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Three dimensional groundwater flow model of the Nanoose-Deep Bay area, Nanaimo Lowland, British Columbia

N. Benoit and D. Paradis

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Abstract

The Nanaimo Lowland Groundwater Study is a collaboration between the British Columbia (BC) Ministry of Environment (MoE), Ministry of Forests, Lands, and Natural Resource Operations (MFLNRO), the Regional District of Nanaimo (RDN), and the Geological Survey of Canada (GSC). This Open File reports on the three-dimensional (3D) groundwater flow model (3DGFM) for the Nanaimo Lowland aquifer system developed to support improved sustainable groundwater management of the Nanaimo Lowland. The study area represents a coastal strip running from Nanoose to Deep Bay in the eastern part of Vancouver Island and covers approximately 580 km^2. The groundwater flow model was based on the 3D hydrostratigraphic model (3DHSM) developed by Benoit et al. (2015). The hydrostratigraphic units were converted into a numerical grid and representative hydraulic properties were assigned based to each unit on statistical analysis of available values. The groundwater resurgences present along the steep slopes of the main riverbanks and at the shoreline were simulated with seepage boundary conditions allowing for a vertical hydraulic link between the main Quadra Sand aquifer and surface water bodies. Hydraulic conductivity and groundwater recharge rate were further calibrated through numerical inversion using static hydraulic heads recorded in existing wells and estimated baseflow values from streamflow records. Simulation results that two distinct groundwater flow systems: (1) the Quadra aquifer system with groundwater divides closely matching watershed boundaries containing relatively fresh water; and (2) the extensive bedrock aquifer system with older water and a flow patterns generally directed toward the sea coast. Simulations also reveal discharge to rivers and streams mainly from the Quadra Sand aquifer and the Capilano sediments, often locally present along the main river channels, with low contribution from the bedrock. Exception is the Englishmen River where the Quadra Sand is inexistent and the river is in direct hydraulic contact with the bedrock aquifer. The Quadra Sand aquifer is naturally protected from sea intrusion due to the higher altitude with respect to sea level, whereas the bedrock aquifer appears vulnerable to encroachment especially under heavy pumping conditions close to the shoreline. This 3DGFM provides then a meaningful framework for the understanding of the regional hydrogeology of Nanoose-Deep Bay aquifer system that would contributes to support sustainable management of groundwater resources.

1. Introduction

Groundwater is an important source of potable water in the Nanaimo Lowland area, British Columbia (BC). To support improved sustainable groundwater management of the Nanaimo Lowland a three dimensional hydrostratigraphic model (3DHSM) and groundwater flow model (3DGFM) were developed for a representative area of the Nanaimo Lowland aquifer system. The Nanaimo Lowland Groundwater Study was a collaboration between the BC Ministry of Environment (MoE), Ministry of Forests, Lands, and Natural Resource Operations (MFLNRO), the Regional District of Nanaimo (RDN), and the Geological Survey of Canada (GSC). The study area extends 60 km south-east from Deep Bay to Nanoose Bay, BC, on the eastern coast of Vancouver Island (Figure 1).

This Open File documents the 3DGFM, which is based on the 3DHSM published by Benoit et al. (2015). The main objective of the present study is to better understand the regional groundwater flow system of the Deep-Nanoose Bay area. This is achieved using a 3DGFM of the study area calibrated with hydraulic head and baseflow data. This document details the construction of the numerical model (Section 2), results of the calibration process (Section 3), and various numerical simulations aimed at illustrating the dynamics of the aquifer system (Section 4). The digital 3DGFM data are presented in Appendix A.

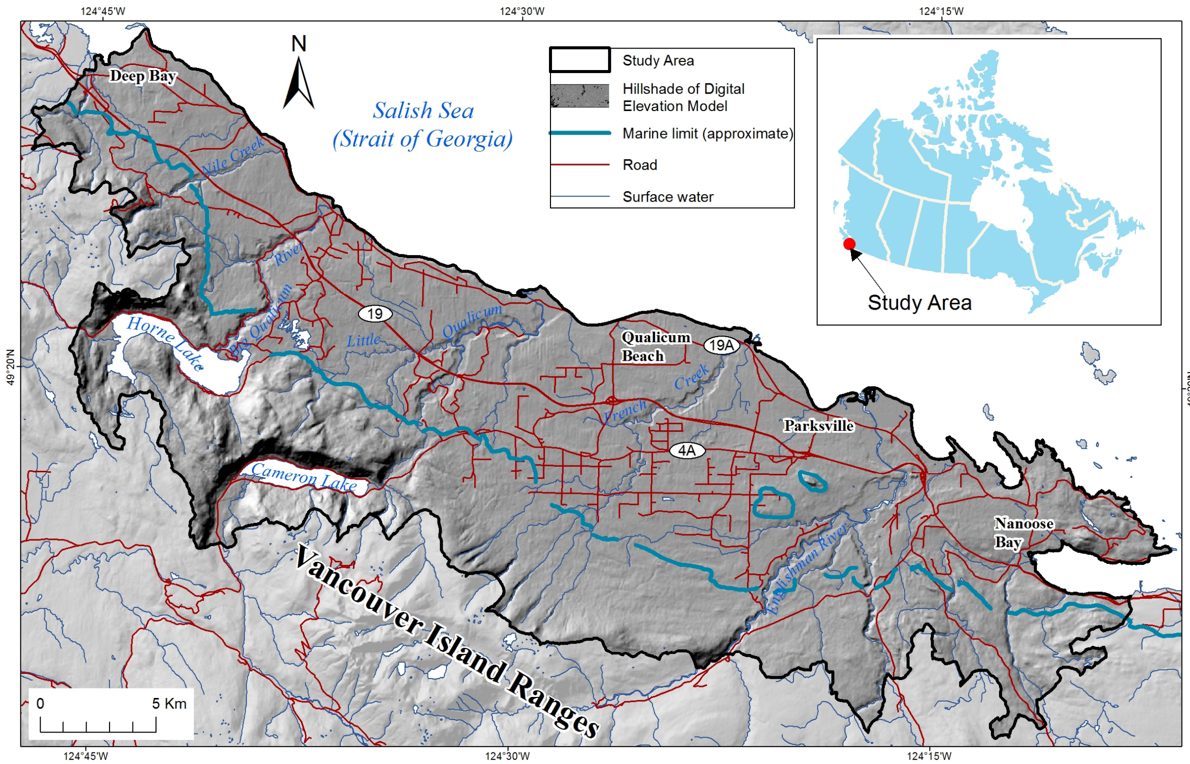

Figure 1: Location map of the Nanoose-Deep Bay study area in the Nanaimo Lowland on Vancouver Island, BC.

2. Construction of the Three Dimensional Groundwater Flow Model

The 3DGFM was developed using FeFlow 6.2 (Diersch, 2014). This section describes the construction of the 3DGFM. It includes the conversion from the 3DHSM to the 3DGFM, the definition of the boundary and initial conditions, and description of the material properties.

2.1 Hydrostratigraphy to Groundwater Flow Model

The development of the 3DHSM is described by Benoit et al. (2015). The 3DHSM represents the conceptual model of the aquifer system architecture consisting of 7 granular units overlying 2 bedrock units (Figure 2). For the 3DGFM, a two-dimensional (2D) aerial mesh was built using the Triangle algorithm (Shewchuk, 1996). It was adjusted to reproduce the relatively steep slopes along the major rivers, where seepage flow is expected to be important (Figure 3). The 9 hydrostratigraphic layers built in LeapFrog Hydro (ARANZ Geo Limited, 2015) were then reassigned to 14 layers. The top 7 layers of the 3DHSM represent the unconsolidated sediments, whereas the lower 7 layers represent the 2 bedrock units with essentially decreasing hydraulic conductivity with depth. All the 14 geologic layers were converted to a corresponding groundwater flow simulation layer. A 3D groundwater simulation grid for FeFlow was then built using these layers and the previously generated 2D mesh.

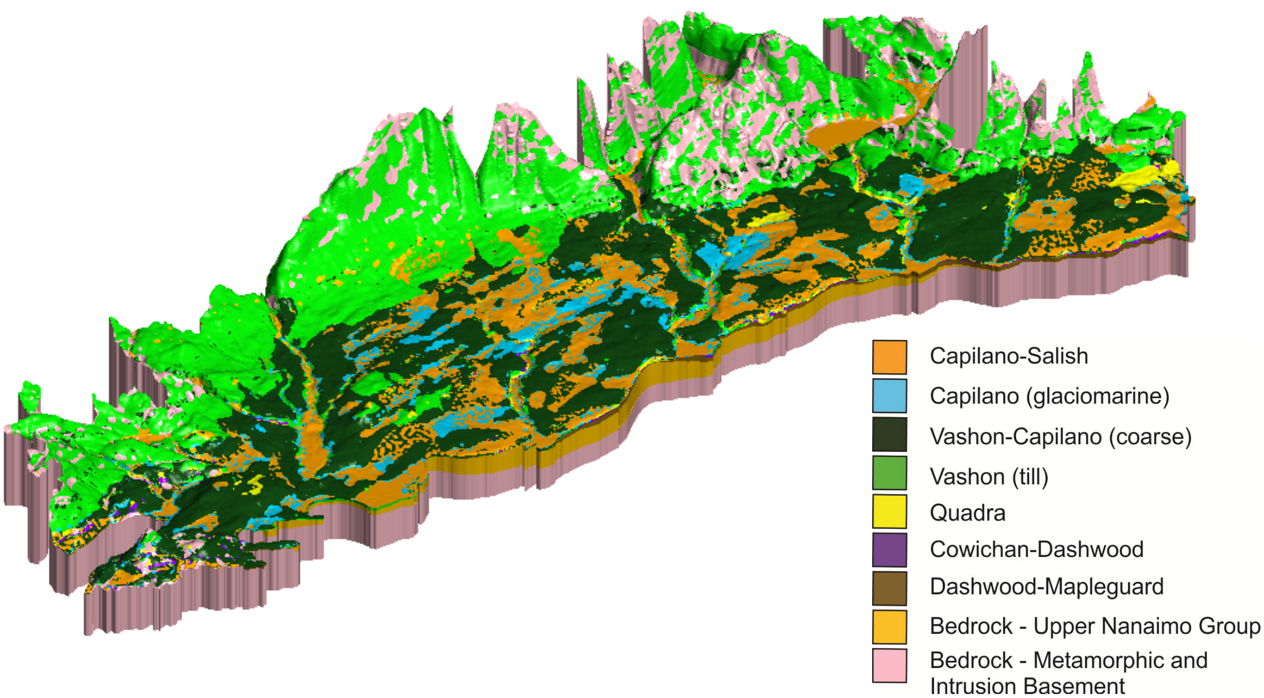

Figure 2 : Three dimensional hydrostratigraphic model (3DHSM) of the Nanoose-Deep Bay study area used as the conceptual model of the aquifer system architecture for the three dimensional groundwater flow model (3DGFM).

