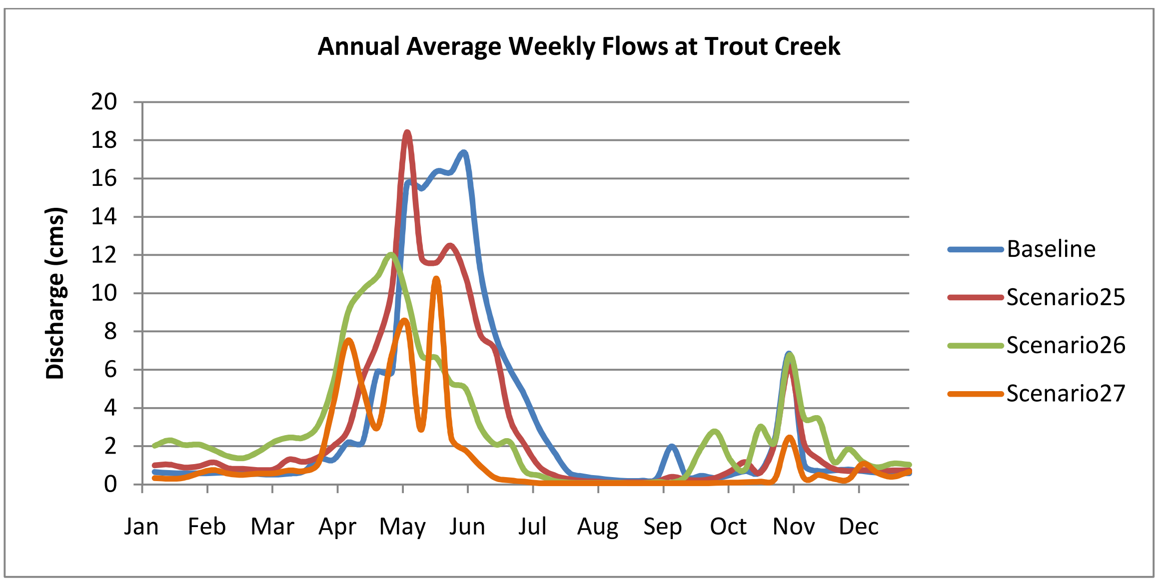

Weekly Average Discharge at Mission Creek - Scenario26
Discharge (cms)
90
80
70
60
50
40
30
20
10
0
2041
2042
2043
2044
2045
2046
2047
2048
2049
2050
2051
2052
2053
2054
2055
2056
2057
2058
2059
2060
2061
2062
2063
2064
2065
2066
2067
2068
2069
2070


Weekly Average Discharge at Mission Creek - Scenario27
Discharge (cms)
45
40
35
30
25
20
15
10
5
0
2011
2012
2013

Tributary Flows – Trout Creek

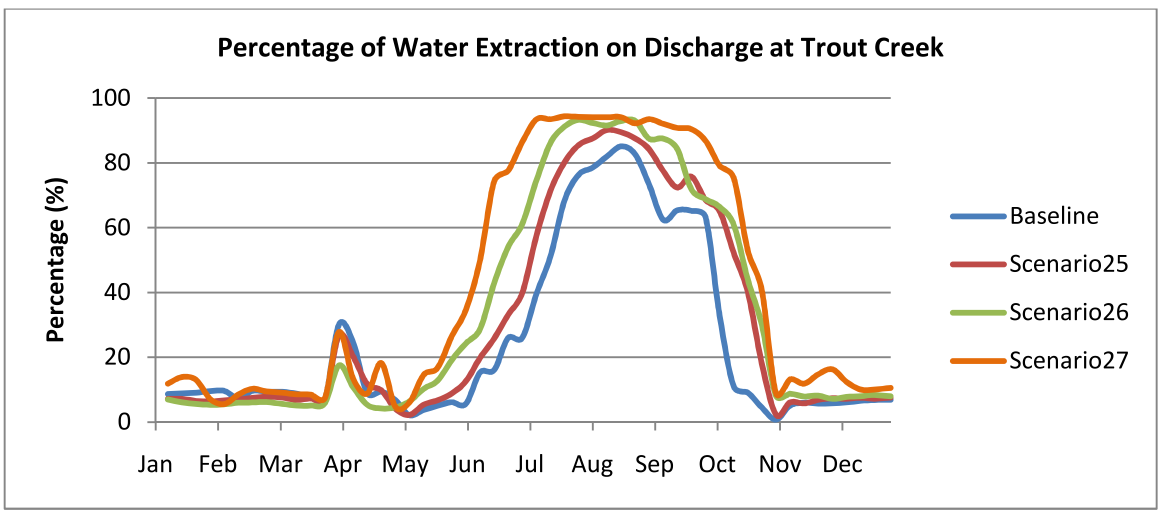
Summary of Average Quarterly Flow in Trout Creek

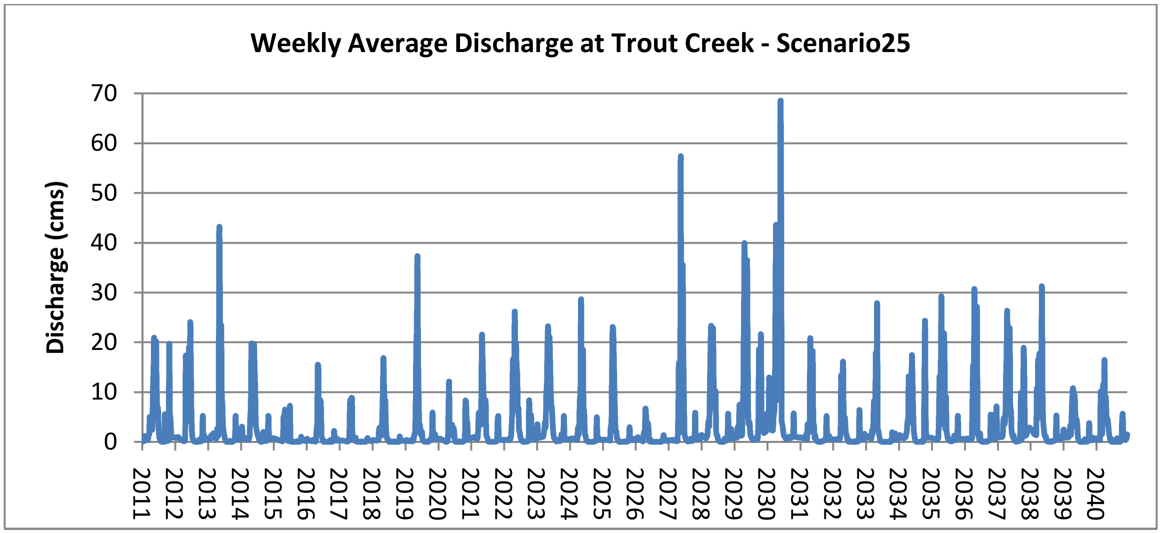
		Baseline	Scenario 25	Scenario 26	Scenario 27
Quarter 1	Discharge(cms)	0.66	1.03	2.09	0.60
	Difference (%)		56	218	-9
Quarter 2	Discharge(cms)	9.51	8.60	6.78	4.19
	Difference (%)		-10	-29	-56
Quarter 3	Discharge(cms)	1.06	0.43	0.52	0.07
	Difference (%)		-60	-51	-93
Quarter 4	Discharge(cms)	1.30	1.45	2.17	0.56
	Difference (%)		12	67	-57
Annual	Discharge(cms)	3.14	2.86	2.86	1.34
	Difference (%)		-9	-9	-57

