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Three dimensional hydrostratigraphic model of the Nanoose – Deep Bay Area, Nanaimo Lowland, British Columbia

N. Benoit, D. Paradis, J.M. Bednarski, T. Hamblin, and H.A.J. Russell

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doi:10.4095/296302

Recommended citation
Benoit, N., Paradis, D., Bednarski, J.M., Hamblin, T., and Russell, H.A.J., 2015. Three dimensional hydrostratigraphic model of the Nanoose-Deep Bay area, Nanaimo Lowland, British Columbia; Geological Survey of Canada, Open File 7796, 1 .zip file. doi:10.4095/296302

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Abstract

To support improved sustainable groundwater management of the Nanaimo Lowland, British Columbia (BC), a three-dimensional (3D) hydrostratigraphic model was developed for the Nanaimo Lowland aquifer system. The study area is a coastal strip running from Nanoose to Deep Bay on eastern Vancouver Island (~580 km^2). The 3D model was developed using existing driller's logs, published cross-sections and new data which include rotosonic coring, borehole geophysics logs, seismic reflection profiles and surficial geology mapping. The detailed surficial geology consists of 31 different units which, for modelling, are grouped into 9 major hydrostratigraphic units (from youngest to oldest): Capilano-Salish (sand aquifer), Capilano glaciomarine (silty clay aquitard), Vashon-Capilano (coarse sand and gravel aquifer), Vashon (till aquitard), Quadra (sand aquifer), Cowichan-Dashwood (compact silt aquitard), Dashwood-Mapleguard (sand aquifer), sedimentary bedrock and metamorphic bedrock (aquifer near surface with potential decreasing with depth). This succession of Late Pleistocene to Holocene sediments is up to 140 m thick and is present over most of the study area, thinning to the southwest with rising topography and bedrock outcrops. Capilano-Salish and Vashon-Capilano deposits are shallow and contain unconfined aquifers with relatively high vulnerability to surface contamination and low groundwater resource potential due to their limited thicknesses. Quadra Sand is the most exploited aquifer unit. It underlies the ubiquitous and low permeability Vashon till and it overlies Cowichan-Dashwood aquitard or bedrock. Quadra sediment has an average thickness of 19 m and it is generally above sea and river levels. This would minimize the potential of seawater intrusion and direct surface water extraction, respectively, in the event of intensive groundwater extraction in Quadra unit. The Quadra is an important aquifer, however only about one-third of its thickness is saturated likely due to the overlying Vashon till aquitard that limits groundwater replenishment. Dashwood-Mapleguard sand is a lower confined aquifer unit that extends below sea level. It may have hydrogeological properties and resource potential similar to the Quadra sand, but it is present only in areas where the bedrock elevation is low, generally closer to the coastline. It may be more vulnerable to sea water intrusion, and remains poorly understood. The relatively low permeability regional bedrock aquifers of the Nanaimo Group are generally exploited only where the Quadra aquifer is not present. Their hydrogeological potential is poorly understood due to lack of subsurface data. This hydrostratigraphic model will be used to support groundwater flow modelling.

1 Introduction

Groundwater is an important source of potable water in the Nanaimo Lowland area, BC. Its availability and quality are governed by the sedimentary facies, the 3D, architecture and hydrogeological properties of unconsolidated sediments and bedrock units. To support sustainable groundwater management of the Nanaimo Lowland, a 3D hydrostratigraphic model (HSM) and groundwater flow model (GFM) were developed for the Nanaimo Lowland aquifer system. This report documents the 3D hydrostratigraphic modelling results. The results of the GFM are presented in the Open File OF7845 (Benoit et al., 2015).

The Nanaimo Lowland Groundwater Study was a collaboration with 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 southwest to northeast along the eastern coast of Vancouver Island from Deep Bay to Nanoose Bay, BC, (Figure 1). The GSC contribution to the study is part of the Groundwater Geoscience Program (2009-2014) assessment of 30 Key Canadian Aquifers (http://www.nrcan.gc.ca/earth-sciences/resources/federal-programs/groundwater-geoscience-program/10909).

The principal aim of this study was to better understand the composition, distribution and stratigraphic architecture of the hydrostratigraphic units. Development of a 3D model provides a basis for integrating knowledge gained during the course of the study and forms a framework for a numeric groundwater flow model (Benoit et al., 2015). The objective of this report is to summarize the development of the 3D hydrostratigraphic model of the Nanaimo Lowland. Detailed analyses of thickness and elevation range of each unit are documented. The hydrostratigraphic layer distributions are presented in 3D volumes and cross-sections. The digital HSM data are provided in Appendix A.

2 Study Area

2.1 Location and Physiography

The Nanaimo Lowland is an approximately 10 km wide and 150 km long low relief coastal strip along the southeastern part of Vancouver Island, BC. To the southwest it is bounded by the Vancouver Island Ranges (up to 1800 metres above sea level (masl)) and to the northeast by the Strait of Georgia. The selected study area within the Nanaimo Lowland is approximately 580 km^2 (10 km by 60 km) from Nanoose Bay to Deep Bay in the north (Figure 1). This comprises, essentially, the coastal plain below the last de-glaciation maximum sea level rise of approximately 150 masl (Bednarski, 2015). The coastal plain is predominantly composed of Pleistocene deposits of variable thickness and isolated outcroppings of bedrock that are incised by five major rivers draining from west to east. Within the study area, the topography ranges from sea level at the coast, up to 1819 masl (Mount Arrowsmith). The coastal plain terrain is sub-horizontal with slopes < 6% except along incised rivers valleys (up to 20%). Two major lakes are present in the study area: Horne and Cameron lakes.

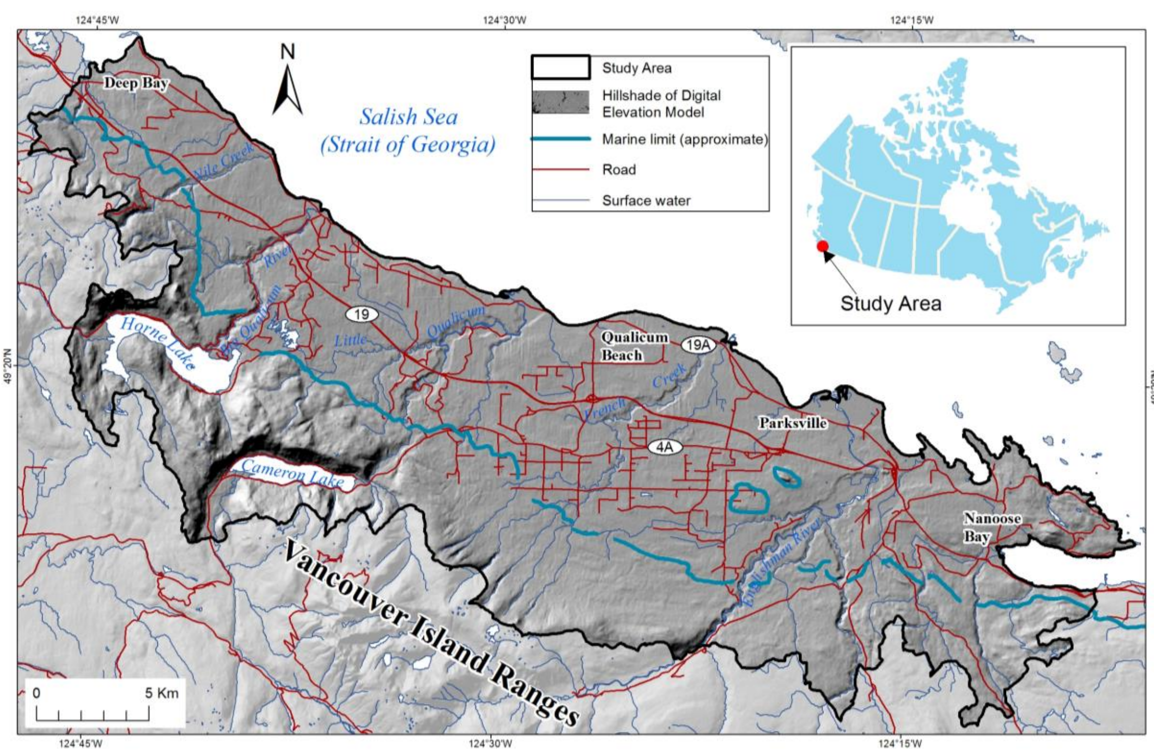

Figure 1: Location map of the Nanoose-Deep Bay study area in the Nanaimo Lowland on Vancouver Island, BC.