The Figure 3 shows a 3D view of the FeFlow 3D simulation grid, which consists of 2,412,018 elements, 1,363,440 nodes distributed into 14 layers. The maximum size of the elements is < 120 m with an arithmetic mean of approximately 50 m. The simulation grid respects Delaunay criterion for 99.97% of the elements and has interior angle ranging from 60 to 120 degree for 99.6% of the elements.

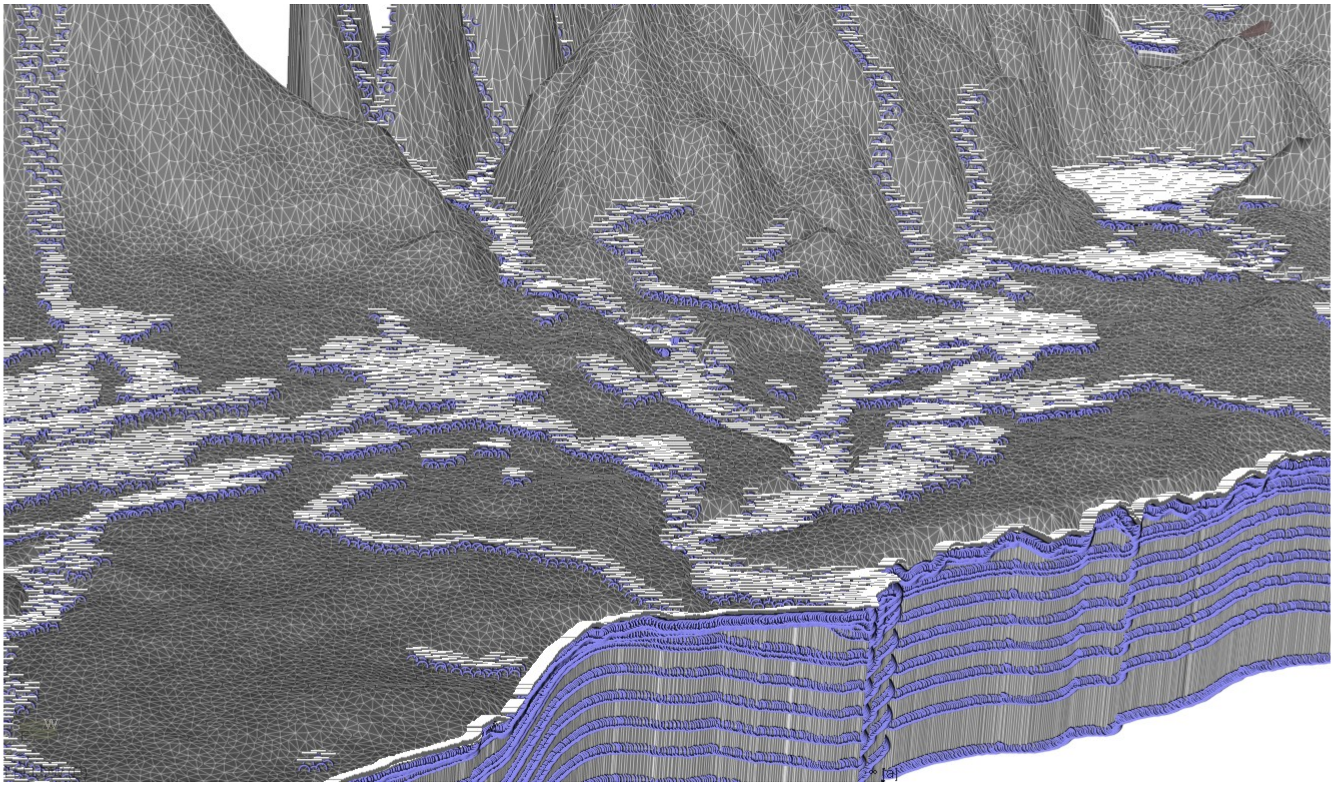

Figure 3 : Close-up view of the simulation grid applied in the three dimensional groundwater flow model (3DGFM). The two-dimensional mesh with refinement along the main rivers (white dots) is given on top of the model.

2.2 Boundary Conditions

The model includes Dirichlet (prescribed head) and Neumann (prescribed flux) types of boundary conditions. Northwest and southeast lateral boundaries of the 3DGFM were set as no flow boundary condition to approximately represent the groundwater divides (Figure 4). Along the coast, all nodes with elevation greater or equal to sea level (0 m) were simulated with the seepage face boundary condition (Figure 4 – blue and white colours). The seepage face boundary condition in FeFlow allows water to discharge to the surface when the hydraulic head is higher than the elevation of the ground surface. For nodes along the coast with an elevation below sea level a constant head equal to the sea level (0 m) was imposed, thus assuming horizontal flow at the coast (Figure 4 – blue colour). This was considered to be a reasonable approximation, as the fresh groundwater flow system below sea level is expected to make discharge near the coast at the fresh water and saline water interface according to the Ghyben-Herzberg principle (Drabbe and Badon-Ghyben, 1889; Herzberg, 1901). The elevation of the bottom layer of the model was chosen deep enough (500 m below sea level) to avoid interference with imposed stresses (e.g., groundwater withdrawal in pumping wells) on the surficial layers of the 3DGFM. This basal layer is a no flow boundary in the model (Figure 4).

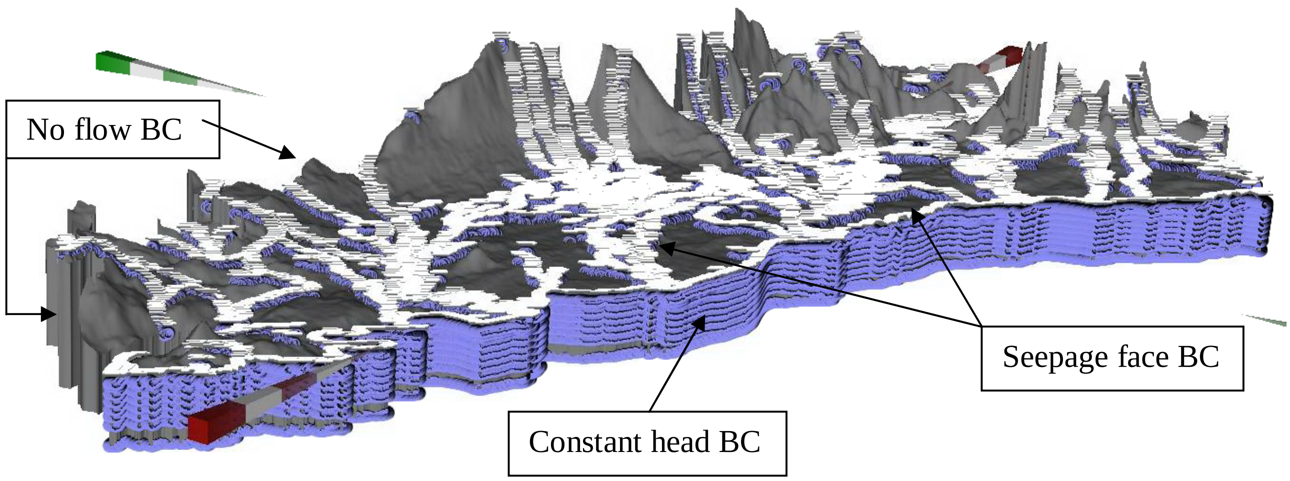

Figure 4: Boundary conditions (BC): Constant head BC (blue circle), Seepage face BC (blue circle with white line), and No flux BC (absence of symbol).

No information was available to assess the groundwater contribution from the mountain areas to the lowlands. An arbitrary recharge rate was thus assigned to cells representing intrusive crystalline bedrock to simulate the position of the water table (Figure 6). The recharge rate was adjusted during the calibration process to assess the unknown influx from the mountains. Seepage conditions were used to represent groundwater discharge observed along the flanks of the main rivers (Figures 3, 4 and 5). Thus, when simulated hydraulic heads are larger than the elevation of the ground elevation, excess water is evacuated from the model to adjust the water table to the same elevation as the soil surface. This excess water is, however, not completely discarded from the model as it is becomes part of the baseflow in the water budget analysis. In the conceptualization of the groundwater flow, seepage water along the steep slopes of the main rivers will eventually reach streams through surface runoff and/or hypodermic flow. Figure 5a illustrates the conceptual model of the groundwater - surface water interaction in the lowlands. Figure 5b shows the integration of the conceptual model in the numerical model, where nodes representing the permeable Capilano-Salish and Quadra units are simulating the seepage faces near the river.