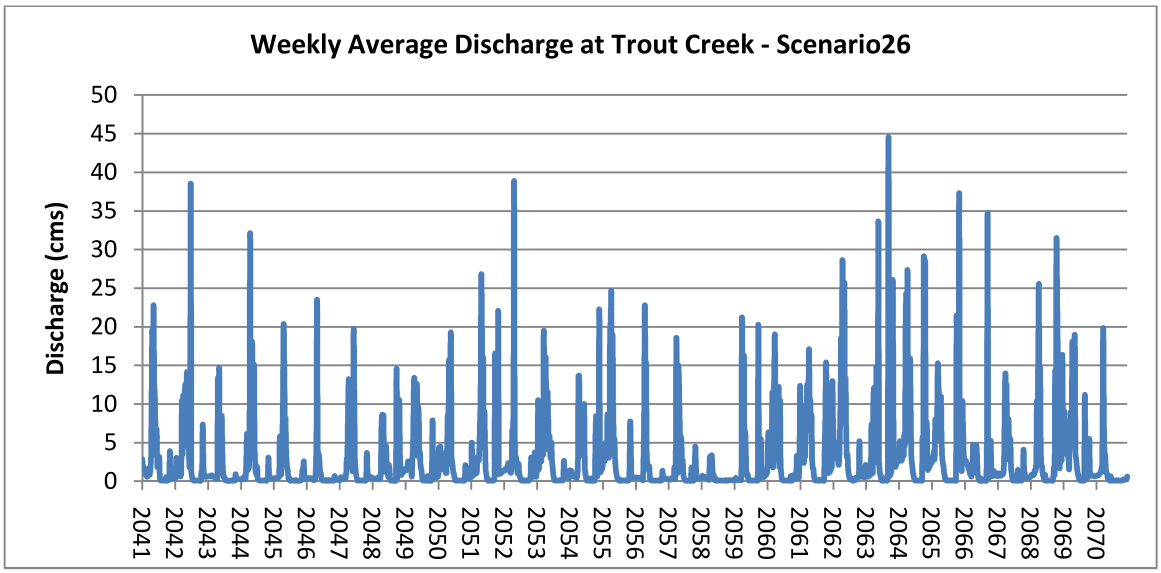


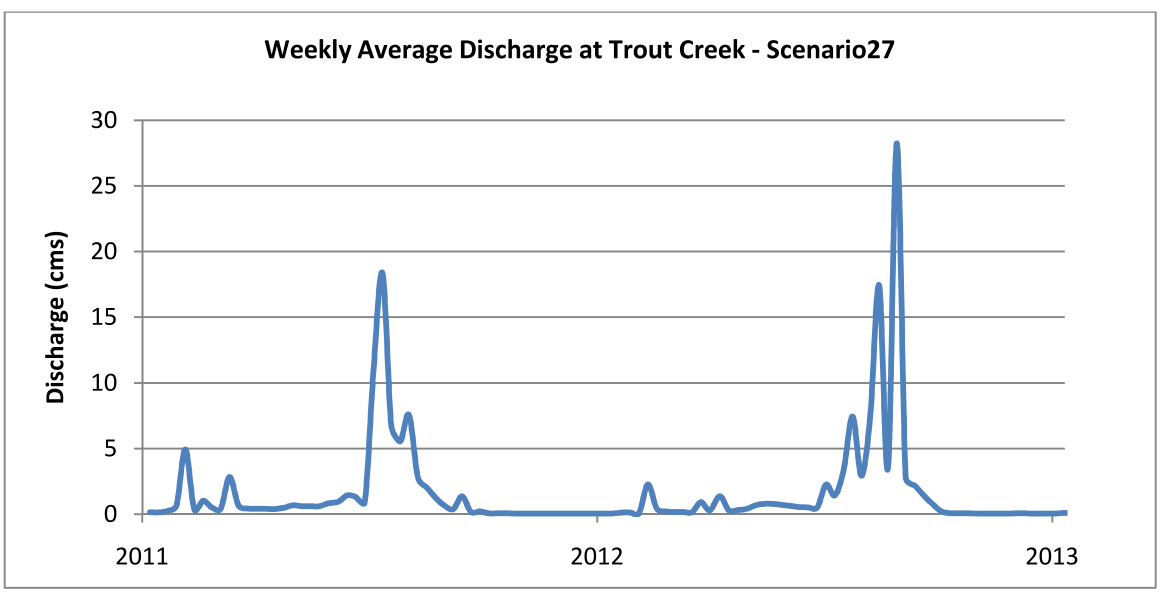
Summary of Average Quarterly Extraction from Trout Creek (as % Discharge)

		Baseline	Scenario25	Scenario26	Scenario27
Quarter 1	Discharge (cms)	0.70	1.07	2.13	0.64
	Extraction (cms)	0.04	0.04	0.05	0.04
	Difference (%)	9	7	6	10
Quarter 2	Discharge (cms)	9.90	9.03	7.29	4.66
	Extraction (cms)	0.39	0.43	0.50	0.47
	Difference (%)	12	14	19	29
Quarter 3	Discharge (cms)	1.83	1.23	1.35	0.95
	Extraction (cms)	0.76	0.81	0.84	0.88
	Difference (%)	66	76	84	92
Quarter 4	Extraction (cms)	1.36	1.56	2.28	0.67
	Extraction (cms)	0.06	0.11	0.12	0.11
	Difference (%)	8	18	21	27
Annual	Discharge (cms)	3.47	3.23	3.25	1.74
	Extraction (cms)	0.39	0.43	0.50	0.47
	Difference (%)	25	30	34	41




Weekly Average Discharge at Trout Creek - Scenario25
Discharge (cms)
70
60
50
40
30
20
10
0
2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035 2036 2037 2038 2039 2040

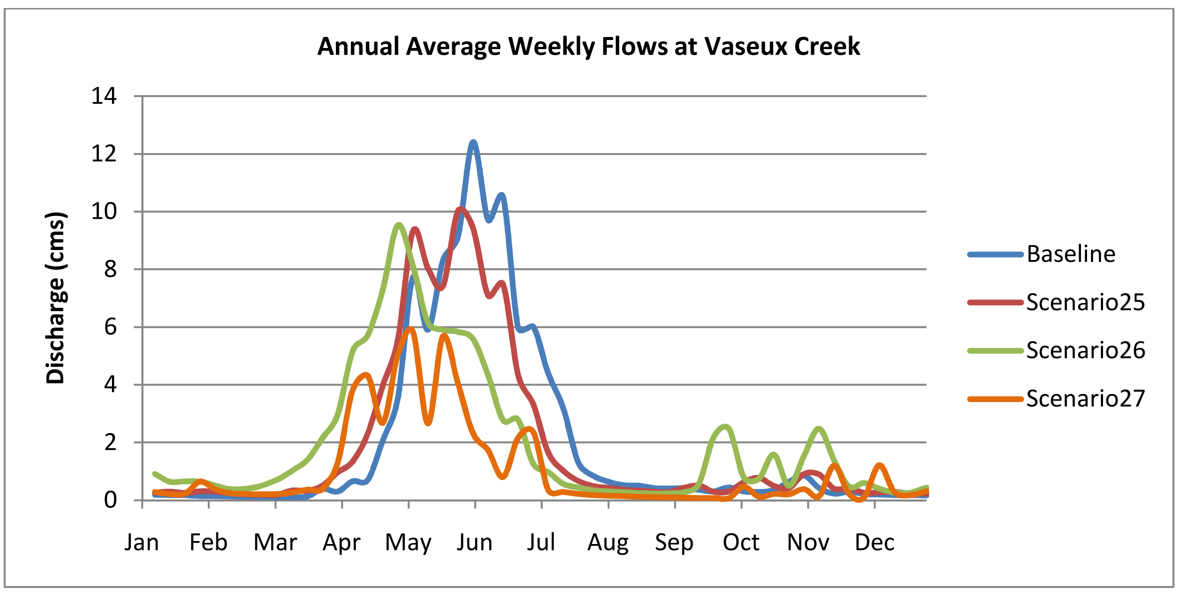

Weekly Average Discharge at Trout Creek - Scenario26
Discharge (cms)
50
45
40
35
30
25
20
15
10
5
0
2041 2042 2043 2044 2045 2046 2047 2048 2049 2050 2051 2052 2053 2054 2055 2056 2057 2058 2059 2060 2061 2062 2063 2064 2065 2066 2067 2068 2069 2070


Weekly Average Discharge at Trout Creek - Scenario27
Discharge (cms)
30
25
20
15
10
5
0
2011
2012
2013

Tributary Flows – Vaseux Creek

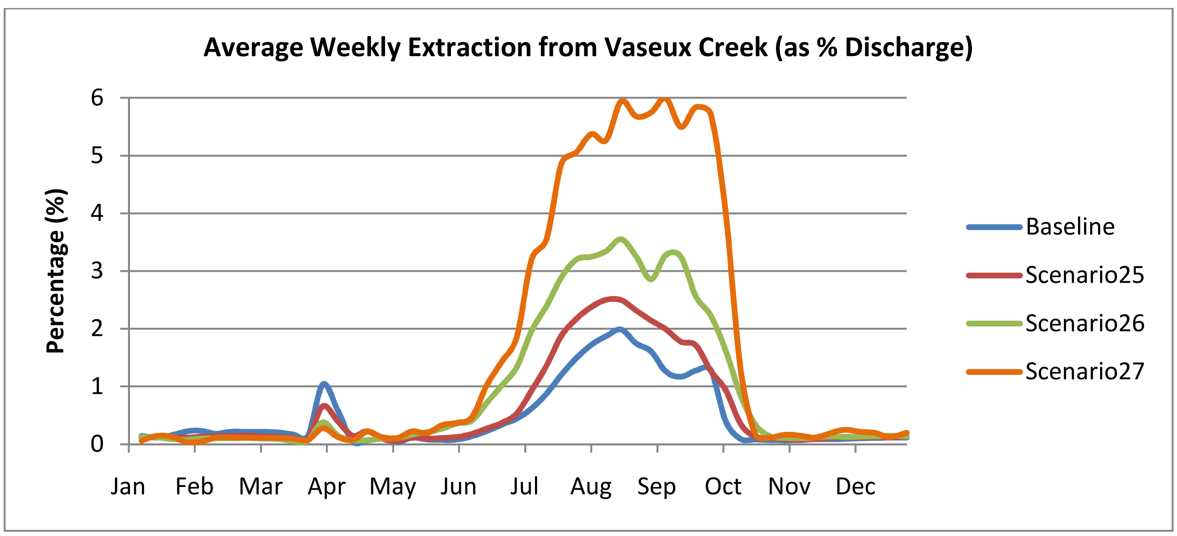
Summary of Average Quarterly Flow in Vaseux Creek

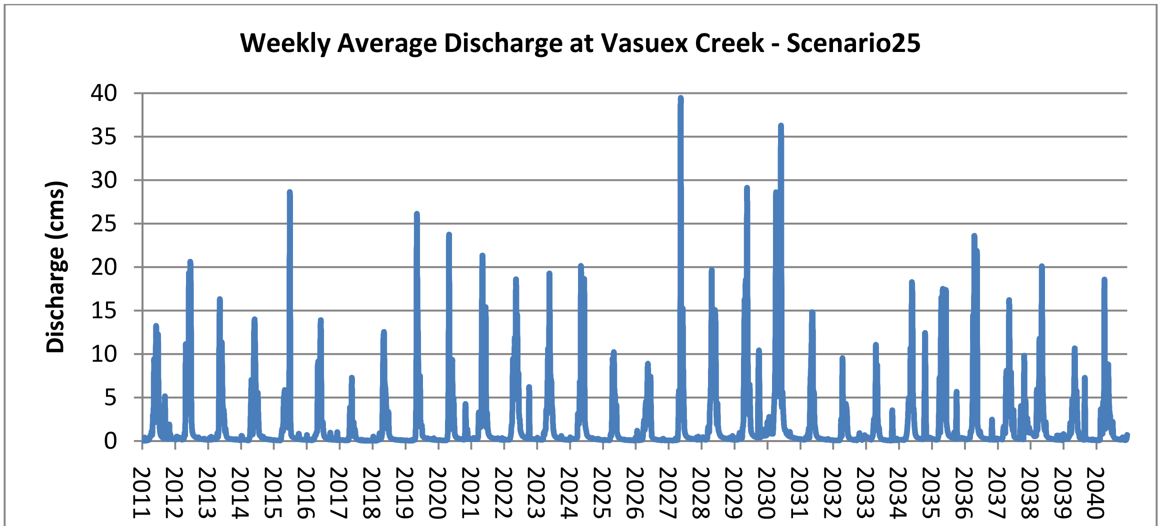
		Baseline	Scenario 25	Scenario 26	Scenario 27
Quarter 1	Discharge(cms)	0.16	0.29	0.82	0.31
	Difference(%)		84	424	95
Quarter 2	Discharge(cms)	5.92	5.94	5.55	3.26
	Difference(%)		0	-6	-45
Quarter 3	Discharge(cms)	1.41	0.75	0.74	0.31
	Difference(%)		-47	-48	-78
Quarter 4	Discharge(cms)	0.33	0.48	0.88	0.39
	Difference(%)		47	168	18
Annual	Discharge(cms)	1.98	1.87	2.00	1.07
	Difference(%)		-5	1	-46

