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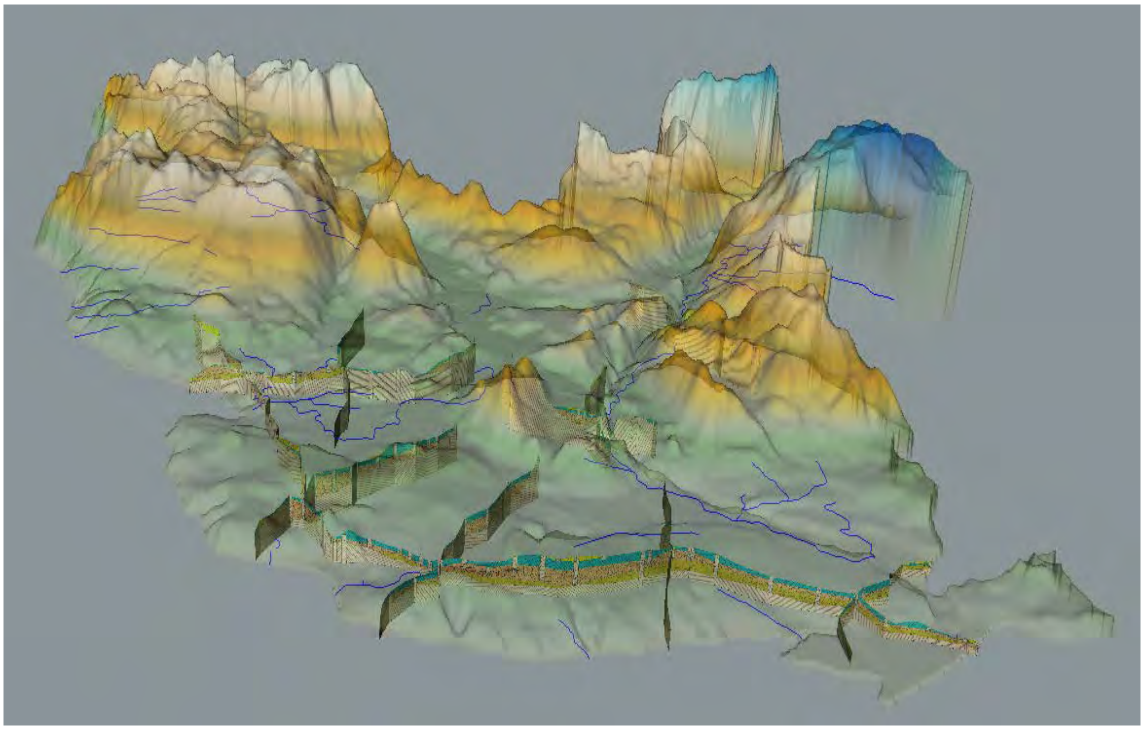
Detailed Aquifer Mapping Study: Shawnigan Lake Area, Vancouver Island, B.C.

Zidra Hammond, Andrew Hinnell, and John Clague



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Lengyel, T. 2018. Shawnigan Lake area topography and cross-sections, looking southwest.

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EXECUTIVE SUMMARY

WorleyParsons Canada Services Ltd (operating as Advisian) were retained by the British Columbia Ministry of Environment and Climate Change Strategy (ENV) to undertake Stage II detailed aquifer mapping for the Shawnigan Water Precinct and surrounding watershed extents on southeast Vancouver Island, British Columbia (Study Area). This area has been identified as a priority for aquifer characterization based on known concerns with water availability, high population density, and local dependency on groundwater. This report advances the understanding of hydrogeological conditions to support management of local water resources under the *Water Sustainability Act*.

Stage II detailed mapping focuses on advancing the geologic understanding of the Study Area and developing a hydrogeologic conceptual site model (CSM) to revise/update existing aquifer mapping and support further hydrogeological investigations. To meet the goals of the study, a database of available information was compiled including 3,741 registered well records, existing bedrock and surficial geology mapping, topography, surface water features, and spring locations. Lithology data was processed into key lithology terms for bedrock and unconsolidated deposits to support subsurface interpretations. A bedrock surface, thickness map for unconsolidated material (isopach), and 20 geological cross-sections were prepared to support CSM development and aquifer mapping updates.

A total of four bedrock and five unconsolidated aquifers have been updated in the Study Area as follows (aquifer numbers provided in brackets):

- Bedrock aquifers: Cowichan Bay (198), Koksilah River Valley (202), Shawnigan Lake/Cobble Hill/Mill Bay (203), and Malahat Ridge (208);
- Unconsolidated aquifers: Cherry Point (197), Fairbridge (199), Heather Bank (201), Shawnigan Lake (205), and Mill Bay (206).

Bedrock aquifer mapping covers the majority of the Study Area while unconsolidated aquifers are generally mapped along the east edge of the Study Area adjacent to the coast and surrounding Shawnigan Lake.

Updates to aquifer mapping focused on using regional scale physical and hydraulic boundaries (e.g. groundwater divides or streamlines, geologic contacts, and surface water bodies) to support water management efforts. Mapped aquifers may extend beyond or include areas where registered wells do not currently exist; therefore, there is some uncertainty in aquifer boundaries, particularly for confined unconsolidated and bedrock aquifers that may be refined as additional information becomes available.

Limited information is currently available on how mapped faults in the Study Area influence hydrogeology. As such, general conceptual geological models of fault zone hydrogeology for the different bedrock types have been considered. Faults are represented in bedrock mapping as areas of enhanced permeability but require further field verification.

Further data collection efforts and studies are recommended to advance the understanding of hydrogeological conditions. This includes ongoing efforts to expand the extent of the regional groundwater observation network, further bedrock characterization, hydrogeologic studies (e.g. geochemical studies, groundwater-surface water interactions studies, and confirmatory mapping of springs), and development of tools to support sustainable water resource management (e.g. numerical model development, update of water budgets, and mapping of potential saltwater intrusion).

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ACRONYMS

B.C.	British Columbia
BCACS	British Columbia Aquifer Classification System
BCGS	British Columbia Geographical System
CSM	conceptual site model
DEM	Digital Elevation Model
EcoCat	Ecological Reports Catalogue
ENV	Ministry of Environment and Climate Change Strategy
FLNR	Ministry of Forests, Lands, Natural Resource Operations and Rural Development
GW	groundwater
HGU	hydrogeological units
ID	identifier or identification number
SCWPS	South Cowichan Water Plan Study
TRIM	Terrain Resource Information Management
URL	uniform resource locator (website address)
WSA	*Water Sustainability Act*
WTN	well tag number

1. INTRODUCTION

1.1 General

The British Columbia Ministry of Environment and Climate Change Strategy (ENV) retained WorleyParsons Canada Services Ltd., operating as Advisian, to undertake Stage II detailed aquifer mapping (the Project) for the Shawnigan Water Precinct and surrounding watershed extents (the Study Area) on southeast Vancouver Island, British Columbia (B.C.). This area has been identified as a priority for aquifer characterization based on concerns with respect to water availability, high population density, and local dependency on groundwater.

Stage II detailed mapping focuses on advancing the geologic understanding of the Study Area to support development of a hydrogeologic conceptual site model (CSM) and to revise/update existing aquifer mapping. Current aquifer mapping in the Study Area has been completed based on existing provincial guidelines (Berardinucci and Ronneseth 2002). The Project will support management of local water resources under B.C.'s *Water Sustainability Act* (WSA).

1.2 Objectives

The main objectives of the Project include the following:

- Compile existing technical information relating to geology, hydrogeology, and geophysical data for the area;
- Develop a hydrogeological framework CSM for the Study Area, including hydrogeological cross-sections to support interpretations;
- Revise and update existing mapped aquifer extents based on the CSM; and
- Provide recommendations on future data collection efforts to advance the understanding of groundwater in the area.

The ENV engaged with local stakeholders in December 2017 to communicate the Project and obtain feedback. Supplemental information was provided by Cowichan Tribes and the Mill Bay Waterworks.

1.3 Study Area

The Study Area is located on the southeast portion of Vancouver Island (Figure 1). It is bordered by Saanich Inlet to the east. Extents to the north, west, and south generally coincide with watershed boundaries. The Study Area is approximately 20 km wide and 35 km long.

The Malahat, Hatch Point, Est-Patrolas, Kil-Pah-Las, and Theik First Nation Reserves are fully contained within the Study Area, while the Cowichan First Nation Reserves are partially contained within the Study Area. As shown in Figure 1, several communities are located within the Study Area including Shawnigan Lake, Bamberton, Malahat, Cobble Hill, Mill Bay, Hillbank, Cowichan Bay, Cowichan Station, Fairbridge and a portion of Eagle Heights and Koksilah.

The majority of the Study Area is within the boundary of the Cowichan Valley Regional District. A small portion in the southern extents of the Study Area is within the Capital Regional District.

1.4 Previous Studies and Plans

Existing studies that include all of or parts of the Study Area were reviewed, and the information integrated into the CSM (Table 1). All studies, with the exception of the South Cowichan Water Plan Study (SCWPS) and the memorandum from Straker and MacDonald, were available through the ENV's Ecological Report Catalogue (EcoCat).

Table 1: Summary of key historical studies and plans.

Author	Date	Title
Straker, J. and MacDonald, R.	Aug 2017	Memorandum Re: Hydrologic Mapping for the CVRD
Harris, M. and Usher, S.	Oct 2017	Preliminary Groundwater Budgets, Cobble Hill/Mill Bay Area, Vancouver Island, B.C.
Carmichael, V.	Mar 2014	Compendium of Re-evaluated Pumping Tests in the Cowichan Valley Regional District, Vancouver Island, British Columbia
van der Gulik, T., Neilsen, D., Fretwell, R. and Tam, S.	Jun 2013	Agricultural Water Demand Model, Report for the Cowichan Valley Regional District. Victoria, B.C.: B.C. Ministry of Agriculture and Agriculture and Agri-Food Canada.
Newton, P. and Gilchrist, A.	Apr 2010	Technical Summary of Intrinsic Vulnerability Mapping Methods for Vancouver Island
WorleyParsons	Feb 2009	South Cowichan Water Plan Study: A Preliminary Assessment of Water Supply & Needs within the South Cowichan Region
Zubel, M.	Oct 1985	Maps: Cobble Hill, Static Water Level, Overburden Thickness, Bedrock Elevation, Depth to Water, cross-section Lines
ENV	Feb 2006	Shawnigan-Goldstream Water Allocation Plan
ENV	Sep 1986	Cowichan-Koksilah Water Management Plan
ENV	1996 to 2012	Aquifer mapping reports for bedrock Aquifer No. 197, 198, 200, 2002, 203, 204, 207, 208, 942 and unconsolidated Aquifer No. 199, 201, 205, and 206

1.5 Scope of Work

The scope of work consisted of the following key tasks:

- Data Gathering – compilation and review of publicly available data sources, including but not limited to previous studies, aquifer mapping reports, geologic maps, and geophysical data.
- Site Visit – visual observations of the geomorphic expressions of the Quaternary units and bedrock outcrops in the Study Area to inform interpretation.
- Geologic Interpretation/Conceptual Geologic Model – stratigraphic and hydrostratigraphic interpretations of the Study Area, including cross-section preparation to support development of the CSM.
- Mapping and Reporting – Updated aquifer mapping based on CSM in ESRI shapefile format. Preparation of a report detailing the methodology and results of the three-dimensional interpretation of hydrostratigraphy.

2. APPROACH

2.1 Data Sources

A summary of the data used for the Project is presented in Table 2. Data were publicly available or provided directly by ENV. Supplementary information collected through stakeholder engagement by ENV was also considered but is not summarized in Table 2.

