Natural Resources Canada
Ressources naturelles Canada

GEOLOGICAL SURVEY OF CANADA
OPEN FILE 7877

Nanoose Bay – Deep Bay Area, Nanaimo Lowland Groundwater Study Atlas, Regional District of Nanaimo, British Columbia

H.A.J. Russell and N. Benoit
(compilers)

2016

GEOLOGICAL SURVEY OF CANADA
OPEN FILE 7877

Nanoose Bay – Deep Bay Area, Nanaimo Lowland Groundwater Study Atlas, Regional District of Nanaimo, British Columbia

H.A.J. Russell and N. Benoit
(compilers)

2016

doi:10.4095/298868

Recommended citation

Russell, H.A.J. and Benoit, N., 2016. Nanoose Bay – Deep Bay Area, Nanaimo Lowland Groundwater Study Atlas, Regional District of Nanaimo, British Columbia; Geological Survey of Canada, Open File 7877, 74 p. doi:10.4095/298868

NANOOSE BAY – DEEP BAY AREA, NANAIMO LOWLAND GROUNDWATER STUDY ATLAS

Regional District of Nanaimo, British Columbia

Russell, H.A.J. and Benoit, N.
(compilers)

Bednarski, J., Benoit, N., Carmichael, V.P., Crow, H.L., Cummings, D.I., Gilchrist, A., Grasby, S., Hamblin, A.P., Henderson, G., Knight, R.D., Lapcevic, P., Paradis, D., Pisani, J., Pugin, A.J-M., Russell, H.A.J., Wang, S., and Wei, M.
(contributors)

Natural Resources Canada
Ressources naturelles Canada

Geological Survey of Canada, OPEN FILE 7877

CANADA
1842
GEOLOGICAL SURVEY - COMMISSION GÉOLOGIQUE

REGIONAL
DISTRICT
OF NANAIMO

BRITISH
COLUMBIA
Ministry of
Forests, Lands and
Natural Resource Operations

BRITISH
COLUMBIA
The Best Place on Earth
Ministry of
Environment

LIST OF CONTRIBUTORS

Bednarski, Jan
Geological Survey of Canada
Natural Resources Canada
9860 West Saanich Road, Sidney, BC, V8L 4B2
email: jan.bednarski@canada.ca

Benoit, Nicolas
Geological Survey of Canada
Natural Resources Canada
490, rue de la Couronne, 3e étage, Québec, QC, G1K 9A9
email: nicolas.benoit@canada.ca

Carmichael, Vicki P.
Formerly Ministry of Environment
PO Box 9362, Stn Prov Govt, Victoria, BC, V8W 9M1

Crow, Heather L.
Geological Survey of Canada
Natural Resources Canada
601 Booth St., Ottawa, ON, K1A 0E8
email: heather.crow@canada.ca

Cummings, Don I.
DCGeo
12 Decarie St., Aylmer, QC, J9H 2M3
email: cummings1000@gmail.com

Gilchrist, Alan
Department of Geography
Vancouver Island University
900 Fifth Street, Nanaimo, BC, V9R 5S5
email: alan.gilchrist@viu.ca

Grasby, Steve
Geological Survey of Canada
Natural Resources Canada
3303 33 Street NW, Calgary, AB, T2L 2A7
email: steve.grasby@canada.ca

Hamblin, Anthony (Tony) P.
Geological Survey of Canada
Natural Resources Canada
3303 33 Street NW, Calgary, AB, T2L 2A7
email: tony.hamblin@canada.ca

Henderson, Graeme
Water Protection
Ministry of Forests, Lands and Natural Resource Operations
2080A Labieux Rd., Nanaimo, BC, V9T 6J9
email: graeme.henderson@gov.bc.ca

Knight, Ross D.
Geological Survey of Canada
Natural Resources Canada
601 Booth St., Ottawa, ON, K1A 0E8
email: ross.knight@canada.ca

Lapcevic, Pat
Water Protection
Ministry of Forests, Lands and Natural Resource Operations
2080A Labieux Rd., Nanaimo, BC, V9T 6J9
email: pat.lapcevic@gov.bc.ca

Paradis, Daniel
Geological Survey of Canada
Natural Resources Canada
490, rue de la Couronne, 3e étage, Québec, QC, G1K 9A9
email: daniel.paradis@canada.ca

Pisani, Julie
Regional District of Nanaimo
6300 Hammond Bay Road, Nanaimo, BC, V9T 6N2
email: jpisani@rdn.bc.ca

Pugin, André J-M.
Geological Survey of Canada
Natural Resources Canada
601 Booth St., Ottawa, ON, K1A 0E8
email: andre.pugin@canada.ca

Russell, Hazen A.J.
Geological Survey of Canada
Natural Resources Canada
601 Booth St., Ottawa, ON, K1A 0E8
email: hazen.russell@canada.ca

Wang, Shusen
Canadian Centre for Mapping and Earth Observation
Natural Resources Canada
560 Rochester St., Ottawa, ON, K1S 5K2
email: shusen.wang@canada.ca

Wei, Mike
Ministry of Environment
PO Box 9362, Stn Prov Govt, Victoria, BC, V8W 9M1
email: mike.wei@gov.bc.ca

CONTENTS

INTRODUCTION

This hydrogeological atlas is the culmination of a five-year collaborative project on the regional groundwater resources of British Columbia's (BC) Nanaimo Lowland area between Nanoose Bay, in the south, and Deep Bay, in the north. The project was initiated by the Regional District of Nanaimo (RDN), the BC Ministry of Forests, Lands, and Natural Resources (MFLNR), and the BC Ministry of Environment (MoE).

The Geological Survey of Canada (GSC) joined the project in 2009 owing to its responsibility to map Canada's major aquifers. This was a major recommendation of a report of the Standing Senate Committee on Energy, the Environment, and Natural Resources, released in 2005. The report *Water in the West: Under Pressure* noted that our limited knowledge of our groundwater resources was a critical issue that needed to be addressed. Sound management of groundwater resources for current and future users can only be based on an understanding of the characteristics of the aquifers and the processes that control groundwater availability. The Nanaimo Lowland is one of 30 key Canadian aquifers identified by the GSC.

The GSC completed the data collection phase of the project in 2014. In a parallel study, contracted by the RDN, the Calgary-based consulting firm Waterline Resources Inc., conducted a literature search of published sources to assemble a report on legacy data (Waterline, 2013), and this material has been used for this atlas. Archival data obtained from the MoE Water Well Database has also been integrated with other project data in the atlas.

This atlas contains thematic maps presenting compiled and interpreted data as well as results regarding the geology, hydrology, and hydrogeology of the study area. It is a summary of the study investigations. For more detailed information, readers are referred to the appropriate cited documents.

The atlas provides information collected and presented within the context of a basin analysis study and is a tool to aid understanding of regional groundwater in support of sound management of the resource. The objective of a basin analysis study is the collection of geoscience data to support the interpretation of the paleogeographic history of the basin. Such a framework provides a predictive framework of the sedimentary history and arrangement of geological units. Efficiency of delivery and quality protection efforts are complemented by water availability studies and analysis as are contained in the atlas. These provide the science necessary to effectively plan for land-use and groundwater allocations in the coming years.

Acknowledgements

Support from GSC program managers Alfonso Rivera and Yves Michaud is greatly appreciated. Early work in formulating the project parameters was advanced by Larry Barr, MFLNR, and Celine Davis, MoE. Overall project management was provided by Vicki Carmichael, MoE; Pat Lapcevic, MFLNR; and Steve Grasby, GSC. Mike Donnelly, Christina Metherall, and Julie Pisani provided the RDN project management.

Elizabeth Macey and Dave Sargent of GSC-Calgary, and Ruth Boivin and Natalie Côté of GSC-Québec prepared graphics and provided cartographic support. Christy Vodden, freelance, edited the text, and freelance graphic artists Donna Ferguson and Glenn Ferguson did the final layout and design.

The report benefited from an internal review by Charles Logan, GSC.

Cover photo credit: André Pugin, GSC.

1. STUDY REGION OVERVIEW

1.1. Hydrogeological Regional Overview

Wei, M., British Columbia Ministry of the Environment (Victoria, BC)

The study area, along the central east coast of Vancouver Island, is part of the Canadian Cordillera Hydrogeological Region (Sharpe et al., 2014). Its mild climate and great natural beauty have made it a desirable place to live and a popular tourist destination. It is also one of the areas on Vancouver Island with the greatest reliance on groundwater as a water supply. Two major population centres of the area (the City of Parksville and the Town of Qualicum Beach), as well as many rural residents with their own wells, use groundwater as their main source of water.

The area is underlain by bedrock of the Nanaimo Group of sedimentary rocks in the lowland and by a mix of crystalline bedrock in the mountainous areas. In bedrock, groundwater typically occurs in fractures and faults (**Figure 1.1.1**). There are two practical implications. First, the permeability of fractured bedrock and the yield from water wells drilled into bedrock tend to be limited. Second, the water storage potential in this type of bedrock is very low, resulting in generally quick responses of the bedrock aquifer to hydraulic and chemical changes. This means recharge from precipitation occurs quickly in fractured bedrock, for example, within a matter of days in the Englishman River watershed.

Unconsolidated aquifers comprising sand and gravel are the main aquifers in the study area. The bedrock surface, land topography, and surficial geology influence the occurrence and characteristics of these aquifers.

The Quadra Sand aquifer is an important unconsolidated aquifer in the study area that supplies groundwater to residents of the communities of Parksville and Qualicum Beach. Meltwater rivers deposited the sand when glacial ice advanced south along what is now the Strait of Georgia more than 15,000 years ago (Clague and Luternauer, 1983). It was subsequently covered locally by glacial till, which formed an overlying confining layer. Because the permeability of sand is much greater than the permeability of fractured bedrock, this sand aquifer supports greater well yields and is a target when developing larger groundwater supplies. Other, more recent, sand and gravel deposits formed at the end of the last Ice Age or along alluvial rivers such as the Little Qualicum River, and they are also productive aquifers in the study area.

The study area is located in a coastal hydrologic regime. Much of the precipitation, which is the main source of recharge, falls in the winter months. Monitoring of ambient groundwater levels in BC observation wells within the study area has shown that recharge to the aquifers generally peaks in late winter-early spring.

Groundwater is the main supply of water for the City of Parksville, the Town of Qualicum Beach, and the Nanoose Peninsula supplied by an RDN-operated system. It is the principal source of supply for rural residents with individual wells. Diversion and use of groundwater in the area can have a variety of impacts. Excessive withdrawal of groundwater from sand and gravel aquifers can deplete groundwater supplies by lowering groundwater levels. Groundwater pumping from sand and gravel aquifers can also deplete flow in local streams, affecting fish habitat and surface water users if the aquifer and the stream are hydraulically connected. This can be particularly problematic in late summer when water demand is high and stream flow is low.

Many of the streams in the study area already have water allocation restrictions. One solution is an artificial aquifer recharge system to store water in a Quadra Sand aquifer by diverting water from the Englishman River during the winter months when stream flow is high, treating it, and injecting it into the aquifer to be used later in the summer.

In coastal areas, over-pumping can also decrease groundwater discharge to the sea and trigger intrusion of seawater into local aquifers, diminishing their usefulness as a water supply. Experience on Vancouver Island and the Gulf Islands suggests the risk of saltwater intrusion is greatest where groundwater withdrawal occurs in close proximity to the ocean and the size of the recharge area is limited.

Understanding the physical characteristics of aquifers in the study area, as well as the physical processes that control groundwater availability is critical to sound management of the area's groundwater resources for both the current population and future generations.

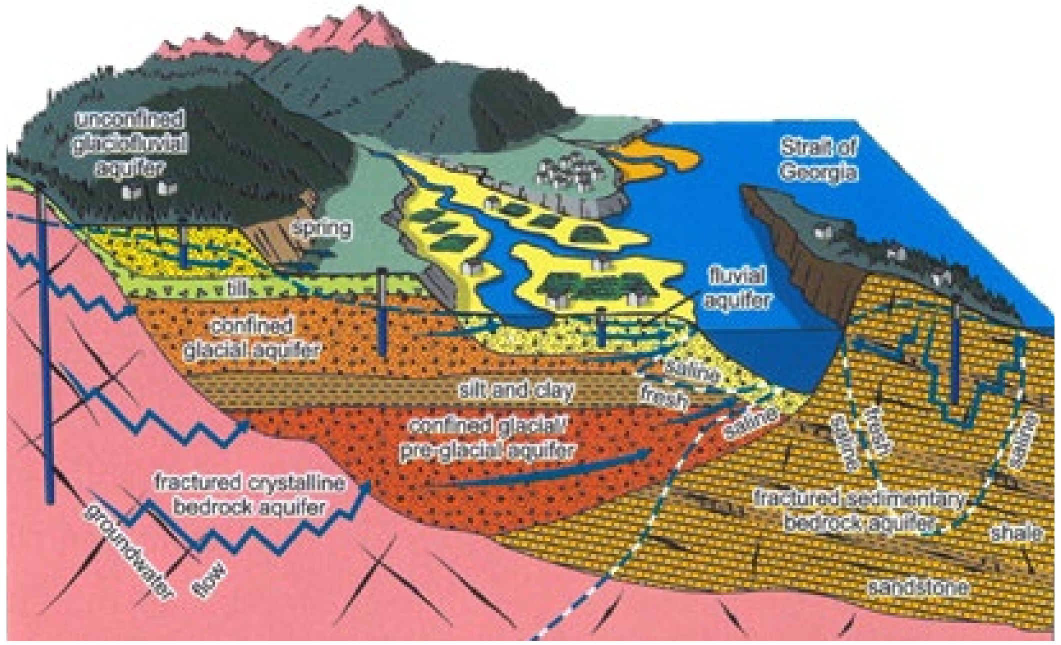


Figure 1.1.1. **Schematic diagram showing different types of aquifers in the coastal setting of the Cordillera Hydrogeologic Region, for example, the Nanoose – Deep Bay study area on the east coast of Vancouver Island. Fractured sedimentary and crystalline bedrock aquifers are illustrated by the banded dark yellow and pink coloured bedrock, respectively. The Quadra Sand confined aquifer is depicted in orange, overlain by the glacial till in green. More recent alluvial and glaciofluvial aquifers are coloured in bright yellow (from Wei et al., 2014).**

Wei, M., 2016. 1.1 Hydrogeological Regional Overview; in Russell, H.A.J., and Benoit, N., (compilers); Nanoose Bay – Deep Bay Area, Nanaimo Lowland Groundwater Study Atlas, Regional District of Nanaimo, British Columbia; Geological Survey of Canada, Open File 7877.

1. STUDY REGION OVERVIEW

1.2. Groundwater Use

Pisani, J., Regional District of Nanaimo (Nanaimo, BC)

Between Deep Bay, in the north, and Nanoose Bay, in the south of the study area, the primary source for community water supply is groundwater. The main community water supply systems consist of three improvement districts (local service authorities), one private purveyor, seven regional (RDN) water service areas, and two municipal utilities. Each of these community supply systems relies on a groundwater source. There are also some smaller community well operations (for example, that service a mobile home park) that rely on groundwater, as well as a significant number of properties with their own wells.

It is a challenge to quantify water use in the study area, as groundwater extraction has not historically been licensed in BC. Nevertheless, the major municipal water suppliers all meter usage, primarily for billing purposes. In addition to relying on groundwater, Parksville and the RDN service area on the Nanoose Peninsula use surface water from the Englishman River for their water supply from May through October. This limited seasonal use is due to high turbidity in the river water during the winter months. A new river intake and a water treatment plant are currently in the design phase, with construction commencing in June 2016. By 2018, the Englishman River will provide surface water to Parksville and Nanoose Bay year-round. This is a favourable option to serve a growing population, while protecting local aquifers as groundwater levels have declined in the Parksville area (BC observation well #304) over the past several years.

By contrast, groundwater levels in BC observation well #295 near Qualicum Beach, north of Parksville, are steady and increasing (**Figure 1.2.1A**). This demonstrates the variable groundwater conditions in the region. There are a significant number of unregistered wells in the region because the province has not required the registration of private wells. Estimates indicate, however, that there are about 4900 private wells on properties outside of the municipalities (excluding the properties in community water service areas). These wells are not metered, so usage data is not available.

An estimated use of water from private wells was based on an average demand per land-use type, which was applied to the limited data available in the RDN Water Budget Study (Waterline, 2013). The resulting calculation of the total annual groundwater diversion for human use from private wells, and agriculture and community systems was 22,336,047 m^3. The area of the survey included the 22 mapped aquifers identified by the MoE, but the total water diversion is likely from additional unmapped aquifers.

The greatest cumulative demand on water comes during the summer months, when gardens are being watered, farms require irrigation, seasonal residents move back to the area, and peak tourism season occurs. This peak-use period puts a strain on local groundwater and surface-water supplies, at a time when precipitation is lacking and demand for water is double or triple that during the winter.

In response, efforts are being made to reduce water consumption, not only in this peak period, but all year-round. RDN Water Service areas have successfully decreased water consumption from 356 L per capita to 280 L per capita between 2001 and 2014. This can be attributed to a billing structure that charges based on usage, public education programs, rebate programs to encourage installation of water-efficient toilets, and home visits offered to assist with outdoor irrigation efficiency enhancements. There is still opportunity for improvement on the water conservation front, specifically in areas such as Qualicum Beach where there is less groundwater stress and fewer water restrictions, resulting in higher consumption at 346 L per capita per day. By comparison, the European average daily water use is below 200 L per capita.

The population in this region is growing, and there is increasing demand on water resources. If water use can become more efficient and if measures are put in place to protect water quality, there can be enough clean water to supply the region, even with the projected population growth. Protecting groundwater quality by implementing cosmetic pesticide bans, encouraging private wellhead construction upgrades, and supporting stormwater management best practices are all part of the regional approach.

These water conservation and water quality protection efforts rely on water availability studies and analysis that provide the science to effectively plan for land-use and groundwater allocations in the coming years.

The major systems' annual water use (2014)

Town of Qualicum Beach, serving ~9,350 people:

1,574,962 m^3 groundwater

City of Parksville, serving ~12,685 people:

657,169 m^3 surface water + 1,239,550 m^3 groundwater = 1,896,719 m^3

RDN Nanoose Peninsula, serving ~4,576 people:

218,071 m^3 surface water + 434,390 m^3 groundwater= 652,461 m^3

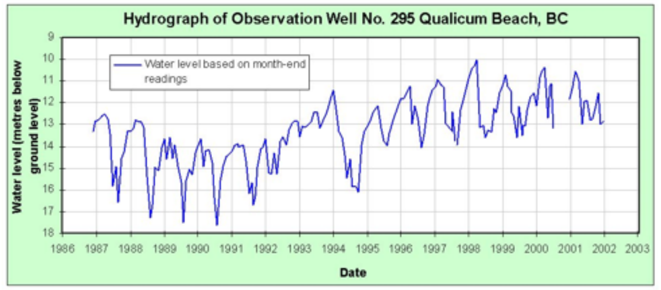
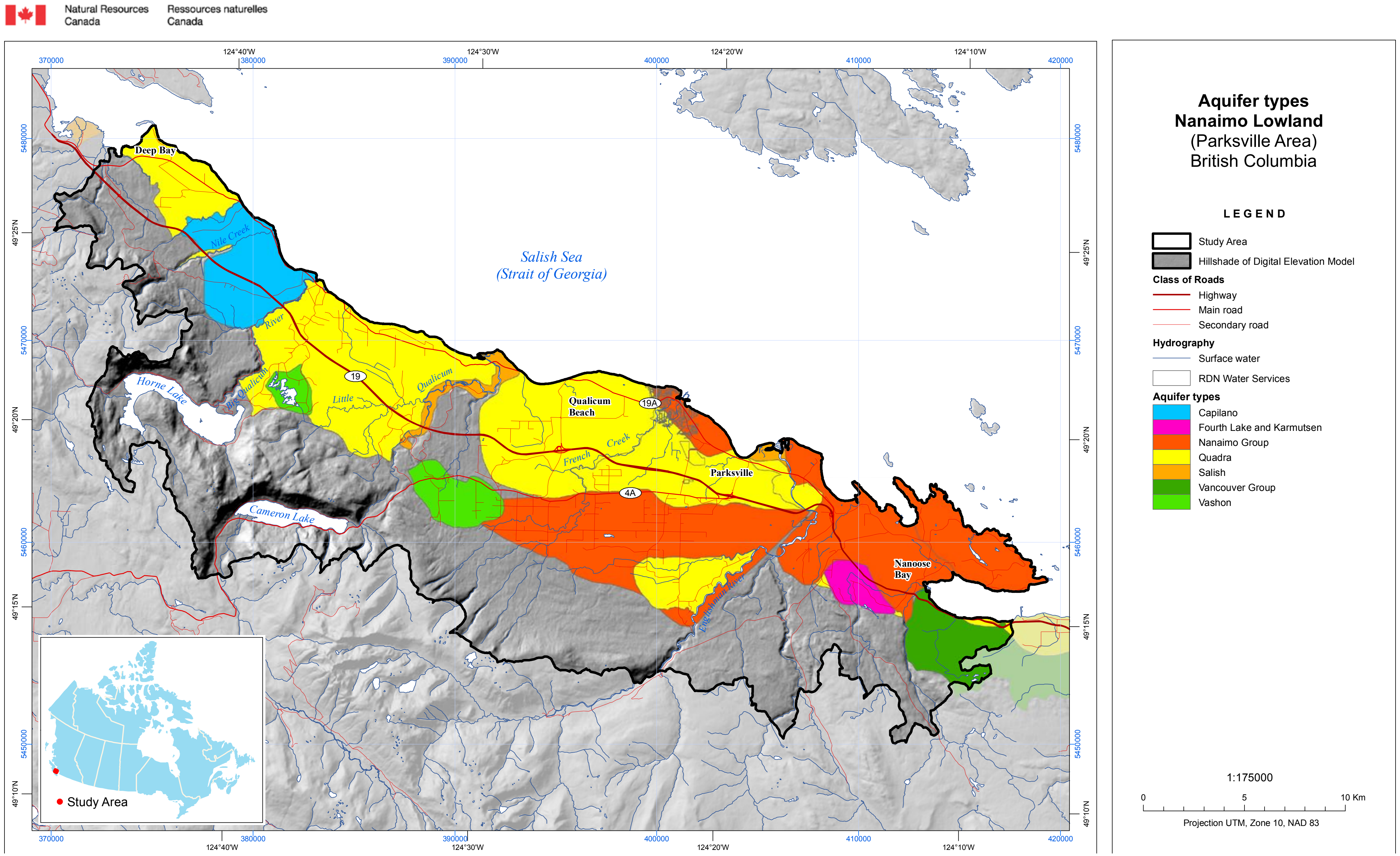


Figure 1.2.1. **A) Groundwater levels in BC observation well #295 near Qualicum Beach.**

Figure 1.2.1. **B) Groundwater pumping system for the Town of Qualicum Beach (courtesy of the Town of Qualicum Beach).**

Pisani, J., 2016. 1.2 Groundwater Use; in Russell, H.A.J., and Benoit, N., (compilers); Nanoose Bay – Deep Bay Area, Nanaimo Lowland Groundwater Study Atlas, Regional District of Nanaimo, British Columbia; Geological Survey of Canada, Open File 7877.

1.2. Groundwater Use **– Map 1**



1. STUDY REGION OVERVIEW

1.3. Data Collection and Data Sources

Russell, H.A.J., Benoit, N., and Paradis, D., Geological Survey of Canada (Ottawa, ON; Quebec City, QC)

Geology exerts a primary control on the flow of surface water and groundwater. As a result, geological frameworks can be used to predict where significant recharge and discharge areas (source waters) are located, as well as where aquifers are more susceptible to surface contamination.

A basin analysis approach was applied in the study area to advance understanding of the basin framework, using new data collected as an aid to interpretation of the basin history and, consequently, to provide a predictive guide for future studies and understanding. Development of a sound geological framework that integrates available geological, geophysical, geochemical, and hydrogeological data is central to this approach (**Figure 1.3.1**).

To achieve this, existing data were compiled, including:

- Public water wells database (MoE, 2013). After filtering and validation 708 bedrock wells and 570 surficial wells were used for this project.
- Surficial geological map including stratigraphic columns (12) and a cross-section (Fyles, 1963).

New data collection included (**Map 2**):

- Surficial geology mapping that updated the surficial geology and stratigraphy (Bednarski, 2015).
- Bedrock outcrop analysis: 61 outcrops were measured for stratigraphic/sedimentologic interpretation and analysed for fracture orientation (Hamblin, 2012; Hamblin and McCartney, 2014) and one 215 m long bedrock core was collected for analysis.
- Seismic reflection surveys: 42 km of two-dimensional (2D) seismic reflection surveys were collected along 15 lines using a mini-vibe energy source and a land-streamer geophone array (e.g., Pugin et al., 2013).
- Rotosonic coring: three cores of surficial sediments ranging from 65 to 140 m with lithological descriptions and stratigraphic interpretations supported by geochemical analysis (Knight et al., 2015).
- Borehole geophysics: surveys in five wells (four surficial and one bedrock) that included gamma, induction, temperature, fluid resistivity, magnetic susceptibility and compressional (p-wave) and shear (s-wave) wave logs (Crow et al., 2014).
- Water chemistry data for the Englishman River (Provencher et al, 2013; Provencher, 2014).

These data were assembled and used to support construction of a 3D hydrostratigraphic model (Benoit et al., 2015a), that was used as the framework for a groundwater flow model (Benoit et al., 2015b) to advance understanding of regional groundwater flow in aquifer systems of the study area.

This hydrogeological atlas contains thematic maps presenting compiled and interpreted data, as well as results regarding the geology, hydrology, and hydrogeology of the study area. The atlas is a summary of the study investigations and is not a comprehensive overview of the groundwater resource of the region. For additional details readers are referred to the appropriate cited documents.

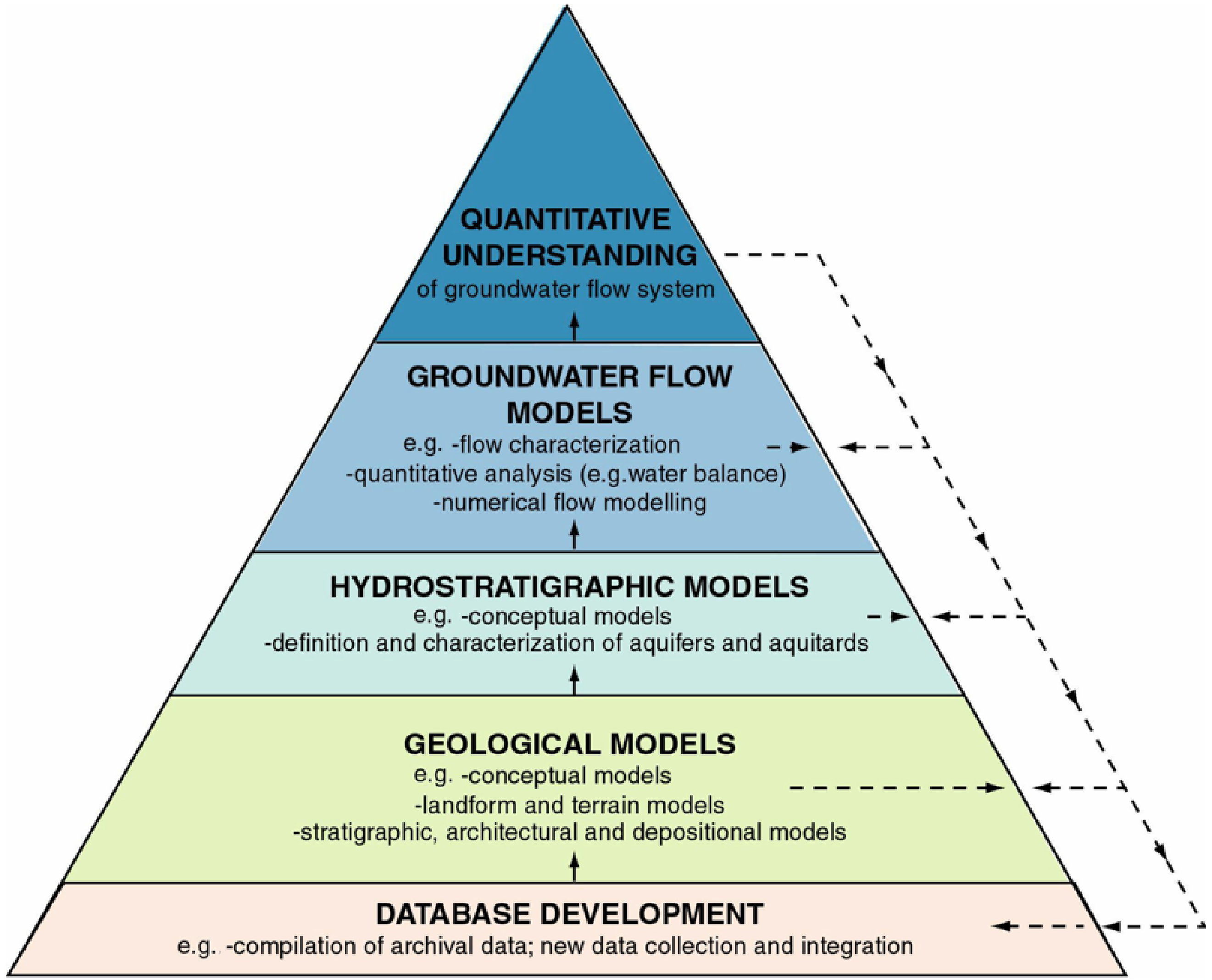
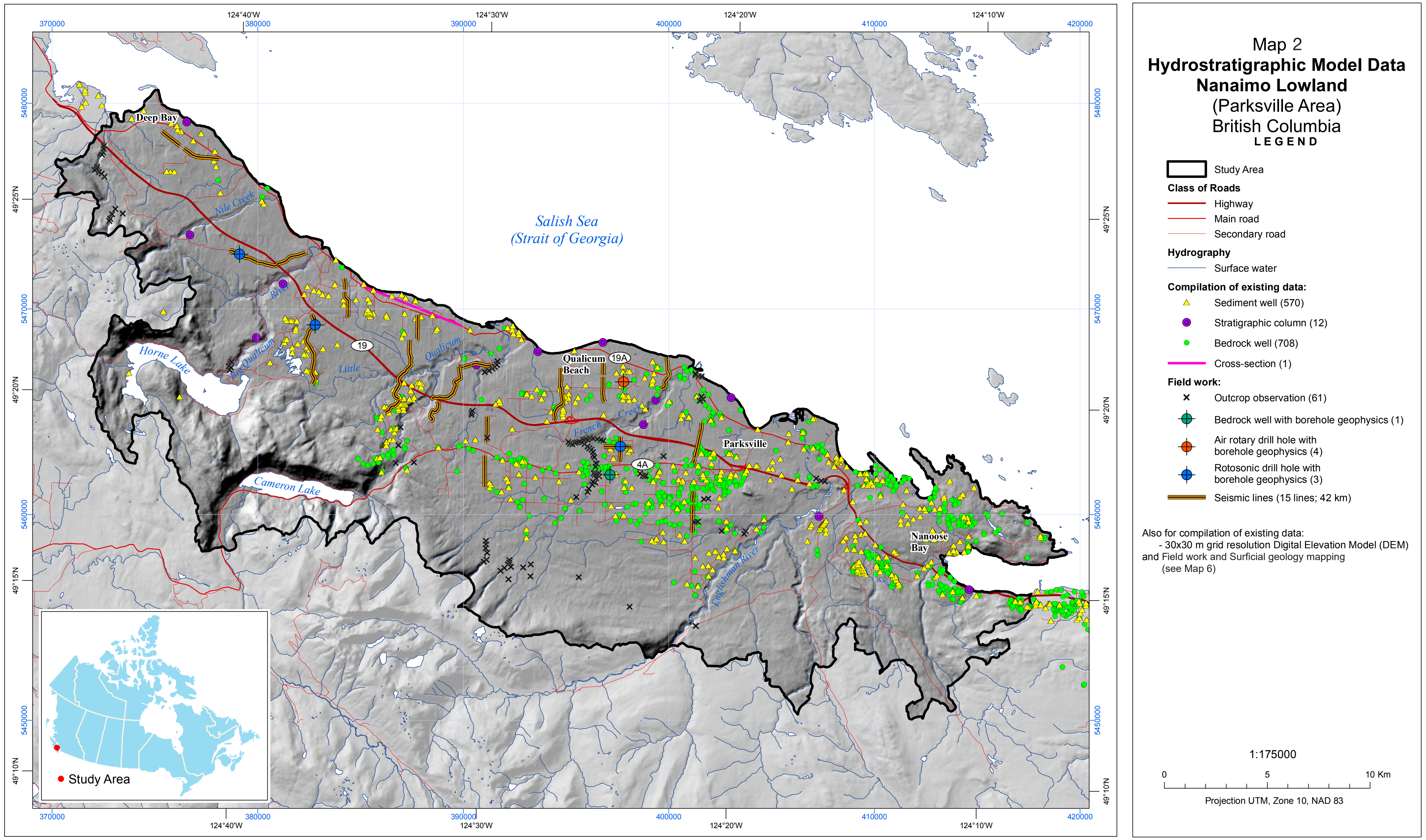


Figure 1.3.1. Schematic framework for data integration and conceptualization leading to a quantitative understanding of a groundwater flow system. A feedback loop is included to indicate that at any stage new information can be gathered to further refine the definition of the groundwater flow system. Data collection and model development (geological, hydrostratigraphic, and groundwater flow) are generally carried out according to the objective of the quantitative assessment (from Sharpe et al. 2002).

