

CULTUS LAKE WATERSHED NUMERICAL GROUNDWATER FLOW MODEL

Prepared for:

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EXECUTIVE SUMMARY

The Department of Fisheries and Oceans Canada (DFO) commissioned the preparation of a numerical groundwater flow model for the Cultus Lake watershed as part of a broader project to evaluate nutrient loading to Cultus Lake. The objective of the groundwater flow modeling was to evaluate the groundwater balance in to and out of Cultus Lake and to provide a calibrated model on which to base future solute transport modeling.

The development of the three-dimensional steady-state numerical groundwater flow model included preparation of a conceptual model, model design and methodology, model calibration and sensitivity analysis.

The calibrated model accurately simulates the regional groundwater flow regime based on the conceptual model; local groundwater flow systems were not incorporated in the model. The overall water balance for the model is $305,590 \text{ m}^3/\text{d}$ inflow and $305,850 \text{ m}^3/\text{d}$ outflow with a percent discrepancy of -0.08%. The groundwater balance flowing into and out of Cultus Lake is estimated at 210,640 m³/d.

The model was calibrated to static water levels from wells in the study area with a normalized root mean square (NRMS) of 9.5% between calculated and observed hydraulic heads. The sensitivity analysis indicated that the model is highly sensitive to hydraulic conductivity input values. Refined ranges of input values may allow for improved calibration of the model in the future.

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1.0 INTRODUCTION

The Department of Fisheries and Oceans Canada (DFO) commissioned the preparation of a numerical groundwater flow model for the Cultus Lake watershed as part of a broader project to evaluate nutrient loading to Cultus Lake. The aim of the groundwater flow model is to characterise the water balance of groundwater flowing in to and out of Cultus Lake. The flow model will form the basis for future solute transport modeling that will evaluate the transport of nutrients into Cultus Lake. The following report presents the three-dimensional numerical groundwater flow model design, methodology, and calibration.

1.1 STUDY AREA DESCRIPTION

Cultus Lake is located approximately 10 kilometres (km) south of Chilliwack, British Columbia. It is located in a valley bound by Vedder Mountain to the west and the International Ridge to the east. The valley south of Cultus Lake is called the Columbia Valley which extends into the United States. The international border between Canada and the United States is located approximately 6 km to the south of Cultus Lake. The valley north of Cultus Lake extends in a northeast direction towards the Chilliwack River, which lies approximately 3 km to the north. **Figure 1** illustrates the study area location and principal features.



Figure 1 Study Area Location and Features

The topography of the valley bottom north of Cultus Lake slopes gently towards the Chilliwack River at a gradient of 0.005. In the Columbia Valley south of Cultus Lake, the topography is largely dominated by a raised terrace, which slopes towards the lake at a gradient of 0.05. The steep terrace face is located approximately 500 metres (m) from the lake shore.

The Cultus Lake watershed is defined along the high topography of the adjacent mountains and is bound by the Chilliwack River to the north and a groundwater flow divide to the south¹. The study area is based on the outline of the watershed; however for modeling purposes, the study area only includes the valley and not the adjacent mountains (see Section 2.3 and 3.1 for further discussion of the study area). Cultus Lake is situated relatively centrally in the study area with a northern and southern valley component on either side. The Columbia Valley comprises the southern portion of the study area.

1.2 OBJECTIVE

The objective of the groundwater flow modeling is to evaluate the groundwater balance in to and out of Cultus Lake and to provide a calibrated model on which to base future solute transport modeling. The model was designed to represent the groundwater flow regime on a scale relative to the entire study area and, therefore, discrete local flow systems were not incorporated.

1.3 SCOPE OF WORK

The following tasks were completed in developing the model:

- Develop a steady-state groundwater flow model based on annual averages of measured input parameters specific to the study area;
- Calibrate the steady-state flow model using static water levels recorded in well completion reports and surveyed water table data collected by the British Columbia Ministry of Environment (BC MOE) within the study area;
- Generate a water balance for the aquifer, focusing on groundwater inputs and outputs from Cultus Lake; and,
- Perform a model sensitivity analysis.

¹ A groundwater flow divide was identified across the Columbia Valley and is discussed in further detail in Section 2.3.

2.0 HYDROGEOLOGICAL CONCEPTUAL MODEL

The following sections describe the data that inform the hydrogeological conceptual model of the study area. The data were compiled from various sources, including government databases, maps and publications.

2.1 HYDROLOGY

The principal surface water feature within the study area is Cultus Lake. The lake covers an area of approximately 6 km² with a stage of 44.5 metres above sea level (masl). The maximum depth of the lake is 44 m below ground surface (mbgs) according to bathymetry data provided by the DFO and, therefore, the lake bottom is at an approximate elevation of 0.5 masl. Multiple creeks originate at high elevation in the adjacent mountains and terminate within the valley floor. The primary surface water feature providing inflow to Cultus Lake is Frosst Creek, which originates in the International Ridge. The primary surface water outflow from the lake is the Sweltzer River which drains into the Chilliwack River. **Figure 2** shows the significant surface water features within the watershed.



Figure 2 Surface Water Features

Historical stream flow data are available for the Chilliwack River, Sweltzer River, and Frosst Creek from Environment Canada Archived Hydrometric Data (Environment Canada, 2011). The hydrometric stations are located at the inflow and outflow to Cultus Lake as well as the confluence of the Sweltzer and Chilliwack Rivers (Figure 2). The periods of record span from 1911-2010; however, they are not continuous for every year within that date range. The mean monthly and annual flow rates in cubic metres per second (m³/s) are presented on **Figure 3**.



Figure 3 Historical Mean Monthly Flow Rates for Major Surface Water Features

Streamflow data were also obtained from the DFO for stations located along Watt Creek, Teapot Creek, Windfall Creek, Smith Falls, Fin Creek, Ascaphus Creek, and Spring Creek (Figure 2). Stream discharge measurements were recorded bi-weekly from May to September 2011 as presented in **Figure 4**.