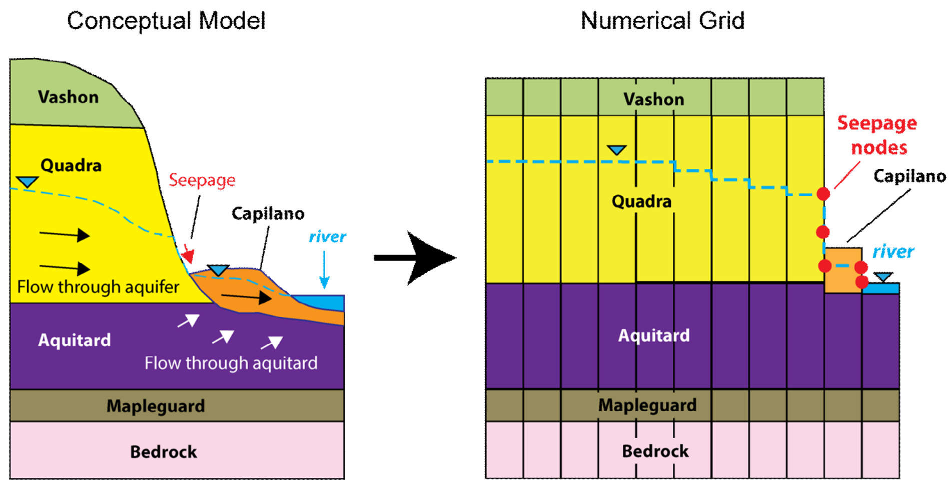

Figure 5 : a) Conceptual model of the groundwater - surface water interactions in the lowlands. b) Integration of the conceptual model into the numerical model applying seepage conditions.

The recharge rate over the lowland area was assessed based on the separation of the baseflow from the river hydrographs (Section 2.3) and adjusted during the calibration. Baseflow is the portion of streamflow that comes from groundwater (e.g., Furey and Gupta, 2001). Recharge rate values were obtained for each watershed and a seepage condition was applied to the nodes of the first layer to adjust the water table elevation with respect to the soil infiltration capacity and topography.

2.3 Baseflow Estimation

In addition to the hydraulic head, a baseflow calibration was conducted for the lowland part of Nile Creek, Big Qualicum, Little Qualicum and Englishmen Rivers. Important components of a streamflow are direct precipitation, surface runoff, baseflow and hypodermic flow. Baseflow can be estimated from the analysis of streamflow records and, for assumed steady state flow condition, baseflow can be used as an estimation of the recharge rate to the aquifer. Table 1 compares the average annual baseflow values obtained for 7 consecutive days with the lowest flow conditions, and using a physically based filter method by Furey and Gupta (2001). These two methods were considered to provide an estimate of the potential minimum and maximum expected baseflow values (e.g., Rivard et al., 2014). Note that only the baseflow contribution in the lowland was considered (Figure 6). The relative proportion of baseflow in the lowland and in the mountain region was estimated for the streamflow records from two stream gaging station located along the Big Qualicum River at the edge of the mountains and in the lowland, respectively. The same proportion was then applied in the other watersheds assuming comparable surface water and groundwater dynamics. The baseflow for each watershed was then estimated as a sum of the flux extracted from the model at nodes corresponding to seepage faces. In Table 1, the simulated values are given in the column 3DGFM. They indicate that simulated baseflow falls well within the estimates from the 7-days low flow (min) and from the Furey-Gupta (max) methods. The Big Qualicum River flow is regulated with a few dams and more information is needed to better understand the impacts on the baseflow, in particular during the summer season low flow conditions.

Table 1 : Average baseflow estimated by the hydrograph separation methods (7-day low flow and Furey and Gupta) and simulated by the numerical model (3DGFM).

Rivers	Period	Baseflow (x 10^4 m^3/d)			Ratio C/A (-)	Ratio C/B (-)
		A: 7-Day Low Flow	B: Furey and Gupta (2001)	C: 3DGFM		
Nile creek	1960-86	1.07	1.59	1.35	1.27	0.85
Big Qualicum	1960-74	1.05	14.4	4.44	0.42	0.31
Little Qualicum	1960-86	3.28	6.29	5.45	1.66	0.87
Englishmen	1970-71; 1979-86	4.22	8.70	4.61	1.09	0.53

2.4 Hydraulic Conductivity

The hydraulic conductivity (K) is a measure of the ease with which water flows through the saturated porous medium. As the present model was calibrated under steady state flow conditions, the hydraulic conductivity was used as a major calibration parameter. Most K values for each hydrostratigraphic unit were obtained from the analyses of available pumping tests (MoE, 2013, Table 2). Other K values were drawn from the literature, in particular for the low-K units (Batu, 1998; Henderson and Vograss, 1962; Hornberger et al., 1998). In general, the hydraulic conductivity for sedimentary bedrock units varies over several orders of magnitude according to the degree of consolidation and weathering (Surrette et al., 2008). For the Nanaimo Group (sandstone), Henderson and Vograss (1962) reported a K value as low as 10^{-10} to 10^{-9} m/s, whereas Hornberger et al. (1998) and Singhal and Gupta (1999) suggest larger range from 10^{-10} to 10^{-6} m/s. The reported range for fractured siltstones and shales is

10^{-7} to 10^{-4} m/s (Hornberger et al., 1998; Singhal and Gupta, 1999). The final hydraulic conductivities and recharge rates were obtained by numerical inversion (see Section 3.2) using Pest algorithm embedded in Feflow (Doherty, 2002).

Table 2: Reported hydraulic conductivity ranges for each hydrostratigraphic unit.

Hydrostratigraphic units	Horizontal hydraulic conductivity K_{xy} (m/s)[1,2] min	max	Sources
Lake bottom	5.0×10^{-9}	2.5×10^{-7}	Batu (1998)
Capilano-Salish	3.4×10^{-4}	1.0×10^{-2}	Carmichael (2013)
Capilano (glaciomarine)	5.0×10^{-9}	2.5×10^{-7}	Batu (1998)
Vashon-Capilano (coarse)	9.0×10^{-6}	8.0×10^{-4}	Carmichael (2013)
Vashon (till)	5.0×10^{-8}	5.0×10^{-6}	Batu (1998)
Quadra	2.0×10^{-6}	4.6×10^{-3}	Carmichael (2013)
Cowichan-Dashwood	5.0×10^{-9}	2.5×10^{-7}	Batu (1998)
Dashwood-Mapleguard	2.0×10^{-6}	4.6×10^{-3}	Carmichael (2013)
Bedrock Lower Nanaimo Group	4.6×10^{-7}	3.5×10^{-5}	Carmichael (2013)
	1.0×10^{-10}	5.0×10^{-4}	Henderson and Vograss (1962); Hornberger et al. (1998); Surrette et al. (2008)
Bedrock Metamorphic and Intrusion Basement	2.3×10^{-6}	3.5×10^{-6}	Carmichael (2013)
	2.0×10^{-9}	5.2×10^{-5}	Batu (1998)

[1] Vertical hydraulic conductivity range: K_z min = $K_{xy}/10$ and K_z max = K_{xy}

[2] In the mountainous area, an homogeneous hydraulic conductivity value of 1×10^{-4} m/s was set for the first 3 m representing a weathered zone (Welch and Allen, 2014).

3. Model Calibration

The 3DGFM was calibrated for a saturated steady state condition assuming that the model represents average annual flow conditions. The calibration process was carried out against 247 water well levels extracted from the provincial database, water levels in 21 monitoring wells, and 4 baseflow estimates (Figure 6). The parameters adjusted during the calibration process were: K, groundwater recharge and the influx from the mountain regions. The architecture of the aquifer system was assumed to be the best possible realization and remained unchanged (Benoit et al., 2015). The calibration parameters were modified until a satisfactory match between the simulated and observed hydraulic heads and baseflow values. First, the 3DGFM was roughly calibrated by the trial-and-error method. Further refinement and fine adjustment was carried out applying the numerical inversion within the Pest algorithm (Doherty, 2002). Potential discrepancies between simulated and observed targets can be explained as a result of water withdrawal effects (evident in a few areas of intensive pumping), errors in measurements (head) and estimations (baseflow). The transient effects, such as intra and inter-annual groundwater level fluctuations in response to climatic variability also contribute to model discrepancies (Anderson and Woessner, 1990).