Russell, H.A.J., Benoit, N., and Paradis, D., 2016. 1.3 Data Collection and Data Sources; in Russell, H.A.J., and Benoit, N., (compilers); Nanoose Bay – Deep Bay Area, Nanaimo Lowland Groundwater Study Atlas, Regional District of Nanaimo, British Columbia; Geological Survey of Canada, Open File 7877.

1.3. Data Collection and Data Sources – **Map 2**

Natural Resources Canada Ressources naturelles Canada



Map 2
Hydrostratigraphic Model Data
Nanaimo Lowland
(Parksville Area)
British Columbia

LEGEND

▭ Study Area

Class of Roads
- Highway
- Main road
- Secondary road

Hydrography
- Surface water

Compilation of existing data:
- ▲ Sediment well (570)
- ● Stratigraphic column (12)
- ● Bedrock well (708)
- Cross-section (1)

Field work:
- × Outcrop observation (61)
- ⊕ Bedrock well with borehole geophysics (1)
- ⊕ Air rotary drill hole with borehole geophysics (4)
- ⊕ Rotosonic drill hole with borehole geophysics (3)
- Seismic lines (15 lines; 42 km)

Also for compilation of existing data:
- 30x30 m grid resolution Digital Elevation Model (DEM)
and Field work and Surficial geology mapping
(see Map 6)

1:175000

0 5 10 Km

Projection UTM, Zone 10, NAD 83

1.4. Physiography

Bednarski, J., Geological Survey of Canada (Sidney, BC)

The study area covers about 580 km^2 of the Nanaimo Lowland from the First Nation community of Nanoose to Deep Bay (**Map 3**). The Nanaimo Lowland physiographic region can be regarded as the unsubmerged southwestern part of the Georgia Depression (Holland, 1964; Mathews, 1986). Located on the southeast coast of Vancouver Island, the study area forms a relatively flat coastal plain extending about 10 km inland along 150 km of coast. It is bound to the west by the flanks of the northwest-trending Vancouver Island Ranges and to the east by the Strait of Georgia (Salish Sea). Bedrock in the area consists mainly of igneous and metamorphic rocks of Wrangellia Terrane unconformably overlain by sedimentary rocks of the upper Cretaceous Nanaimo Group.

In general, the Nanaimo Lowland is a gently rising coastal plain (gaining 150 m in elevation in about 10 km) and consists of many low cuesta-like ridges separated by narrow valleys formed by differential erosion of the underlying rocks. Erosion along the northwest-southeast structural trend was enhanced by large southeast-flowing glaciers that occupied the Georgia Depression during past glaciations. Extensive glacial erosion is also evident in the Vancouver Island Ranges, indicated by the presence of steep-sided valleys, closed rock basins, and cirques. Much of this erosion was by local valley glaciers emanating from the Vancouver Island Ranges.

The Vancouver Island Ranges trend northwest and rise in the study area to over 1819 m in elevation at Mount Arrowsmith, which is the highest point of southern Vancouver Island and the headwaters of the Englishman River (**Map 3**). Although ice-free now, well-developed cirques on Mount Arrowsmith show that the Englishman River valley was modified by a valley glacier fed by several former cirque glaciers.

The coastal plain has been incised by several major rivers emanating from the mountains. The main streams draining the study area are (from west to east): Nile Creek, Qualicum River, Little Qualicum River, French Creek, and Englishman River. These north and northeast flowing rivers exposed key stratigraphic sections along their courses.

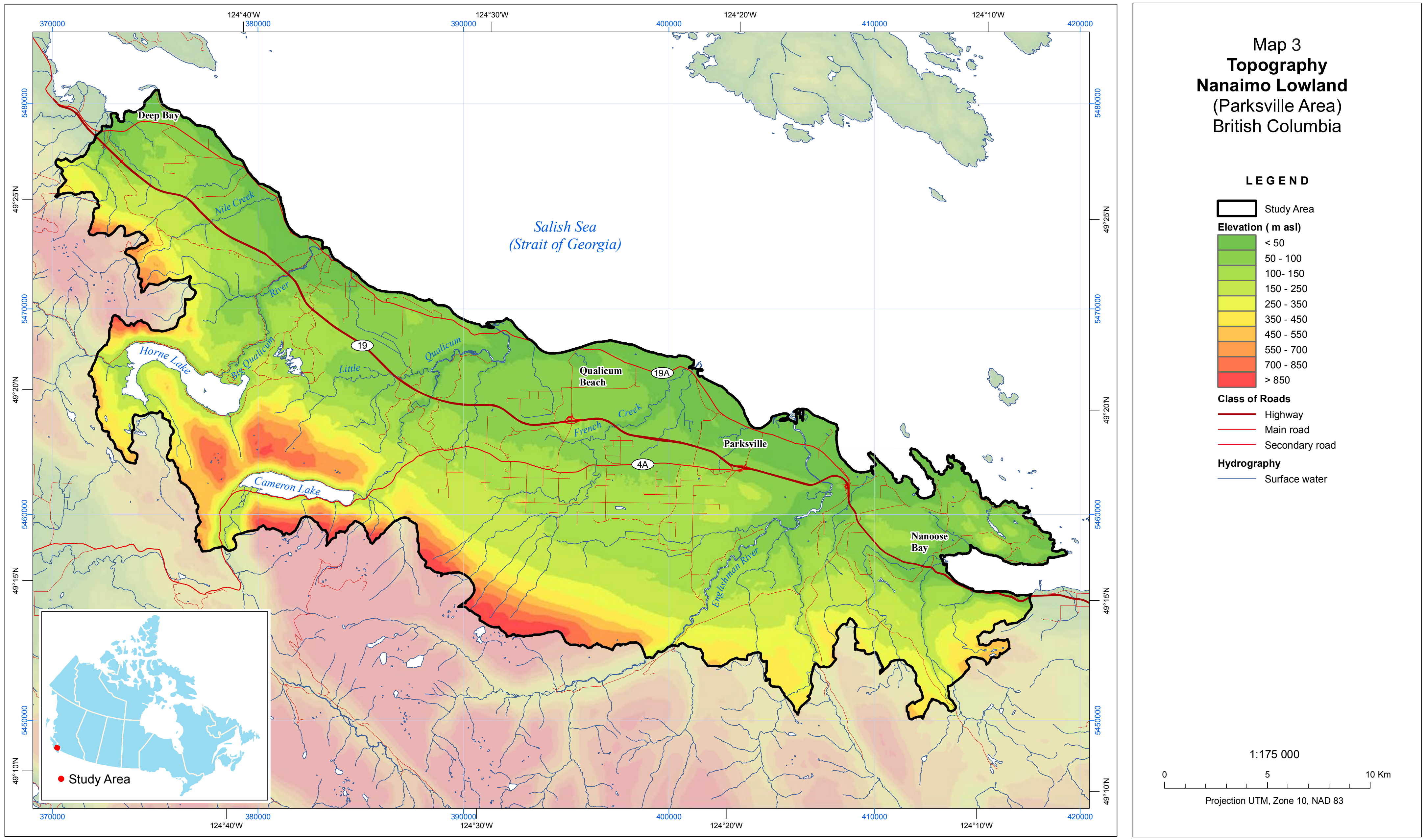
Figure 1.4.1. View from Little Mountain, Parksville, westward toward the Vancouver Island Ranges. Note the low relief forested lowland.

Bednarski, J., 2016. 1.4 Physiography; in Russell, H.A.J., and Benoit, N., (compilers); Nanoose Bay – Deep Bay Area, Nanaimo Lowland Groundwater Study Atlas, Regional District of Nanaimo, British Columbia; Geological Survey of Canada, Open File 7877.

1. STUDY REGION OVERVIEW

1.4. Physiography – **Map 3**

Natural Resources Canada Ressources naturelles Canada



1.5. Land Use/Cover

Wang, S., Canada Centre for Mapping and Earth Observation (Ottawa, ON)

Land cover refers to any surface cover on the ground, whether it is vegetation, urban infrastructure, water, bare soil, and so on. Identifying, and mapping land cover is useful for monitoring studies over time, resource management, and a range of planning activities. Mapping land cover provides a baseline from which other activities and processes can be monitored and assessed.

The land-use/cover map for the study area was produced at a 10 m spatial resolution using spectral remote sensing data (**Map 4**). The area is dominated by coniferous forest, with urban regions present along the coast. The logging industry has been active in the region, resulting in a large percentage of the coniferous forest being in varying stages of regeneration. Validations of the map using independent data from in situ geo-tagged pictures (**Figure 1.5.1**) show that the average accuracy of the 18-class land cover map was 86%.

SPOT Satellite Data

A SPOT image for the study area, acquired in August 2011 at 10 m resolution, was used as the main data source to generate the land-use/cover (**Map 4**). A cloud-free Landsat image, collected in July 2010, was used to infill a small, contaminated area in the SPOT image. Ancillary data included 1:50,000 digital elevation model (DEM) as well as road, rivers, and lake vectors acquired from Natural Resources Canada. Field data were collected and processed for training purposes and for validating the derived land-use/cover product.

Method

The SPOT data was originally classified using the Enhanced Classification Method. Field data and expert knowledge were relied on to label the classes. Landsat imagery from 1984, 1995, and 2010 were used to determine the approximate age of forest disturbance. They were also used to help separate deciduous forest from shrub. Masks were created for urban areas, agriculture, and urban grasslands (parks and fields) through manual interpretation. (**Figure 1.5.2**)

Application

Land-cover mapping provides a baseline dataset for planning, for assessment of potential disturbances to watershed areas, and to support source water protection. It provides a synoptic, rapid, and cost effective means of updating and monitoring changes in vegetation, forestry activity, agricultural practices, and urban development within a watershed that may impact recharge to aquifers and flow to streams. It is a common preliminary product in groundwater studies.

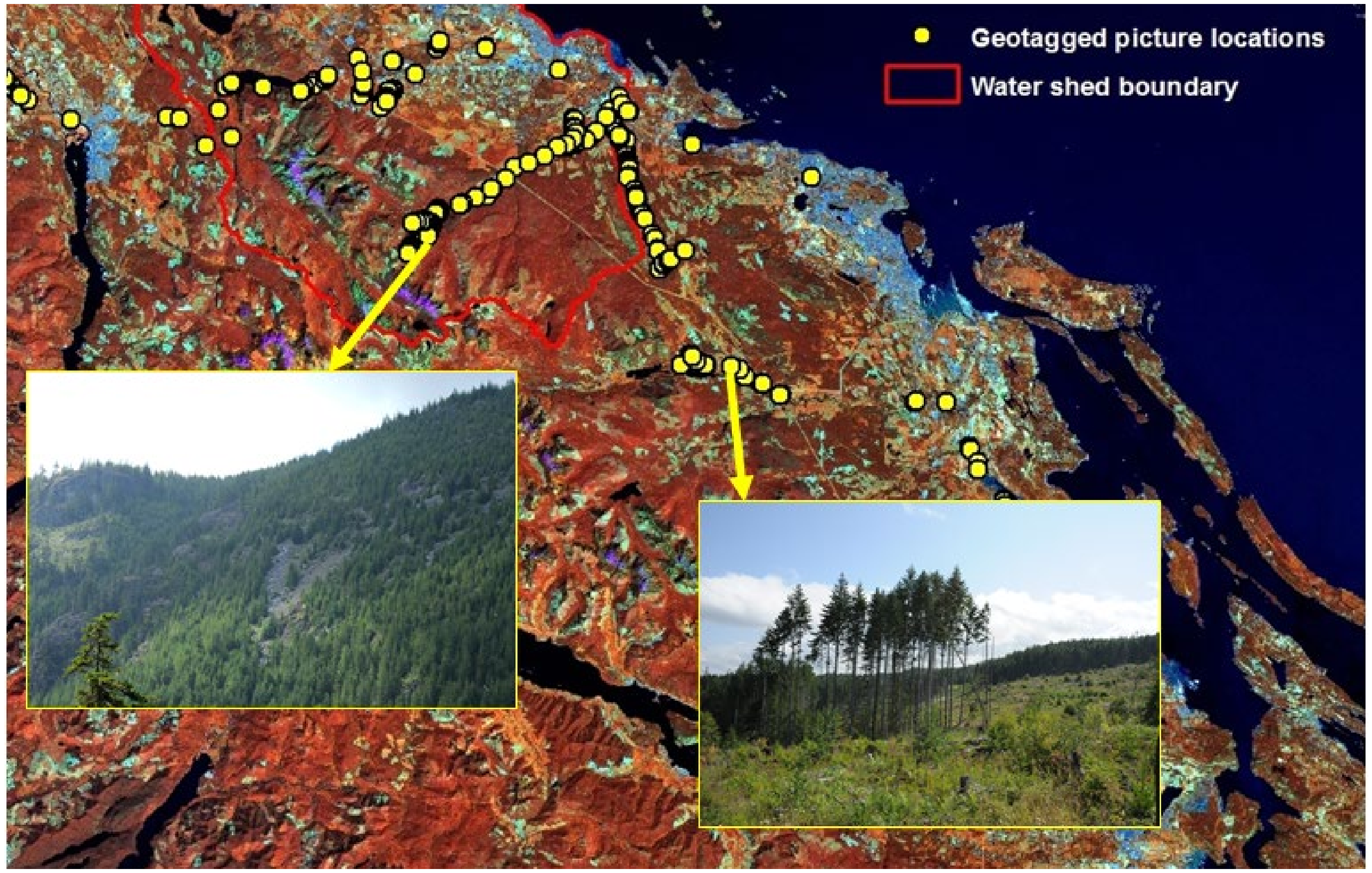


Figure 1.5.1. Map of the location of geo-tagged field pictures and two examples.

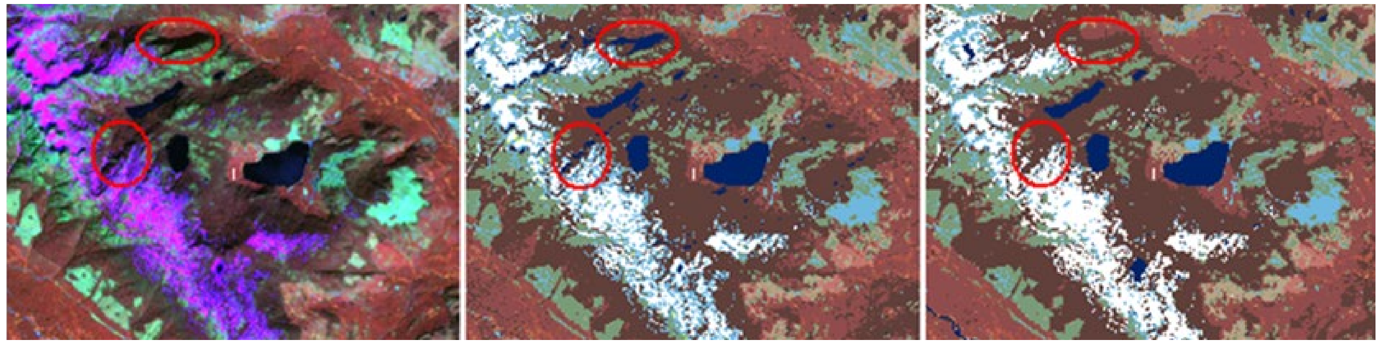
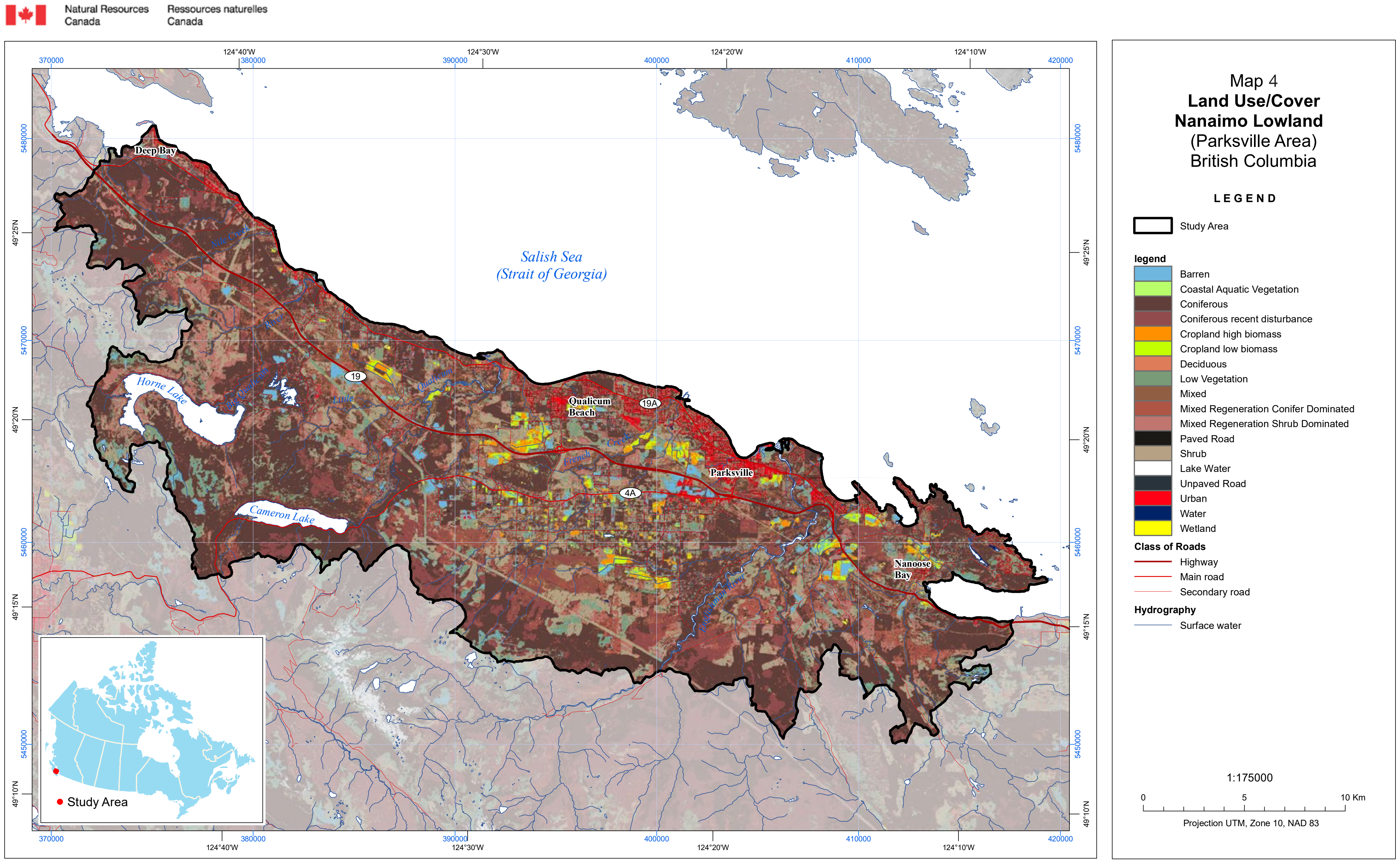


Figure 1.5.2. An example of shadow correction: original SPOT image (left) with shadows on north-facing shadowed areas interpreted as water in initial classification (middle), and corrections made using the slope mask in the finished classification (right).

Wang, S., 2016. 1.5 Land Use/Cover; in Russell, H.A.J., and Benoit, N., (compilers); Nanoose-Deep Bay Area, Nanaimo Lowland Groundwater Study Atlas, Regional District of Nanaimo, British Columbia; Geological Survey of Canada, Open File 7877.

1.5. Land Use/Cover – **Map 4**



2. GEOLOGY

2.1. Bedrock Geology

Hamblin, A.P., Geological Survey of Canada (Calgary, AB)

Principles of Bedrock Aquifer Study

The study and understanding of sedimentary bedrock aquifers incorporates four components:

- **Mapping:** delineating the 2D distribution of identifiable bedrock lithologies at the earth's surface and beneath the unconsolidated surficial deposits in river and coastal sections.
- **Stratigraphy:** identifying the layering, interbedding, and lateral extents at depth of large-scale potential bedrock aquifer and aquitard zones in the subsurface, and how these horizons were deposited through geological time.
- **Sedimentology:** studying the vertical and lateral dimensions and internal characteristics and qualities of individual bedrock horizons, and the way fluids may be stored and flow through them, as determined by the ancient environments in which these rocks were deposited.
- **Structural geology:** observing the distribution and trends of folds, faults, and fractures that determine the present-day geographical distribution in the subsurface that may disrupt the continuity at depth of aquifer and aquitard bodies and fluid flow, or conversely, could provide new conduits for fluid transport.

To begin to understand aquifer characteristics, storage capacity, internal permeability barriers, and fracture patterns of the potential aquifer horizons, as well as the sealing capacity of the potential aquitard zones, 61 surface outcrops within and outside the study area and one long core (215 m in length) were measured and described (**Figure 2.1.1**). More detailed information and data from these outcrops is summarized by Hamblin (2015), and from the core (Hamblin and McCartney, 2014; Zhai and Grasby, 2014). The Nanaimo Group rocks exhibit characteristics and qualities that make them good targets for groundwater exploration and have geological characteristics, which are not random, but have a systematic stratigraphic and structural arrangement.

An **aquifer** is rock unit that can contain enough water to yield economically significant quantities of water.

An **aquitard** is a sediment (rock) unit that has such fine-grained or cemented matrices (pore spaces) that forms a barrier to groundwater flow. When it overlies an aquifer, it provides an additional level of protection against contamination entering the aquifer from the surface.

An **unconformity** is the contact between sedimentary rocks that are significantly different in age, or between sedimentary rocks and older, eroded igneous or metamorphic rocks.

Geological Setting

The Nanaimo Group is of Upper Cretaceous age (deposited about 70-90 million years ago), with the sedimentary bedrock unconformably overlying the Devonian-Jurassic metamorphic, sedimentary, and volcanic Wrangellia Terrane that was accreted onto the western margin of North America prior to Nanaimo Group deposition (Monger, 1989; Mustard, 1994). The Nanaimo Group comprises a total stratigraphic thickness of up to 4 km, and it is subdivided into 11 formations (Muller and Jeletzky, 1970; Mustard, 1994), of which only the lower eight are present in the study area (**Figure 2.2.1**).

On eastern Vancouver Island, these strata form an overall eastward-dipping ramp, sloping into the adjacent Georgia Strait (**Figure 2.1.1**). This geometry determines that lower stratigraphic units are present in surface outcrops and the near subsurface to the west, whereas higher stratigraphic units are present in surface outcrops and the near subsurface to the east.

Throughout the region, the Nanaimo Group is deformed by post-depositional tectonic compression into northwest-trending folds, and broken by northwest-trending faults (Yorath et al., 1992; Journeay and Morrison, 1999). In addition, northeast-trending fractures are present in many outcrops and likely extend into the subsurface. The fracture distribution increases the aquifer potential and rate of recharge at shallow depths (Mackie, 2002).

Hamblin, A.P., 2016. 2.1 Bedrock Geology; in Russell, H.A.J., and Benoit, N., (compilers); Nanoose Bay - Deep Bay Area, Nanaimo Lowland Groundwater Study Atlas, Regional District of Nanaimo, British Columbia; Geological Survey of Canada, Open File 7877.

2. GEOLOGY

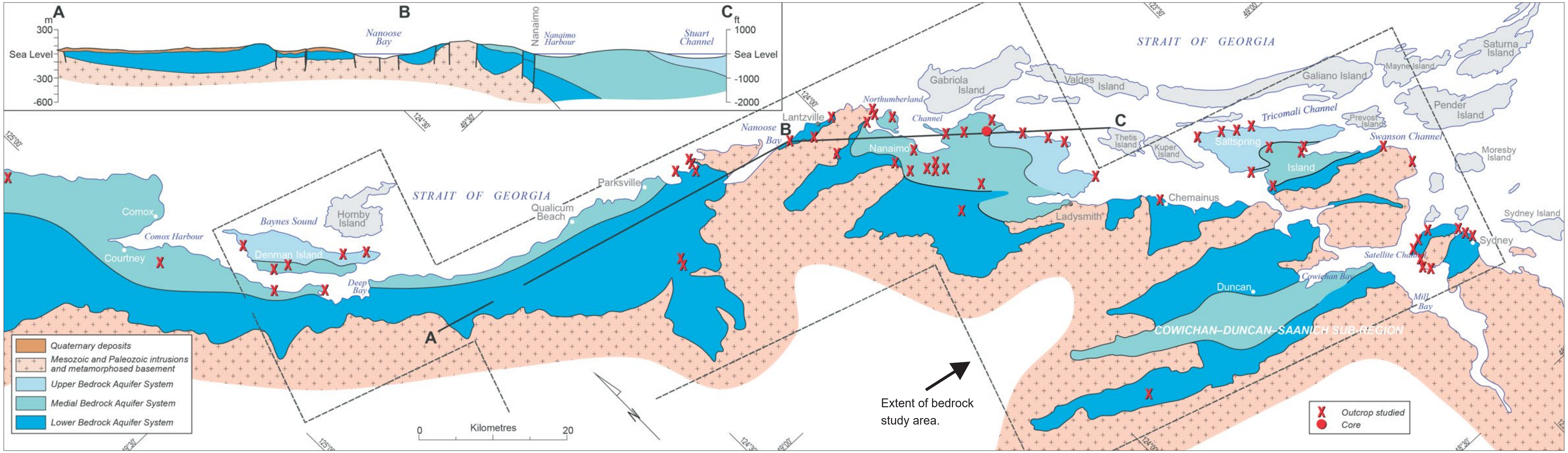


Figure 2.1.1. Simplified distribution of interpreted bedrock aquifer systems of the Nanaimo Group geology with location of outcrop and core locations. Area encompasses a larger area than the Nanoose – Deep Bay area of the hydrogeological study.

2.2. Nanaimo Group

Hamblin, A.P., Geological Survey of Canada (Calgary, AB)

The Nanaimo Group displays a prominent pattern of alternating coarse-grained (potential regional-scale aquifer zones) and fine-grained (potential regional-scale aquitard zones) formations (**Figure 2.2.1**). This succession represents a sequence from the erosional unconformity surface at the base of the Nanaimo Group, through units deposited in a variety of ancient non-marine/marginal marine environments, to those deposited in primarily deeper marine settings. The geology of the Nanaimo Group suggests that the laterally extensive coarser-grained formations may be mappable regional aquifers with potential for new groundwater resources, whereas the intertonguing laterally extensive finer-grained formations may be mappable regional aquitard seals.

Similarly, within each formation-scale aquifer zone, the stratigraphic alternation of smaller-scale individual coarse-grained and fine-grained bodies will separate formations into more local smaller-scale aquifer bodies separated by thinner, less continuous aquitard horizons. This may provide a conceptual prospecting model for vertically stacked, multiple aquifer targets, on both local and regional scales. Extensive fracturing is commonly observed in the Nanaimo Group and is important in enhancing aquifer potential. The extent and orientation of the fracturing in the subsurface is currently unknown. The quality of the water in these potential aquifers may be brackish at depth.

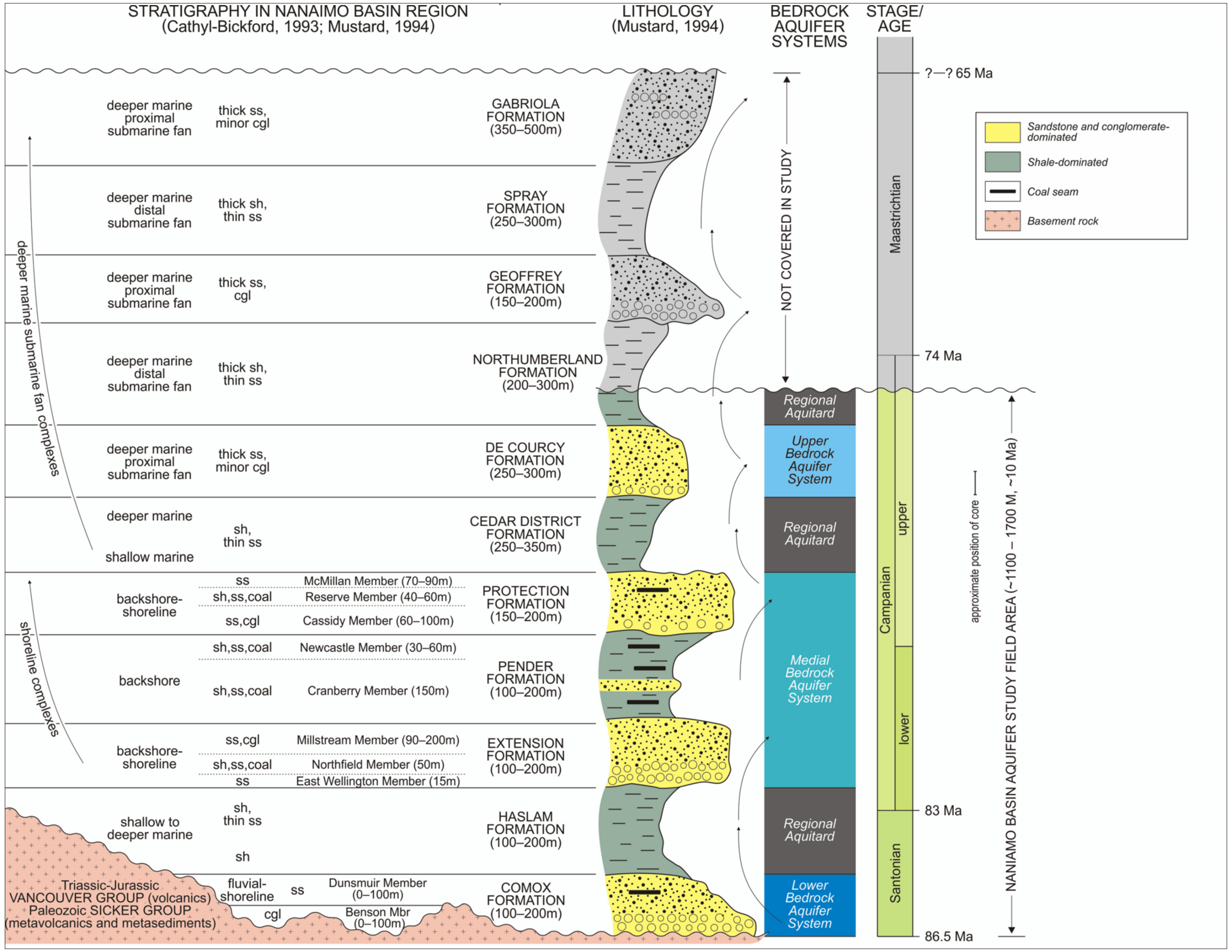


Figure 2.2.1. Simplified stratigraphy illustrating alternating coarse-grained (aquifer) and fine-grained (aquitard) units, and interpreted bedrock aquifer systems (simplified from Muller and Jeletzky, 1970; Cathyl-Bickford, 1993; and Mustard, 1994).