Figure 4 Flow Rates of Minor Surface Water Features (May – September 2011)

According to the streamflow data recorded by the DFO, Windfall, Watt and Ascaphus Creek had no baseflow (i.e. went dry) during August 2011. Some limited baseflow may have been present, but not at measurable flow rates with the instrumentation used. Discharge measurements on select dates were also collected from stations 11, 12, and 13 on Frosst Creek and station 14 on Sweltzer River. Discharge rates ranged from 0.13 to 2.46 m³/s for the Frosst Creek stations and 1.06 to 6.03 m³/s for the Sweltzer River station. Discharge measurements were only recorded in all Frosst Creek stations for one sampling date, August 17, 2011.

2.2 SITE STRATIGRAPHY

According to a report prepared by the BC MOE on the hydrogeology of the Columbia Valley (BC MOE, 2000; herein referred to as the "Columbia Valley Report"), the bedrock geology of Mount Vedder is primarily metasedimentary sandstone, conglomerate and shale, whereas International Ridge is primarily composed of slatey argillite. A fault map prepared by the BC Ministry of Energy and Mines (BCMEM), indicates a fault parallel to and along the western side of Vedder Mountain; however, no faults were mapped within the study area (BCMEM, 2005).

The surficial geology of the study area was mapped across two Geological Survey of Canada (GSC) mapsheets (GSC, 1980). The surficial geology is generally consistent in the valley north and south of Cultus Lake and is composed of glaciofluvial sand and gravel outwash sediments. These materials are part of the Sumas Drift deposits, which are exposed in the greater Lower Fraser Valley region (Armstrong, 1981; Halstead, 1986). Some minor exposures of till are also present along the base of Vedder Mountain north of Cultus Lake. Overlying the Sumas Drift deposits in some areas of the watershed are floodplain channel sands and gravels. These sediments extend from the Chilliwack River in the northern portion and along Frosst Creek in the southern portion of the study area. A thin (i.e. less than 1 m thick) layer of sandy loam soil overlies most of the valley. **Figure 5** shows a generalised map of the surficial geology of the study area with cross-section locations for Figure 6 (A-A') and Figure 7 (B-B') indicated.



Figure 5 Generalized Surficial Geology Map

The thickness of the surficial deposits is not known; however, some water well records from the BC Water Well Database (http://www.env.gov.bc.ca/wsd/data_searches/wells/index.html) indicate bedrock was encountered at elevations ranging from 15 masl in the northern portion to as high as 186 masl in the southern portion of the study area. These elevations are suspect – they are very high relative to the ground surface elevation, indicating only a thin layer of surficial sediments. It is likely that the occurrence

of bedrock recorded in the water well logs represents rock fragments, rather than competent bedrock². In contrast, the Columbia Valley Report indicates that the surficial sediments are at least 100 m thick, thereby implying that bedrock elevations are significantly lower than indicated on the water well logs. Additionally, bedrock mapping performed in the adjacent Sumas Valley for the Abbotsford-Sumas groundwater flow model, an established regional model, indicated that bedrock was at an elevation of approximately 200 m below sea level or -200 masl (Scibek and Allen, 2005). Therefore, there are multiple lines of evidence to suggest that bedrock within the study area is at a lower elevation than indicated on the water well logs. For the purpose of model construction, the bedrock surface is interpreted to be at 200 m below sea level (-200 masl). Deep seismic data would help to confirm the bedrock depth in the valley.

Figure 6 provides a schematic drawing of the stratigraphy of the watershed along cross-section A-A' parallel to the valley. The bedrock is assumed to be horizontal, although it likely slopes or has varying topography.



Figure 6 Schematic Stratigraphic Cross-section

² Inaccurate bedrock depths are common in well records because drillers often mistake rock fragments from cobbles in till as competent bedrock.

2.3 **GROUNDWATER FLOW**

The principal hydrostratigraphic unit within the watershed is the Sumas Drift glaciofluvial sand and gravel outwash. The BC Water Resources Atlas (BCWRA) maps the presence of sand and gravel aquifers throughout the study area. Although deep groundwater flow may also occur within the bedrock, groundwater flow through the sand and gravel aquifer is expected to dominate the groundwater flow regime within the valley due to the anticipated high hydraulic conductivity of the aquifer material. Therefore, the bedrock mountains are not included in the model area.

The sand and gravel of the Sumas Drift forms an unconfined aguifer in the valley. Thus, groundwater elevations measured in wells reflect the water table elevation. Groundwater elevations were obtained from two sources: the BC Water Well Database and the Columbia Valley report. The BC Water Well Database contains records for 93 wells drilled within the study area. Of these well records, 70 of the well logs provide measurements of depth to water at the time of drilling (static water level); however, these well records do not provide ground elevations for the wells to reference the depth measurements. The ground elevations for the wells were determined by plotting the locations of the water wells onto a digital elevation model (DEM) and extrapolating ground elevations for each well. The groundwater elevations at each well were then determined based on the depth to water measurements³. The second source of groundwater elevation data, the Columbia Valley Report, provides data for 27 wells within the southern portion of the valley, which were surveyed in 1997 (BCMOE, 2000). Groundwater elevations vary across the study area. In the uplands of the southern portion of the study area, groundwater elevations range from 84 to 240 masl, whereas they range from 35 to 94 masl in the lowlands near the lake and in the northern portion of the study area. Annual fluctuation in groundwater level is expected to be approximately 1 to 1.1 m based on records from the BCMOE Observation wells 335 and 406, located in the northern portion of the valley and Chilliwack, respectively⁴.

Groundwater flow generally occurs from south to north within the valley. Localised flow towards the center of the valley from the adjacent bedrock mountains is expected; however, the overall groundwater flow regime is northwards. The Columbia Valley report identified that groundwater mounding occurs in the uplands of the Columbia Valley where Blue Creek terminates in the valley floor. A groundwater divide at 155 masl was identified in this area based on the elevation data from 27 surveyed wells (BCMOE, 2000). According to the DEM for the study area, there is also a local topographic high in the vicinity of Blue Creek where ground surface slopes towards the north and south along the Columbia Valley. The groundwater divide is shown on a cross-section B-B' parallel to the Columbia Valley (**Figure 7**), derived from Figure 7A of the Columbia Valley report (BCMOE, 2000).

³ Drillers normally measure static water depths from the top of casing rather than ground surface. Therefore, there is some error introduced if a DEM is used to obtain ground elevation for reference.