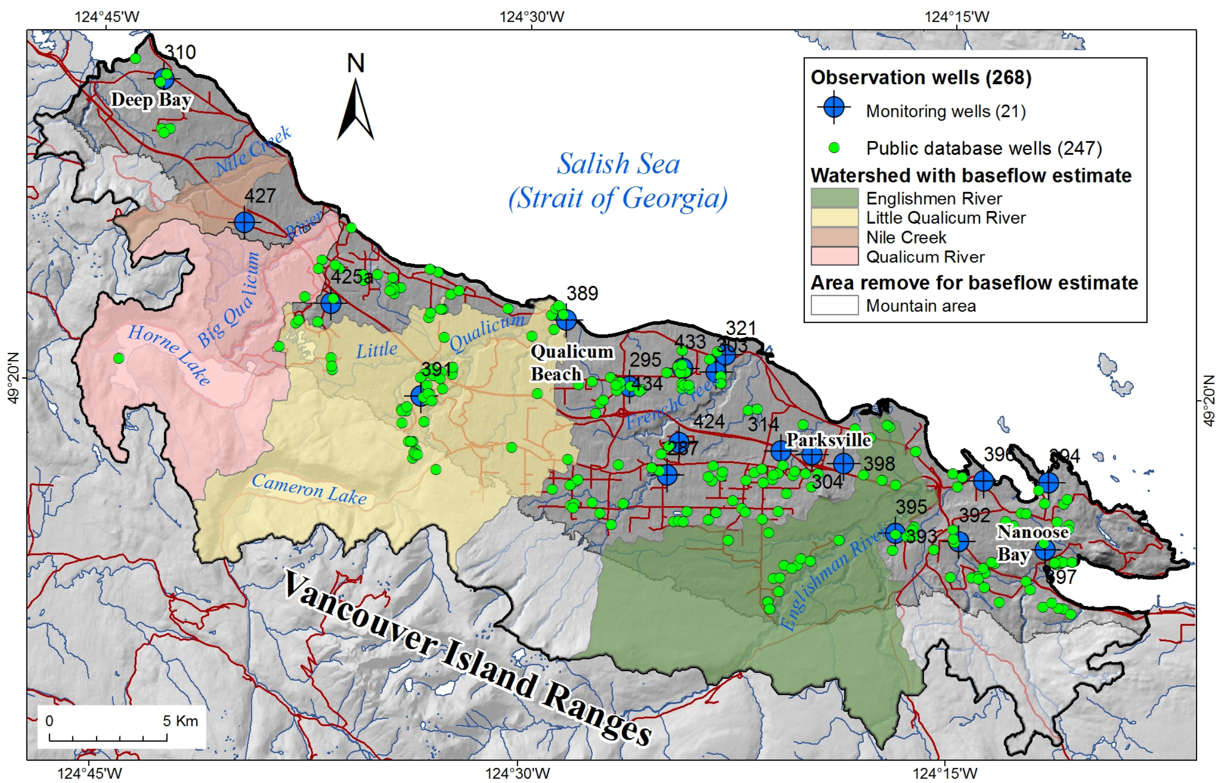

Figure 6: Groundwater wells and watersheds used for calibration of the hydraulic head and baseflow. Only the watershed portions in the lowland area (indicated with darker colors) were considered for baseflow calibration.

3.1 Model calibration

The objective of the model calibration process was to minimize the differences between the observed and simulated hydraulic heads (e.g., mean, absolute mean, and mean square error). The comparison of the final results shows a satisfactory correlation (r = 0.94) with a mean error of -0.2 m, a mean absolute error of 13.1 m, and a mean square error of 317 m^2 (Figure 7a). The best correlation exists for water levels ranging from 50 to 150 masl. Head values lower than 50 masl are characteristic mainly for densely populated areas where intensive pumping occurs. There, the simulated heads are generally higher than field measurements. Including in the groundwater model accurate estimates of the water withdrawal activities would contribute to an improved correlation, however, the pumping rates and time-series history were not adequately constrained to employ in this study. On the other hand, water levels higher than 150 masl are localized in or close to the mountainous area and, again, insufficient measurement data make the calibration difficult.

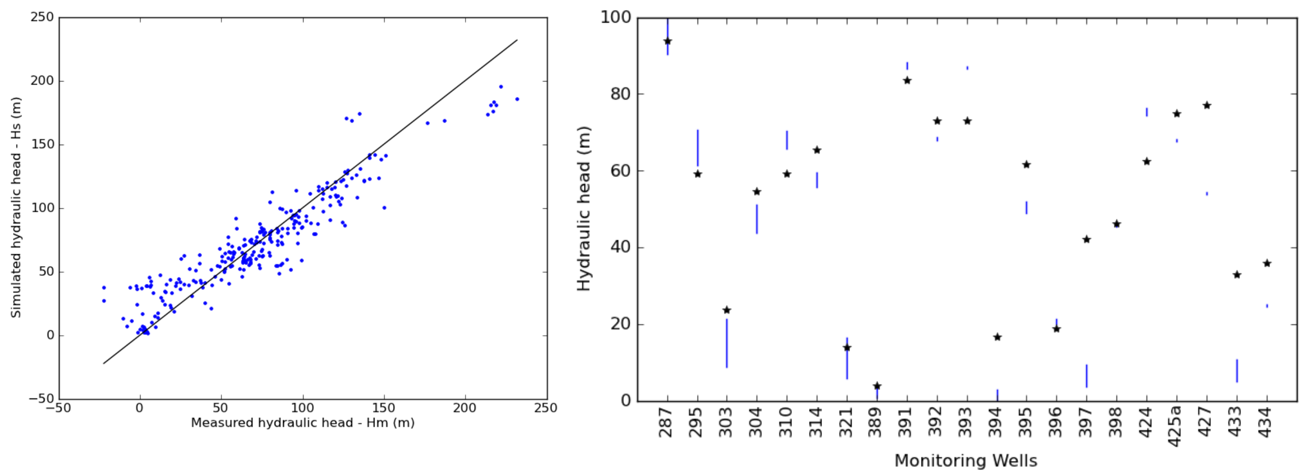

Figure 7: Model calibration a) measured vs. simulated hydraulic heads. When unknown, the position of the well screen was set to the mid-portion of the Quadra Sand unit (when present) or to the top of the bedrock. b) Simulated hydraulic heads for the provincial monitoring wells (black star) and the observed range of hydraulic head variation (blue line).

The simulated heads for monitoring wells (Figure 7b) illustrate the known variation of the hydraulic head. It can be observed that the simulated hydraulic head values generally fall in the vicinity of the observed range of the hydraulic head variation. Higher discrepancies are observed for observation wells close to intensive groundwater withdrawal.

3.2 Calibration parameters

The final hydraulic conductivities assigned to the hydrostratigraphic units are presented in Table 3. The recharge rates calibrated for each of the watershed and for the mountainous area separately are listed in Table 4. Both parameters were adjusted during the calibration process by applying numerical inversion with the embedded Pest algorithm in Feflow (Doherty, 2002). When compared to the initial values (Table 2) the calibrated hydraulic conductivities are close to initial values with the exception of the Dashwood-Mapleguard unit. Additional hydrogeological investigation is required to decrease the relatively high uncertainty in K values for this unit. The spatial distribution of the calibrated horizontal hydraulic conductivity (K_{xy}) is given in Figure 8.

Table 3. Final hydraulic conductivity values K_{xy} (horizontal) and K_z (vertical).

Hydrostratigraphic Unit	Hydraulic Conductivity K_{xy} (m/s)	K_z/K_{xy} (-)
Lake bottom	8.3×10^{-8}	1
Capilano-Salish	3.8×10^{-4}	1
Capilano (glaciomarine)	8.1×10^{-7}	1
Vashon-Capilano (coarse)	7.7×10^{-6}	1
Vashon (till)	4.6×10^{-8}	1
Quadra	2.1×10^{-5}	1
Cowichan-Dashwood	8.1×10^{-9}	1
Dashwood-Mapleguard	1.1×10^{-7}	1
Bedrock <10 m	9.0×10^{-6}	1
Bedrock 10-20 m	7.0×10^{-6}	0.1
Bedrock 20-70 m	3.8×10^{-6}	0.94
Bedrock 70-120 m	1.3×10^{-8}	0.01
Bedrock 120-170 m	9.8×10^{-9}	0.01
Bedrock 170-220 m	1.2×10^{-9}	0.01
Bedrock 220-280 m	1.2×10^{-10}	0.01
Bedrock > 280 m	1.2×10^{-11}	0.01

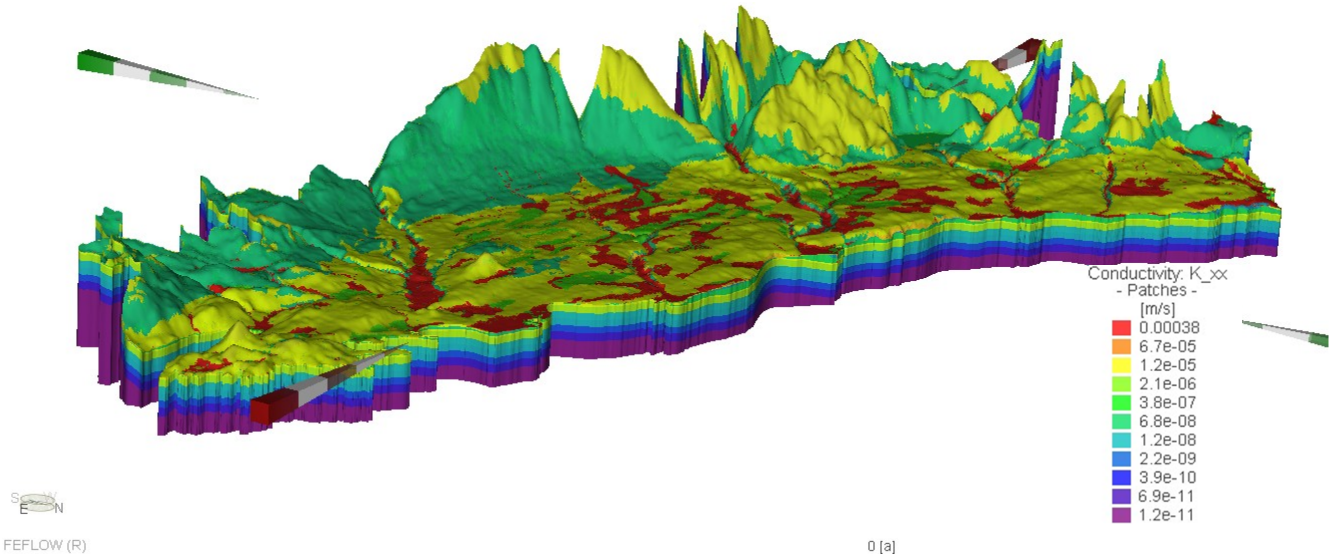

Figure 8 : Spatial distribution of calibrated horizontal hydraulic conductivities for the groundwater flow model.

In Table 4, the calibrated recharge rates are compared to values obtained from baseflow separation for the main watersheds. The average recharge rate for each watershed was obtained by dividing the estimated annual baseflow contribution by the surface area of the watershed. It can be observed from Table 4 that the simulated recharge rates are, in general, slightly higher than the range of values assessed with the 7-day low and the Furey and Gupta method. The exceedance of approximately 12% is still considered to be satisfactory since the relatively high uncertainties related to the choice of the parameters in the Furey-Gupta hydrograph separation method. The simulated recharge rates correlate well with the values reported for a study by Liggett and Gilchrist (2011) and Waterline (2012). For the lowland area, the reported recharge values range between 28 and 500 mm/y with calibrated values ranging from 112 to 396 mm/y (Figure 9).