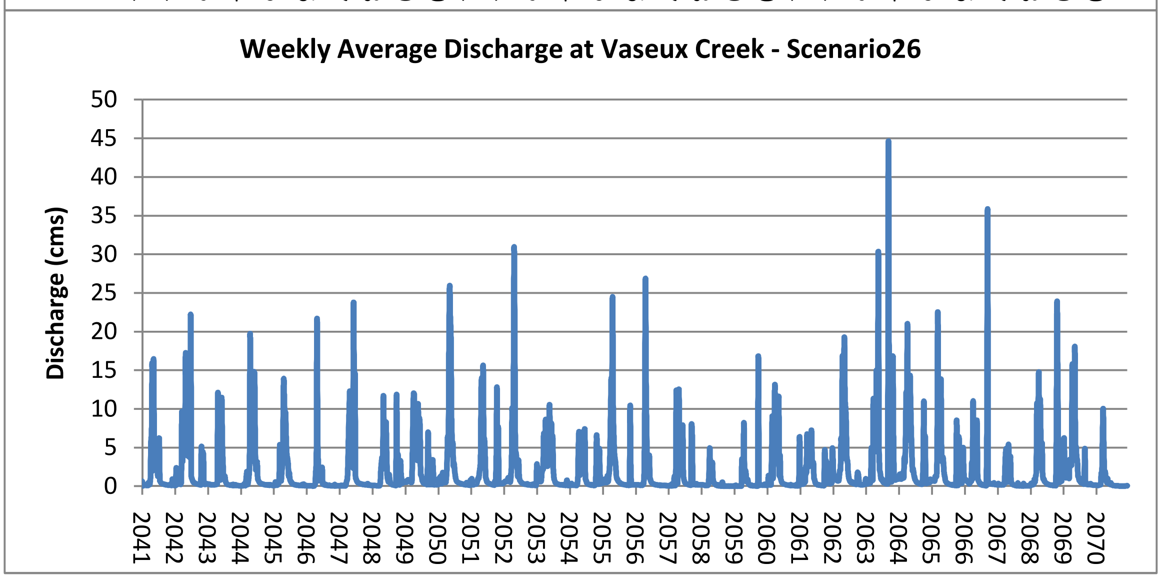


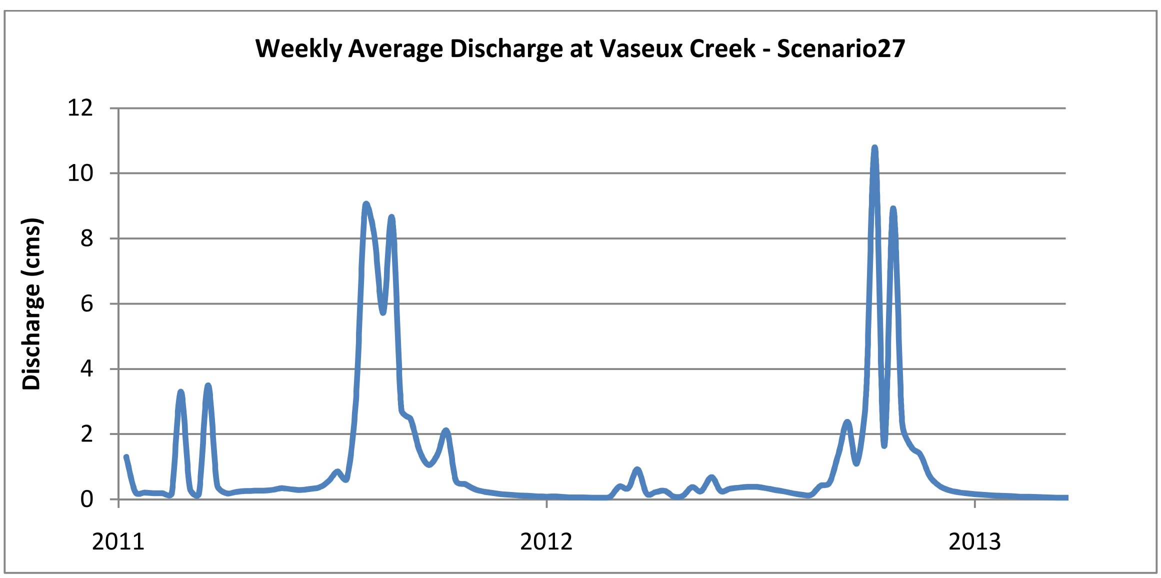
Summary of Average Quarterly Extraction in Vaseux Creek (as % Discharge)

		Baseline	Scenario25	Scenario26	Scenario27
Quarter 1	Discharge (cms)	0.16	0.29	0.82	0.30
	Extraction (cms)	0.0002	0.0002	0.0002	0.0002
	Difference (%)	0.18	0.12	0.09	0.10
Quarter 2	Discharge (cms)	5.92	5.95	5.56	3.27
	Extraction (cms)	0.003	0.004	0.005	0.005
	Difference (%)	0.23	0.22	0.31	0.38
Quarter 3	Discharge (cms)	1.41	0.75	0.75	0.32
	Extraction (cms)	0.006	0.006	0.007	0.007
	Difference (%)	1.32	1.82	2.81	4.97
Quarter 4	Extraction (cms)	0.33	0.48	0.88	0.39
	Extraction (cms)	0.0002	0.0003	0.0004	0.0004
	Difference (%)	0.11	0.19	0.31	0.56
Annual	Discharge (cms)	1.98	1.88	2.00	1.07
	Extraction (cms)	0.003	0.004	0.005	0.005
	Difference (%)	0.48	0.62	0.93	1.59




Weekly Average Discharge at Vasuex Creek - Scenario25
Discharge (cms)
40
35
30
25
20
15
10
5
0
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
2031
2032
2033
2034
2035
2036
2037
2038
2039
2040

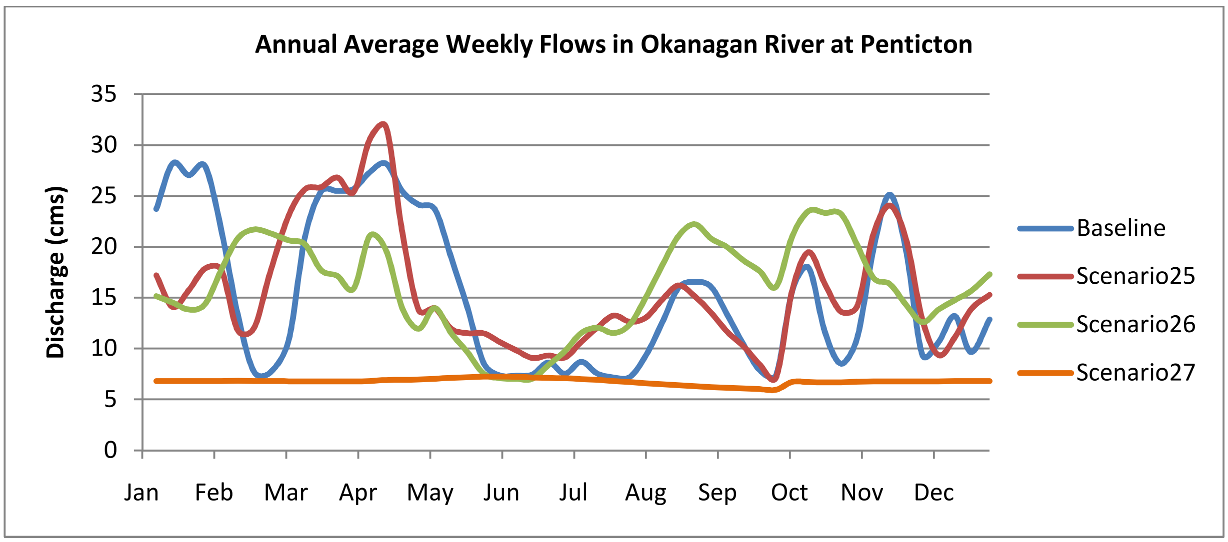

Weekly Average Discharge at Vaseux Creek - Scenario26
Discharge (cms)
50
45
40
35
30
25
20
15
10
5
0
2041
2042
2043
2044
2045
2046
2047
2048
2049
2050
2051
2052
2053
2054
2055
2056
2057
2058
2059
2060
2061
2062
2063
2064
2065
2066
2067
2068
2069
2070

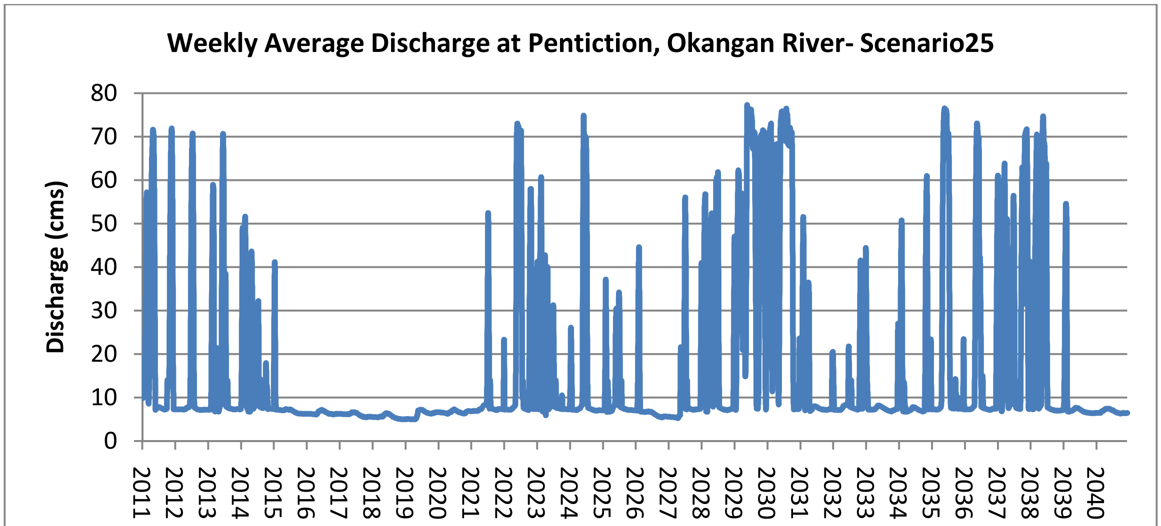

Weekly Average Discharge at Vaseux Creek - Scenario27
Discharge (cms)
12
10
8
6
4
2
0
2011
2012
2013

