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Department of
Earth Sciences

Regional-Scale Groundwater Flow Model of the Kelowna Area and the Mission Creek Watershed, Central Okanagan, BC

Final Report

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EXECUTIVE SUMMARY

This report documents a regional-scale groundwater flow model for the Mission Creek Mission Creek Watershed, which includes the City of Kelowna and surrounding areas. The model was constructed to assess the interconnection and related water balance between broad-scale hydrogeologic units, including upland bedrock and major aquifers of the Kelowna area. The overall methodology follows a recent approach adopted for modeling groundwater flow in mountainous terrain, which was developed for the north Okanagan (Vernon area and BX Creek Watershed; Smerdon et al., 2009). The approach provides a first-order approximation of the groundwater flow system between the upland recharge areas and valley-bottom aquifers, including average groundwater flow rates through bedrock and alluvial aquifers.

The model spans the entire Mission Creek Watershed (53 x 45 km). It was run in Visual MODFLOW under steady-state conditions for both non-pumping and pumping conditions. Estimates of hydraulic conductivity were from BC Ministry of Environment pumping test data for the valley bottom aquifers, estimates of bedrock permeability generated through ongoing work by Voecker at Simon Fraser University, and from other reference values for the range of material types in the valley bottom sediments. Recharge to the valley bottom was derived from research results by Liggett (2008) who modeled basin-wide valley-bottom recharge. Upland recharge to the bedrock was estimated in a similar fashion to previous work by Smerdon et al. (2009).

The non-pumping water balance results for the Base Case Scenario (representing our best estimate of bedrock permeability and upland recharge) permit a comparison with other components of the water budget (e.g., baseflow to Mission Creek, discharge to Okanagan Lake, groundwater discharge from bedrock along the mountain front) that have been measured and calculated as part of ongoing work to characterize the Okanagan Basin water supply and demand. Simulated hydaulic heads compare well with observed water level data, and the distribution of simulated hydraulic heads illustrates the role of Okanagan Lake as a major groundwater discharge feature, and the Mission Creek valley as a conduit to direct upland groundwater to the valley-bottom aquifers, in the regional-scale flow system. Generally, the water table follows the topography of the watershed, and flow in the bedrock is nearly horizontal.

Due to uncertainty in the bedrock permeability and upland bedrock recharge, a sensitivity analysis was completed and the water budgets compared. Three scenarios span a range of reasonable recharge and K values, and results illustrate the sensitivity of model to variations in input data. For all model scenarios, the majority of groundwater flow (89-91%) from the upland areas to the valley-bottom passes below the mapped aquifers of the Kelowna area, and approximately 8-10% of the groundwater flow passes through the bedrock portions in the upper two layers of the model (i.e., bedrock with moderate to high lineament density). The remaining portion of groundwater flow (less than 2%) passes from the upland areas to the valley-bottom flows through the alluvial sediments of the Mission Creek valley. Although the flow rates were different for each scenario (i.e., Base Case, Low/High K Scenarios), the relative proportions remained similar. Direct recharge to the valley bottom was found to be an important component of the valley bottom recharge. Although only 10% of the total recharge to the model, this small amount represents roughly 50% of the recharge to the valley bottom aquifers. So, this is a rather significant amount. Simulated discharge to Mission Creek above the gauging station was compared to measured values. The Base Case simulation resulted in 21,063 m^3/day of baseflow, which is less than reported values. The High K and Low K scenarios resulted in baseflow estimates of 112,481 and 6,303 m^3/day, respectively. For the High K scenario, simulated baseflow conditions are similar to those reported by Summit and Polar Geoscience (2009), suggesting that the higher bedrock K and recharge values are perhaps more reasonable approximations.

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1. INTRODUCTION

1.1. BACKGROUND

Groundwater is an important water supply in the Okanagan Basin and provides drinking water to communities as well as water for irrigation and industry. The Okanagan is one of the driest regions of Canada, and rapid development in the region due to both population and agricultural growth has significantly increased demands on both surface and groundwater resources. While exploitation of surface water is regulated, there is no current legislation governing the development and use of groundwater. This unregulated use of groundwater has the potential to have negative impacts on the sustainable development of the resource, and consequent negative impacts on long term social, economic, and agricultural activity in the watersheds that rely on it.

In order to provide all levels of government with the tools needed to better understand and properly manage the groundwater resource in the basin, a basic understanding of the current groundwater resource, its development, and vulnerability is required. Hydrogeologic mapping and characterization within the Okanagan region will provide important scientific information on the aquifers and their contributing watersheds. Regional numerical groundwater models are one of the main tools used to assess and characterize aquifers.

The Okanagan Region has been targeted for aquifer mapping and characterization through a joint effort between the BC Ministry of Environment (BC MoE) and the Geological Survey of Canada (GSC) under the auspices of the Groundwater Assessment of Okanagan Basin (GAOB) initiative. Several research projects have fallen under this broad groundwater assessment initiative, including Simon Fraser University's (SFU) lead role in the Canadian Water Network collaborative research project entitled "A Basin Approach to Groundwater Recharge in the Okanagan: Bridging the Gap Between Science and Policy." More recently, the Okanagan Supply and Demand Study has led to the generation of a State-of-the-Basin report on Groundwater (Neilson-Welch and Allen, 2007). Ongoing efforts are focusing on deriving the various components of the Basin Water Balance through basin-wide groundwater (Golder Associates and Summit Environmental Consultants; referred to as Golder and Summit, 2009), hydrologic (Summit Environmental Consultants in partnership with Polar Geoscience; referred to as Summit and Polar Geoscience, 2009), and water use studies (Dobson Engineering; referred to as Dobson, 2008). At the time of writing of this report, these individual studies are nearing completion, but have yet to be incorporated into the basin-wide water balance study.

From a groundwater perspective, most of the research has taken place either in the northern Okanagan (Vernon area; e.g., Smerdon et al., 2009) or in the southern Okanagan (Oliver area; e.g., Toews, 2007; Toews and Allen, in press; Toews and Allen, submitted; Toews et al. in press). Liggett (2008) mapped direct groundwater recharge and aquifer vulnerability for the entire Okanagan valley bottom area. However, to date, little attention has been paid to the Central Okanagan despite its growing population. Thus, there is a critical need for information with respect to hydrogeology of the Central Okanagan, including the aquifer characteristics (e.g., location and extent of aquifer and aquitard units, groundwater flow directions, flow rates and sustainable capacities, inter-connection with surface water bodies, location of sensitive recharge areas, factors governing ambient groundwater quality, etc.).

This report documents the development of a regional-scale groundwater flow model for the Kelowna area and Mission Creek Watershed of the central Okanagan.

1.2. PURPOSE AND RESEARCH OBJECTIVES

The primary purpose of this research was to characterize the hydrogeology of the Kelowna area in the central Okanagan, and to construct a groundwater flow model for the major aquifers underlying the City of Kelowna. The Kelowna area was selected because it is the focus of the GSC's groundwater mapping program and because there was an opportunity for collaboration between SFU, the BC MoE, and the GSC.

The original research objectives were:

1. To assist the GSC in constructing a 3-dimensional architecture model of the aquifer(s)[1] in the central Okanagan;
2. To quantify and map the spatial distribution of recharge to the aquifer(s) within the sub-region; and,
3. To construct a 3-dimensional groundwater flow model for the region.

[1] intended to include only the unconsolidated valley bottom aquifers.

Several logistical complications arose during this research project, which required modifications of the original research objectives. These complications were:

1. The geophysical field investigation (seismic survey) was delayed until Fall 2008; and subsequent processing was not completed until early 2009.
2. Preliminary interpretation and integration of the geophysical field investigation and hydrogeologic field mapping results into a 3-dimensional geologic model by the GSC has not been completed as of March 2009.
3. Funding for this collaborative research (from the BC MoE) has been exhausted. The funds were used to support a limited term post-doctoral fellow, whose term is complete.

Considering that these complications prohibited the development of a groundwater flow model for the unconsolidated valley fill aquifers, the original research objectives were revised as follows:

1. To construct a regional-scale groundwater flow model for the entire Mission Creek Watershed; this includes the City of Kelowna and surrounding areas.
2. To use estimates of spatial distribution of recharge for the valley bottom (original objective number 2) determined by J. Liggett (2008), and extend recharge estimation to the upland area using an approach similar to Smerdon et al. (2009).
3. To use estimates of hydraulic properties for the model derived from a) the analysis of aquifer test data in the valley fill materials, and b) estimates of bedrock permeability for the upland areas as derived from fracture modeling (Voeckler, in prep).

1.3. METHODOLOGY AND APPROACH

The overall methodology follows a recent approach adopted for modeling groundwater flow in mountainous terrain, which was developed for the north Okanagan (Vernon area and BX Creek Watershed; Smerdon et al., 2009). The approach provides a first-order approximation of the groundwater flow system between the upland recharge areas and valley-bottom aquifers, including average groundwater flow rates through bedrock and alluvial aquifers. It is expected that these flow rates (i.e., the lateral fluxes that recharge valley-bottom aquifers as mountain block recharge) could be used to develop a finer-scale flow model of the valley aquifers in the Kelowna area following completion of original research objective number 1 by the GSC.

To develop a regional-scale groundwater model, the following scope of work was undertaken:

1. Review Quaternary geology maps, groundwater consulting reports, BC MOE aquifer worksheets, and selected well lithological records for the Kelowna area;
2. Identify major hydrostratigraphic and hydrostructural units by considering the spatial variation in hydraulic properties, utilizing existing BC MOE aquifer polygons, and a draft version of the revised bedrock geology maps from the GSC;
3. Develop a continuous bedrock topographic map from the centerline of Okanagan Lake (approx. 400 m below sea level) to the headwaters of the Mission Creek Watershed (approx. 2300 m above sea level);
4. Review (and revise) distributed recharge values determined by J. Liggett (2008) for the valley-bottom area, and values by Smerdon et al. (2009) for the upland area;
5. Review hydraulic properties derived from pumping tests conducted in the valley bottom aquifers (as summarized by V. Carmichael (unpublished data), and assign appropriate properties to these valley bottom aquifers;
6. Review hydraulic properties derived from a combination of pumping tests and fracture modeling for the upland bedrock regions, and assign appropriate properties to the upland bedrock aquifers;
7. Review available hydrometric data, including the recent compilation report for naturalized flows (Summit and Polar Geoscience, 2009), and assign appropriate physical boundary conditions to the model to represent surface hydrologic features;
8. Characterize and portray a simplified representation of the 3-dimensional stratigraphic and hydrogeologic architecture of the unconsolidated aquifer(s) and bedrock regions in a 3-dimensional groundwater flow model that extends from the centerline of Okanagan Lake to the headwaters of the Mission Creek Watershed;
9. Review the Water Management and Use Study by Dobson (2008) for information on major groundwater users in the Kelowna area;
10. Calibrate the numerical flow model to steady-state conditions, and extract water budget results for inclusion in the future finer-scale modeling of Kelowna area aquifers; and,
11. Conduct a simple particle tracking exercise to determine the capture zones for major groundwater purveyors in the area;

1.4. OUTLINE OF THE REPORT

This report consists of 5 sections. Section 1 provides a background to the study and states the objectives and scope of work. Section 2 describes the physical setting, geology, and simplified hydrogeology of the Mission Creek Watershed. Section 3 describes the conceptual regional-scale model, the numerical model and its calibration. Section 4 presents the modeling results, and conclusions are presented in Section 5.

2. STUDY AREA AND GEOLOGIC SETTING

2.1. LOCATION, PHYSIOGRAPHY, AND CLIMATOLOGY

The Okanagan Basin (8000 km^2) is located in southern British Columbia, Canada (Figure 2.1), and is a narrow, north-south trending valley (~185 km in length) bounded by upland plateaus and mountains that rise up to ~2000 m above the valley floor. The Kelowna area and Mission Creek Watershed model centers on the City of Kelowna, in the central portion of the Okanagan Basin (Figure 2.1). The model area encompasses the Kelowna (Mill) Creek, Mission Creek, and Bellevue Creek topographic catchments. The City of Kelowna is situated at a prominent bend at the mid-point of Okanagan Lake, where the northern segment of the Okanagan Basin contains a small valley that is parallel to Okanagan Lake.

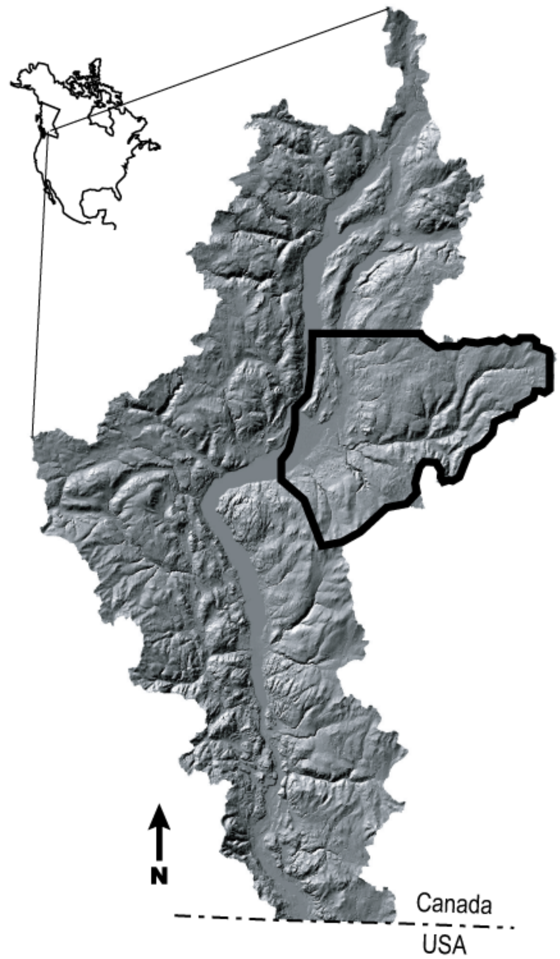

Figure 2.1: Greyscale hillshade of Okanagan Basin, with outline of Kelowna area and Mission Creek Watershed model area.

Within the study area, topography varies from 340 m above sea level (m asl) near Okanagan Lake to 2000 m asl in the headwaters of Mission Creek (Figure 2.2). Ground surface topography was obtained from 25 m horizontal resolution digital elevation data (GeoBase, 2007), which are unprojected 0.75-arc second, Level 1 DEM data.[2] Elevation data were projected on Universal Transverse Mercator (Zone 11), and interpolated onto 100 m resolution grid in SURFER, using the nearest neighbor gridding method.

[2]This is the 1:50000 CDED1 series, which can be accessed at `http://geobase.ca`. At the latitude of the study region, 0.75-arc seconds projects to approximately 22 m north–south by 15 m east–west.