The suitability of the calibrated K and recharge rate values is also confirmed by the global mass balance error of the calibrated model of 0.0002%. This low mass balance error is an indication of a good numerical convergence of the 3DGFM model.

Table 4: Average recharge values estimated by hydrograph separation methods (columns A and B), simulated by the groundwater flow model (column C), and respective ratios.

River	Recharge (mm/y)			Ratio C/A	Ratio C/B
	A: 7-Day low flow	B: Furey&Gupta	C: 3DGFM	(-)	(-)
Nile creek	259	387	289	1.11	0.75
Big Qualicum	259	354	396	1.53	1.12
Little Qualicum	119	228	256	2.15	1.12
Englishmen	48	99	112	2.33	1.13

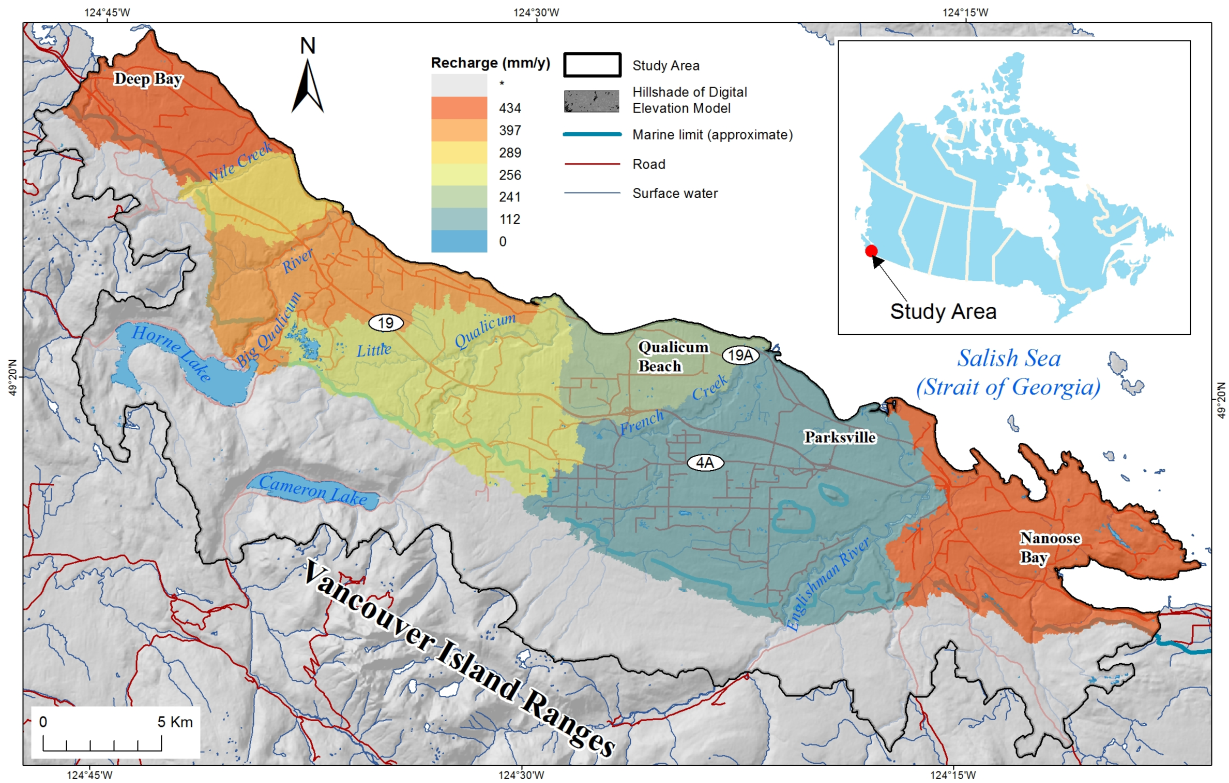

Figure 9: Applied groundwater recharge rates over the surface layer of the groundwater flow model. Note that recharge rates are lower than those depicted in areas where seepage occurs, in particular near the main rivers. In mountains, a recharge rate (not shown) of 450 mm/year was applied to simulate influx to the lowland from the mountains.

4. Description of the Groundwater Flow System

This section describes the dynamics of the groundwater flow system through analysis of the calibrated steady state 3DGFM model. First, potentiometric maps are presented for the Quadra Sand (hydrostratigraphic unit V) and the bedrock (hydrostratigraphic unit IX), the most exploited aquifer units in the study area. The groundwater flow system including groundwater residence times and interaction between hydrostratigraphic units and surface water bodies is discussed next considering the hydrogeological settings defined by Benoit et al. (2015). A typical example of using the regional-scale model for a local-scale investigation is presented at the end.

4.1 Potentiometric Maps

The simulated potentiometric maps for the Quadra unit (hydrostratigraphic unit V) and the bedrock unit (hydrostratigraphic unit IX) are given in Figures 10 and 11, respectively. The groundwater flow in the Quadra unit converges toward the main streams and respects the groundwater divides. Despite the fact that the Quadra unit is generally not in a direct hydraulic contact with the surface water bodies, seepage faces assigned along the riverbanks act as drains and contribute to decreasing the water levels and directing groundwater flow toward the rivers (Figure 10).

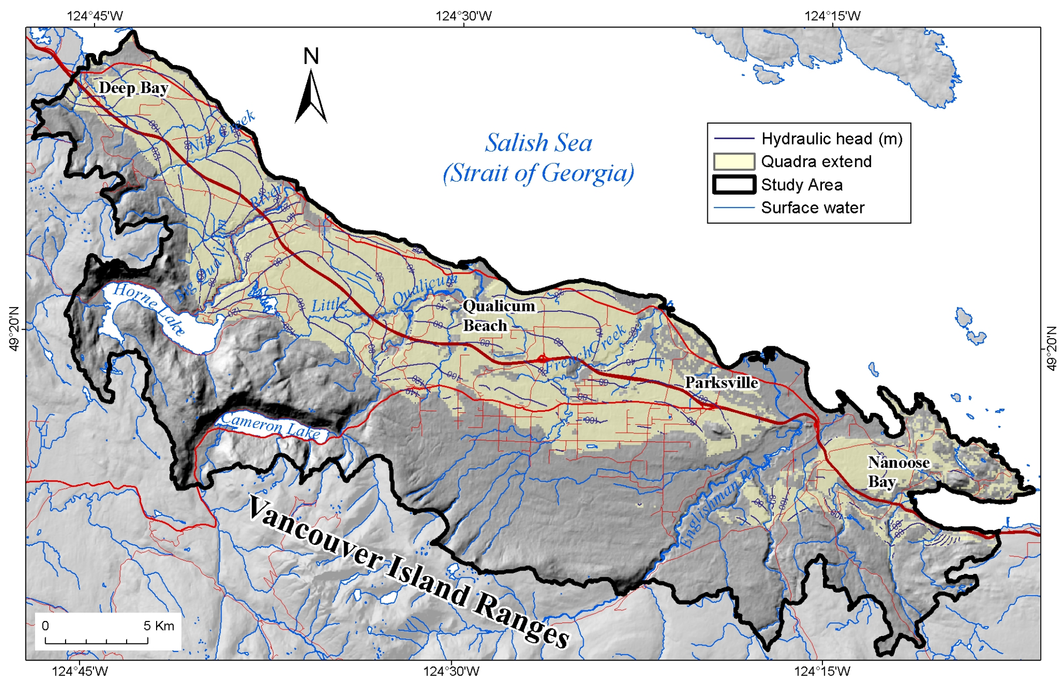

Figure 10: Potentiometric map for the Quadra Sand (hydrostratigraphic unit V).

The potentiometric surface for the top weathered bedrock layers shows different regional trends (Figure 11). The groundwater in bedrock essentially drains toward the coast and in regions where unconsolidated sediments are absent or relatively thin it reproduces narrowly the topographic surface. The analysis of the water budget reveals that 71% of the groundwater is discharging to surface water bodies, whereas the remaining 29% discharges along the coast of the Strait of Georgia.

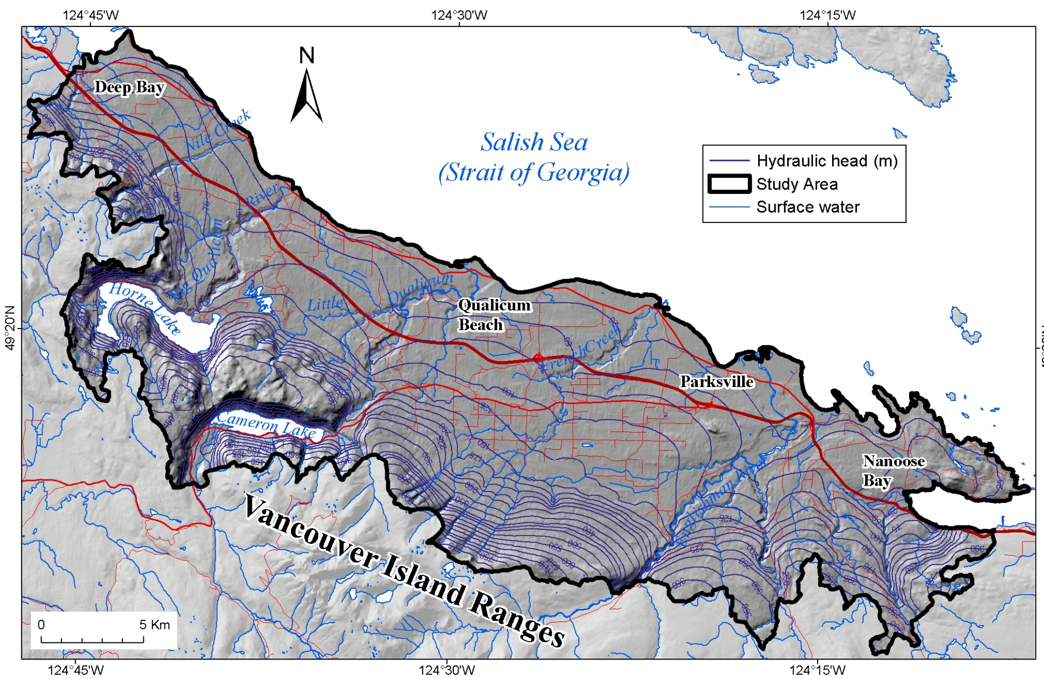

Figure 11: Potentiometric map for the bedrock (hydrostratigraphic unit IX).