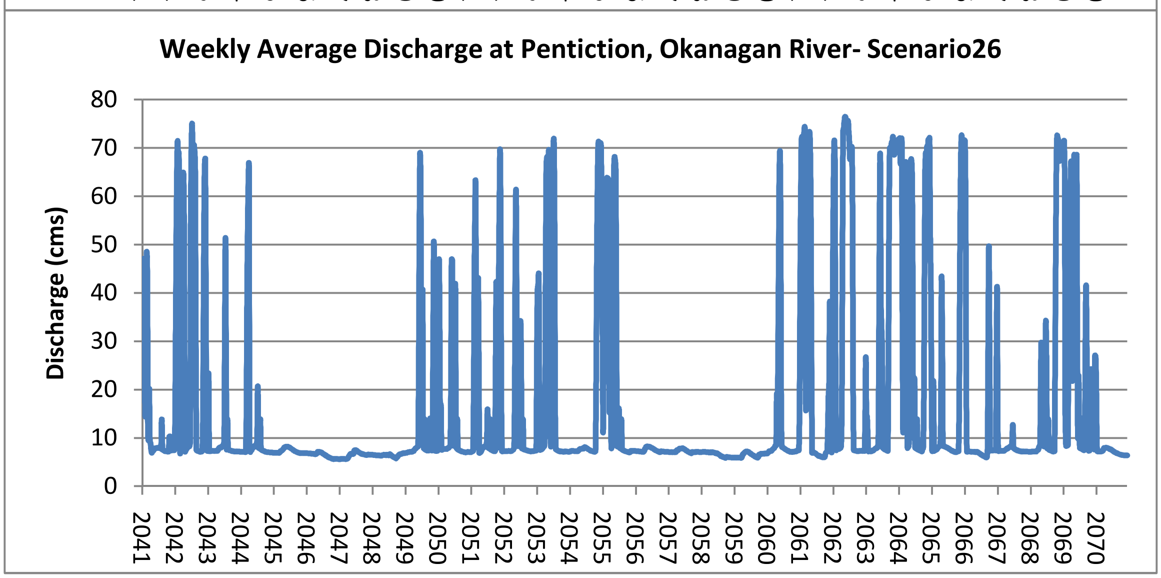
Flows in Okanagan River at Penticton

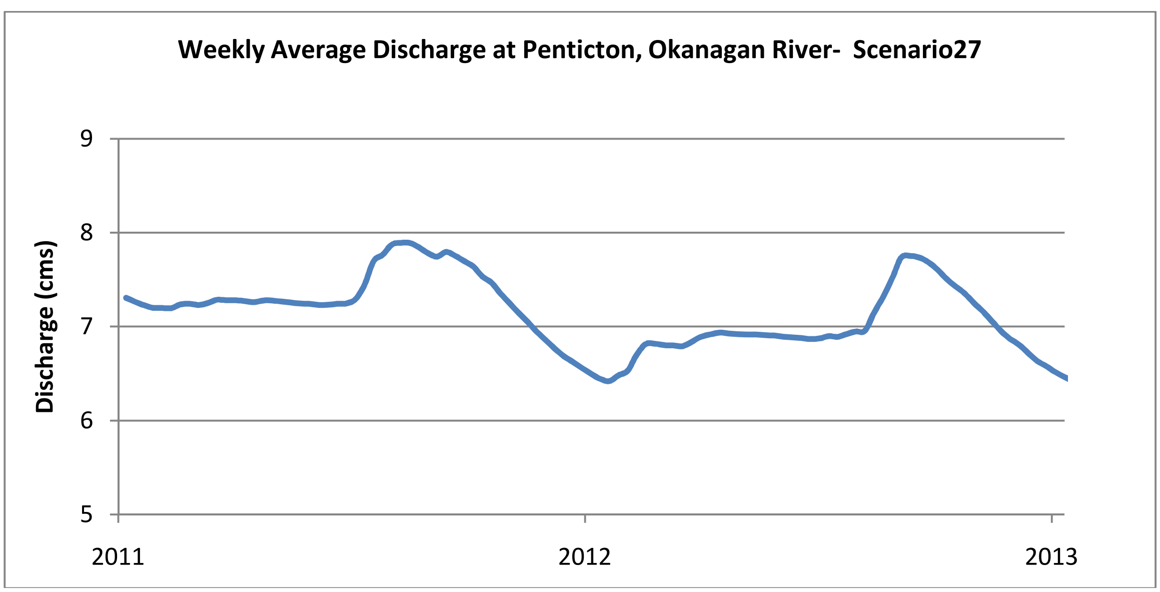
Summary of Average Quarterly Flows in Okanagan River at Penticton

		Baseline	Scenario 25	Scenario 26	Scenario 27
Quarter 1	Discharge(cms)	14.63	16.35	18.26	6.80
	Difference (%)		12	25	-54
Quarter 2	Discharge(cms)	19.41	18.56	17.87	7.05
	Difference (%)		-4	-8	-64
Quarter 3	Discharge(cms)	16.74	15.70	11.75	6.47
	Difference (%)		-6	-30	-61
Quarter 4	Discharge(cms)	10.77	12.21	16.70	6.75
	Difference (%)		13	55	-37
Annual	Discharge(cms)	15.44	15.69	16.02	6.78
	Difference (%)		2	4	-56




Weekly Average Discharge at Pentiction, Okangan River- Scenario25
Discharge (cms)
0
10
20
30
40
50
60
70
80
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
2031
2032
2033
2034
2035
2036
2037
2038
2039
2040

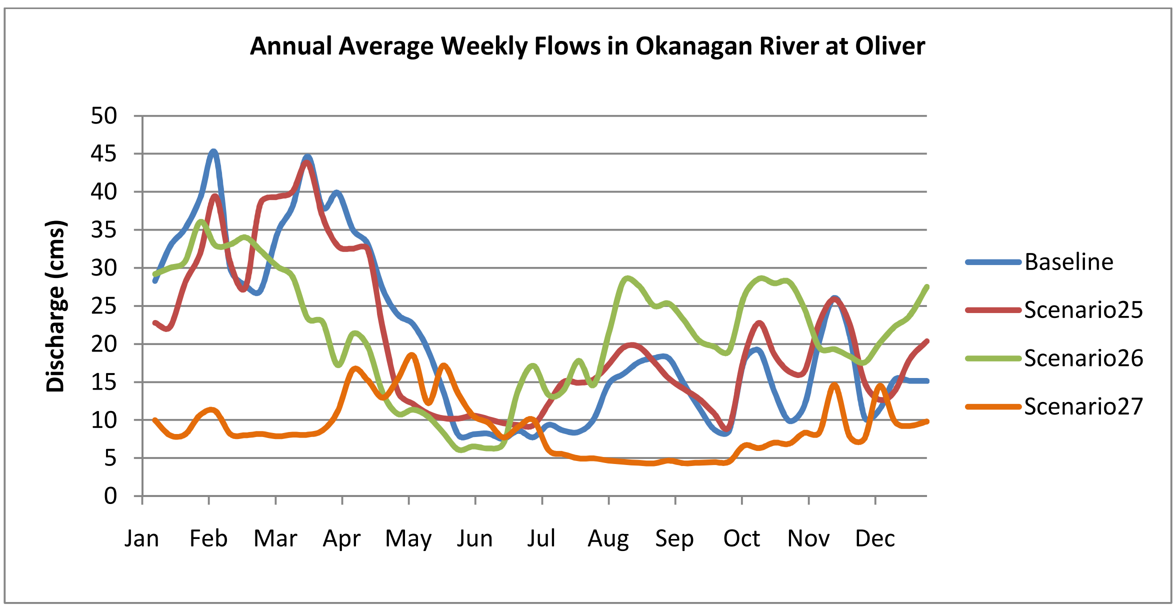

Weekly Average Discharge at Pentiction, Okanagan River- Scenario26
Discharge (cms)
0
10
20
30
40
50
60
70
80
2041
2042
2043
2044
2045
2046
2047
2048
2049
2050
2051
2052
2053
2054
2055
2056
2057
2058
2059
2060
2061
2062
2063
2064
2065
2066
2067
2068
2069
2070