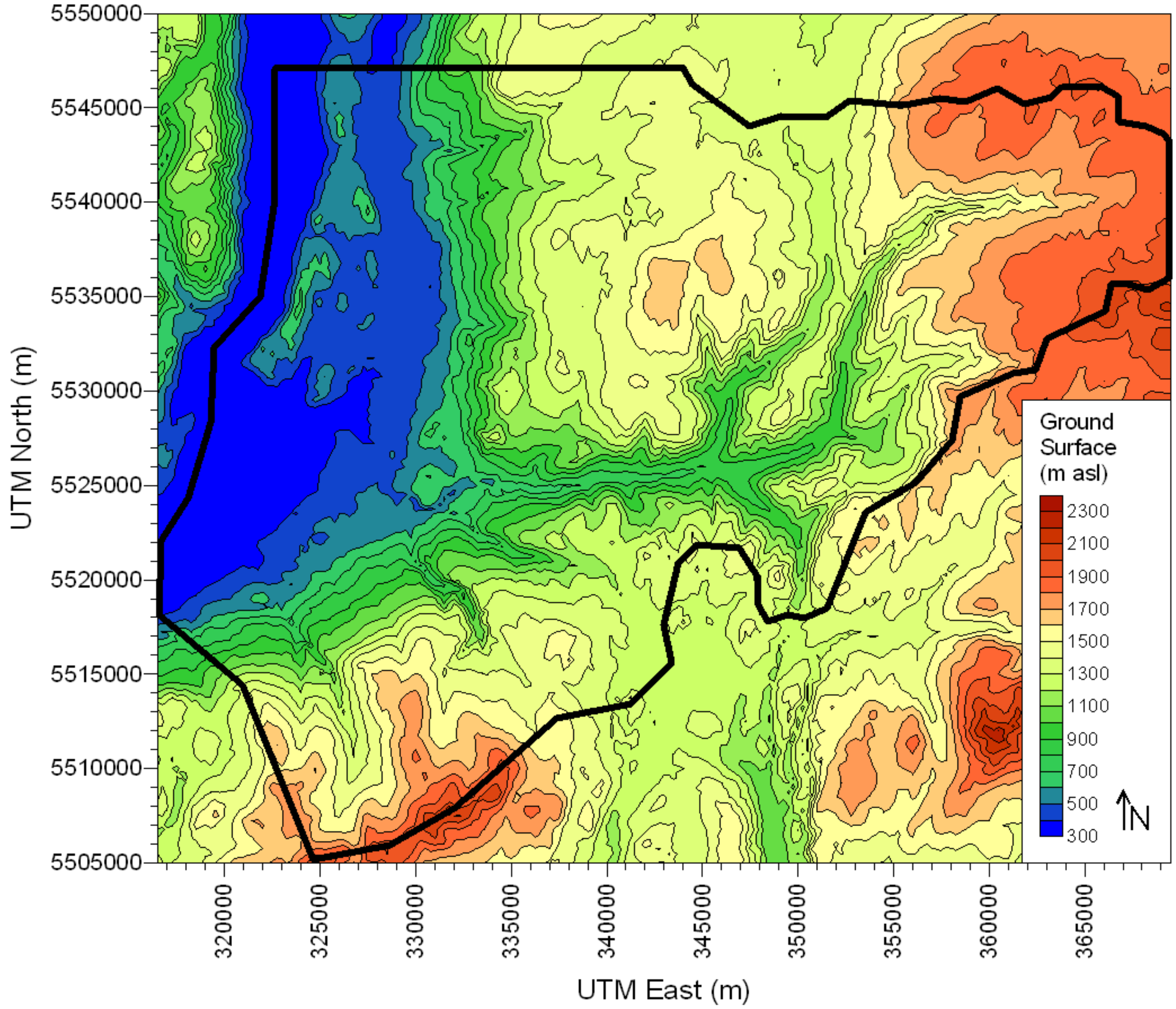

Figure 2.2: Ground surface topography, with outline of Kelowna area and Mission Creek Watershed model area.

The Basin is characterized by a semi-arid continental climate, with an increase in atmospheric moisture from valley bottom to upland areas as well as south to north (Cohen et al., 2004). Average annual precipitation for Kelowna is 381 mm and the average monthly air temperature varies from -3.8 °C to 19.1 °C (Figure 2.3; Canadian Climate Normals 1971 to 2000; Environment Canada, 2006). In the headwaters of Mission Creek, the average maximum snow water equivalent is 541 mm (Station 2F05; BC MoE, 1997).

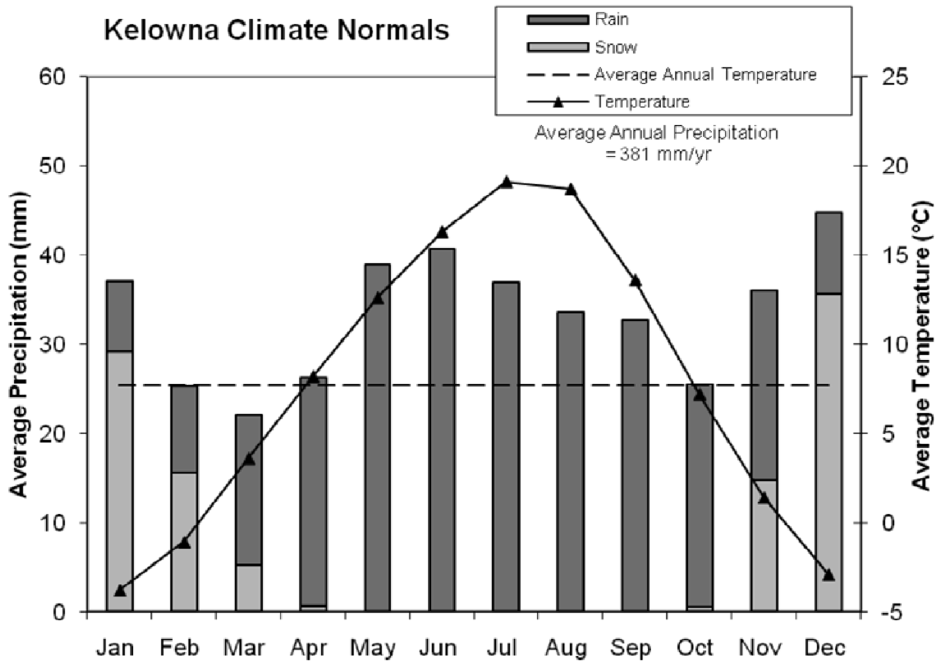

Figure 2.3: Climate normals for Kelowna.

2.2. KELOWNA AREA GEOLOGY

2.2.1. SURFICIAL GEOLOGY

The Okanagan Valley bottom is infilled in with a thick, complex arrangement of Tertiary intermountain basin sediments and more recent unconsolidated Quaternary (including recent Holocene) sediments from repeated glaciation, glaciolacustrian, and alluvial processes. Surficial geologic deposits are comprised of various depositional facies and landforms, including glaciofluvial deposits, kettled outwash, raised and present-day alluvial fans, and glaciolacustrine sediments (Nasmith, 1962, Figure 2.4).

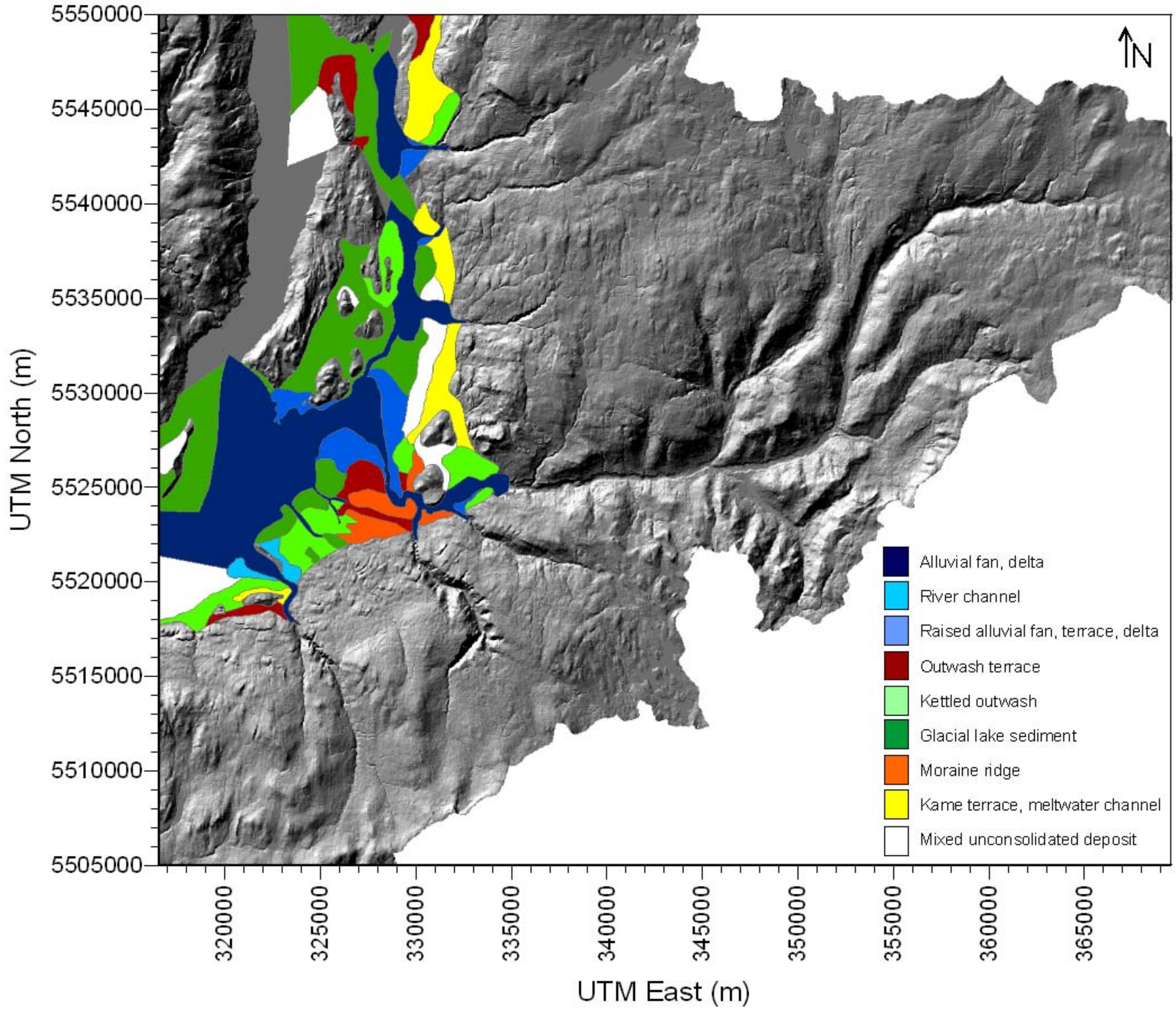

Figure 2.4: Surficial deposits of the Kelowna region (Nasmith, 1962).

2.2.2. BEDROCK GEOLOGY

The linear basin is formed by the Okanagan Valley Fault (Roed, 1995), a major crustal-scale, west-dipping, normal fault offsetting Precambrian to Holocene igneous, metamorphic, and sedimentary rocks (Massey et al., 2005). The bedrock geology map is currently being revised by the GSC, and the following descriptions are taken from a draft version of the revised map (A. Okulitch, unpublished data).

In the Kelowna area, the Okanagan Valley Fault separates the City of Kelowna (west side of the fault), from upland bedrock on the east side of the fault (Figure 2.5). The upland bedrock consists of Proterozoic Okanagan Gneiss, Paleozoic interfoliated schist and paragneiss, and Miocene plateau basalts. On the west side of the fault (beneath Kelowna and in bedrock outcrop in Kelowna), the bedrock consists of Cenozoic White Lake Formation (breccias, mudstone, siltstone) and Cenozoic andesite.

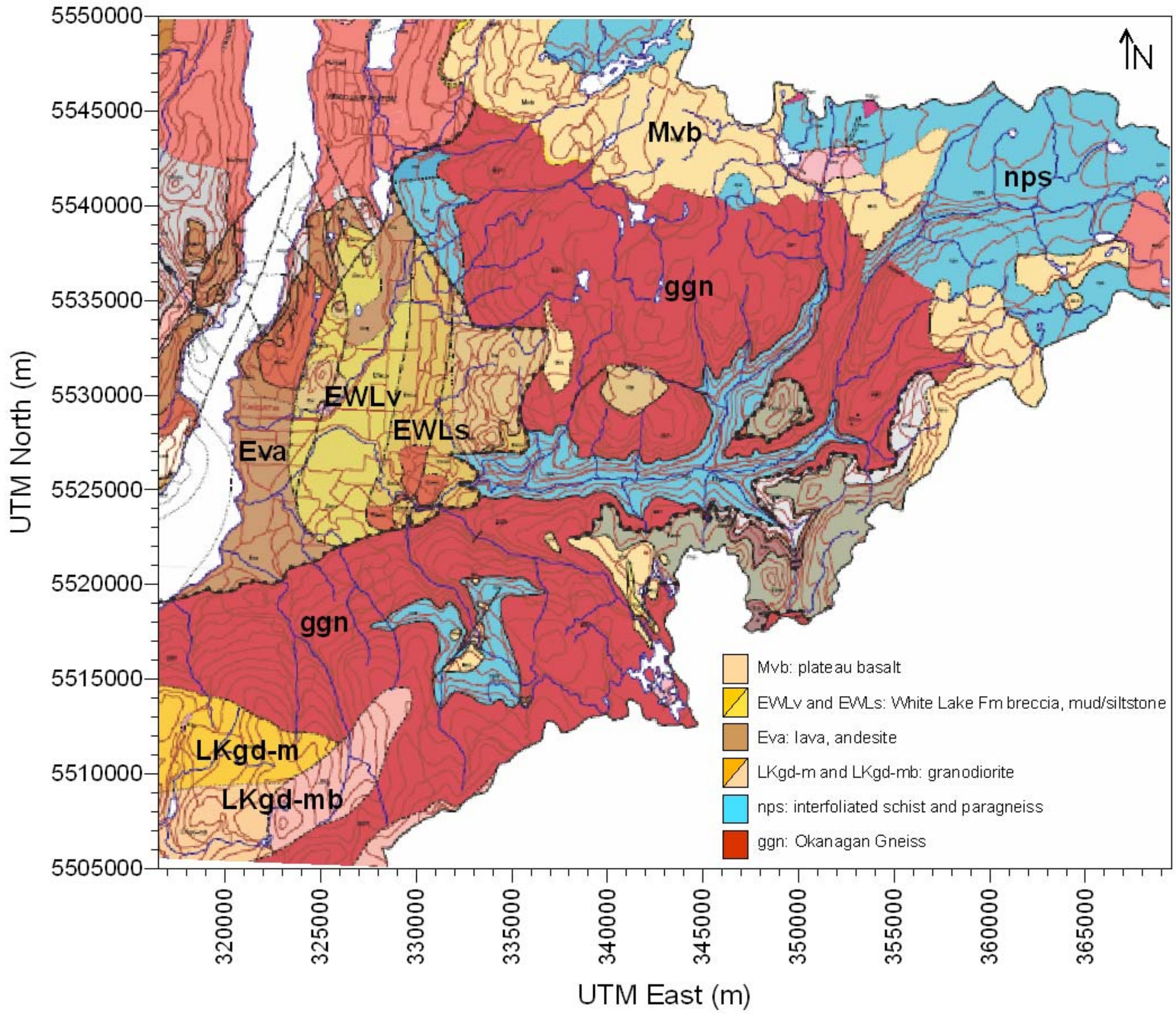

Figure 2.5: Bedrock geology of the central Okanagan basin (Okulitch, unpublished data).

The Okanagan Valley Fault has an associated deep trench along the axis of Okanagan Lake, which results in a bedrock surface that varies considerably. From seismic surveying of Okanagan Lake, Eyles et al. (1991) found the bedrock surface to be approximately 650 m below sea level. For this project, a continuous bedrock surface map was created by combining the seismic profiles of Eyles et al. (1991) with a recent map of drift thickness for the Kelowna area (GSC, unpublished data). These data sources were combined using SURFER, by importing the drift thickness map, and digitizing bedrock depth contours from Eyles et al. (1991). Combined data were krigged (in SURFER) to generate a drift thickness map (Figure 2.6) and bedrock surface map (not shown).