2.2 Bedrock Geology

Bedrock in the study area consists of dark green Devonian to Jurassic-aged volcanic and metamorphic rocks of the Wrangellia terrain (basement) that are unconformably overlain by Upper Cretaceous-aged Nanaimo Group sedimentary rocks:

- Wrangellia rocks are more common in the southern part of the study area and in the mountains. The regional unconformity surface of the basement is commonly fractured and heavily-weathered making the upper meter or so of basement more porous. The basement topography likely influenced the presence, distribution and thickness of the unconformably-overlying lower Nanaimo Group units (Johnstone et al., 2006; Ward and Stanley, 1982).

- The Nanaimo Group is a terrestrial to marine succession formed within a basin during the orogenic development of the Canadian Cordillera in Jurassic-Cretaceous time. Found throughout the basin, it is up to 4 km thick and consists of 11 interfingering sandstone-dominated and shale-dominated formations. However, in the study area, only the lower 8 formations are present. The dominant bedrock units are the Comox and Haslam formations, which are regarded as aquifer of moderate and low capacity. The Comox formation sandstone/conglomerate is commonly between 100-150 m thick, and is overlain by Haslam Formation shale that is 100-150 m thick.

The bedrock geology included in the HSM is simplified into two bedrock units: 1) the Upper Cretaceous Nanaimo Group sedimentary rocks and 2) the Meso-Paleozoic, metamorphosed and intrusive basement (Figure 2). Because of the lack of subsurface data and outcrops, the detailed limits of formations cannot be mapped for this area. Both the Wrangellia basement and Nanaimo Group rocks are fractured. Field observations from 29 scattered outcrops throughout the basin document 163 fracture sets in Nanaimo Group rocks, that have a consistent orientation pattern of ~ NE/SW, with an average orientation of about 30°/120°. This trend is similar to that observed by previous studies. The extent of fractures in the metamorphosed basement are not well known but they may have a similar pattern.

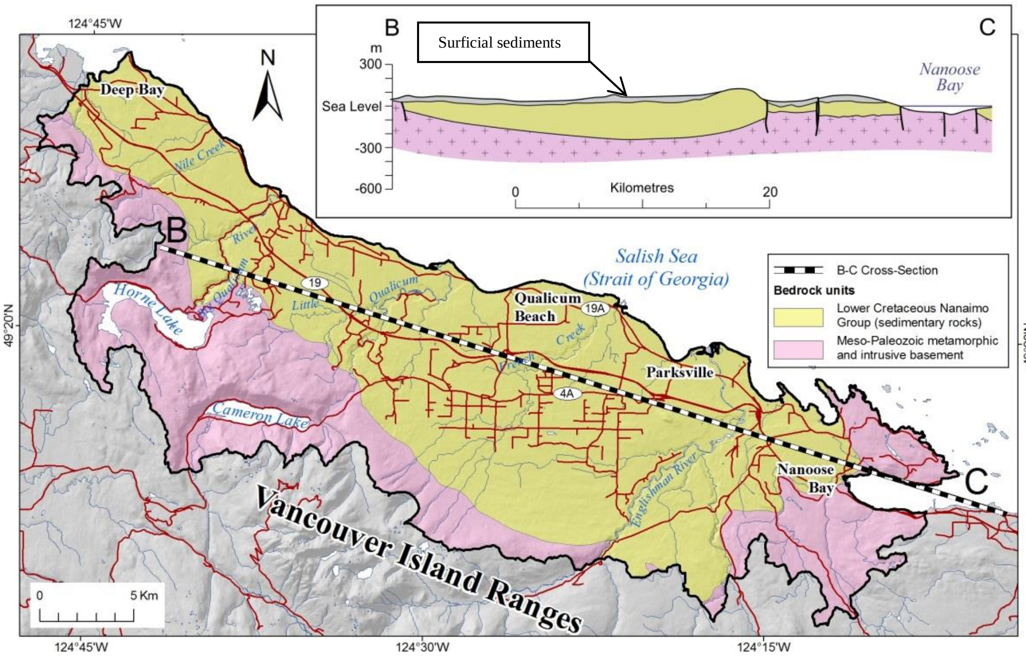

Figure 2 : Simplified bedrock geology map and cross-section of the Nanoose–Deep Bay study area (modified from Hamblin, 2012).

2.3 Surficial Geology

The unconsolidated sediment in the study area is comprised of marine, fluvial and glacial materials of Pleistocene and Holocene age (Figure 3). They generally form an extensive cover and can exceed 100 m in thickness but bedrock outcrops are not uncommon, reflecting the highly variable nature of the sediment thickness (Figure 7). The Nanaimo Lowland is covered by a succession of two groups of glacial deposits (Vashon and Dashwood) separated by non-glacial deposits (Cowichan Head formation) and proglacial outwash deposits (Mapleguard sediments and Quadra Sand), which are postglacial marine and fluvial deposits (Fyles, 1963), as briefly described below (from oldest to youngest):

- Mapleguard sediments are the oldest Pleistocene deposits present in the Nanaimo Lowland. They are composed of bedded sand, silt, clay and minor gravel up to 10 m thick along the sea cliffs, however (Fyles, 1963) reported more than 20 m in Auger borings. Mapleguard sediments are considered more likely to be outwash deposited at the onset of the penultimate glaciation (Hicock, 1980; Hicock and Armstrong, 1983; Ryder and Clague, 1989).

- Dashwood Drift conformably overlies Mapleguard sediments and is commonly less than 10 m thick (Armstrong and Clague, 1977). Dashwood Drift is generally comprised of muddy diamicton glaciomarine sediment overlain by cobbles and gravel, as observed in sea cliffs (Armstrong and Clague, 1977; Fyles, 1963; Hicock and Armstrong, 1983). The gravel is a mixture of plutonic rocks derived from the Coast Mountains and volcanic and sedimentary rocks from the east coast of Vancouver Island. The geochemical signature of Dashwood has an elevated concentration of metals compared to Quadra Sand (Knight et al., 2015). Dashwood Drift was deposited during the penultimate glaciation early Wisconsinan, as deduced from the presence of marine shells which date beyond the range of radiocarbon in overlying sediments (Clague, 1980).

- Cowichan Head Formation unconformably overlies the Dashwood Drift and is up to 21 m thick (Hicock and Armstrong, 1983). The formation has been divided into a lower member of clayey silt and sand with marine shells, and an upper member of sandy silt and gravel, commonly with reddish oxidized hues rich in fossil plant remains (Armstrong and Clague, 1977). Gravel provenance is a mix of volcanic and sedimentary rocks (Armstrong and Clague, 1977; Clague, 1976). Geochemically the Cowichan also has metal concentration similar to Dashwood. The lower member is interpreted as glacimarine, whereas the upper member is attributed to estuarine and fluvial environments (Armstrong and Clague, 1977).

