A MODELING APPROACH TO EVALUATING THE IMPACTS OF CLIMATE CHANGE AND MOUNTAIN PINE BEETLE INFESTATION ON WATER RESOURCES IN THE OKANAGAN BASIN, BRITISH COLUMBIA

Carter Borden[1], Pat Delaney[1], Qiao Ying[1], Jeremy Kobor[1], Brian Guy[2]

ABSTRACT

Rapid population growth coupled with increasing agricultural demands from a burgeoning viticulture industry has resulted in a significant increase in water demand in the Okanagan Basin over the past few decades. The accumulation and melt of snow at higher elevations is the primary mechanism for generating streamflow in the basin and Global Climate Model (GCM) predictions of increases in temperatures will likely result in significant decreases in winter snow accumulations and associated shifts in the timing and magnitude of the spring freshet. The forested areas in the basin are currently experiencing a large-scale mountain pine beetle infestation which also has the potential to significantly alter the hydrology of the basin. In response to these factors and the questions they raise regarding the future sustainability of water supply in the basin, the Okanagan Basin Water Board and its partners began a basin-wide study of the supply and demand of water resources in the basin in 2004.

One component of this study is the construction of a numerical model of the basin using the distributed hydrologic model MIKE SHE. The model utilizes distributed climate data in conjunction with topographic, land cover, and soils information to simulate the dominant hydrologic processes in the basin under a naturalized condition. The modeling work built off several other studies that investigate specific components of the basin hydrology. The model was calibrated to naturalized streamflow hydrographs, snow accumulation data, and independent estimates of lake evaporation and baseflow. The calibrated model provides the framework for evaluating a series of water supply scenarios involving the impacts of climate change, loss of forest cover due to beetle kills, and the combined effects of these two phenomena. The climate change scenarios are based on a series of IPCC scenarios and utilize statistically-downscaled GCM data that is available for the basin at a 500-meter resolution. The impacts of these scenarios addressed changes in snow cover, streamflow, lake storage, and groundwater recharge, and provide the basis for evaluating water demand alternatives. (KEYWORDS: distributed hydrologic modeling, climate change, water management)

INTRODUCTION

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. Phase I of the Okanagan Basin Water Supply and Demand Project provided baseline data and was completed in May 2005. Phase II of this project, Model Development and Calibration, was initiated in 2007 and includes summarizing existing knowledge of surface water resources and the development and calibration of a surface water hydrology model for the Okanagan Basin. During the course of this work, DHI developed and calibrate a surface water hydrology model and a water accounting model, which provides the framework to analyze tributary streamflows, lake levels, and mainstem river flows under a range of climate-change and land-use scenarios. The models developed, the Okanagan Basin Hydrology Model (OBHM) and the Okanagan Basin Water Accounting Model (OBWAM), used the MIKE SHE integrated watershed software.

The purpose of developing the OBHM and OBWAM was to evaluate the basin wide water supply implications of potential changes in climate, land use, water use and mountain pine beetle infestation. This purpose 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)

Paper presented Western Snow Conference 2010
[1]DHI Water Environment, Inc., jcb@dhigroup.com, [2]Summit Environmental Consultants

2. Water use efficiency (current trends vs. increased efficiency)
3. Agricultural land base expansion (present conditions vs. expanded agricultural base)

The general objective of this study was to develop a distributed hydrologic model of the Okanagan Basin (Figure 1) 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 activities were to:

1. Develop/calibrate the OBHM to simulate naturalized conditions,
2. Estimate naturalized weekly streamflows/lake levels from 1996 to 2006 at 81 surface water nodes
3. Incorporate water use data and calibrate the OBWAM to simulate anthropogenic influences,
4. Estimate historical weekly streamflows/lake levels from 1996 to 2006 at 81 surface water nodes, and
5. Analyze future streamflows and lake levels under a range of climate-change and land-use scenarios.