⁴ https://a100.gov.bc.ca/pub/gwl/disclaimerInit.do





Figure 7 Groundwater Flow Divide

Data from aquifer tests conducted within the study area are not available. However, hydraulic properties have been derived from pumping tests conducted in Sumas Drift aquifer materials in the adjacent Sumas Valley and elsewhere in the vicinity (Scibek and Allen, 2005; Cox and Kahle, 1999). These hydraulic properties were used to constrain the calibration of the Abbotsford-Sumas groundwater flow model (Scibek and Allen, 2005). Given their similar origin, the Sumas Drift aquifer materials are expected to have similar compositions and textures in the Sumas Valley and the Columbia Valley. Therefore, preliminary estimates of the aquifer hydraulic properties within the study area are made based on the values presented in the Abbotsford-Sumas modeling report (Scibek and Allen, 2005) for the Sumas Drift hydrostratigraphic unit, as summarised in **Table 1.** Given the uncertainty in these estimates, these values may be varied within the range provided for sandy or gravelly Sumas Drift to achieve model calibration.

| Table 1 Aquifer Hydraulic Propertie |
|-------------------------------------|
|-------------------------------------|

| Hydrostratigraphic Unit | Mean Hydraulic Conductivity K (m/second) | Approximate Range of K (min. to max.) | Mean Storativity | Approximate Range of S (min. to max.) |
|----------------------------|--|---|---------------------|---|
| Sumas Drift (sand) | as Drift (sand) 6.5x10 ⁻⁴ | | 0.0682 | 1.6x10 ⁻⁵ to |
| Sumas Drift (gravel) | 1.2x10 ⁻³ | 2.7x10 ⁻² | 0.0120 | 0.11 |

Note: Data summarised from Table 13 and Table 18 of Scibek and Allen (2005).

2.4 CLIMATE DATA

Climate data for Cultus Lake were obtained from the Environment Canada Cultus Lake Climate Station (ID 1102220) located at an elevation of 45.7 m in the northern portion of the study area. The period of record is from 1950 to present; however, it is not complete, and records are missing for some years. Precipitation in the valley is predominantly in the form of rainfall; minimal snowfall occurs at the climate station. Snowpack does accumulate at higher elevations in the adjacent mountains, however, and may contribute snowmelt as surface water drainage during the spring or deeper groundwater recharge. Annual average rainfall is 1509 mm with the maximum average monthly rainfall occurring in November. The lowest average monthly rainfall occurs in July and August when baseflow is expected to dominate total streamflow. The maximum average daily temperature of 5.5°C occurs in January. **Figure 8** shows the average monthly temperature and rainfall data for the Cultus Lake climate station.



Figure 8 Climate Data for Environment Canada Cultus Lake Climate Station

Evapotranspiration data are not available specifically for the study area; however, estimates of evaporation provided by Agriculture and Agri-Foods Canada for Agassiz, BC (approximately 23 km northeast of the study area) are presented in Figure 4 of the Columbia Valley Report (BCMOE, 2000); the

data are averaged over 1951-1980. Peak evaporation occurs in July at just over 100 mm. Minimum evaporation is reported from November to February.

2.5 RECHARGE AND EVAPOTRANSPIRATION

Diffuse recharge to the aquifer occurs primarily through infiltration of precipitation. This is facilitated by the relatively coarse-grained sediments of the Sumas Drift and a predominantly unpaved ground surface. An additional source of recharge to the groundwater is from surface water discharge, which originates at the valley sides adjacent to the mountains. Several streams and creeks terminate in the valley floor (or into Cultus Lake directly) indicating that streamflow likely infiltrates the groundwater system as focused recharge at points corresponding to the stream-valley contacts. Limited diffuse recharge may also occur through the bedrock itself along the valley walls, entering the groundwater system at depth.

Estimating recharge to the groundwater system requires a significant modeling exercise in itself. Recharge modeling was previously conducted for the Abbotsford-Sumas groundwater flow model (Scibek and Allen, 2005). The recharge modeling was conducted using the HELP model (Hydrologic Evaluation of Landfill Performance; Schroeder et al., 1994). The HELP model is process based and estimates recharge at the base of a sediment column using a climate data series as input. The Abbotsford climate station was used as the base climate station. Runoff and evapotranspiration are also estimated. Scibek and Allen (2005) completed a series of simulations using various combinations of sediment hydraulic properties and water table depth. Spatially distributed recharge to the aquifer was mapped in GIS and applied to the Abbotsford-Sumas groundwater flow model.

Comparing the climate data (precipitation and temperature) between the Cultus Lake and Abbotsford Airport climate stations indicates that climate does not vary significantly between the two stations. In addition, the land use is similar – dominantly agricultural. Therefore, recharge estimates for the valley aquifer were estimated based on the results of the Abbotsford HELP recharge modeling, which provided monthly recharge for different scenarios of soil properties and water table depth. **Figure 9** presents the range of simulated monthly recharge data for the different soil/water table depth combinations.



Figure 9 Recharge Predictions of All HELP Model Scenarios

When the results for all model simulations are compared, two distinct trends are identified. One set of sediment column simulations (Set A in **Figure 9**) indicates maximum recharge occurs between December and January at a rate of approximately 200 mm/month, while the other set of simulations (Set B) shows a delayed recharge response where the maximum recharge of 160 mm/month occurs in March. Set B simulations (with the delayed response) used soil hydraulic conductivities ranging from 7x10⁻⁶ to 6x10⁻⁵ m/s, whereas the Set A simulations used lower hydraulic conductivities. Since the average hydraulic conductivity of the aquifer materials within the study area is expected to be greater than 6x10⁻⁵ m/s (see Table 2), the recharge simulations for Set B are considered more representative of recharge within the valley. However, there is uncertainty in the recharge rates. Average monthly recharge values are shown in **Table 2.** For the steady state model, the average annual recharge will be used as a preliminary estimate; however, annual recharge could vary by as much as 20-30% compared to the estimates used for the Abbotsford-Sumas model.