Table 2: Summary of data sources.

Data Type	Description/Title	Reference
Map	Surficial Geology of the Shawnigan Lake Area (1:50,000)	Blyth, H.E., Rutter, N.W., and Sankeralli, L.M., 1993, Open File 1993-26, Ministry of Energy, Mines and Petroleum Resources Geological Survey Branch.
Map	Geology, Victoria, west of sixth meridian, British Columbia (1:100,000)	Muller, J.E., Geological Survey of Canada, "A" Series Map 1553A, 1983, 1 sheet
Geographic Dataset	British Columbia digital geology (1:250,000 to 1:50,000) including bedrock and faults	Cui, Y., Miller, D., Schiarizza, P., and Diakow, L.J., 2017. Open File 2017-8, Ministry of Energy, Mines and Petroleum Resources, B.C. Geological Survey.
Geographic Dataset	Topography and drainage (1:20,000)	Terrain Resource Information Management (TRIM) mapping
Geographic Dataset	Groundwater Wells and Aquifers database (GWELLS)	Provided by ENV December 2017
Geographic Dataset	Provincial mapped aquifers	B.C. Data Catalogue: WHSE_WATER_MANAGEMENT.GW_AQUIFERS_CLASSIFICATION_SVW
Geographic Dataset	Vulnerability mapping	B.C. Data Catalogue: WHSE_WATER_MANAGEMENT.GW_AQUIFER_VULNERABILITY_POLY
Geographic Dataset	Licensed springs	B.C. Data Catalogue: WHSE_WATER_MANAGEMENT.WLS_POD_LICENCE_SOURCES_SP
Geographic Dataset	Wetlands	B.C. Data Catalogue: WHSE_BASEMAPPING.TRIM_EBM_WETLANDS

2.2 GWELLS

A total of 3,741 well records currently exist in the Study Area from the Groundwater Wells and Aquifers database (GWELLS) (Figure 2). Data processing included standardizing units of measurement, correcting abbreviation and spelling entries, organizing well construction information (i.e., well tag number [WTN], well ID, coordinates, construction date, drilling method, well depth, lithology flag, well use, water supply name), and compiling water-related data (water level, yield, chemistry flag, transmissivity, storativity). Each well was assigned an elevation available from TRIM mapping. Raw lithology descriptions were processed into lithology keywords descriptors as outlined in Table 3.

A distinction between “clean” and “dirty” sand and gravel was included when processing the raw lithologies. Dirty materials were identified based on the use of fine grained adjective(s) in the raw lithology descriptions (e.g. silty). This was deemed important to facilitate delineation of hydrostratigraphic units, particularly when interpreting diamicton or till since it is often described as a mix of several textural classes.

Table 3: Lithology keywords

Geology	Lithology Keyword	
Bedrock	sedimentary	argillite
		conglomerate
		limestone
		sandstone
		shale
		siltstone
	igneous	basalt
		diorite
		granite
		volcanic
	metamorphic	marble
		quartzite
		schist
Unconsolidated	boulder	
	clay	
	fill	
	gravel	
	peat	
	sand	
	sand and gravel	
	sand and gravel (dirty)	
	silt	
	till	
Other	other	

2.3 Cross-Sections

Processed information from GWELLS was uploaded into Strater® to generate cross-sections used to develop a hydrostratigraphic framework for the Study Area. The key lithology terms for each well record were included in the cross-section profile and used to interpret hydrogeologic units (HGU). Adjustments were made to HGU interpretations using an iterative approach until a coherent hydrostratigraphic model was developed. Separate sets of cross-sections were prepared for bedrock and surficial materials to understand geology in relevant detail. Ground surface profiles and water levels are displayed where available.

The locations of bedrock cross-sections (discussed in Section 3.3.2) were selected to provide spatial coverage of the Study Area and to highlight the influence of the bedrock surface on surficial sediment. Bedrock keywords shown at well locations along the cross-section profile were not relied upon for hydrostratigraphic interpretation due to the lack of descriptors in the bedrock information (e.g. bedrock unit was not differentiated and typically described as "bedrock") as well as inconsistencies with existing bedrock mapping. Longer lateral and vertical extents were used for bedrock cross-sections compared to surficial cross-sections to capture the changes in bedrock formations, location of faults, and depth of available lithology data. Fracture zones were identified on bedrock cross-sections based on the interval where "fracture" was included in the raw lithology description. This provides a qualitative indication of the location of fracture zones but is not based on defect spacing or rock quality designations.

The locations of surficial cross-sections (discussed in Section 3.3.3) were selected primarily based on the thickness of surficial sediments, bedrock contours, and the boundaries of existing unconsolidated aquifers. The key lithology terms for surficial materials were used to interpret the lateral and vertical extents of HGUs. Interpretations of surficial geology included reference to existing surficial mapping and review of aerial photography.

2.4 Aquifer Mapping

The British Columbia Aquifer Classification System (BCACS) was developed for regional groundwater planning and management purposes. Descriptors related to well yield (i.e. low, moderate, high), depth to water (shallow, moderately shallow, moderately deep, deep), aquifer productivity (i.e. low, moderate, high), aquifer vulnerability (i.e. low, moderate, high), and aquifer water demand (i.e. low, moderate, high) used in this report are based on the Guide to Using the B.C. Aquifer Classification Maps for the Protection and Management of Groundwater (Berardinucci and Ronneseth 2002).

The CSM provides a simplified, three-dimensional understanding of the essential features of the physical hydrogeological system and its hydraulic behaviour in the Study Area, forming the basis for aquifer mapping. CSM development for the Study Area focused on stratigraphy and hydrostratigraphy but also includes other physical aspects (e.g. topography and drainage), likely groundwater flow directions, and potential recharge/discharge areas.

Bedrock and unconsolidated aquifers were delineated as part of CSM development. Aquifers were delineated based on available information with a focus on using physical and hydraulic boundaries where possible (e.g. groundwater divides or streamlines, geologic contacts or major surface water bodies). Mapped aquifers may extend beyond or include areas where registered wells do not currently exist; therefore, there is some uncertainty in aquifer boundaries, particularly for confined and bedrock aquifers. Thus, interpreted boundaries may be refined as additional information becomes available.

For the purpose of this study, mapping of bedrock aquifers was primarily based on bedrock type and topography. The limestone and crystalline bedrock aquifers have been grouped together. This was deemed appropriate given the limited limestone extents mapped within the Study Area and the mapping approach is focused on regional groundwater management. Bedrock structure (e.g. lineaments, faults, bedding planes and bedrock contacts) can influence the movement of groundwater in bedrock. Limited information is currently available on how mapped faults in the Study Area influence hydrogeology. As such, general conceptual geological models of fault zone hydrogeology for the different bedrock types based on Bense et al. (2013) were considered.

Unconsolidated aquifers were delineated based on topography, the interpolated thickness of unconsolidated material, overlying/underlying units, water levels, and the physical location of deposits within the Study Area. For example, unconsolidated material overlying a bedrock basin was grouped separately from unconsolidated material within a valley setting. Aquifers have been generally combined into aquifer systems due to the uncertainty associated with possible physical boundaries (e.g. major river) or hydraulic boundaries (e.g. groundwater divide).

2.5 Limitations

The aquifer mapping conducted as part of this study was at a level appropriate for Stage II mapping. It relied on existing data sources and did not include collection of new data.

The main data source was GWELLS. The quality of information and the current status of data in GWELLS has not been field verified. The completeness of well record information for the Study Area is uncertain as prior to enactment of the *WSA* in 2016, submission of well construction reports by drillers was voluntary in B.C. Some well records have limited information or conflicting data.

Aquifers have been delineated based on a combination of geologic and hydrogeologic information. Water levels and hydrology (surface-groundwater connections) were generally considered; however, Section 5 recommends additional data collection programs to refine the CSM presented in this study.

3. CONCEPTUAL SITE MODEL

3.1 Geologic History

A summary of the geologic history of the Study Area is presented below summarized from Clague (1981, 1989), Desjardins et al. (1994) and Massey (1988). Most of Vancouver Island consists of rocks of the 'Wrangellia Terrane', an assemblage of crust that originated far from what is now North America and docked (accreted) against the northwest margin of the continent about 100 million years ago. Wrangellian rocks can be broadly subdivided into:

1) a sequence of Devonian (ca. 370 million-year-old) marine and terrestrial volcanic rocks (Sicker and Buttle Lake groups);
2) a sequence of Triassic (ca. 220 million-year-old) marine volcanic rocks and limestone (Vancouver group); and
3) early Jurassic (ca. 200 million-year-old) terrestrial volcanic rocks (Bonanza Formation) and granitic rocks (West Coast Crystalline Complex).

Between about 85 and 65 million years ago, conglomerate, sandstone, and shale of the Nanaimo Group were deposited in nearshore and marine environments along the east margin of the Wrangellia Terrane.

The largely volcanic rocks of the Wrangellia Terrane were subject to metamorphism under moderate temperatures and pressures. They also were intensely fractured and faulted during their accretion against North America. In contrast, Nanaimo Group sedimentary rocks, which were folded and faulted subsequent to deposition, have not been subjected to elevated temperatures and pressures, and thus retain much of their original porosity.

In places Wrangellian Terrane and Nanaimo Group rocks are blanketed by sediments deposited during late Pleistocene (ca. 60,000 to 12,000 years ago) glaciations and, subsequently, during the Holocene or 'postglacial' geological epoch (the past 12,000 years). During at least two glacial cycles, thick glacier ice sourced mainly in the Coast Mountains to the north and east covered Vancouver Island and what is now the Salish Sea. When the cover of ice was greatest, the land surface was depressed to such an extent that the sea was relatively higher than it is today.

Dashwood Drift (Vancouver Island) or Semiahmoo Drift (Vancouver metropolitan area) sediments were deposited during a previous glaciation cycle (circa 50,000 to 60,000 years ago). In the Duncan-Cowichan Bay area, Dashwood Drift consists of till, gravel, sand, and glaciomarine clay and silt deposited on the glacially depressed lowland surface. Where present, these sediments are covered by younger glacial sediments. Their patchy distribution is the result of erosion during the interglacial period ('Olympia interglaciation') separating the Dashwood/Semiahmoo glaciation and the most recent (Fraser) glaciation.

Dashwood Drift is overlain by a unit of sand, silt, and gravel (Quadra Sand) ranging up to about 70 m thick. Quadra Sand was deposited by meltwater streams in front of glaciers advancing down what is now the Salish Sea during the early (or advance) phase of the Fraser Glaciation about 30,000 to 20,000 years ago. Quadra Sand was subsequently overridden and cannibalized by glaciers, and the glacially eroded remnants of the unit were mantled by Vashon till.

The last ice sheet in B.C. disappeared between about 16,000 and 11,000 years ago. As the Salish Sea became ice-free, the land surface in the Duncan-Cowichan Bay area was still depressed by the weight of the remaining ice, and it consequently was flooded by the sea. The sea surface in this area was about 150 m above present sea level. Sediments deposited on this flooded surface as the deglaciation progressed are termed Capilano Sediments. They include gravel, sand, and clayey silt. Capilano Sediments typically lie on Vashon till or, where that unit is missing, on Quadra Sand.

As deglaciation progressed, isostatic rebound occurred, accompanied by a rapid fall in sea level. The Salish Sea surface reached its present level about 12,000 years ago, at which time Capilano Sediments and Vashon till were subject to erosion. Since then, modern (Salish) sediments have accumulated on floodplains of present-day streams and the shoreline of the Salish Sea.

