PART THREE – MODELS

Part Three of this Summary Report describes the three models that have been developed and used in Phase 2 of the Project: the Okanagan Water Demand Model, the Okanagan Basin Hydrology Model, and the Okanagan Basin Water Accounting Model. These models were developed and tested using the data and databases described in Part Two of this Summary Report. Together they simulate the natural and managed movement of water in the Okanagan Basin.

13.0 HOW OKANAGAN WATER CYCLES ARE SIMULATED

The natural water cycles and the effects of human use and management of surface and groundwater in the Okanagan are simulated using all three of these models. For a particular sequence of time (for example the 1996-2006 period, or for a future period, for example 2011 – 2040), the models are run in the following order:

1. the Okanagan Water Demand Model (OWDM); then
2. the Okanagan Basin Hydrology Model (OBHM); then
3. the Okanagan Basin Water Accounting Model (OBWAM).

Each model works on a daily (or even shorter) time-step, but the results are summed internally and output is generated for periods of one week. The climate dataset is the main driver of the OWDM, which computes the irrigation and non-irrigation water needed for each of thousands of discrete parcels of land, and integrates this up to 253 "water use areas". The OWDM links the water used on each "water use area" to its water source, and calculates the weekly need for water from that source to satisfy the demand. The information [weekly water demand for each water use area (both total water use and water use subdivided into various categories) and weekly demand for water from each water source] is delivered to the OkWater database. It is exported from the OkWater database to the OBHM. The OBHM computes naturalized streamflows corresponding to the particular climate dataset. The OBWAM then combines the outputs of the OWDM and the OBHM to account for the effects of water extractions from groundwater and surface water sources, the effects of releases of water from upland reservoirs to meet those demands, and the effects of lake level management decisions to simulate tributary streamflows, Okanagan River flows, and lake levels on the main valley-bottom lakes.

14.0 OKANAGAN WATER DEMAND MODEL

The Okanagan Water Demand Model (OWDM) is used to estimate water demands for all indoor and outdoor purposes in the Okanagan Basin. Development of the OWDM was initiated by the Ministry of Agriculture and Lands (MAL) and Agriculture and Agri-Food Canada (AAFC) following completion of the Phase 1 work program in 2005. With assistance from Environment Canada (EC), MAL and AAFC first developed an agricultural irrigation model for the Okanagan Basin. Three refinements to the agricultural model were made in Phase 2:

1. The model was extended to incorporate other forms of outdoor irrigation, including:
   - Irrigation of domestic properties (e.g. lawns and gardens);
   - Irrigation of municipal land (e.g. parks, boulevards, and schoolyards); and
   - Irrigation of golf courses.

2. The model was expanded to calculate indoor water use (domestic, industrial, commercial, and institutional).

3. The model was modified so it could calculate the volumes of water extracted from surface and groundwater sources to meet the demands. This information was a key input parameter to the Okanagan Basin Water Accounting Model (Appendix J).

This section describes the Okanagan Water Demand Model. Appendix I1 provides a more complete summary of the model, and Appendices I2 and I3 provide additional supporting information.

Agricultural Water Use

The Agriculture (Irrigation) Water Demand Model (van der Gulik et al., 2010), which forms the core of the Okanagan Water Demand Model, is based on a Geographic Information System (GIS) database that contains cadastre information (showing the boundaries of land ownership), crop type, irrigation system type, soil texture and climatic data. This information was assembled from background information as well as high resolution orthophotos and GIS, and was ground-truthed during a comprehensive field program beginning in 2006. Since land uses (including crop type and method of irrigation) were identified and water demands were calculated at the scale of individual land parcels and finer (i.e. polygons, as outlined in blue on Figure 14.1), the model can provide estimates of water demand for individual crops on a parcel of land, or for entire sub-basins, local governments jurisdictions, or water purveyor areas by summing the demands within those areas. To incorporate the range in climates throughout the Basin, the gridded climate data sets described in Section 5.0 and Appendix N were used in the model. A detailed description of how the model calculates irrigation water demands is provided in Appendix I2. The model calculates optimal water demand. Calculated water use would equal actual use if all irrigators watered at optimal rates, and did not over-water or under-water their crops.