| | J | F | М | Α | М | J | J | Α | S | 0 | Ν | D | Annual (mm/year) |
|-----------------------------------|-------|-------|-------|-------|-------|------|------|------|------|------|-------|-------|---------------------|
| Average Recharge (mm/month) | 144.2 | 154.9 | 156.6 | 124.9 | 97.6 | 68.4 | 54.2 | 43.3 | 34.1 | 26.4 | 23.6 | 80.1 | 1008.3 |
| Minimum Recharge (mm/month) | 85.4 | 127.5 | 118.9 | 85.7 | 63.3 | 47.2 | 34.8 | 26.8 | 19.9 | 14.7 | 10.8 | 27.8 | 662.7 |
| Maximum Recharge (mm/month) | 194.7 | 171.4 | 168.6 | 142.4 | 121.7 | 91.5 | 72.4 | 59.4 | 47.9 | 40.6 | 132.5 | 156.1 | 1399.0 |

| Table 2 | Recharge Estimates for Input to the Groundwater Flow Model |
|---------|--|
|---------|--|

2.6 CONCEPTUAL MODEL WATER BALANCE

In developing the hydrogeological conceptual model for the study area the water balance was assessed in a qualitative fashion. The different components contributing to groundwater inflow and outflow within the study area were considered. A model-derived water balance was conducted using the output from the groundwater flow model, as discussed in Section 4.3.

In principle, the amount of water entering the aquifer should equal the amount of water leaving the aquifer on an average annual basis as represented in a steady-state model. The components that comprise the inflow include recharge from precipitation, stream flow recharging the groundwater system (both along the streams and where streams enter the valley), irrigation return flow, possible septic system recharge, deep groundwater inflow from the bedrock, and upgradient groundwater inflow from any adjacent aquifers. On an average annual basis, the dominant inflows include recharge from precipitation, recharge from streams flowing through the valley, and focused recharge where streams enter the valleys. Deep groundwater inflow is assumed to be small as is groundwater flow originating upgradient, given the presence of the groundwater divide to the south (see **Figure 7**). Irrigation return flow in the study area is assumed to be minimal as are septic system sources given the low density of houses.

The components that comprise the outflow include evapotranspiration, groundwater exiting the system via streamflow, withdrawal (pumping) and/or surface water diversions, and groundwater outflow downgradient. Surface water extractions are expected to have minimal effect on the overall water balance due the limited quantities withdrawn (average 34 cubic metres per day (m³/d)) relative to the size of the watershed.

3.0 MODEL DESIGN AND METHODOLOGY

The three-dimensional numerical groundwater flow model for the Cultus Lake watershed was prepared using the software package Visual Modflow (version 10, Schlumberger, 2010). Visual Modflow is the graphical user interface that runs the three-dimensional, block-centered finite difference MODFLOW 2000 code (United States Geological Survey (USGS), 2010). The Visual Modflow interface allows the user to design the model and visualise output results.

The following sections describe the specific input parameters and modeling approach used to develop the groundwater flow model for the study area.

3.1 MODEL DOMAIN AND BASE MAP

The model domain encompasses the valley bottom area within the Cultus Lake watershed. The base map for the model domain was extracted from the DEM for two BC Geographic System (BCGS) mapsheets: 92G010 and 92H001. A hillshade image of the model domain was imported into Visual Modflow and georeferenced to Universal Transverse Mercator (UTM) coordinates. The basemap for the model was rotated so that the model domain was oriented parallel to the valley. The extent of the domain covers an area of approximately 10 km east-west and 11 km north-south; areas of the model domain outside of the study area are deactivated⁵. As discussed previously in Section 2.3, the groundwater flow regime is dominated by groundwater flow through the valley and, therefore, groundwater flow through the mountains was not modeled. Therefore, although the model domain covers a large area, the active model domain only includes the valley itself. The model domain, base map and study area are shown on **Figure 10**.

⁵ In finite difference codes, cells lying outside the model domain (for which a solution is not required) can be deactivated. As such, no solution is generated for inactive cells.



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Figure 10 Model Domain and Study Area

Ground surface elevations were obtained from the DEM for the study area and imported to Visual Modflow as a GIS point shape file. Each cell of the top layer of the model was assigned a ground surface elevation. Therefore, although the DEM resolution was 0.75 m, the resulting ground surface elevation resolution in the model is dependent on the initial grid spacing. No ground surface elevations were imported for inactive grid cells; a constant elevation from the nearest active grid cell was automatically applied.

3.2 GRID

The horizontal grid spacing includes 400 columns and 300 rows, resulting in grid cell dimensions of approximately 35 by 37 m. The model has a vertical grid of 21 layers. The top 8 layers are approximately 8 m thick and the deeper layers have a maximum thickness of 15 m. The layers mimic the ground surface and gradually grade to a horizontal layering. The maximum elevation in the model domain is 300 masl and the bottom of the model domain is at -200 masl (as discussed in the following Section 3.3). **Figure 11** shows a vertically exaggerated cross-section of the model domain at row 196 (roughly corresponding to the mid-line of the valley). The inactive cells are shaded a darker grey.



3.3 BEDROCK ELEVATION

The elevation of the bedrock surface below the valley was assumed to be horizontal at -200 masl throughout the study area, based on the bedrock mapping conducted for the Abbotsford-Sumas groundwater flow model (Scibek and Allen, 2005). In reality the bedrock topography is likely more varied; however, for the purposes of this modeling exercise and in the absence of more detailed bedrock elevation data, it is reasonable to apply a flat bedrock surface deep below the valley ground surface (see Section 2.2).

3.4 MODEL HYDRAULIC PROPERTIES

Based on the stratigraphy of the area, a single hydrostratigraphic unit (Sumas Drift) was identified for groundwater flow within the study area (see Section 2.2). In the absence of stratigraphic data to refine distinct zones within the Sumas Drift, a consistent hydraulic property zone was applied to all areas and layers of the model. The hydraulic properties for the zone were initially selected to represent the sandy aquifer material, rather than the gravelly material (i.e. the lower range). Therefore, the initial hydraulic conductivity (K) was 6.5×10^{-4} m/s, the specific storage was assumed to be 1×10^{-5} and the specific yield was 0.068^{6} . The aquifer was assumed to be isotropic in the x-y plane so that Kx equals Ky. The K value in the z-direction (Kz) is unknown and was estimated to be an order of magnitude lower than that of the x- and y-directions (Kx and Ky) as is common practice. Other hydraulic properties, such as total porosity and effective porosity are based on literature values for the aquifer materials expected within the study area (Wiedemeier, 1999). The initial hydraulic properties selected for the model are summarised in **Table 3**.