3.2 Topography and Drainage

The topography, surface water features, and major watersheds of the Study Area are shown in Figure 3. The elevation of the Study Area ranges from 0 to 840 metres above sea level (masl). The physiographic units within the Study Area include the Nanaimo Lowland which is flanked on the western side by the Vancouver Island Ranges. The Nanaimo Lowland is the low-lying land between elevations of 0 to 600 masl that consists of many low, cuesta-like ridges separated by narrow valleys (Holland 1976). The Vancouver Island Ranges rise to up to 840 masl within the Study Area.

Portions of the Cowichan and Victoria watersheds and a limited part of the San Juan River watershed fall within the Study Area. The largest streams in the Study Area are the Koksilah River and Shawnigan Creek. The Koksilah River originates in the Vancouver Island Ranges and flows north-easterly in a steep valley before entering a broader valley and discharging into Cowichan Bay. A southern section of Shawnigan Creek originates near the south end of the Study Area and flows north towards Shawnigan Lake. The northern section of Shawnigan Creek begins at the northeast end of Shawnigan Lake and flows in a general southeasterly direction towards Mill Bay.

There are eight major lakes in the area, with Shawnigan Lake being the largest. Shawnigan Lake is located centrally within the Study Area. It is a natural freshwater lake with an average depth of 12 m and a maximum depth of 52 m (Rieberger 2007). The water level of the lake is controlled by a dam on Shawnigan Creek (Rieberger 2007).

Saanich Inlet lies along much of the eastern extents of the Study Area. It is a glacial fjord eroded during the Pleistocene Epoch and has a characteristic “U-shaped” cross-section with steep sides and a broad flat floor. The fjord has a maximum depth of 234 m (Ocean Networks Canada 2018).

3.3 Hydrostratigraphy

3.3.1 Hydrostratigraphic Unit

The hydrostratigraphic column for the Study Area illustrating the age, stratigraphy, and corresponding HGU is presented in Figure 4. The hydrostratigraphic column was prepared with consideration of the geologic history of the region and refined through a review of available lithology information.

As shown in Figure 4, bedrock stratigraphy is based on the condensed group/suite geological unit designation (Sicker Group, Bonanza Group, etc.). The hydrostratigraphy has been separated into three HGUs to represent aquifers in sandstone, limestone, and crystalline bedrock.

Unconsolidated stratigraphy is based on Quaternary units described in Section 3.1. HGU units with permeable deposits have been designated as aquifers while non-permeable deposits are inferred to be aquitards. Stratigraphic units have been used to prepare cross-sections through the unconsolidated materials (Figure 5). HGUs have been used to delineate aquifer extents.

3.3.2 Bedrock

Bedrock Stratigraphy

Wrangellian Terrane rocks (Sicker, Buttle Lake, Vancouver, Bonanza groups, Westcoast Crystalline Complex) along with Island Plutonic Suite, Leech River Complex, and Nanaimo Group rocks are present in the Study Area (Figure 6). A description of each rock unit is provided below based on Cui et al. (2017).

Wrangellian Terrane rocks are located within the northern half and central portion of the Study Area. They are predominantly volcanic rocks. Basaltic volcanic rocks of the Duck Lake Formation of the Sicker Group are the oldest in the Study Area. The Duck Lake Formation includes pillowed and massive basalt flows, monolithic basalt breccia and pillow breccia, chert, jasper and cherty tuff, felsic tuffs, massive dacite and rhyolite, and magnetite-hematite-chert iron formation. The majority of mapped faults in the Study Area transect this bedrock type.

The extents of the Buttle Lake Group and the Vancouver Group rocks within the Study Area are relatively small. The Buttle Lake Group includes the Mount Mark Formation. This formation is composed of sedimentary rocks including massive crinoid limestone, bedded calcirudite and calcarenite, chert, cherty argillite and siltstone, and marble (Cui et al. 2017). Karst erosional feature are possible in these areas. Basalt of the Karmutsen Formation is the predominant rock type of the Vancouver Group. The Karmutsen Formation includes pillowed basalt flows, pillow breccia, hyaloclastite tuff and breccia, massive amygdaloidal flows, minor tuffs, as well as interflow sediment and limestone lenses.

The Bonanza Group is located centrally within the Study Area and includes massive amygdaloidal and pillowed basalt and andesite flows, dacites, rhyolite with green and maroon tuffs, feldspar crystal tuff, breccia, tuffaceous sandstone, argillite, pebble conglomerate, and minor limestone.

The Westcoast Crystalline Complex underlies most of the southern half of the Study Area. It ranges from Paleozoic to Jurassic in age and includes quartz diorite, tonalite, hornblende-plagioclase gneiss, quartz-feldspar gneiss, amphibolite, diorite, agmatite, gabbro, marble, and metasediments.

The Island Plutonic Suite in the northern half of the Study Area includes granodiorite, quartz diorite, quartz monozonite, diorite, agmatite, feldspar, and feldspar porphyry as well as minor gabbro and aplite.

The Leech River Complex has been mapped on the southern tip of the Study Area. The Leech River Complex consists of metamorphic and volcanic rocks primarily including greenstone, greenschist metamorphic rocks, and biomodal volcanic rocks.

The Nanaimo Group is present in the northeastern portion of the Study Area. The Nanaimo Group consists of non-metamorphosed sedimentary rocks deposited on top of the Wrangellia Terrane rocks during the Cretaceous Period. This group is composed of conglomerate, coarse to fine sandstone, siltstone, shale and coal.

Bedrock Faults

The locations of mapped faults within the Study Area are shown in Figure 6. Several faults have been mapped across different bedrock units in the Study Area. The San Juan fault is the largest fault in the Study Area. It extends in an easterly direction across the Study Area but regionally spans from northwest of Port Renfrew to south of Cowichan Bay. The San Juan Fault is a northeast-dipping thrust fault that marks the southern limit of Wrangellia (Muller 1983). Although probably inactive today, the San Juan Fault is a wide zone of fractured rocks that may convey water.

The concept of a fault zone is used to describe groundwater movement in the area of a fault (Bense et al. 2013). The fault zone refers to the volume of bedrock where permeability has been altered by fault-related deformation. The fault zone commonly includes a fault core surrounded by a damage zone. The fault zone can consist of an individual fault zone or a system of fault zones which can be segments of a larger scale fault structure (Bense et al. 2013).

Bedrock Surface

The majority of the Study Area has bedrock at or near ground surface, except for the northeastern portion where bedrock is overlain by unconsolidated sediments. A bedrock surface map (Figure 6) was created using lithology information from GWELLS and surficial mapping to inform Stage II mapping (not intended for modeling). Wells where bedrock was encountered were filtered to gather point data to delineate the bedrock surface. Elevation point data from TRIM datasets within areas mapped as bedrock outcrops or bedrock covered by a veneer of surficial material were also used. Additional control points were added to ensure the bedrock surface extended below unconsolidated deposits using automated methods that would require further review to refine the bedrock surface for groundwater modeling purposes. Kriging techniques within Surfer® were used to produce a gridded bedrock surface at a 20 m resolution. The bedrock surface was also corrected to be at least 1 m below the existing ground surface in areas where insufficient point data existed to constrain interpolation. Data deemed erroneous (e.g. outliers) were removed and the bedrock surface was re-interpolated. The review of potentially erroneous data points was limited to the most obvious occurrences appropriate for the scope of the Stage II mapping presented herein.

The bedrock surface (Figure 6) is highly irregular and ranges in elevation from -100 to 840 masl. The bedrock surface is inferred to have been deepened and modified through erosion by glaciers and controlled by faults, with minor influence from pre-Pleistocene uplift (Holland 1976).

In the western portion of the Study Area, the Koksilah River has deeply incised bedrock along the mapped San Juan Fault. A localized bedrock depression is present in the Shawnigan Lake area. Near the east arm of Shawnigan Lake, an inferred bedrock valley slopes towards Mill Bay. An east-west trending bedrock ridge is located north of this bedrock valley between Mill Bay and Cobble Hill. The bedrock ridge is mantled by unconsolidated sediments.

North of the bedrock ridge and east of the pre-Cretaceous bedrock is a low-lying basin generally below 20 masl. This basin coincides with sedimentary rocks of the Nanaimo Group which are softer and thus have undergone more erosion than the pre-Cretaceous bedrock found at higher elevations.

Bedrock Cross-Sections

A total of seven (7) bedrock cross-sections were prepared (Appendix A) with locations shown on Figure 5. Bedrock cross-sections were prepared to show the distribution of the different rock groups in the Study Area, identify fracture zones, and to highlight the influence of the bedrock surface on surficial sediments. The three cross-sections aligned in a north-south direction are labeled BNS1 through BNS3, while the four cross-sections aligned in a west-east direction are labeled BWE1 through BWE4.

BNS1 is the longest cross-section and crosses several pre-Cretaceous bedrock groups. The bedrock surface begins near a local bedrock low, intersects the Koksilah River valley, and then is relatively flat in the area of Shawnigan Lake. The bedrock surface begins to rise at the southern end of Shawnigan Lake.

BNS2 shows the bedrock profile near the boundary of the pre-Cretaceous rocks and the Nanaimo Group. The surface of the Nanaimo Group is the lowest and generally the flattest in the cross-section. Unconsolidated sediments that overlie bedrock in the northern and southern portions of the cross-section are separated by a local bedrock high. The most-easterly north-south cross-section, BNS3, shows the low-lying Nanaimo Group surface overlain by glacial deposits and the bedrock ridge that separates these deposits further south.

BWE1 crosses the north end of the Study Area and shows a local bedrock low within the pre-Cretaceous bedrock and then the low-lying surface of the Nanaimo Group. The surface of the Nanaimo Group slopes to the east with a progressively thicker cover of unconsolidated deposits to the east. BWE-2 begins within the Koksilah River valley and shows a relatively thin cover of unconsolidated deposits until the Nanaimo Group is reached. Unconsolidated deposits are over 100 m thick in a bedrock depression of relatively low relief in the Nanaimo Group. The surface of the Nanaimo Group steepens towards Saanich Inlet near the east end of the cross-section.

BWE3 is the longest west-east cross-section and is aligned centrally within the Study Area. The bedrock surface drops from 140 masl in the west to approximately 40 masl in the east along this cross-section. The San Juan fault is intersected several times along the cross-section. The movement of the fault is inferred to create abrupt changes in the bedrock surface that have been covered by glacial sediments. This cross-section also highlights erosion of the bedrock surface near the east arm of Shawnigan Lake, showing a general decreasing slope of the surface towards Saanich Inlet.

BWE4 is the most southerly west-east cross-section. It highlights the vertical range in the bedrock surface within the Study Area from approximately 590 masl in the west to 10 masl in the east. Unconsolidated deposits cover the north slope of a local bedrock high that slopes towards Saanich Inlet.

Fracture zones are shown on the bedrock cross-sections. The distribution and extent of the fracture zones are based on raw lithology descriptions provided in well records as described in Section 2.3; therefore, representation may be limited but this provides an initial indication of bedrock quality. Fracture zones were primarily identified for pre-Cretaceous bedrock. Limited fracture zones were identified in the Nanaimo Group, potentially due to the drilling method or relatively small fracture size, but they likely exist. A relatively high number of fracture zones are present in the area of Shawnigan Lake which also coincides with the locations of several faults (BNS1, BWE3).