This report summarizes the development of the OBHM and briefly describes the development of OBWAM and the results of a limited number of future scenarios. Full description of the effort is documented in "Okanagan Basin Hydrologic and Water Accounting Model" (DHI, 2009).

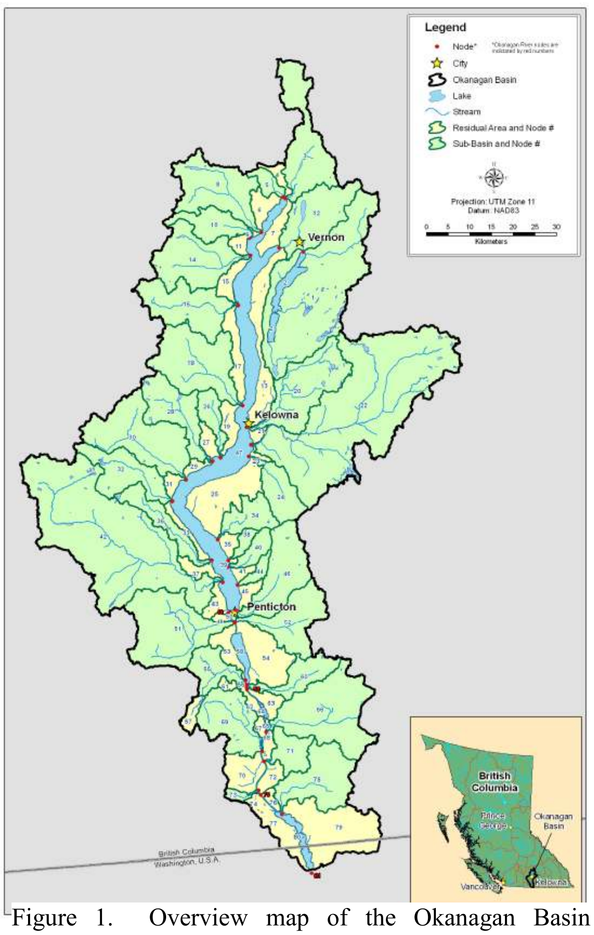

Figure 1. Overview map of the Okanagan Basin showing the locations of the 81 surface water nodes (Summit and Polar, 2009)

HYDROLOGIC MODEL

Hydrologic Model Overview

The foundation of the OBWAM is the Okanagan Basin Hydrology Model (OBHM) which was constructed using the DHI's MIKE SHE and MIKE 11 sofware. MIKE SHE is numerical hydrologic model that simultaneously simulates all of the major components of the land-based phases of the hydrologic cycle including snowmelt, evapotranspiration, 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 can be dynamically linked to the one-dimensional hydrodynamic surface water model, MIKE 11, for a complete representation of the hydrologic system. MIKE SHE/MIKE 11 has a GUI interface and many pre- and post-processing tools to aid setup and analysis of data. Selection of MIKE SHE/MIKE 11 for this study was based on the recommendations of Water Management Consultants (2008) in a report prepared for OBWB.

Physical processes included in the OBHM are snowmelt, evapotranspiration, overland flow, unsaturated flow, groundwater flow and channelized flow (Table 1). This section describes in detail how each process works and what major inputs and parameters are for each process.

Snowmelt (SN): 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, degree day coefficient, minimum snow storage for full coverage, and maximum wet snow fraction as well as functions to account for incoming solar radiation, heat content of rainfall, and sublimation.

Evapotranspiration (Potential and Actual) (ET): The ET module in MIKE SHE uses meteorological and vegetative data to simulated 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. 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 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 five different storages (snow, canopy, ponded water, unsaturated zone, and 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.

Table 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

Overland Flow (OF): 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 overland flow algorithm interacts with the channel flow, unsaturated zone, 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 (UZ): To simulate flow in the unsaturated zone, the MIKE SHE software has three options depending on the level of complexity required for the analysis and the available data. The algorithms, listed in order of increasing complexity, are the Two-Layer Water Balance Method, the Gravity Flow Procedure, and the Richards Equation. 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, water content in the root zone, infiltration, evapotranspiration, and groundwater recharge.