Hamblin, A.P., 2016. 2.2 Nanaimo Group; in Russell, H.A.J., and Benoit, N., (compilers); Nanoose Bay - Deep Bay Area, Nanaimo Lowland Groundwater Study Atlas, Regional District of Nanaimo, British Columbia; Geological Survey of Canada, Open File 7877.

2.2. Nanaimo Group (continued)

Lower Bedrock System

The regionally extensive Lower Bedrock system consists of a combination of the basal unconformity and the lowest coarse-grained unit (Comox Formation). It is up to 200 m thick and is present at the surface in the west and south of the Bedrock Study Area and in the shallow subsurface eastward, lying deeper toward the east (**Figure 2.1.1**).

The heavily fractured unconformity surface and the unsorted rubble associated with it form a thin enhanced aquifer zone immediately overlying impermeable basement rocks (**Figure 2.2.2A,B**). The Comox Formation sandstone and conglomerate are generally coarse-grained near the base (**Figure 2.2.2B**) and finer-grained and well sorted toward the top (**Figure 2.2.2C**). It is interpreted to be a braided fluvial and shoreline beach deposit and is the lowest potential aquifer zone of the Nanaimo Group, which fills topographic lows on the underlying unconformity surface (**Figure 2.2.2A**).

Within the Comox Formation, individual sandstone/conglomerate bodies should be fairly thick, laterally extensive, and have fair-to-excellent aquifer potential. This combination of units forms a major, regionally extensive system that offers the best regional and local bedrock aquifer potential. It is also a significant zone of surface infiltration recharge in the western areas of the Bedrock Study Area where it outcrops at higher elevations. The overlying Haslam Formation is up to 200 m thick of siltstone and mudstone with minor sandstone interbeds. This is interpreted as marine shelf to deeper slope deposits, which form an important regionally extensive aquitard zone (**Figure 2.2.2D**).

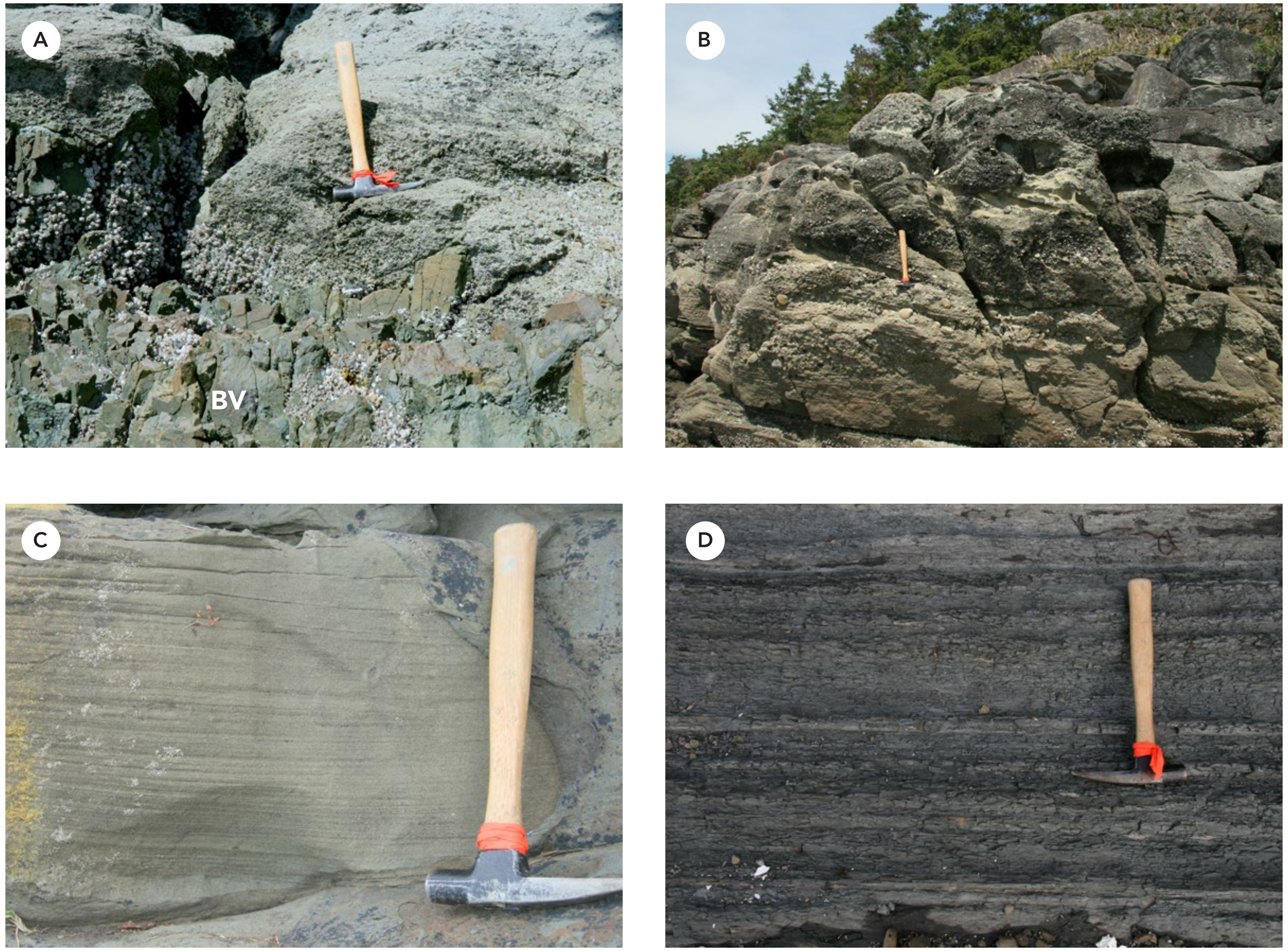


Figure. 2.2.2. A) Comox Formation coarse-grained sandstone overlying basal unconformity and basement volcanics (BV), Lower Bedrock System, Pacific Biological Station near Nanaimo. **B)** Lower Comox Formation porous and permeable coarse-grained sandstone to pebble conglomerate (braided fluvial), Lower Bedrock System, South Ruckle Park. **C)** Upper Comox Formation porous and permeable fine- to medium-grained sandstone (shoreline), Lower Bedrock System, Blunden Point near Lantzville. **D)** Haslam Formation marine mudstone with thin siltstone interbeds, aquitard seal to Lower Bedrock System, Erskine point, Saltspring Island.

2.2. Nanaimo Group (continued)

Medial Bedrock Aquifer System

The regionally extensive Medial Bedrock System consists of five formations and is present over most of the eastern part of the Bedrock Study Area at surface, and in the shallow subsurface is up to 600 m thick, consisting of three formations (**Figure 2.1.1**). The basal Extension Formation sharply overlies the Haslam Formation, and is up to 200 m of conglomerate and coarse sandstone with minor coal. It is interpreted to be alluvial fan to braided fluvial deposits, and is a potential aquifer zone (**Figure 2.2.3A**). It is succeeded by the Pender Formation of up to 200 m of siltstone, sandstone, and mudstone with significant coal, it is interpreted to represent deposition in coastal and floodplain environments, from which coal was mined for many decades.

The overlying Protection Formation is up to 200 m of sandstone with minor mudstone, and is interpreted to be deposits of shallow marine shelf to coastal setting. It is an additional potential aquifer zone (**Figures 2.2.3B,C**), and was quarried for building and grinding stone on Newcastle Island. This system may offer significant regional and local bedrock groundwater potential in the eastern and northern areas where it outcrops, as well as in the shallow subsurface.

Individual aquifer bodies can be thick and may be laterally extensive. They could also have variable but fair-to-good aquifer characteristics. The overlying Cedar District Formation of up to 300 m of mudstone and siltstone with minor sandstone interbeds is interpreted to be deposits of deeper marine shelf to deeper slope or submarine fan environments (**Figure 2.2.2D**). It forms an important regionally extensive aquitard zone over large areas (**Figure 2.1.1, 2.2.2D**).

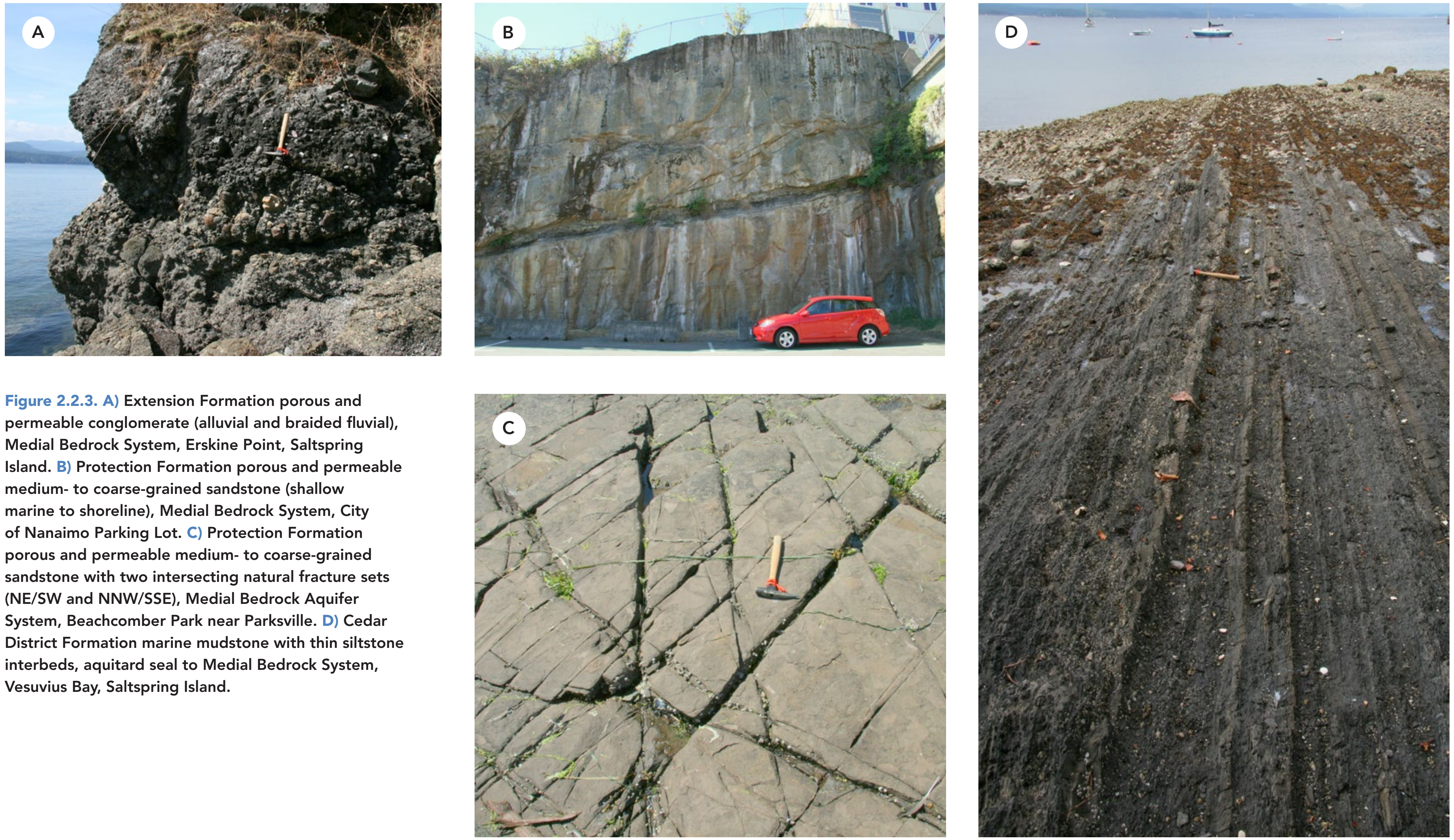


Figure 2.2.3. A) Extension Formation porous and permeable conglomerate (alluvial and braided fluvial), Medial Bedrock System, Erskine Point, Saltspring Island. B) Protection Formation porous and permeable medium- to coarse-grained sandstone (shallow marine to shoreline), Medial Bedrock System, City of Nanaimo Parking Lot. C) Protection Formation porous and permeable medium- to coarse-grained sandstone with two intersecting natural fracture sets (NE/SW and NNW/SSE), Medial Bedrock Aquifer System, Beachcomber Park near Parksville. D) Cedar District Formation marine mudstone with thin siltstone interbeds, aquitard seal to Medial Bedrock System, Vesuvius Bay, Saltspring Island.

2.2. Nanaimo Group (continued)

Upper Bedrock System

The locally significant Upper Bedrock System consists of the uppermost coarse-grained unit and is present in outcrops and the shallow subsurface only in the easternmost part of the Bedrock Study Area (**Figure 2.1.1**). The De Courcy Formation is up to 300 m of sandstone with lesser conglomerate, and is interpreted to be deposits of deep submarine canyon and fan environments. It is the only unit encountered in the recently cored subsurface well (**Figure 2.2.4A**). Within the De Courcy Formation, individual sandstone units can be thick, laterally extensive, and may have good aquifer characteristics. The De Courcy is overlain locally by the Northumberland Formation's mudstone and siltstone with minor sandstone interbeds (up to 200 m thick) that are interpreted to be deep marine slope and submarine fan deposits (**Figure 2.2.4B**). This may constitute a locally developed potential aquitard zone.

For the Upper Bedrock System, unlike the other systems that are only observed in surface outcrops, there are data on the presence of significant subsurface matrix porosity (sandstones have 2-10% porosity) and permeability (sandstones have 3-105 millidarcys permeability) based on data from the single cored well of the study (**Figure 2.2.4A**).

A full assessment of the aquifer potential of the various bedrock units of the Nanaimo Group and the possible contribution of porous- versus fracture-controlled aquifer properties needs additional work that was beyond the scope of this project.

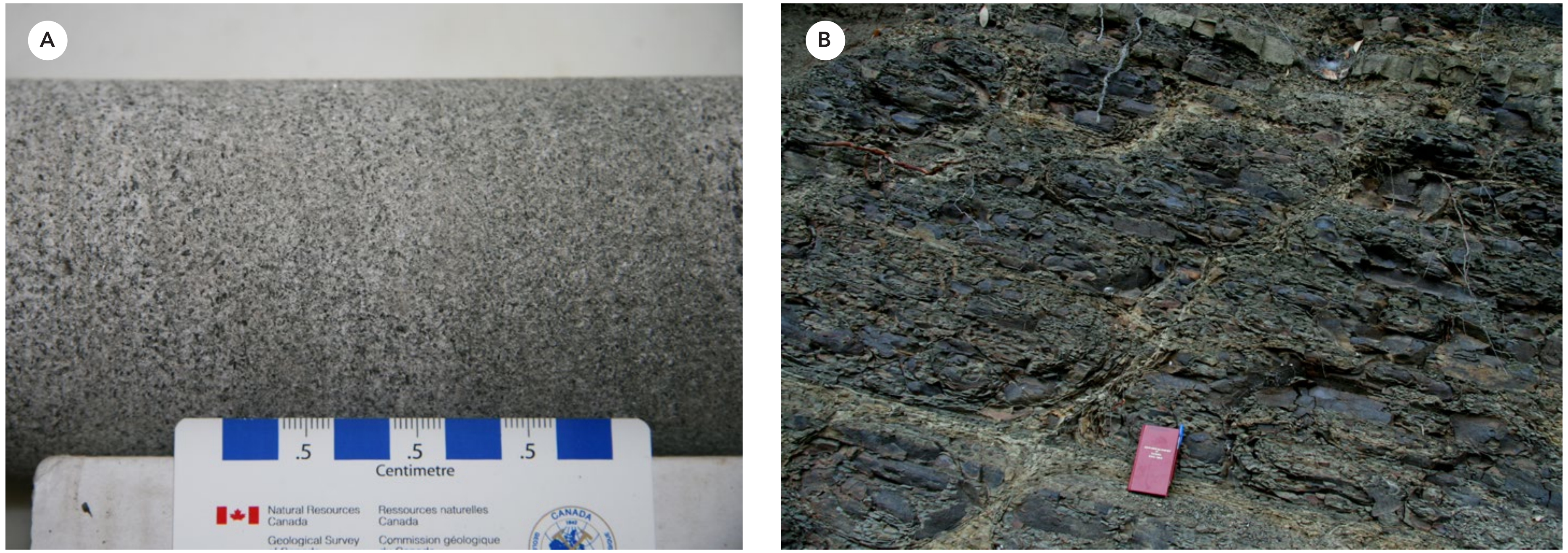
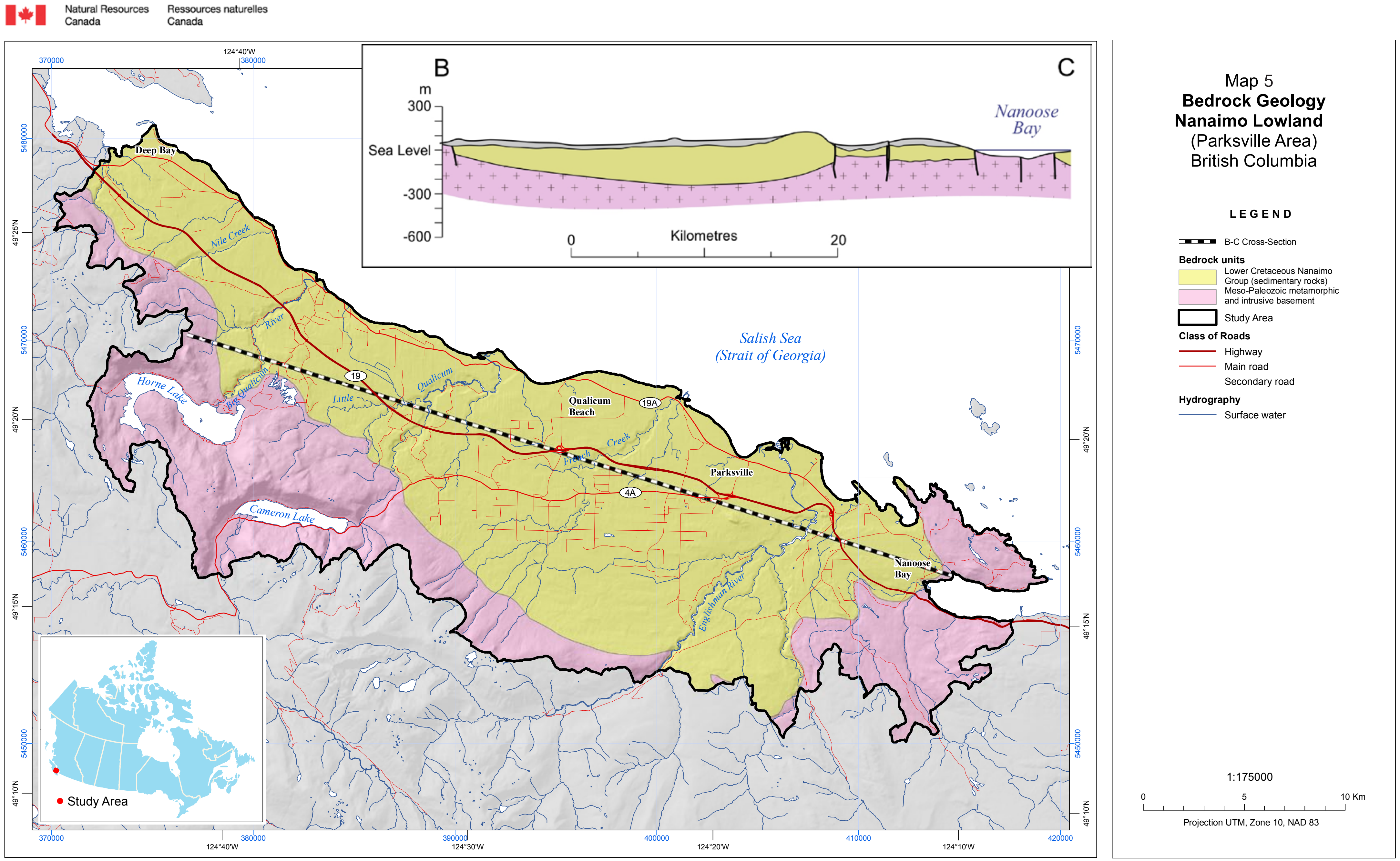


Figure. 2.2.4 A) DeCourcy Formation porous and permeable coarse-grained sandstone (submarine fan) from subsurface core, Upper Bedrock System, near Cedar. B) Northumberland Formation marine mudstone (deep slope) with natural fractures, aquitard seal to Upper Bedrock System, St. Mary Lake road cut, Saltspring Island.

2.2. Nanaimo Group – **Map 5**



2.3. Glacial Geological History

Bednarski, J., Geological Survey of Canada (Sidney, BC)

Cordilleran Ice Advance

The advance of the Cordilleran Ice Sheet on southern Vancouver Island was characterized by a lobe of the ice sheet flowing from the Coast Mountains southeastward down the Georgia Depression and impinging on the eastern flank of Vancouver Island (**Figure 2.3.1A**). As the ice filled the Georgia Depression, it divided into two lobes, with one flowing along Puget Lowland, and the other along the Strait of Juan de Fuca.

On the southeast coast of Vancouver Island glaciolacustrine sediments were deposited into lakes dammed by the lobe (Alley and Chatwin, 1979). At its maximum, around 14,000 years ago, the Cordilleran Ice Sheet surmounted most of the Vancouver Island Ranges with an estimated thickness of up to 1500 m and flowed southwest across Vancouver Island to the continental shelf (Clague, 1981). Subsequent retreat of the ice from the maximum extent occurred over 4000 years, with almost complete deglaciation by about 10,000 years ago.

The Cordilleran Ice Sheet first advanced into the Georgia Depression as tongues of ice flowing down the fiords to the sea. The ice was relatively thin compared to the depth of water, so the glaciers became buoyant and likely formed calving glaciers and ice shelves in places. Glacial debris melting out from beneath the ice settled through the water column depositing a mix of coarse rock debris and fine sediment. These deposits are commonly fossiliferous and provide a useful dating control. Glaciomarine sedimentation ceased during the glacial maximum when the sea in the Georgia Depression was completely displaced by the Cordilleran Ice Sheet, and the ice was in direct contact with the seabed (Clague, 1981, 1986).

During the initial Cordilleran ice lobe advance along the Georgia Depression, meltwater was directed southeast towards the margins, depositing extensive proglacial Quadra Sand outwash that was subsequently overridden by the ice and deposition of the Vashon Till.

The Quadra Sand is thought to have originated either as a series of distinct outwash fans and deltas that became amalgamated during the advance, or a formerly continuous outwash plain infilling the Georgia Depression that was subsequently partially eroded by the overriding ice. The Quadra Sand is one of the most important aquifers in the Nanaimo Lowland. The Nanaimo Lowland also has thick sequences of outwash associated with the advance of local Vancouver Island glaciers.

Deglaciation

Deglaciation of the Nanaimo Lowland was marked by thinning and separation of the Cordilleran lobe from the Vancouver Island valley glaciers (**Figure 2.3.1B**). Once separation occurred, ice-contact glaciofluvial terraces and deltas were deposited along the retreating ice margins (Spider Lake is an example). Eventually the sea flooded the area from the southeast, and glaciofluvial deltas were built into a high postglacial sea reaching 150 m above modern sea level. In places, such as the Englishman River Valley, the local valley glaciers may have persisted and even re-advanced after the retreat of the Cordilleran lobe. A similar late glacial resurgence has also been documented in other parts of Vancouver Island (Lian and Hickin, 1993; Alley and Chatwin, 1979).

By 6000 years ago, sea level was below present (Hutchinson, et. al., 2004). Where sediment supply was adequate, the main rivers built deltas into progressively lower sea levels. In other places, streams crossing the lowland either cut terraces into pre-existing glacial deposits, or cut narrow canyons into the bedrock. Modern alluvium is confined to the lower reaches of larger rivers.

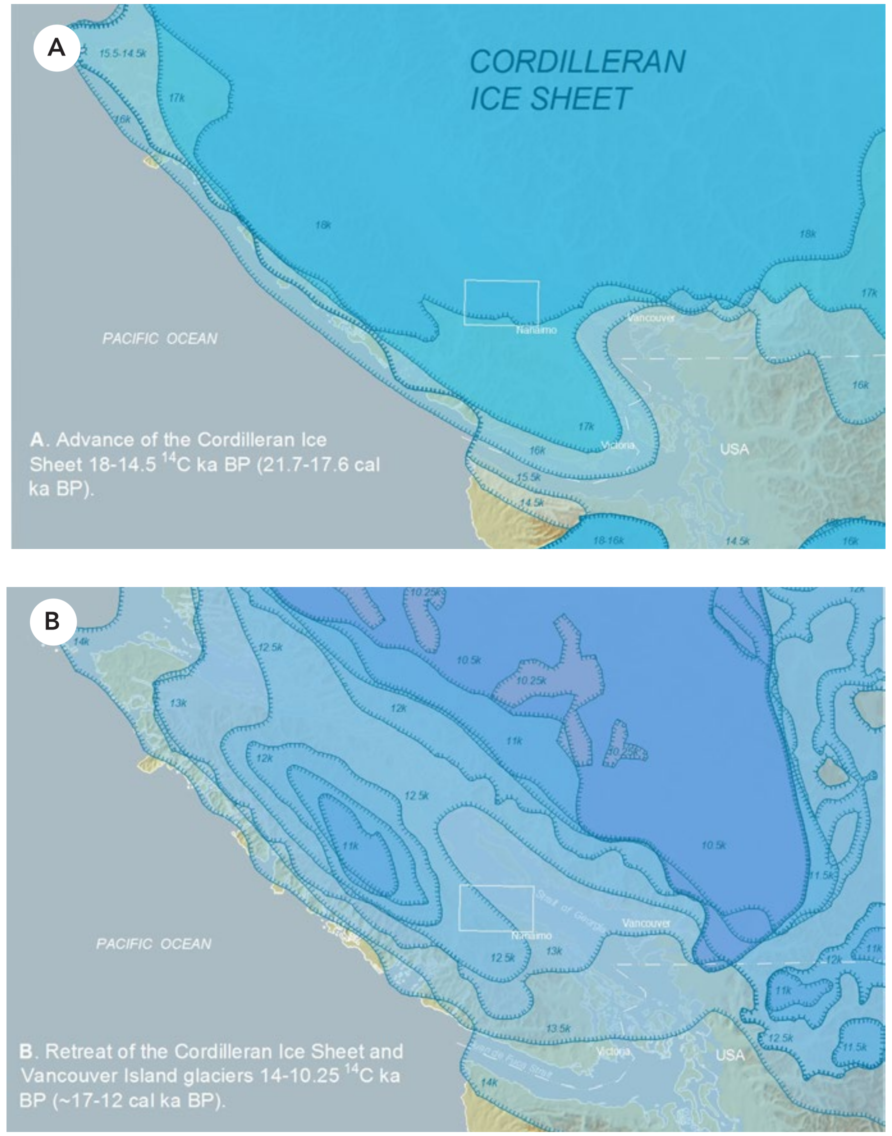


Figure 2.3.1 A) Advance of the Cordilleran Ice Sheet 18,000-14,500 radiocarbon years before present (^{14}C ka BP). **B)** Retreat of the Cordilleran Ice Sheet and Vancouver Island glaciers 14,000-10,250 ^{14}C ka BP. Darker blue colours represent younger ages and inferred ice configuration.

Bednarski, J., 2016. 2.3 Glacial Geological History; in Russell, H.A.J., and Benoit, N., (compilers); Nanoose Bay - Deep Bay Area, Nanaimo Lowland Groundwater Study Atlas, Regional District of Nanaimo, British Columbia; Geological Survey of Canada, Open File 7877.

2.4. Surficial Stratigraphic Framework

Bednarski, J., Geological Survey of Canada (Sidney, BC) and Cummings, D.I., DC Geo (Aylmer, QC)

The thick unconsolidated sediment underlying the study area records a succession of two glacial intervals separated by a period of nonglacial sedimentation, all overlain by postglacial marine and fluvial deposits (Fyles, 1963; **Table 2.5.1**; **Figures 2.4.1, 2.4.2**).

Numerous radiocarbon dates and good stratigraphic control suggest that the base of the succession is early to middle Wisconsinan in age (100,000 to 75,000 years ago; Hicock and Armstrong, 1983). Older last interglacial Sangamonian (125,000 to 100,000 years ago) deposits have been identified near Victoria, BC, (Muir Point Formation; Alley and Hicock, 1986), and it is possible that such deposits exist but remain unrecognized in the Nanaimo Lowland. Such deposits are beyond the range of radiocarbon dating.

There are six main surficial geological units that make up the stratigraphic framework in the study area (**Table 2.5.1**).

Mapleguard Sediments – Dashwood Drift – Penultimate Glaciation

The Mapleguard Sediments (Fyles, 1963) are the oldest Pleistocene deposits identified in the Nanaimo Lowland. They are bedded sand, silt, clay, and minor gravel that underlie glacial deposits at the base of a few sea cliffs northwest of Qualicum Beach. Based on pollen assemblages and clast origin, Mapleguard Sediments are considered to be outwash deposited at the onset of the penultimate glaciation (Hicock, 1980; Hicock and Armstrong, 1983; Ryder and Clague, 1989).

The Dashwood Drift includes a single till, up to 9 m thick, bounded by glaciofluvial, ice contact, and glaciomarine to marine sediments. It was deposited during the early Wisconsin penultimate glaciation (Hicock and Armstrong, 1983).

Cowichan Head Formation – Olympia Nonglacial Interval

The Cowichan Head Formation has been divided into a lower marine member of clayey silt and sand, and an upper member of estuarine and fluvial sandy silt and gravel that is rich in fossil plant remains. At the community of Dashwood, the Cowichan Head Formation consists of 9 m of organic-rich silt, gravel, and peat, with minor sand. The basal silts have casts of marine shells in places, whereas, the upper organic material consists of detrital woody fragments, grasses, mosses, and sedges. There is at least 2.4 m of compact peat, probably deposited in a boggy floodplain (Alley, 1979). Radiocarbon dates range from 25.8 to 40.5 ka 14C BP (Armstrong and Clague, 1977). Fossil pollen and beetle assemblages suggest that the climate fluctuated between conditions similar to present and cooler than present (Armstrong and Clague, 1977).