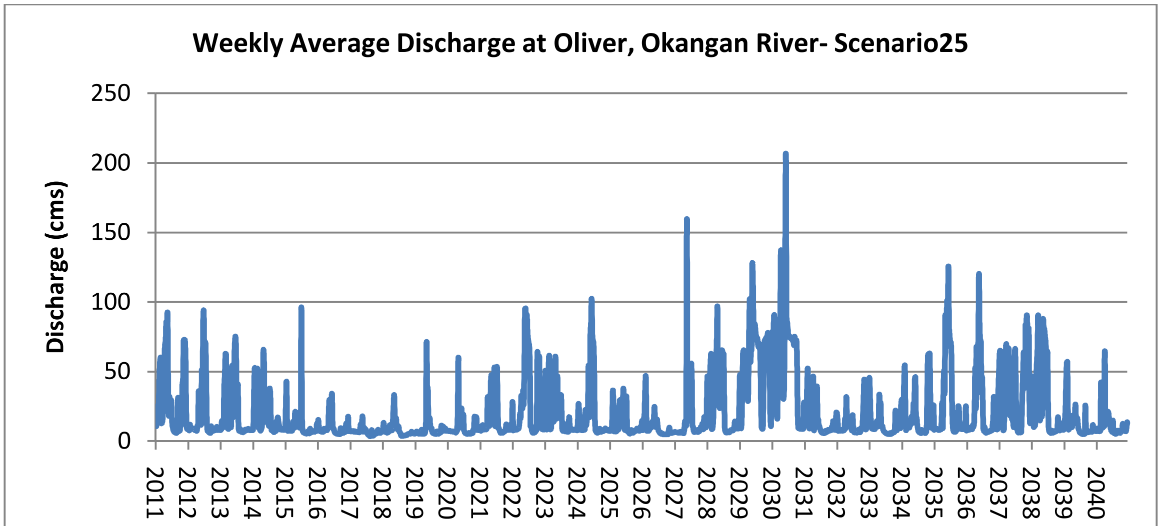

Weekly Average Discharge at Penticton, Okanagan River- Scenario27
Discharge (cms)
5
6
7
8
9
2011
2012
2013

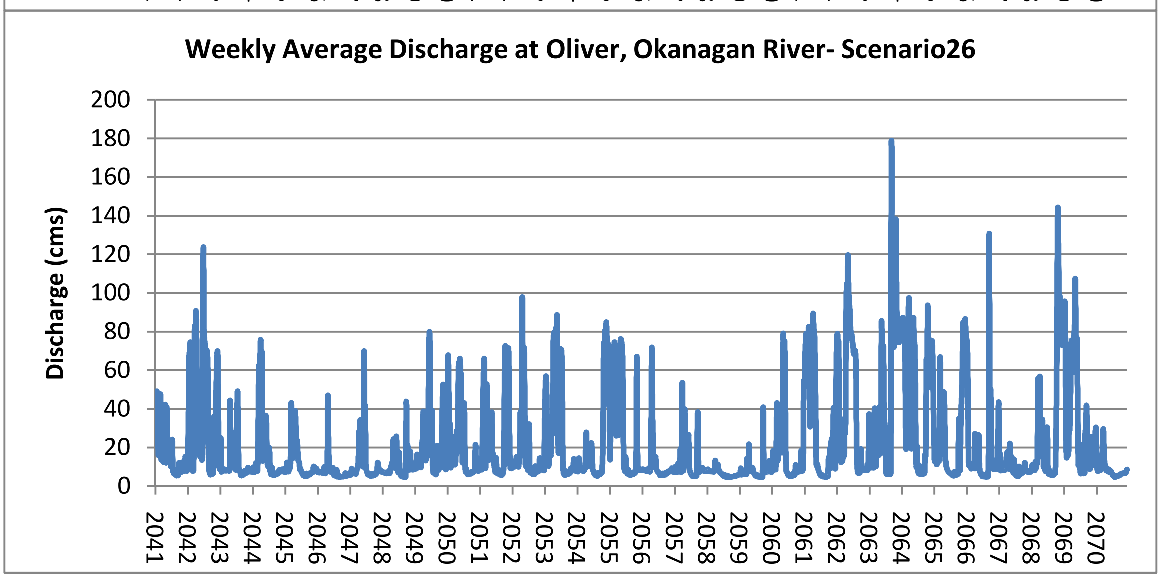
Flows in Okanagan River at Oliver

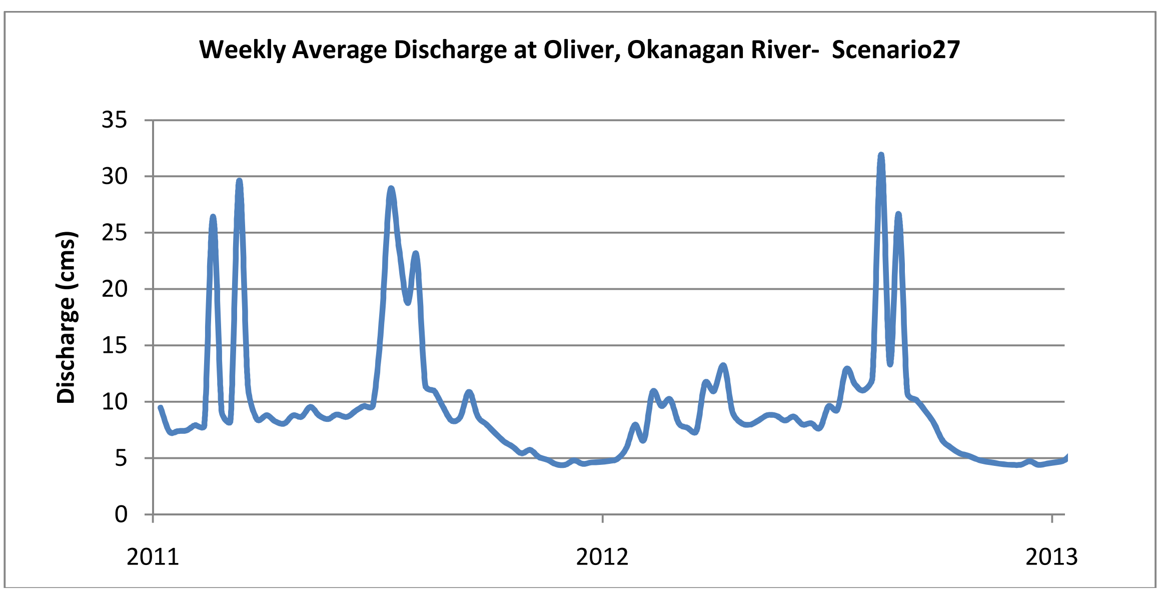
Summary of Average Quarterly Flows in Okanagan River at Oliver

		Baseline	Scenario 25	Scenario 26	Scenario 27
Quarter 1	Discharge(cms)	16.24	18.89	23.24	8.76
	Difference (%)		16	43	-46
Quarter 2	Discharge(cms)	33.48	32.47	30.05	13.07
	Difference (%)		-3	-10	-61
Quarter 3	Discharge(cms)	18.78	16.13	12.11	5.14
	Difference (%)		-14	-36	-73
Quarter 4	Discharge(cms)	12.70	14.90	20.73	9.02
	Difference (%)		17	63	-29
Annual	Discharge(cms)	20.37	20.54	21.32	8.96
	Difference (%)		1	5	-56

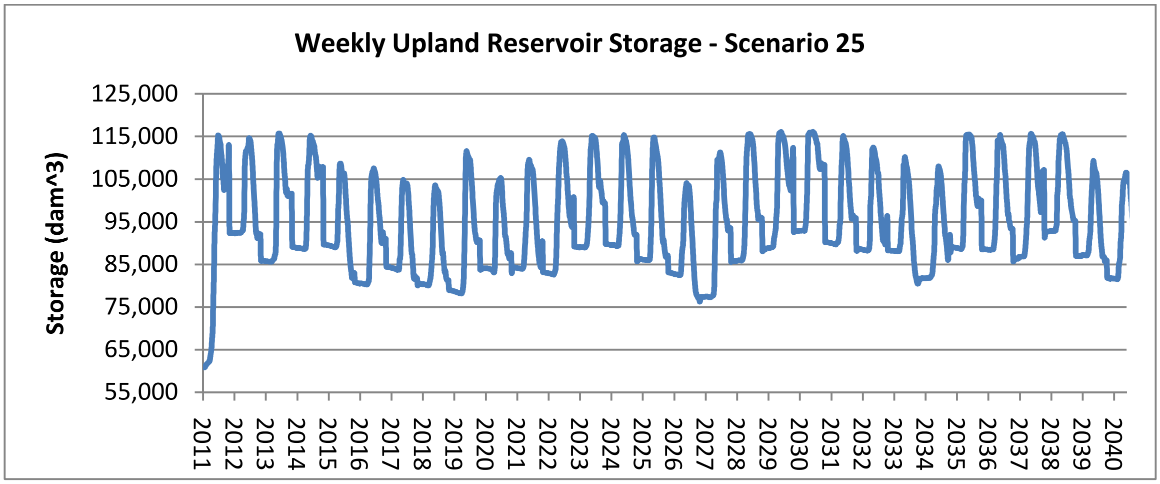


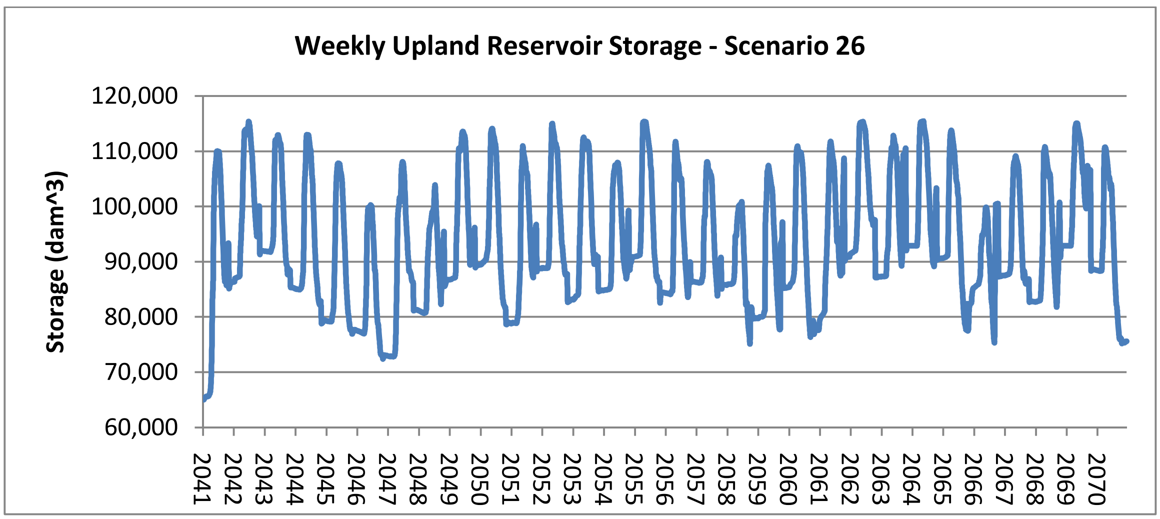

Weekly Average Discharge at Oliver, Okangan River- Scenario25
Discharge (cms)
250
200
150
100
50
0
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
2031
2032
2033
2034
2035
2036
2037
2038
2039
2040