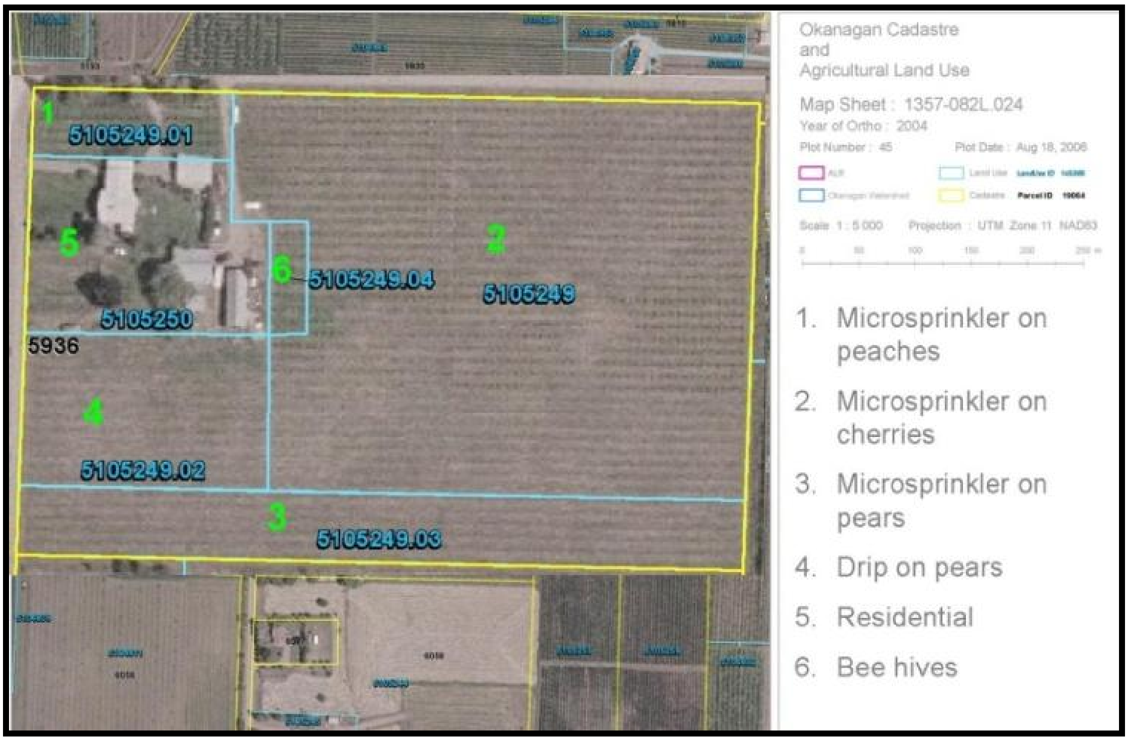

Figure 14.1 Example map sheet showing the resolution of the imagery used and the designated land use within a specific cadastre (i.e. property boundary).

Non-Agricultural Outdoor Water Use

The same methodology was used to estimate water demands on non-agricultural lands as was used for agricultural land. It was assumed that the "crop" on the non-agricultural irrigated areas was "turf grass".

A combination of image/aerial photo analysis, GIS techniques, and local government and BC Assessment data were used to identify the non-agricultural irrigated areas. These techniques were used to identify "green spaces" within residential, industrial, commercial, and institutional properties – i.e. areas likely under irrigation. These areas were then added to the database and used in the Okanagan Water Demand Model.

Indoor Water Use

Indoor water use by residential, industrial, commercial, and institutional users was incorporated into the Okanagan Water Demand Model by obtaining the BC Assessment Authority information on all land parcels in the Okanagan Basin, and assigning average daily water use values by land parcel based on an analysis of water meter records from key municipalities (Appendix I3). The average daily water use per water use category was entered into the database and used in the Okanagan Water Demand Model. Descriptions of the methods used to compute water use for each category are presented in Appendix I3.

Water Extractions from Streams, Lakes and Groundwater

To support the Okanagan Basin Water Accounting Model, it was necessary for the Okanagan Water Demand Model to link water demands on the land to extractions from water sources (e.g. streams, lakes and aquifers). Two steps were taken:

- A map of "water use areas" was developed that covers all areas in the Okanagan Basin where water is used (Attachment 3); and
- The source(s) of water supplying each of the delineated "water use areas" was identified.