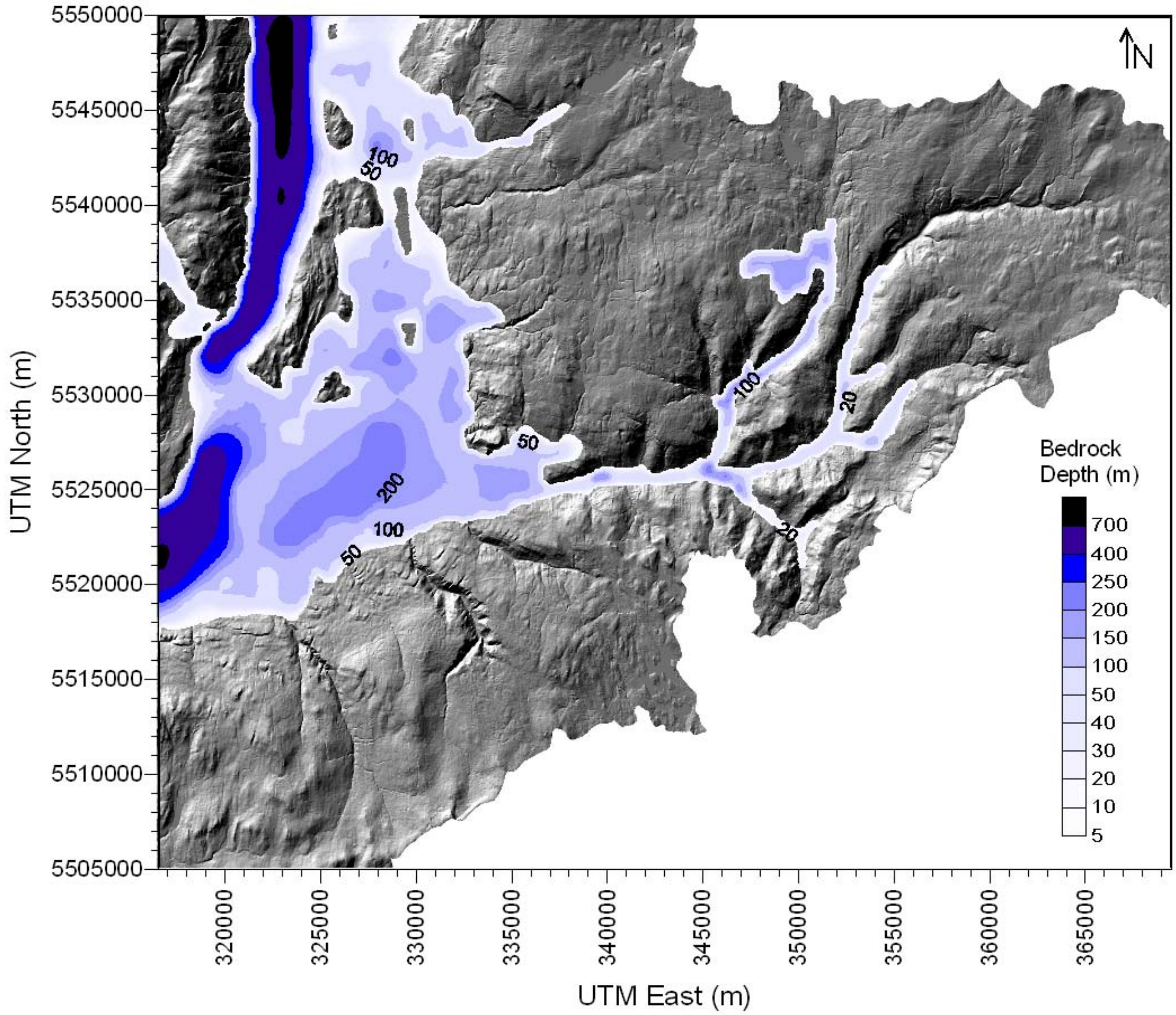

Figure 2.6: Drift thickness map, compiled from sediment thickness in the Kelowna area (GSC, unpublished data) and seismic profiles of Okanagan Lake (Eyles et al., 1991).

3. REGIONAL-SCALE GROUNDWATER FLOW MODEL

3.1. MODEL DOMAIN

A regional-scale groundwater flow model was constructed for the Kelowna area and Mission Creek Watershed. The intent of this model was to assess the interconnection and related water balance between broad-scale hydrogeologic units, including upland bedrock and major aquifers of the Kelowna area. The GSC is developing a comprehensive understanding of the valley fill hydrostratigraphy, from which a finer-scale groundwater flow model could be constructed in the future. Thus, the focus of the regional-scale model was to estimate groundwater flow rates (water budget components) from the upland recharge area and support subsequent finer-scale analysis of the aquifers in the Kelowna area.

The model area extended from Okanagan Lake to the headwaters of the Mission Creek Watershed, covering an ground surface elevation range of 340 to 2000 m asl (Figure 2.2). The area spanned from 316500 to 369500 m UTM East, and from 5505000 to 5550000 m UTM North (for a total size of 53 km x 45 km). The lateral boundaries of the model area correspond to the centreline of Okanagan Lake, and topographic catchments of Kelowna (Mill) Creek, Mission Creek, and Bellevue Creek. The model was developed with the MODFLOW code (Harbaugh et al., 2000), using the Visual MODFLOW interface (v4.3; Schlumberger Water Services, 2008). Steady-state flow was simulated for a conceptualized representation of the geology of the study area, for mean annual recharge, and for stream and lake levels representative of the baseflow period. The model was calibrated to static groundwater levels from the BC WELLS Database (BC MoE, 2006) and estimates of baseflow to Mission Creek. A sensitivity analysis was also competed, to quantify a range of water budget results possible from a range of potential (and uncertain) input parameters. Using the calibrated model, the capture zones

3.1.1. GRID DESIGN

The finite difference grid was set to 200 x 200 m horizontal resolution with telescoping mesh refinement in the vicinity of major groundwater extraction areas (50 x 50 m; Figure 3.1), having 265 columns and 225 rows (59,625 grid cells per layer). Ground surface was assigned elevations from the 100 m horizontal resolution digital elevation model shown in Figure 2.2. To include regional-scale flow through the bedrock and the complete depth of Okanagan Lake, the base of the model grid was set to 1000 m below sea level. The grid was subdivided into 6 layers, with varying thicknesses (Figure 3.2).

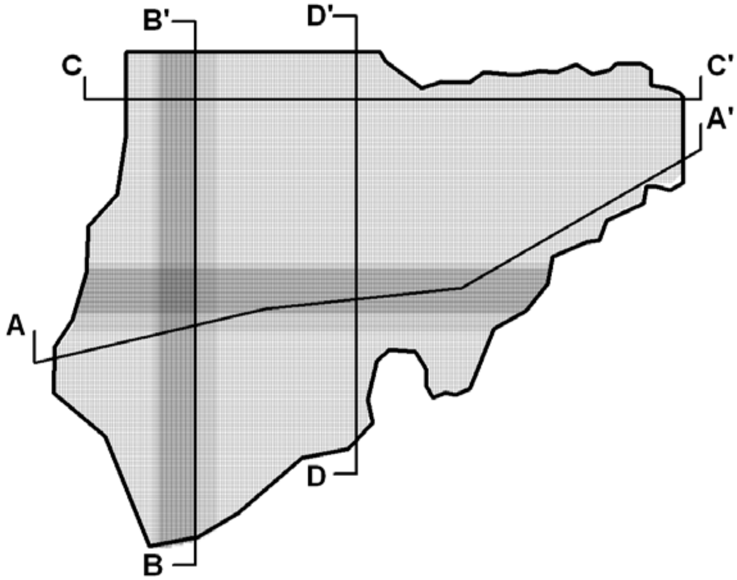

Figure 3.1: Plan view of the model grid, with grid cell refinement in the vicinity of major groundwater well fields in the Kelowna area. Cross section locations described in the report are also shown.

The uppermost layer (Layer 1) was designed to be approximately 100 m thick in the vicinity of Kelowna, and 25 m thick along the Mission Creek valley. The base of Layer 1 was held at a constant elevation of 1000 m asl around the perimeter of the model domain. The base of Layer 1 was created in SURFER by digitizing control points that coincided with known ground surface contours, and then assigning elevation values based on location (i.e., 100 m less in the vicinity of Kelowna, 25 m less along Mission Creek). Control points were kriged in SURFER to create the base of Layer 1, which was subsequently imported to Visual MODFLOW.

The thicknesses of Layers 2 and 3 were approximately 100 m in the vicinity of Kelowna, such that the base of Layer 3 corresponded with sea level (i.e., 0 m asl). Outside the Kelowna area, Layers 2 and 3 had variable thicknesses that divided the complete depth of the model space equaly (Figure 3.2). This approach to vertical discretization of the model grid allowed for the Tertiary and Quaternary unconsolidated sediments underlying Kelowna to be represented by 3 distinct layers. Layer 4 and 5 also had varying thickness, such that the base of Layer 5 had a contant elevation of -400 m asl (i.e., 400 m below sea level). The bottom layer had a uniform thickness of 600 m. The translation of geologic materials to the model grid is discused in the next section.

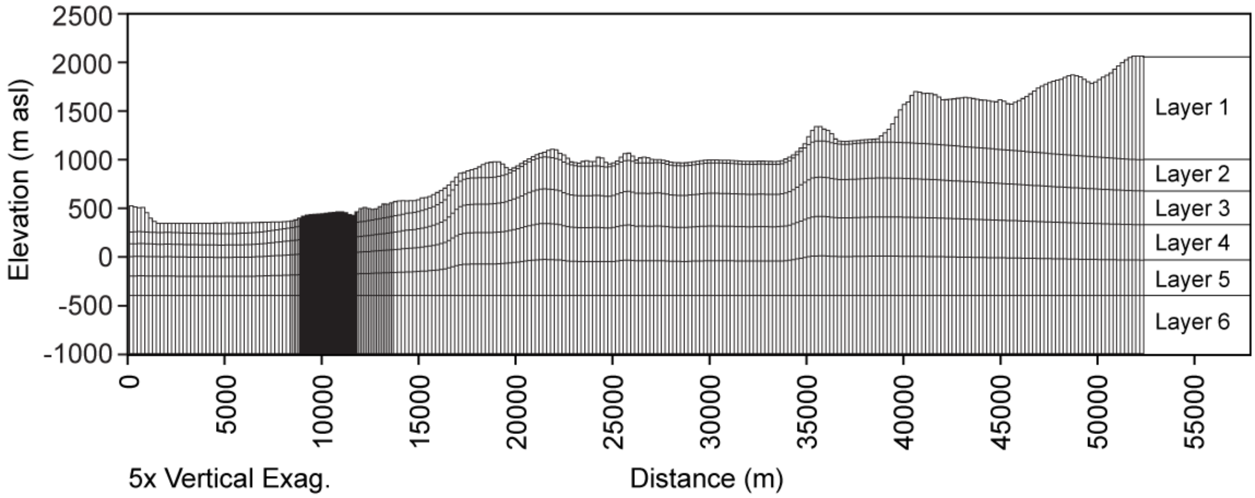

Figure 3.2: Representative west to east cross section of the model grid, located approximately along the mid-line of the model (similar to cross section A-A').

3.2. MATERIAL PROPERTIES

3.2.1. HYDROSTRATIGRAPIC AND HYDROSTRUCTURAL UNITS

To construct a regional-scale groundwater flow model of the Kelowna area and entire Mission Creek Watershed, the hydrostratigraphy of complex surficial deposits was greatly simplified for the Kelowna area. Conceptualized representation of hydrostratigraphic units (Figure 3.3) was developed from a combination 1) the aquifers delineated according to the BC Aquifer Classification System (Berardinucci and Ronneseth, 2002), and 2) the lateral extent of surficial geologic deposits (Nasmith, 1962). Layer thickness was interpreted from a groundwater assessment for the City of Kelowna (AGRA, 1998), selected well lithology data (BC MoE, 2006), and the depth to bedrock map described in Section 2.2.2.

Unconsolidated deposits were simplified to 5 categories, including: sand and gravel deposits associated with BC Aquifer 463, sand and gravel deposits associated with BC Aquifer 464, alluvial sediments at the interface between the upland segment of the Mission Creek valley and the Kelowna area, valley fill material along the Mission Creek valley (encompassing BC Aquifer 461), and remaining unconsolidated deposits in the vicinity of the City of Kelowna. These deposits are primarily represented in Layer 1 of the model, which varies in thickness from 25 m along the Mission Creek valley, to up to 100 m in the Kelowna area

The unconsolidated deposits of the Okanagan Valley, in the vicinity of the City of Kelowna extend to depths of 200 metres, and are assumed to consist of silt, clay, and fine sand (AGRA, 1998). Very few wells penetrate these particular unconsolidated deposits, and presumably, the recent seismic surveying by the GSC will aid in defining major stratigraphic layers of these deposits. In the regional-scale model, these deposits are present in portions of Layers 2 and 3 (Figure 3.4), corresponding to the depths shown on Figure 2.6. These unconsolidated deposits were assumed to extend underneath Okanagan Lake, and are also present in a small portion of Layer 4 (extreme left side of cross-section A-A').

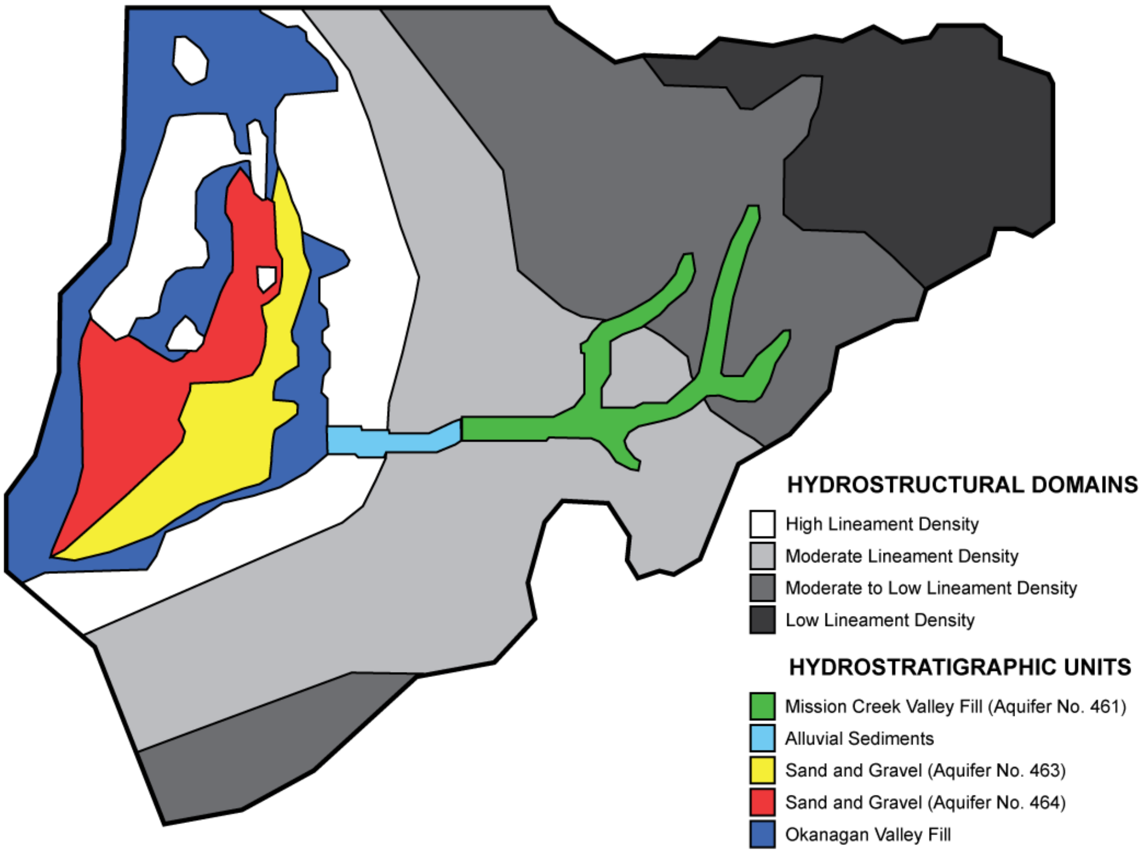

Figure 3.3: Generalized hydrostratigraphic and hydrostructural domains of the Kelowna area, represented in Layer 1 of the groundwater flow model.

The bedrock geology was conceptualized as 6 separate hydrostructural units, which were differentiated based on proximity to the Okanagan Valley Fault (OK Fault), the density of bedrock lineaments (assumed to represent fracture zones), and depth. Four of the hydrostructural units are exposed at surface, while two others lie at depth. As discussed earlier, the Okanagan Valley Fault seperates Cenozoic bedrock to the west, and Proterozoic and Paleozoic bedrock to the east (Figure 2.5). Associated with the Okanagan Valley Fault, major lineaments have been mapped by the GSC using aerial (ortho) photos and LandSat imagery (Figure 3.5). The density of the lineaments (i.e., the number of lineaments per unit area) varies throughout the region. In general, the density is highest near Okanagan Valley Fault, near the valley bottom and decreases upland, away from the fault. Lineament mapping, however, is complicated by vegetation and soil cover, urban development, and Quaternary fill, particularly in the Kelowna area (as seen in Figure 3.5), but was successful at identifying these different zones in other areas of the Basin (Voeckler and Allen, 2008).