⁶ Specific yield is defined for unconfined aquifers, while storativity is defined for confined aquifers. The aquifer in the valley is unconfined. Note, however, that storage properties are not used in a steady-state model. They are only needed for transient models.

Table 3 Initial Hydraulic Properties

| Hydraulic Conductivity (m/s) | | | Specific | Specific Storage (m ⁻¹) | Total Porosity | Effective | |
|---------------------------------|----------|----------|----------|-------------------------------------|-------------------|-----------|--|
| Kx | Ку | Kz | riela | | Forosity | Polosity | |
| 6.5x10⁻⁴ | 6.5x10⁻⁴ | 6.5x10⁻⁵ | 0.068 | 1x10 ⁻⁵ | 0.30 | 0.25 | |

3.5 BOUNDARY CONDITIONS

The following sections describe the boundary conditions designated in the model.

3.5.1 No Flow (Zero Flux)

No-flow (or zero flux) boundaries are placed along the base of the model to represent the sedimentbedrock contact at depth. No-flow boundaries are also present along the inactive grid cells that border the study area. These boundary conditions assume that there is negligible flow to or from the bedrock to the aquifer both at depth and along the valley sides.

3.5.2 Constant Head

The groundwater divide within the southern portion of the study area (as discussed in Section 2.3) is represented in the model by a constant (or specified) head boundary of 155 masl. This boundary allows for flow to originate at the divide. The constant head boundary is assigned as a straight line, perpendicular to the Columbia Valley in the vicinity of Blue Creek at the most upgradient part of the model. The boundary is assigned to the layers that span the elevation 155 masl; in this case layers 4, 5, and 6.

Cultus Lake is also represented by a constant head boundary of 46 m (the measured lake stage, see Section 2.1). Specifying a head for the lake is intended to represent the mean annual lake level⁷. The constant head boundary is assigned to the full horizontal extent of the lake as seen on the basemap and extends down the lake-sediment contact to the maximum depth of 0 masl. Therefore, the constant head boundary of 46 m is assigned to layers 1 to 6.

3.5.3 River

The Chilliwack River is represented by a river boundary. This type of boundary condition varies the flux to and from the river depending on the head difference between the aquifer and the river, and takes into account the composition of the riverbed. The stage of the river is assumed to be the same as the ground elevation along the length of the river. This assumption is considered reasonable based on photographs

⁷ Controls on lake stage (such as precipitation, evaporation, surface water inflow/outflow, and groundwater inflow/outflow) are incorporated into the set level. To model the lake itself would require a surface water-groundwater coupled code.

of the river and anecdotal information that the river is flat and relatively even with the surrounding ground surface. A linear gradient was selected from 53 masl at the most easterly point to 34 masl at the most westerly point of the river within the active model domain. The river width was specified as 10 m, the depth of the river is 1 m, and the thickness of the riverbed is 1 m. The hydraulic conductivity of the riverbed was assumed to be 6.5×10^{-5} m/s, the same as the initial Kz for the rest of the model domain. **Table 4** presents the values used to represent the river boundary condition for the Chilliwack River.

Table 4 Initial River Boundary Condition Specifications

| | Chilliwack River |
|--|------------------|
| River Elevation Start (masl) | 53 |
| River Elevation End (masl) | 34 |
| River Width (m) | 10 |
| Depth of River (m) | 1 |
| Riverbed Thickness (m) | 1 |
| Riverbed Hydraulic Conductivity (m/s) ¹ | 6.5x10⁻⁵ |

Notes: ¹ Riverbed conductance was based on the initial Kz for the rest of the model domain.

3.5.4 Stream

Frosst Creek and Sweltzer River are represented in the model by stream boundary conditions. Stream boundaries allow for exchange between the stream and the aquifer along stream segments using stream flow at selected points as a control. Stream segments were plotted along the flowpath of both surface water bodies. All stream segments assumed a linear gradient between the specified start and end point stream stage elevations.

Frosst Creek is composed of 3 stream segments between the DFO gauge stations 13, 12 and 11 (**Figure 2**) along the flowpath of the creek. Inflows to the stream segments were specified in cubic meters per day (m³/d) based on the August 2011 discharge rates from the DFO stream discharge measurements at stations 13 and 12 (Section 2.1). Discharge data for all stations along Frosst Creek were only available for August 2011. Sweltzer River is composed of a single stream segment; inflow to the stream was specified based on the DFO stream discharge data from station 14. **Table 5** presents the values used to define the stream boundary conditions.

| | | Frosst Creek | Sweltzer River | |
|---|----------------------|------------------------------|----------------------|----------------------|
| Segment | 1 | 2 | 3 | 1 |
| Stream Elevation Start (masl) | 232 | 218 | 88 | 45.5 |
| Stream Elevation End (masl) | 218 | 88 | 45.5 | 34 |
| Stream Inflow (m ³ /d) ¹ | 11232 | upgradient flow ² | 34560 | 216000 |
| Streambed Width (m) | 5 | 5 | 5 | 5 |
| Streambed Depth (m) | 1 | 1 | 1 | 1 |
| Streambed Thickness (m) | 0.5 | 0.5 | 0.5 | 0.5 |
| Streambed Hydraulic Conductivity (m/s) ³ | 6.5x10 ⁻⁵ | 6.5x10 ⁻⁵ | 6.5x10 ⁻⁵ | 6.5x10 ⁻⁵ |

Table 5 Initial Stream Boundary Condition Specifications

Notes: ¹ Stream inflow was based on the discharge data measured in August 2011 (see Section 2.1).

² Inflow was based on flow through the previous stream segment since there is no discharge measurement station at this stream segment.

³ Streambed conductance was based on the initial Kz for the rest of the model domain.