- Quadra Sand, which overlies the Cowichan Head Formation, is generally found above sea level and below 100 masl, and can exceed 75 m in thickness. It consists of horizontally and cross-stratified, well-sorted sand with minor silt and gravel with wood and peat lenses in its lower portions. Geochemically the Quadra is distinguished from other units by the Sr concentrations throughout the unit (including the upper Cowichan Head Formation; Knight et al., 2015). Quadra is interpreted to be outwash deposited during the transition from non-glacial to glacial conditions at the onset of the Fraser Glaciation (Armstrong and Clague, 1977; Clague, 1977, 1976). In general the Quadra sands can be regarded as proglacial outwash formed subaerially on outwash plains extending across and along the margins of the present-day Strait of Georgia. The Quadra Sand is the most important water-bearing unit in the study area.

- Vashon Drift unconformably overlies Quadra Sand with thicknesses generally up to 30 m, except at observed locations where depressions left by heavily eroded Quadra Sand were filled by approximately 60 m of drift (Fyles, 1963). Over the lowland, Vashon Drift tends to be a sandy diamicton except within some valleys where the matrix is more clayey. Vashon Drift also includes sand and gravel in eskers, kame terraces, and ice-contact fans and deltas deposited by meltwater streams during early deglaciation. The geochemical signature of Vashon has a number of complicated trends over the unit thickness related to various element groupings (Knight et al., 2015). The streams initially would have flowed along the margins of the retreating Cordilleran and local glaciers, with some deltas or terraces building into short-lived ice-dammed lakes. As the Cordilleran ice occupying Georgia Depression thinned, the sea inundated coastal lowland to an elevation of at least 150 masl.

- Capilano sediments generally conformably overly the Vashon Drift, except locally where the Capilano sediments unconformably overly Quadra Sand. Capilano sediments are up to 25 m thick. Lower Capilano sediments are coarse glaciofluvial outwash gravel and sand, with minor diamicton. Geochemically there is a decrease in concentration from the base of the Capilano Sediments upwards for Ba, Ca, K, Rb, and Zn and there is an increase in the concentration for Cu, Fe, Mn, and V (Knight et al., 2015). Thick glaciomarine and marine sediments were deposited in isostatically depressed coastal areas. These deposits are considered to be postglacial, but still affected by rapid emergence and influxes of glacial meltwater during early deglaciation. Relative sea level fell from elevations of approximately 150 to 50 masl in the first thousand years following deglaciation, eventually reaching a minimum 15 m below present sea level (Hutchinson et al., 2004). Consequently, continued uplift led to entrenching and terracing of late glacial and older deposits and vegetated slopes reduced the level of aggradation. Fluvial terraces formed in valleys and deltas prograded seaward where sediment supply was adequate. Deltaic and alluvial sediment grading to modern sea level and are commonly classified as Salish sediments.

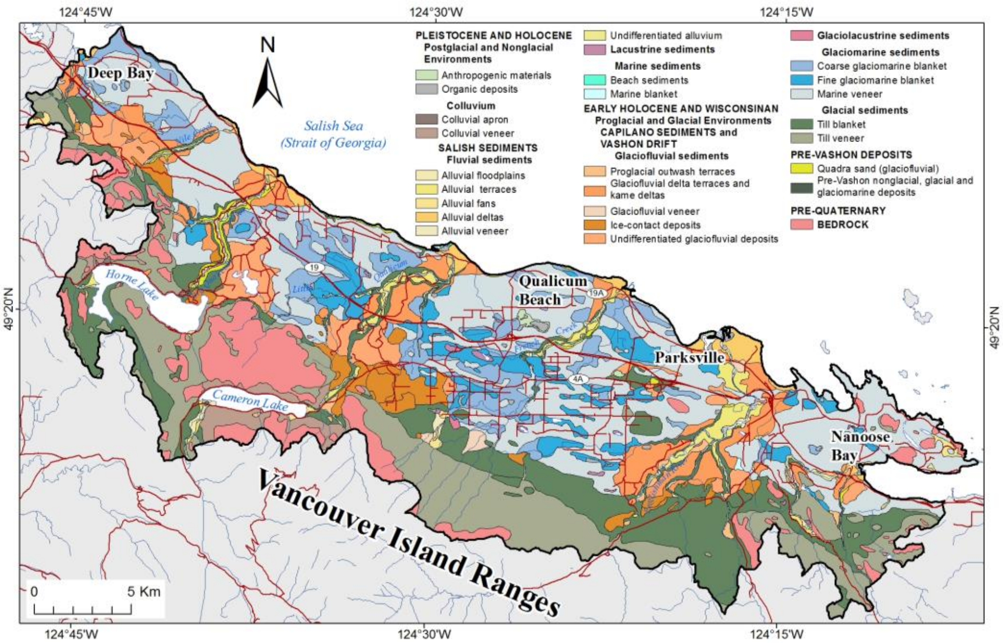

Figure 3 : Surficial geology map of the Nanoose–Deep Bays study area (modified from Bednarski, 2015).

3 Hydrostratigraphic Modelling Approach

The HSM defines the distribution and thickness of the hydrostratigraphic units in 3D based on a synthesis of available geological and hydrogeological information. The integration of available data for the construction of the hydrostratigraphic model was mainly completed using Leapfrog Hydro software (ARANZ Geo Limited, 2015). Leapfrog-Hydro is a 3D geographical information system (GIS) that is also designed to support transfer of the hydrostratigraphic model to a numerical grid for groundwater flow simulations (e.g. FeFlow, MODFLOW).

3.1 Data Sets

The hydrostratigraphic model was built from existing geological information and additional data collected from fieldwork carried out by the GSC specifically for this project (Figure 4). The compilation of existing data includes:

- Digital Elevation Model (DEM) at a 30x30 m grid resolution (GeoData, 2013);
- Public wells database (MoE, 2013, p. 20): After filtering and validation 708 bedrock wells and 570 surficial wells were retained.
- Surficial geological map including stratigraphic columns (12) and a cross-section from (Fyles, 1963);

Within a basin analysis framework (Sharpe et al., 2002) additional data were collected to enhance the geological knowledge of the area. This approach provides an improved framework for data interpretation and the development of a paleogeographic understanding of the basin to provide a more reliable predictive framework. Much of the new field data collection has focused on improved understanding of: i) the composition of the Nanaimo Group rocks; ii) the composition and hydrostratigraphic architecture of the surficial sediments (vertical and horizontal connectivity); and iii) the physical and geochemical properties of sediment and rock units. Thus fieldwork carried out by the GSC mainly involved:

- Surficial geology mapping: update of the surficial geology and stratigraphy (Bednarski, 2015);
- Bedrock outcrops analysis: 61 outcrops were measured for stratigraphic/sedimentologic interpretation and analysed for fracture orientation (Hamblin, 2012; Hamblin and McCartney, 2014);
- Seismic reflection surveys (Figure 4): 42 km of two dimensional (2D) seismic reflection surveys collected along 15 lines using a mini-vibe energy source and a land-streamer geophone array (e.g., Pugin et al., 2013).
- Rotosonic coring: 3 cores of surficial sediments ranging from 65 to 140 m with lithological descriptions and stratigraphic interpretations supported by chemostratigraphic analysis (Knight et al., 2015);
- Borehole geophysics (Figure 4): surveys in 5 wells (4 surficial and 1 bedrock) that include gamma, induction, temperature, fluid resistivity, magnetic susceptibility and compressional (*p*-wave) and shear (*s*-wave) waves logs (Crow et al., 2014). Three of the unconsolidated wells were rotosonic holes converted into observation wells and 2 were existing observation wells from the BC observation well network for groundwater level and quality.