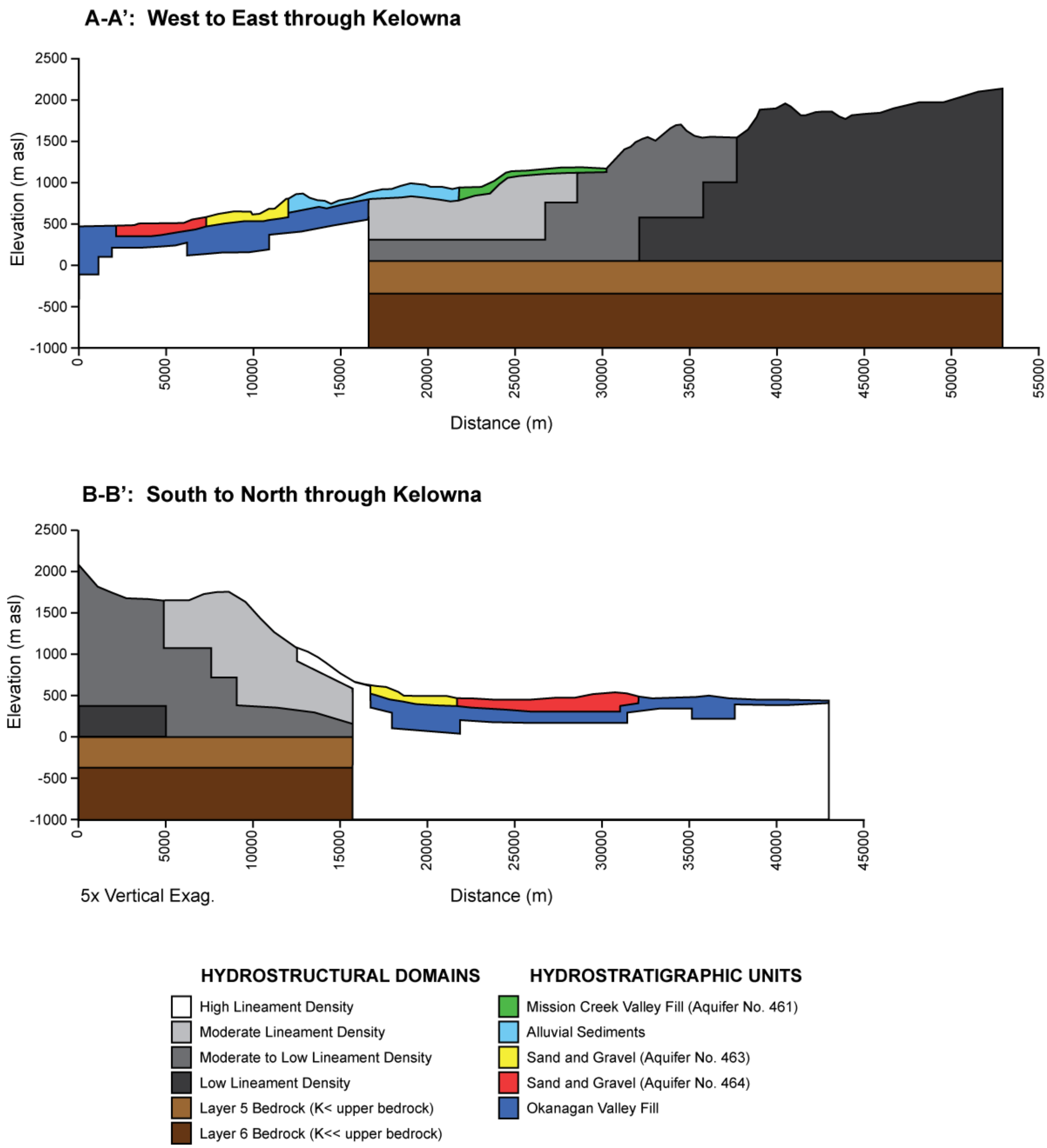

Figure 3.4: Generalized hydrogeologic cross sections through the Kelowna area.

For this study, the bedrock was classified based on the apparent lineament density (Voeckler and Allen, 2008). Zones with high lineament density are thought to correspond to areas of increased bedrock permeability, whereas low lineament density zones correspond to lower bedrock permeability (Voeckler, in prep). Estimates of the hydraulic properties were assigned, as discussed in the next section. Thus, the bedrock units in the regional-scale flow model were concepualized as illustrated by the density of lineaments both east and west of Okanagan Valley Fault (Figures 3.3 and 3.4).

With increased depth, Lawson (1968) illustrated that the permeability of the bedrock decreases exponentially in the Okanagan Highlands. To accommodate permeability reduction, Layers 5 and 6 were considered to have different hydraulic parameters than overlying bedrock units as illustrated with the < upper bedrock and << upper bedrock categories in Figures 3.3 and 3.4.

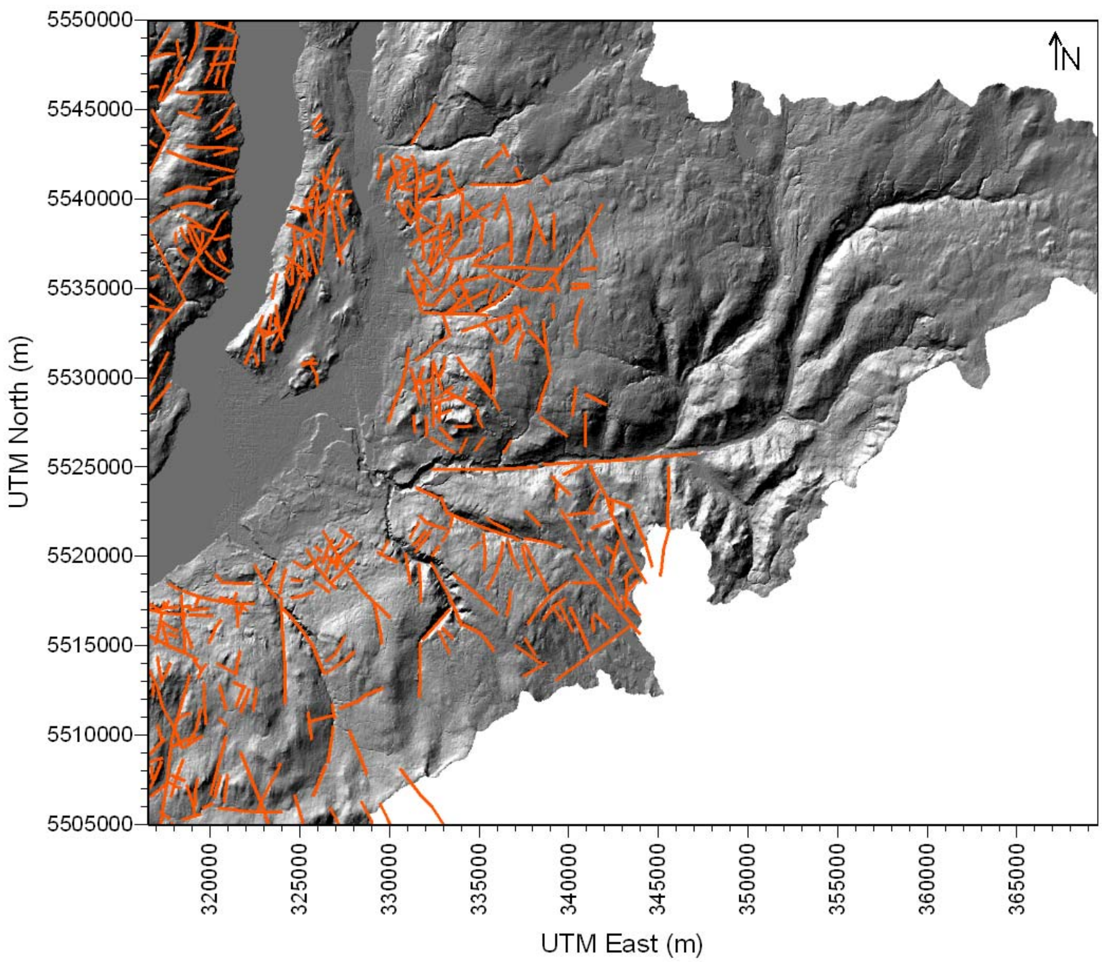

Figure 3.5: Bedrock lineaments determined by the GSC for the central Okanagan.

3.2.2. HYDRAULIC PROPERTIES

As part of the GAOB initiative, available pumping test data for the aquifers of the Okanagan Basin were compiled and interpreted by the BC MoE (V. Carmichael, unpublished data). For the Kelowna area, this has produced 24 estimates of the hydraulic condtivity (K) for BC Aquifer 463, and 4 estimates of the hydraulic condtivity for BC Aquifer 464 (Table 3.1). Accordingly, in the regional-scale flow model, the sand and gravel deposits representing BC Aquifers 463 and 464 were assumed to have K_{xy} of 2.2×10^{-3} m/s and 1.7×10^{-3} m/s, respectively (Table 3.2), representing the geometric mean values obtained for each aquifer. At the time of writing this report, estimates of K for these two aquifers were not available from the Groundwater Phase 2 report (Golder and Summit, 2009).

Table 3.1: Summary of hydraulic conductivity (K) values determined by BC MoE for confined aquifers in the Kelowna area (V. Carmichael, unpublished data), which are identified using BC well tag numbers (WTN). The geometric mean K includes all data in the pumping test analyses.

	WTN	Mean K (m/s) from Jacob and Theis analyses	K (m/s) from recovery data	WTN	Mean K (m/s) from Jacob and Theis analyses	K (m/s) from recovery data
BC Aquifer 463	251	4.9E-02		54004	1.6E-02	
	251	2.4E-03	1.3E-03	54004	7.2E-03	2.8E-02
	251	2.6E-03	6.3E-03	58827	6.1E-03	
	19148	1.1E-03	1.1E-03	59011		1.1E-03
	23805	2.1E-04		82339	1.3E-03	1.4E-03
	25837	1.5E-04	1.4E-04	82340	4.1E-03	2.7E-02
	31816	2.2E-03	3.2E-03	82348	1.4E-03	
	31816	7.3E-04		82348	3.2E-03	1.3E-03
	31817	4.9E-03	4.5E-03	82377	2.3E-03	4.5E-03
	34272			82390	9.9E-04	2.0E-03
	34272	1.3E-03	5.6E-03	82395		3.3E-04
	35486	4.2E-03	4.4E-03	82395	1.4E-04	
	36228	6.5E-04	3.5E-03	82665	1.8E-02	
	41982	2.3E-03	1.2E-03	82665	3.3E-03	6.9E-03
	42285	1.2E-03		84003	6.7E-04	
	44358	1.8E-03	6.2E-03	84682	3.1E-03	8.3E-03
	50051		1.9E-04			

	WTN	Mean K (m/s) from Jacob and Theis analyses	K (m/s) from recovery data
BC Aquifer 464	160	8.9E-04	4.1E-04
	23703	5.3E-03	
	52067	7.6E-04	3.2E-03
	82386	2.0E-03	3.8E-03

BC Aquifer	Geometric Mean K (m/s)
463	2.2E-03
464	1.7E-03

For the remaining unconsolidated deposits, K values were assumed based on the textural description of the geologic feature. The Alluvial Sediments and Mission Creek Valley Fill (including Aquifers 461 and 463) were assumed to have K_{xy} of 1×10^{-6} m/s and 1×10^{-5} m/s, respectively. The Okanagan Valley Fill in the vicinity of Kelowna is described as interbedded silt, clay, and fine sand (AGRA, 1998), and was assumed to have K_{xy} of 1×10^{-7} m/s. For each of the unconsolidated hydrostratigraphic units, the anisotropy ratio (K_{xy}:K_z) was assumed to be 10:1 to mimic the effect of having interbedded layers of finer-textured sediments (e.g., clay and silt lenses) that would reduce vertical K. The exception was the Okanagan Valley Fill, which were assumed to have K_{xy}:K_z of 50:1.

Table 3.2: Hydraulic conductivity and anisotropy assigned to each hydrogeologic unit in the regional-scale flow model. The colours correspond to generalized hydrostratigraphic units, and hydrostructural domains based on fracture density shown on Figure 3.3 and 3.4.

	Hydrostructural Domains	K_{xy} (m/s)	K_z (m/s)	K_{xy}:K_z
Bedrock	High Lineament Density	1.6E-06	7.5E-07	2.1:1
	Moderate Lineament Density	2.8E-07	2.8E-07	1:1
	Moderate to Low Lineament Density	1.5E-07	1.5E-07	1:1
	Low Lineament Density	1.9E-08	1.1E-08	1.7:1
	Layer 5 Bedrock (K < upper bedrock)	1.0E-08	1.0E-08	1:1
	Layer 6 Bedrock (K << upper bedrock)	1.0E-09	1.0E-10	10:1
	Hydrostratigraphic Units	**K_{xy} (m/s)**	**K_z (m/s)**	**K_{xy}:K_z**
Unconsolidated Deposits	Mission Creek Valley Fill (Aquifer No. 461)	1.0E-05	1.0E-06	10:1
	Alluvial Sediments	1.0E-06	1.0E-07	10:1
	Sand and Gravel (Aquifer No. 463)	2.2E-03	2.2E-04	10:1
	Sand and Gravel (Aquifer No. 464)	1.7E-03	1.7E-04	10:1
	Okanagan Valley Fill	1.0E-07	2.0E-09	50:1

The permeability of the bedrock and relation to fracture density was mapped and modeled for the Penticton and Naramata areas, and at various spatial scales, as part of Ph.D. research by H. Voeckler (Voeckler, in prep). At the mountain block scale, the estimates for $K_{x,y}$ (and K_z) ranged from 1.6×10^{-6} m/s to 1.9×10^{-8} m/s, with varying degrees of anisotropy (Table 3.2).

3.3. BOUNDARY CONDITIONS

3.3.1. LATERAL BOUNDARIES AND SURFACE WATER

With the exception of Okanagan Lake and the southern shoreline of Wood Lake, the sides of the model area correspond to topographic divides, which were assumed to coincide with underlying groundwater divide and set as no-flow boundaries.

Okanagan Lake, Wood Lake, and Ellison Lake were defined as constant head boundary conditions of 342 m asl, 391 m asl, and 425 m asl, respectively. Wood Lake and Ellison Lake represent relatively small hydrologic features in the regional-scale model, and were assigned only to Layer 1. Bathymetric maps of Okanagan Lake were obtained from the BC MoE Fish and Wildlife Branch, and used to define the vertical extent of the Okanagan Lake hydraulic boundary. In the vicinity of North Kelowna, (Ellison Lake region), Okanagan Lake is approximately 200 m deep, and in the central part of the City of Kelowna, Okanagan Lake is approximately 60 m deep. The constant head boundary was copied to portions of Layers 2 and 3 in the model, corresponding to the approximate bathymetry. By assigning these lakes as constant head boundaries, it is assumed that their levels are held at a constant elevation. There will be a flux of groundwater to and/or from these lakes, that will remain constant under steady state conditions.

Creeks were defined using river, constant head, and drain boundary conditions following the parameters listed on Table 3.3. For small creeks located within the valley-bottom, the river boundary condition was specified with a stage 1 m below ground level, a river bottom 3 m below ground level, a width of 3 m, and the conductance was calculated internally within Visual MODFLOW, based on the vertical hydraulic conductivity (K_z) of the hydrogeologic unit in which the river boundary was specified. These values were assumed to represent “typical” small creeks in the valley-bottom area, and further refinement and/or calibration of the parameters was not completed during the modelling process. The interaction of shallow groundwater and these rivers is expected to be complex, and governed by finer-scale hydrogeologic conditions than are represented in the regional-scale model.