The "water use area" map along with identified water sources was incorporated into the Okanagan Water Demand Model. Therefore, in addition to estimating water demands for each "water use area", the model also estimates water extractions from each surface source or groundwater source needed to supply those demands[7].

Model Output

The results of the Okanagan Water Demand Model for the 1996-2006 period are provided in Appendix C and are summarized in Section 6.0 of this report. Future scenario results are summarized in Section 18.0. Recommendations for model improvements are made in Section 20.0.

[7] For this work, surface sources were identified at the node level (i.e. sub-basin or residual area), and groundwater sources were identified at the aquifer level.

15.0 OKANAGAN BASIN HYDROLOGY MODEL

Overview

The Okanagan Basin Hydrology Model (OBHM) is a customized surface water and groundwater hydrology model covering the entire Okanagan Basin, based on the MIKE SHE/MIKE 11 integrated modelling system developed by DHI Water and Environment ULC (DHI). The MIKE SHE/MIKE 11 system simulates all of the land-based phases of the hydrologic cycle (Figure 15.1).

The OBHM was developed and calibrated against naturalized conditions for the period 1996 through 2006. The output (estimates of naturalized streamflows) is fed into the Okanagan Basin Water Accounting Model (OBWAM) (Section 16.0) that is used to assess water supply and demand in the Basin. This section highlights key attributes of the OBHM; Appendix J provides a complete technical description of the OBHM and the OBWAM. Further details on MIKE SHE are provided in DHI (2009).

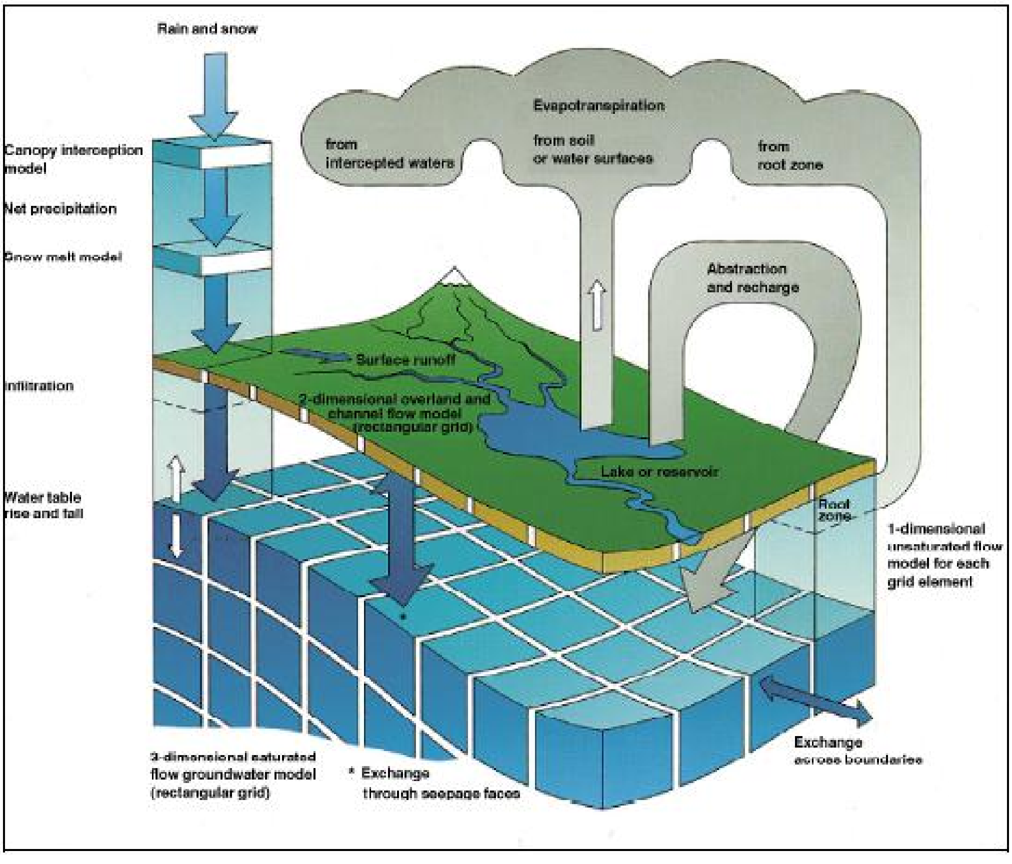

Figure 15.1 Simplified diagram of the hydrologic cycle identifying the processes incorporated in the Okanagan Basin Hydrology Model.