3.5.5 Recharge

An initial recharge of 1000 mm, representing the annual average recharge (as discussed in Section 2.5), was applied across the top surface of the entire model domain. The majority of the creeks flowing off the mountains terminate directly into Cultus Lake. Therefore, zones of additional recharge centered around these points were not defined, since Cultus Lake is represented by a constant head boundary. Although deep groundwater flow may recharge the valley via the bedrock mountains, this source of recharge is not likely a significant contribution relative to the groundwater flow within the valley (i.e. the groundwater flow in the valley dominates the groundwater budget, see Section 2.3).

3.6 WATER BALANCE ZONES

The Zone Budget application in Visual Modflow was used to evaluate the groundwater balance between different components of the watershed. Five water budget zones were defined for the active model grid, as described in **Table 6** and shown on **Figure 12**.

Table 6Water Balance Zones

| Zone | Description |
|------|---|
| 1 | Aquifer. This zone includes all areas of the model domain, unless specified as another zone. |
| 2 | Frosst Creek Upper . This zone extends from the point where Frosst Creek enters the model domain to the DFO gauging station 12 at the base of the terrace. |
| 3 | Frosst Creek Lower . This zone extends from the DFO gauging station 12 at the base of the terrace to Cultus Lake. |
| 4 | Sweltzer River. This zone extends from Cultus Lake to the edge of the model domain at Chilliwack River. |
| 5 | Cultus Lake. This zone covers the full spatial extent and depth of Cultus Lake. |



Figure 12 Water Budget Zones

Zone Budget uses the groundwater flow model output to calculate sub-regional groundwater budgets for each specified zone. The amount of flow is quantified in m³/d and the sources of inflow and receptors of outflow are identified.

3.7 OBSERVATION WELLS

The static groundwater elevations for wells within the study area were incorporated into the model as observation wells. The groundwater elevation data provide the principal dataset with which the model output is evaluated (i.e. the model calibration dataset). A total of 70 wells from the BC Water Well Database were imported to the model. Since neither the depth nor the length of the screened intervals is provided in the well records, the screen elevations were assumed to be the same as the elevation of the bottom of the well.

3.8 SOLVER SETTINGS

The aquifer is unconfined (i.e. a water table aquifer). Therefore, the re-wetting function was applied to allow the cells in the vicinity of the streams to become dry and wet through during the iterations of the model solution. The re-wetting settings were relaxed slightly since the wet stream cells were underlain by dry cells above the water table and this caused complex re-wetting scenarios. The re-wetting threshold was set to 0.1 m and evaluated every 5 iterations to allow the model to get closer to a solution before checking for re-wetting. Additionally, re-wetting was activated from the sides and bottom of the cells.

There are multiple solvers available to obtain model convergence, each solver using a slightly different method. In order to achieve a model solution with the re-wetting function applied, the solver SAMG (Algebraic Multigrid Methods for Systems) was used. SAMG is effective at solving the complex re-wetting function that can cause oscillation in other solvers.

4.0 RESULTS

4.1 PRELIMINARY MODEL RESULTS

The preliminary groundwater flow was evaluated based on comparing the simulated heads to the observed heads at the observation wells. The performance of the model is evaluated by plotting the calculated vs. the observed heads on a graph, where a 1:1 ratio would suggest a perfect fit. Various statistics, including the normalized root mean square (NRMS), are used to quantify the fit. In general, the NRMS percentage should be less than 10% to indicate a reasonably calibrated model (Anderson and Woessner, 1992).

Applying the initial input values to the model (see Section 3.0), the NRMS of the first model run was 11.7%, suggesting a reasonable overall fit of simulated heads to the observed heads. The distribution of the calculated heads with respect to the observed heads indicated three distinct groupings of wells: A, B and C (**Figure 13**) where the fit was less than ideal. The wells displaying similar distribution on the calibration graph were located in the same areas of the model domain. Therefore, areas of the model domain in need of further calibration were identified. Group A wells are located in Lindell Beach, immediately south of Cultus Lake, where the calculated heads were greater than the observed heads. Group B wells are located in the uplands of the Columbia Valley where the calculated heads were lower than the observed heads. Group C wells are located in the northern portion of the valley where the calculated heads were relatively similar in value, and did not represent the range of observed heads in that area of the model domain. The following section describes the steps taken to calibrate the model.



Figure 13 Initial Calibration Graph

4.2 MODEL CALIBRATION

Model calibration is a process that involves varying the input parameters within a reasonable range (as suggested by their uncertainty) according to the conceptual model in order to find the best match between the simulated and observed hydraulic heads at observation wells.

The initial input parameters used in the model (**Tables 3, 4 and 5**) were based on a wide range of generalised values for the watershed (see Section 2.0). In order to improve the model calibration, the initial input parameters were varied within a pre-determined range that reflects their uncertainty.

4.2.1 Hydraulic Conductivity

Hydraulic conductivity was found to have a significant impact on the model results. Increasing the hydraulic conductivity to 1.0x10⁻³ m/s improved the calibration; however, it also caused Frosst Creek to dominate the groundwater flow regime, providing direct recharge to the groundwater in the uplands of Columbia Valley, contrary to the conceptual model. Decreasing the hydraulic conductivity to 2.0x10⁻⁴ m/s improved calibration for Group B (see **Figure 13**) and maintained the expected groundwater flow regime. Increasing the vertical anisotropy (the difference between Kx and Kz) did not improve calibration. Instead, removing the vertical anisotropy, such that Kz was made equal to Kx and Ky, improved the calibration

(NRMS decreased by 0.3%). Although it is expected that some degree of vertical anisotropy is present in the aquifer⁸, anisotropy was removed.

A zone of low hydraulic conductivity (6.5x10⁻⁶m/s) was assigned surrounding Cultus Lake sides and the lake-bottom to represent finer-grained lakebed sediments that are expected to accumulate. However, during further calibration this zone was removed. While it might be expected that a zone of lower hydraulic conductivity lakebed sediments is present, inclusion of these sediments did not result in a good model fit. The permeability of the lakebed sediments may be high so that the effect of the lakebed sediments is on a local scale surrounding the lake. For the purposes of this modeling exercise, the lakebed sediments were ignored.

The streambed and riverbed conductivities ultimately were increased to 2.0x10⁻⁴ m/s to reflect the change in hydraulic conductivity and vertical anisotropy for the aquifer.