Groundwater Flow (SZ): The saturated zone component of MIKE SHE calculates the saturated subsurface flow using either fully three-dimensional flow finite difference solution or a simplified linear reservoir groundwater algorithm. The OBHM uses the simplified linear reservoir groundwater algorithm 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). If a stream is present in a given subbasin, 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.

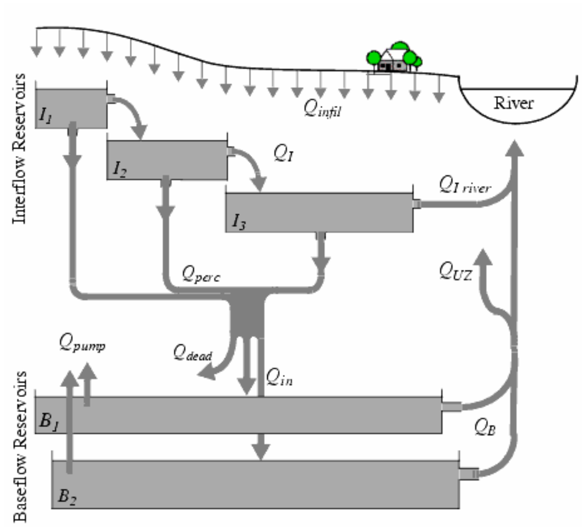

Figure 2. Schematic diagram for the subcatchment-based linear reservoir groundwater method

Channelized Flow: MIKE 11 is an one-dimensional hydro-dynamic 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.

Model Construction

The Okanagan Basin Hydrologic Model (OBHM) domain was set to match the full watershed boundary of the Okanagan River Basin upstream of Zosel Dam near the outlet of Osoyoos Lake (**Error! Reference source not found.**). The domain represents the ~8,024 km^2 watershed using 500 m by 500 m square grid cells which calculate, for each grid cell, the overland flow, unsaturated flow, and evapotranspiration. This grid resolution is consistent with the resolution of the gridded climate datasets used as input for the OBHM (Duke et al, 2008a). The groundwater calculations occur based on subcatchments rather than at the model grid resolution and the channel flow calculations occur at discrete node locations. The groundwater subcatchments were developed based on the aquifer delineation study (Golder, 2009) while the node locations agree with those identified in the flow naturalization study (Summit and Polar, 2009).

The OBHM simulation period extends from September 1, 1995 to December 31, 2006 but the model results are only evaluated 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 reach equilibrium from the assumed initial conditions. In particular, realistic initial soil moisture and initial snow depth conditions are inherently difficult to estimate, so by giving the model this four month “warm-up” period, the model can determine initial conditions at the beginning of the simulation period based on the simulation results.

Table 2 briefly outlines the data, processing, and sources of the spatial data a description of the spatial data. In addition, the river network was generated based on the national hydro-network shape file and included a branch running through each of the five main lakes, rivers, and major tributaries. 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 and thus no geometry was required. Boundary conditions include the inflow from MIKE SHE (upstream and distributed sources) and the Okanagan River near Oroville gage