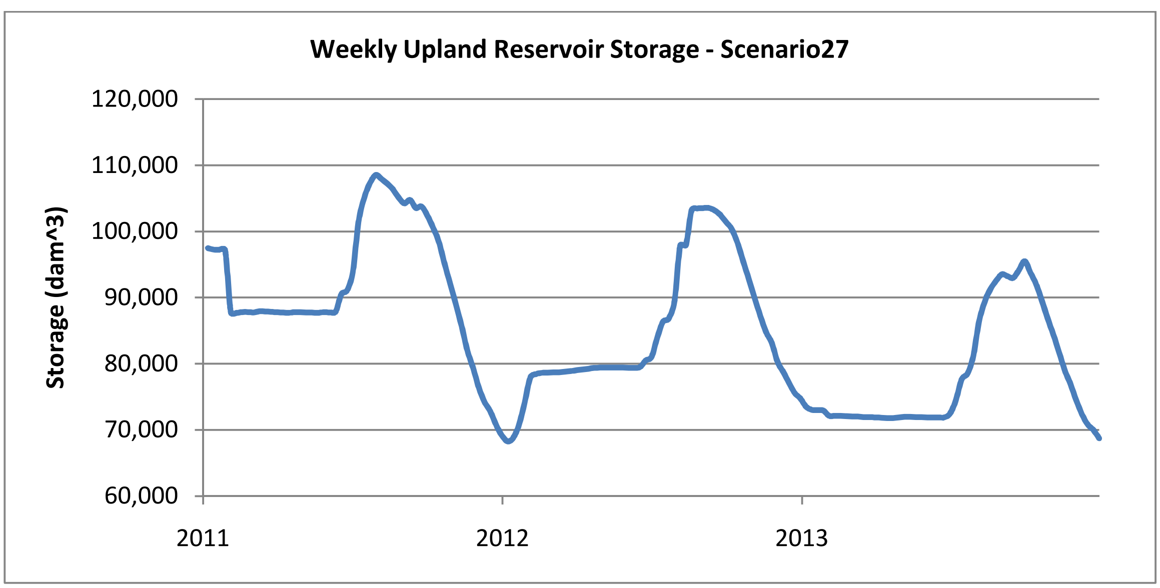

Weekly Average Discharge at Oliver, Okanagan River- Scenario26
Discharge (cms)
200
180
160
140
120
100
80
60
40
20
0
2041
2042
2043
2044
2045
2046
2047
2048
2049
2050
2051
2052
2053
2054
2055
2056
2057
2058
2059
2060
2061
2062
2063
2064
2065
2066
2067
2068
2069
2070


Weekly Average Discharge at Oliver, Okanagan River- Scenario27
Discharge (cms)
35
30
25
20
15
10
5
0
2011
2012
2013