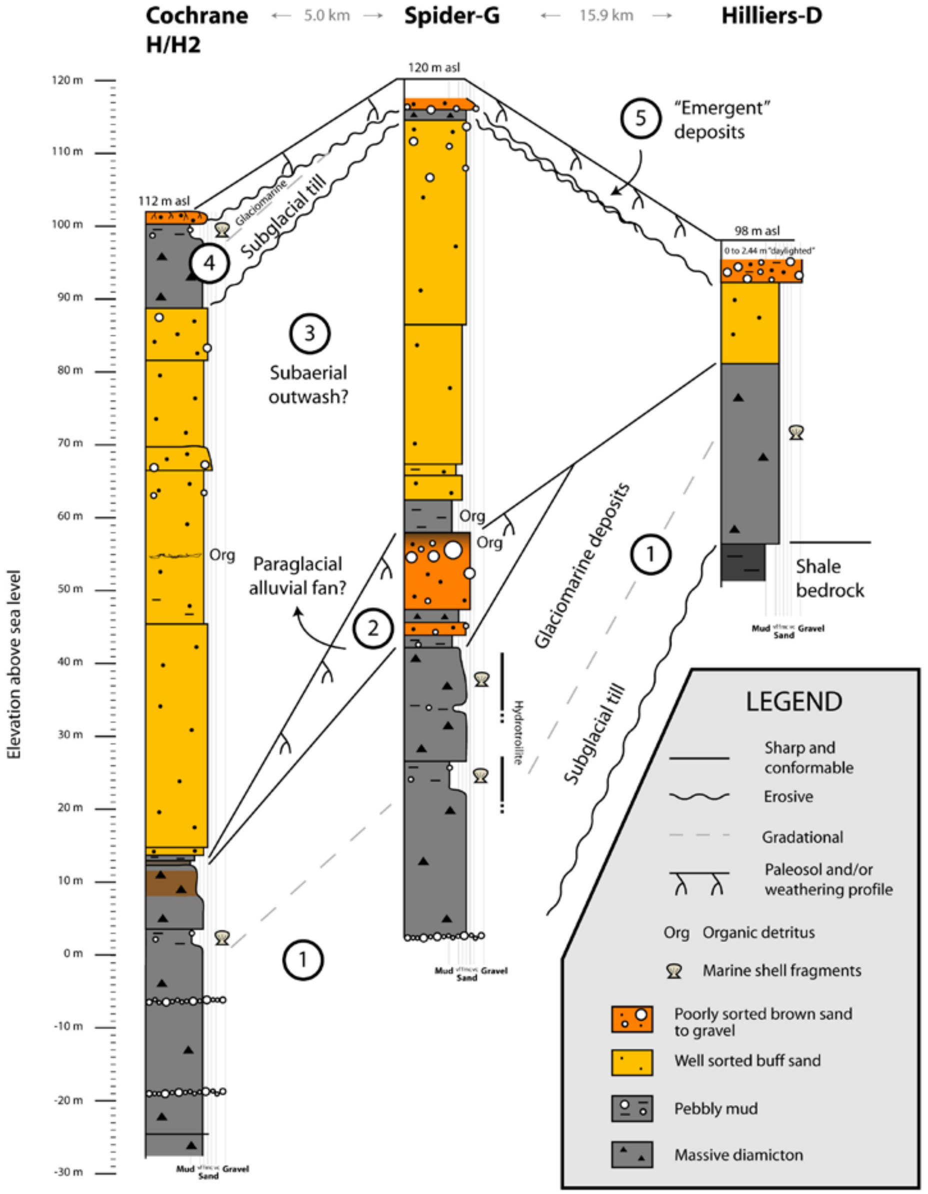


Figure 2.4.1 Stratigraphic logs of rotosonic core highlighting succession from surface of Vashon Drift (4), Quadra Sand (3), Cowichan Head Formation (2), and Dashwood Drift (1).

Bednarski, J., and Cummings, D.I., 2016. 2.4 Surficial Stratigraphic Framework; in Russell, H.A.J., and Benoit, N., (compilers); Nanoose Bay - Deep Bay Area, Nanaimo Lowland Groundwater Study Atlas, Regional District of Nanaimo, British Columbia; Geological Survey of Canada, Open File 7877.

2.4. Surficial Stratigraphic Framework (continued)

Quadra Sand – Fraser Glaciation

The Quadra Sand consists of horizontally and cross-stratified, well-sorted sand with minor silt and gravel that is up to 75 m thick and overlies the Cowichan Head Formation. The sediment has been described as "white sand" with a composition reflecting Coast Mountain and Georgia Depression sources, rather than sources from the Vancouver Island Ranges. The lower parts of the Quadra Sand have wood and peat lenses suggesting it is subaerial outwash that extended across and along the margins of the present-day Strait of Georgia. Clague (1981) envisioned a "prograding apron or blanket down the axis of the Georgia Depression." The basal radiocarbon age of the Quadra Sand decreases from north to south. It is 28,800 14C BP near Comox, 27,000 14C BP at Dashwood (Alley, 1979), 18,300 to 18,700 14C BP east of Vancouver, and 15,000 14C BP near Seattle, which is the southern limit of the outwash (Clague, 1976).

Vashon Drift – Fraser Glaciation

The Vashon Drift includes surface till and various ice-proximal deposits and moraines deposited during the last glaciation. It unconformably overlies the Quadra Sand and can be 30 m thick. On the lowland, the tills tend to be sandy diamictons, but in some valleys the matrix is more clayey. The lithologic composition of the drift reflects Coast Mountain and Georgia Depression sources (like the underlying Quadra Sand), rather than from the Vancouver Island Ranges.

The Georgia Depression was covered by Cordilleran ice after about 17,000 to 18,000 14C BP, but the maximum extent of the Cordilleran Ice Sheet in the Strait of Georgia/Puget Lowland occurred between 14,400 to 15,000 14C BP, with deglaciation of the Strait of Georgia ~13,000 14C BP.

Capilano Sediments – Fraser Glaciation to Postglacial

The Capilano Sediments are coarse glaciofluvial outwash gravels and sands, with minor diamictons. Thick glaciomarine and marine sediments were deposited in isostatically depressed coastal areas. Fluvial terraces formed in valleys, and deltas prograded into the basin where sediment supply was adequate. As the ice melted away, the upper complex of late glacial sediments included in the Vashon Drift transitioned into Capilano Sediments. 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 ~150 to 50 m in the first thousand years following deglaciation, eventually reaching a minimum 15 m below present sea level about 11,300 calibrated radiocarbon years before present (cal BP). Sea level has remained near present since 6000 cal BP (Hutchinson et al., 2004).

Salish Sediments – Postglacial – Modern

The Salish Sediments were deposited by geomorphic processes that are still active today. In the Nanaimo Lowland these sediments are related to modern sea, river, and lake levels, and to recent mass wasting (Armstrong and Brown, 1954). In general, sediments up to 5 m above present base levels are regarded as Salish. Most significant Salish Sediments are channel and floodplain deposits on the floors of river valleys and deltas.

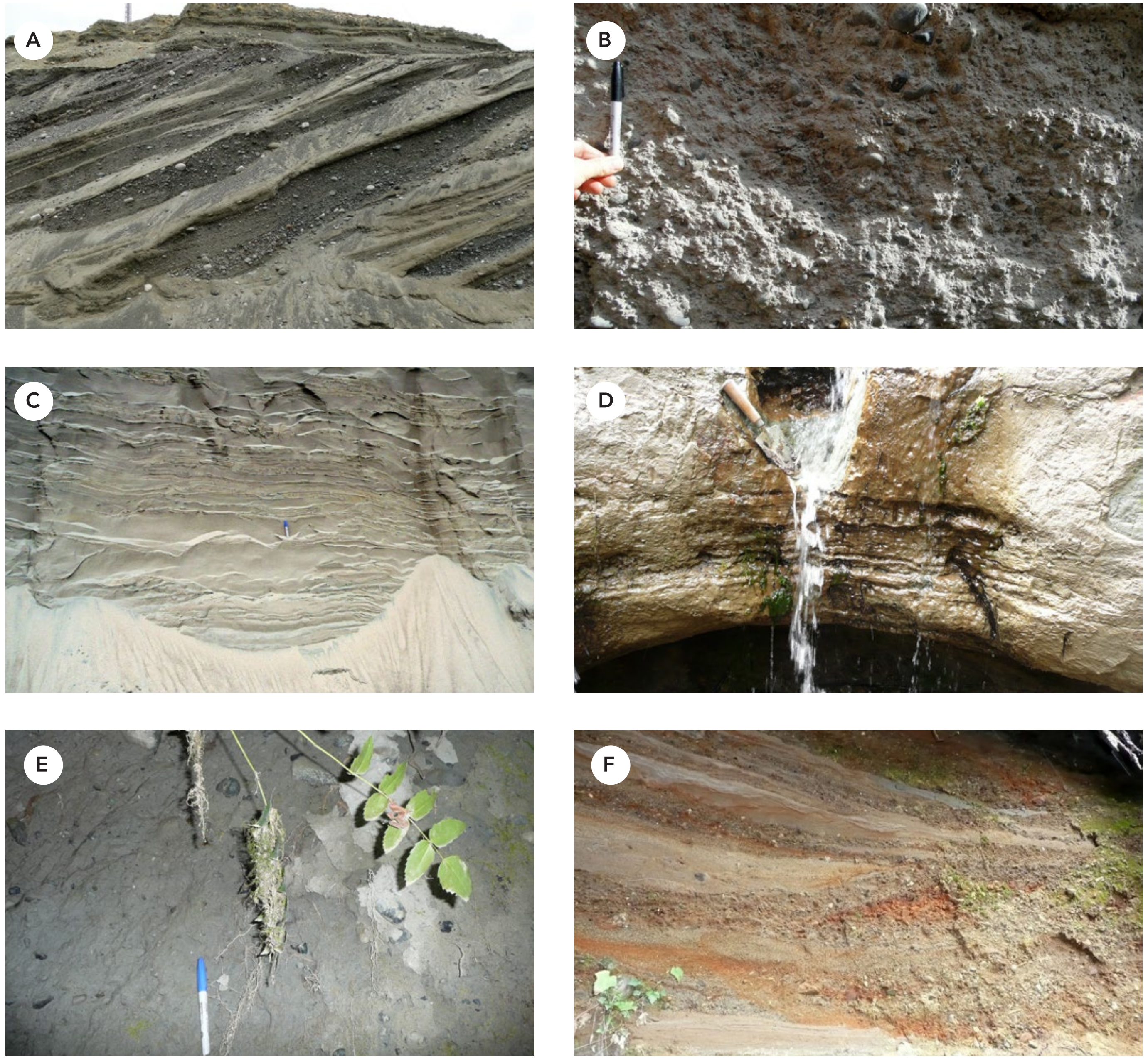


Figure 2.4.2. **A)** Capilano: foreset bedded gravel in a glaciofluvial delta (photo by A. Pugin). **B)** Vashon: diamicton with sandy silt rich matrix and abundant clasts. **C)** Quadra Sand: cross-bedded and fine- to medium-grain sand. **D)** Cowichan Head: thin-bedded sand and silt. **E)** Dashwood: dense muddy diamicton. **F)** Mapleguard: cross-stratified gravely sand.

2.5. Surficial Geology

Bednarski, J., Geological Survey of Canada (Sidney, BC)

Previous surficial mapping of the study area was completed by Fyles (1963). Using the stratigraphic framework largely developed by Fyles (1956), a new surficial map has been generated as part of the study, based on selected fieldwork and an updated protocol. The protocol was, as follows: manual delineation of the surficial units by interpretation of aerial photographs, composite satellite images, and digital elevation model (DEM). Additional stratigraphic information was derived from the BC Water Well Database, BC aggregate resource potential database (Massey, et. al. 1998), soils maps (Jungen, 1985), seismic reflection data and rotosonic cores collected during the study. Most of the fieldwork and ground verification was along road access, stream banks, and coastal cliffs.

Surficial unit boundaries were based on surface expression and topography with field checking. Most distinct boundaries were defined by specific landforms; however, many of the surficial units are thin and discontinuous with lateral gradations of facies. Where access was not possible, or the area was heavily forested, the unit boundaries are approximate.

The stratigraphy exposed along the rivers is usually not continuous, so that some units were extrapolated along river valleys. In most places a thin veneer of slope wash obscures the stratigraphy and the stratigraphy is inferred from intervening exposures. Most of the deposits are closely linked to the past glacial history of the Nanaimo Lowland. The relative proportions of the principal mapped surficial units are illustrated in the pie diagram (**Figure 2.5.1**) accompanying **Map 6**. Note that important aquifers and aquitards, such as the Quadra Sand and pre-Vashon sediments, respectively comprise only a small fraction of the material exposed at the surface. Significant groundwater recharge would be restricted to alluvium and glaciofluvial deposits covering some 18% of the total area.

Radiocarbon Age		Stage/Substage	Climatostratigraphy	Lithostratigraphic Unit	Environment of Deposition and Principal Materials
ka cal BP	ka cal BP	Holocene	Postglacial	Salish Sediments	**Swamp/Organic Deposits:** organic matter and mud **Slope Deposits:** alluvial fans of poorly sorted gravels: landslide debris, colluvium **Lacustrine:** fine-grained sediments deposited in lakes **Marine:** littoral sediments, sand, gravel and silt at the present shoreline **Fluvial:** deltaic and channel floodplain, stratified gravel, sand and silt
10	11.6	Late Wisconsinan		Capilano Sediments	**Slope Deposits:** alluvial fans of poorly sorted gravels; landslide debris, colluvium **Glaciofluvial to Fluvial:** stratified sand and gravel, postglacial deltaic sediments and channel flood plain deposits **Glaciomarine to Marine:** stoney silt, sand and clay, contains marine shells and rare wood; diamictons in places
13	15.6		Fraser Glaciation	Vashon Drift	**Glaciofluvial / Ice Contact:** poorly sorted gravels, sands and silts; stratified; Kame and kame deltas **Glacial:** sandy to clayey diamicton, till; in places lenses of stratified sediments
18	21.8			Quadra Sand	**Glaciofluvial:** stratified sand, minor gravel and silt, well-sorted, in places organic rich near base
27.1	31.1	Mid-Wisconsinan	Olympia Nonglacial Interval	Cowichan Head Formation	**Marine to Fluvial:** pebble-gravel, peat with pebbles and wood **Marine:** clay, stony clay, silt, shells; basal laminations in places laminated
40	43.6				
>50 *beyond the range of radiocarbon dating*		Pre-Wisconsinan	Penultimate Glaciation	Dashwood drift *(including Mapleguard sediments)*	**Glaciomarine:** stoney silts and clay with sand lenses and shells **Glacial:** sandy to silty diamicton, till containing silt and gravel lenses

Table 2.5.1. **Subdivision of Late Quaternary deposits and events, east central Vancouver Island.**

Bednarski, J., 2016. 2.5 Surficial Geology; in Russell, H.A.J., and Benoit, N., (compilers); Nanoose Bay - Deep Bay Area, Nanaimo Lowland Groundwater Study Atlas, Regional District of Nanaimo, British Columbia; Geological Survey of Canada, Open File 7877.

2. GEOLOGY

2.5. Surficial Geology – **Map 6**

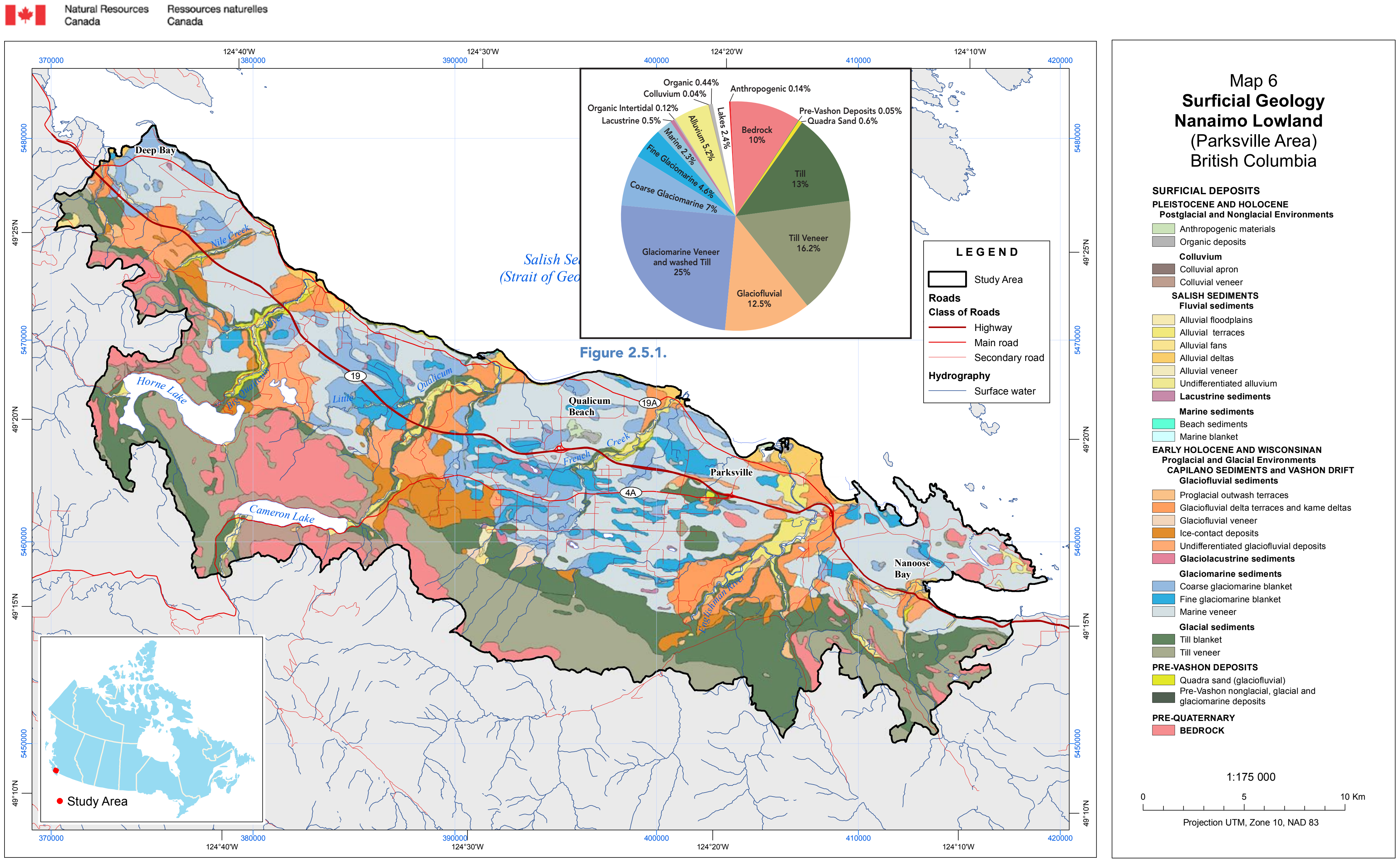


Figure 2.5.1.

2.6. Geochemistry using pXRF Spectrometry

Knight, R.D., Geological Survey of Canada (Ottawa, ON)

Geochemical data is crucial to defining chemical and mineralogical variations within sediments. This data complements sediment description, grainsize data, downhole geophysics, and aids stratigraphic correlations. Geochemistry can provide insight into potential water-rock interactions and, consequently, the chemistry of groundwater. Geochemistry can also provide information that is crucial to the development of basin stratigraphy, provenance (where the sediment came from) studies, and consequently the production of accurate 3D basin models.

Methods

For this study a portable X-ray fluorescence spectrometer (pXRF) was used to collect geochemical data on sediment cores. Samples from the Spider and Cochrane core were prepared for analysis by freeze-drying, disaggregation, and sieving to <63 µm (silt and clay) size fraction. The samples were then placed in plastic vials and sealed with 4 micron film. Data was acquired using a handheld Thermo Scientific, Niton XL3t GOLDD spectrometer in Soil Mode (**Figure 2.6.1**). A detailed description of the methodology is provided by Knight et al. (2015). Individual elemental concentrations are plotted adjacent to a stratigraphic section for the Cochrane borehole in **Figure 2.6.2**.

Results

To our knowledge, this is the first baseline geochemical study of the surficial sediments in the region, and it provides the potential for new insights into the definition and correlation of the region's stratigraphic units. It further provides collaborative data support for inferred provenance of these sediments. Fortuitously, the geochemistry of the granitic plutons of the Coast Mountains has a distinctly different geochemical signal to that of the Vancouver Island Ranges, which are characterized by mafic volcanics and base metal showings. Three distinct and interesting findings emerge from this geochemistry: i) stratigraphic unit characterization, ii) subdivision of stratigraphic units, and iii) provenance determination.

i) The major stratigaphic units are characterized by distinct and, in some cases, diagnostic geochemical signals. The Mapleguard Sediment and the basal Cowichan Head Formation have a signal higher in Cr and Cu by comparison to the Quadra Sand, which is uniquely characterized by the strong negatively autocorrelated signal of Sr, with similarities to alkaline plutonic rocks.

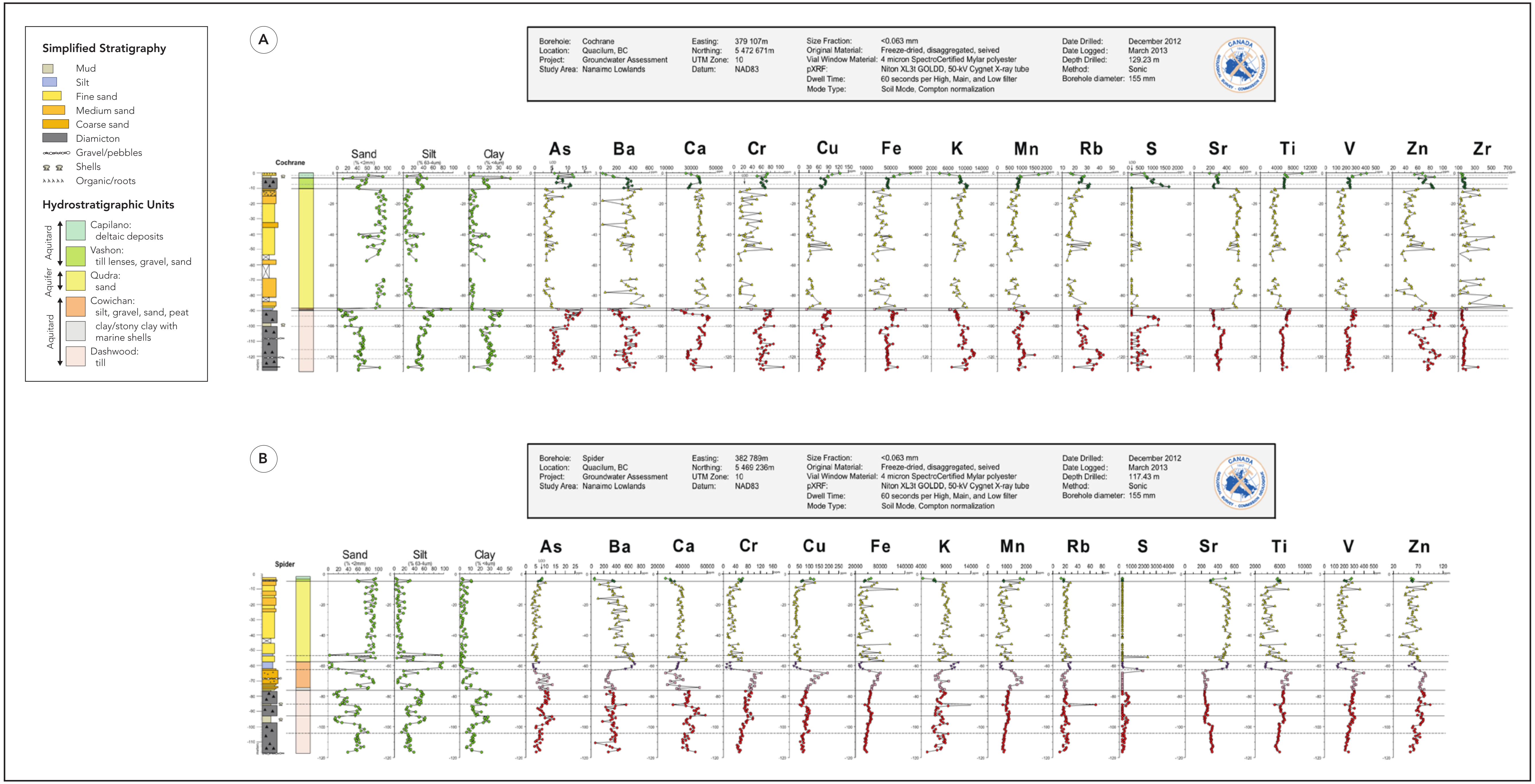
ii) Geochemical data allows for a number of stratigraphic units to be further subdivided beyond visual sedimentological logging. For example, within the Dashwood Drift, five units are identified based on changes in the trend of single elemental concentrations. For most elements the concentrations are proportional to changes in abundance of silt and/or clay. The Dashwood Drift and lower Cowichan Head have an increase in concentration of Cr, Cu, Fe, V, and Zn, with a corresponding decrease in Sr. The lowermost unit in the Dashwood Drift is differentiated from the overlying unit by changes in Ca, Cu, K, Mn, Rb, and Zn. Unit 3 is differentiated from unit 2 by a decrease in Rb concentrations. Unit 5 displays S concentrations with a mean of 1053 ppm compared to a range of mean values from 486-248 ppm for the other units. It is also characterized by an upward trending decrease in Ca concentration from 264 ppm at the base to 187 ppm at the top of the unit.

iii) The upper Cowichan Head and the Quadra Sand illustrate how geochemistry can be used for provenance determination. Both formations display a marked decrease in elemental abundances compared to both the underlying and overlying stratigraphic units for Cr, Cu, Fe, and Ti, whereas there is a marked increase in elemental abundances for Ca and Sr. The Sr concentration provides a unique signal for these formations with a mean concentration of 511 ppm for them, whereas for all other units it ranges from 201 to 285 ppm. Additionally the Vashon Drift and Capilano Sediments can be differentiated from each other by changes in concentration of Cu, Fe, Mn, and V (Knight et al., 2015).

Figure 2.6.1. Portable spectrometer (Thermo Scientific, Niton XL3t GOLDD) used to acquire geochemical data.

Knight, R.D., 2016. 2.6 Geochemistry using pXRF Spectrometry; in Russell, H.A.J., and Benoit, N., (compilers); Nanoose Bay - Deep Bay Area, Nanaimo Lowland Groundwater Study Atlas, Regional District of Nanaimo, British Columbia; Geological Survey of Canada, Open File 7877.

2.6. Geochemistry using pXRF Spectrometry (continued)



A

Borehole: Cochrane
Location: Quacilum, BC
Project: Groundwater Assessment
Study Area: Nanaimo Lowlands
Easting: 379 107m
Northing: 5 472 671m
UTM Zone: 10
Datum: NAD83
Size Fraction: <0.063 mm
Original Material: Freeze-dried, disaggregated, seived
Vial Window Material: 4 micron SpectroCertified Mylar polyester
pXRF: Niton XL3t GOLDD, 50-kV Cygnet X-ray tube
Dwell Time: 60 seconds per High, Main, and Low filter
Mode Type: Soil Mode, Compton normalization
Date Drilled: December 2012
Date Logged: March 2013
Depth Drilled: 129.23 m
Method: Sonic
Borehole diameter: 155 mm

B

Borehole: Spider
Location: Quacilum, BC
Project: Groundwater Assessment
Study Area: Nanaimo Lowlands
Easting: 382 789m
Northing: 5 469 236m
UTM Zone: 10
Datum: NAD83
Size Fraction: <0.063 mm
Original Material: Freeze-dried, disaggregated, seived
Vial Window Material: 4 micron SpectroCertified Mylar polyester
pXRF: Niton XL3t GOLDD, 50-kV Cygnet X-ray tube
Dwell Time: 60 seconds per High, Main, and Low filter
Mode Type: Soil Mode, Compton normalization
Date Drilled: December 2012
Date Logged: March 2013
Depth Drilled: 117.43 m
Method: Sonic
Borehole diameter: 155 mm

Figure 2.6.2. Geochemical trends for Cochrane (A) and Spider (B) cores for 15 selected elements plotted adjacent to sediment log, stratigraphic correlation, and grain-size.

2.7. Borehole Geophysics

Crow, H.L., Geological Survey of Canada (Ottawa, ON)

To complement core logging and provide an enhanced baseline dataset to support broader uses of geophysics in the area (e.g., seismic reflection surveys), borehole geophysical logging was completed in one bedrock borehole and four sediment boreholes (Crow et al., 2014). Data collected can contribute to improved characterization of hydrostratigraphic units and provide direct information on aquifer properties such as fracture density, geometry, and areas of increased groundwater flow.

Borehole geophysical logs provide a means of identifying and characterizing lithological units based on variations in their chemical and physical properties. They can augment geological logging by providing information on changes in sedimentary properties that may not be visible in the core, or across intervals of missing core, and where boundaries are uncertain due to the logging of cuttings. Geophysical logging in sediment boreholes was conducted inside a 2.5” diameter PVC piezometer, and in an open bedrock hole.

In sediment boreholes, geophysical tools included gamma methods (natural gamma and gamma-gamma density), and induction methods (apparent conductivity and magnetic susceptibility), and both are used to interpret changes in lithology. Downhole seismic methods — compression (P) and shear (S) wave travel times — were used to identify variation in lithology and compaction, and the presence of reflecting horizons, and to ground truth the surface seismic profile data.

Fluid temperature logs were collected to identify anomalies caused by groundwater flow behind the PVC piezometer, and to identify thermal gradients in the near surface. In the open bedrock borehole, the natural gamma probe, induction tools, and fluid temperature tool were used, as described above. This suite was augmented with the use of a fluid conductivity tool to identify changes in groundwater conductivity; a heat pulse flow meter to identify the direction and volume of any vertical flow moving through the wellbore between any transmissive fractures; and televiewers to collect high resolution digital and acoustic images of the borehole wall, used to identify geological variations, and fracture apertures at the borehole wall.

Results: Sediment Boreholes

In the sediment boreholes, induction logs (apparent conductivity and magnetic susceptibility) were used to identify changes in the main stratigraphic units. The magnetic susceptibility log revealed elevated and highly varying response in the Quadra Sand (20 – 80 ppt SI), and low response (10 – 25 ppt SI) with little variation in the diamictons (**Figure 2.7.2A**). The conductivities were relatively low (<20 mS/m) in sands, moderate (20 – 50 mS/m) in diamictons, and elevated (30 – 70 mS/m) in muds, however, these levels are well below conductivities expected for pore waters with full marine salinities. Velocity logs revealed highly variable stiffness in the diamictons, indicating a complex subglacial structure, possibly caused by multiple glacial advance and retreat cycles. Velocity logging is a key support for the interpretation and transformation of seismic reflection survey data from time scale to depth (metres) scale. It allows for the development of a variable velocity model, rather than assumptions about uniform velocity.

The fluid temperature logs indicated that groundwater temperatures are primarily controlled by depth below ground surface in equilibrium with the thermal gradient at depth, although material type (i.e. aquitard vs. aquifer) can also influence the temperature gradients.

Results: Bedrock Borehole

In the bedrock borehole, unlike in the surficial sediment boreholes, the borehole remains open and unlined, with direct access to the borehole walls. Consequently it is possible to characterize the downhole lithological variation using the optical televiewer, together with the suite of tools used in the surficial boreholes, (natural gamma, apparent conductivity, and magnetic susceptibility logs). As would be expected for shale, the magnetic susceptibility is low and unvarying (**Figure 2.7.2B**). The logs indicate that the bedrock is shale-dominated with only a few thin (<10 cm) sandstone beds in the upper 47 m. Sandstone beds are more common and increase in thickness in the lower half of the borehole (47 – 90 m), indicating a possible transition toward a sandstone-dominated formation at greater depth.

The fluid temperature log provides a stable baseline temperature profile in the upper 90 m of the borehole. At the time of logging, the minimum temperature was recorded at a depth of 46.70 m, reflecting the depth to which surface climactic conditions are currently influencing subsurface temperatures. Results of the pumped flow meter tests indicate that flow is entering the borehole through a fracture at the base of casing; there are no other significant fluid-transmitting fractures evident in the bedrock. Between 47 – 48 m depth, a sudden increase in fluid conductivity occurs that is coincident with a change in bedrock geology. There is, however, no associated rise in bulk apparent conductivity, implying that the increase is limited to the borehole fluid and not the surrounding formation. This may be a reflection of a deeper (likely saline) fluid that is slowly infusing upwards through the rock due to an imbalance in hydraulic heads associated with the open hole. To infer saltwater intrusion or even connate water migration would require permeability, hydraulic head, and geochemical profiles along the borehole to study the hydraulic conditions, and the composition and age of the fluid (i.e. young waters versus older connate waters).