For their integration in LeapFrog Hydro, all data were projected to a common datum and UTM reference grid (NAD 1983, Zone 10N).

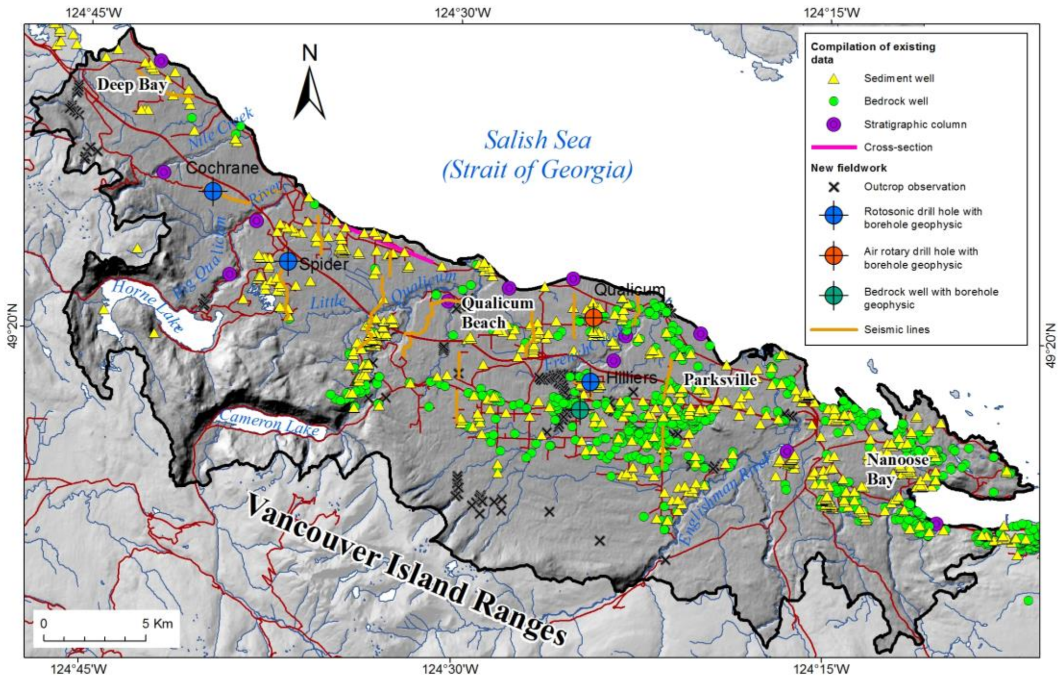

Figure 4 : Spatial distribution of the data used for the construction of the 3D hydrostratigraphic model of the Nanoose–Deep Bay study area.

3.2 Hydrostratigraphic Units

Hydrostratigraphy is the relation between geology and hydrogeological properties of materials (sediments or rocks) that compose an aquifer system. The hydrostratigraphic column in Figure 5 shows the relationships between the various geological and hydrogeological units for the study area. The lithostratigraphic column is based on a standard succession that is widely recognized in sea cliffs and rivers banks (Fyles, 1963) as well as in deep rotosonic wells drilled for this study.

The Vashon (geological unit 7), the Dashwood (2) tills and the Cowichan Head Formation (units 3 and 4), which are mostly silt and clay, are considered aquitard units. The Vashon till is hydrostratigraphic unit IV (Vashon-Till), whereas the Cowichan Head Formation and the Dashwood till are merged into a single hydrostratigraphic unit, namely the Cowichan-Dashwood unit (VI).

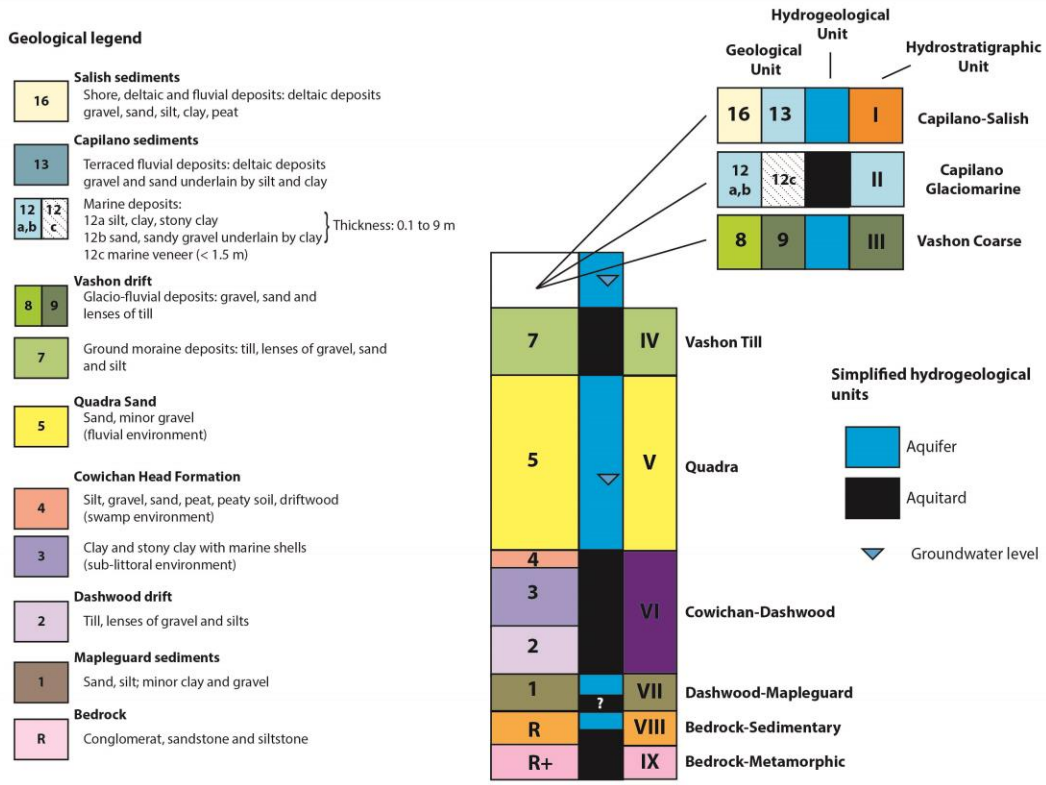

Figure 5 : Hydrostratigraphic units with correspondence to surficial and bedrock geology (Geological legend modified after Fyles, 1963).

From Figure 5, we also recognize five distinct aquifer units, which are the Capilano-Salish (hydrostratigraphic unit I), the Vashon coarse (III), the Quadra (V), the Dashwood-Mapleguard (VII) and the sedimentary bedrock (VIII) aquifers. The surficial aquifers are mostly discontinuous in nature and are composed of coarse glaciofluvial deposits (geological units 8 and 9) or deltaic and fluvial sediments (geological units 13 and 16). The glaciofluvial aquifers are located at the mountain/lowland junction, whereas the deltaic and fluvial sediments are close to main rivers (Figure 3). Salish sediments (16) along rivers are mostly recent fluvial deposits that are not considered to be aquifers, but could form important water storage units and could play a crucial role in the interaction between surface water and groundwater. Elsewhere, the study area is covered by marine deposits (12a-c) that are relatively impermeable due to their mostly fine grain-size (Capilano-Glaciomarine, II). The thickness of those sediments is highly variable ranging from a few centimeters to up to 12 m. The surficial aquifer system is composed of the Capilano-Salish (I) and the Vashon-Coarse (III) hydrostratigraphic units.