Development of the Okanagan Basin Hydrology Model

The OBHM utilizes the MIKE SHE and MIKE 11 modelling platforms developed by DHI. MIKE SHE is used to simulate the land-based processes of the hydrologic cycle, including snowmelt, evapotranspiration, overland flow, sub-surface flow within the unsaturated zone (i.e. above the groundwater table), and groundwater flow. MIKE 11 is used to simulate flows along the Okanagan River and through the main valley-bottom lakes, where flow regulation by dams and control structures exerts a major influence on river flows and lake levels. A summary of the specific methods used to simulate the hydrologic cycle is provided in Table 15.1. Additional features of the OBHM are as follows:

- In order to utilize the available climate datasets (Appendix N), a 500 m by 500 m grid resolution was adopted for the OBHM. As a result, the overland flow, unsaturated flow, and evapotranspiration calculations in the model are each computed for every 500 m square grid cell in the Basin.
- Groundwater calculations are based on the aquifers defined in the conceptual groundwater model (Appendix E), not at the 500 m by 500 m model grid resolution. The aquifers are simplified as linear reservoirs.
- Streamflow calculations occur at discrete node locations defined in the Hydrology State of the Basin Report (Appendix G).
- Model results were evaluated for the period from January 1, 1996 to December 31, 2006 (11 years), the period for which natural and naturalized flow estimates were developed in the Hydrology State of the Basin Report (Appendix G).
- The topography of the Basin was defined by a digital elevation model of the entire Basin, at an original resolution of 30 m; however, for the purposes of the model the resolution was resampled to 500 m.
- Detailed lake bathymetry was merged with the topography and incorporated into the model.
- Daily minimum and maximum temperature[8] and daily precipitation were extracted from the climate datasets (Appendix N). Additional calculations were performed to generate daily potential evapotranspiration (PET) using a modified Penman-Monteith method.

[8] An accurate representation of the spatial and temporal distribution of air temperature is arguably the most important factor influencing the OBHM'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, which is the dominant runoff-generating process operating in the Basin.

Table 15.1 Summary of methods used by the OBHM to simulate the Okanagan hydrologic cycle.

Process	Method used in the Okanagan Basin Hydrology Model
Snowmelt	**Modified Degree-Day Method**, whereby the rate of melting increases as the air temperature increases. The main input parameters required are: 1) melting threshold temperature, 2) degree day coefficient, 3) minimum snow storage for full coverage, and 4) maximum wet snow fraction.
Overland flow	**Explicit Finite Difference Method**, whereby the model 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 input parameters are: 1) Manning's roughness coefficient, 2) detention storage, and 3) initial water depth. The overland flow algorithm interacts with the channel flow, the unsaturated zone, and the saturated zone components of the model.
Sub-surface flow within the unsaturated zone	**Two-Layer Water Balance Method** that functions in conjunction with the evapotranspiration 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 requirements are the following soil properties: 1) volumetric moisture content at saturation, 2) field capacity, 3) wilting point, and 4) saturated hydraulic conductivity. Values for 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 contents at saturation and at field capacity provides an estimate of the storage capacity of the soil; while the difference between the moisture contents at field capacity and at the wilting point 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 assumed to be uniform across the entire depth of the unsaturated zone, thus simulated infiltration is not dependent on the soil moisture content.
Evapotranspiration (ET) (Potential and Actual)	**Two-Layer Water Balance Method** is used 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 defined as the (area of leaves)/ (area of the ground) and can vary between 0 and 7 (dimensionless ratio) depending on the vegetation type. LAI values were based on a combination of satellite imagery, land cover maps, and maps identifying forest disturbance by Mountain Pine Beetle, fire and forest harvesting. The Rooting Depth (RD) represents the maximum depth of active roots in the root zone. Values for rooting depths were obtained from the literature for similar vegetation, climate and soil conditions.
Groundwater flow	**Linear Reservoir Approach** is used to represent the groundwater system. This approach subdivides the watershed into a series of interdependent, shallow interflow reservoirs and deeper baseflow reservoirs that contribute to stream baseflow. 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 groundwater flow 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.