In summary, the borehole geophysical logs, pXRF spectrometry, geological cores, and seismic surveys provide a framework to interpret existing and future hydrogeological information (e.g., driller’s well logs) with respect to the regional hydrogeological context. This will contribute to a better understanding of the aquifer system in the Nanaimo Lowland study area.

Figure 2.7.1. Data collection of borehole geophysics, geophysical sonde in borehole, and digital data capture.

Crow, H.L., 2016. 2.7 Borehole Geophysics; in Russell, H.A.J., and Benoit, N., (compilers); Nanoose Bay - Deep Bay Area, Nanaimo Lowland Groundwater Study Atlas, Regional District of Nanaimo, British Columbia; Geological Survey of Canada, Open File 7877.

2.7. Borehole Geophysics (continued)

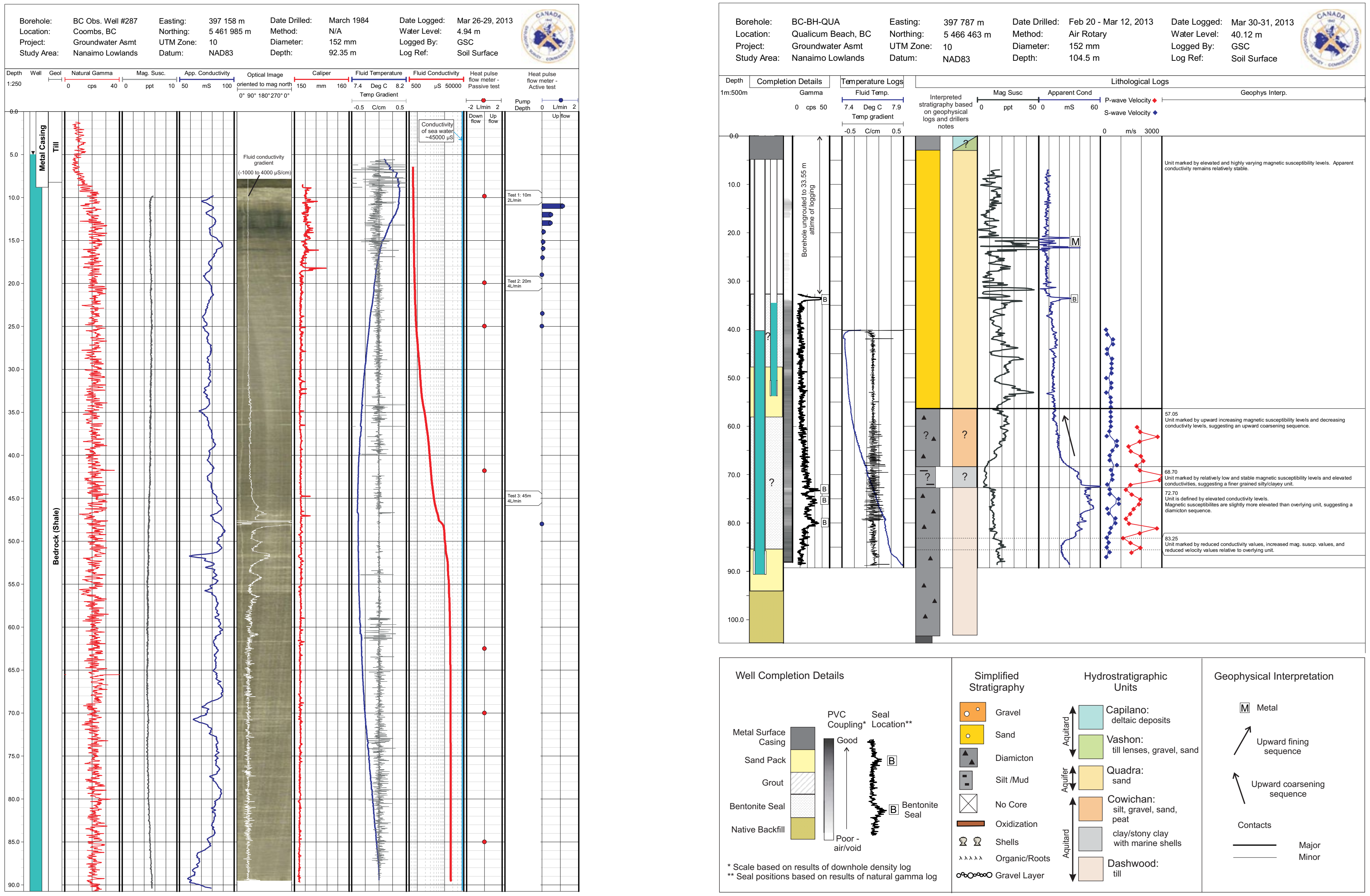


Figure 2.7.2. (A) Geophysical logs of bedrock borehole for observation well #287 near Coombs. (B) Geophysical logs of sediment borehole for the Cochrane well north of Qualicum Beach.

3. HYDROGEOLOGY

3.1. Climate and Hydrology

Paradis, D., and Benoit, N., Geological Survey of Canada (Quebec City, QC)

Climate

The Nanaimo Lowland study area has a moderate oceanic climate (Peel et al., 2007) with mild dry summer months and cool wet winter months (**Figure 3.1.1**). The area has an average total annual precipitation for the 1981 – 2010 Climate Normal Period of 1139 mm at the Coombs station (1021850 in **Map 7**). This is comparable with recorded climatic data at other stations in the study area, although precipitation is more abundant for the northwest stations (**Table 3.1.1** and **Map 7**). Precipitation in the area generally falls as rain (96%). The small proportion of precipitation falling as snow (4%) is ephemeral, with snow cover lasting generally only a few days after precipitation. The mountain regions typically get precipitation as snow during the winter months, and it melts in late spring. Annual total precipitation in the mountains is typically up to 5000 mm in Mount Arrowsmith, showing the influence of the altitude of the Vancouver Island Ranges (Waterline, 2013).

Stream Flow

Table 3.1.2 and **Map 7** present the hydrometric stations located in the study area and the most significant record of stream-flow data. Stream-flow records or hydrographs generally reflect different physical processes that are responsible for water flow through the watershed to the river. The most significant processes that affect stream-flow are direct precipitation, surface runoff, interflow, and baseflow (Fetter, 1994). Direct precipitation on surface water bodies and surface runoff are the processes that explain flow peaks observed on stream-flow records (**Figure 3.3.1**). Surface runoff occurs only when the precipitation rate exceeds the infiltration capacity of the soil. In areas where soils have a high infiltration capacity, this process may occur only during very intense precipitation or significant snow melt events. For the study area, the low infiltration capacity of the bedrock in the mountainous area and the steepness of the slopes produce important stream-flow peaks (**Table 3.1.2**).

Interflow, which is lateral flow within the unsaturated zone, is generally not as important as surface runoff, but a lag in flow time can contribute significantly to stream flow after peak flow. Thin permeable soil overlying fractured bedrock of low permeability would provide a favourable geological condition for interflow. Water that reaches the water table is stored in the aquifer and, if infiltrated water causes the water table to rise, groundwater discharge into nearby streams will also increase. This is known as baseflow. Baseflow is generally an important small contribution to stream flow, and it generally sustains stream flow in the summer, winter, and during drought periods.

According to stream flow (**Table 3.1.2**), the main rivers in the study area are dominated by surface runoff, as the ratio of the maximum (~surface runoff dominated) to the minimum (~baseflow dominated) stream flow is in the range of two orders of magnitude. This is attributed to the impervious bedrock and thin surficial cover of the mountainous area, and to the significantly greater precipitation in this region.

Station	Location	Elevation (m)	Average Annual Precipitation			Average Daily Temperature		
			Rain (mm)	Snow (cm)	Total (mm)	Min (°C)	Max (°C)	Mean (°C)
1025240	Mud Bay	4	1631	56	1687	5.3	14	9.7
1026565	Qualicum Fish Research	8	1272	37	1309	5.5	13.6	9.6
1024638	Little Qualicum Hatchery	30	1048	35	1083	4.2	14	9.1
1021850	Coombs	98	1093	45	1139	4	14.4	9.2

Table 3.1.1 Average monthly total precipitation (rain and snow) and daily temperature for the Climate Normal Period (1981-2010) at weather stations located in the lowland area.

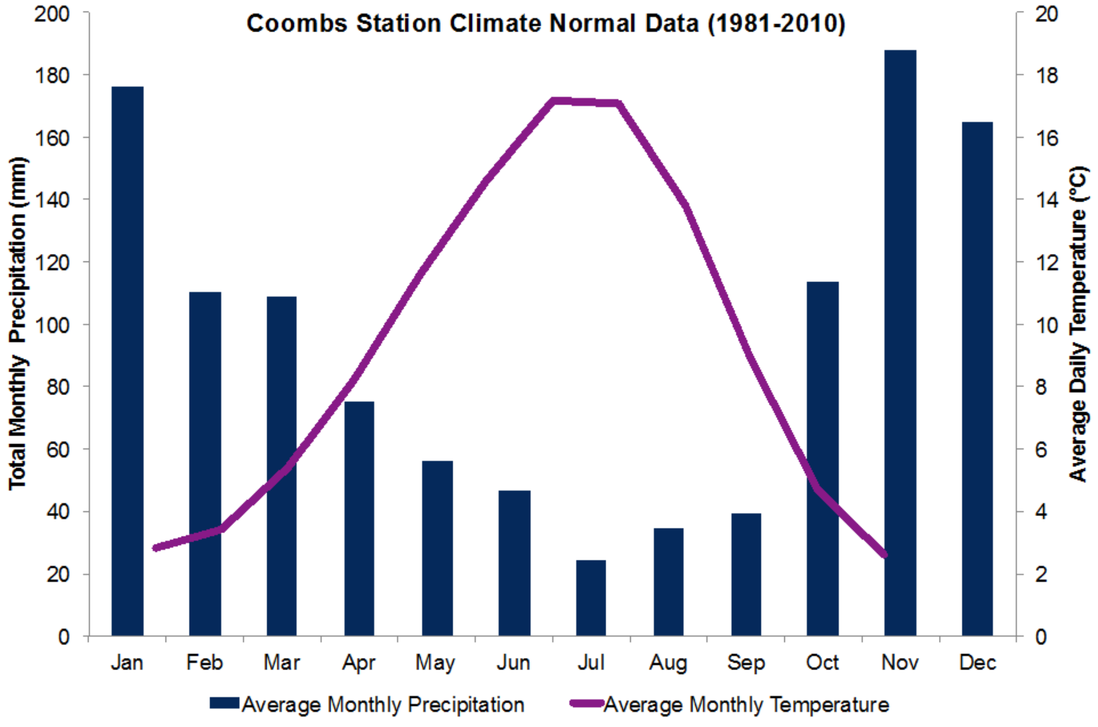
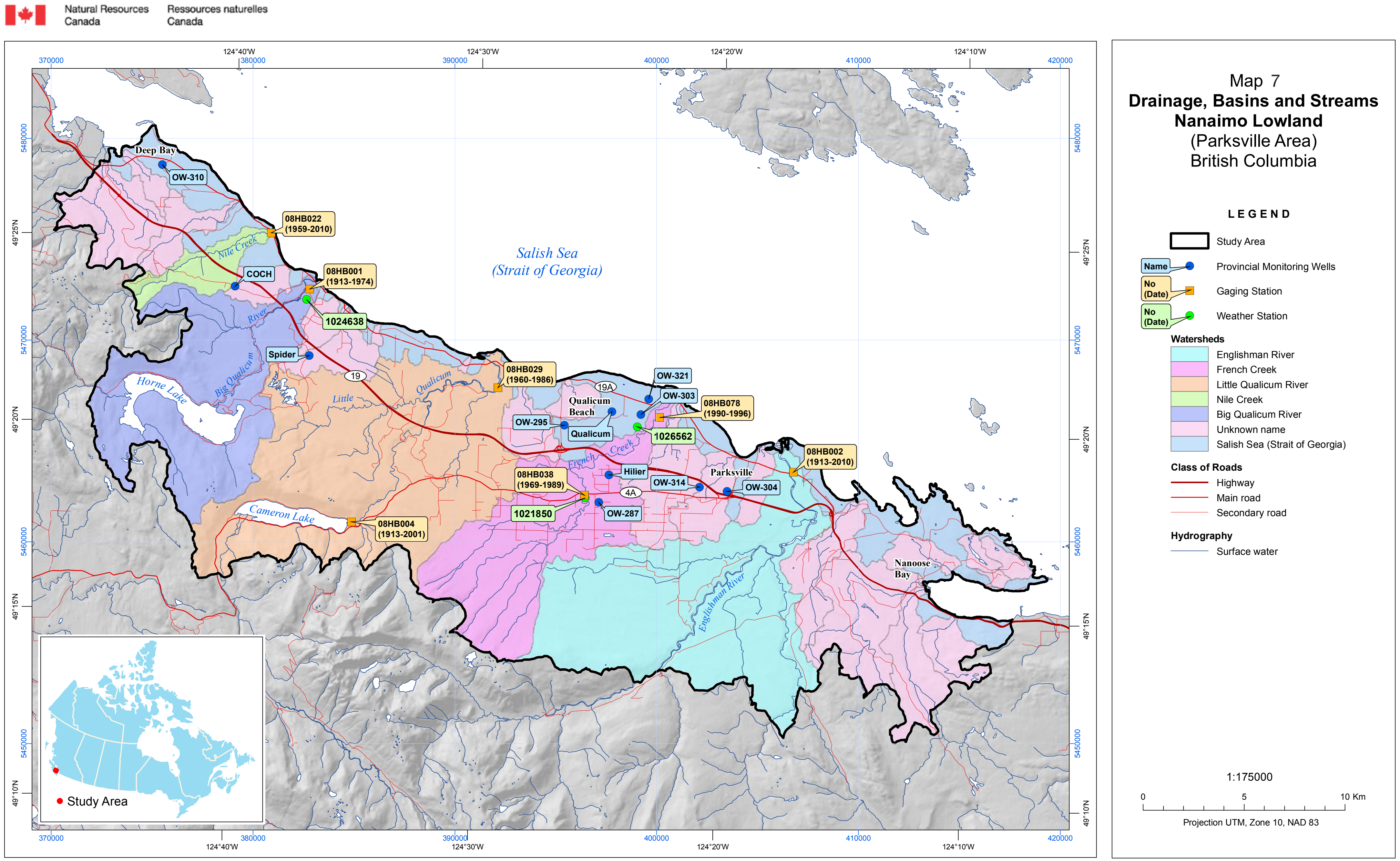


Figure 3.1.1. Average monthly total precipitation (rain and snow) and daily temperature for the Climate Normal Period (1981-2010) at Coombs weather station (1021850 in Map 7).

Paradis, D. and Benoit, N., 2016. 3.1 Climate and Hydrology; in Russell, H.A.J., and Benoit, N., (compilers); Nanoose Bay - Deep Bay Area, Nanaimo Lowland Groundwater Study Atlas, Regional District of Nanaimo, British Columbia; Geological Survey of Canada, Open File 7877.

3.1. Climate and Hydrology – **Map 7**



3.1. Climate and Hydrology (continued)

Station	River	Period of Record	Surface Drainage (km²)	Natural or Regulated	Average Stream Flow (m^3/s) Min	Max	Mean	Average Stream Flow Ratio (Max/Min)
08HB037	Rosewall Creek	1968-78	43	Natural	0.004	46	2.6	11 453
08HB022	Nile Creek	1960-Present	15	Natural	0.2	18	1.0	121
08HB001	Big Qualicum River	1956-74	146	Regulated	1.6	30	7.2	35
08HB029	Little Qualicum River	1960-86	237	Regulated since 1978	1.2	94	12	84
08HB004	Little Qualicum River at Cameron Lake	1913-2001	135	Regulated since 1978	0.9	78	9.0	104
08HB078	French Creek above Pump House	1990-96	79	Natural				
08HB038	French Creek at Coombs	1969-71; 1983-89	58	Natural				
08HB002	Englishman River at Parksville	1913-17; 1979-71; 1979-2012	316	Regulated since 1999	0.5	288	15	610

Table 3.1.2. Description of the main hydrometric stations available for the study area.

Figure 3.1.2. Englishman River above Bridge Park during a period of relatively low flow.

3.2. Leaf Area Index

Wang, S., Canada Centre for Mapping and Earth Observation (Ottawa, ON)

Surface processes of the water cycle are an important aspect of understanding the groundwater recharge. Evapotranspiration (ET) is the total amount of moisture lost back to the atmosphere due to evaporation/sublimation from the soil/snow surface (E) and transpiration through the plant leaves (T). It is one of the most important surface processes constraining the potential infiltration through the soil surface and aquifer recharge. ET is most strongly influenced by the plant leaf transpiration for vegetated land surface. The mapping of the leaf area index (LAI), as depicted in **Map 8**, is an important step for the reliable estimate of ET. LAI is defined as half of the total plant foliage area per unit of horizontal ground surface area, and the higher the LAI, the greater the implied transpiration. LAI is commonly calculated using multispectral satellite imagery (e.g. SPOT 5), land-cover information, and field-based measurements.

The LAI map for the study area was calculated using SPOT 5 imagery, a 25 m digital elevation model to correct for terrain effects, and field survey LAI estimation using digital hemispherical photography. This LAI map represents the peak-growing season of 2011 at a 30 m spatial resolution. A total of 104 ground plots (50 – 120 m^2) were sampled across the region from July 15 – 30, 2011. This includes upward and downward digital hemispheric photographs (**Figure 3.2.1**) spaced within each plot, together with notes on stand characteristics. The location of each ground plot was determined using global positioning systems (GPS) to ±5 m accuracy.

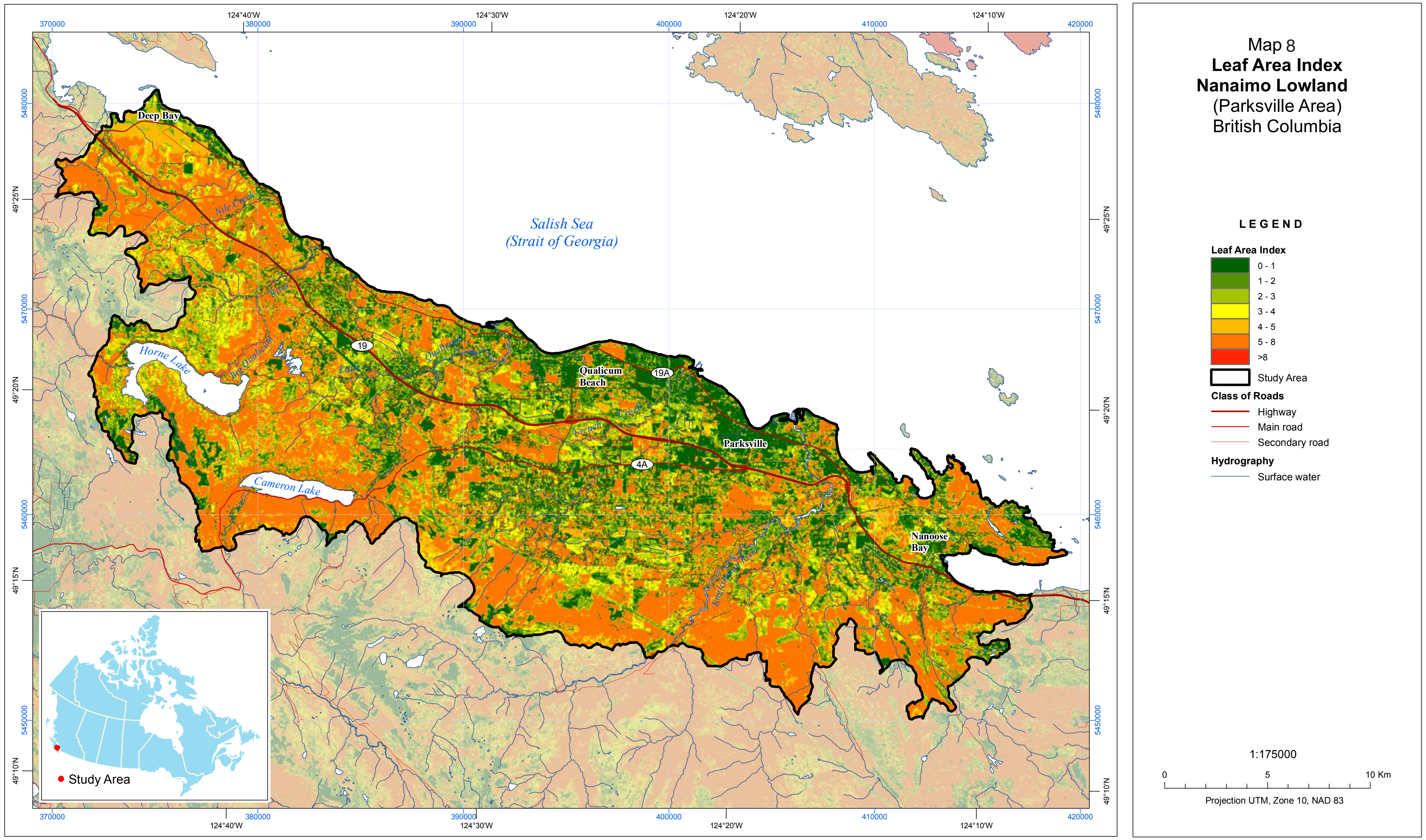
To estimate LAI, the land-cover classes were used to determine the approach. Different vegetation indices calculated using the three spectral channels (near Infrared, red, and short-wave infrared) were used for different land-cover classes (Maloley et al., 2013). These include using the reduced simple ratios (RSR) for primary and secondary forested, shrub and wetland areas, and the normalized difference vegetation index (NDVI) for low vegetation areas and crops. The final product was filtered using a 3x3 median filter to remove artifacts. Primary forest covers were estimated to have a Root Mean Square Error (RMSE) of 0.912, whereas secondary forest covers had a RMSE of 0.755. The RMSEs for low vegetation (grassland), high biomass crop, and low biomass crop were estimated at 0.68, 0.44, and 0.78, respectively. Spatial errors due to ortho-correction are estimated to be ±10 m, and should have negligible impact on the LAI analysis.

Figure 3.2.1. Up-looking and down-looking hemispherical photograph for overstory and understory leaf area index (LAI) estimation.

Wang, S., 2016. 3.2 Leaf Area Index; in Russell, H.A.J., and Benoit, N., (compilers); Nanoose Bay - Deep Bay Area, Nanaimo Lowland Groundwater Study Atlas, Regional District of Nanaimo, British Columbia; Geological Survey of Canada, Open File 7877.

3.2. Leaf Area Index – **Map 8**

Natural Resources Canada   Ressources naturelles Canada



3.3. Groundwater Recharge

Paradis, D., and Benoit, N., Geological Survey of Canada (Quebec City, QC)

Hydrograph separation methods are used for the analysis of daily stream-flow records in a watershed to estimate groundwater recharge (e.g. Rivard et al. 2013). These approaches assume that nearly all groundwater discharges to the river, and that regulation and diversion of stream flow, are negligible. Hydrograph separation methods are generally semi-empirical filters that are applied to stream-flow records to extract the groundwater component, and specifically the baseflow.

Figure 3.3.1 shows an example of baseflow estimation using the 7-Day Low Flow and the Furey-Gupta (Furey and Gupta, 2001) methods. The 7-Day Low Flow method assumes that the minimum recorded stream flow, when precipitation is the lowest, corresponds to the groundwater contribution to the river that would be observed all year long, whereas the Furey-Gupta method is a semi-empirical filter that mimics the annual variations of groundwater contribution for days when baseflow is hindered by other components of the stream flow. According to the previous assumptions inherent to each hydrograph separation method, the recharge values obtained for each watershed by the two methods were considered for groundwater modelling purposes as minimum and maximum values, respectively (**Table 3.3.1**). Recharge values for watersheds located in Hydrogeological Context A vary between 205 and 338 mm/yr for the 7-Day Low Flow method and between 400 and 504 mm/yr for the Furey-Gupta method. These values correspond to groundwater recharge in the Quadra unit (V) that commonly discharges to rivers through seepage flow. Recharge value for the Englishman River is between 48 mm/yr (7-Day Low Flow) and 99 mm/yr (Furey-Gupta), as expected from the low permeability of the sediments in this area that are mainly till and bedrock (Hydrogeological Context C; Figure 4.4.1).

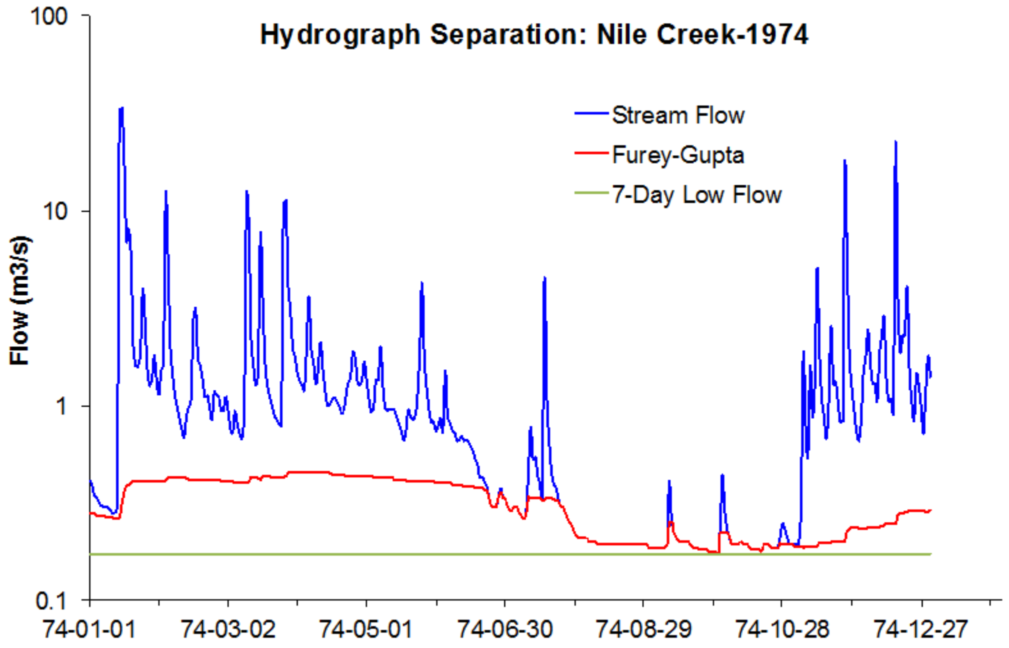


Figure 3.3.1. Hydrograph separation for groundwater recharge estimation for Nile Creek (08HB022 in Map 9) for the year 1974.

Watershed	Estimation Period	Groundwater Recharge (mm/y)	
		7-Day Low Flow	Furey-Gupta
Nile Creek	1960-86	338	504
Big Qualicum	1960-74	338	461
Little Qualicum	1960-86	205	400
Englishman	1970-71; 1979-86	48	99

Table 3.3.1. Annual groundwater recharge estimated using hydrograph separation methods for the main watersheds of the study area. Note that the baseflow estimate for French Creek is not available due to a major stream-flow diversion that precluded the application of hydrograph separation methods.

Paradis, D. and Benoit, N., 2016. 3.3 Groundwater Recharge; in Russell, H.A.J., and Benoit, N., (compilers); Nanoose Bay - Deep Bay Area, Nanaimo Lowland Groundwater Study Atlas, Regional District of Nanaimo, British Columbia; Geological Survey of Canada, Open File 7877.


brodie

3.4. Provincial Observation Well Network

Henderson, G. and Lapcevic, P., British Columbia Ministry of Forests, Lands and Natural Resource Operations (Nanaimo, BC)

The BC Provincial Observation Well Network has been collecting data for groundwater levels and quality since 1961. Over 400 wells have been included in the network, and there are approximately 190 active wells currently collecting data across the province. There are 22 active observation wells in the study area (**Map 9**). The wells are equipped with pressure transducers, and aspects of the network are automated by satellite telemetry communication (**Figure 3.4.1**). Groundwater chemistry samples are routinely obtained from the wells and analyzed. These continuous dedicated monitoring stations collect hourly water-level measurements and the data are published online. Between 2010 and 2013, 15 sites in the study area were added to the BC Provincial Observation Well Network. These additions were supported through the collaborative efforts of RDN, the City of Parksville and the Town of Qualicum Beach, the MoE, the MLNRO, and the GSC. These stations will eventually contribute to a broader base-line dataset (i.e., greater than 10 years) that is essential to understand the aquifer system for its sustainability, as variation in water level and chemistry reflects the aquifer system response to various stresses (e.g., pumping, climate, land-use change). For long-term groundwater level trends in observation wells, refer to the BC State of the Environment web site at **http://www.env.gov.bc.ca/soe/indicators/water/wells/index.html**.

Groundwater Levels

Hydrographs from two observation wells, located in close proximity to community water system production wells and influenced by diversion and use, are presented in **Figure 3.4.2**. Both are screened in the Quadra Sand aquifer. Both hydrographs exhibit similar long-term variations, although the signal is more subdued in well #310. The water level in well #304 has declined by around 7 m over the period of record and suggests long-term decline in groundwater levels in the aquifer. Digital hourly data collection started around 2003 and is evident in the hydrograph as thicker lines.

A comparison between water levels in a bedrock aquifer well (#287) and an unconsolidated aquifer well (#424) is presented in **Figure 3.4.3**. Well #287 is screened in unconsolidated sediment and is impacted by pumping interference much more than well #424. In December 2013, a drawdown response is visible in both monitoring wells, despite their being 1.5 km apart and in two separate aquifers and aquifer types.

Groundwater Chemistry

As illustrated in **Figure 3.4.4** inset on **Map 9**, major ion chemistry for the majority of observation wells in the study area plots on a piper plot as Ca-HCO_3 shallow, fresh groundwater. Two wells (#287 and #433) plot as deeper Na-HCO_3 groundwater influenced by ion exchange, and #424 plots as Ca-SO_4 groundwater.

Figure 3.4.1.
Satellite telemetry system.