Storage in Uplands Reservoirs

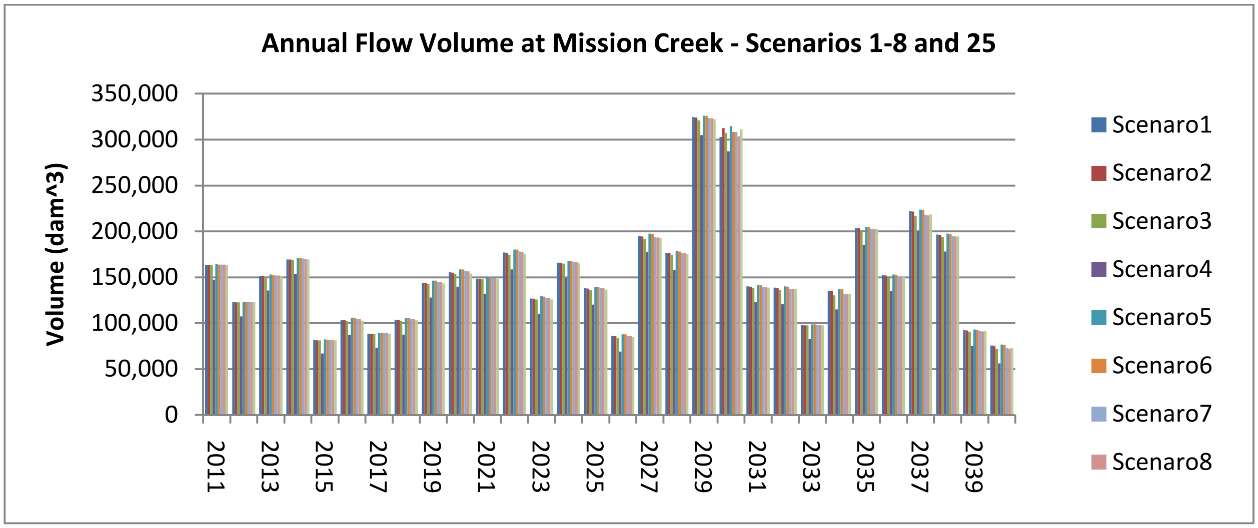






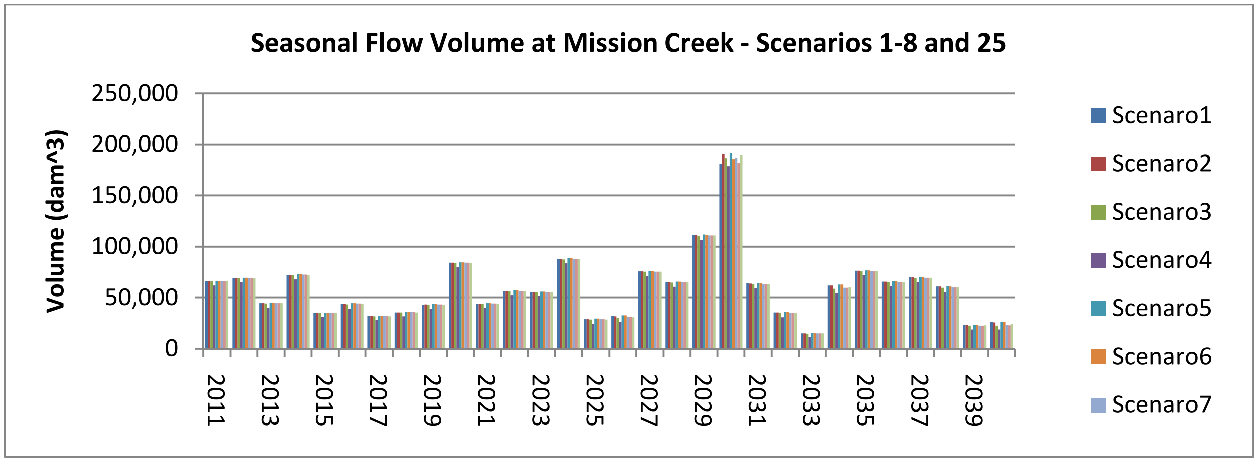
Appendix G
Water Use Scenarios Results

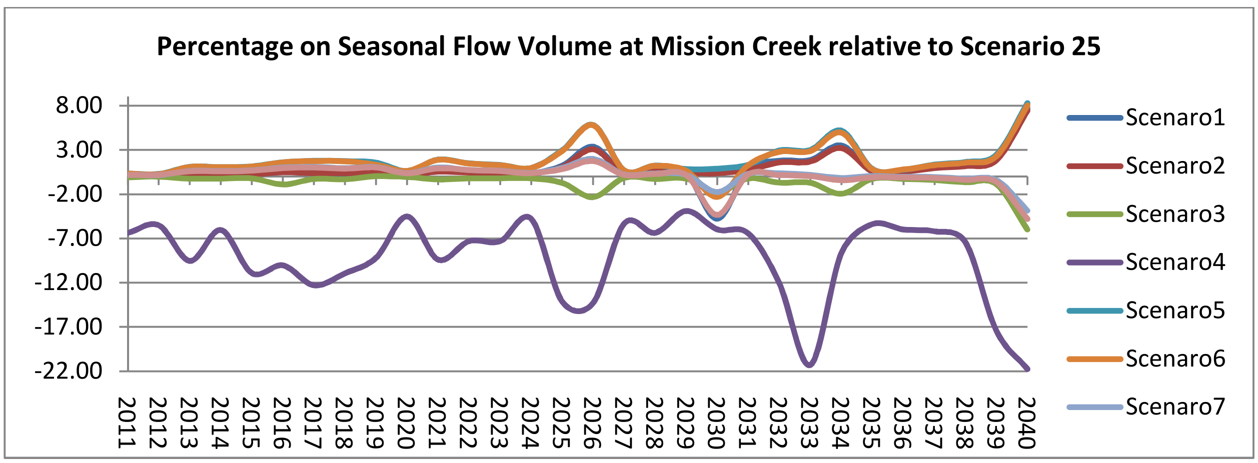
Flow Volumes at Mission Creek



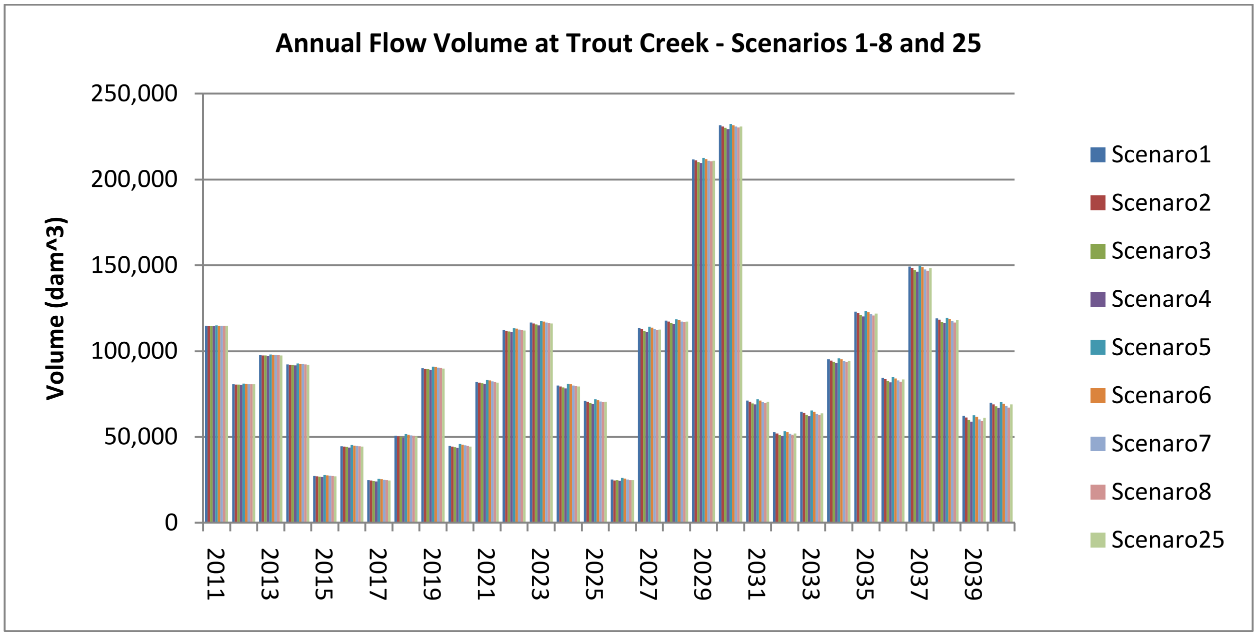
% Change in Average Annual Flow Volumes at Mission Creek

	S1	S2	S3	S4	S5	S6	S7	S8	S25
S1		0.02	-1.08	-11.26	1.28	0.98	-0.03	-0.30	-0.56
S2	-0.02		-1.10	-11.28	1.26	0.96	-0.05	-0.32	-0.58
S3	1.09	1.11		-10.29	2.39	2.09	1.06	0.79	0.53
S4	12.69	12.72	11.48		14.13	13.80	12.66	12.36	12.06
S5	-1.26	-1.24	-2.33	-12.38		-0.29	-1.29	-1.56	-1.81
S6	-0.97	-0.95	-2.04	-12.13	0.29		-1.00	-1.27	-1.53
S7	0.03	0.05	-1.05	-11.24	1.31	1.01		-0.27	-0.53
S8	0.30	0.32	-0.78	-11.00	1.58	1.28	0.27		-0.26
S25	0.56	0.58	-0.53	-10.77	1.85	1.55	0.53	0.26	


Seasonal Flow Volume at Mission Creek - Scenarios 1-8 and 25
Volume (dam^3)
250,000
200,000
150,000
100,000
50,000
0
2011
2013
2015
2017
2019
2021
2023
2025
2027
2029
2031
2033
2035
2037
2039
Scenaro1
Scenaro2
Scenaro3
Scenaro4
Scenaro5
Scenaro6
Scenaro7

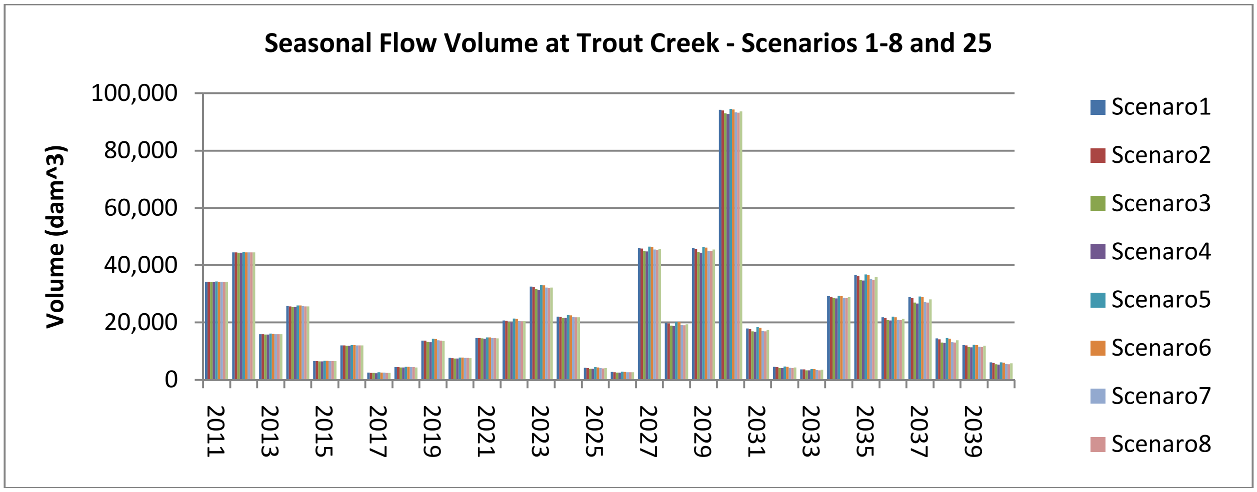

Percentage on Seasonal Flow Volume at Mission Creek relative to Scenario 25
8.00
3.00
-2.00
-7.00
-12.00
-17.00
-22.00
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
2031
2032
2033
2034
2035
2036
2037
2038
2039
2040
Scenaro1
Scenaro2
Scenaro3
Scenaro4
Scenaro5
Scenaro6
Scenaro7

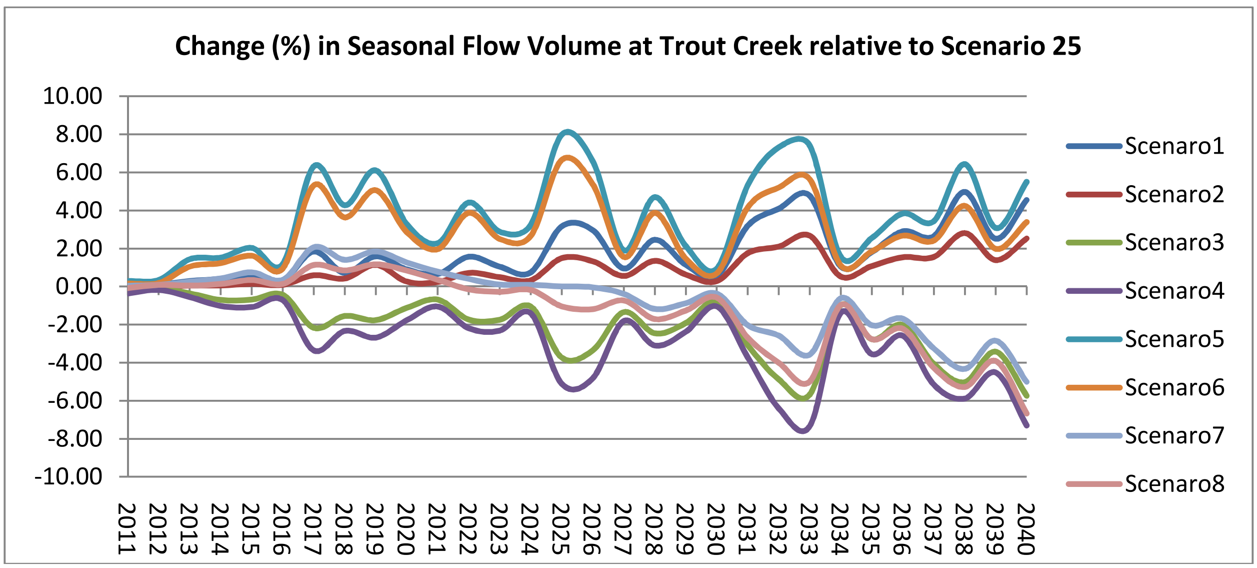
Flow Volumes at Trout Creek



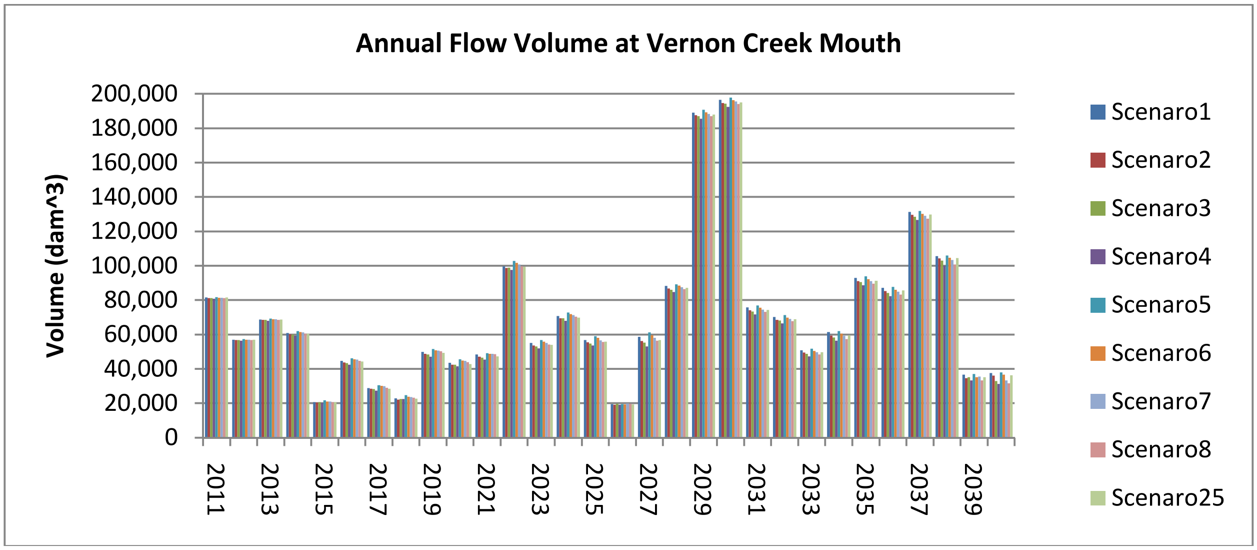
% Change in Average Annual Flow Volumes at Trout Creek