Mission Creek was assigned a constant head boundary condition along its full length. This choice of boundary condition aimed to replicate presence of the surface water feature in the incised creek valley (i.e., a specified line source and sink of water along the thawleg of the Mission Creek valley). Specified hydraulic heads were defined for each cell representing the creek, and assigned a specified head equal to 1 m below ground level. The groundwater model effectively generates the baseflow component of the streamflow. This boundary condition can be expected to dominate the groundwater flow model, as it essentially serves to control the water table throughout the domain.

Table 3.3: Summary of boundary conditions for lakes and creeks in the regional-scale groundwater flow model.

Surface Water Boundary		Boundary Condition	Value(s)
Lakes	Okanagan Lake	Constant Head	342 m asl
	Wood Lake		391 m asl
	Ellison Lake		425 m asl
Mission Creek	Upper	Constant Head	1 m bgs
	Lower		1 m bgs
Valley-bottom Creeks (< 600 m asl)	Kelowna Creek	River	Stage = 1 m bgs
	Scotty Creek		Riverbed Bottom = 3 m bgs
	Vernon Creek		Conductance = K_z of hydrostrat unit
	Bellevue Creek		Width = 3 m
Upland Creeks (> 600 m asl)	Kelowna Creek	Drain	Elevation = 1 m bgs Conductance = K_z of hydrostrat unit
	Scotty Creek		
	Vernon Creek		
	Bellevue Creek		
	KLO Creek		
	Hydraulic Creek		
	Belgo Creek		
	Joe Rich Creek		

m bgs = metres below ground surface

With the exception of Mission Creek, the creeks located above valley-bottom, where the creek valley would typically be incised into bedrock, were represented by drain boundary conditions that were specified at 1 m below ground level. Drain boundaries have been shown to adequately represent upland creeks in mountainous catchments (Johnson et al., 2007; Smerdon et al., 2009), where groundwater discharge subsequently flows quickly through a stream network (i.e., as baseflow). Drain conductance was calculated internally within Visual

MODFLOW, based on the vertical hydraulic conductivity (K_z) of the hydrogeologic unit in which the drain was specified. The use of drain boundaries allows groundwater to discharge from the subsurface, but does not replicate surface water flow.

3.3.2. DIRECT RECHARGE

Estimates of groundwater recharge are meant to quantify the amount of water from the atmosphere that migrates to the groundwater regime. The recharge process results from a complex transfer of energy and moisture at the land surface; and relates climate, vegetation, characteristics of the soil, and depth to the water table. Quantifying groundwater recharge in the Okanagan Basin is a topic on on-going research at Simon Fraser University (directed by Dr. Diana Allen), and was a focus of the recent Canadian Water Network (CWN) research project entitled "A Basin Approach to Groundwater Recharge in the Okanagan: Bridging the Gap Between Science and Policy." As part of the CWN project, direct recharge to the entire valley-bottom area of the Okanagan Basin was modelled with the HELP code (Hydrologic Evaluation of Landfill Performance; Schroeder et al. 1994) by Liggett (2008). Also as part of the CWN project, direct recharge to the entire BX Creek Watershed was estimated by Smerdon et al. (2009) using a combination of MIKE-SHE for the valley bottom and a water balance approach for the upland areas. Analysis of the findings of these studies showed that the HELP code over predicts recharge rates when compared to more rigorous Richard's equation-based modeling techniques such as MIKE-SHE (Smerdon et al., 2009). Thus, there is uncertainty in the valley bottom estimates the derived strictly from the model used. This uncertainty is primarily related to the estimate of Actual Evapotranspiration (AET), which appears to be under-estimated in HELP; however, there are few measured values to confirm this conclusion.

Direct recharge to the valley bottom is considered to be a very small component of the overall water budget in these semi-arid to arid valley bottom areas, but can represent an important fraction of the recharge to the valley bottom aquifers. As discussed later, irrigation return flow can significantly augment recharge in these areas, but estimates of the percentage of water that returns to the aquifer relative to the applied irrigation amount are difficult to obtain and are largely a function of crop type. For this reason, irrigation return flow was not considered in this study.

Based on the results for BX Creek (as well as results from other arid valley bottom areas) the overall conribution of direct (diffuse) recharge to the valley bottom aquifers is relatively minor (~22% of the total) in comparison to other water sources. Specifially, it was also found that the majority of replenishment to the valley-bottom aquifers in the Vernon area occurred laterally from groundwater flowing through the bedrock mountain block adjacent to the valley-bottom. Thus, for the regional-scale groundwater flow model of the Kelowna area, the direct recharge estimates were based on results from these prior CWN projects. No additional recharge modeling was undertaken. For the valley bottom area, the distribution (i.e., spatial pattern) of direct recharge was assumed to follow the pattern determined by Liggett (2008). Spatial variations in direct recharge are the result of variation in the soil texture and land cover across the valley-bottom.

For the upland area of the flow model, the pattern of spatial distribution for direct recharge was assumed to follow elevation bands, as described by Smerdon et al. (2009). The average annual precipitation for Kelowna (381 mm) is about 78% of the average annual precipitation in Vernon (484 mm). Similarly, the approximate snow water equivalent (SWE) for Mission Creek headwaters is about 74% of SWE at Silverstar Mountain (541 mm and 730 mm, respectively). Considering that the valley-bottom and upland annual precipitation is lower in Kelowna than it is in the Vernon area, it was assumed that the groundwater recharge rates in the Kelowna area would also be approximately 78% and 74% of those determined for the Vernon area, depending on elevation. Therefore, the resulting map of groundwater recharge used in the regional-scale flow model (Figure 3.6) is a combination of the spatial patterns by Liggett (2008) for the valley-bottom and Smerdon et al. (2009) for the uplands. The recharge rates were scaled from the values of Smerdon et al. (2009) based on average annual precipitation (78% for the lowlands, 74% for the uplands).

The scaled recharge rates shown on Figure 3.6 were also compared with the approximate annual recharge calculated using the annual water table rise recorded at BC MoE Observation Well 115 (located in the Mission Creek watershed, shown on Figure 3.8). Assuming a specific yield of 0.01 (i.e., 1%), the mean annual recharge rate based on the water level rise varies from 34 to 77 mm per year (Figure 3.7). Although there is uncertainty in the assumption of a specific yield value, the corroboration of recharge rates shown on Figure 3.6 and Figure 3.8 indicates that distributed recharge in the groundwater flow model is reasonable for a "Base Case" scenario. The sensitivity of the flow model to different combinations of recharge and bedrock K will be discussed later.

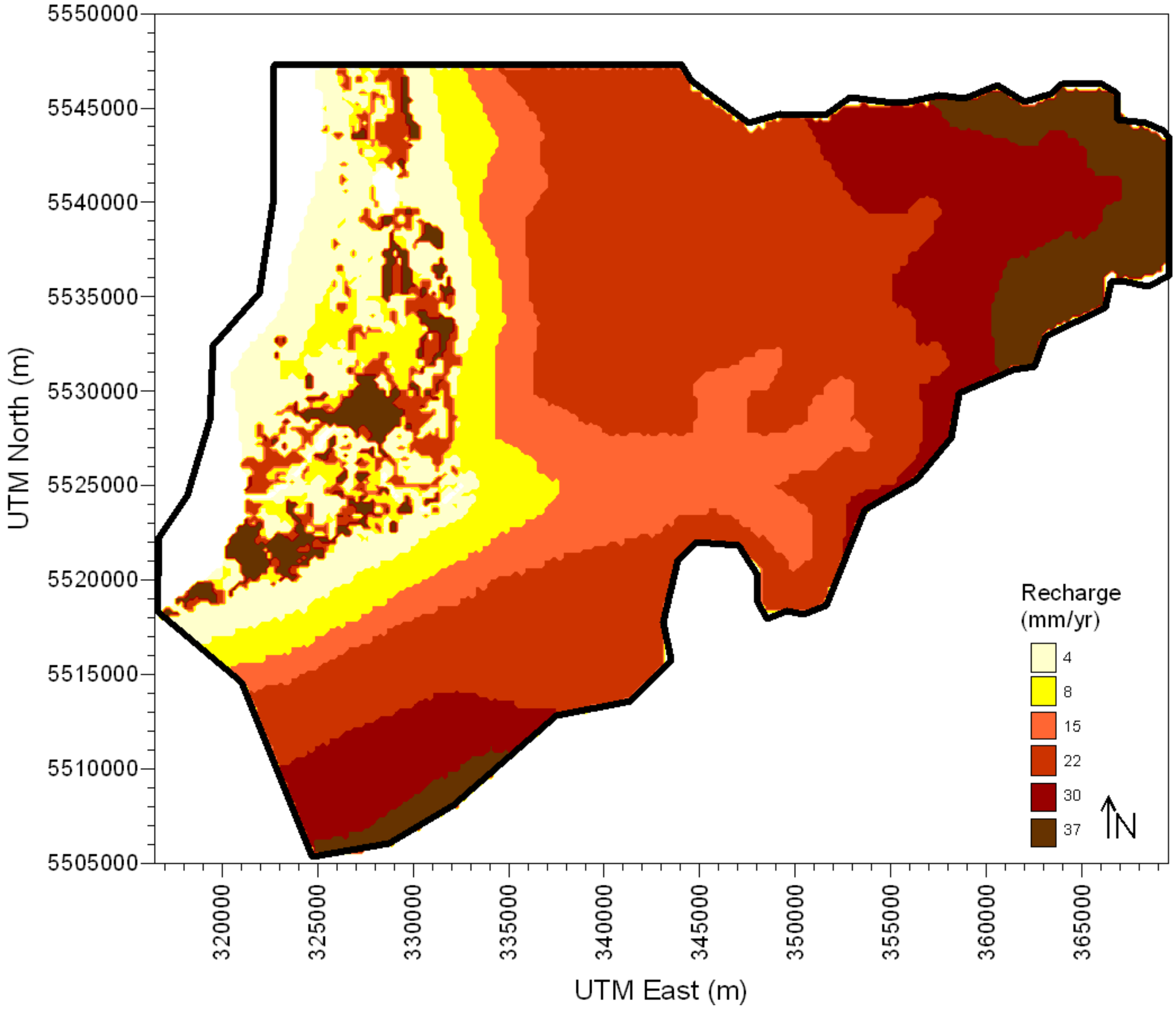

Figure 3.6: Distribution of mean annual groundwater recharge, which was determined from a combination of spatial results from Liggett (2008) and rates scaled from Smerdon et al. (2009).

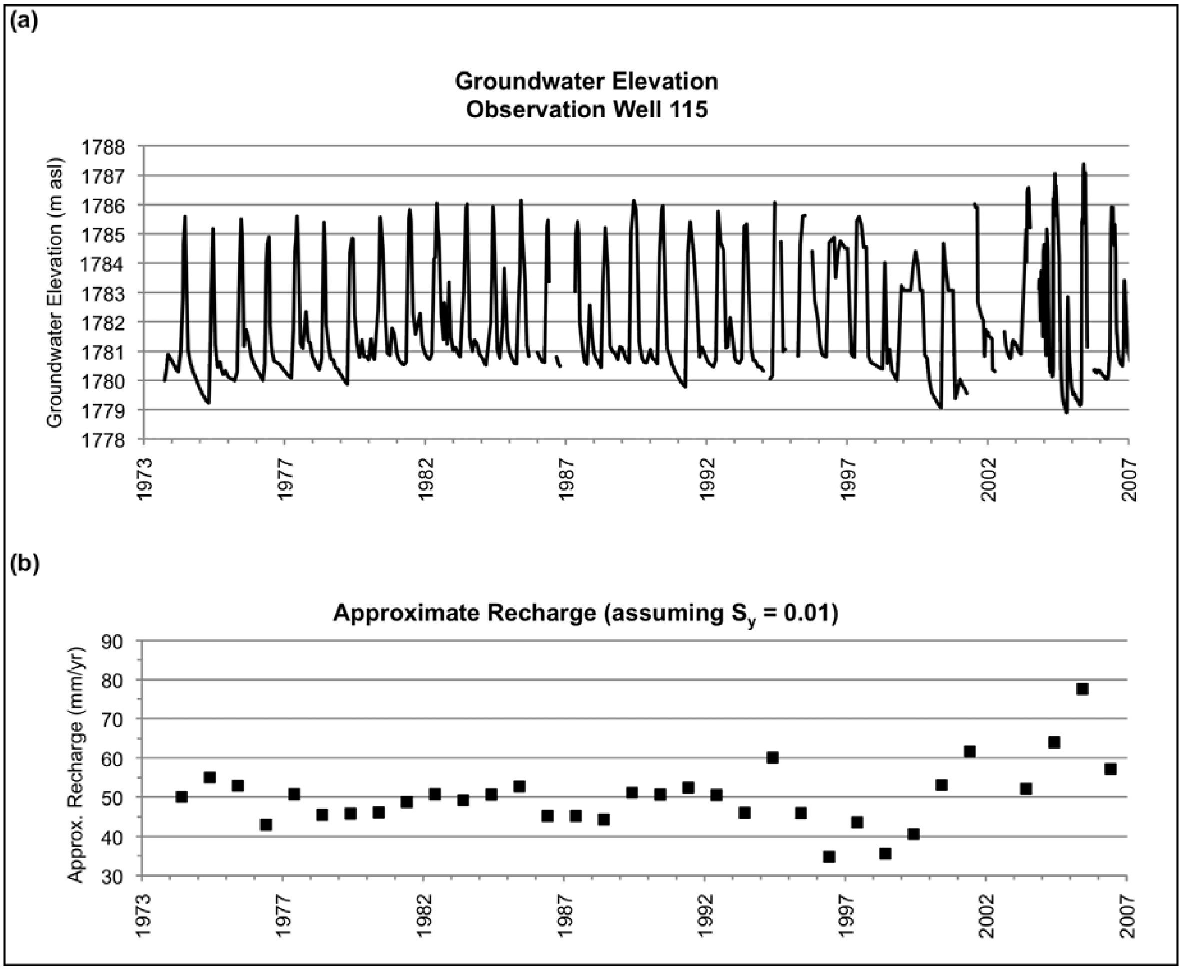

Figure 3.7: (a) Hydrograph of groundwater elevation for BC Observation Well No. 115, located in the upland bedrock area of the Mission Creek watershed (location shown on Figure 3.8). (b) Approximate annual groundwater recharge rate, determined from observed water level rise and assumed specific yield value of 0.01.

3.3.3. PUMPING WELLS AND PARTICLE TRACKING

Major groundwater users in the Kelowna area were identified in the Okanagan Water Management and Use report by Dobson (2008) as part of Phase 2 of the Okanagan Water Supply and Demand Project. The report by Dobson (2008) summarizes surface and groundwater use for 81 specific points of interest (calculation nodes) along the Okanagan Basin. Private groundwater wells were not included in the study, but are assumed to extract a negligible amount of groundwater at the regional scale. For the calculation nodes in the vicinity of Kelowna (nodes 13, 20, 22, 23), annual water use was summarized for each major groundwater user (Table 3.3). Where there was more than one well, the average use per well was calculated by assuming an equal pumping rate for all wells.

A portion of this water is used for irrigation during the growing season. The amount depends on purveyor, but on average is approximately 18% of the total reported use for all wells combined. If it is assumed that roughly 25% of this irrigation water recharges the aquifer, this amounts to 1030 m^3/day – likely a small component of the overall water balance in this particular area. Irrigation return flow was not considered because is it likely a small component of the overall water balance and because information on irrigated areas was not readily available. Therefore, all the water pumped from the aquifers is considered a loss to the water balance. The implication of not including ~18% irrigation return flow is discussed later.

Groundwater extraction was simulated using the Well (WEL) Package in MODFLOW, using the pumping rates in Table 3.3. The location (Figure 3.6), and depth range of screens for each well were assumed to fall within Layer 1 of the regional-scale model. The wells were only activated once the model was calibrated to allow for a naturalized groundwater flow simulation and water balance calculation.

Although the regional-scale groundwater flow model was not designed to focus on finer-scale details of the Kelowna area, backward tracking particles were placed in a circle around the South East Irrigation District and Rutland Waterworks well fields to illustrate potential capture zones for these well fields. This area of the model was designed with a refined grid spacing (50 x 50 m) to more accurately simulate the capture zone for each well field. All hydrostratigraphic units (unconsolidated materials) were assumed to have an effective porosity of 0.15 and total porosity of 0.30. Particle tracking was simulated by the MODPATH package.