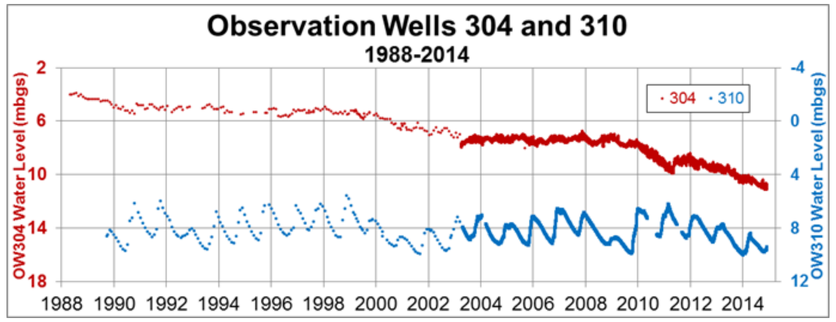


Figure 3.4.2. **Hydrographs for observation well #304 (Quadra Sand aquifer #216) and #310 (Quadra Sand aquifer #416) illustrating the decline in water level under the influence of municipal production.**

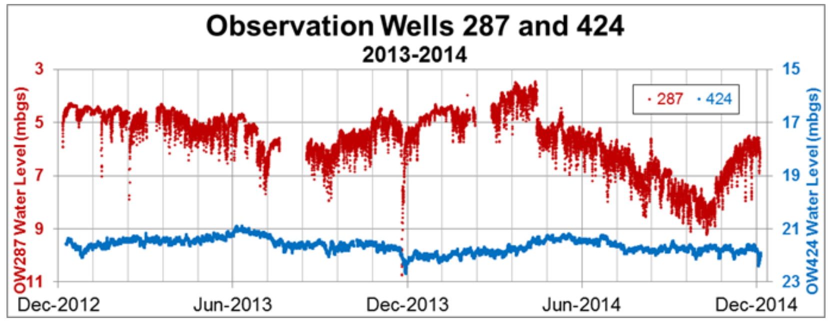
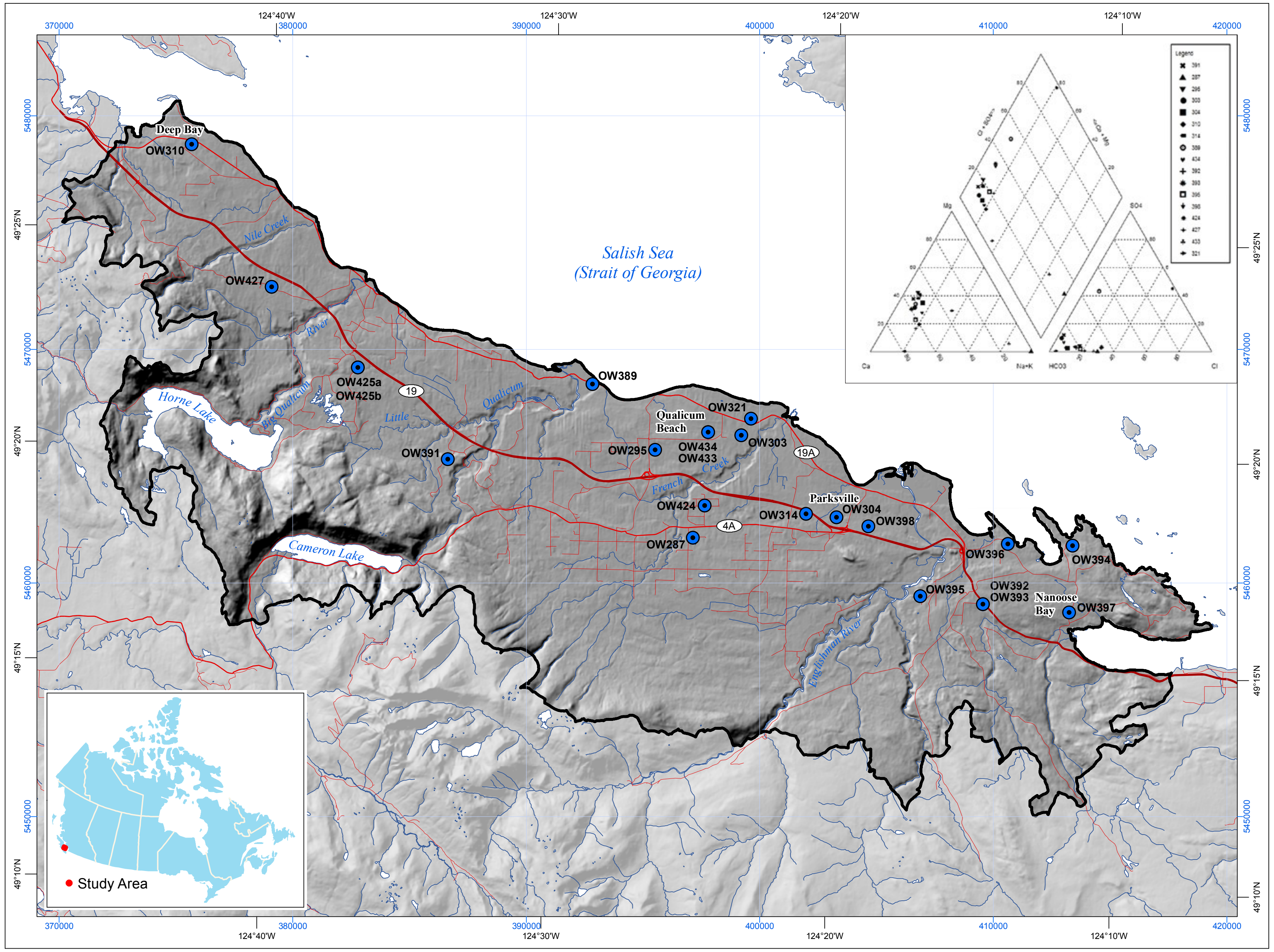


Figure 3.4.3. **Hydrographs for observation well #287 (sedimentary bedrock aquifer #220) and #424 (Quadra Sand aquifer #216) highlighting the influence of pumping.**

Henderson, G. and Lapcevic, P., 2016. 3.4 Provincial Observation Well Network; in Russell, H.A.J., and Benoit, N., (compilers); Nanoose Bay - Deep Bay Area, Nanaimo Lowland Groundwater Study Atlas, Regional District of Nanaimo, British Columbia; Geological Survey of Canada, Open File 7877.

3.4. Provincial Observation Well Network – **Map 9**

Natural Resources Canada Ressources naturelles Canada



Map 9

Observation Well Network

Nanaimo Lowland

(Parksville Area)

British Columbia

LEGEND

▨ Study Area

Class of Roads

- Highway
- Main road
- Secondary road

Hydrography

- Surface water

● Observation Well

Figure 3.4.4. Inset figure is Piper Plot of groundwater chemistry from monitoring wells. Legend refers to BC monitoring well ID.

1:175,000

0 5 10 Km

Projection UTM, Zone 10, NAD 83

3.5. Re-evaluation of Pumping Tests in the RDN

Carmichael, V.P., formerly with British Columbia Ministry of Environment (Victoria, BC)

Existing pumping test data from wells in the Regional District of Nanaimo (RDN) were collected and re-analyzed to generate a consistent data set of hydraulic properties such as transmissivity (T), hydraulic conductivity (K), and storativity (S) for some of the aquifers in the study area (Carmichael, 2013). The pumping test data was accessed through consultant reports and MoE files from 1960 to 2009.

Time-drawdown data from 75 pumping tests were analyzed. The pumping tests included one-time tests for a single pumping well, tests of wells with groundwater level monitoring at one or more observation wells, and multiple pumping tests conducted on the same well within a short period or with an interval of years between tests. Most of the wells were drilled into unconsolidated material — only eight of the water supply wells were drilled into fractured bedrock.

The pumping test data were analyzed using a consistent approach that included the use of the derivative method (**Figure 3.5.1**) to first identify the period of radial flow (Allen, 1999). This period was used for analysis by curve-matching (e.g., Theis Recovery Method) and semi-log straight-line methods (e.g., the Cooper-Jacob and Theis methods) to determine aquifer hydraulic properties (T, S) on a consistent basis. The derivative method was also used to identify the dominant behaviour at different stages of the pumping test, e.g., borehole storage at early time, radial flow and/or boundary conditions at later time.

The results were summarized by aquifer type found within the Cordillera Hydrogeological Region of Canada (Wei et al., 2007). Transmissivities ranged from 200 to 8442 m^2/day for unconsolidated aquifers. Storativity ranged from 9.8 x10^{-3} to 3.3 x10^{-7} for both confined and unconfined unconsolidated aquifers. Hydraulic conductivities ranged from 0.14 to 1830 m/day (**Figure 3.5.2**). Values ranged over three orders of magnitude for confined sand and gravel aquifers (type 4b) and were several orders of magnitude lower for wells drilled into bedrock compared to wells drilled into unconsolidated materials.

There were 20 wells (17 pumping and three observation wells) that showed the influence of a positive boundary, which was inferred to be related to a constant head boundary (e.g., stream or lake).

Negative boundaries were observed in 13 pumping wells or 18% of the pumping tests. Due to the complex geology in this area, some of the pumping tests showed evidence that, as the pumping test progressed, the water was likely being sourced from less permeable sediments that limit the recharge to the aquifer the well is drilled into. The capacity of these aquifers is likely limited, ultimately, by the rate of recharge through the less permeable sediments, which surround the aquifer.

Proper pumping test practices, such as conducting the pumping test using a constant rate of withdrawal, greatly assist in the analysis and interpretation of pumping test data. The consistent use of an analytical methodology (i.e., the derivative method) provides reliable data for others to use. The results of this analysis were used in the development of the conceptual, analytical, and numerical flow models in this project.

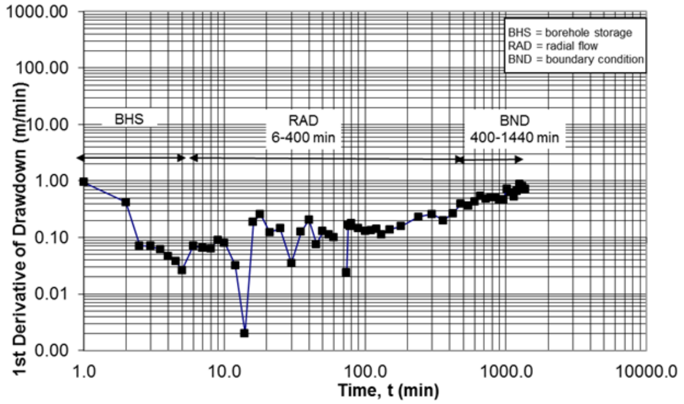


Figure 3.5.1. Example of a derivative plot for a constant-rate pumping test from a well drilled into a confined unconsolidated (sand and gravel) aquifer, showing the different flow regimes encountered during the test. Borehole storage (BHS) is evident in the first few minutes at the start of the pumping test, followed by a period (~400 minutes) of radial flow (RAD). During the last 1000 minutes of the pumping test, the rate of drawdown increases, suggesting a decrease in aquifer transmissivity or a negative boundary has been encountered.

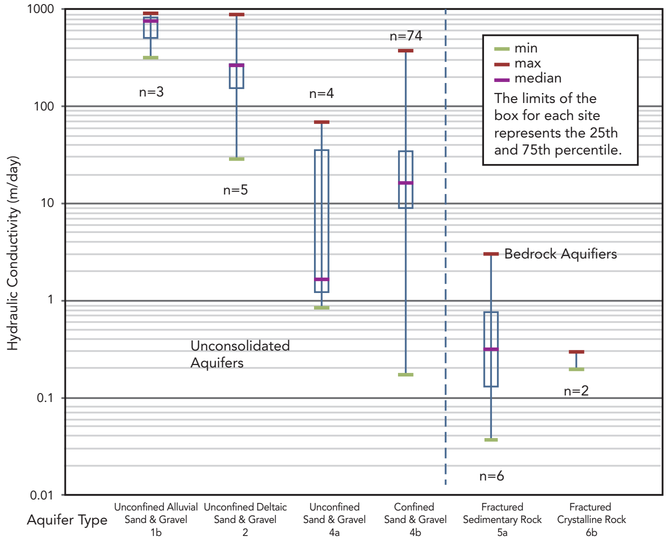


Figure 3.5.2. Boxplots showing hydraulic conductivity values (m/d) for study wells drilled into the different aquifer types.

Carmichael, V.P., 2016. 3.5 Re-evaluation of Pumping Tests RDN; in Russell, H.A.J., and Benoit, N., (compilers); Nanoose Bay - Deep Bay Area, Nanaimo Lowland Groundwater Study Atlas, Regional District of Nanaimo, British Columbia; Geological Survey of Canada, Open File 7877.

4. HYDROSTRATIGRAPHY

4.1. General Hydrostratigraphy

Benoit, N., and Paradis, D., Geological Survey of Canada (Quebec City, QC)

Hydrostratigraphy is the relation between geology and the hydrogeological properties of the sediments or rocks that compose an aquifer system. The hydrostratigraphic column (**Figure 4.1.1**) outlines the relationships between various geological and hydrogeological units of the study area. The lithostratigraphic column is based on a standard succession that is widely recognized in sea cliffs and riverbanks (Fyles, 1963), as well as in deep rotosonic wells of this study (**Figure 2.4.1**). The hydrostratigraphy commonly consists of aquifer and aquitard units. In the study area, an aquifer is any unit that can supply adequate water for domestic household purposes. The area's most exploited aquifer is the Quadra Sand.

The principal aquitard units are (**Figure 4.1.1** and **Table 4.1.1, 4.1.2**), the Vashon and the Dashwood (see section 2.4 and 2.5) tills, as well as the Cowichan Head Formation at the base of the Quadra Sand, which is mostly silt and clay. The Cowichan Head Formation and the Dashwood till are merged into a single hydrostratigraphic unit, named the Cowichan-Dashwood unit (VI).

Five distinct aquifer units are recognized (**Figure 4.1.1** and **Table 4.1.2**), which are the Capilano-Salish (I), the Vashon-Capilano coarse (III), the Quadra (V), the Dashwood-Mapleguard (VII), and the sedimentary bedrock (VIII). The surficial aquifers are mostly discontinuous and are composed of coarse glaciofluvial deposits or deltaic and fluvial sediments. Salish sediments along rivers are mostly recent fluvial deposits that are generally permeable, but of limited extent. Elsewhere, the study area is covered by marine deposits that are relatively impermeable due to their fine-grain size (Capilano-Glaciomarine, II). The thickness of those sediments is highly variable from a few centimetres to up to 12 m.

The Quadra hydrostratigraphic unit (V), which forms the aquifer under the Vashon unit (IV), is present almost everywhere over the study area except along the main rivers, where the Quadra unit (V) has been eroded by rivers or cut-and-filled by the Vashon till (IV), and in the vicinity of the Englishman River (see **Figure 4.4.1** on Hydrogeological Context). The upper part of the Quadra unit (V) is coarser and has the best aquifer potential; however, groundwater occupies only a small thickness of the unit.

According to Fyles (1963), the Mapleguard proglacial outwash deposits (VII) could be coarser than the Quadra (V) and have the potential to be good aquifers; however, the sediment architecture and composition of the unit are not well understood.

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

Hydrostratigraphic Unit	Hydraulic Conductivity (m/s)		Source
	min	max	
I-CAPILANO-SALISH (aquifer)	3.4×10^{-4}	1.0×10^{-2}	Carmichael (2013)
II-CAPILANO (glaciomarine fine) (aquitard)	5.0×10^{-9}	2.5×10^{-7}	Batu (1998)
III-VASHON-CAPILANO (coarse) (aquifer)	9.0×10^{-6}	8.0×10^{-4}	Carmichael (2013)
IV-VASHON (till) (aquitard)	5.0×10^{-8}	5.0×10^{-6}	Batu (1998)
V-QUADRA (aquifer)	2.0×10^{-6}	4.6×10^{-3}	Carmichael (2013)
VI-COWICHAN-DASHWOOD (aquitard)	5.0×10^{-9}	2.5×10^{-7}	Batu (1998)
VII-DASHWOOD-MAPLEGUARD (aquifer / aquitard)	2.0×10^{-6}	4.6×10^{-3}	Carmichael (2013)
VIII-Sedimentary Bedrock (Lower Nanaimo Group)	1.0×10^{-10}	5.0×10^{-4}	Carmichael (2013); Henderson and Vograss (1962); Hornberger et al. (1998); Surrette et al. (2008)
IX-Metamorphic and Intrusion Bedrock (aquitard)	2.0×10^{-9}	5.2×10^{-5}	Carmichael (2013); Batu (1998)

Table 4.1.1. Hydraulic conductivity for each hydrostratigraphic unit based on existing data for the study area and literature for similar geological material. Presented statistics are: minimum (min) and maximum (max) values.

Hydrostratigraphic Unit	Upper Elevation (masl)			Lower Elevation (masl)			Median Thickness (m)
	min	max	med	min	max	med	
I-CAPILANO-SALISH	3	369	91	-2	152	87	1
II-CAPILANO (glaciomarine fine)	-2	152	79	-23	162	75	2
III-VASHON-CAPILANO (coarse)	-21	297	91	-27	454	80	5
IV-VASHON (till)	-27	1026	122	-51	137	100	7
V-QUADRA	-47	141	78	-50	85	53	15
VI-COWICHAN-DASHWOOD	-48	84	44	-49	26	26	13
VII-DASHWOOD-MAPLEGUARD	-45	26	15	-75	40	-6	14

Table 4.1.2. Elevation and thickness of the hydrostratigraphic units for the hydrostratigraphic model of the study area. Statistics presented are: minimum (min), maximum (max) and median (med) values.

Benoit, N., and Paradis, D., 2016. 4.1 General Hydrostratigraphy; in Russell, H.A.J., and Benoit, N., (compilers); Nanoose Bay - Deep Bay Area, Nanaimo Lowland Groundwater Study Atlas, Regional District of Nanaimo, British Columbia; Geological Survey of Canada, Open File 7877.

4.1. General Hydrostratigraphy (continued)

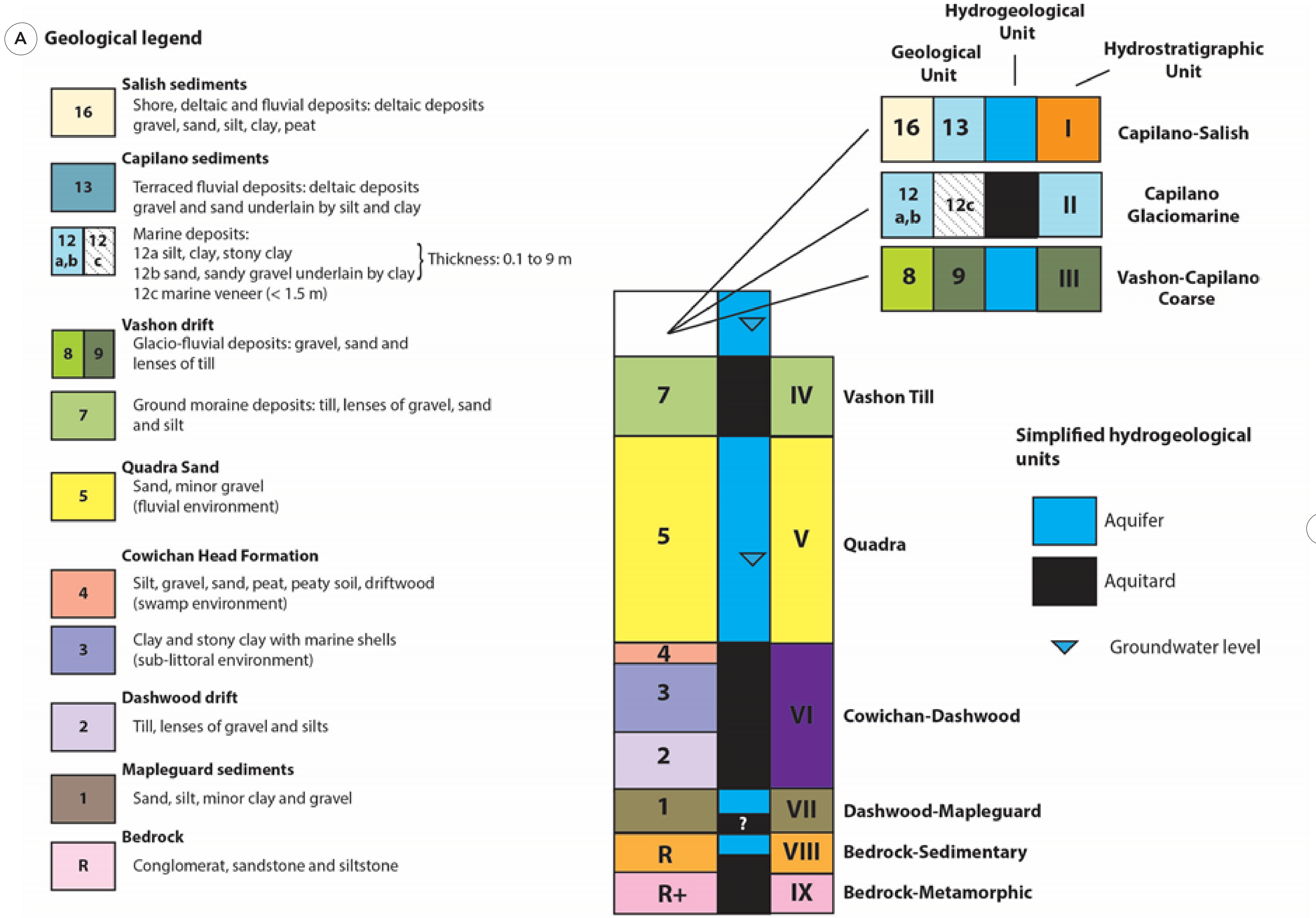


Figure 4.1.1. A) Hydrostratigraphic units (identified by numerals I to IX) with correspondence to surficial and bedrock geology (numbered) for the study area.

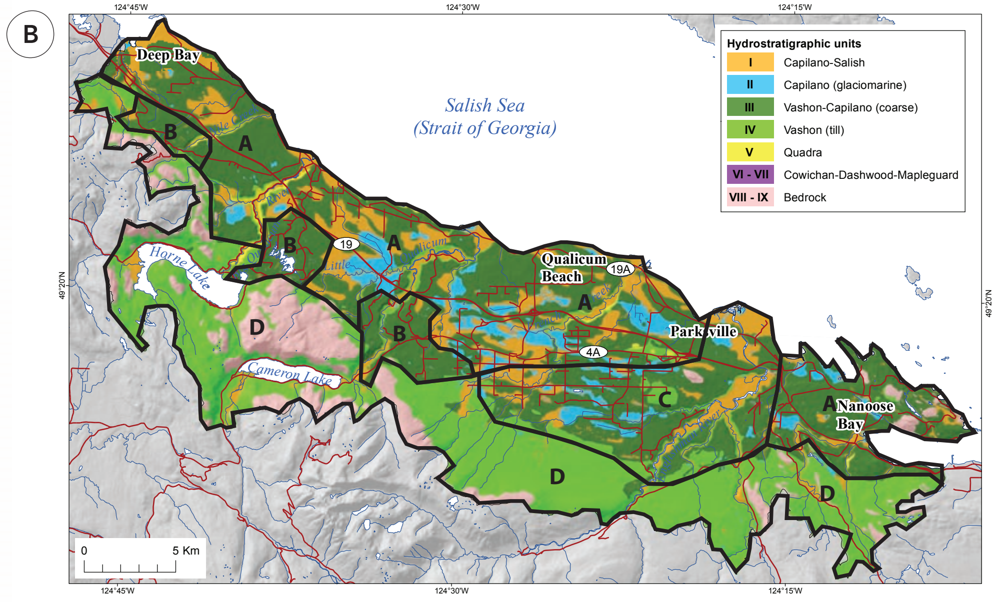


Figure 4.1.1. B) Distribution of Hydrostratigraphic contexts, see section 4.4 for additional details.

4.2. 3D Hydrostratigraphic Model

Benoit, N., and Paradis, D., Geological Survey of Canada (Quebec City, QC)

Based on available data (**Map 1**) and the general hydrostratigraphy of the study area (**Figure 4.1.1**), a 3D hydrostratigraphic model was constructed using Leapfrog-Hydro software (ARANZ Geo Limited, 2015), which is a 3D geographical information system (GIS). The 3D model defines the distribution and thickness of the hydrostratigraphic units, and represents bedrock and surficial units from 400 m below sea level to 1129 m above sea level. The data support for the model limits the geological realization of fine-scale facies changes (horizontal and vertical) and, hence, geological heterogeneity of the model is only adequate to support regional hydrogeological study. Data support generally diminishes with depth and, in areas of thickest sediment the lower units (Mapleguard and Dashwood), are constrained only by seismic reflection data.

The architecture of the aquifer system is defined using contact surfaces separating each hydrostratigraphic unit. These are ordered according to their relative chronology (from younger to older; **Figure 4.1.1**):

I – Capilano-Salish

II – Capilano (glaciomarine)

III – Vashon-Capilano (coarse)

IV – Vashon (till)

V – Quadra

VI – Cowichan-Dashwood

VII – Dashwood-Mapleguard

VIII – Sedimentary bedrock (Lower Nanaimo Group)

IX – Metamorphic and intrusive bedrock

The bedrock topography was interpolated from a topographic digital elevation model (DEM), outcrop observations, and bedrock-sediment contacts identified in public water well records and seismic surveys. All unconsolidated sediment hydrostratigraphic surfaces were constrained using the topographic DEM, the bedrock topography and existing stratigraphic columns and cross-sections, surficial geology maps, rotosonic cores, and seismic surveys. When well depths and geological descriptions allowed, hydrostratigraphic information, extracted from public water well records, was also used to interpolate sediment contact surfaces.

Sediment thickness and spatial distribution of each hydrostratigraphic unit are presented in **Figure 4.2.1**. **Table 4.1.2** presents descriptive statistics of unit elevation and thickness based on interpolated volumes of the hydrostratigraphic model.

Observations

A few observations can be made from **Figure 4.2.1** and Table **4.1.2**:

- Capilano-Salish and Capilano glaciomarine sediments are the thinnest units with a median thickness of 1 and 2 m, respectively. These units are present extensively, though with discontinuous cover over the lowland part of the study area,
- 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.
- Quadra, Cowichan-Dashwood, and Dashwood-Mapleguard are the thickest units with median values between 16 and 19 m, and mostly present along the coast between Deep Bay and Parksville. Elsewhere, south of Parksville and toward the mountains, these units are rarely observed.
- The Dashwood-Mapleguard unit is expected to have a spatial distribution similar to the Quadra unit; however, it will be more influenced by bedrock topography and likely only occurs in bedrock lows. Its distribution and character are uncertain due to the lack of data.

Benoit, N., and Paradis, D., 2016. 4.2 3D Hydrostratigraphic Model; in Russell, H.A.J., and Benoit, N., (compilers); Nanoose Bay - Deep Bay Area, Nanaimo Lowland Groundwater Study Atlas, Regional District of Nanaimo, British Columbia; Geological Survey of Canada, Open File 7877.

4.2. 3D Hydrostratigraphic Model (continued)

Natural Resources Canada
Ressources naturelles Canada

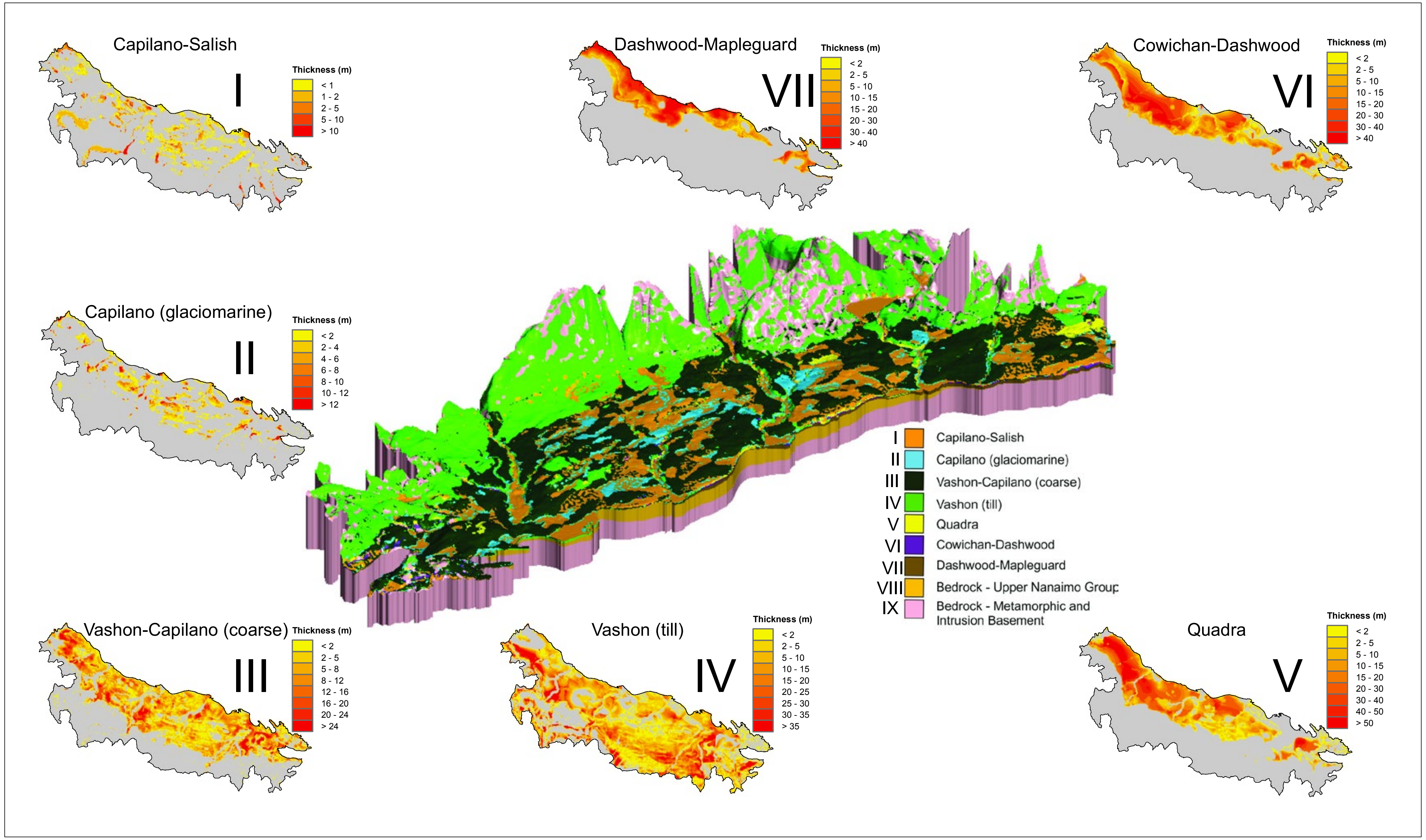


Figure 4.2.1. 3D representation of the hydrostratigraphy and distribution and thickness of the hydrostratigraphic units for the study area.

4.3. Sediment Thickness

Benoit, N., and Pugin, A.J-M., Geological Survey of Canada (Quebec City, QC; Ottawa, ON)

The sediment thickness for the seven unconsolidated hydrostratigraphic units is presented in **Map 10**. Sediment deposits of up to 210 m thick are present in the western part of the study area. Two other smaller areas, near Qualicum Beach and Nanoose Bay, have modelled thick deposits. Seismic data (**Figure 4.3.1**) and the Cochrane and Spider boreholes (**Figure 2.4.1**) indicate that thick deposits are more extensive than anticipated from the provincial water well record. It should be noted, however, that the interpolation process might also contribute to an overestimation of the thicknesses, because there are only a few deep boreholes and seismic survey data to constrain the interpolation at depth.

Elsewhere, in particular in the Englishman River, total sediment thickness is thinner and rarely exceeds 40 m.