The Quadra hydrostratigraphic unit (V) aquifer under the Vashon unit (IV) is present almost everywhere over the study area except along the main rivers where the Quadra Sand has been eroded by rivers or cut-and-filled by the Vashon till. The upper part of the Quadra Sand shows an important fluvial erosional contact. Large cut-and-fill channels could be present at the top of this unit. According to Fyles (1963), Mapleguard proglacial outwash deposits could be coarser than the Quadra Sand and are expected to have good aquifer potential; however, the vertical and spatial extend of this unit is not well constrained. As for the Quadra-Cowichan sequence (geological units 5, 4 and 3) the grain-size of Mapleguard sediment is expected to be finer with depth and could transition into an aquitard unit.

The sedimentary bedrock aquifer (VIII) is mostly sandstone and conglomerate (Lower Nanaimo Group Comox Formation) in the study area and generally has low to moderate aquifer potential especially when fractures are present. Metamorphic and Intrusion bedrock (IX) in the area is generally considered to be an aquitard unit and only a few wells are reported from this formation.

3.3 Model Boundaries, Contact Surfaces and Volumes

The hydrostratigraphic model is bounded to the north by the Strait of Georgia, to the south by the limit of the Salish Sea, to the west and east by the boundaries of the Nile Creek and Englishman River watersheds, respectively (Figure 1). The lower contact of the model is fixed at an elevation of 400 m below sea level in the bedrock, whereas the top is constrained by the DEM. The 2D plane mesh resolution of the model was set to 70 m, which was applied to each contact surface.

The architecture of the aquifer system is defined within the model boundaries using contact surfaces separating each hydrostratigraphic unit, which are ordered according to their relative chronology, as follows from top (younger) to bottom (older):

I. Capilano– Salish;
II. Capilano (Glaciomarine);
III. Vashon– Capilano (Coarse);
IV. Vashon (till);
V. Quadra;
VI. Cowichan-Dashwood;
VII. Dashwood – Mapleguard;
VIII. Bedrock – Lower Nanaimo Group;
IX. Bedrock – Metamorphic and Intrusive Basement.

For purposes of modelling in the LeapFrog environment, all basal unit contacts are defined as depositional surfaces. That is, younger surfaces do not cut older surfaces.

The bedrock surface was interpolated from outcrop observations and bedrock-sediment contacts identified in public water well records and seismic surveys. Depths to unit contacts for seismic data were calibrated with rotosonic core descriptions, surrounding wells and *p*- and *s*-waves travel times from borehole geophysical logs. Seismic bedrock-sediment (bedrock topography) contacts were sampled every 500 m along profile lengths and integrated with outcrop and well information for kriging using SGeMS (Boucher, 2013). The bedrock elevation was thus estimated by kriging with external drift on the DEM using an omnidirectional variogram with four structures (variance proportion, range in meters): (i) nugget (0.3, 0); (ii) spherical (24.9, 1240); (iii) Gaussian (31.2, 6076); and (iv) spherical (43.6, 7688). The estimated elevations and variogram parameters were calibrated by cross-validation for resulting mean absolute and root mean square errors of 0.63 m and 11.3 m, respectively. The interpolated bedrock surface generated with SGeMS was then integrated within LeapFrog Hydro as a grid surface. Note that some wells that were drilled in deep sediment, without intercepting bedrock, were used as a bedrock surface maximum.

All other contact surfaces that correspond to unconsolidated sediments were defined in Leapfrog Hydro and constrained between the DEM and the bedrock topography using existing stratigraphic columns and cross-sections, the updated surficial geology map, rotosonic cores and seismic surveys. Elevation constraints were also imposed on some hydrostratigraphic units according to their respective depositional environment. When well depths and geological descriptions allowed, hydrostratigraphic information extracted from public water well records were also used to interpolate sediment contact surfaces. For interpolation of punctual data, Leapfrog software uses a dynamic interpolation method called FastRBF™ developed by ARANZ Geo. The model was then compared to the surficial geology mapping and data quality and based on professional judgment corrections were imposed. In this case, the most effective correction was to export the vertices of each of the surfaces of the model and apply the corrections with a Python script that treats each vertex as a borehole. The script ensures that the surface geology constrains the surfaces. Finally, surfaces were imported back into Leapfrog Hydro and volumes representing each hydrostratigraphic unit were built

4 Hydrostratigraphic Model of the Nanoose – Deep Bay Area

This section describes a series of analyses that summarize the hydrostratigraphic model of the Nanoose –Deep Bay area. Hydrostratigraphic unit thicknesses and distinct hydrogeological contexts are presented as well as insights about surface water / groundwater interaction and the potential for salt-water intrusion are discussed.

4.1 Unit Thicknesses

Sediment thickness and spatial distribution of each non-bedrock hydrostratigraphic unit are presented in Figure 6. Table 1 presents descriptive statistics of unit elevation and thickness based on interpolated volumes of the hydrostratigraphic model. A few observations can be made from Figure 6**Figure 6** and Table 1. Firstly, Capilano-Salish and Capilano Glaciomarine sediments are the thinnest units with a median thickness of 1 and 2 m, respectively. These units are widespread over the lowland part of the study area; however, Capilano-Salish and Capilano Glaciomarine units are discontinuous. Secondly, Quadra, Dashwood-Cowichan and Mapleguard are the thickest units with median values between of 13 and 15 m. These units are mostly present along the coast between Deep Bay and Parksville; however, south of Parksville and toward the mountains these units are rarely observed. The Mapleguard unit is expected to have a spatial distribution similar to the Quadra unit, due to similar depositional processes, but likely less extensive given the major erosive intervals that took place after its deposition. Its true extent is, however, uncertain due to a lack of deep boreholes in the area. Finally, Vashon-Capilano (coarse) and Vashon (till) occur over most of the study area and their thicknesses are generally between that of the previous units with median thickness of 5 and 7 m, respectively.

The total sediment thickness for all (non-bedrock) hydrostratigraphic units is presented in Figure 7. Very thick sediment deposits are present in the western part of the study area with thicknesses up to 210 m. Two other smaller areas near Qualicum Beach and Nanoose Bay have deposits with thicknesses similar to the western area. These thick values may be interpolation artefacts as they are unsupported by borehole or seismic data. Elsewhere, total sediment thickness is thinner and rarely exceeds 40 m. Seismic data and the Cochrane and Spider boreholes indicate that thicker deposits are certainly present, particularly toward the northwest where data intercepting bedrock is sparse.