Table 15.1 (continued)

<table>
<tr><th>Process</th><th>Method used in the Okanagan Basin Hydrology Model</th></tr>
<tr><td>Groundwater flow</td><td>Each interflow reservoir requires a value for:
Specific Yield: The volume of water released per unit surface area of aquifer per unit decline in total hydraulic 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
Unsaturated Zone 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</td></tr>
<tr><td>Channel flow</td><td>MIKE 11 is a one-dimensional hydrodynamic modelling tool that is 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 was 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.</td></tr>
</table>

Model Calibration

The OBHM was calibrated against data from eight natural streams, eight "high confidence" naturalized hydrographs developed in a parallel study (Appendix G), and snow water equivalent data at 21 locations throughout the Basin for the 1996-2006 period. Additionally, the model output was compared against other naturalized hydrographs (Appendix G), estimates of lake evaporation from a parallel lake evaporation study (Appendices F1 and F2), and previous estimates of various components of the overall water budget (Appendices C, D, and E).

In general, the pattern and timing of snow accumulation and melt in the model agrees well with the observed snow water equivalent data (Figure 15.2), but the model has a tendency to over-predict snow accumulation at low elevations and under-predict snow accumulation at high elevations.

The simulated total flow volume agrees well with the natural and high confidence level naturalized hydrographs (Figure 15.3) 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 by the model during the autumn months that are larger than recorded values. The simulated winter baseflow however agrees well with the comparison data.

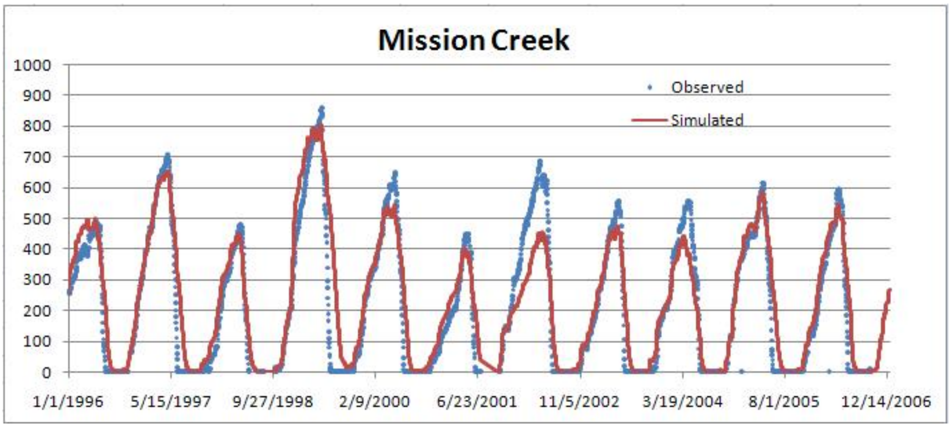

Figure 15.2 Comparison of simulated snow water equivalent (mm) with snow pillow data from the Mission Creek sub-basin.

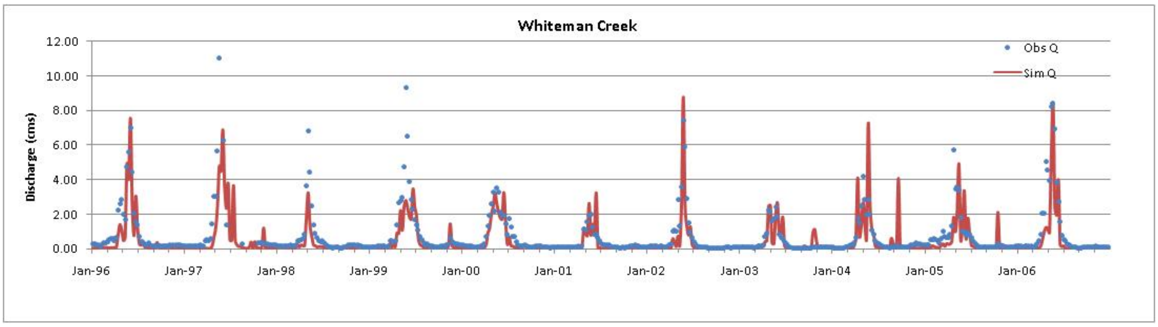

Figure 15.3 Comparison of simulated and observed discharge at Whiteman Creek.