	S1	S2	S3	S4	S5	S6	S7	S8	S25
S1		-0.61	-1.29	-1.89	0.73	0.22	-0.56	-1.06	-0.64
S2	0.61		-0.68	-1.29	1.35	0.84	0.05	-0.45	-0.03
S3	1.30	0.69		-0.61	2.05	1.53	0.74	0.23	0.66
S4	1.93	1.30	0.61		2.68	2.16	1.35	0.85	1.27
S5	-0.73	-1.34	-2.01	-2.61		-0.51	-1.29	-1.78	-1.37
S6	-0.22	-0.83	-1.51	-2.11	0.51		-0.78	-1.28	-0.86
S7	0.56	-0.05	-0.73	-1.34	1.30	0.79		-0.50	-0.08
S8	1.07	0.45	-0.23	-0.84	1.81	1.30	0.50		0.42
S25	0.65	0.03	-0.65	-1.26	1.38	0.87	0.08	-0.42	


Seasonal Flow Volume at Trout Creek - Scenarios 1-8 and 25
Volume (dam^3)
100,000
80,000
60,000
40,000
20,000
0
2011
2013
2015
2017
2019
2021
2023
2025
2027
2029
2031
2033
2035
2037
2039
Scenaro1
Scenaro2
Scenaro3
Scenaro4
Scenaro5
Scenaro6
Scenaro7
Scenaro8

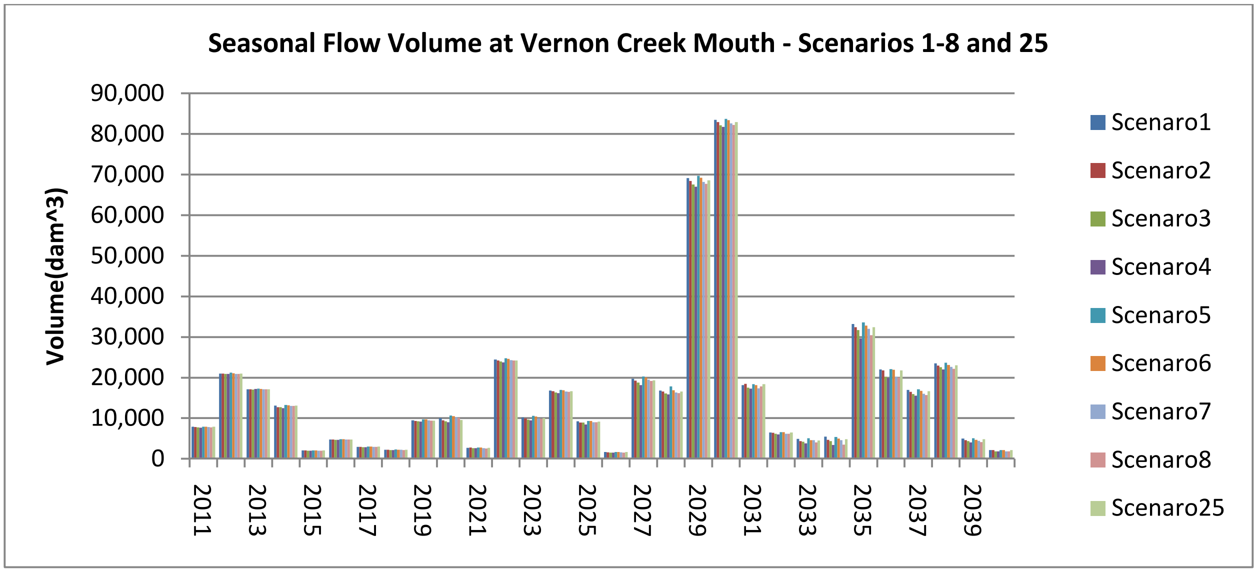

Change (%) in Seasonal Flow Volume at Trout Creek relative to Scenario 25
10.00
8.00
6.00
4.00
2.00
0.00
-2.00
-4.00
-6.00
-8.00
-10.00
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
2031
2032
2033
2034
2035
2036
2037
2038
2039
2040
Scenaro1
Scenaro2
Scenaro3
Scenaro4
Scenaro5
Scenaro6
Scenaro7
Scenaro8

Flow Volumes at Vernon Creek at Mouth of Penticton

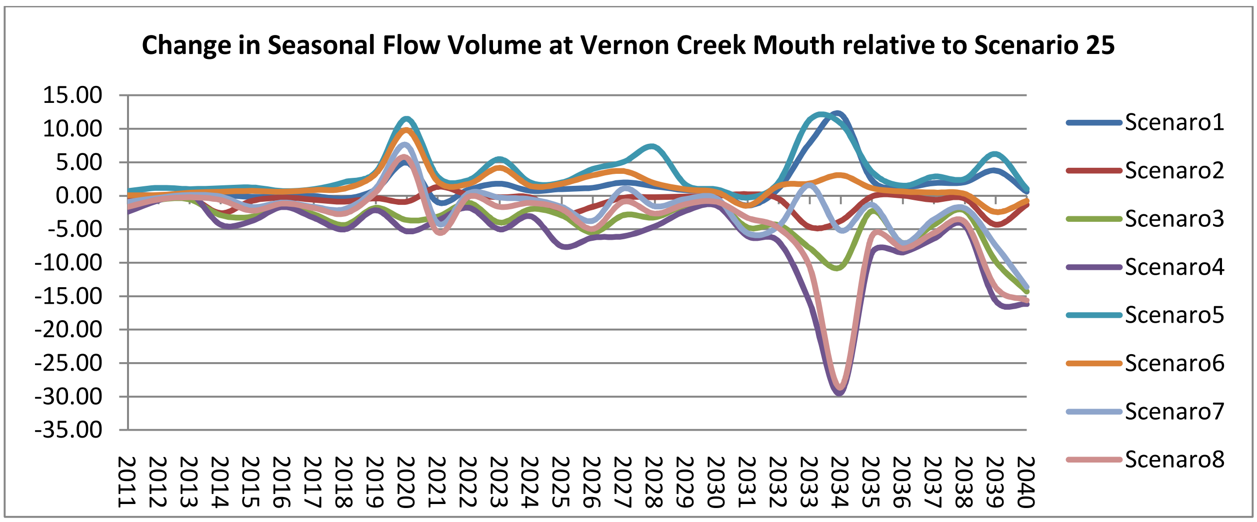


% Change in Average Annual Flow Volumes at Vernon Creek

	S1	S2	S3	S4	S5	S6	S7	S8	S25
S1		-1.76	-2.41	-4.24	1.66	0.23	-0.72	-2.25	-1.29
S2	1.79		-0.67	-2.53	3.48	2.02	1.06	-0.50	0.48
S3	2.47	0.67		-1.88	4.18	2.71	1.74	0.17	1.15
S4	4.43	2.60	1.91		6.17	4.67	3.68	2.09	3.09
S5	-1.64	-3.36	-4.01	-5.81		-1.41	-2.34	-3.85	-2.90
S6	-0.23	-1.98	-2.64	-4.46	1.43		-0.95	-2.47	-1.51
S7	0.72	-1.05	-1.71	-3.55	2.40	0.96		-1.54	-0.57
S8	2.30	0.50	-0.17	-2.04	4.00	2.53	1.56		0.98
S25	1.31	-0.48	-1.14	-2.99	2.99	1.54	0.58	-0.97	



Seasonal Flow Volume at Vernon Creek Mouth - Scenarios 1-8 and 25
Volume(dam^3)
90,000
80,000
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
2011
2013
2015
2017
2019
2021
2023
2025
2027
2029
2031
2033
2035
2037
2039
Scenaro1
Scenaro2
Scenaro3
Scenaro4
Scenaro5
Scenaro6
Scenaro7
Scenaro8
Scenaro25



Change in Seasonal Flow Volume at Vernon Creek Mouth relative to Scenario 25
15.00
10.00
5.00
0.00
-5.00
-10.00
-15.00
-20.00
-25.00
-30.00
-35.00
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
2031
2032
2033
2034
2035
2036
2037
2038
2039
2040
Scenaro1
Scenaro2
Scenaro3
Scenaro4
Scenaro5
Scenaro6
Scenaro7
Scenaro8

Flow Volumes at Vaseux Creek

% Change in Average Annual Flow Volumes at Vaseux Creek

	S1	S2	S3	S4	S5	S6	S7	S8	S25
S1		0.00	0.00	0.00	0.01	0.01	0.02	0.01	-0.01
S2	0.00		0.00	0.00	0.01	0.01	0.02	0.01	-0.01
S3	0.00	0.00		0.00	0.01	0.01	0.01	0.01	-0.01
S4	0.00	0.00	0.00		0.01	0.01	0.01	0.01	-0.01
S5	-0.01	-0.01	-0.01	-0.01		0.00	0.00	0.00	-0.02
S6	-0.01	-0.01	-0.01	-0.01	0.00		0.01	0.00	-0.02
S7	-0.02	-0.02	-0.01	-0.01	0.00	-0.01		0.00	-0.02
S8	-0.01	-0.01	-0.01	-0.01	0.00	0.00	0.00		-0.02
S25	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	

Flow Volumes in Okanagan River at Penticton

% Change in Average Annual Flow Volumes in Okanagan River at Penticton

	S1	S2	S3	S4	S5	S6	S7	S8	S25
S1		-0.36	-1.17	-4.38	0.86	0.58	-0.39	-0.68	-0.38
S2	0.36		-0.81	-4.03	1.22	0.94	-0.02	-0.32	-0.02
S3	1.18	0.81		-3.25	2.05	1.77	0.79	0.49	0.79
S4	4.58	4.20	3.36		5.47	5.18	4.17	3.86	4.18
S5	-0.85	-1.21	-2.01	-5.19		-0.28	-1.23	-1.53	-1.23
S6	-0.57	-0.94	-1.74	-4.93	0.28		-0.96	-1.25	-0.96
S7	0.39	0.02	-0.78	-4.01	1.25	0.97		-0.30	0.00
S8	0.69	0.32	-0.49	-3.72	1.55	1.27	0.30		0.30
S25	0.38	0.02	-0.79	-4.01	1.25	0.97	0.00	-0.30	