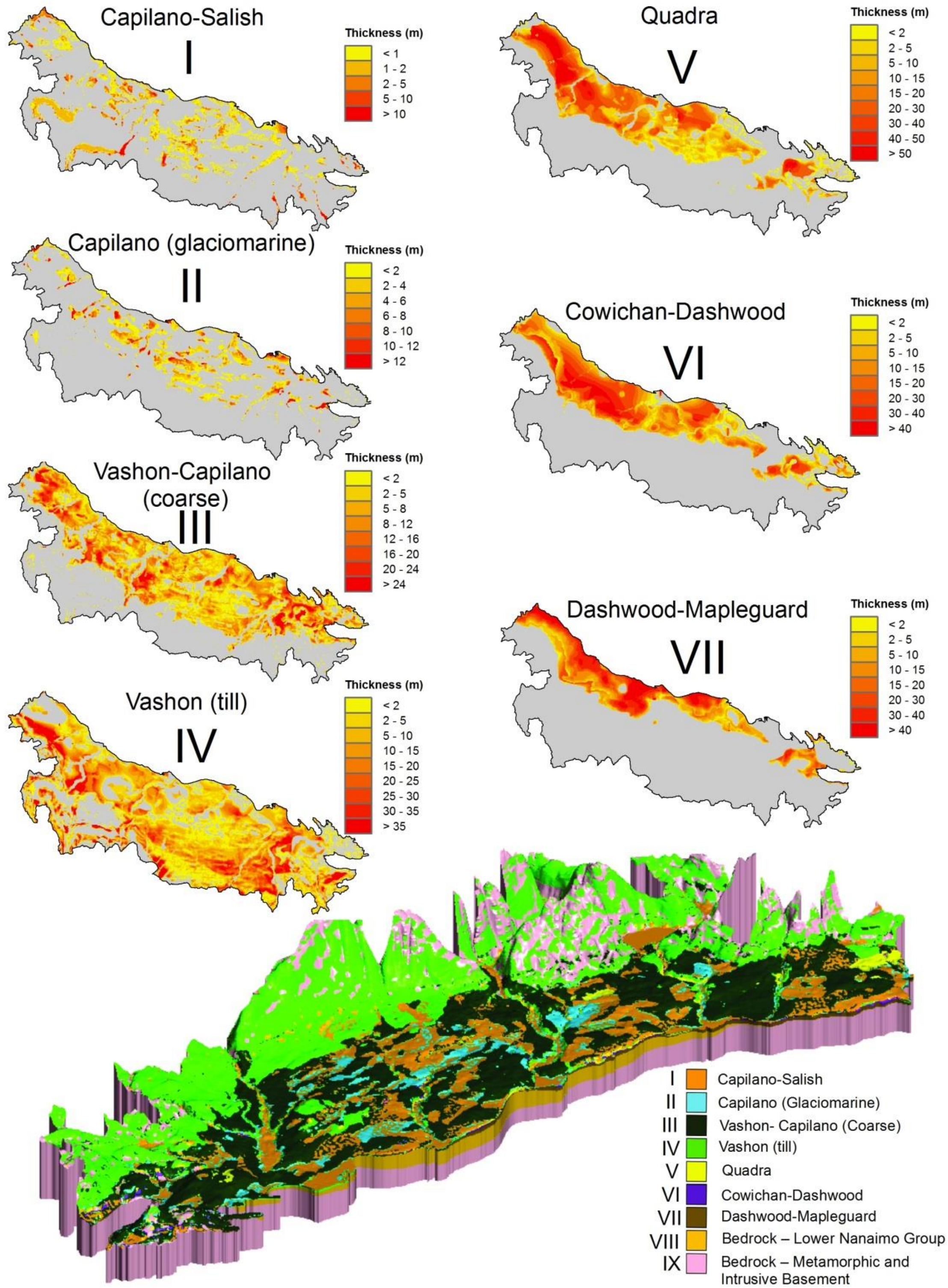

Figure 6 : Isopach of sediment thickness for each hydrostratigraphic unit (vertical exaggeration: 5x).

Table 1: Elevation and thickness of the hydrostratigraphic units based on the hydrostratigraphic model of the Nanoose - Deep Bay area, BC. Presented statistics are: minimum (min), maximum (max), mean, median (med) and the 95% confidence interval for thickness (95% c.i.).

Hydrostratigraphic units	**Top elevation**				**Base elevation**				**Thickness (m)**		
	min	**max**	**mean**	**med**	**min**	**max**	**mean**	**med**	**mean**	**med**	**95% c.i.**
I-CAPILANO-SALISH	3	369	95	91	-2	152	84	87	2	1	10
II-CAPILANO (glaciomarine fine)	-2	152	71	79	-23	162	68	75	4	2	12
III-VASHON-CAPILANO (coarse)	-21	297	92	91	-27	454	82	80	8	5	24
IV-VASHON (till)	-27	1026	171	122	-51	137	77	100	12	7	38
V-QUADRA	-47	141	74	78	-50	85	51	53	19	15	54
VI-DASHWOOD-COWICHAN	-48	84	45	44	-49	26	18	26	16	13	41
VII-MAPLEGUARD	-45	26	11	15	-75	40	-8	-6	19	14	48

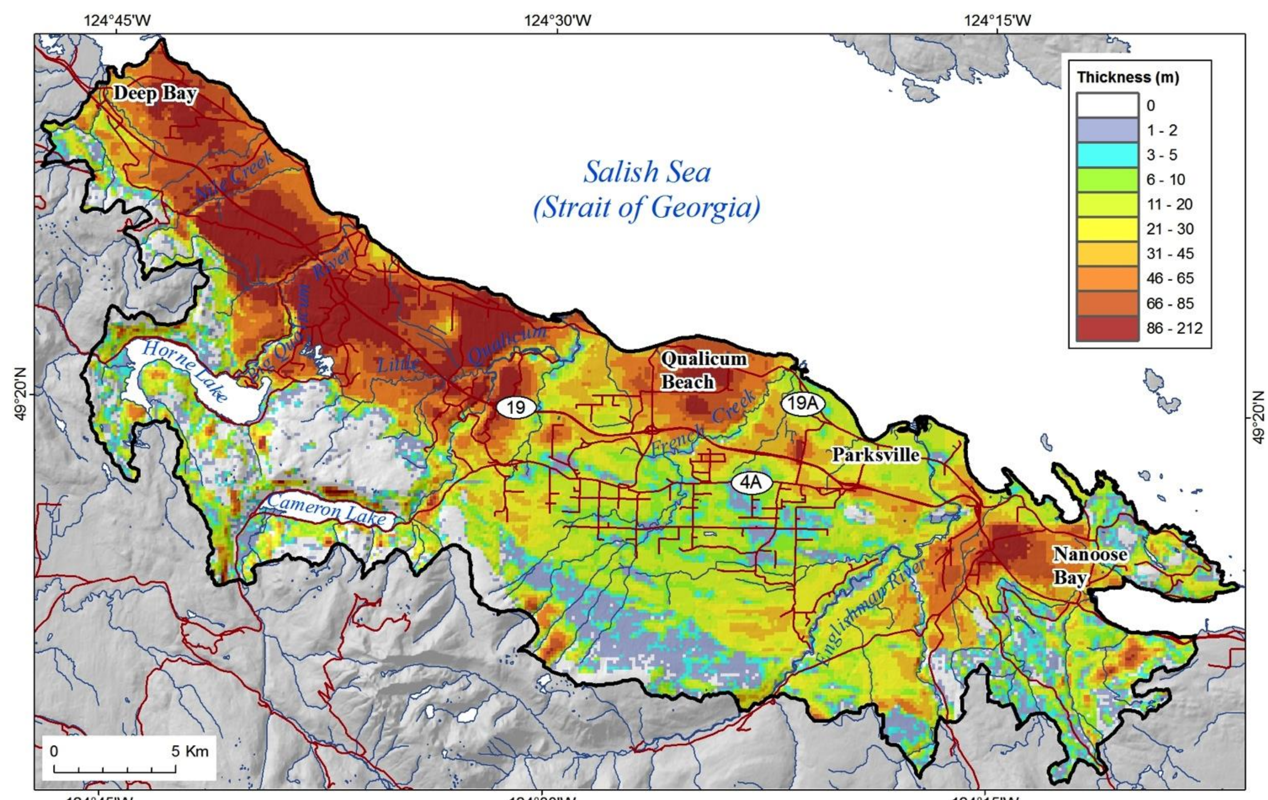

Figure 7: Isopachs of total sediment thickness above bedrock.

4.2 Hydrogeological Contexts

To illustrate the dynamics of the aquifer system, it is helpful to define regional hydrological contexts (Figure 8). Four distinct contexts were identified based on model layer geometries with similar spatial relationships. It is assumed that, being within a similar setting and having similar hydrological properties, groundwater exchanges between hydrostratigraphic units would be similar within each context.