3.3.3 Unconsolidated Material

Surficial Geology

A brief overview of the surficial map of Blyth et al. (1993) shown in Figure 8 is provided below. A large portion of the Study Area is mountainous with bedrock at surface (bedrock outcrop, R) or covered by a veneer of colluvium (Cv) or till (Mv). Dashwood Drift, the oldest unconsolidated material in the Study Area, is not known to be present at the ground surface but does occur locally at depth.

Glaciofluvial sand and gravel (sgFGf) that typically underlies till are inferred as Quadra Sand (Figure 8). Near the downstream end of the mountainous section of Koksilah River valley, the steep slopes are blanketed by postglacial colluvium. This colluvium overlies glaciofluvial gravels along both banks (Cb/sgFG) and is inferred to be fluvial/deltaic Capilano Sediments.

The Vashon till and marine deposits associated with the Capilano Sediments have been combined into one hydrostratigraphic unit inferred as a regionally extensive aquitard. Although Blyth et al. (1993) seem to interpret these sediments as glaciolacustrine, they are believed to be glaciomarine. This stratigraphic unit consists of hummocky diamicton interspersed with glaciolacustrine silts and clays (dMbh/$LGp)

(Figure 8). Glaciolacustrine clays and silts that overlie fluvial sands and gravels mapped at the northern end of the Koksilah River and lacustrine silts mapped along the eastern bank of the Koksilah River ($LGp) have been grouped into this hydrostratigraphic unit based on the understanding these sediments are of a marine origin.

Fluvial and deltaic Capilano Sediments and postglacial Salish fluvial sediments have been combined into one hydrostratigraphic unit based on the fact that they are permeable and could serve as an aquifer. Fluvial sands and gravels are present along most of the Koksilah River (sgF).

Unconsolidated Material Thickness

An isopach showing the thickness of unconsolidated material in the Study Area is shown in Figure 9. Thicknesses were determined by subtracting the interpolated bedrock surface (Figure 7) from the ground surface (Figure 3). Areas with thick surficial materials were targeted for more detailed interpretation since they have the greatest potential for the presence of unconsolidated aquifers.

As shown in Figure 9, surficial deposits typically are thickest (up to 100 m) and most extensive in the northeastern section of the Study Area where they overlie eroded Nanaimo Group sedimentary bedrock. These deposits are bounded by the rising slope of pre-Cretaceous rock to the west.

Relatively thick (up to 60 m) surficial deposits are also inferred near the north-east arm of Shawnigan Lake, within the bedrock valley that slopes towards Saanich Inlet (Figure 7). Pockets of unconsolidated material exist on the north side of Mount Wood, within local bedrock valleys. In addition, unconsolidated sediment underlies the downstream end of the mountainous section of the Koksilah River valley.

Other areas where more than 5 m of surficial deposits have been inferred are speculative and based on the difference in elevation between the bedrock and ground surface topography. These areas do not have wells or other geologic information by which the sediment thickness could be confirmed. There may also be areas within the Study Area that have considerable unconsolidated deposits that have not been identified due to a lack of data.

Unconsolidated Cross-Sections

A total of 13 cross-sections focusing on unconsolidated deposits have been prepared (Appendix B) with locations shown on Figure 5. Unconsolidated cross-section locations were selected to visualize the spatial relationship of aquifers and aquitards and the influence of the bedrock surface on this distribution. The cross-sections aligned in a north-south direction are labeled UNS1 through UNS7, and the west-east cross-sections are labelled UWE1 through UWE6. A description of the lateral and vertical distribution of stratigraphic units summarized by geographical location (Northeast Bedrock Depression, East of Shawnigan Lake, and Koksilah River) is provided below.

Northeast Bedrock Depression

The Northeast Bedrock Depression is coincident with the spatial extent of the Nanaimo Group in the northeast section of the Study Area and includes the thickest unconsolidated deposits in the Study Area (Figure 7). Cross-sections prepared for this area include UNS1, UNS2, UNS3, UWE1, UWE2, UWE3, and UWE4. Based on the cross-sections, the unconsolidated materials within this area are contained within a basin where bedrock elevations range from approximately -10 masl on the northwest to approximately 65 masl on the southeast. The deposits are bordered by pre-Cretaceous rocks along the western extent and by Saanich Inlet to the east.

Dashwood Drift typically is present below 40 masl and overlies bedrock. This unit has been eroded during the interglacial period (Olympia interglaciation) separating the Dashwood/Semiahmoo glaciation and the most recent (Fraser) glaciation. Sand and gravel is interbedded within till or in some places is inferred to be in contact with the Quadra Sand unit (UNS1). The lateral and vertical distribution of Dashwood sand and gravel is variable and inferred to be discontinuous (UNS1, UWE1, UWE2).

A large erosional remnant of the Quadra Sand unit underlies a whaleback-shaped ridge that is located in the Northeast Bedrock Depression. Quadra Sand is interpreted to overlie the Dashwood Drift. The Quadra Sand unit is up to 70 m thick in some areas (UNS3), thinning to approximately 10 m in the north (UNS1) and south (UNS3).

The Capilano/Vashon till unit is interpreted to cover most of the Quadra Sand unit in the area. The thickness of marine Capilano Sediments is relatively thin (< 5 m) but combined with the Vashon till the total thickness can reach 40 m (UNS1, UNS2, UWE1, UWE3). A number of springs occur in this area (Figure 3), suggesting that water from the saturated zone of the Quadra Sand can discharge to the surface.

East Shawnigan Lake

East Shawnigan Lake includes the eroded bedrock surface extending from near the east arm of Shawnigan Lake to Saanich Inlet, north of Mount Wood. Cross-sections UNS4, UNS5, and UWE5 have been prepared for this area.

The bedrock topography has the shape of a bowl ranging in elevation from 120 masl in the west to 15 masl in the east (UWE5) and from approximately 70 m in the north (UNS3) to 150 masl in the south (UNS4). The hummocky ground surface in this area is the result of glacial infilling of the bedrock surface (UWE5). Dashwood Drift is up to 30 m thick (UWE5) and overlies bedrock in most cross-sections. At higher elevations it is either thin or absent. Quadra Sand is approximately 10 to 20 m thick. Capilano/Vashon till can be up to 30 m thick (UNS5) but is typically less than 5 m thick or inferred to be absent (UNS4, UWE5). Deltaic or fluvial deposits of the Capilano and Salish sediments are present at elevations up to 150 masl (UNS4), which is inferred to be the maximum elevation reached by the sea after glacial retreat.

Koksilah River Valley

The upper Koksilah River Valley is bordered by areas where bedrock either is exposed at the surface or covered with a veneer of colluvium. Within the valley, Holocene-age fluvial sand and gravel deposits are present where the valley widens. Where the valley bottom is narrow, Holocene fluvial sediments are patchy and thin and the Koksilah River is interpreted to flow over bedrock.

3.4 Groundwater Flow

Flow in Bedrock

Groundwater flow occurs through sedimentary and crystalline bedrock units in the Study Area. Sandstone and conglomerate of the Nanaimo Group are expected to act as aquifers with groundwater flow occurring through intergranular pore spaces and bedrock deformities (e.g. fractures, bedding planes). Limestone and calcareous bedrock of the Vancouver Group (Quatsino Formation) and the Buttle Lake Group can have similar permeability to sandstone, but subsequent dissolution can cause a range of solution openings (e.g. widened joints to caverns) that increase porosity and enhance permeability.

Crystalline bedrock of the Island Plutonic Suite and Westcoast Crystalline Complex as well as volcanic bedrock of the Vancouver Group (Karmutsen Formation), Sicker Group, and the Bonanza Group generally have relatively low permeability with the majority of groundwater flow occurring along faults and fractures.

The impact of faults on groundwater flow in different bedrock units is complex and can be wide-ranging. Limited information is available on how mapped faults in the Study Area impact groundwater movement. As such, a general overview of fault zone hydrogeology based on Bense et al. (2013) is provided below.

Fault zones can act as barriers, conduits, or a combination of conduit-barrier systems to groundwater flow. Fault zone processes that impact permeability include particulate flow, fracturing, brecciation, sediment mixing/clay smear, and cataclasis (breakage of grains). Larger-scale processes that influence permeability in the fault zone include compaction, cementation, dissolution, and regional stress conditions in the bedrock.

In the absence of open-fracture networks, fault zones in sandstone are likely to behave as a barrier to groundwater flow because of reduced permeability due to cataclasis in both the fault core and damage zone (see Section 3.3.2). Faults in crystalline, volcanic, and carbonate bedrock behave similarly to conduit-barrier systems where the damage zone typically has a higher permeability compared to the fault core. The main fault processes are typically brecciation or cataclasis in the fault core and fracturing in the damage zone. Fault processes in volcanic bedrock may be accompanied by mineralization. Faults cutting through carbonate bedrock have a wider-range of hydrogeological behaviours and will often be dominated by secondary dissolution and precipitation processes.

Groundwater flow rates within bedrock fracture zones are expected to be rapid compared to flow within surficial deposits. The majority of groundwater flow in bedrock aquifers usually occurs within 100 m of the surface (WorleyParsons 2009). If fault systems represent groundwater flow pathways, sub-regional and regional groundwater flow may also occur at depths of hundreds of metres and across adjacent surface watersheds.

Flow in Unconsolidated Material

The oldest unconsolidated deposits in the Study Area are associated with the Dashwood Drift. Dashwood till and clay layers are expected to act as aquitards while interbedded sand and gravels form aquifers. The Quadra Sand is an aquifer but may potentially be saturated only at lower elevations or where it is underlain by Dashwood Drift low permeability materials. Marine Capilano deposits and Vashon till are inferred to be aquitards. Unconfined aquifers within the Study Area are typically associated with deltaic and fluvial deposits within the Capilano and Holocene sediments.

Groundwater flow patterns in surficial aquifers largely mirror topography and/or are controlled by bedrock topography, flowing from areas of higher elevation to areas of lower elevation. Faults have been mapped below unconsolidated sediments located in the Nanaimo Group basin (Figure 6). Fault zones may behave as combined conduit-barrier systems due to sand and/or clay smearing in the fault core with minimal impact on permeability within the damage zone (Bense et al. 2013).

3.5 Recharge and Discharge

A quantitative review of recharge mechanisms for the area are provided in Harris and Usher (2017). A brief overview of key recharge and discharge concepts for the Study Area are presented below.

Groundwater recharge is expected to occur where water flowing over the exposed bedrock surface or within the veneer of colluvium on bedrock encounters near-surface expressions of fracture zones. Groundwater recharge of surficial aquifers can occur by infiltration of precipitation as well as irrigation in agricultural areas); however, this may be limited by the marine Capilano Sediments and Vashon till units. Local infiltration rates can vary depending on the degree of weathering of surficial materials (e.g. fractures in till). Recharge could also occur via mountain block recharge, leakage between layered unconsolidated aquifer systems, leakage from surface waterbodies and watercourses, and/or from underground sources where coarse-grained sediments are in direct contact with discharging bedrock fracture zones. Generally, only a portion of total precipitation results in groundwater recharge primarily due to evapotranspiration, runoff, and storage in the vadose zone.

Groundwater discharge is usually detectable as base flow in creeks, as linear seepage zones or spring lines on hillsides, and as ponds, lakes, or wetlands in low-lying surface depressions.

4. UPDATED AQUIFER MAPPING

4.1 Bedrock Aquifers

A total of four bedrock aquifers have been updated in the Study Area as shown in Figure 10 with details summarized in Table 4. Aquifer summary reports are provided in Appendix C. Bedrock aquifer mapping covers the majority of the Study Area. Faults are represented in bedrock mapping as areas of enhanced permeability. This interpretation needs to be field verified.