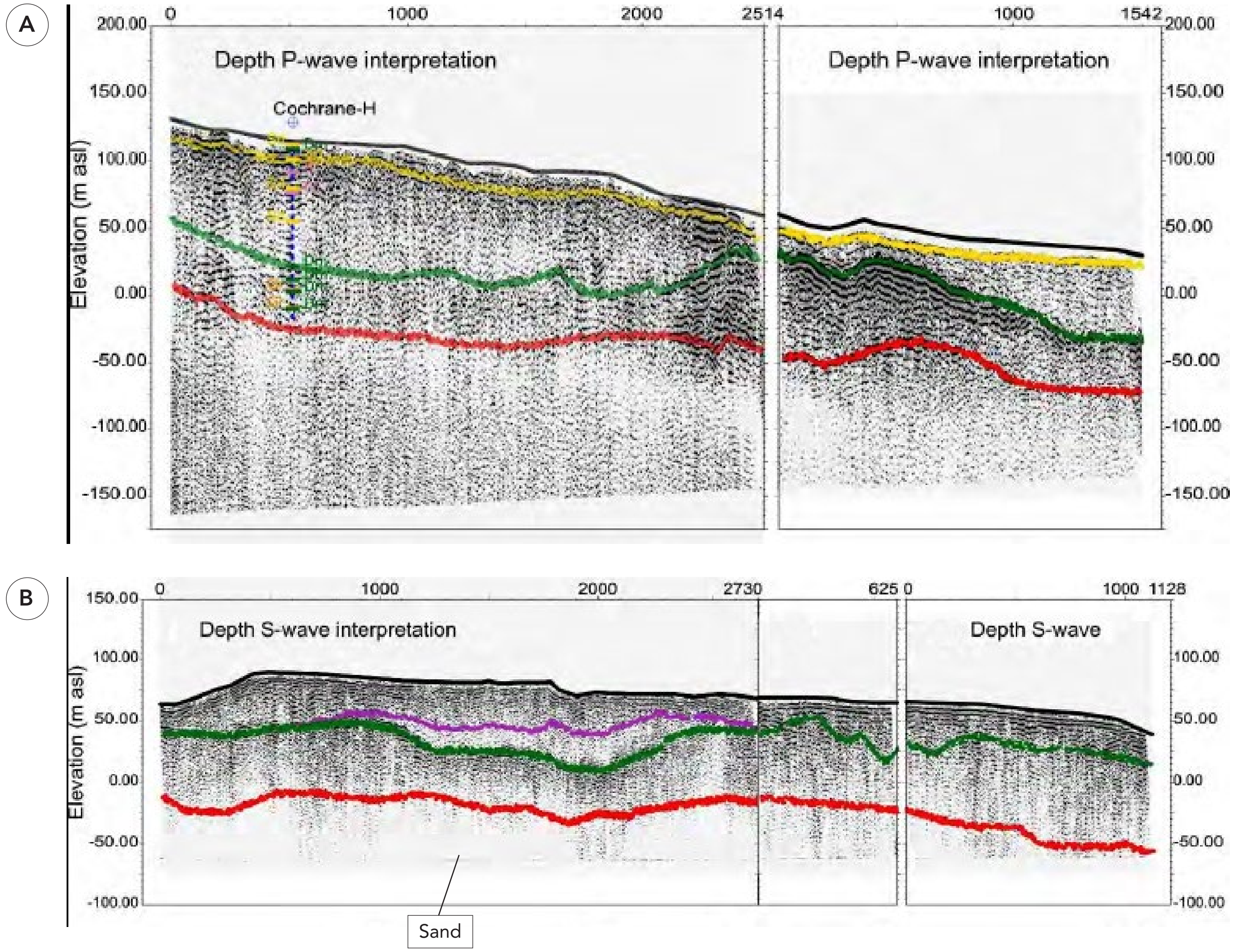


Figure 4.3.1. Illustrative seismic reflection profiles of: i) depth to bedrock (red line), ii) lateral continuity of seismic units, iii) units confined to topographic lows, iv) irregular lower contact of seismic units.

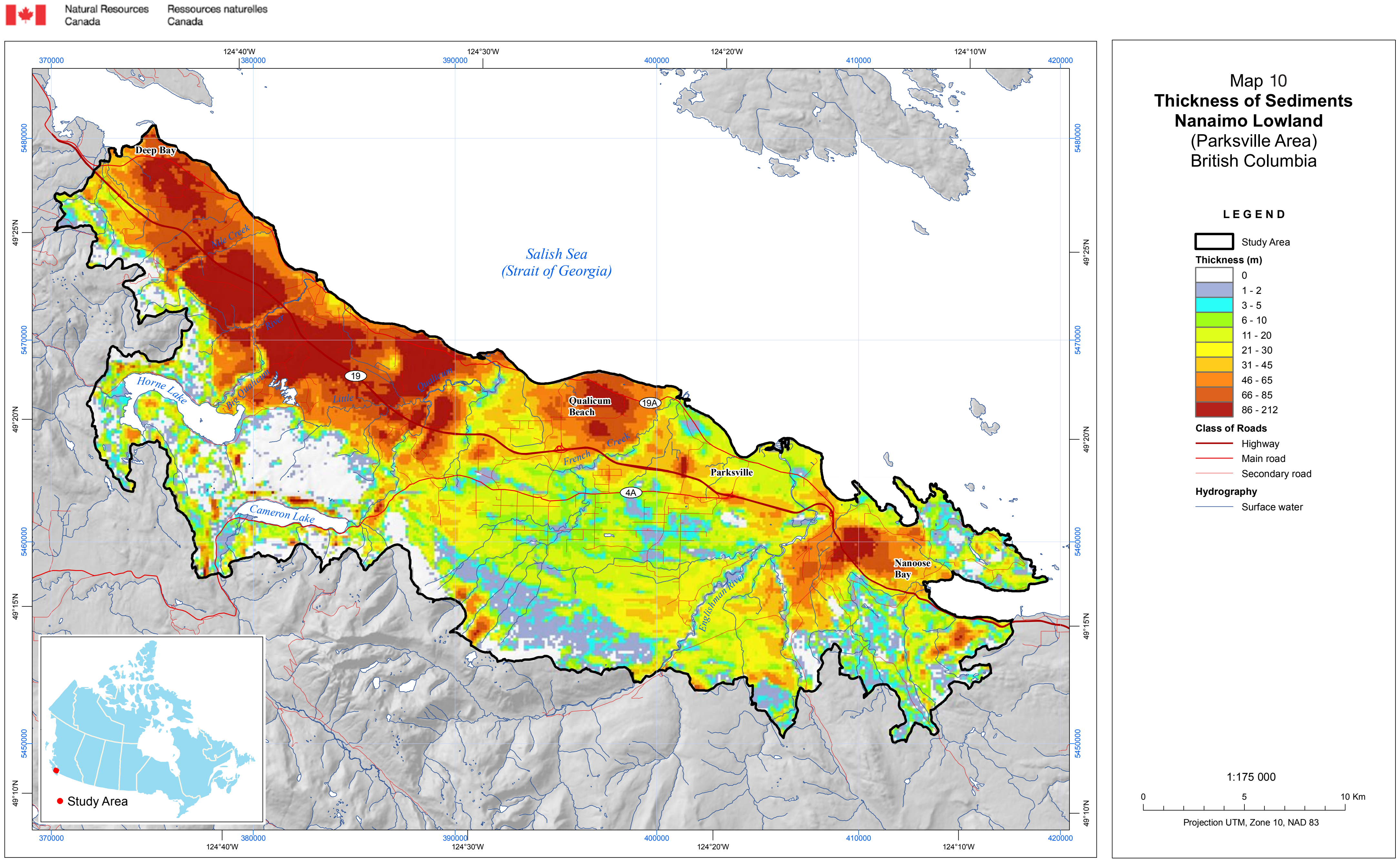
A) Seismic profile in the vicinity of Cochrane borehole. Note that a thin layer (<2 m) of the Cowichan Head Formation below the Quadra Sand has been identified in rotosonic cores, but is not resolved in the seismic data. (Red line – Bedrock, green line – Base of Quadra, yellow line – Base of Vashon.)

B) Shear wave seismic reflection profile. Note lateral continuity of principal seismic units, colours as defined in A. Purple lines highlights seismic sub unit of Quadra Sand filling buried valley cut into Cowichan-Dashwood or Dashwood-Mapleguard hydrostrat graphic units.

Figure 4.3.2. Vibroseis towing land streamer array of geophones.

Benoit, N., and Pugin, A. J-M., 2016. 4.3 Sediment Thickness; in Russell, H.A.J., and Benoit, N., (compilers); Nanoose Bay - Deep Bay Area, Nanaimo Lowland Groundwater Study Atlas, Regional District of Nanaimo, British Columbia; Geological Survey of Canada, Open File 7877.

4.3. Sediment Thickness – **Map 10**



4. HYDROSTRATIGRAPHY

4.4. Hydrogeological Contexts

Paradis, D., Geological Survey of Canada (Quebec City, QC)

Four hydrogeological contexts are identified for the study area (**Figures 4.1.1, 4.4.1** and **4.4.2**):

Lowland Context (A): The Lowland hydrogeological context is the standard succession and is applicable to most of the study area. It includes portions of Nile Creek, Qualicum River, Little Qualicum River, and French Creek, all of which flow over the lowland of the eastern part of the study area, as well as a small area of the western part. This context is thus present on both sides of the Englishman River Context. Most of the hydrostratigraphic units are present within the Lowland hydrogeological context, except near the main rivers where the sequence has been eroded by fluvial incision. Indeed, most surficial units, in particular the Quadra Sand, are disconnected from rivers at those locations, and seepage faces are observed along valley sides. Permeable Capilano sediment is also present along the rivers and, despite its limited spatial distribution, it can play a role in regulating surface water and groundwater interactions due to its storage properties.

Cameron-Horne Lakes Context (B): The Cameron-Horne lakes hydrogeological context is similar to the Lowland Context, except that the surficial unit is 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 local, shallow aquifer that is expected to be perched over impermeable Vashon till 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 different from the other two contexts present in the lowland area. 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, but with lower discharge due to less impermeable material. Capilano deposits along the Englishman River (especially downstream) could form important riverbank storage and moderate the groundwater-surface water interaction.

Mountains Context (D): The Mountains hydrogeological context is located on the flanks of the mountainous area, and it is essentially composed of till (generally thin) over metamorphic and intrusion bedrock.

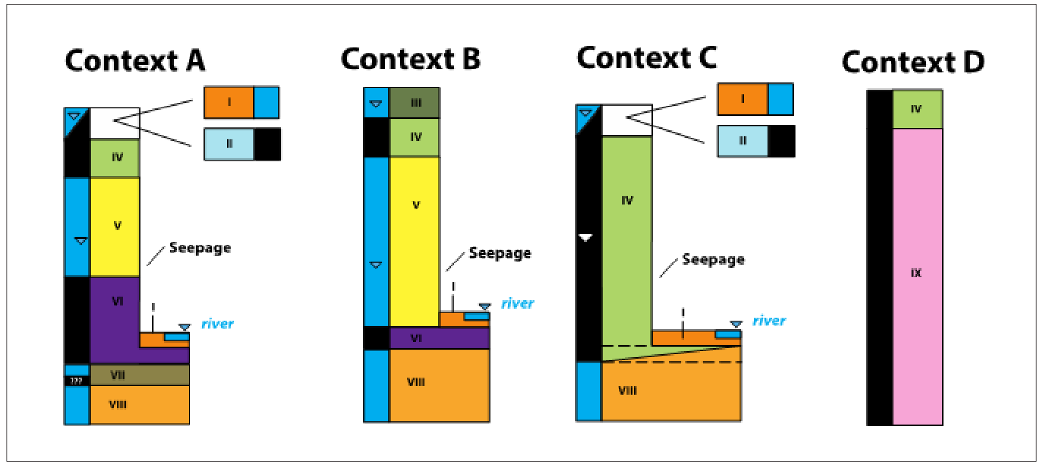


Figure 4.4.1. Hydrogeological contexts
A) Lowland
B) Cameron-Horne Lakes
C) Englishman River
D) Mountains

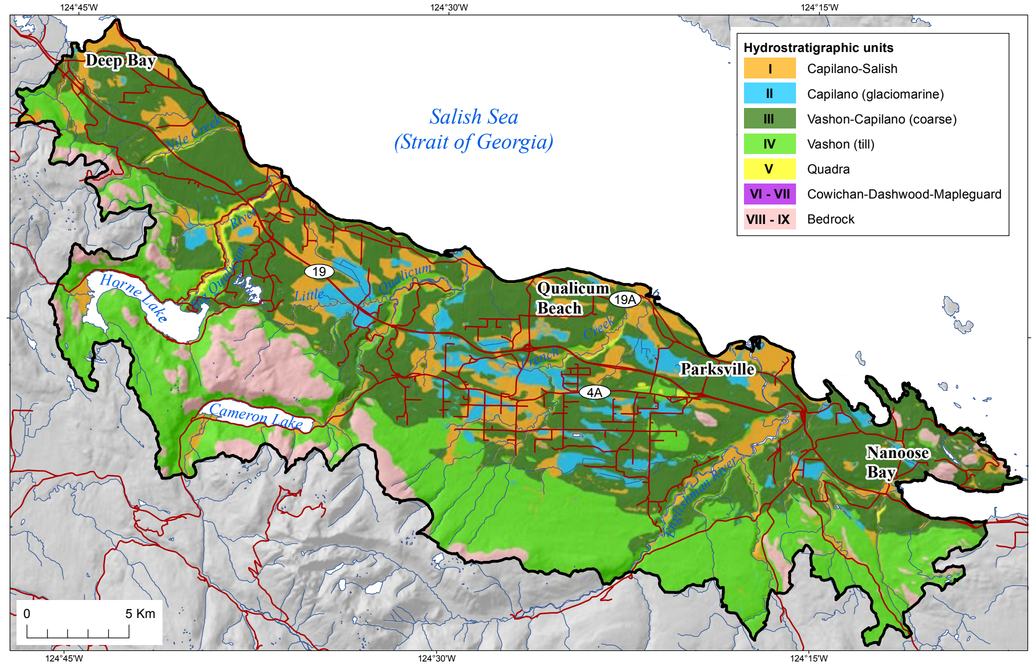


Figure 4.4.2. According to the thickness and spatial distribution of each hydrostratigraphic unit, four distinct hydrogeological contexts were defined to schematize the dynamics of the aquifer system. It is assumed that groundwater exchange between hydrostratigraphic units is similar within each context.

Paradis, D. and Benoit, N., 2016. 4.4 Hydrogeological Contexts; in Russell, H.A.J., and Benoit, N., (compilers); Nanoose Bay - Deep Bay Area, Nanaimo Lowland Groundwater Study Atlas, Regional District of Nanaimo, British Columbia; Geological Survey of Canada, Open File 7877.

5. HYDROGEOLOGICAL MODELLING

5.1. Groundwater Flow Model

Benoit, N., and Paradis, D., Geological Survey of Canada (Quebec City, QC)

To help understand and quantify regional groundwater flow in the study area, a numerical groundwater flow model was constructed (Diersch, 2014). The numerical model used the 3D hydrostratigraphic model as the input for the hydro-architecture. There are uncertainties in hydrostratigraphic unit geometry, hydraulic properties, and boundary conditions, mainly due to the resolution of available data with respect to the size of the study area. Consequently the numerical model was calibrated using existing hydraulic head measurements in wells and against baseflow values estimated from streamflow records available for the main rivers (Benoit and Paradis, 2015).

Model Construction

For the construction of the 3D groundwater flow model, the nine-layer hydrostratigraphic model was converted into 14 numerical simulation grids. For bedrock, there is decreasing hydraulic conductivity with depth due to decreasing number of water-bearing fractures. Each layer of the numerical grid was subdivided into triangular elements to model the topography, in particular, the steep slopes along the major rivers where seepage flow is expected to be important. The final 14-layer 3D simulation grid includes 2,412,018 triangular elements with mean size of 50 m and 1,363,440 nodes (**Figure 5.1.1**).

The boundaries of the numerical model correspond to natural hydraulic limits of the aquifer system, which includes:

a) No flux boundary to represent groundwater divides (northwest and southeast lateral boundaries; bottom of the model).

b) Constant head for nodes below sea level along the seashore to model the effect of the fresh-saline water interface.

c) Seepage condition to represent seepage flow along the main rivers and coastline: a seepage condition allows water extraction from the model when the hydraulic head is larger than the elevation of the ground elevation, thus modelling seepage flow with the hydraulic head equal to ground elevation.

d) Constant flux for surficial cells representing the intrusive bedrock to simulate the position of the water table in this area, in order to estimate groundwater flux from the mountain area to the lowland. This flux was adjusted during the calibration process.

e) Constant and uniform flux was imposed for each sub-watershed. The flux simulates the groundwater recharge. The recharge rates were adjusted during the calibration.

Model Calibration

The groundwater flow model was calibrated for saturated steady-state condition assuming that the model represents average natural past conditions. The model was calibrated based on 247 water-well levels (**Figure 5.1.2**) extracted from the provincial database, 21 monitoring wells, and baseflow estimates from four rivers.

Any discrepancies between simulated and observed calibration targets (hydraulic head and baseflow) could be the result of pumping effects, which are evident in a few areas of intensive pumping; error measurements (head) and estimations (baseflow); or transient effects due to intra- and inter-annual groundwater level fluctuations. The groundwater flow model was first calibrated manually by a trial-and-error process and further refined by numerical inversion (Doherty, 2002). Note that hydraulic conductivity values, recharge rates, and mountain influx (through flux adjustment for the mountains area) were adjusted during the calibration process. The architecture of the aquifer system was not modified.

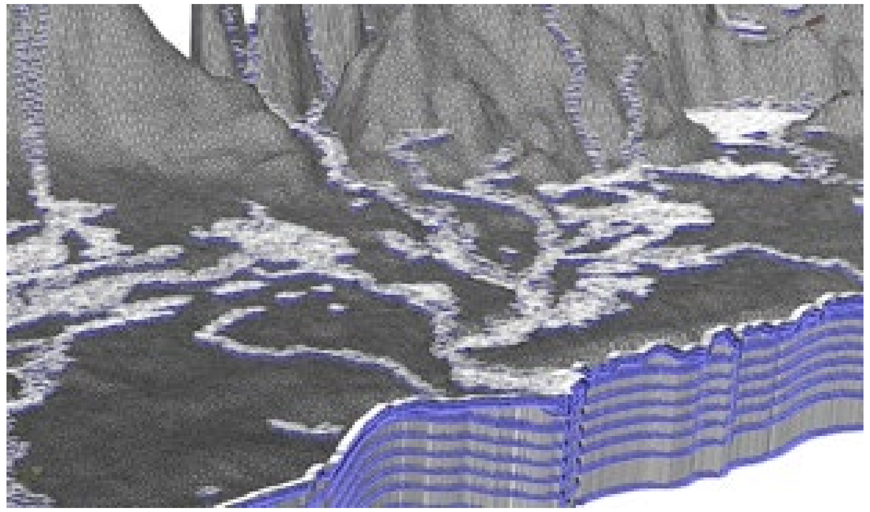


Figure 5.1.1. Close up of the 3D simulation grid for groundwater flow simulations. On top, the 2D triangular mesh with refinement along the main rivers to simulate seepage flow (white dots).

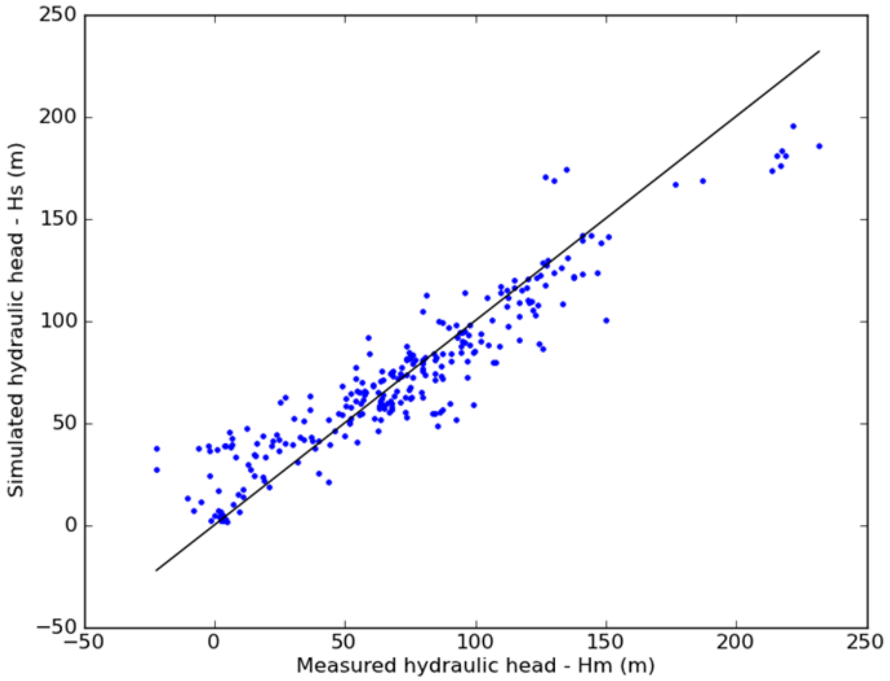


Figure 5.1.2. Comparison of measured and simulated hydraulic heads for the calibration. The global mass balance error for the calibrated model was below 0.01%.

Benoit, N., and Paradis, D., 2016. 5.1 Groundwater Flow Model; in Russell, H.A.J., and Benoit, N., (compilers); Nanoose Bay - Deep Bay Area, Nanaimo Lowland Groundwater Study Atlas, Regional District of Nanaimo, British Columbia; Geological Survey of Canada, Open File 7877.

5.2. Aquifer System Description

Benoit, N., and Paradis, D., Geological Survey of Canada (Quebec City, QC)

Map 11 and **Map 12** present potentiometric maps from the groundwater flow model for the sedimentary bedrock unit (VIII) and the Quadra unit (V), respectively. The potentiometric maps for the two flow systems highlight that the general groundwater flow direction is toward the Strait of Georgia with a component toward the main rivers. Comparison of **Map 11** and **Map 12** reveals that the flow component toward the rivers is more important for the Quadra Unit (V) than for the bedrock unit (VIII). This is likely due to the fact that the Quadra unit (V) drains to the rivers through a seepage face, while the bedrock unit (VIII) is confined below the rivers by the low permeability Cowichan-Dashwood unit (VI), as illustrated in **Figure 5.2.1**. Groundwater flow simulation indicates that groundwater in the Quadra unit (V) is relatively young (< 70 years). In contrast groundwater age in the sedimentary bedrock (VIII) is generally greater than a few hundred years (Benoit et al., 2015b). This estimation has not been verified by independent water sampling and dating.

Surface and Groundwater Interaction

Based on field observations and the hydrostratigraphic model, the main rivers in the study area have incised surficial sediments with depths of erosion up to 50 m, and three different surface water–groundwater interactions can be expected (**Figure 5.2.1**):

Seepage Flow: Seepage flow occurs when an aquifer or aquitard is exposed at the surface and creates a seepage face or resurgence at the soil surface. For the Lowland Context and the Cameron-Horne Lakes Context, the Quadra unit (V) is eroded to its base along river valleys, creating seepage faces along the valley sides. The magnitude of the seepage flow is proportional to the permeability of the sediments and the hydraulic gradient near the river valley. Rivers, however, commonly flow over the underlying compact Dashwood till, and the Quadra unit (V) is not directly in hydraulic contact with the river water. As a consequence, pumping in the Quadra unit (V) can intercept groundwater that otherwise would flow into the rivers, and pumping generally cannot directly draw water from rivers. For the Englishman River Context, 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: The Capilano-Salish unit (I) commonly forms low river terraces and the immediate riverbank within the broader valleys. There is often a rapid connection between river water and groundwater in these riverbank terraces of coarse alluvium. Seepage water from the adjacent Quadra unit (V), 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. They could, however, represent an important water storage capacity that could play a crucial role in regulating stream flow. Water diversion from the Capilano-Salish unit (I) is virtually the same as direct use from the adjacent river courses.

Aquitard and Bedrock Flow: To a lesser extent, groundwater in aquitard Cowichan-Dashwood (VI) and sedimentary bedrock (VIII) units in direct contact with rivers can also contribute to river flow. However, the magnitude of this flux is small due to the relatively low permeability of the aquitard units, except locally where gravel lenses or fractures may be present.

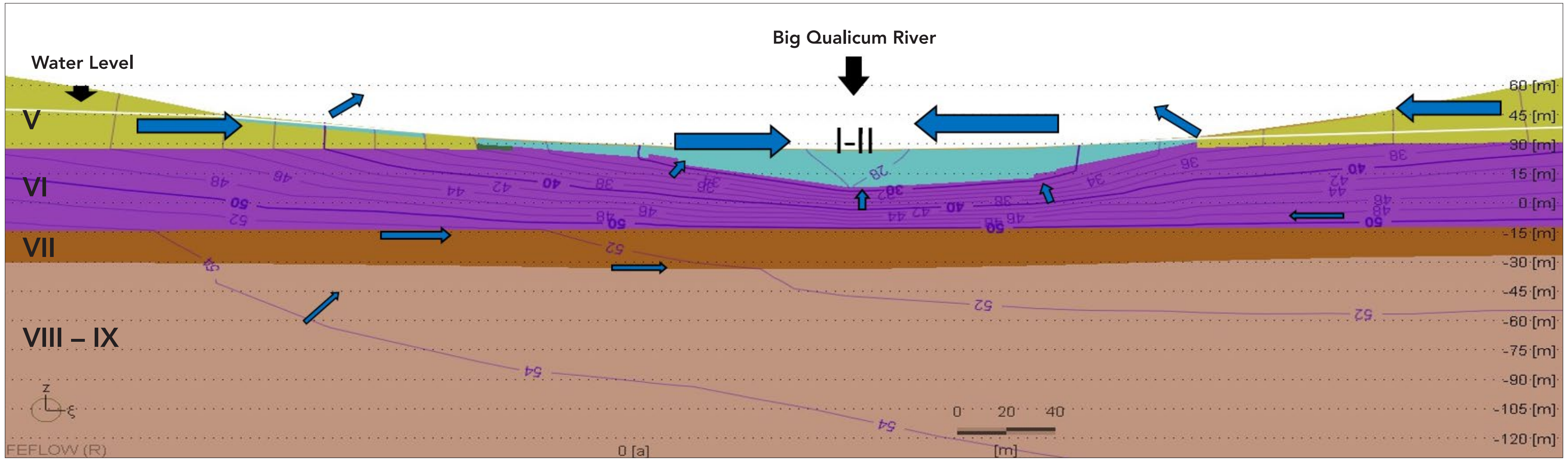
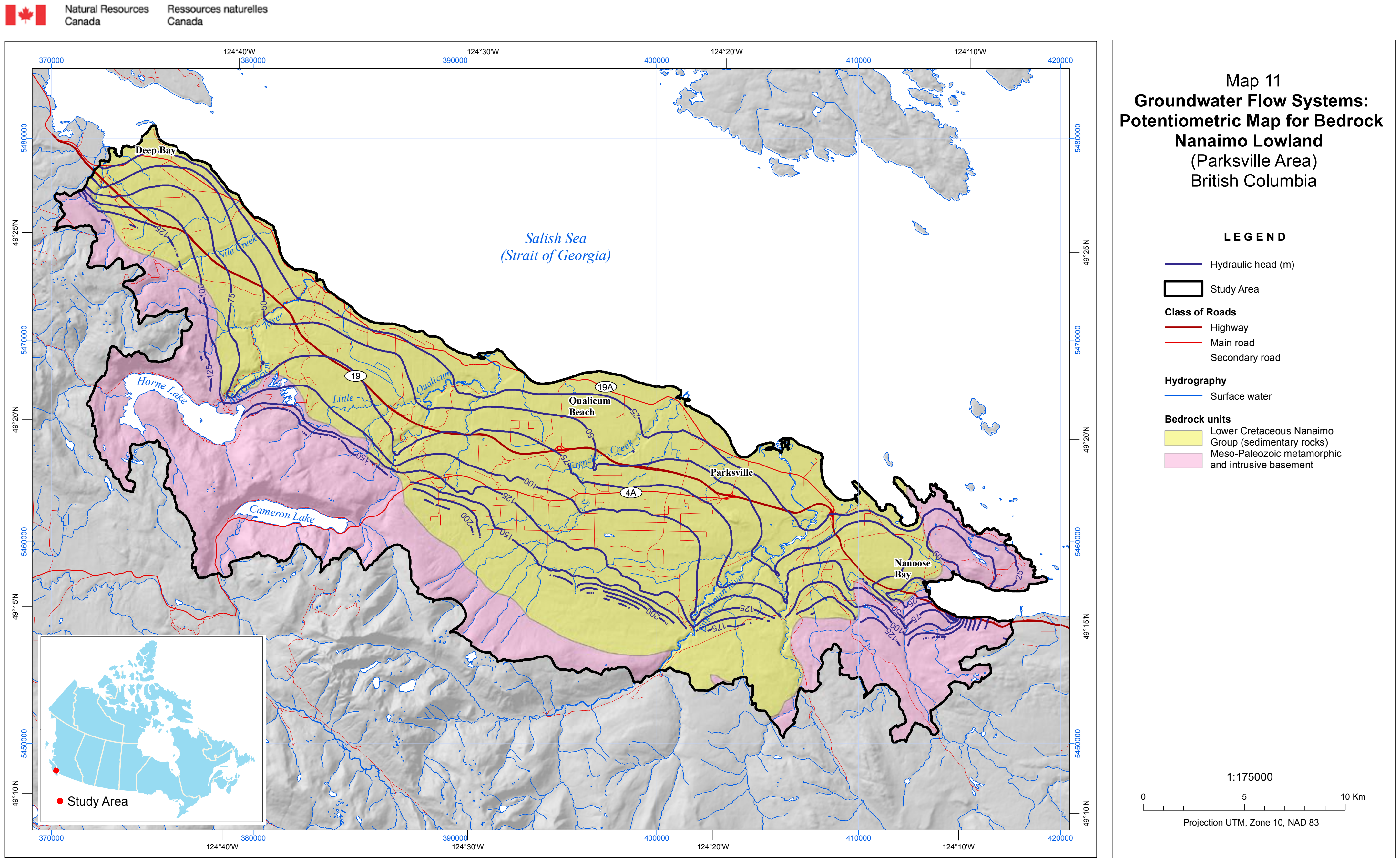


Figure 5.2.1. Cross-section of the Big Qualicum River and the relationship between the river and the various hydrostratigraphic units. Purple lines represent hydraulic heads.

Benoit, N., and Paradis, D., 2016. 5.2 Aquifer System Description; in Russell, H.A.J., and Benoit, N., (compilers); Nanoose Bay - Deep Bay Area, Nanaimo Lowland Groundwater Study Atlas, Regional District of Nanaimo, British Columbia; Geological Survey of Canada, Open File 7877.

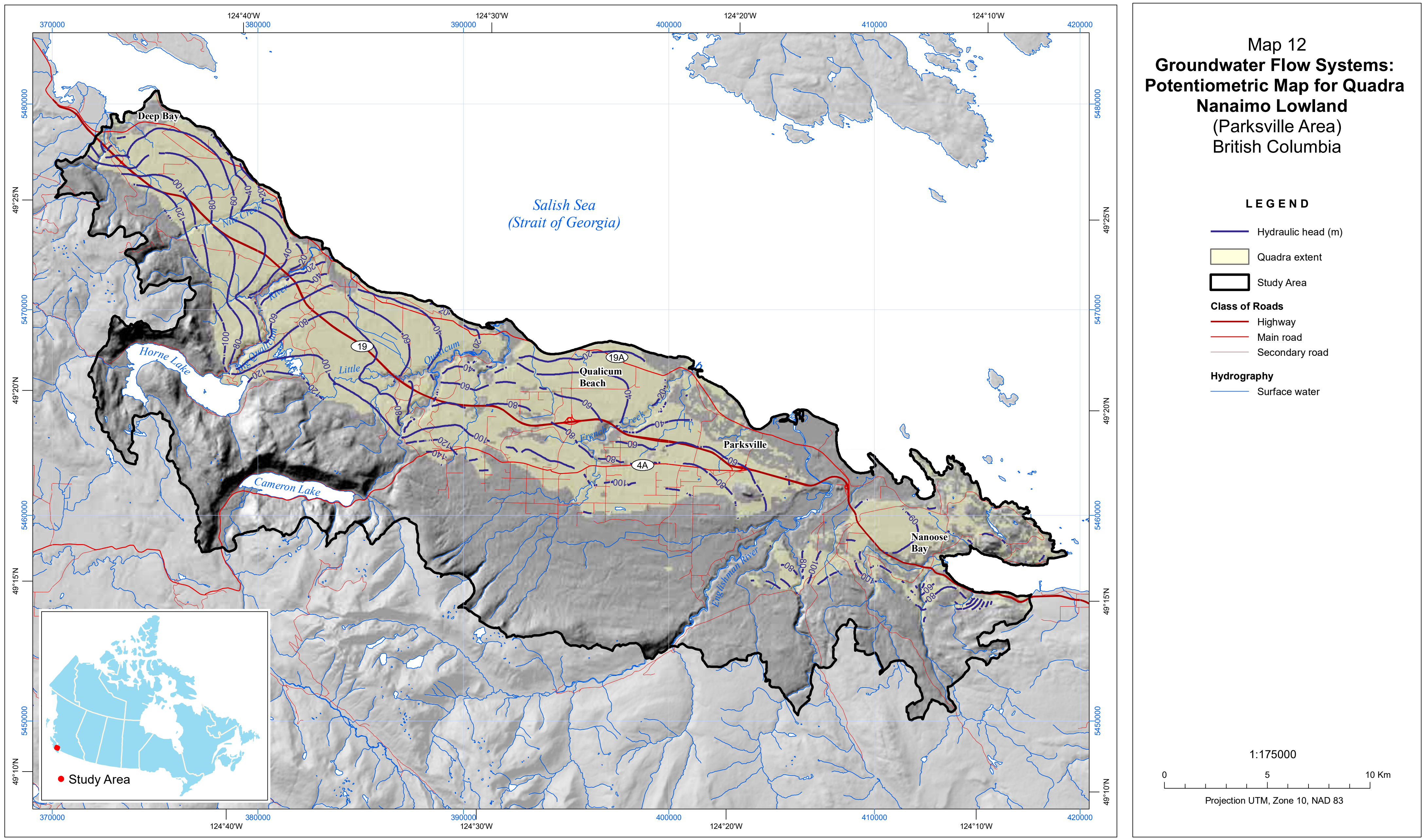
5.2. Aquifer System Description – **Map 11**



Map 11
Groundwater Flow Systems: Potentiometric Map for Bedrock Nanaimo Lowland
(Parksville Area)
British Columbia

5.2. Aquifer System Description – **Map 12**

Natural Resources Canada
Ressources naturelles Canada



Map 12
Groundwater Flow Systems: Potentiometric Map for Quadra Nanaimo Lowland
(Parksville Area)
British Columbia

5.3. Aquifer Vulnerability: DRASTIC

Gilchrist, A., Vancouver Island University (Nanaimo, BC)

Maps of intrinsic aquifer vulnerability are useful tools to help in land-use planning and decision making when protecting groundwater resources. They model how the natural materials and conditions intrinsically act to resist the infiltration of aquifers by pollution introduced at the ground surface. DRASTIC is a common indexing method developed by the U.S. Environmental Protection Agency (Aller et. al., 1987). It has been used widely to determine groundwater vulnerability. The term DRASTIC is an acronym derived from the seven parameters used in the calculation: Depth to water, Recharge, Aquifer media, Soil media, Topography, Impact of vadose zone media, and aquifer hydraulic Conductivity (**Table 5.3.1**). These seven parameters were mapped across Vancouver Island from available data, and the ratings were then combined to produce the final DRASTIC map shown in **Map 13** (Liggett and Gilchrest, 2013).