- **Lowland Context (A):** This hydrogeological context is essentially the complete succession previously depicted in Figure 5 and covers most of the study area. This context includes portions of Nile Creek, Qualicum River, Little Qualicum River and French Creek that flow over the lowland on the eastern part of the study area as well as a small area on the western part. Most of the hydrostratigraphic units are present within the Lowland hydrogeological context, except near the main rivers where the sequence has been heavily eroded by fluvial incision. Most surficial units, in particular Quadra Sand, are disconnected from rivers at those locations and seepage faces could be observed along valley sides. Permeable Capilano sediment is also present along the rivers and it can play a role in regulating surface water and groundwater interactions due to its storage capacity, however their spatial distribution is limited. Note that seepage water is expected to reach rivers as surface runoff and/or hypodermic or saturated flow within Capilano sediment.

- **Cameron-Horne lakes Context (B):** This context is similar to the lower Lowland Context, except that the surficial unit is essentially composed of important sand and gravel glaciofluvial deposits (Vashon coarse). This context is located at the outlet of Cameron and Horne lakes in the lowland area. The Vashon coarse unit can be an important aquifer and is expected to be either perched over impermeable Vashon till (as see for hydrostratigraphic column for context B in Figure 8) or in direct contact with the Quadra unit. The nature of the hydraulic connection between the Vashon coarse unit and underlying aquifers is not well understood as no boreholes with reliable geological descriptions are available. The Mapleguard sediments may not be present at this elevation.

- **Englishman River Context (C):** The hydrogeological context of the Englishman River is completely different from the two previous contexts. The distribution of this context closely matches the watershed limits of the Englishman River, which essentially flows on till and bedrock units. Like other major rivers in the study area, seepage faces could be observed along incised river valley slopes. Capilano deposits along the Englishman River (especially downstream) could form important riverbank storage and moderate groundwater-surface water interaction.

- **Mountains Context (D):** The context is essentially located on the flanks of the mountainous area. This context is mostly composed of till (generally thin) over metamorphic and intrusive bedrock.

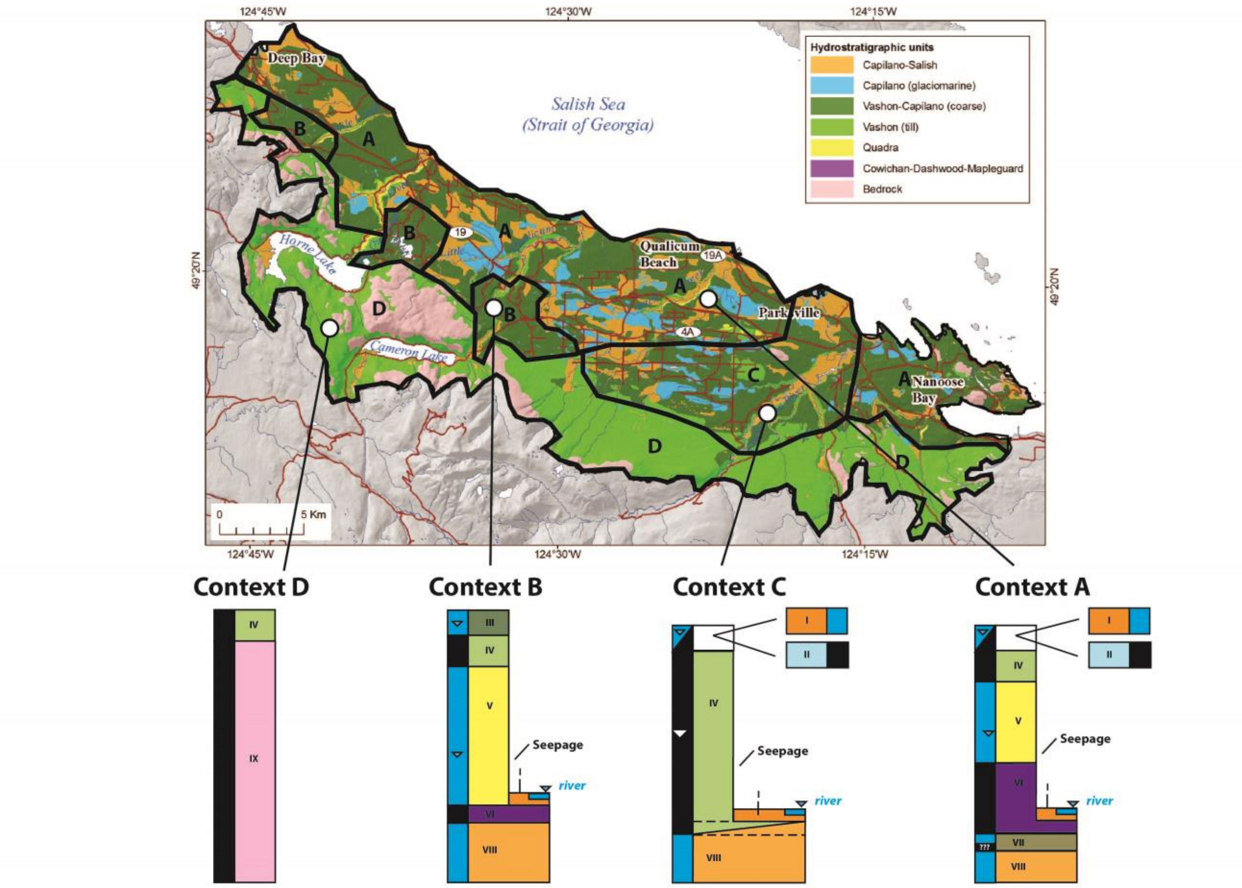

Figure 8. Distribution of the major hydrogeological contexts with representative hydrostratigraphic columns for each context (refer to Figure 5 for symbols and colour codes).

4.3 Surface Water and Groundwater Interaction

Based on field observations, terrain analysis of digital elevation models (DEM), and the hydrostratigraphic model, the main rivers in the study area have incised surficial sediments with erosion depths of up to 50 m. Three different surface water/groundwater interactions can be expected as illustrated in Figure 9 for Context A:

- **Seepage flow:** Seepage flow occurs when an aquifer or aquitard is exposed at the surface and creates a seepage face or springs at the ground surface. For the Lowland and Cameron-Horne lakes contexts (A and B), Quadra Sand is eroded down to its base, which creates seepage faces along the river cliffs. Of course, the magnitude of the seepage flow is proportional to the permeability of the Quadra Sand and the hydraulic gradient near the river valley slopes. Rivers, commonly flow over the underlying compact Dashwood till and the Quadra aquifer is not directly in hydraulic contact with river water. As a consequence, pumping in the Quadra unit can intercept groundwater that otherwise would flow into the rivers; however, pumping cannot generally directly draw water from rivers. For the Englishman River Context (C), where the river flows mostly on till and/or bedrock, the magnitude of the seepage flow is expected to be low in comparison to the other two contexts.

- **Riverbank flow:** Salish sediment (recent fluvial deposits) commonly form low river terraces and the immediate river bank within the broader valleys. There is commonly a rapid connection between river water and groundwater in these river bank terraces made of coarse alluvium. Seepage water from adjacent Quadra aquifer (Context A and B) or Vashon till and/or bedrock (Context C), surface runoff and direct precipitation may all infiltrate Salish sediments. Salish sediments are not considered important aquifer units due to their limited extent and thickness; however, they could represent important water storage capacity that could play a crucial role in regulating stream flow. Extraction from Salish sediment could directly affect water levels in adjacent river courses due to short distance and high hydraulic conductivity.

- **Aquitard and Bedrock flow:** To a lesser extent, groundwater in aquitard and bedrock units in direct contact with rivers can also contribute to river flow. The magnitude of this flux is expected to be small due to the relatively lower permeability of the aquitard and bedrock units, except locally where gravel lenses or fractures (bedrock top) may be present (Contexts A, B and C).