4.2 Unconsolidated Aquifers

A total of five unconsolidated aquifers have been updated in the Study Area as shown in Figure 11 with details summarized in Table 4. Aquifer summary reports are provided in Appendix C. Aquifers within unconsolidated sediments are present along the east edge of the Study Area adjacent to the coast and in the Shawnigan Lake area.

Table 4: Updated aquifer mapping summary

#	Name	Descriptive Location	Litho - Stratigraphic Unit	Vulnerability (1)	Subtype (2)	Materials	Quality Concerns (3)	Quantity Concerns (4)	Artesian Conditions	Observation Well Number (Active)
198	Cowichan Bay	Includes Cowichan Bay, Cowichan Station, Hillbank, and Fairbridge	Sedimentary Bedrock	C	5a	Bedrock	Some	Unknown	Yes	
202	Koksilah River Valley	Upgradient Koksilah River Valley	Crystalline Bedrock	B	6b	Bedrock	Some	Unknown	Yes	
203	Shawnigan Lake/ Cobble Hill/ Mill Bay	Includes Shawnigan Lake area, Cobble Hill, and Mill Bay	Crystalline Bedrock	B	6b	Bedrock	Some	Local	Yes	380, 439, 470
208	Malahat Ridge	East and south slope of Malahat Ridge	Crystalline Bedrock	B	6b	Bedrock	Unknown	Unknown	No	
197	Cherry Point	Includes Cowichan Bay, Cowichan Station, Hillbank, Cherry Point, and Dougan Lake	Quadra Sand/ Dashwood Drift	B	4b	Sand and Gravel	Some	Regional	Yes	233, 320, and 345
199	Fairbridge	West of Koksilah River, includes Fairbridge	Quadra Sand/ Dashwood Drift	B	4b	Sand and Gravel	Unknown	Unknown	Yes	
201	Heather Bank	West slope of Cobble Hill, along the east banks of the Koksilah River	Quadra Sand/ Dashwood Drift	A	4a/b	Sand and Gravel	Some	Unknown	No	
205	Shawnigan Lake	Shawnigan Lake area	Quadra Sand/ Dashwood Drift	A	4a/b	Sand and Gravel	Some	Local	No	
206	Mill Bay	Includes Mill Bay and Cobble Hill	Quadra Sand/ Dashwood Drift	A	4a/b	Sand and Gravel	Some	Local	Yes	

Notes:

1) A – high vulnerability, B – moderate vulnerability, C – low vulnerability to surface contamination.
2) Aquifer subtype description available through the B.C. Data Catalogue https://catalogue.data.gov.bc.ca
3) Based on available information. A more detailed review of water quality data would be required to understand water quality concerns.
4) Water budget studies are required to better understand water availability.

5. RECOMMENDATIONS

Based on the Stage II aquifer mapping study for the Shawnigan Water Precinct, beneficial next steps towards further hydrogeological characterization within the Study Area are identified below to support sustainable groundwater management.

5.1 Regional Groundwater Observation Network

There are currently six active provincial groundwater observation wells within the Study Area, in addition to an unknown number of monitoring sites operated by municipal water systems, and private well owners. Coordination at the regional level would provide a long-term data resource upon which groundwater management within the Shawnigan Lake Area could be founded, including:

a. Establishing/monitoring the amount of groundwater present in the aquifer system such that:
   i. expected trends and/or annual cycles in water levels can be tracked and thereby be confirmed for ongoing sustainability verification purposes;
   ii. if there are any unexpected changes in water levels or water level trends, they could be detected early, thus facilitating informed forward planning and/or decision-making; and
   iii. understanding decadal to sub-centennial variability and climate change impacts on the hydrologic cycle to inform decision-making and to manage variability in water availability.

b. Periodic upgrading of the conceptual hydrogeological model facilitated by ongoing data acquisition, thus providing a sound basis upon which to conduct forward planning and/or decision-making.

c. Confirming the temporal stability of key naturally-occurring hydrochemical constituents at the aquifer level provides:
   i. sentinel monitoring of water quality within the aquifer, allowing an appropriate response to changes in water quality and planning for water management; and
   ii. identification of any emerging natural variability in regional water quality.

5.2 Geological Characterization

In addition to drilling programs that could be conducted as part of expanding the existing regional groundwater monitoring network, the following specific studies would provide additional geological information to enable further refinement of the geological conceptual model.

a. Influence of faults on the groundwater flow regime: Targeted drilling of monitoring wells that intersect select fault zones, followed by hydraulic testing (e.g. packer tests) and geophysical logging (e.g. acoustic televiewer, flowmeter, temperature, and fluid conductivity) could be used to establish the role of faults in the local flow system.

b. Characterization of fracture systems in bedrock: Characterization of fractures would inform the conceptual understanding of potential water resources in areas of prospective bedrock aquifers. A characterization program could include lineament mapping (for bedrock outcrop areas), drilling, hydraulic testing, and geophysical logging to understand the distribution, density, aperture and orientation of fracture networks and potential hydraulic connectivity between fracture networks. Some existing well records include estimates of yield from fracture intervals. A statistical review of this data could be completed to identify factors that influence bedrock aquifer productivity (e.g. topographic location, distance to faults, bedrock type) and to provide direction for a broader characterization program.

c. Nanaimo Group bedrock surface: The Nanaimo Group bedrock surface is interpolated using lithology data from GWELLS. Further review of control points used to create this surface is required prior to use in a groundwater model. Where well data is sparse, seismic surveys could be used to map the bedrock surface, as a change in seismic velocity can be expected between the unconsolidated sediment and bedrock.

d. Establishment of local/regional stratotypes would facilitate interpretations of geology in a more consistent manner.

5.3 Hydrogeological Characterization

The conceptual hydrogeological model indicates general linkages along groundwater flow paths, between adjacent aquifers, and between groundwater and surface water within the Study Area. Refining this understanding would provide information to support protection of groundwater resources.

a. Geochemical Studies: The Stage II aquifer mapping has been conducted based on hydrostratigraphic interpretations. This geologically based interpretation would be enhanced by geochemical studies that could include the collection and analysis of groundwater and surface water samples for major ions as well as oxygen and hydrogen isotopes. Geochemical studies that include analysis of chloride, sodium, and boron could also advance understanding of any impacts on groundwater quality from saltwater intrusion.

b. Groundwater/Surface water interactions: The Koksilah River and Patrolas Creek are two key surface water features in the Study Area that have been studied with respect to water quality and quantity (Ministry of Environment and Parks 1986, Dessouki 2010, Smorong and Epps 2014). In addition, significant drainage areas within the Study Area identified in ENV (2006) include: Garnet Creek, Manley Creek, Shawnigan Creek, Johns Creek, Spectacle Creek, Bamber Creek, Irving Creek, and Arbutus Creek. A more detailed review of existing information for these creeks is recommended to provide an improved understanding of the groundwater flux to surface water bodies (or vice versa). Ideally field data are available to determine groundwater recharge/discharge zones along the surface water features (minimum two gauge stations required) to support numerical model development.

c. Groundwater discharge zones: Springs have been observed in the Study Area. Confirmatory mapping of these springs and the spatial association of the springs with geologic units would allow a clearer understanding of the discharge zones from bedrock aquifers and the potential interconnection between bedrock and unconsolidated aquifers. Under the right conditions, drone-based thermal sensors can facilitate rapid mapping for seeps, however, vegetation present in the area may inhibit their use.

d. Consistency/continuity in aquifer mapping: Bedrock aquifers AQ196, AQ200, AQ204, AQ207 and unconsolidated aquifer AQ199 are now obsolete. A detailed review of unconsolidated aquifers AQ185, AQ186, AQ187, and AQ188 is recommended to provide consistency/continuity in the aquifer mapping approach to the north of the Study Area.

5.4 Sustainable Groundwater Management

Groundwater is an important water supply and environmental resource that is likely to come under increasing development pressure. Sustainable groundwater management will be an important aspect in the future to secure development in the region. Two detailed studies related to water balance have already been completed for the area to support sustainable groundwater management efforts (van der

Gulik et al. 2013, Harris and Usher 2017). The following additional activities would support the goal of establishing optimum sustainable groundwater resource utilization in the Study Area.

a. Construction of an integrated groundwater/surface water model to determine water budgets and support water allocation, particularly for the unconsolidated aquifers. Hydrostratigraphic units defined in this report can form the basis for groundwater model construction.

b. A calibration dataset is required for numerical model development. GWELLS contains water levels, transmissivity, and storativity values. This information can be used as a starting point for the calibration dataset. However, refinement of the conceptual model based on recommendations provided in Section 5.1 to 5.3 as well as a current water level dataset to support generation of potentiometric contours for each hydrostratigraphic unit is recommended prior to or as part of compiling the calibration dataset.

c. The proposed model could be used to assess future water availability and sustainability for the Shawnigan Water Precinct. Such an assessment could include an analysis of future growth projections and the potential changes to the hydrologic cycle associated with climate change. This assessment would provide valuable information about projected future groundwater availability.

d. The unconsolidated and bedrock aquifers bordering Saanich Inlet, Satellite Inlet and Cowichan Bay may be susceptible to saltwater-intrusion because of groundwater extractions. Understanding this vulnerability would allow adaptive management for sustainable groundwater development. Existing saltwater intrusion could be mapped using electrically based geophysical techniques which would be sensitive to the contrast in the pore water electrical conductivity associated with fresh versus saline pore water. A groundwater flow model can substantially support the sustainable management of a coastal aquifer.

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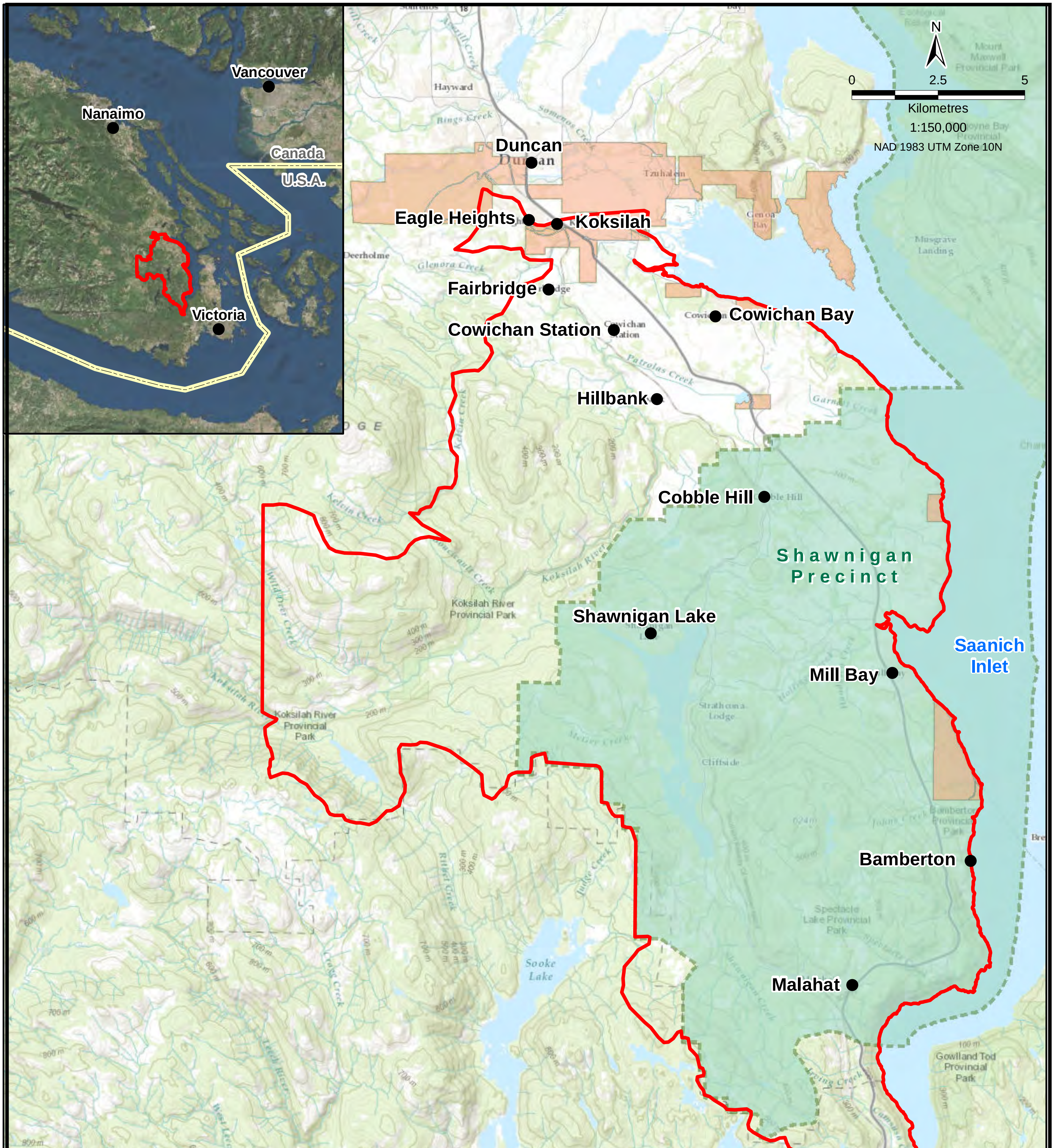
FIGURES