Table 2. Description of the spatial data used in the OBHM

Data Type	*Module*	*Description and Pre-Processing*	*Sources*
Topography (DEM)	SN, OL	Two DEMs were merged, re-sampled to a 100 m resolution, and re-projected to the BC Albers projection. MIKE SHE re-sampled to 500 m.	• Canada: (Geobase, 2008), • US: (Natural Resource, WA, 2002)
Land Cover Map	ET, OL, UZ	To account for the variation in vegetation, four 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 (in Canada) and NLCD (in US). This base map was further subdivided by a simplified version of the biogeoclimatic zones and further subdivided again to account for major disturbances resulting from Mountain Pine Beetle (MPB) infestation, wildfires, and timber harvesting. The final land cover map used in the model consists of the 14 base land cover categories subdivided by the four biogeoclimatic zones, then further subdivided into undisturbed areas and the three disturbance categories to define 67 land cover categories.	• Canada: Vegetation Resources Inventory (VRI, 2005) • US: National Land Cover Database (NLCD, 2001) • Biogeoclimatic zones (BECWeb, Ministry of Forests and Range, 2008) • Severity of attack from MPB (Ministry of Forests and Ranges, 2008b)
Leaf Area Index (LAI)	ET, UZ	Raster images (1 km grid) collected every 10-days from April 1st to October 31st (1998 to 2005). For each undisturbed polygon, the annual average 10-day LAI value from June 1st to September 1st was calculated and repeated for each simulation year. For disturbed polygons, the average 10-day LAI values were calculated from June 1st to September 1st for each year.	• CCRS, NRC, 2006
Climate	SN, ET, OL, UZ	GIS interpolation techniques and all 11 climate station data to generate basin-wide 500 m by 500 m gridded surfaces of daily minimum and maximum temperature and daily precipitation. Generated daily potential evapotranspiration (PET) surfaces using a modified Penman-Monteith formulation	• Okanagan Climate Data Interpolator (Duke et al., 2008a; Duke et al., 2008b)
Degree-Day Coefficient (DDC)	SN	Okanagan Basin was divided into three DDC zones consisting of forested area, open area, and a combined logged area and major forest fire areas to reflect the spatial variation associated to land cover and temporal variation associated to seasonal change of solar radiation, snowpack in terms of density and compaction. Result, spatial and temporal varying DDC with a sinusoidal pattern.	• Haverly et. al (1978) • Kuusisto (1980)
Soils	UZ	Four soil maps were used to generate the soil map used in the OBHM. For Canada, three individual soil maps were available that cover the valley-bottom area, upland areas, and the Tulameen area. For the U.S., a soil map was taken from the NRCS's Soil Survey Geographic Database (SSURGO). Result was a soil map consolidated from 298 (raw maps) to 25 major soil types.	• Canada: (Agriculture and Agri-Food Canada, 2001) • US: (NRCS, 2008).
SZ zones	SZ	For simulating interflow, the basin was divided into two interflow reservoirs types: an upland reservoir delineated by merging all bedrock aquifers together, and a lower reservoir delineated by merging all of the alluvial aquifers together. Baseflow reservoirs were delineated by merging the hydraulically connected bedrock and alluvial aquifers.	• Golder, 2009

for the downstream requirement (USGS Water Data, 2008). 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. Information regarding how the structures at each lake are operated was available from a Lake Operation Plan for each lake and from the Fish Water Management Tool (FWMT, 2008).

HYDROLOGY MODEL CALIBRATION

Overview of Approach

For calibration, the OBHM was compared the results of the model against data which included overall water budgets, snow water equivalent data, streamflow hydrographs and flow volumes, historical inflow data for Okanagan Lake, lake level data, and lake evaporation data (from the lake evaporation study). Since the OBHM was being run for a 11-year period that represented a full range of climatic conditions including very wet year (1996, 1997) and very dry years (2001, 2003), it was determined that the model would be calibrated against the entire simulation period which minimized the necessity of a separate verification period. Following a sensitivity analysis of all parameters, the parameters focused upon during calibration included detention storage, riverbed leakage coefficient, soil moisture contents, saturated hydraulic conductivity, degree day coefficient, Manning's coefficient, and time constants for interflow and baseflow.

Calibration Results

As stated above, calibration comparison included overall water budgets, snow water equivalent data, streamflow hydrographs and flow volumes, historical inflow data for Okanagan Lake, lake level data, and lake evaporation data. Due to space, results are only presented below for the water budget, hydrographs and lake levels.

Overall Water Budgets

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). The simulated ET is towards the high end of the previous estimates for the basin at 80.9% of the incoming precipitation (Table 3). The 1974 Supply and Demand Study also 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). 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).