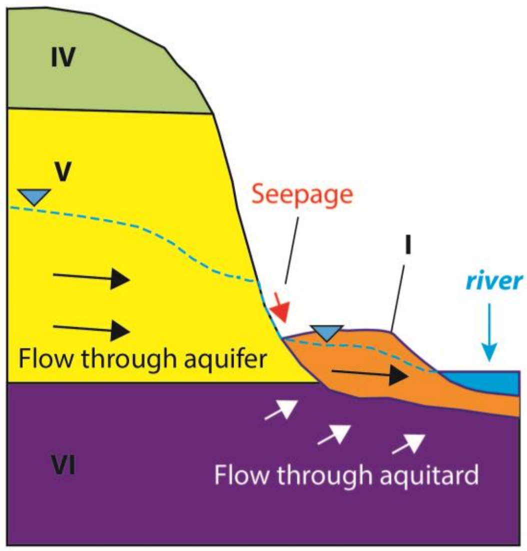

Figure 9. Schematic representation of surface water and groundwater interactions.

4.4 Sea-Water Intrusion

Analysis of the hydrostratigraphic model reveals insights relative to aquifer vulnerability due to sea-water intrusion. Based on its elevation above sea level, the heavily exploited Quadra Sand aquifer is likely to be only slightly affected by sea-water intrusion, even under intensive pumping near the coast (Figure 10). Salt-water intrusion caused by pumping is more likely to occur in underlying Mapleguard aquifer and bedrock units, where a fresh water/sea water interface may be present.

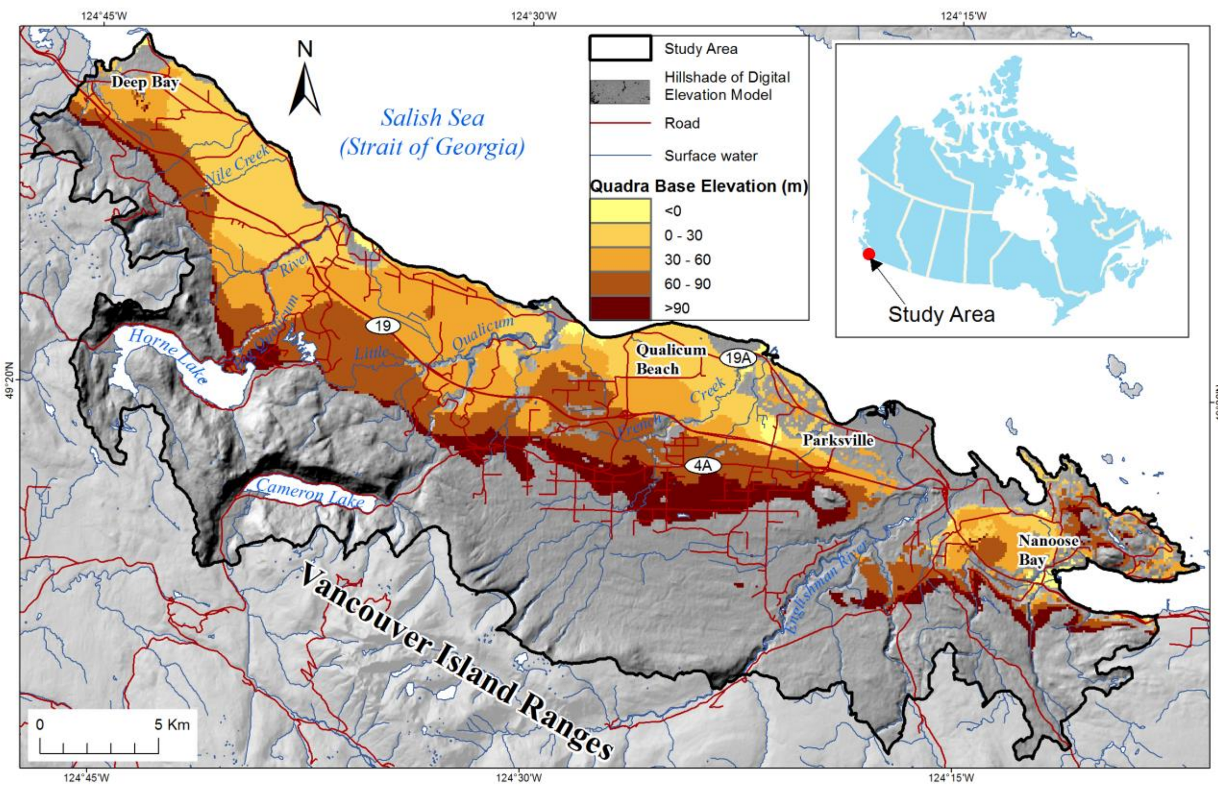

Figure 10. Elevation map of the Quadra Sand base with respect to sea level. Values indicate Quadra Sand base above sea level in meters.

5 Summary

The main objective of this study was to better understand the composition, distribution and stratigraphic architecture of the hydrostratigraphic units of the Nanaimo Lowland aquifer systems within the Nanoose to Deep Bay area on eastern Vancouver Island, BC. The work focuses mainly on surficial hydrostratigraphic units. The modelling results provide detailed analyses of thickness and elevation range of each hydrostratgraphic unit and 3D hydrogeological settings for regional groundwater flow modelling. This report contains numerical files of the hydrostratigraphic model of the Nanaimo Lowland aquifer system and supporting discussion of the geographic and geologic settings.

The study area has four hydrogeological contexts: Lowland, Cameron - Horne lakes, Englishman River, and Mountains. The main aquifer, Quadra, is located in the Lowland context and is hydraulically disconnected from the incised main rivers (seeping along valley slopes). Pumping in the Quadra unit cannot directly draw water from the rivers. Seepage water from the Quadra aquifer, surface runoff, and direct precipitation may all infiltrate Salish sediments. Salish sediments are not an important aquifer but can play a crucial role for water storage and regulating stream flow. Rivers are most commonly flowing over the underlying compact Dashwood till and bedrock. In the Englishman River context, the Quadra extent is very limited and river flows mostly on till and/or bedrock. The magnitude of the seepage flow is expected to be low in comparison to the other contexts. The elevation of the Quadra base (> 11 masl) means this unit has a low vulnerability to sea-water intrusion. Salt-water intrusion caused by pumping is more likely to occur in underlying Dashwood - Mapleguard aquifer and bedrock units, where a fresh water /sea water interface may be present. The Vashon coarse unit can also be an important aquifer but its relative position makes it more vulnerable to surface contamination and drought compared to Quadra Sand that is overlain by Vashon till. Also, thick saturated Vashon coarse unit is limited over the lowland and it may likely form only local aquifers.

Acknowledgements

Technical support and constructive discussions with S. Grasby, P. Lapcevic, M. Wei, V. Carmichael, A. Pugin, G. Anderson, S. Barroso and G. Wendling help to improve the quality of the work. An internal review by Charles Logan helped to clarify the report. The authors would like to thank Y. Michaud for support as Program Manager of the Groundwater Geoscience Program. This report is a contribution of the Aquifer Assessments and Support to Mapping - Groundwater Inventory Project of the Groundwater Geoscience Program.

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Appendix A : Numerical model files

The numerical files include thickness of each unconsidered hydrostratigraphic unit in a georeferenced raster format.

Hydrostratigraphic unit numbers	**Hydrostratigraphic unit names**	**Raster names**
I	Capilano–Salish	capisal1
II	Capilano (Glaciomarine)	capiglacio2
III	Vashon–Capilano (Coarse)	vashcapi3
IV	Vashon (till)	vashtil4
V	Quadra	quadra5
VI	Cowichan-Dashwood	cowidash6
VII	Dashwood–Mapleguard	dashmaple7