4.2 Regional Hydrogeological Settings

Figure 12 presents the spatial distribution of the major hydrogeological settings together with the respective hydrostratigraphic columns (Benoit et al. 2015).

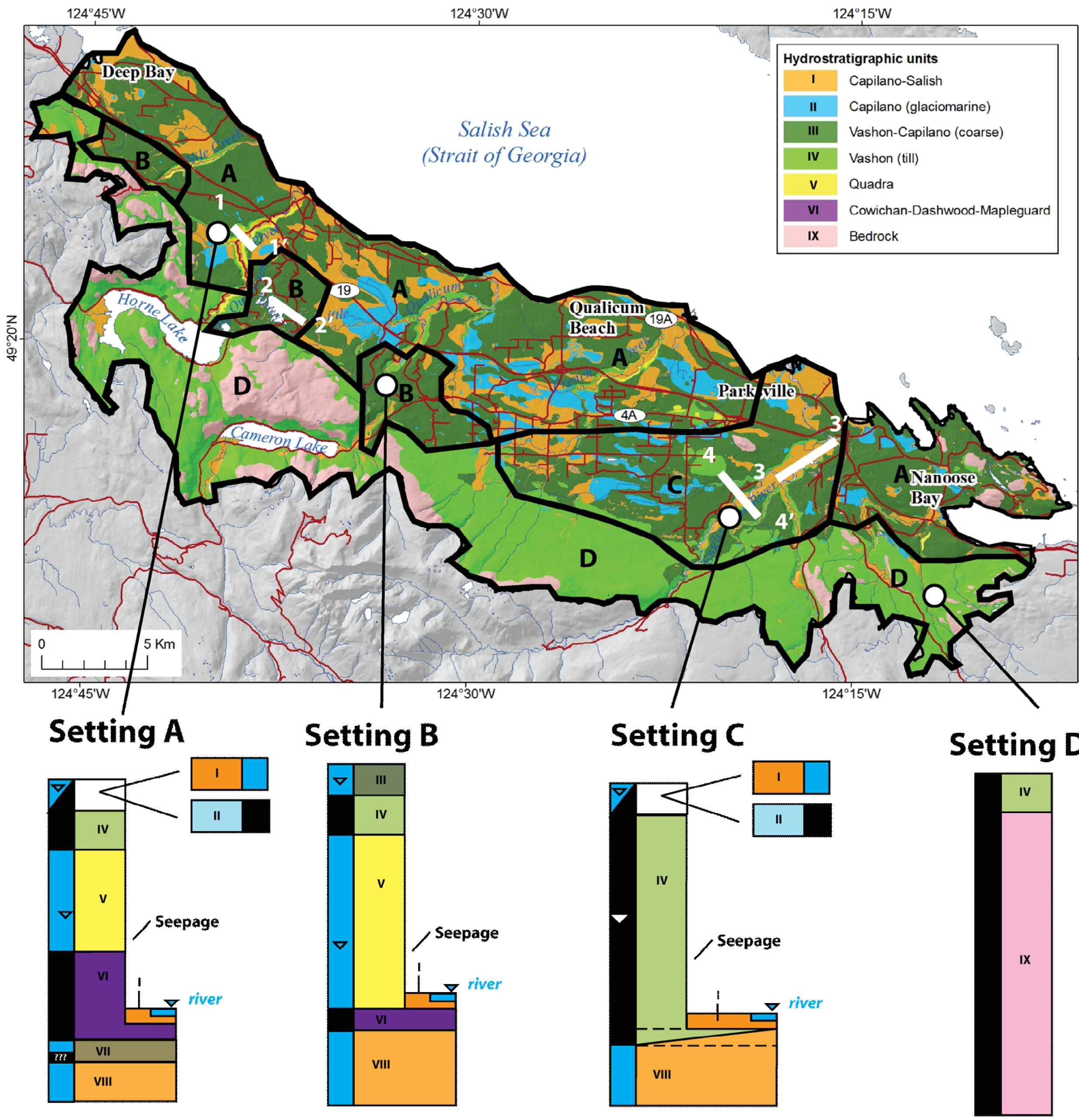

Figure 12: Distribution of the major hydrogeological settings together with respective hydrostratigraphic columns (modified from Benoit et al. 2015). Solid white lines indicate locations of cross-section given in Figures 14, 15, 16 and 17.

4.2.1 Lowland (A)

These hydrogeological settings are representative for Nile Creek, Qualicum River, Little Qualicum River and French Creek in the eastern-central portion of the study area, and for the extreme western portion in the vicinity of the Nanoose Bay. Almost all of the hydrostratigraphic units are present with the exception of the main rivers where the stratigraphic sequence has been heavily eroded by fluvial incision. Quadra sand seepage faces are commonly set back form the modern river which occupies a narrow portion of the main river valleys and are flanked by low alluvial terraces. As a result, most of the surficial units, in particular the Quadra Sand, are disconnected from surface waters and seepage faces could be observed along the valley walls and along the river banks (Figure 12 and Figure 14). Seepage occurs when the aquifer and/or aquitard units are exposed at the surface and create a seepage face or springs. Most of this water eventually reaches the river through surface runoff or short flow paths through the alluvial terraces. For example, it was estimated in the Big Qualicum valley that groundwater discharging from the Quadra Sand to the rivers as seepage had an average travel time of < 30 years (Figure 13a). As well, bearing in mind that: (i) rivers commonly flow on Capliano sediments overlying the compact Dashwood till, and (ii) Quadra aquifer is not in direct hydraulic contact with surface waters, the groundwater withdrawal from the Quadra unit will intercept groundwater that will otherwise seep to the rivers. It will, however, rarely directly draw water from the rivers through induced recharge.

Groundwater from bedrock will also eventually end up as surface water, but at a much slower rate (Figure 14). Travel times for bedrock groundwater are up to 200 years (Figure 13b). Longer travel times are the results of longer travel distances and reduced flow velocity due to the less permeable Cowichian-Dashwood unit. The streamlines illustrated in Figure 13b are mainly within the top weathered bedrock layer with higher K values when compared with the underlying bedrock layers. The groundwater in the deeper layers will be considerably older. The permeable Capilano sediments are also present along the rivers and, due to the relatively high storage capacity, can impact the interactions between the groundwater and surface waters. This is indicated in Figure 14 by higher flux values.