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). Groundwater recharge accounted for 6.5% of incoming precipitation which is towards the low end of the previous estimates (Table 3).

Table 3. Results of the water budget analysis

Water Balance Term	*Total Depth (mm)*	*Mean Annual Depth (mm)*	*Relative to Precipitation (%)*
Precipitation	7113.78	646.71	
ET	5757.74	523.43	80.9%
Recharge	459.62	41.78	6.5%
Runoff	846.46	76.95	11.9%

Snow Water Equivalent Data

Snow data were available from the Ministry of Environment at 19 snow survey stations for the calibration period. The sites range in elevation from 1266 m to 1834 m and the snow data (both snow depth and snow water equivalent (SWE) data) at these sites was generally collected between December and the middle of June of the following year. 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. For calibration, the SWE data was compared to the simulated SWE values at the corresponding locations in the model.

In general, the pattern and timing of snow accumulation and melt is well-captured by the model. At some locations such as Greyback Reservoir (Figure 3a), 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 under-predicted at Whiterocks Mountain (Figure 3b) and over-predicted at Similkameen (Figure 3c). Overall mean errors (ME) range from -165 to 120 mm with a mean ME of -7 mm. The mean root mean square errors (RMSE) is 107 mm (range: 45 to 208 mm) and a mean correlation coefficients (R) of 0.80 (range: 0.39 to 0.90). In general the calibration is best at the higher elevation stations 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.