MINISTRY OF ENVIRONMENT

STAGE II DETAILED MAPPING STUDY

STUDY AREA LOCATION

BRITISH COLUMBIA Ministry of Environment and Climate Change Strategy	Date: 01-MAY-18	Drawn by: AM	Edited by: AM	App'd by: ZH
	Advisian WorleyParsons Group		WorleyParsons Project No. 307071-01251	
			FIG No 1	REV 0

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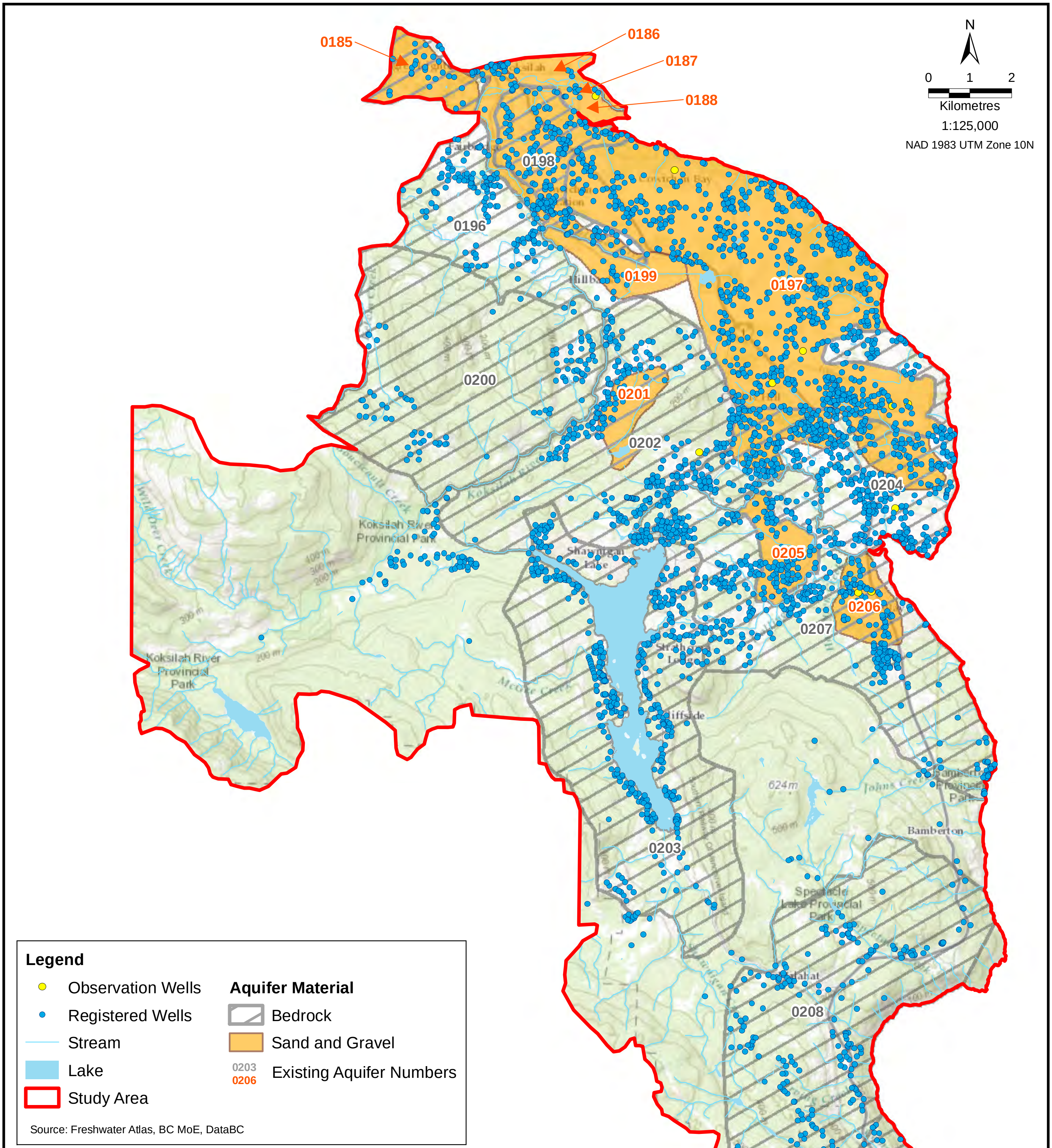
FILE LOCATION: U:\YVR\307071\01251_BCME_GeoInAqMa\10_Eng\16_Geomatics\01_Mxd\StageII_Detailed_Mapping_Study\2018-02-21_Fig1_Study_Area_Location.mxd

SAVE DATE & TIME: 01/05/2018 10:37:13 AM

ISSUING OFFICE: BURNABY GIS

Imagery Source: Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, © OpenStreetMap contributors, and the GIS User Community
Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community



MINISTRY OF ENVIRONMENT
STAGE II DETAILED MAPPING STUDY

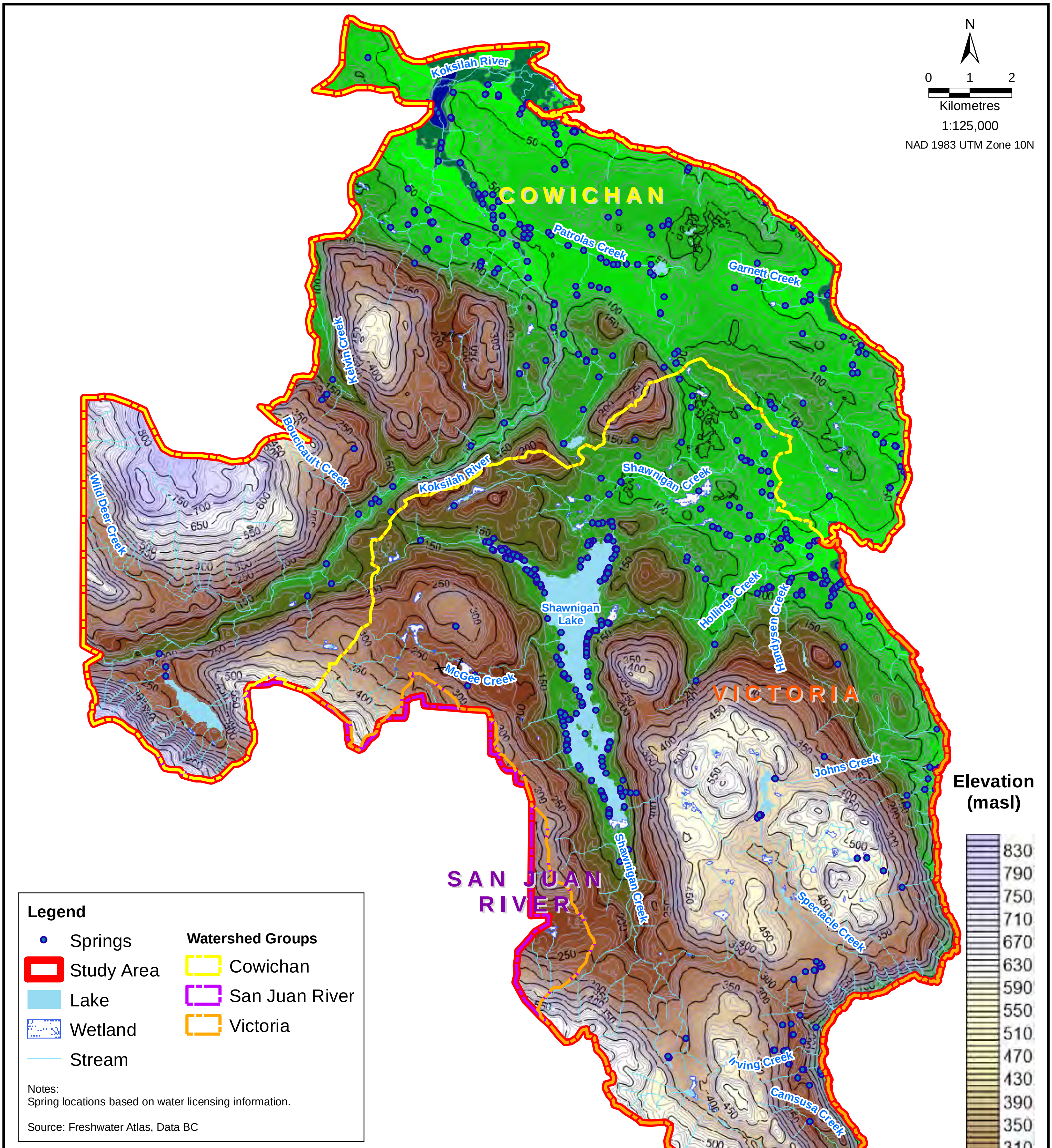
REGISTERED WELLS AND EXISTING MAPPED AQUIFERS

Date: 01-MAY-18	Drawn by: AM	Edited by: AM	App'd by: ZH
BRITISH COLUMBIA Ministry of Environment and Climate Change Strategy	Advisian WorleyParsons Group	WorleyParsons Project No. 307071-01251	
		FIG No 2	REV 0

FILE LOCATION: U:\YVR\307071\01251_BCME_GeolnAqMa\10_Eng\16_Geomatics\01_Mxd\StageII_Detailed_Mapping_Study\2018-02-21_Fig2_Registered_Wells_and_Existing_Mapped_Aquifers.mxd