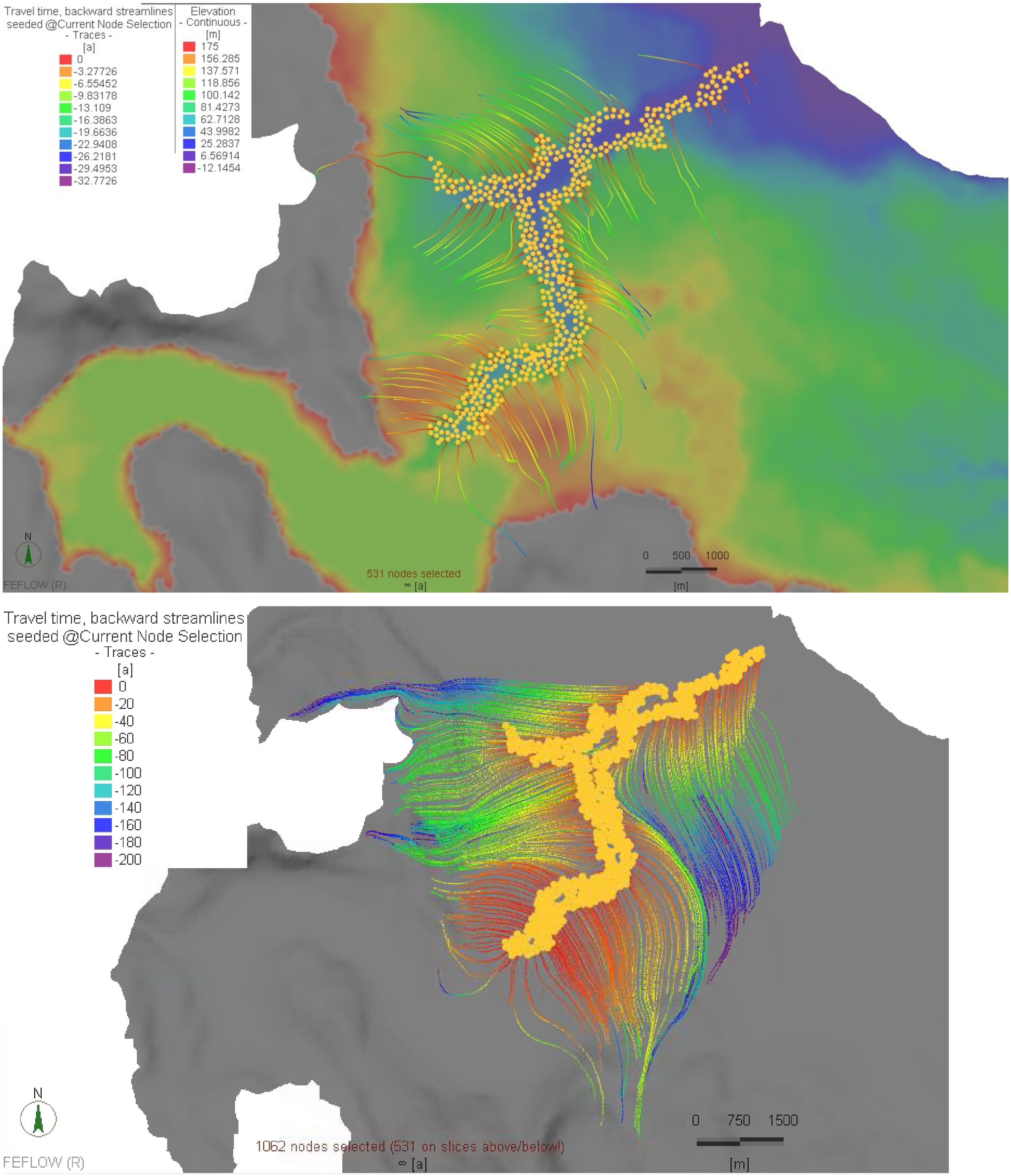

Figure 13: Big Qualicum valley with topography as background. a) Quadra Sand (yellow nodes) and b) top of bedrock (yellow nodes) with travel time streamlines discharging from Quadra. The travel time scale (years) is for backward direction from nodes. Travel time estimates are based on a constant flow porosity of 10% for the unconsolidated sediments and 1% for the bedrock.

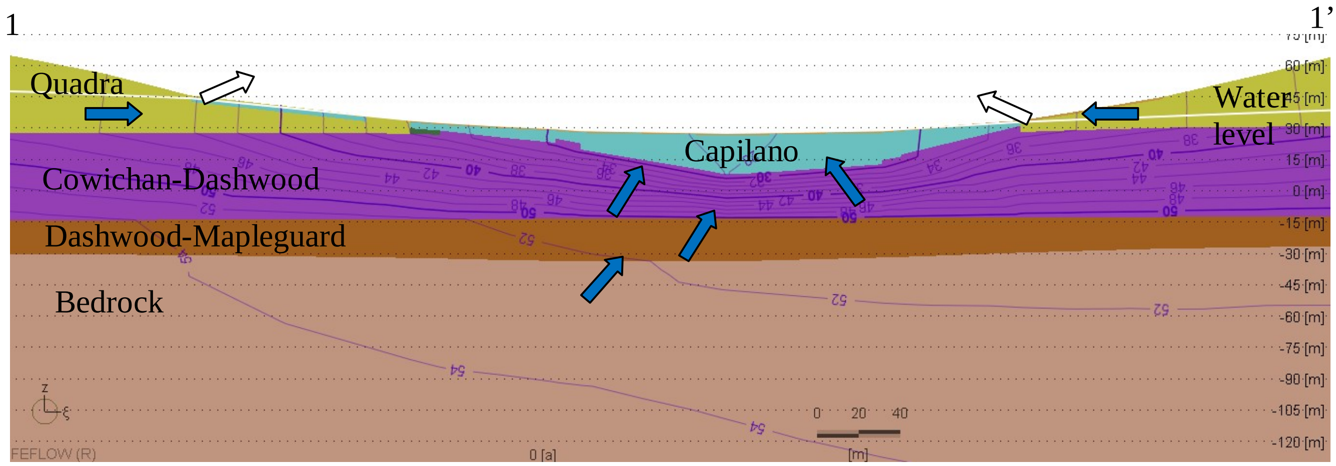

Figure 14: Cross-section 1-1’ (see Figure 12 for location). Seepage occurs when Quadra Sand is exposed at the surface and generates a seepage face or springs (Near Big Qualicum river). White line indicates water table, purple contours represent hydraulic head, and blue and white arrows indicate saturated groundwater flow and seepage, respectively.

4.2.2 Cameron-Horne Lakes (B)

The groundwater flow at the outlet of Cameron and Horne lakes (setting B) area is similar to that of the Lowland setting A. The key difference is that the surficial units consist of considerable glaciofluvial sand and gravel deposits of the Vashon coarse unit (Figure 12). The Vashon coarse unit represent an important aquifer perched over the low permeability Vashon till or in direct contact with the Quadra unit (Figure 15). The nature of the hydraulic connection between the Vashon coarse unit and underlying aquifer units is poorly understood and no borehole with reliable geological descriptions was available for this study. According to the stratigraphic model, the Vashon coarse and Quadra sand units are two distinct aquifers when separated by the till. Each aquifer unit displays saturated mainly horizontal flow (Quadra bedrock top) or unsaturated flow (Vashon coarse). The hydraulic gradient suggests that the Vashon till contributes lower recharge than the Quadra unit. At this elevation, the deeper Mapleguard sediments may not be present.

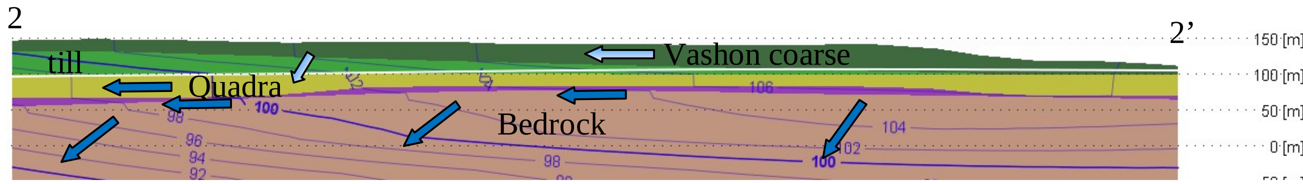

Figure 15 Cross-section 2-2' (see Figure 12 for location), Cameron-Horne lakes with the Vashon coarse unit highlighted in yellow. The hydraulic connection between the Vashon coarse unit and underlying aquifers is indicated with arrows: blue arrows for saturated groundwater flow and light blue arrows for seepage. White line indicates the water table and the blue and purple contours are hydraulic head.

4.2.3 Englishman River (C)

The hydrogeological setting and the groundwater flow at the Englishman River (setting C) are completely different from the two previous cases. Spatially, the stratigraphy is defined by the watershed limits of the Englishman River, which generally flows on till and bedrock units. The Capilano deposits along the Englishman River (especially in the downstream portion) display important storage capacity and moderate groundwater-surface water interaction (Figure 16). Within the broader valleys, the Salish sediments (recent fluvial deposits) commonly form lower river terraces and the immediate riverbank. A direct hydraulic connection is expected between the river and groundwater in these riverbank terraces. Seepage water from the adjacent aquifer (Vashon coarse) together with the surface runoff and direct precipitation may infiltrate Salish sediments (Figure 17). Those sediments are not considered to be important aquifer unit due to their limited extent and thickness, however, they represent important water storage capacity that impacts the contribution to stream flow. Groundwater extraction from the Salish sediments will necessarily affect discharge to the adjacent streams. The groundwater flow in bedrock units, when in direct contact with the surface waters, also contributes to the river discharge. However, the magnitude of this flux is comparatively low due to the relatively low permeability of the bedrock units, an exception occurs when fracture flow or weathered bedrock is present (see nodal flux, Figure 17). In general, the hydrostratigraphic settings in the Englishman River watershed (C), characterized with streams flowing mostly on till and/or bedrock, generate lower seepage flow when compared to the other two cases.

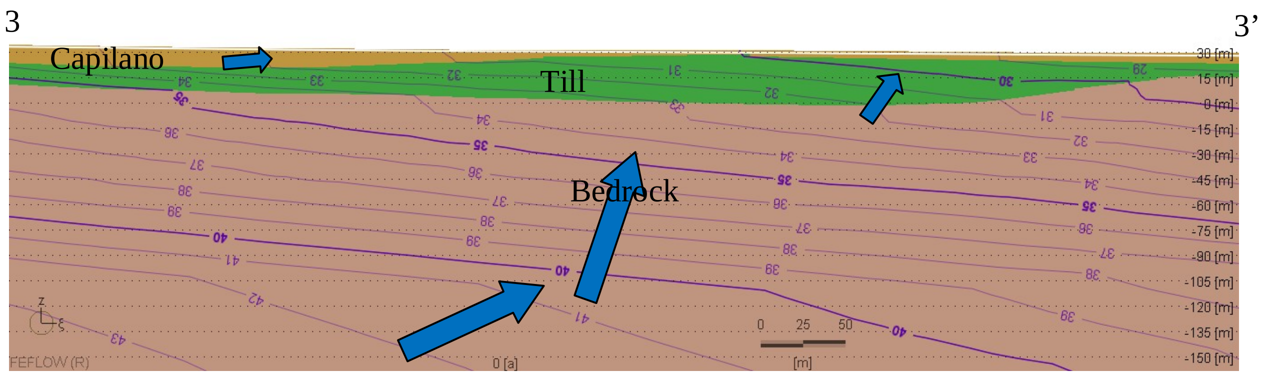

Figure 16: Cross-section 3-3’ parallel to the Englishmen River (see Figure 12 for location). White line represents water table; purple contours are hydraulic heads, and blue arrows indicate the direction of the saturated groundwater flow.