Several methods are available for computing evaporation from the main valley lakes in the Okanagan (Appendices F1 and F2). For consistency with the Okanagan Water Demand Model, the Penman-Monteith equation was chosen.

While the model was calibrated and compared to a wide variety of data, the majority of this data consists of estimates from other studies, rather than measured data. This makes it difficult to know if differences between simulated and "observed" components of the hydrologic cycle are due to deficiencies in the model or deficiencies in the comparison data.

That the model appears capable of reproducing observed snow water equivalent and natural and naturalized hydrographs reasonably well largely reflects the high quality of the air temperature data in the climate datasets. However, these datasets are based on extrapolations of observed data and have limitations. It is likely that where the model does not represent streamflows well (such as occasionally occurs in late fall), the differences between simulated and observed conditions are likely largely due to the limitations of the climate datasets.

An overall water balance for the Basin, derived using the water management and use information presented in Section 6.0 and the information presented in other sections, including the present section, is presented in Figure 6.1. An average annual water balance for Okanagan Lake is presented in Figure 6.2. Inflow to the lake is small relative to the volume of the lake - only about 1/60 of the volume of the lake is refreshed each year.

Recommendations for improvement of the OBHM are made in Section 20.0.

16.0 OKANAGAN BASIN WATER ACCOUNTING MODEL

Overview

The Okanagan Basin Water Accounting Model (OBWAM) was developed to combine the results of the Okanagan Water Demand Model (OWDM) and the Okanagan Basin Hydrology Model (OBHM). The OBWAM is used to determine the influence of humans on water within the Basin.

Development of the OBWAM involved combining the calibrated OBHM (Section 15.0) with water management and demand information. The model was then verified against the available streamflow and lake level data. Through this process, improvements were made to the model to achieve a better calibration to the observed lake levels in the main valley lakes and Okanagan River flows.

Development of the Okanagan Basin Water Accounting Model

The human influences that are accounted for in the OBWAM are thoroughly described in Appendix B, and include:

- The operation of reservoirs in the upland portions of the Basin, which capture runoff in the spring and release water in the summer;
- Surface return flows, including municipal wastewater discharge to waterbodies, specifically Okanagan Lake and Okanagan River;
- Groundwater return flows, including septic system discharge and losses of surface water by percolation to groundwater as a result of over-irrigation;
- Water imports from sources outside the Basin;
- Water extractions from surface water (e.g., streams and lakes); and
- Water extractions from groundwater.

These human influences were quantified by parallel Phase 2 studies and models (Appendices C, D, E, and I) for the calibration period 1996-2006, and were used to develop weekly time series of the "net water use", which accounts for all the above-noted human influences at each point-of-interest in the Basin. Net water use was then subtracted within the OBWAM from the modelled natural streamflows to determine actual streamflows.

Calibration of the Okanagan Basin Water Accounting Model

The goal of calibrating the OBWAM 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.

Computer model calibration is necessary before considering use of the model for predictive or scenario modelling purposes.

Tributary Streamflows

Once the net water use data were accounted for in the OBWAM, modelled streamflows were verified against the measured streamflows in regulated tributaries. Figure 16.1 provides a plot comparing the simulated and observed flows in Mission Creek (a complete series of calibration plots and statistics is provided in Appendix J). Since Mission Creek is the most significant tributary in the Basin, it is a key indicator of how well the OBWAM is calibrated. As shown in Figure 16.1, the simulated flows are close to the actual flows, both during peak flows and during low flows, and in both wet years and dry years.