Table 7 shows the initial and final hydraulic properties for the aquifer sediments, the streambed and riverbed sediments.

| Table 7 | Calibrated Model Hydraulic Parameters |
|---------|---------------------------------------|
|---------|---------------------------------------|

| Parameter | Initial Value | Calibrated Value ¹ |
|------------------------------|----------------------|-------------------------------|
| Kx and Ky (m/s) | 6.5x10 ⁻⁴ | 2.0x10 ⁻⁴ |
| Kz (m/s) | 6.5x10 ⁻⁵ | 2.0x10 ⁻⁴ |
| Riverbed Conductivity (m/s) | 6.5x10 ⁻⁵ | 2.0x10 ⁻⁴ |
| Streambed Conductivity (m/s) | 6.5x10 ⁻⁵ | 2.0x10 ⁻⁴ |

Notes:

¹ The calibrated hydraulic conductivity is slightly lower than the mean values (Section 2.3); however, it is within the range of values for the aquifer material (see Table 1).

4.2.2 Pumping Wells

Lindell Beach is a residential area with 25 water wells indicated in the BCWRA. In order to improve calibration for Group A (**Figure 13**), the extraction of groundwater for the Lindell Beach community was simulated in the model. Fourteen (14) pumping wells were assigned in Lindell Beach to represent pumping conditions in the area. Note that only 14 of the 25 water wells in that area had observed water levels. Each well is assumed to be pumping at an annual average rate⁹ of 15 m³/d, except for two wells operated by the Aquadell Acres Golf Course, which are assumed to be operating 12 hours a day, 6 months of the year (May through September). The water well records for these two wells indicate an estimated yield of 300 US gallons per minute (USgpm) or 1,635 m³/d; therefore, the annual average

⁸ It is common for thin layers of lower conductivity sediments to accumulate during deposition; however, these layers appear not to have a significant impact on the overall groundwater flow regime.

⁹ Based on an estimated occupancy of two people per household using 300 liters per day per person.

pumping rate for each well is assumed to be 408 m³/d. An RV park is also present in Lindell Beach; however, it is unknown whether there are water hook-ups provided at the park.

By simulating groundwater extraction in Lindell Beach, the calibration of Group A improved slightly (NRMS decreased by 0.012%). With higher pumping rates than estimated above, the calibration improved significantly (NRMS decreased by 1%). However, without more information about water usage in Lindell Beach, there is insufficient justification for increasing the pumping regime above the estimated residential consumption as described above. Table 8 summarizes the simulated pumping regime in Lindell Beach.

Table 8 Pumping Rates for Lindell Beach

| | Initial Value | Calibrated Value |
|--|---------------|------------------|
| Residential Pumping Well Extraction Rate (m ³ /d) | 0 | 15 |
| Golf Course Pumping Wells Extraction Rates (m ³ /d) | 0 | 408 |

4.2.3 Constant Head

The constant head elevation of the groundwater divide was raised by 1 m to represent the approximate maximum annual fluctuation in groundwater levels. This improved the calibration (RMS decreased by 0.1%); however, it created unnatural mounding in the vicinity of the groundwater divide that does not agree with the conceptual model. The groundwater divide elevation was maintained at 155 masl, as surveyed by the BCMOE (see Section 2.3).

The annual fluctuation in lake stage for Cultus Lake is not known; however, the constant head boundary representing the lake was raised and lowered by 2 m. Varying the lake level within this range did not improve the calibration and the lake stage was left at the annual average elevation of 46 m. However, lake level variations will affect the regional groundwater gradients to and from the lake under transient conditions.

4.2.4 Water Balance

The overall water balance for the model is 305,590 m³/d inflow and 305,850 m³/d outflow, with a percent discrepancy of -0.08%. The low discrepancy indicates that the model convergence was very good. A detailed discussion of the components of the water balance in relation to the qualitative water balance discussed under the conceptual model is provided below.

4.1 FINAL MODEL RESULTS

4.1.1 Hydraulic Head Distribution

The simulated hydraulic head distribution (**Figure 14**) agrees with the conceptual model for the overall groundwater flow regime. Groundwater flows from the groundwater divide in the south of the valley, northwards towards the lake and into the northern valley portion towards the Chilliwack River. **Figure 14** provides screenshots of the predicted hydraulic head equipotentials in plan-view and in cross-section.



(b)

Figure 14 Predicted Hydraulic Head Equipotentials (5 m contour starting with 150 masl on left side to 40 on the right) (a) in plan-view and (b) cross-section. The dark grey space represents the inactive cells; the light grey space represents dry cells.

4.1.2 Final Model Parameters

The final model calibration had a NRMS of 9.5% (**Figure 15**). The predicted hydraulic heads in the area of Lindell Beach (Group A wells) and the uplands of Columbia Valley (Group B wells) are still over- and under-estimated, respectively. However, the overall fit of the model is improved over the initial model.

Figure 15 shows the calibration graph for the calibrated model.



Figure 15 Calibrated Model Calibration Graph

Although the parameter values applied to the model provide a reasonable calibration, improved calibration may be achieved by refining the conceptual model with additional data. Each parameter works in unison with other parameters to affect the model results. Therefore, erroneous input values for one parameter may be cancelled out or amplified by another parameter. Non-unique solutions are particularly common for steady-state models. The greater the ranges of uncertainty in parameter values, the more numerous are the realizations.

Additional data that may support improved calibration include:

- Aquifer testing to provide in situ estimates of hydraulic conductivity;
- Estimates of actual residential groundwater extraction, particularly in Lindell Beach;
- Land-use coverage of the study area, which may alter recharge estimates; and,
- Identification of industries or businesses that may rely on large-scale groundwater withdrawals (e.g. irrigation).