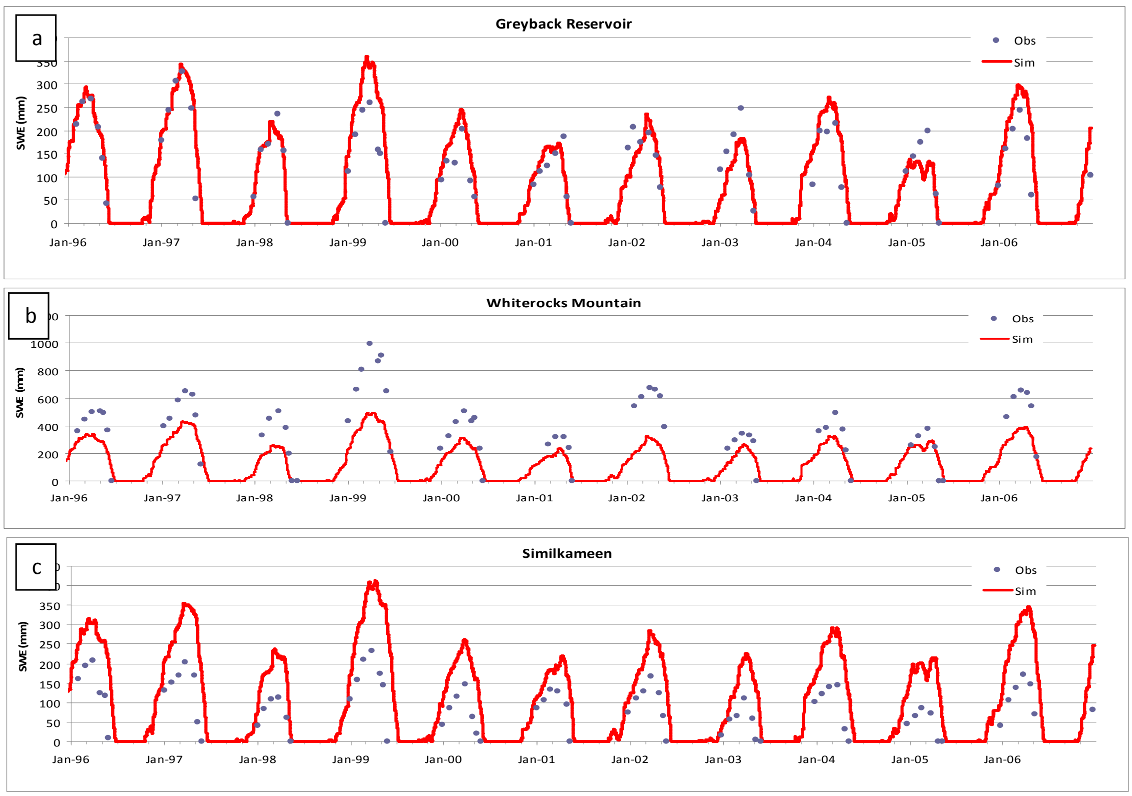

Figure 3 a, b, c. Comparison of actual and simulated SWE.

Streamflow

Weekly naturalized hydrographs were generated for 81 nodes locations around the basin as identified in State of the Basin report (Summit and Polar, 2009). For calibration, the 81 nodes were ranked as natural and high, medium and low confidence level based the quality hydrometric and/or water use information used to generate the hydrographs. The breakdown of nodes was 9 natural (associated with gages) and 8 high, 15 moderate, and 49 low level of confidence nodes. The model was calibrated against the 9 Natural and 8 High Confidence Level Nodes. Attempts to further calibrate with regard to the Moderate Confidence Level Nodes reduced the calibration accuracy at the Natural and High Confidence Level Nodes and was abandoned.

The calibration statistics for the Natural Nodes have ME values ranging from -0.18 to 0.10 m^3/s, with a mean ME values of <0.01 m^3/s (Table 4). The low mean ME value indicates that overall the over- and under-predictions tend to balance. The RMSE values range from <0.01 to 0.05 m^3/s with a mean of 0.02, and correlation coefficients (R) range from 0.58 to 0.82 with a mean of 0.69. The calibration statistics for the High Confidence Level Nodes have 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 values range from 0.03 to 0.27 m^3/s with a mean of

0.08 and correlation coefficients (R) range from 0.60 to 0.86 with a mean of 0.74. A good indication of the overall quality of the calibration can be taken from Mission Creek, which is one of the largest tributaries in the basin. It demonstrates a very good fit between the simulated hydrograph and the naturalized observed hydrograph with respect to both baseflow and the timing and magnitude of the spring snowmelt signal. Hydrographs for each are not shown in this document.

Table 4. Comparison of total simulated streamflow volume with the total volume indicated in the Natural and High Confidence Level Node data. High flow period is from April through August and low flow period occurring during the remainder of the year.

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

In April 2009, the overall calibration results were good in terms of total volume, volume of high flow period and low flow period, and timing but the model sometimes simulated runoff events that were either much smaller or in some cases non-existent in the natural and naturalized data. In most cases, these events occur when the model simulates significant accumulation and then subsequent rapid melting of snow. In a few cases, the events are not associated with snow melt and are instead driven by runoff generated from rainfall. Upon further investigation of the gridded temperature data, it was discovered that the temperatures are unrealistically high in the temperature dataset thus over-predicting snowmelt rates. Based on a series of tests, a revised temperature dataset was generated to improve the high elevation values and to 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.

SCENARIO ANALYSIS

Following construction and calibration of the OBHM, the OBWAM was developed/calibrated and demonstration scenarios simulated. A brief discussion of OBWAM and Scenarios are presented below. Full description of the OBWAM development and calibration as well as the Scenarios is found in *Okanagan Basin Hydrologic and Water Accounting Model* (DHI, 2009).

Okanagan Basin Water Accounting Model (OBWAM)

The process of developing the OBWAM involved taking the calibrated OBHM and introducing the impacts of human influences at each node location. Anthropogenic impacts incorporated into the model include domestic/municipal water use, agriculture use, silvicultural activities, and structure operations. The model was then verified against the available monitoring data and subsequent improvements were introduced to achieve a better calibration to the observed lake levels and discharges along the Okanagan River and the mainstem lakes. Although the initial OBHM calibration was accepted, it was clear that additional improvements would still need to be made to the calibration of the OBWAM model for historical conditions in order to be accepted as a reliable indicator of future conditions. The primary adjustments to the model included:

- 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 anomalous spring and fall streamflow peaks,
- Incorporating water use by domestic, municipal, and agricultural users, 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 result of these adjustments was an OBWAM that has been successfully calibrated to accurately reproduce a continuous hydrologic response over a wide range of climate conditions from 1996-2006 and accurately represents the real-time operational logic of the dams on each of the mainstem lakes in the Okanagan Basin.