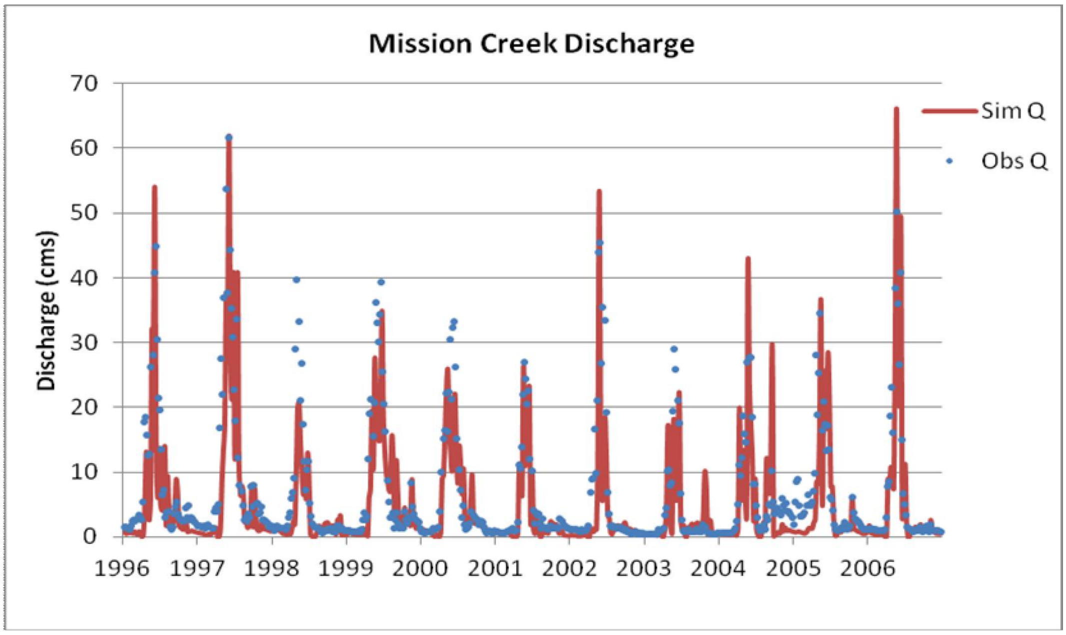

Figure 16.1 Simulated vs. observed streamflows in Mission Creek.

Lake Levels and Outflows

Calibration of the OBWAM to the mainstem lake levels and Okanagan River discharges was challenging. The data quality of the lake levels and river discharges is good, and the operational rules are well documented in dam operating plans, but implementation of the rules is at the discretion of the dam operator. As a result, there are some observed lake levels which could not be reproduced by the model because the observed levels contradict the written rules by which the lakes are supposed to be operated. Therefore, the calibration of the operational rules involved several iterations to find the right combination of rule priorities, frequency of gate adjustment, and gate level increment schemes.

In general, the results show a good fit between the simulated and observed lake levels, and a reasonable fit for the discharge from Okanagan Lake. 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 more frequently than they are in reality, and this leads to frequent oscillations of the modelled discharge from the lakes.

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 operation calibration effort was spent on getting a good fit between the simulated and observed water levels on Okanagan Lake and discharge from the lake. Figure 16.2 shows a plot of the simulated vs. observed water levels at Okanagan Lake, and Figure 16.3 shows a plot of the simulated vs. observed discharges from Okanagan Lake at Penticton. Calibration plots and statistics for lake levels and discharge from the other mainstem lakes (Kalamalka, Skaha, Vaseux, and Osoyoos) are included in Appendix J.

For Okanagan Lake, the lake level shows a very good fit during normal and wet years, but the model 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.