SAVE DATE & TIME: 01/05/2018 11:01:48 AM

USER NAME: ashling.mulcahy
ISSUING OFFICE: BURNABY GIS



MINISTRY OF ENVIRONMENT
STAGE II DETAILED MAPPING STUDY

TOPOGRAPHY AND DRAINAGE

Date:	09-JAN-19	Drawn by:	AM	Edited by:	AM	App'd by:	ZH

British Columbia Ministry of Environment and Climate Change Strategy

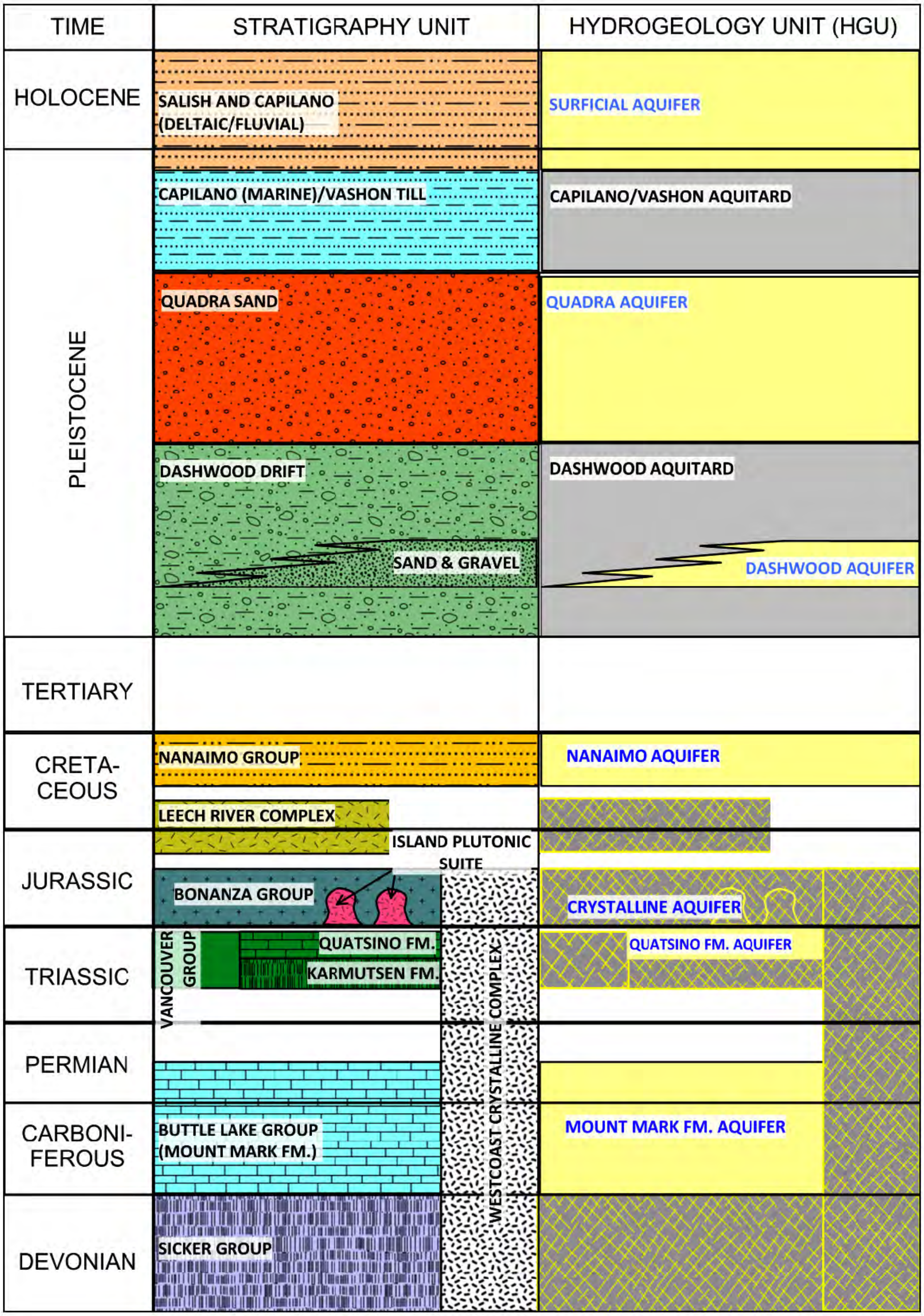
Advisian WorleyParsons Group

WorleyParsons Project No. 307071-01251

FIG No 3 REV 0

FILE LOCATION: U:\YVR\307071\01251_BCME_GeoInAqfMa\10_Eng\16_Geomatics\01_Mxd\StageII_Detailed_Mapping_Study\2019-01-08_Fig3_Topography_and_Drainage.mxd

USER NAME: Ashling.Mulcahy
ISSUING OFFICE: BURNABY GIS
SAVE DATE & TIME: 09/01/2019 8:14:46 AM



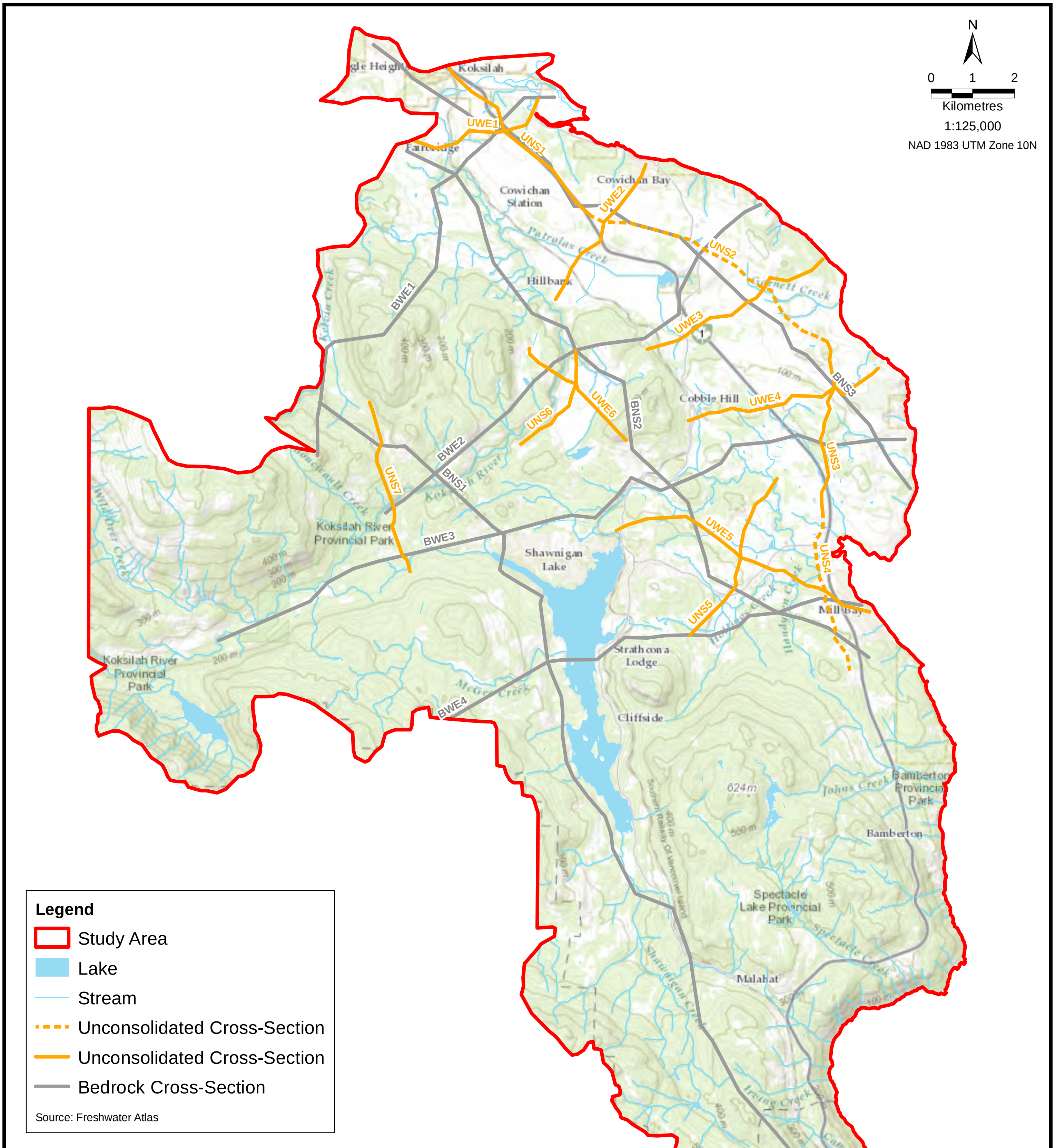
MINISTRY OF ENVIRONMENT
STAGE II DETAILED MAPPING STUDY

HYDROSTRATIGRAPHIC COLUMN

Date: 06-MAY-18	Drawn by: AM	Edited by: ZH	App'd by: ZH
Advisian WorleyParsons Group		WorleyParsons Project No. 307071-01251	
		FIG No 4	REV 0

BRITISH COLUMBIA Ministry of Environment and Climate Change Strategy

FILE LOCATION: \\WorleyParsons.com\CA\Data\YVR\307071\01251_BCME_GeoInAqfMa\10_Eng\16_Geomatics\01_Mxd\StageII_Detailed_Mapping_Study\2018-06-05_Fig4_Hydrostratigraphic_Column.mxd
SAVE DATE & TIME: 06/05/2018 8:13:24 PM
USER NAME: zidra.hammond
ISSUING OFFICE: BURNABY GIS



MINISTRY OF ENVIRONMENT
STAGE II DETAILED MAPPING STUDY

CROSS-SECTION LOCATION PLAN

Date: 01-MAY-18	Drawn by: AM	Edited by: AM	App'd by: ZH
Advisian WorleyParsons Group		WorleyParsons Project No. 307071-01251	
		FIG No 5	REV 0

BRITISH COLUMBIA Ministry of Environment and Climate Change Strategy

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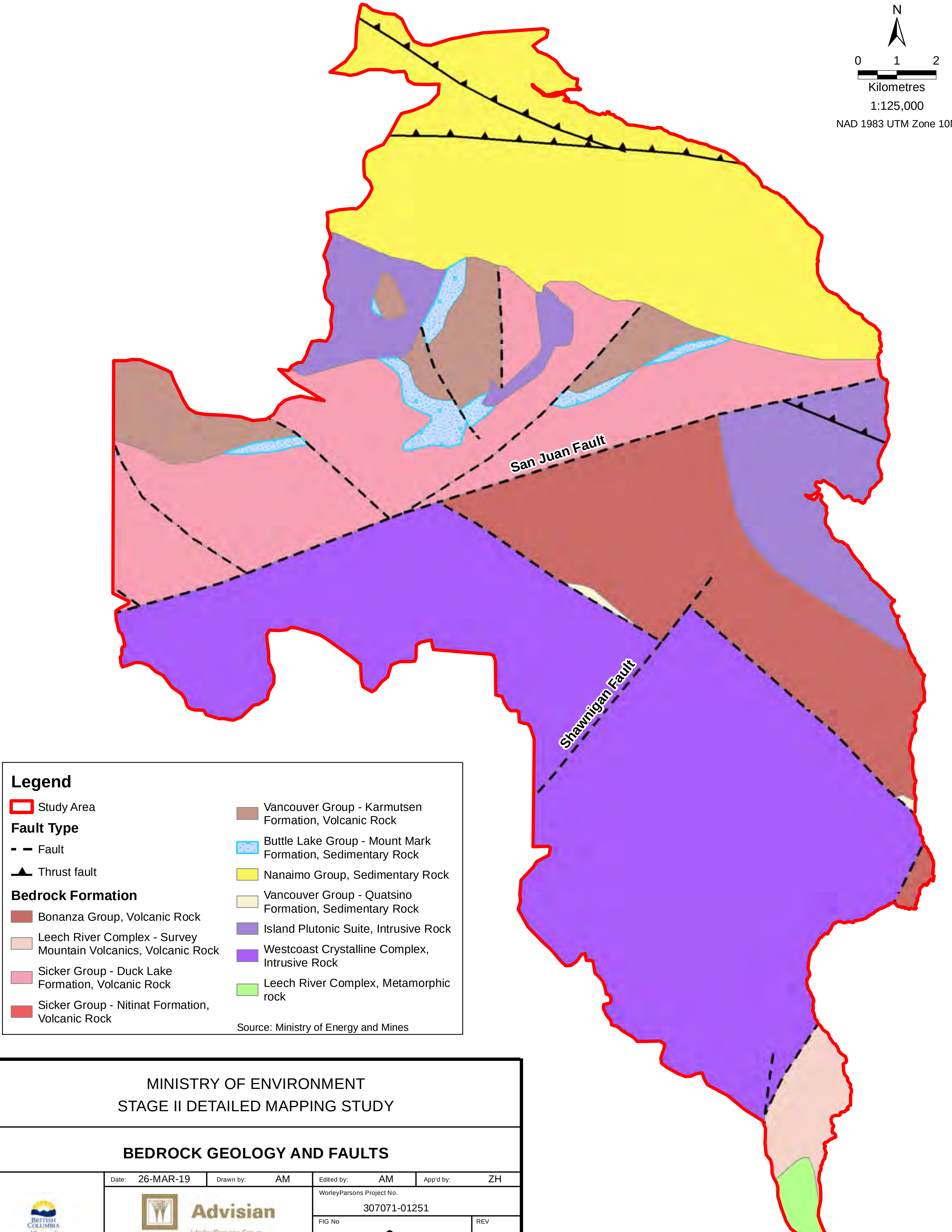
FILE LOCATION: U:\YVR\307071\01251_BCME_GeoInAqfMa\10_Eng\16_Geomatics\01_Mxd\StageII_Detailed_Mapping_Study\2018-03-05_Fig5_Cross_Section_Location_Plan.mxd