Table 3.4: Summary of major groundwater users in the Kelowna area. Data compiled by Dobson (2008) as part of the Okanagan Water Supply and Demand Project.

Water User	Water Use		Number of Wells	Pumping Rate per Well (m^3/d)
	ML/yr	m^3/d		
Black Mountain Irrigation District (BMID)	776	2126	3	709
Glenmore Ellison Irrigation District (GEID)	2669	7312	5(4)*	1828
Greystoke Irrigation District (GID)	35	96	1	96
Rutland Waterworks (RWD)	3294	9025	4	2256
Sunset Ranch Water Utility (SRWU)	268	734	1	734
South East Kelowna Irrigation District (SEKID)	336	921	3	307
Others*	871	2386	4	597

* extracted from 4 wells in the regional-scale model
** 5 wells, 2 combined

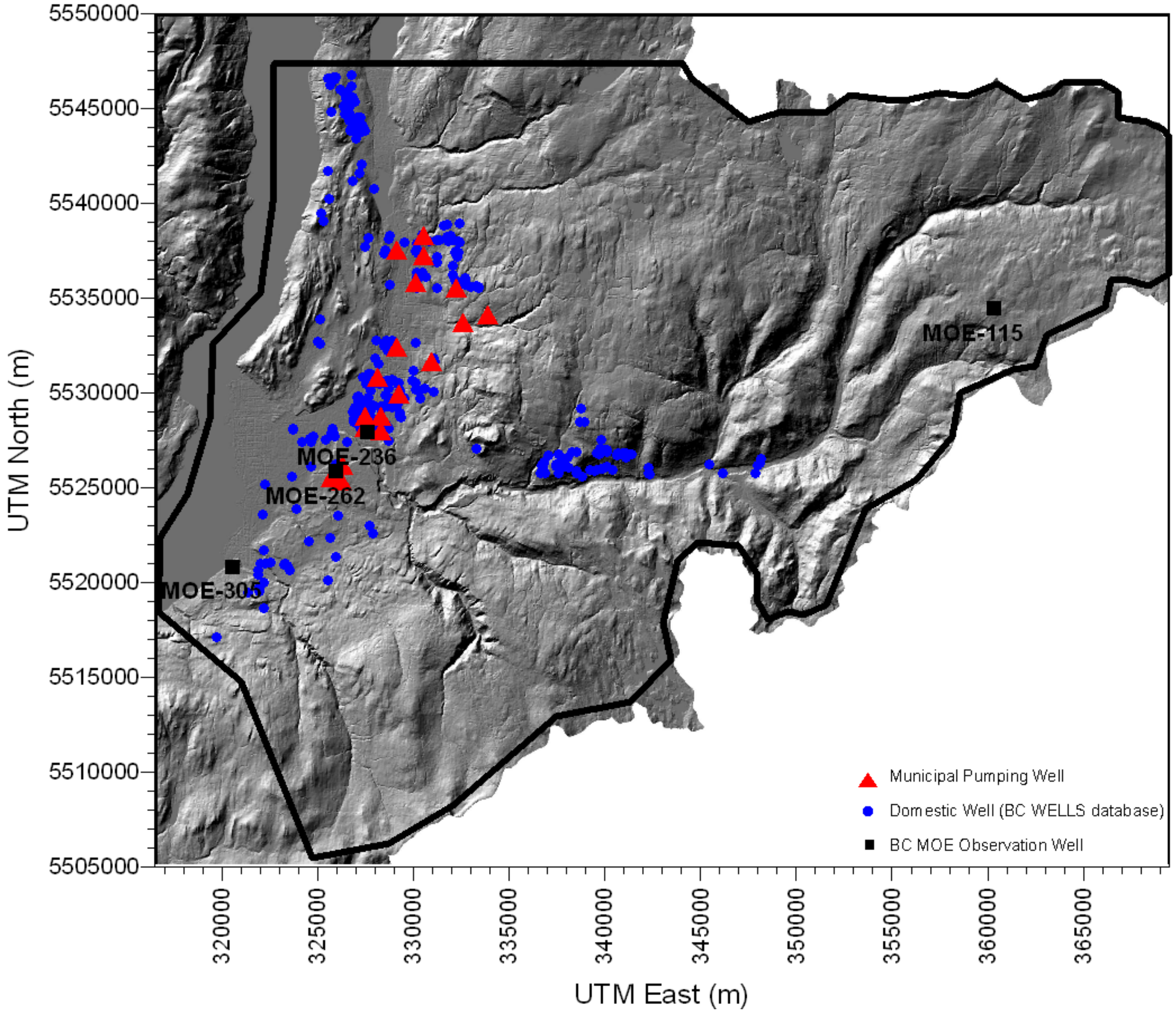

Figure 3.8: Major groundwater production wells and domestic wells reported in the BC WELLS database. Pumping rates for municipal wells correspond to those in Table 3.3. The pumping rates for domestic wells were considered negligible in the model.

3.4. CALIBRATION AND SENSITIVITY ANALYSIS

Generally, the modeling procedure would proceed through development of a conceptual model (the assumptions and details decribed to this point of the report), then undergo calibration through trial-and-error adjustment of model parameters to better fit observed data (e.g., hydraulic heads and baseflow to Mission Creek). Results from steady state flow models are typically considered non-unique, and equivalent results could be replicated with different recharge and K values (Jyrkama and Sykes, 2007; Sanford, 2002).

In this project, simulated steady-state hydraulic heads were evaluated by comparing results with water level data for water wells from the BC WELLS Database (BC MoE, 2006). Simulated baseflow to Mission Creek was compared with naturalized low-flow estimates reported by Summit and Polar Geoscience (2009) and the low-flow study by Obedkoff (1990). Comparison to both hydraulic heads and a flux value helped overcome the problem of non-unique model results in the this study.

The least well known components of the groundwater flow system for the Mission Creek Watershed are the bedrock hydraulic conductivity and rate of groundwater recharge. However, the distribution and rates of groundwater recharge used in this regional-scale model are somewhat unique, in that they have been derived for the Okanagan Basin, and are not a result of a calibration process. To investigate the sensitivity of the least well known input parameters (i.e., bedrock K and upland recharge), a sensitivity analysis was completed. The bedrock K and recharge rates were increased and decreased by a factor of 5. A factor of 5 for bedrock K spans a reasonable range of K values for bedrock units, based on the preliminary findings of Voeckler (in prep). Compared to the “Base Case” values presented on Table 3.2, the increase and decrease of K (and recharge) are referred to as “High K” and “Low K” scenarios.

3.5. WATER BUDGET

The intent of this modeling exercise was to evaluate the upland to valley-bottom contributions of groundwater flow (i.e., the regional-scale flow) and the overall water budget. Water budget components were quantified using the Zone Budget package in Visual MODFLOW (v4.3; Schlumberger Water Services, 2008) for targeted areas-of-interest for regional groundwater flow in the Okanagan Basin. Groundwater flow through shallow (model layers 1 and 2) and deep (model layers 3 to 6) bedrock, into the valley-bottom sediments was compared with flow through the alluvial sediments along the Mission Creek valley (Figure 3.9). Conceptually, these represent typical groundwater flow paths connecting the upland recharge areas to valley-bottom groundwater resources. Zone Budget was also used to approximate the baseflow to Mission Creek and the regional discharge to Okanagan Lake.

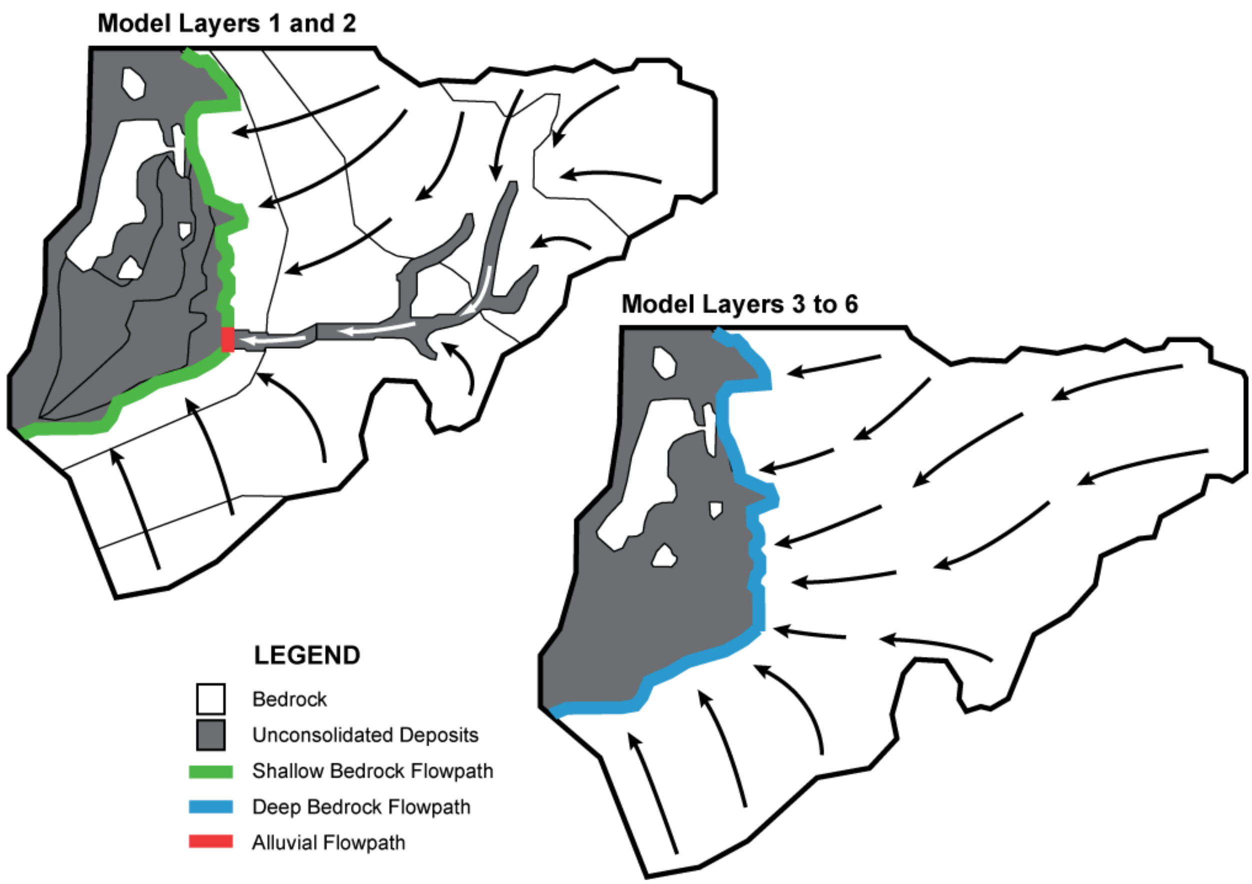

Figure 3.9: Zone Budget components to assess groundwater flux from uplands to the valley-bottom area of the model. Hydrogeologic units have been grouped into bedrock and unconsolidated deposits, and the approximate groundwater flow direction is indicated with arrows.

4. MODEL RESULTS

4.1. HYDRAULIC HEAD DISTRIBUTION

Simulated hydraulic heads generally appear to follow topography (Figure 4.1), and were compared to water level data for 366 water wells from the BC WELLS Database (BC MoE, 2006). The normalized root mean square error is 4.6% of the hydraulic head range for the watershed (Figure 4.2), which is relatively small and indicates that errors are likely a minimal component of the overall groundwater flow simulation (Anderson and Woessner, 1992). However, this error equates to a hydraulic head difference of 68.1 m, suggesting that although the simulated hydraulic heads might represent the watershed-scale flow system, they may not be suitable for addressing finer-scale analyses.

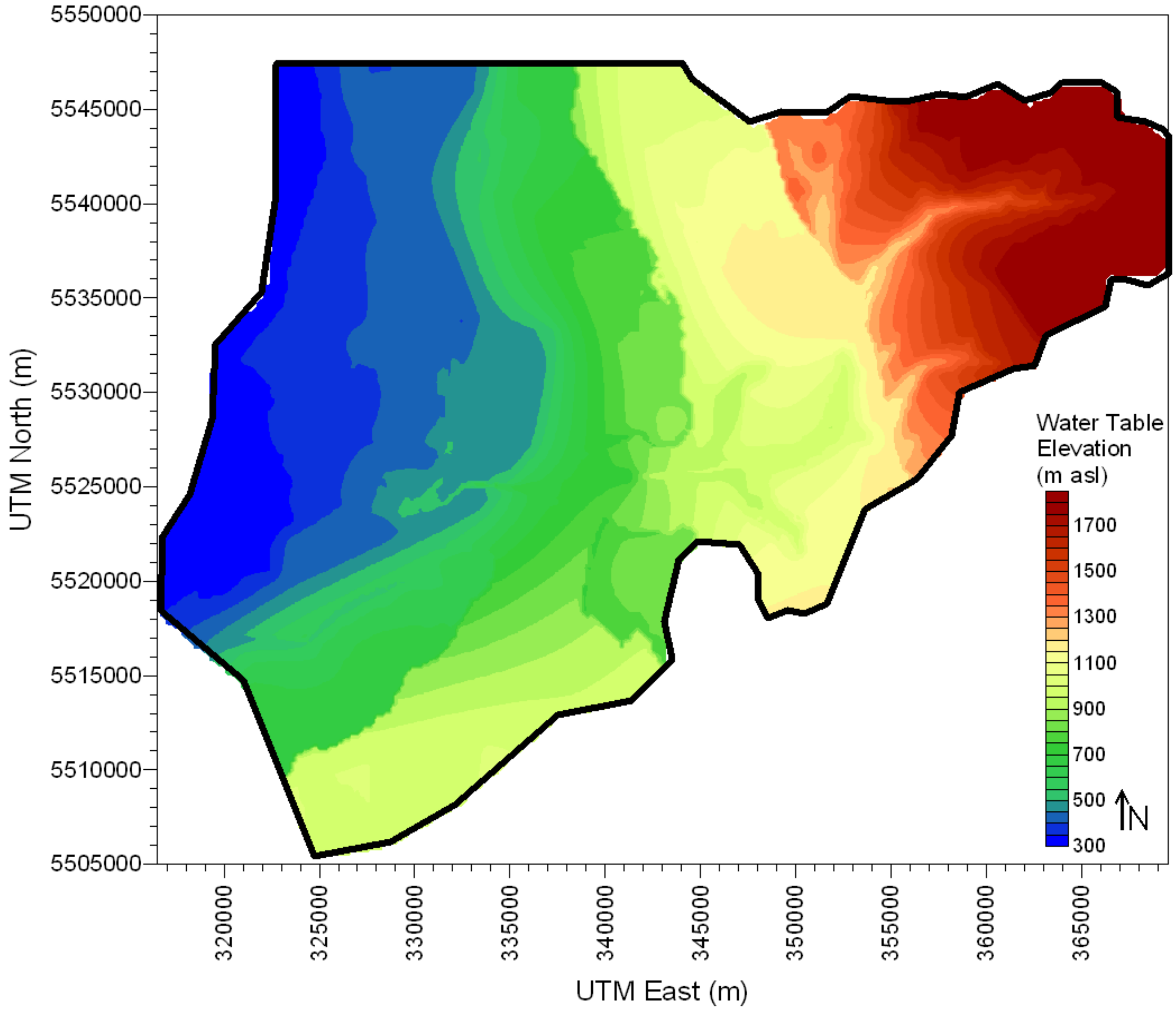

Figure 4.1: Shaded contours of simulated water table (50 m interval).