Scenario Analysis

To demonstrate the OBWAM effectiveness, a limited range of possible future conditions were modeled to evaluate the 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. For the demonstration, DHI chose one of the six available global climate models (CGCM2-A2) and assumed that the main influences on climate (global emissions of greenhouse gases) were well predicted by the latest International Panel on Climate Change. Although limited in range of climatic outcomes, the effort provided an excellent demonstration of the OBWAM's capability to be used in for a more extensive evaluation of potential climate change impacts. The climate conditions were examined in light of:

- 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).

In addition, recognizing the historic significance of the 1929-1931 drought sequence in the Okanagan Basin, DHI used data from the future scenarios climate model to simulate a possible future three-year dry sequence by examining the bias-corrected climate data during the period from 2010 – 2100 and choosing the three driest years (2076, 2033, and 2026) and assuming they occur in succession. This scenario period is referred to as the Drought period. Full description of the 27 scenarios construction and results is found in *Okanagan Basin Hydrologic and Water Accounting Model* (DHI, 2009). Below is a short description of the outcome from the scenario modeling.

Selected Results

Depending on the scenario, climate (temperature, precipitation, and ET), LAI, rooting depth, land cover (vegetation coverage), DCC, and water demand were spatially and temporally changed to represent the future conditions. The land cover was changed to represent different agricultural and silvicultural practices, influence of fire, and MPB infestation. An example of adjusting DCC for the influence of clearcut pine is shown in Figure 4. Note, the in Figure 4 relationship is applied to every cell containing designated as either undisturbed or clearcut pine.

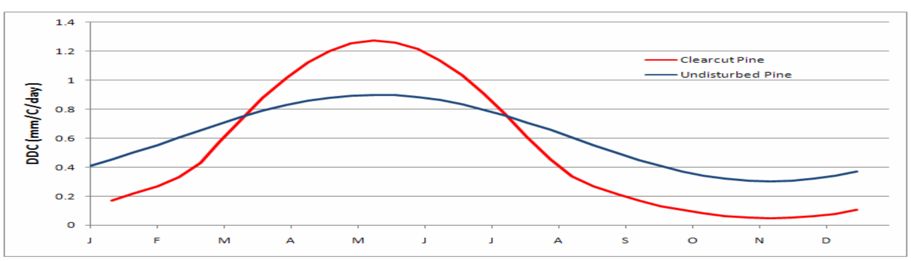

Figure 4. Adjustment for silvicultural influence on DCC throughout the year.

Example results from the analysis included lake levels during the drought scenario (Figure 5) influence on timing of the spring freshet at Mission Creek (Figure 6), and maximum SWE (Figure 7). As the OBWAM is a distributed model, similar results are available throughout the model domain and channel network.

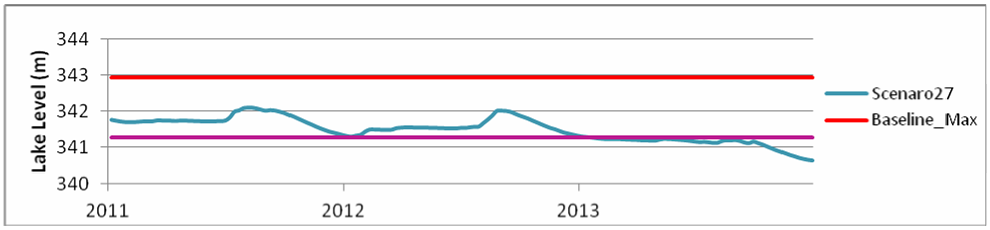

Figure 5. Okanagan Lake level during the drought scenario (Scenario 27)