B’

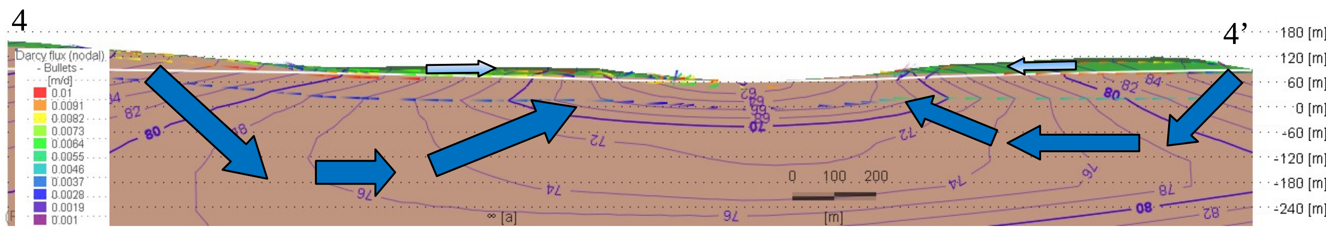

Figure 17: Cross-section 4-4’ perpendicular to the Englishmen River (see Figure 12 for location). White line represents water table; purple contours are hydraulic heads, blue arrows indicate the direction of the saturated groundwater flow, and seepage is shown with light blue arrows.

4.3 Example of Use of the Regional Flow Model for Groundwater Management

The use of the regional 3DGFM model for sustainable management of the groundwater resource must be conducted with extreme care. As discussed earlier, the data used, the model assumptions and the resolution and its calibration are not sufficient for accurate and direct use at local scales. The purpose of the regional model is for summary assessment of the groundwater components for a given scenario and for the planning of future work. With those caveats the following example is presents a model scenario of an intensive groundwater extraction exposed to potential sea-water intrusions near the coastline (Figure 18 and Figure 19).

The water well draws groundwater mainly from the Quadra and Mapleguard unit. The simulated groundwater divides illustrated in Figures 18 and 19 indicate that no salt-water intrusion will reach the well. As can be observed in these figures, the Quadra sand is located at altitudes higher than the sea water level and cannot be directly affected by sea intrusion for the specified withdrawal rate, 4,312 m^3/d. On the other hand, salt-water intrusion caused by the extraction is more likely to occur for wells completed in underlying Mapleguard aquifer and bedrock units, as it can be deduced from Figure 19 for case with higher pumping rate or for well located closer to the coast line. These units are in direct hydraulic connection with the sea (lie below marine limit) and fresh water/salt water interface may be present. These findings show the utility of the regional model to test various pumping scenarios and for pre-selection of locations of new wells and piezometers for further local investigation.

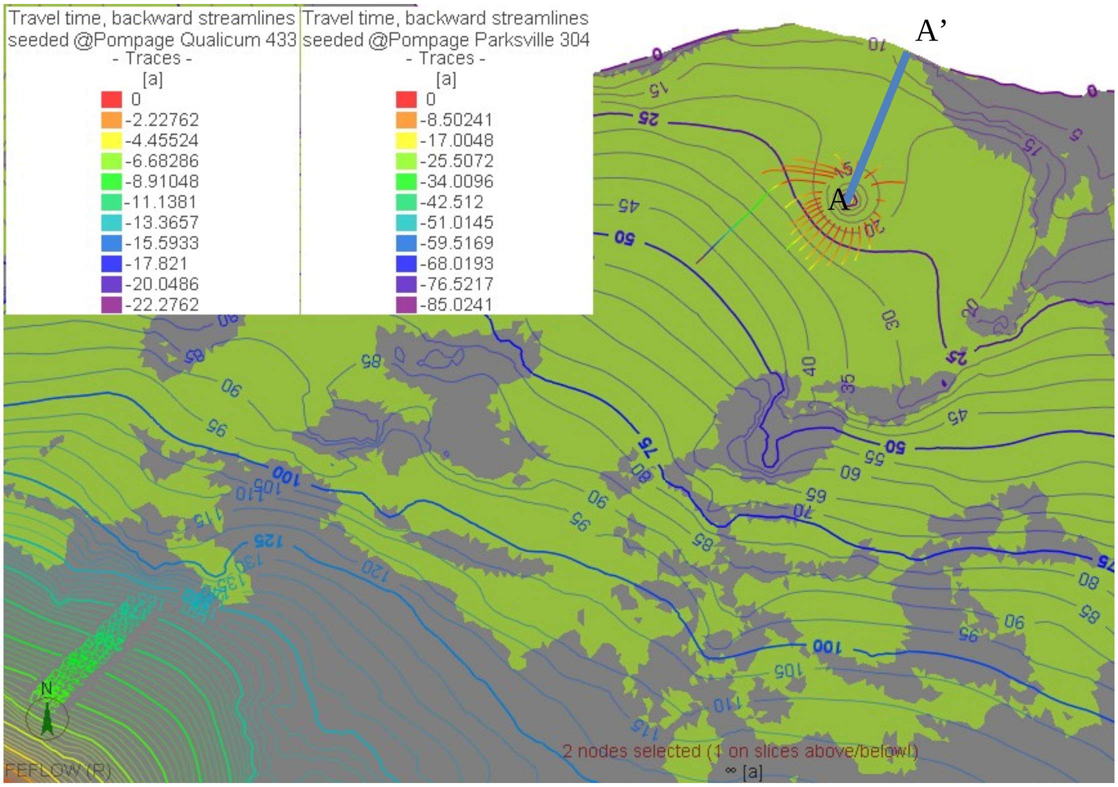

Figure 18 : 2D Aerial view of the groundwater withdrawal of 4,312 m^3/d on hydraulic heads with travel time streamlines. Green area represents extend of the Quadra unit. Location of cross-section A-A' for Figure 19 is also given.

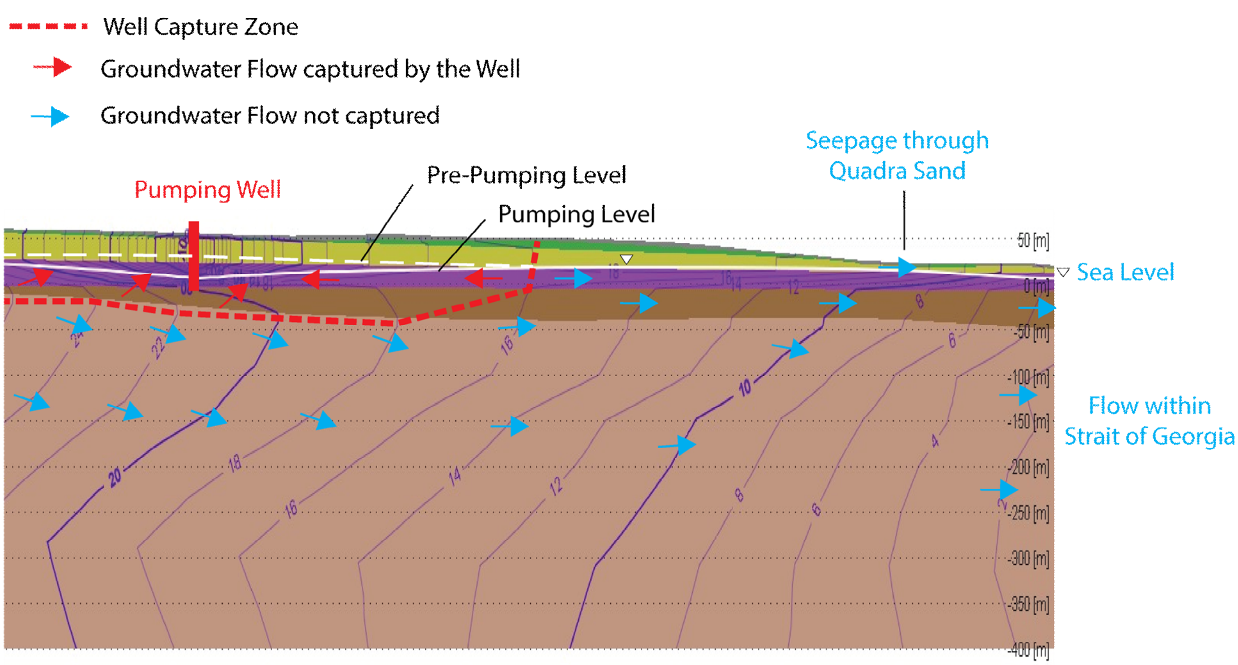

Figure 19 : Cross-section A-A' showing well capture zone for an hypothetical pumping well. Cross-section location is shown in Figure 18.

5. Conclusions

A regional groundwater flow model, 3DGFM, of the Nanoose-Deep Bay aquifer system on eastern Vancouver Island, BC, was presented. 3DGFM was built integrating the existing hydrostratigraphic model of the study area, 3DHSM, along with existing hydrogeological information, such as groundwater levels, hydraulic properties of surficial sediments and bedrock units, and baseflow estimates from river hydrograph records. 3DGFM was calibrated against available groundwater levels in water and monitoring well. Hydraulic conductivity and recharge rates were used as calibration parameters. A steady state simulations was conducted using the calibrated model to provide insights on the major characteristics of the aquifer system such as recharge rate, groundwater residence time, and interactions between surface water and groundwater. This regional model provides a framework for more local scale work that can more appropriately address sustainable management of the groundwater resources. Due to the scale of the study area, the complexity of the aquifer system and the assumptions introduced in 3DGFM, its main purpose is to provide regional picture of the groundwater resources that can be used to constrain local hydrogeological investigations.

Certain gaps in knowledge of the regional hydrogeology have been observed during this study which will need to be addressed in order to improve the reliability and accuracy of 3DGFM and future modelling, such as :

(i) streamflow gaging stations at the mountain outlets to complement the existing gauging network in the lowland areas;

(ii) groundwater samples analysed for age to better constraint the groundwater flow systems and residence times;

(iii) additional hydraulic property characterisation of both low permeability and aquifer units, which includes definition of hydraulic property variability for main hydrostratigraphic units;

(iv) Better define surface water withdrawal and well pumping rate histories.

The addition of such information to the 3DGFM provided in this study would improve the hydrogeological framework of Nanoose-Deep Bay aquifer system and support refinement of sustainable groundwater resources management.

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Appendix A

Numerical model file

File : Nanaimo_GW_model.fem

Feflow ASCII Interchange FEM Format version 6.208