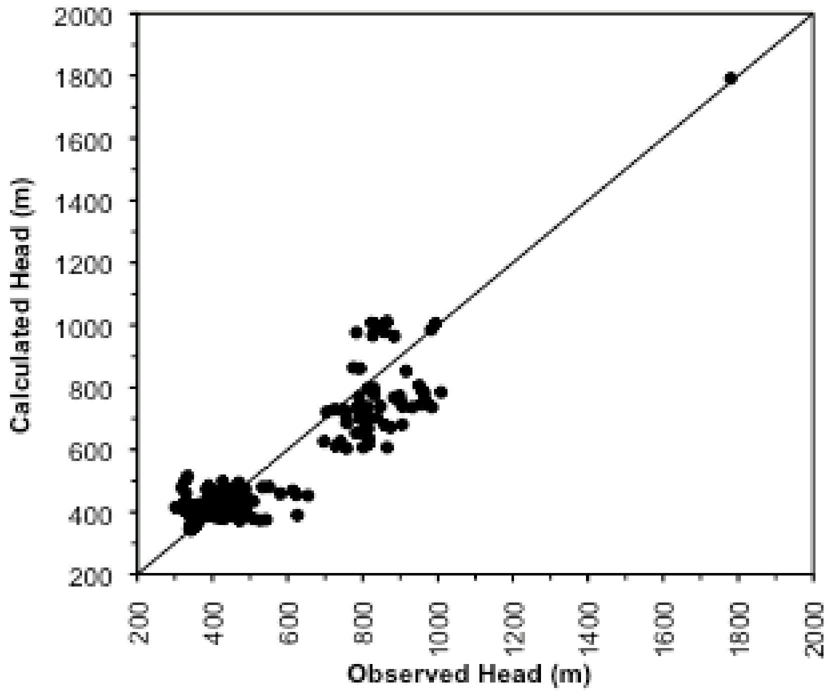

Figure 4.2: Simulated and observed hydraulic heads for the regional-scale groundwater flow model. The root-mean-square-error (RMSE) from 366 water wells from the BC WELLS database is 4.6%.

The distribution of hydraulic heads illustrates the role of Okanagan Lake and the Mission Creek valley in the regional-scale flow system. Okanagan Lake is a major groundwater discharge feature, and the presence of the Mission Creek valley functions as a conduit to direct upland groundwater to the aquifers in the Kelowna area. The regional-scale flow system can be further illustrated by cross-sections from the upland to valley-bottom and across the Mission Creek valley (Figures 4.3 and 4.4). The orientation of the cross sections is shown on Figure 3.1.

In the upland bedrock units, the 2:1 and 1:1 anisotropy establishes nearly vertical hydraulic head contours, indicating nearly horizontal groundwater flow at the regional-scale. Cross section A-A' generally follows the Mission Creek valley thawleg, and shows varying steepness of the horizontal hydraulic gradient in the upland area. The increase in horizontal hydraulic gradient between 40,000 and 45,000 m on the distance axis generally corresponds to the location of the Mission Creek valley. In contrast, cross section C-C', which extends through upland bedrock absent of a major creek valley, illustrates tendancy for uniform lateral groundwater flow. Cross section A-A' also illustrates the effect of high K aquifers of the Kelowna area, which cause more vertical flow to occur at the confluence of bedrock groundwater flow and flow through the

Mission Creek valley sediments (i.e., at the transition from bedrock to Okanagan Valley Fill deposits (shaded blue on the cross sections). It is expected that more detalied knowledge of the hydrostratigraphy of the Kelowna area (prepared by the GSC) will help elucidate groundwater flow patterns in the aquifers and aquitards of the Kelowna area.

The perpendicular cross section through the Kelowna area (B-B' on Figure 4.4) again illustrates the transition across the interface of bedrock and the sediments of the Kelowna area. The dominant groundwater flow direction on the right-side of cross section B-B' is perpendicular to the cross section, toward Okanagan Lake. The perpendicular cross section in the upland area, shows the influence of the Valley Fill Deposits along the Mission Creek valley. When these cross sections are combined with the plan-view distribution of hydraulic heads, it is clear that the contrast in hydraulic conductivity, compared to the bedrock, creates a large-scale preferential path for groundwater to move readily to the valley bottom, through the sediments of the Mission Creek valley.

The distribution of simulated hydraulic heads provides a broad-scale context for the groundwater resources of the Kelowna area. While the complexity of the hydrostratigraphy for the Kelowna area has been simplified in this regional-scale model (i.e., major mapped aquifers are represented by a single layer, and overlying confining units are not represented), the results illustrate the various flowpaths of groundwater that would replenish valley-bottom aquifers. The role of narrow alluvial aquifers (located in tributary valleys of the mainstem of Okanagan Lake) has also been shown to replenish shallow aquifers in the Vernon area by Smerdon et al. (2009).

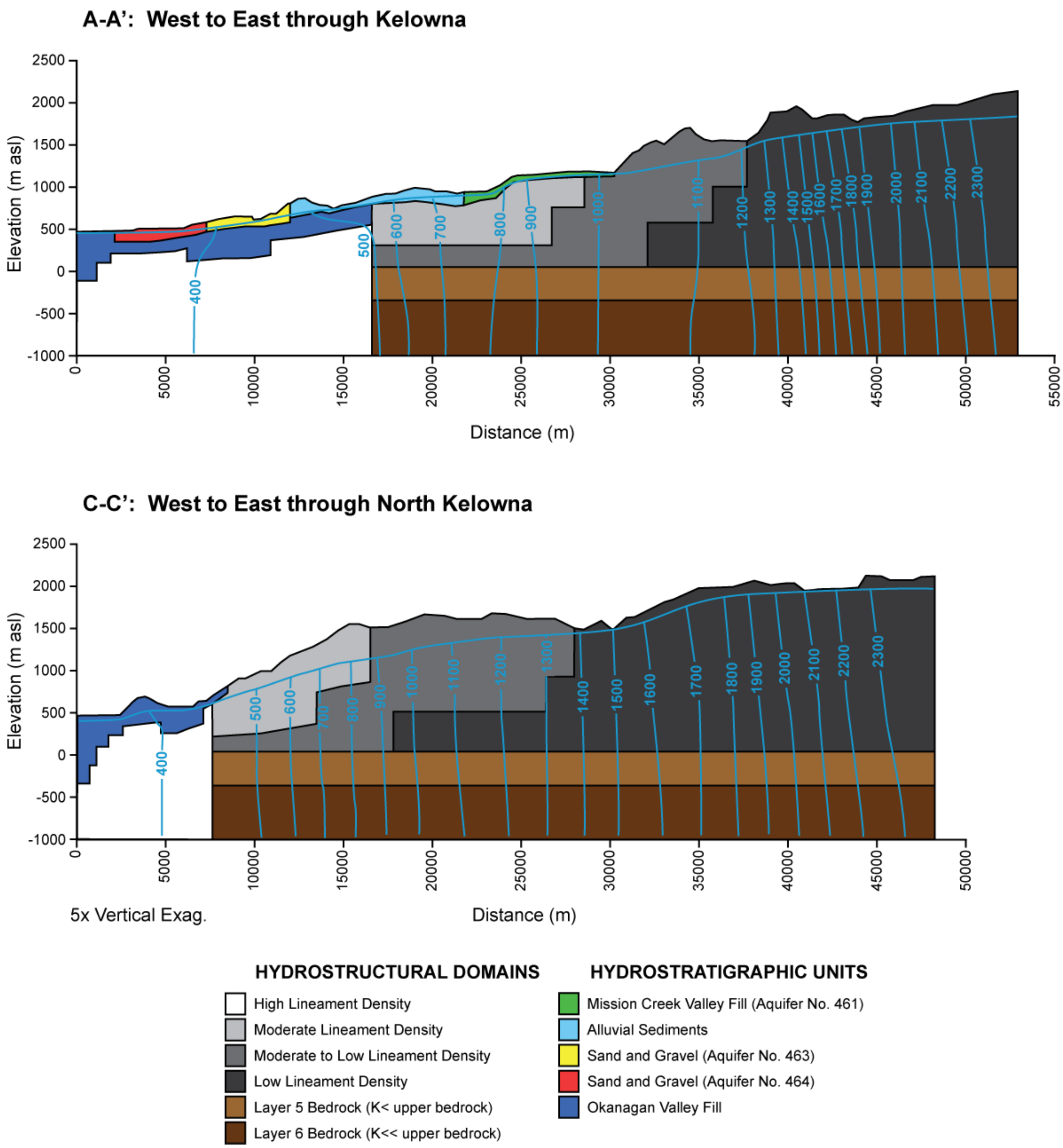

Figure 4.3: West to east cross sections of simulated hydraulic head (100 m contour interval) through the Kelowna area.

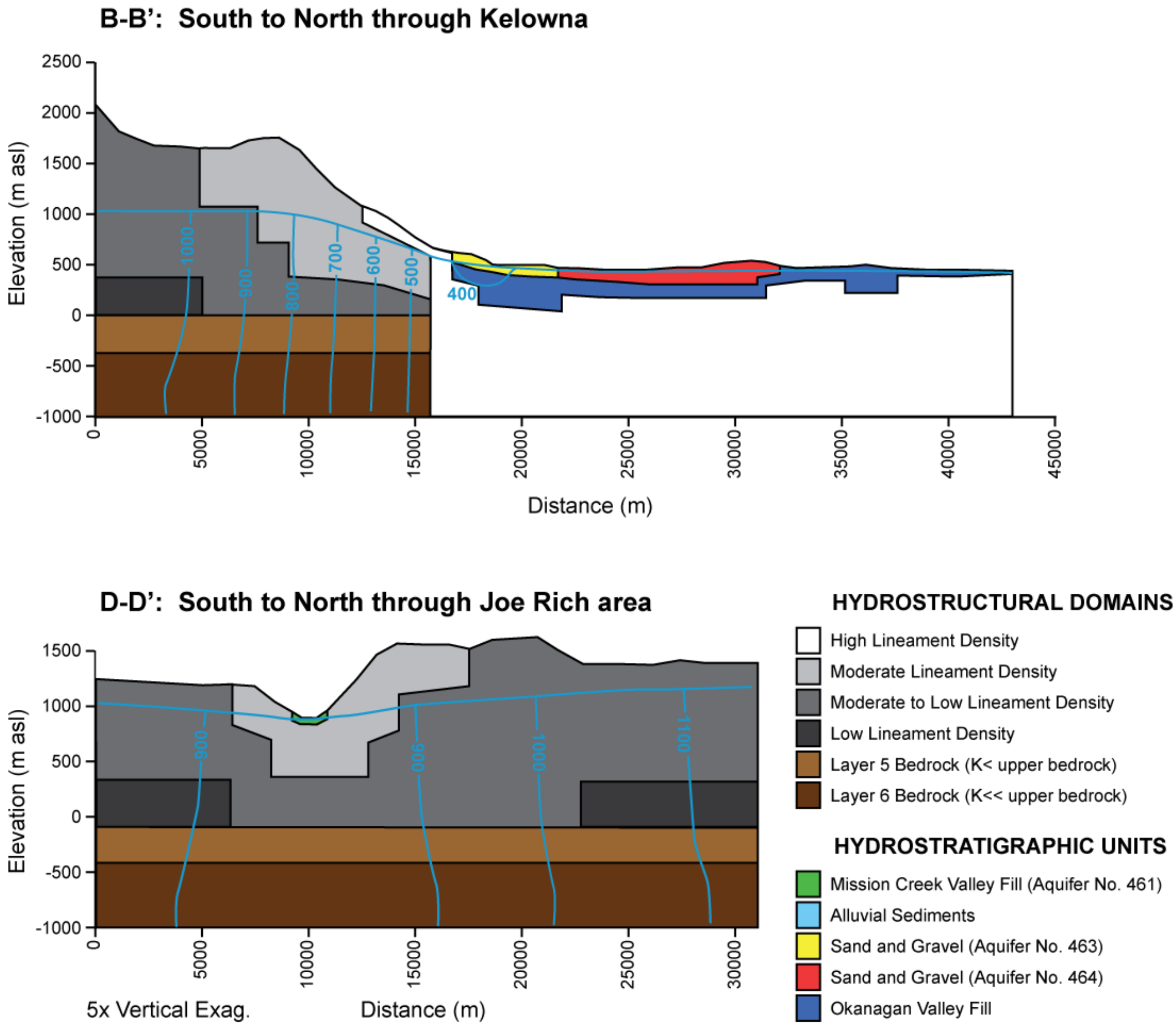

Figure 4.4: South to north cross sections of simulated hydraulic head (100 m contour interval).

4.1. SENSITIVITY ANALYSIS AND WATER BUDGET

Valley bottom aquifers in the Okanagan Basin are typically replenished from one or more of three mechanisms: (i) seepage from mountain streams and rivers; (ii) groundwater flow from the adjacent mountain block (mountain block recharge); and, (iii) direct (or diffuse) recharge to the valley bottom. A single mechanism may not characterize any given region, and the relative contribution of each method will depend on climatic and geologic conditions. The water budget determined from Zone Budget analysis seeks to quantify flow rates through different groundwater flow paths, considering different 3 combinations of bedrock K and recharge (i.e., Base Case, and Low/High K Scenarios). Bedrock K and recharge were augmented (or decreased) by a factor of 5 each, for the High K and Low K scenarios, respectively.

4.1.1. BASEFLOW TO MISSION CREEK

The recent report by Summit and Polar Geoscience (2009) contained estimates of the naturalized flows in Mission Creek, in addition to the observed low flow estimates reported by Obedkoff (1990). Establishing a record of naturalized flows is a challenging exercise, and there is some discrepancy between the findgings of Obedkoff (1990) and Summit and Polar Geoscience (2009). Naturalized low flows of Obedkoff (1990; 63,072 m^3/day) are approximately 50% of the lowest flows reported by Summit and Polar Geoscience (2009; 125,280 m^3/day). The estimates by Summit and Polar Geoscience are considerably higher than the flows posted on Environment Canada's website for Mission Creek.

In the groundwater flow model, baseflow was estimated from the mass balance of boundary conditions that represent the portion of Mission Creek located above the location of the stream gauge used to determine low flows by Obedkoff (1990) and Summit and Polar Geoscience (2009; Water Survey of Canada gauge 08NM116). The results are shown on Table 4.1. The Base Case simulation resulted in 21,063 m^3/day of baseflow, which is less than either reported value above. Thus, for this Base Case, which utilizes bedrock K values of Voeckler and Allen (2009), and recharge estimates based on Smerdon et al. (2009), baseflow to Mission Creek may be underestimated by as much as as factor of six compared to these other studies.

The High K and Low K scenarios resulted in baseflow estimates of 112,481 and 6,303 m^3/day, respectively. For the High K scenario, simulated baseflow conditions are similar to those reported by Summit and Polar Geoscience (2009), suggesting that the higher bedrock K and recharge values are perhaps more reasonable approximations. The Low K scenario has bedrock K values and recharge rates that seem lower than anticipated, but are provided to illustrate the sensitivity of the results to relatively small changes to bedrock K and recharge rates.

In both sensitivity analysis scenarios, the hydraulic head distribution is the same, suggesting that these are two possible (and reasonable) results for the groundwater flow model.

Table 4.1: Summary of Zone Budget components and global water balance for the groundwater flow model under non-pumping conditions.

Zone Budget Components (m^3/day)	Low K Scenario	Base Case	High K Scenario
Approx. baseflow to Mission Creek (above gauge 08NM116)	6303	21063	112481
Approx. discharge to Okanagan Lake	477640	502030	622090
Flux across shallow bedrock (model layers 1 and 2)	1520	3583	16772
Flux across deep bedrock (model layers 3 to 6)	12269	42405	204802
Flux through alluvial sediments	171	427	1815
Total flux across upland-to-valley bottom interface (Σ)	*13960*	*46415*	*223389*

Global Mass Balance (m^3/year)	Low K Scenario		Base Case		High K Scenario	
	Flow In	Flow Out	Flow In	Flow Out	Flow In	Flow Out
Recharge (dominantly upland)	8143266	0	25984320	0	123785000	0
Rivers (streams in valley)	26963050	8698685	26636410	9191773	25329440	12347130
Drains (streams at high elevation)	0	206	0	97	0	119
Wells	0	0	0	0	0	0
Constant Head (Mission Creek and Okanagan Lake)	1933279000	1959688000	1933736000	1977165000	1931972000	2068739000
Total (Σ)	1968385316	1968386891	1986356730	1986356870	2081086440	2081086249
Difference between total in flow and out flow	*-1575.00*		*-140.40*		*191.41*	

4.1.2. REGIONAL-SCALE WATER BUDGET

Use of the Zone Budget package with the flow model allowed both the volumetric fluxes for specific areas-of-interest and the global water balance to be quantified for steady-state conditions.