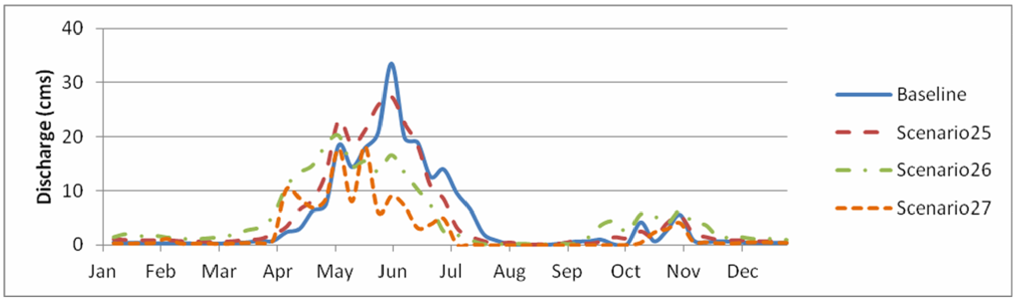

Figure 6. Annual average weekly flows at Mission Creek for scenarios 25, 26, and 27

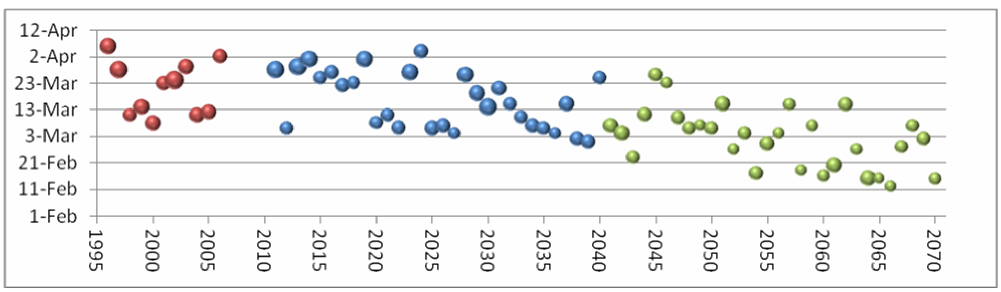

Figure 7. Maximum SWE by time of year with current operation and only the influence of climate change. Value of the x-axis is year.

CONCLUSIONS

The Okanagan Basin Hydrology Model (OBHM) was successfully developed using the MIKE SHE integrated watershed software which incorporates 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 from 1996 through 2006. The model simulated all of the land-based phases of the hydrologic cycle: evapotranspiration, overland flow, unsaturated flow, groundwater flow, and channel flow. The model was calibrated against nine natural hydrographs, eight high confidence level naturalized hydrographs developed in a parallel study, and snow water equivalent data at 21 locations throughout the basin

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 Node naturalized hydrographs as does the flow volume simulated during the spring snowmelt period. The model over-predicts flow volumes during the low-flow period and 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 and the simulated baseflow agrees well with the comparison data.

The OBHM was then used to develop the Okanagan Basin Water Accounting Model (OBWAM). Upgrades to the OBHM include better bathymetry of the lakes, temperature distribution, and operation of dams as well as incorporation of water user data. The resulting 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 of potential changes in climate, land use, water use, and mountain pine beetle infestation. This objective was successfully demonstrated by running 27 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 considered population growth, water use efficiency, and agricultural land base expansion. 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.
- 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 foreseeable future. However, 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; 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 will be approximately one half of the normal inflows resulting in the levels for Okanagan Lake dropping below the normal operating range but still maintaining minimum flows in the Okanagan River.

These aforementioned results 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.

It is anticipated that the OBHM and OBWAM will provide the Okanagan water authorities with a solid platform from which to manage water into the future.

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