4.1.3 Water Balance

In general, the movement of groundwater between the different water budget zones is as expected according to the conceptual model. Groundwater recharges Frosst Creek along the terrace and lowlands of Lindell Beach. Cultus Lake receives inflow from the upgradient aquifer and Frosst Creek, and provides outflow to the downgradient aquifer and Sweltzer River. **Table 6** presents the quantitative results of the water balance.

| Zone | | 1 - Aquifer | 2 - Frosst | 3 - Frosst | 4 - Sweltzer River | 5 - Cultus Lake | |
|---------------------|---------------|---------------------|---------------|---------------|-----------------------|--------------------|--|
| | | | upper | lower | | | |
| | Recharge | 50791 | 45 | 150 | 300 | 57 | |
| Inflow | Constant | 171427 (groundwater | | | | | |
| | Head | divide) | 0 | 0 | 0 | 9878 | |
| | | 9803 (Cultus Lake) | | | | | |
| | Stream/River | 21110 | 11232 | 25599 | 0 | 0 | |
| | Leakage | 24445 | 11252 | | | 0 | |
| | From Aquifer | - | 1167 | 45329 | 45362 | 199990 | |
| | Upgradient | | - | 154 | 109 | 714 | |
| | Zone | - | | | 100 | /14 | |
| | Total | 305590 | 12454 | 71231 | 45770 | 210640 | |
| Outflow | Constant | 6042 | 0 | 0 | 0 | 200720 | |
| | Head | 0042 | | | 0 | 200730 | |
| | Pumping Wells | 981 | 0 | 0 | 0 | 0 | |
| | Stream/River | 6637 | 0 | 43640 | 15576 | 0 | |
| | Leakage | 0037 | | | 43370 | U | |
| | To Aquifer | - | 12276 | 26868 | 194 | 9803 | |
| | Downgradient | | 154 | 714 | | 109 | |
| | Zone | - | 134 | | - | 100 | |
| | Total | 305850 | 12430 | 71231 | 45770 | 210640 | |
| Percent Discrepancy | | -0.08% | 0.19% | 0% | 0% | 0% | |

Table 9Quantitative Water Balance Results

Notes: All values in m³/day unless otherwise noted.

The total groundwater flow in and out of Cultus Lake is 210,640 m³/d. The majority (95%) of inflow to the lake comes from the upgradient aquifer, whereas the majority (95%) of outflow from the lake is controlled by the constant head boundary to maintain the average annual lake stage. Groundwater generally enters

the lake as horizontal flow along the ends of the lake; minimal groundwater inflow occurs through the lake bottom. The inflow from stream leakage to the upper zone of Frosst Creek represents the initial flow rate specified for the stream boundary condition (see Section 3.5.4). The inflow and outflow along the lower zone of Frosst Creek indicates that the aquifer is discharging to the stream along the lower reach. Inflow to Sweltzer River occurs primarily from the aquifer to maintain the specified initial flow rate. The aquifer receives 56% of total inflow from the groundwater divide constant head boundary and 65% of the total outflow discharges directly to Cultus Lake.

4.2 SENSITIVITY ANALYSIS

A sensitivity analysis was conducted to evaluate how sensitive the model results are to the uncertainty in the input parameters. Two input parameters were varied, namely hydraulic conductivity and recharge, which were based on a range of values as presented in the conceptual model. This analysis focussed on changes in the water balance due to variation in these input parameters.

The sensitivity analysis was performed by decreasing and increasing the parameter base value (calibrated value) one at a time. The K value was not decreased as model convergence could not be achieved at K values lower than the base case. The model was run for each individual deviation from the calibrated input parameters and the change in simulated water balance and NRMS monitored. **Table 10** presents the results of the sensitivity analysis.

| Input Properties | Base Prop Case R | | y Value ge ² | Simulate Balance | Simulated Water Balance (m ³ /d) ³ | | Percent Change in Water Balance ⁴ | | Change in NRMS ⁵ | |
|-----------------------|----------------------|-----|----------------------------|---------------------|---|-------|---|--------|-----------------------------|--|
| | Value ¹ | Low | High | Low | High | Low | High | Low | High | |
| Kx = Ky =Kz (m/s) | 2.0x10 ⁻⁴ | n/a | 6.5x10 ⁻⁴ | n/a | 669020 | n/a | +218% | n/a | +0.1% | |
| Recharge (mm/year) | 1000 | 600 | 1200 | 210420 | 211060 | -0.1% | +0.2% | +0.03% | +0.01% | |

Table 10 Sensitivity Analysis Results

Notes: n/a – not applicable since model convergence not achieved for lower K values.

¹ Value based on calibrated model input.

 2 Values represent the minimum and maximum within a reasonable range.

³ Water balance for Cultus Lake inflow.

⁴ As compared to the base case water balance inflow of 210,640 m^3/d .

⁵ As compared to the base case NRMS of 9.5%.

The sensitivity analysis demonstrated that hydraulic conductivity has a significant effect on the model results. When K is increased, the water balance increased by 218%. Additionally, the model was not able to converge when K was decreased indicating that it is highly sensitive to changes in K. In contrast, the recharge values do not have as large an effect on the model results (i.e. the water balance changes by - 0.1% to +0.2%). The NRMS also changed more when K was altered than when recharge was altered, however, the changes in NRMS were not significant for either parameter alteration. Reliable model calibration requires well-defined constraints in the form of reasonable ranges based on field data for the

input parameters. The results of the sensitivity analysis indicate that the model is highly sensitive to hydraulic conductivity input and, therefore, refining estimates of this parameter for the study area through future data acquisition would have a significant impact on improved calibration of the groundwater flow model.

5.0 CONCLUSIONS

A steady-state three-dimensional numerical groundwater flow model for the Cultus Lake watershed was developed based on study-area specific and estimated input parameters. The model accurately simulated the regional groundwater flow regime based on the conceptual model for the study area. However, since the model was developed to represent the groundwater flow regime on a regional scale, predicted groundwater flow was not accurate at the local scale in all areas of the model domain.

The water balance for the model is 305,590 m³/d inflow and 305,850 m³/d outflow with a percent discrepancy of -0.08%. The groundwater flow into and out of Cultus Lake is estimated at 210,640 m³/d. Cultus Lake receives inflow from the upgradient aquifer and Frosst Creek, and provides outflow to the downgradient aquifer and Sweltzer River.

The model was calibrated using static water levels in wells in the study area with a resulting NRMS of 9.5% between calculated and observed hydraulic heads. A sensitivity analysis indicated that the model is highly sensitive to hydraulic conductivity input values, as is commonly the case. Refined ranges in input values may allow for improved calibration of the model in the future.

Overall, the model provides a reasonable simulation of groundwater flow for the Cultus Lake watershed on which to base future solute transport modeling.

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