Methods

DRASTIC requires specific map data to complete the analysis, and most of it is readily available from government agencies and other sources. A key source of information was the BC WELLS database, which contains well information including lithological layers and the depth to water when the well was drilled or dug. Aquifers are found either in unconsolidated surficial material, typically sand and gravel deposits, or in fractured bedrock, and different data are used to define the DRASTIC parameters depending upon the aquifer type. Where well data were available, the lithology logs were used to create a surficial overburden thickness map, which was compared to the classification of mapped aquifers according to the BC MoE (Berardinucci and Ronneseth, 2002).

The analysis showed that mapped aquifers were accurately defined using a 10.5 m threshold of overburden thickness. In areas with a greater overburden thickness, aquifers were classified as surficial, and where the thickness was less, aquifers were classified as being in bedrock. Where no well data existed, terrain maps were used to define the potential aquifer type, with blankets of unconsolidated sediments assumed to be surficial aquifers, and in their absence to be bedrock aquifers.

Results

The results of the DRASTIC analysis are presented in **Map 13**. The mapping is limited in extent by the depth-to-water parameter, which can only be derived where there are wells, and these wells are restricted to developed lands, mostly along the coast. The vulnerability assessment assumed that all aquifers were unconfined, although some mapped aquifers are known to be confined, which provides a conservative evaluation. If an aquifer is known to be confined, then the intrinsic vulnerability is lower than indicated by this study.

The DRASTIC map (**Map 13**) represents the vulnerability of the uppermost aquifer only. If there are lower aquifers in the sequence, then these will be less vulnerable, but in most cases the uppermost aquifer is the most developed and, hence, the target for this study. However, it should be noted that there are many shallow (e.g. dug) wells on Vancouver Island that do not penetrate into the uppermost aquifer, but likely tap into small bodies of water-bearing deposits that are perched above the main aquifer. Such wells are typically for domestic use and are likely to be more vulnerable than the main aquifer below due to their shallow depth.

The DRASTIC map is based on existing mapping and other resources, and is the best available estimate of intrinsic aquifer vulnerability. The map provides a regional screening tool for informing land-use decisions that need to take regional aquifer vulnerability into account. It is not accurate enough, however, to assess local conditions. In many cases, more detailed hydrogeological studies will be required to better characterize and confirm the results of this study, especially in areas with limited well data.

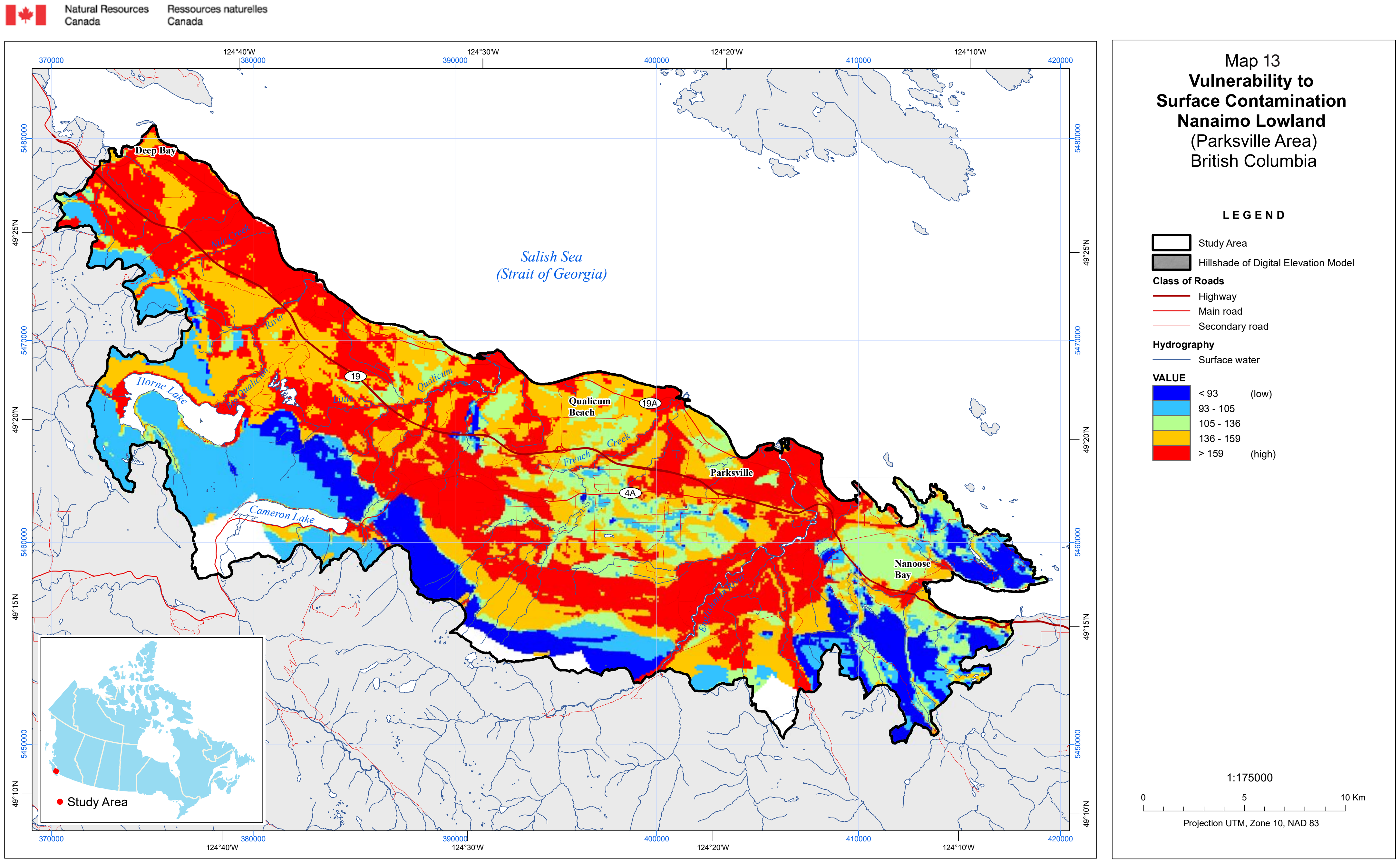
A digital version of the map is available from iMapBC (URL: maps.gov.bc.ca)

	Parameter	Impact on intrinsic aquifer vulnerability	Weight*
D	Depth to water	As water depth decreases, vulnerability increases, due to shorter transport time between the surface and the aquifer, and less time for natural attenuation	5
R	Recharge	Greater recharge promotes faster downward contaminant movement; therefore, the higher the vulnerability	4
A	Aquifer media	In general, larger grain sizes and more intense fracturing lead to a higher vulnerability, because of increased permeability and decreased natural attenuation potential	3
S	Soil media	Areas with thin coarse textured soils will have a higher vulnerability than thick fine grained materials, such as silts, which have slower infiltration and a higher natural attenuation capacity	2
T	Topography (slope)	Represented by the slope. The lower the slope, the higher the vulnerability due to less runoff and a higher potential for infiltration of contaminants into the subsurface	1
I	Impact of vadose zone	A higher permeability of the vadose zone material leads to a higher vulnerability, due to decreased time for natural attenuation of any contaminants	5
C	(hydraulic) Conductivity	The faster water and contaminants can move through an aquifer unit, the greater the likelihood of the contaminant spreading throughout the aquifer; therefore, the higher the hydraulic conductivity of an aquifer the higher the vulnerability	3

Table 5.3.1. **Description of the DRASTIC parameters.**

Gilchrist, A., 2016. 5.3 Aquifer Vulnerability: DRASTIC; in Russell, H.A.J., and Benoit, N., (compilers); Nanoose Bay - Deep Bay Area, Nanaimo Lowland Groundwater Study Atlas, Regional District of Nanaimo, British Columbia; Geological Survey of Canada, Open File 7877.

5.3. Aquifer Vulnerability: DRASTIC – **Map 13**



5.4. Hydrochemistry of the Englishman River

Grasby, S., Geological Survey of Canada (Calgary, AB)

In the Englishman River watershed, water from the river and from groundwater are important sources of drinking water for the local communities. The river also has a significant economic value to the fisheries. Chinook, chum, coho, sockeye, and pink salmon, as well as cutthroat, rainbow, and steelhead trout are all present at some point during the year, and support important fisheries. Increasing population, development, and existing industrial and commercial land-use practices, combined with the impacts of a changing climate, present challenges for the sustainable management of the water supply. Understanding the degree and nature of surface and groundwater interaction is essential to any sustainable management initiatives.

Method

The chemistry of groundwater is naturally controlled through reactions with the igneous and sedimentary rocks and minerals that comprise the groundwater aquifers. These reactions tend to give groundwater higher levels of total dissolved material and a composition that is dominated by dissolved calcium and bicarbonate, as compared to river water that quickly runs over the land surface and has less time for geochemical reactions (Provencher et al., 2013; Provencher, 2014). The river has very fresh water, with an average total dissolved solids (TDS) content of 43 mg/L, except near the mouth where it is influenced by seawater. Groundwater has higher TDS levels, and this tends to increase with depth (up to 660 mg/L). Shallow wells (< 80 m) have TDS < 110 mg/L. These geochemical 'fingerprints' of groundwater, along with stable isotope data, which also identify sources of water, can help elucidate what proportion of the Englishman River is fed from groundwater discharge.

Results

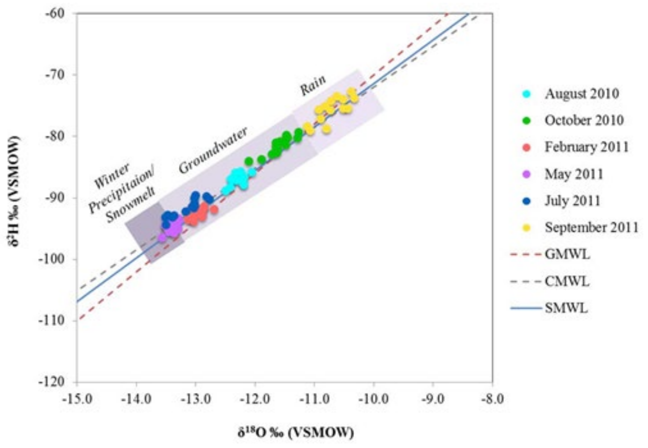
Stable isotope data demonstrate that groundwater originates as precipitation, but during its transient time underground, it takes on groundwater chemical characteristics influenced by aquifer lithologies and residence time. The data indicate that the river is dominated by snowmelt water during May, whereas it is dominated by rainfall during higher precipitation periods in the fall. Snowmelt water and most of the rainfall are transported to the river through the surface runoff process. Stable isotope data show that groundwater contributes a majority of river flow during other times of the year (**Figure 5.4.1**) — particularly in late summer and the winter months, when it constitutes the majority of surface-water discharge. This signal is also present in the river chemistry, which takes on characteristics of groundwater during these periods, becoming more dominated by Ca-HCO_3. These results show that, throughout much of the year, the Englishman River is intimately linked to groundwater aquifers in the basin, with varying proportions of surface runoff water and groundwater feeding the river.

Terminology used in Figure 5.4.1

GWML – Global Meteoric Water Line

CMWL – Canadian Meteoric Water Line

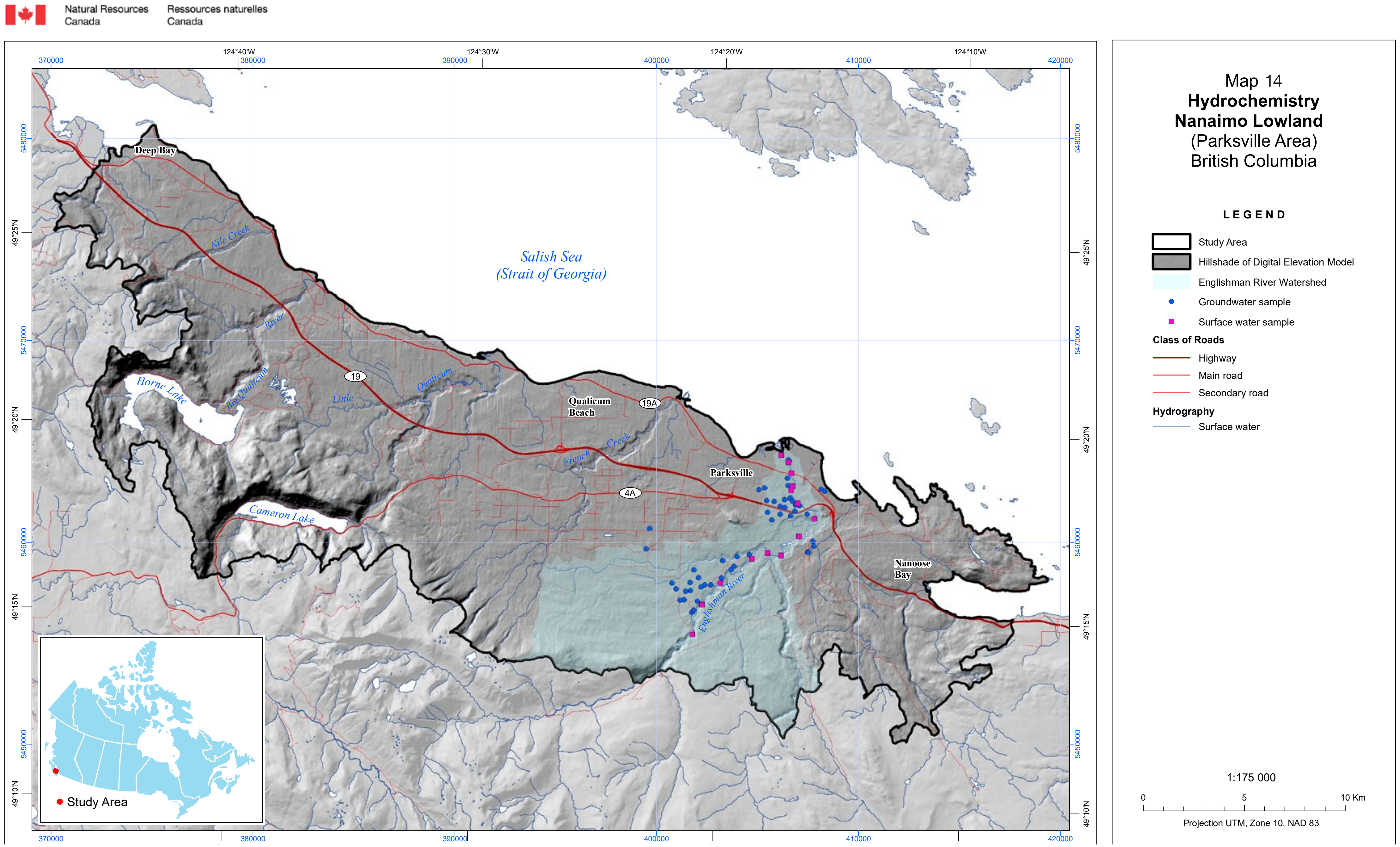
SMWL – Saturna Meteoric Water Line



Figures 5.4.1 Interpretation of isotope signal according to source, snow, groundwater, and rain (e.g. GMWL) in the legend.

Grasby, S., 2016. 5.4 Hydrogeochemistry of the Englishman River; in Russell, H.A.J., and Benoit, N., (compilers); Nanoose Bay - Deep Bay Area, Nanaimo Lowland Groundwater Study Atlas, Regional District of Nanaimo, British Columbia; Geological Survey of Canada, Open File 7877.

5.4. Hydrochemistry of the Englishman River – **Map 14**



6. REFERENCES

Allen, D.M. 1999. An assessment of the methodologies used for analyzing hydraulic test data in British Columbia. Final Report for Groundwater Section, Water Management Branch, British Columbia Ministry of Environment, Lands and Parks, Victoria, B.C., Queen's Press, March 1999, 84 pp. ISBN 0-7726-3914-0

Aller, L., Bennett, T., Lehr, J., Petty, R., and Hackett, G. 1987. DRASTIC: A Standardized System for Evaluating Ground Water Pollution Potential Using Hydrogeologic Settings. EPA-600/2-87-035, National Water Well Association, Dublin, Ohio / EPA Ada. Oklahoma. 641 pp.

Alley, N.F. 1979. Middle Wisconsin stratigraphy and climatic reconstruction, southern Vancouver Island, British Columbia. Quaternary Research, v. 11, 213-237.

Alley, N.F., and Chatwin, S.C. 1979. Late Pleistocene history and geomorphology, southwestern Vancouver Island, British Columbia. Canadian Journal of Earth Sciences, v. 16, 1645-1657.

Alley, N.F. and Hicock, S.R. 1986. The stratigraphy, palynology, and climatic significance of pre-middle Wisconsin Pleistocene sediments, southern Vancouver Island, British Columbia. Canadian Journal of Earth Sciences, v.23, 369–382. doi:10.1139/e86-039

Armstrong, J.E., and Brown, W.L. 1954. Late Wisconsin marine drift and associated sediments of the lower Fraser Valley, British Columbia, Canada. Geological Society of America, Bulletin, v. 65, 349-364.

Armstrong, J.E., and Clague, J.J. 1977. Two major Wisconsin lithostratigraphic units in southwestern British Columbia. Canadian Journal of Earth Sciences, v. 14, n. 7, 1471-1480. doi:10.1139/e77-128

Batu, V., 1998. Aquifer Hydraulics: A Comprehensive Guide to Hydrogeologic Data Analysis, 1st edition, Wiley-Interscience, New York.

Bednarski, J. 2014. Surficial geology and Pleistocene stratigraphy from Deep Bay to Nanoose Harbour, Vancouver Island, British Columbia, Geological Survey of Canada, Open File 7681. doi:10.4095/295609

Benoit, N., Paradis, D., Bednarski, J. M., Hamblin, T., and Russell, H.A.J. 2015a. Three dimensional hydrostratigraphic model of the Nanoose - Deep Bay area, Nanaimo Lowland, British Columbia. Geological Survey of Canada, Open File 7796; 30 pp., doi:10.4095/296302

Benoit, N., and Paradis, D. 2015. Three dimensional groundwater flow model of the Nanoose-Deep Bay area, Nanaimo Lowland, British Columbia. Geological Survey of Canada, Open File 7845, 1 zip file. doi:10.4095/297046

Berardinucci, J., and Ronneseth, K., 2002. Guide to Using the BC Aquifer Classification Maps for the Protection and Management of Groundwater report. BC Ministry. Water, Land and Air Protection.

Carmichael, V.E. 2013. Compendium of Re-evaluated Pumping Tests in the Regional District of Nanaimo, British Columbia. B.C. Ministry of Environment, 941 pp. [electronic resource]. http://a100.gov.bc.ca/pub/acat/public/viewReport.do?reportId=36013

Cathyl-Bickford, C.G. 1993. Geology and petrography of the Wellington Seam, Nanaimo coalfield, Vancouver Island. Unpublished MSc Thesis, University of British Columbia, 184 pp.

Clague, J.J. 1976. Quadra Sand and its relation to the late Wisconsin glaciation of southwest British Columbia. Canadian Journal of Earth Sciences, v. 13, 803-815. doi: 10.1139/e76-083

Clague, J.J. 1981. Late Quaternary Geology and Geochronology of British Columbia, Part 2: Summary and Discussion of Radiocarbon-Dated Quaternary History. Geological Survey of Canada, Paper 80-35, 1981; 41 pp, doi:10.4095/119439

Clague, J.J. 1986. The Quaternary stratigraphic record of British Columbia – evidence for episodic sedimentation and erosion controlled by glaciation. Canadian Journal of Earth Sciences, v. 23, 885-894.

Clague, J. J., and Luternauer, J. L. 1983. Field Trip Guidebook, Trip 6, Late Quaternary Geology of Southwestern British Columbia. GAC-MAC-CGU Joint Annual Meeting, Victoria, BC, Canada, 120 pp.

Crow, H.L., Knight, R.D., Russell, H.A.J., Pugin, A.J-M., and Cartwright, T.J. 2014. Downhole geophysical data from five boreholes in the Nanaimo Lowlands, British Columbia; Geological Survey of Canada, Open File 7567, 1 zip file. doi:10.4095/294925

Diersch H-J.G. 2014. FEFLOW, Finite Element Modeling of Flow, Mass and Heat Transport in Porous and Fractured Media. Springer Heidelberg. DOI: 10.1007/978-3-642-38739-5

Doherty, J. 2002. Manual for PEST, 5th edition. Brisbane, Australia: Watermark Numerical Computing. Downloadable from: www.sspa.com/pest

Fetter C. W. 1994. Applied hydrogeology, Prentice-Hall Inc., New Jersey, 598 pp.

Furey, P.R. and Gupta, V.K. 2001. A physically based filter for separating base flow from streamflow time series. Water Resources Research 37: doi: 10.1029/2001WR000243. issn: 0043-1397.

Fyles, J.G. 1956. Surficial geology of Horne Lake and Parksville map-areas, Vancouver Island, British Columbia. Unpublished PhD Thesis, The Ohio State University, 258 pp.

Fyles, J.G. 1963. Surficial geology of Horne Lake and Parksville map-areas, Vancouver Island, British Columbia. Geological Survey of Canada, Memoir 318. 142 pp. doi:10.4095/100545

Hamblin, A.P. 2012. Upper Cretaceous Nanaimo Group of Vancouver Island as a potential bedrock aquifer zone: summary of previous literature and concepts. Geological Survey of Canada, Open File 7265, 1 CD. doi:10.4095/292106

Hamblin, A.P. 2015. Detailed measured sections, bedrock aquifer/aquitard facies and potential bedrock aquifer systems of the Upper Cretaceous Nanaimo Group, Nanaimo Lowland, eastern Vancouver Island. Geological Survey of Canada, Open File 7849, 40 pp. doi:10.4095/296979

Hamblin, A.P., and McCartney, T. 2014. The hydrogeological characteristics of the Upper Cretaceous De Courcy Formation (Nanaimo Group), from a subsurface core, groundwater observation well, Cedar, British Columbia. Geological Survey of Canada, Open File 7628. doi:10.4095/294859

Henderson, G.G.L., Vograss, L.W., 1962. Geology of the Gulf Island area.

Hicock, S.R. 1980. Pre-Fraser Pleistocene stratigraphy, geochronology, and paleoecology of the Georgia Depression, British Columbia. Unpublished PhD thesis, University of Western Ontario, London, Ontario, 230 pp.

Hicock, S.R., and Armstrong, J.E. 1983. Four Pleistocene formations in southwest British Columbia: their implications for patterns of sedimentation of possible Sangamonian to early Wisconsinan age. Canadian Journal of Earth Sciences, v. 20, 1232-1247.

Holland, S.S. 1964. Bulletin 48: Landforms of British Columbia: A Physiographic Outline. British Columbia Ministry of Energy, Mines and Petroleum Resources

Hornberger, G.M., Raffensperger, J.P., Wiberg, P.L., and Eshleman, K.N. 1998. Elements of Physical Hydrology. Johns Hopkins University Press, Baltimore.

Hutchinson, I., James, T.S., Reimer, P.J., Bornhold, B.D., and Clague, J.J. 2004. Marine and limnic radiocarbon reservoir corrections for studies of late and postglacial environments in Georgia Basin and Puget Lowland, British Columbia, Canada and Washington, USA. Quaternary Research (New York) v. 61,193-203. doi:10.1016/j.yqres.2003.10.004

Journeay, J.M., and Morrison, J. 1999. Field investigations of Cenozoic structures in the northern Cascadia forearc, southwestern British Columbia. Geological Survey of Canada, Current Research 1999-A, 239-250.

6. REFERENCES

Jungen, J. R. 1985. MoE Technical Report 17: Soils of Southern Vancouver Island. MoE, Surveys and Resource Mapping Branch, Victoria.

Knight, R.D., Reynen, A.M.G., Grunsky, E.C., and Russell, H.A.J. 2015. Chemostratigraphy of the late Pleistocene Dashwood Drift to Capilano Sediment succession using portable XRF spectrometry, Nanaimo, British Columbia, Canada; Geological Survey of Canada, Open File 7651, 1 .zip file. doi:10.4095/295688

Liggett, J.E., and Gilchrist, A. 2013. Technical summary of intrinsic vulnerability mapping methods in the regional districts of Nanaimo and Cowichan Valley, British Columbia; Geological Survey of Canada, Open File 6168, 73 pp. doi: 10.4095/287315

Mackie, D.C. 2002. An integrated structural and hydrogeologic investigation of the fracture system in the Upper Cretaceous Nanaimo Group, southern Gulf Islands, British Columbia. Unpublished MSc Thesis, Department of Earth Sciences, Simon Fraser University.

Maloley, M., Fernandes, R., Canisius, F., and Butson, C. 2013. Peak Season Leaf Area Index for the Nanaimo Aquifer – 2011; Geological Survey of Canada, Open File 7149. doi:10.4095/293342

Massey, N.W.D., Matheson, A., and Bobrowsky, P.T. 1998. Aggregate Resource Potential of the Nanaimo Area (parts of NTS 92B12, 92B13, 92C09, 92C16, 92F01, 92F02, 92F07, 92F08, 92G01); B.C. Ministry of Energy and Mines, Open File 1998-12.

Mathews, W.H. 1986. Physiographic map of the Canadian Cordillera. Geological Survey of Canada, "A" Series Map 1701A, 1986; 1 sheet, doi:10.4095/122821

Monger, J.W.H., 1989. Overview of Cordilleran geology. In Western Canada Sedimentary Basin, B.D. Ricketts (ed.), Canadian Society of Petroleum Geologists, Special Paper 30, 9-32.

Muller, J.E., and Jeletzky, J.A. 1970. Geology of the Upper Cretaceous Nanaimo Group, Vancouver Island and Gulf Islands, British Columbia. Geological Survey of Canada, Paper 69-25, 77 pp.

Mustard, P.S. 1994. The Upper Cretaceous Nanaimo Group, Georgia Basin. In Geological Hazards of the Vancouver Region, Southwestern British Columbia, J.W.H. Monger, (ed.), Geological Survey of Canada, Bulletin 481, 27-95.

Peel, M.C., Finlayson, B.L., and McMahon, T.A. 2007. Updated world map of the Köppen–Geiger climate classification. Hydrol. Earth Syst. Sci. 11, 1633–1644.

Provencher, S. K. 2014. Geochemical Assessment of Surface Water-Groundwater Interaction in the Englishman River Watershed, British Columbia. Unpublished MSc. Thesis, University of Calgary, 194 pp.

Provencher, S.K., Mayer, B., and Grasby, S.E. 2013. Aqueous geochemistry of the Englishman River Watershed, Parksville, British Columbia for use in assessment of potential surface water-groundwater interaction; Geological Survey of Canada, Open File 7406, 32 pp. doi:10.4095/292678.

Pugin, A.J-M., Pullan , S.E., and Duchesne, M.J. 2013. Regional hydrostratigraphic and insights into fluid flow through a clay aquitard from shallow seismic reflection data. The Leading Edge vol. 32, no. 7, 742-748, doi:10.1190/tle32070742.1

Rivard, C., Lefebvre, R., and Paradis, D. 2013. Regional recharge estimation using multiple methods: an application in the Annapolis Valley, Nova Scotia, Canada. Environmental Earth Sciences v. 71, no. 3, 1389-1408, doi: 10.1007/s12665-013-2545-2

Ryder J.M., and Clague, J.J. 1989. British Columbia (Quaternary stratigraphy and history, Cordilleran Ice Sheet). In Chapter 1 of Quaternary Geology of Canada and Greenland, Fulton, R.J. (ed.), Geological Survey of Canada, Geology of Canada no. 1, (Also Geological Society of America, Geology of North America Series v. K-01), 48-58.

Sharpe, D.R., Hinton, M.J., Russell, H.A.J., and Desbarats, A.J. 2002. The Need for Basin Analysis in Regional Hydrogeological Studies: Oak Ridges Moraine, Southern Ontario. Geoscience. Canada 29, 3–19.

Sharpe, D.R., Russell, H.A.J., Dyke, L., T., Grasby, S., Gleeson, T., Michaud, Y., Savard, M.M., Wei, M., and Wozniak, P. 2014. Chapter 8, Hydrogeological Regions of Canada; in Rivard A. (ed.), Canada's Groundwater Resources, 266-299.

Surrette, M., Allen, D.M., Journeay, M., 2008. Regional evaluation of hydraulic properties in variably fractured rock using a hydrostructural domain approach. Hydrogeol. J. 16, 11–30.

Yorath, C.J., Sutherland Brown, A., Campbell, R.B. and Dodds, C.J. 1992. The Insular Belt. In Geology of the Cordilleran Orogen in Canada, H. Gabriesle and C.J. Yorath (eds.), Geological Survey of Canada, Geology of Canada, no. 4 and Geological Society of America, Geology of North America/Decade of North American Geology, v. G-2, 354-361.

Waterline 2013. Regional District of Nanaimo Phase One Water Budget Project.

Wei, M., Ronneseth K., Allen, D.A., Kohut, A.P., Turner B., Grasby S., and Park E. 2007. Types and General Characteristics of Aquifers in the Canadian Cordilleran Hydrogeologic Region, 8th Joint CGS/IAHCNC Groundwater Conference, October 2007, Ottawa, Canada.

Wei, M., Ronseth, K., Allen, D.M., Kohut, A.P., Grasby, S.E., and Turner, B. 2014. Chapter 9, Cordilleran Hydrogeological Region. In Canada's Groundwater Resources, Rivera, A. (ed.), 302-357.

Zhai, L., and Grasby, S.E. 2014. Petrographic study of the Nanaimo Group from OW-11-01-Nanaimo Obs Well 390. Geological Survey of Canada, Open File.