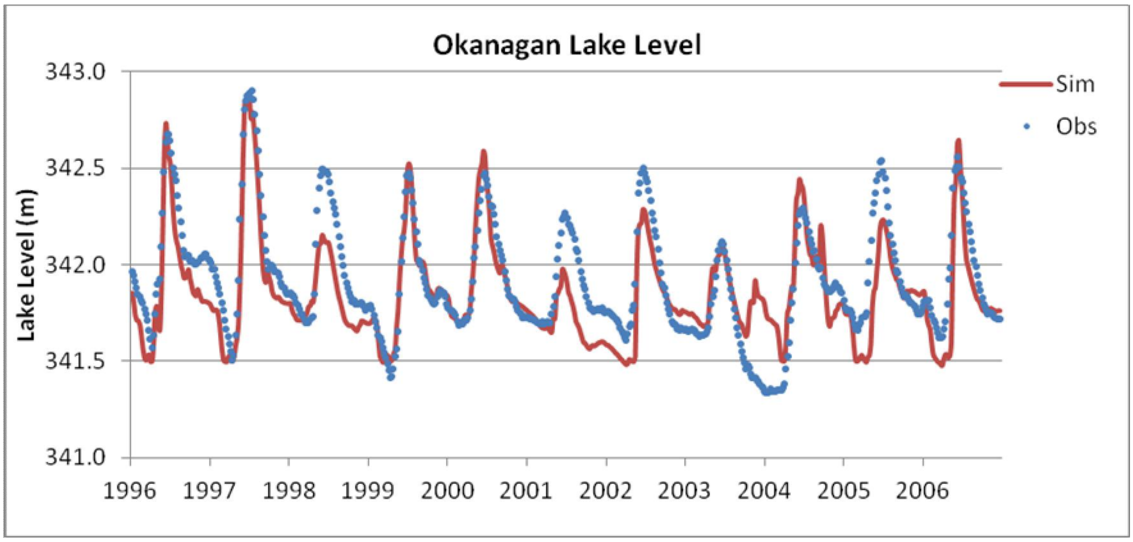

Figure 16.2 Simulated vs. observed Okanagan Lake levels.

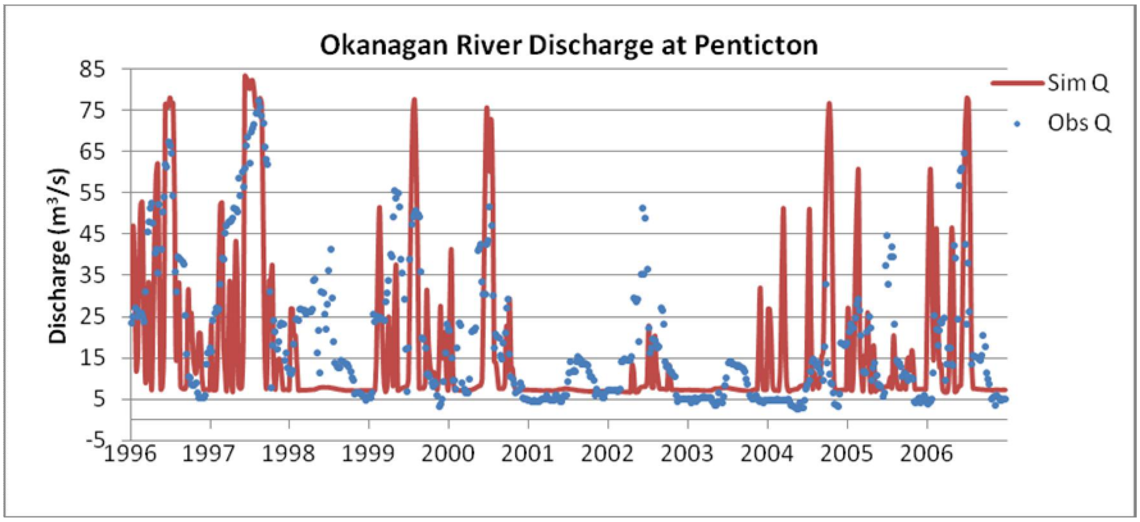

Figure 16.3 Simulated vs. observed discharge of Okanagan River at Penticton.

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. This limitation could not be overcome during Phase 2, and should be investigated further in future phases of the Project.

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. 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 Okanagan River was reasonably well represented, but it was strongly influenced by frequent modelled gate adjustments as the model attempted to meet the operational rules.

Summary

The OBWAM developed during Phase 2 is a sophisticated, flexible and scalable model capable of incorporating physical data inputs that represent the spatially and temporally variable hydrologic characteristics of the Okanagan Basin, and the influences of human water storage and withdrawals. 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. As a decision support tool, the model can help evaluate the impacts of potential climate change and water use considerations on the Basin-wide water supply. Recommendations for improving the model are provided in Section 20.0.