Volumetric groundwater flow was determined for three distinct flow paths, which are illustrated on Figure 3.9: (i) shallow groundwater flow in bedrock with high lineament density; (ii) deeper groundwater flow through bedrock below the upper aquifers of Kelowna; and, (iii) shallow groundwater flow through the unconsolidated alluvial sediments of the Misson Creek valley. Groundwater flow rates through these different pathways is governed by the hydraulic conductivity of bedrock units and rate of groundwater recharge. These parameters are not well defined for the upland regions of the Okanagan Valley, and are a topic of current research (Voeckler, in prep). Thus, there is a large degree of uncertainty for model input parameters (K and recharge), which will cause some uncertaintly in model results due to the fact that estimates can vary by orders of magnitude. Furthermore, as described above, there is also some discrepancy between different estimates of baseflow to Mission Creek. Additional constraints to both of these variables (bedrock K and baseflow) would significantly help constrain uncertainty in the results.

Flow rates through each of the flow paths shown on Figure 3.9 are presented on Table 4.1. For each scenario (Base Case, and Low/High K Scenarios), the majority (89-91%) of groundwater flow from the upland areas to the valley-bottom is through the deep bedrock in layers 3 to 6. Approximately 8-10% of the groundwater flow passes through the bedrock portions in the upper two layers of the model, which corresponds to approximately 200 m below the ground surface in the Kelowna area. The balance of flow (roughly 1-2%) derives from the alluvial fill beneath Mission Creek. The significantly higher amount of deep bedrock flow is likely because the K value for the Okanagan Valley Fill (blue unit in Figures 4.3 and 4.4), which abuts against the upland bedrock in layer 2, has a lower K value than the bedrock; therefore, flow from the upland areas is directed below this layer (i.e., below layer 2). Of course, if the K value for this unit were increased by an order of magnitude (not simulated), the water balance would change. Above this Okanagan Valley Fill layer is the unconsolidated aquifer sediments of layer 1. The K value for layer 1 is higher and could transmit water effectively, but this layer is quite thin and does not offer as good a groundwater outlet from the upland area. Thus, recharge to the shallow alluvial sediments around Kelowna is likely small compared to the deeper groundwater flow.

For comparison, Golder and Summit (2009) assumed that 85% of the groundwater recharge in upland areas flowed through a very shallow (< 50m) weathered bedrock unit, and that only 15% of the upland recharge infiltrated to the deeper groundwater layers. The results of this current modeling study would appear to contradict these results; however, there is a fundamental difference in the conceptual models between the two studies. In this study, the upper highly fractured (or weathered) bedrock was assumed to be thicker than 50m, and upwards of 500m for each bedrock zone. The thin veneer of sediment overlying the bedrock and the weathered bedrock itself were not incorporated into the model. Rather, it was assumed that this shallow interflow zone would direct water readily to the stream network and would not contribute to “groundwater” flow. The K value was also assigned a decreasing value with depth as might be expected due to fractures closing under increased pressure, but effectively, the upper 500m or so of the bedrock was considered permeable with reasonable K values assigned. For this reason, it is not appropriate to compare the results of this study to those of Golder (2009) in respect of the percentage of shallow and deep bedrock flow. These differences in conceptual model for the upland bedrock areas are highly uncertain and additional research is needed to be able to constrain the conceptual model for upland areas.

Direct (diffuse) recharge to the valley bottom aquifers is estimated at 6554 m^3/day or $2.3x10^6$ m^3/year. Although only 10% of the total recharge to the model, this small amount represents roughly 50% of the recharge to the valley bottom aquifers. So, this is a rather significant amount.

As noted above, less than 2% of the groundwater passing from the upland areas to the valley-bottom flows through the alluvial sediments of the Mission Creek valley. This low volume, relative to the percentage of flow through the bedrock (99%) is generally in agreement with the findings of Golder (2009; Draft report) in which they state that “the mean annual flow through these [Kelowna] aquifers is surprisingly small compared to other aquifers in the Basin.” However, upon review of the draft report, actual values could be readily identified.

The total amount of groundwater flow passing across the upland-to-lowland transition (Figure 3.9) is 46,415 m^3/day for the Base Case scenario, which is comparable to the range of baseflow supplied to Mission Creek. Thus, mountain front recharge, encompassing flow through the bedrock (mountain block recharge) and flow beneath Mission Creek in the alluvial sediments is slighly higher than the amount of water discharging as baseflow along Mission Creek.

A global mass balance report, for flow into and out of major boundary conditions in the model, has also been included on Table 4.1. Total annual recharge increases significantly as applied recharge and bedrock K increases as it is the combination of these two factors that allow water to enter the model. The river boundary condition, which were assigned to the small valley bottom creeks) function largely as sources for groundwater; there is more flow in than out, by 35% for the base case, but ranging from 32% to 48% for the low and high K scenarios, respectively. Negligible groundwater is lost or gained by the upland streams that were assigned as drain boundary conditions. However, as noted above, there is likely very shallow groundwater flow not captured by this model that would interact with these streams.

Finally, there is a significant amount of flow in and out of the constant head boundary condition nodes. These nodes correspond to Mission Creek. Upon close inspection of the zone budget results, almost all of this water flow occurs between Lower Mission Creek and the sand and gravel sediments in Aquifers 463 and 464. This is because there is immediate connection between the aquifer and stream as the conductance values are the same as the aquifer materials. In fact, the river boundary conditions used for the other streams also have conductance values that are the same as the aquifer materials, so in fact, the river boundary condition used is, defacto, a constant head boundary condition. What this means is that there is very strong interaction between Mission Creek (lower reach) and the aquifer, and that on average roughly 10^7 m^3/year of water is lost from the aquifer to the stream (more out than in, Table 4.1). In fact, this water budget item dominates the entire water balance and is likely due to the high permeability of the sediments and the winding route of lower Mission Creek over these sediments. Clearly, these results are suspect and require additional information on the nature of the stream sediments to further constrain the conductance values. A lower conductance value would limit the interaction considerable and lower the overall budget component. However, even with a reduced flow back and forth, it is likely that there is some loss of groundwater to this stream in the lower valley area. Finally, the difference between total inflow and outflow is negligible, indicating nearly a zero mass balance error.

4.1. WELL PUMPING AND CAPTURE ZONES

The Base Case model was re-run with the pumping wells activated to assess changes to the overall water budget components and to undertake a capture zone analysis. The wells represent a loss of groundwater. As noted earlier, roughly 18% of the total amount of groundwater extracted is used for irrigation, and of that amount, roughly 25% may recharge the valley bottom aquifers by irrigation return flow (this amount is uncertain). However, this amounts to only 1030 m^3/day (3.76×10^5 m^3/year) – a small fraction of the overall water balance.

Table 4.2 summarizes the results of the water balance for the Base Case model with pumping. Comparision of the water budget components with Table 4.1 suggests that the effect of pumping on the overall water budget is minimal.

Although the regional-scale groundwater flow model was not designed to focus on finer-scale details of the Kelowna area, backward tracking particles were placed in a circle around the South East Irrigation District (SEKID) and Rutland Waterworks (RWD) well fields to illustrate potential capture zones. These capture zones are an alternative to the calculated fixed radius (CFR) capture zones often used for delineating capture zones for well head protection plans (Foley et al., 2005). The position and path of backward tracking particles were plotted for a timeframe of 1 year (assuming an effictive porosity of 0.15 and total porosity of 0.30). Therefore, these particle tracks can be considered the approximate path groundwater would travel for 1 year prior to being captured by the SEKID and RWD well fields.

The particle tracks illustrate that groundwater in these well fields likely originates from the location where Mission Creek crosses the Moraine Ridge and Outwash Terrace (Figure 2.4) at the upper portion of the surficial deposits near Kelowna (Figure 4.5). Although these deposits were not explicitly considered in the regional-scale flow model, the source of groundwater for these well field appears to be linked to groundwater flow from the alluvial sediments of the Mission Creek valley and the interaction with Mission Creek.

Table 4.2: Summary of Zone Budget components and global water balance for the groundwater flow model under pumping conditions.

Zone Budget Components (m^3/day)	Base Case (Pumping)
Approx. baseflow to Mission Creek (above gauge 08NM116)	21044
Approx. discharge to Okanagan Lake	501930
Flux across shallow bedrock (model layers 1 and 2)	3584
Flux across deep bedrock (model layers 3 to 6)	44252
Flux through alluvial sediments	426
Total flux across upland-to-valley bottom interface (Σ)	*48262*

Global Mass Balance (m^3/year)	Base Case (Pumping)	
	Flow In	Flow Out
Recharge (dominantly upland)	25984320	0
Rivers (streams in valley)	26960840	8605254
Drains (streams at high elevation)	0	97
Wells	0	6962010
Constant Head (Mission Creek and Okanagan Lake)	1936100000	1973478000
Total (Σ)	1963060840	1989045361
Difference between total in flow and out flow	*-240.80*	

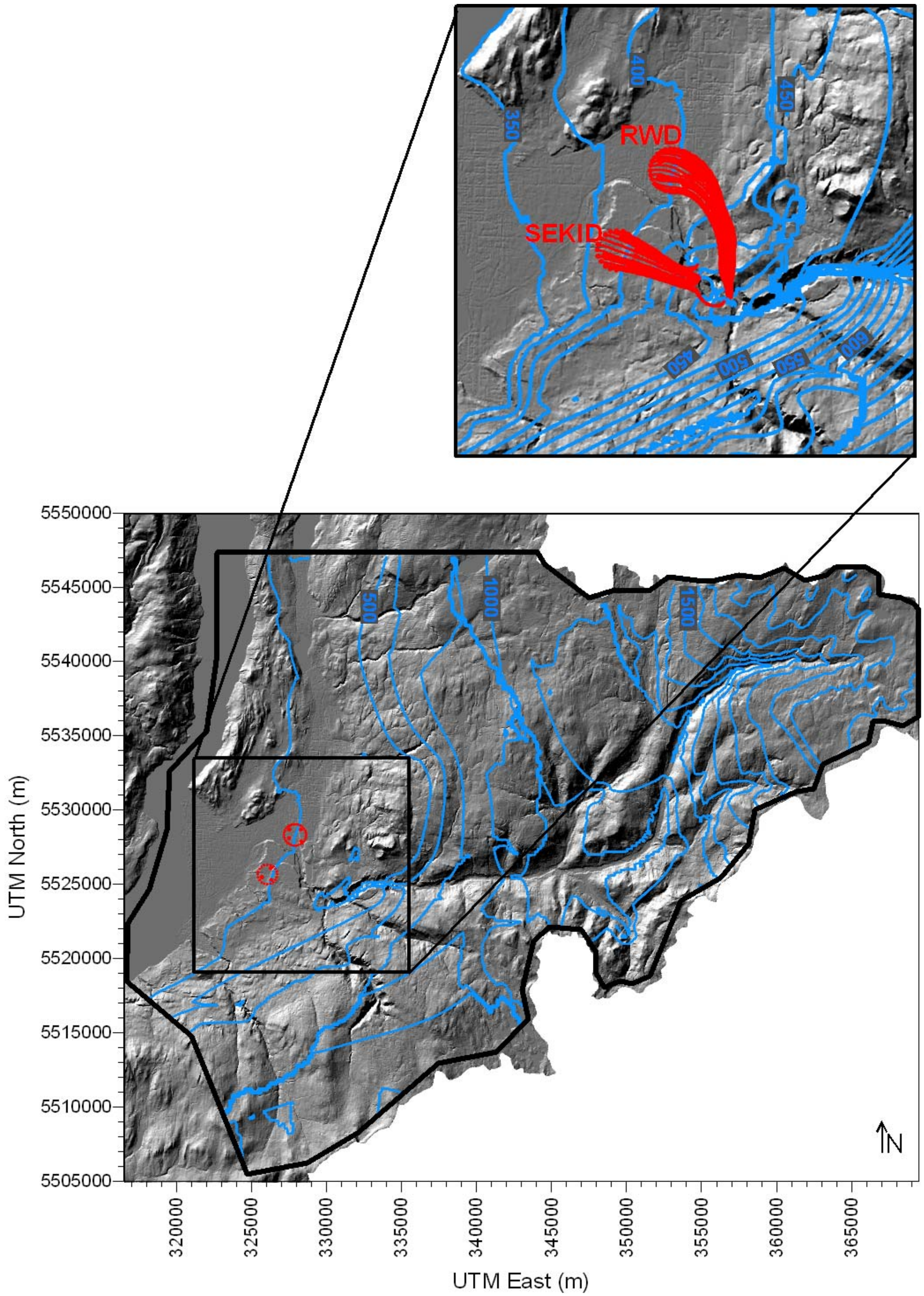

Figure 4.5: Potential capture zones for the South East Irrigation District (SEKID) and Rutland Waterworks (RWD) well fields. Simulated water table contour interval is 100 m on the watershed-scale map and 25 m on the inset map.

5. CONCLUSIONS

The Kelowna area and Mission Creek Watershed is located in the central portion of the Okanagan Basin, and spans an elevation range from 340 m above sea level (m asl) near Okanagan Lake to 2000 m asl in the headwaters of Mission Creek. The Mission Creek Watershed is the largest sub-basin within Okanagan Basin, and is comprised of complex hydrostratigraphy in the valley-bottom area, as well as bedrock with varying lineament (fracture) density. The assemblage of these geologic features, and climatic conditions, governs regional-scale groundwater flow in the central Okanagan.

The Okanagan Valley bottom is filled with a thick, complex arrangement of sediments from glacial and fluvial processes to form aquifers and aquitards of the Kelowna area. These sediments are up to 250 m thick beneath the City of Kelowna, and many hundreds of metres thick beneath Okanagan Lake. Okanagan Valley Fault has influenced the hydrostructural domains in this central Okanagan area. Bedrock formations are different on either side of the fault, and from a groundwater flow perspective, can be grouped together based on the approximate lineament density (which is assumed to correspond with K).

A regional-scale groundwater flow model was constructed for the Kelowna area and Mission Creek Watershed in MODFLOW, to assess the interconnection and related water balance between broad-scale hydrogeologic units, including upland bedrock and major aquifers of the Kelowna area. The model spans the entire Mission Creek Watershed (53 x 45 km), and steady-state simulated hydaulic heads compare well with observed water level data. The distribution of simulated hydraulic heads illustrates the role of Okanagan Lake as a major groundwater discharge feature, and the Mission Creek valley as a conduit to direct upland groundwater to the valley-bottom aquifers, in the regional-scale flow system. Generally, the water table follows the topography of the watershed, and flow in the bedrock is nearly horizontal.

Based on a sensitivity analysis, simulated baseflow to Mission Creek can be nearly replicated by the Base Case and High K scenarios. These two scenarios span a range of reasonable recharge and K values, as well as two different estimates for baseflow to Mission Creek, and illustrates the sensitivity of model results to the possible variation in input data that is generally unknown (i.e., upland recharge and bedrock K).

For the steady-state groundwater flow model, water budget components were calculated for upland to valley-bottom flowpaths (including: shallow groundwater flow in bedrock with high lineament density; deeper groundwater flow through bedrock below the aquifers of Kelowna; and, shallow groundwater flow through the unconsolidated alluvial sediments of the Misson Creek valley). The majority of groundwater flow (89-91%) from the upland areas to the valley-bottom passes below the mapped aquifers of the Kelowna area, and approximately 8-10% of the groundwater flow passes through the bedrock portions in the upper two layers of the model (i.e., bedrock with moderate to high lineament density). The remaining portion of groundwater flow (less than 2%) passes from the upland areas to the valley-bottom flows through the alluvial sediments of the Mission Creek valley. Although the flow rates were different for each scenario (i.e., Base Case, Low/High K Scenarios), the relative proportions remained similar. Thus, the findings of this modelling study could be used to define boundary conditions for more focussed analyses of the aquifers in the Kelowna area (i.e., a smaller-scale model), and compare with alternative water budget analyses.

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