SAVE DATE & TIME: 01/05/2018 11:09:36 AM

USER NAME: ashling.mulcahy
ISSUING OFFICE: BURNABY GIS



MINISTRY OF ENVIRONMENT

STAGE II DETAILED MAPPING STUDY

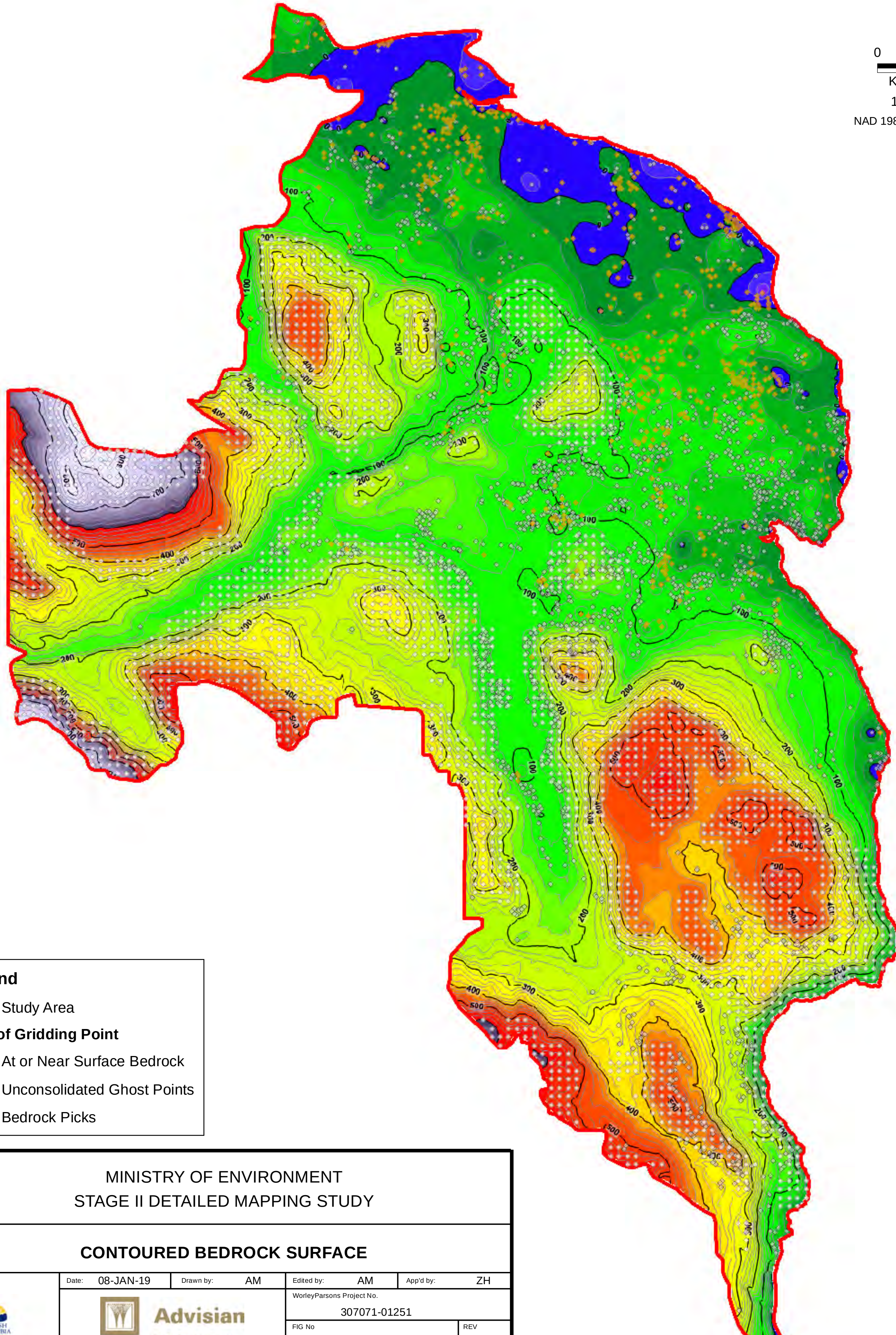
BEDROCK GEOLOGY AND FAULTS

Date: 26-MAR-19	Drawn by: AM	Edited by: AM	App'd by: ZH
Advisian WorleyParsons Group		WorleyParsons Project No. 307071-01251	
		FIG No 6	REV 0

FILE LOCATION: U:\YVR\307071\01251_BCME_GeoInAqfMa\10_Eng\16_Geomatics\01_Mxd\StageII_Detailed_Mapping_Study\2018-02-21_Fig6_Bedrock_Geology_and_Faults.mxd

SAVE DATE & TIME: 01/05/2018 11:45:42 AM

USER NAME: Ashling.Mulcahy
ISSUING OFFICE: BURNABY GIS



N

0 1 2

Kilometres

1:125,000

NAD 1983 UTM Zone 10N

Elevation (masl)

820
780
740
700
660
620
580
540
500
460
420
380
340
300
260
220
180
140
100
60
20
-20
-60
-100

Legend

Study Area

Type of Gridding Point

- At or Near Surface Bedrock
- Unconsolidated Ghost Points
- Bedrock Picks

MINISTRY OF ENVIRONMENT
STAGE II DETAILED MAPPING STUDY

CONTOURED BEDROCK SURFACE

Date: 08-JAN-19	Drawn by: AM	Edited by: AM	App'd by: ZH
		WorleyParsons Project No. 307071-01251	
		FIG No 7	REV 0

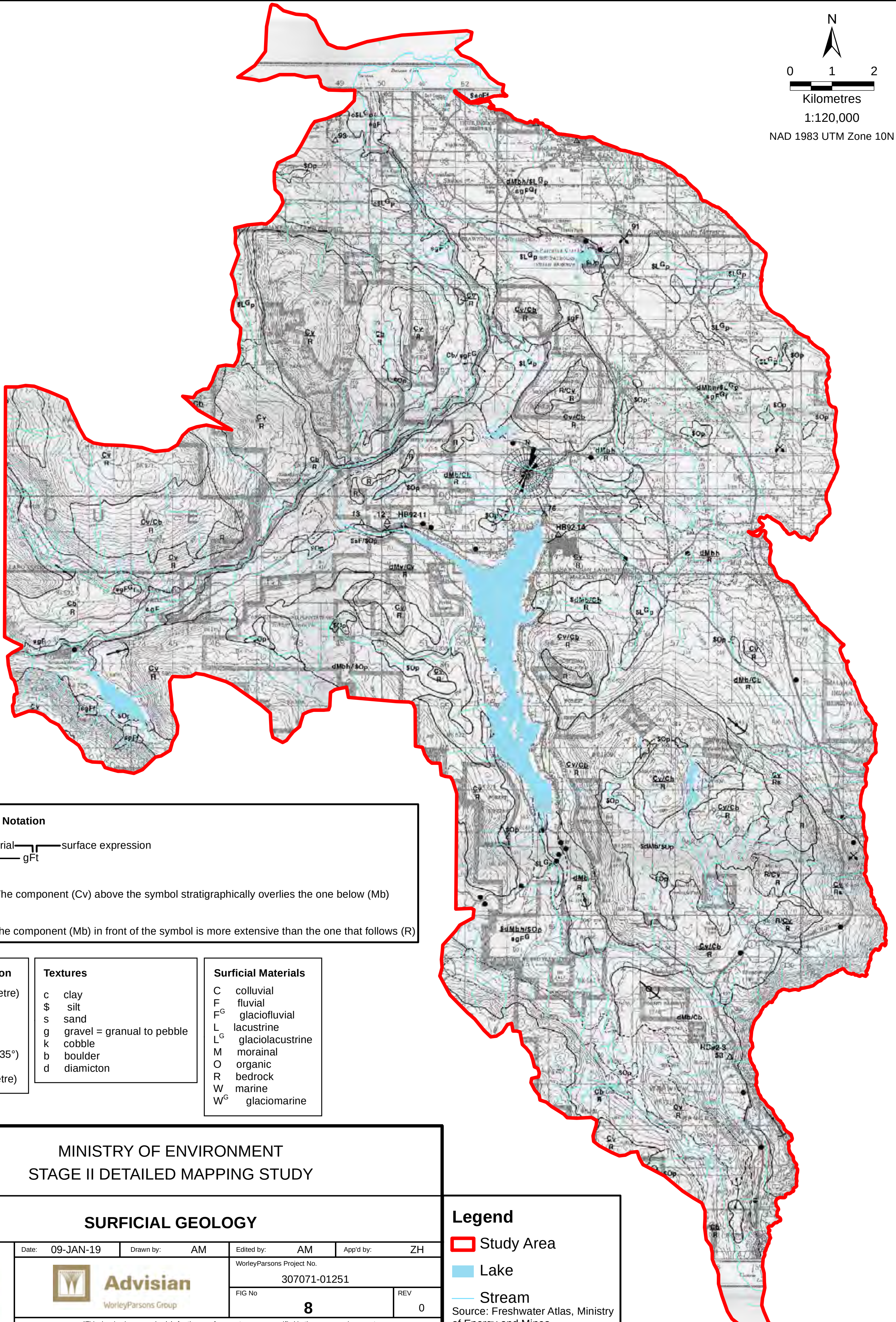
British Columbia Ministry of Environment and Climate Change Strategy

Advisian WorleyParsons Group

FILE LOCATION: \\WorleyParsons.com\CAIData\YVR\307071\01251_BCME_GeoInAqfMa\10_Eng\16_Geomatics\01_Mxd\StageII_Detailed_Mapping_Study\2018-03-05_Fig7_Contoured_Bedrock_Surface.mxd

SAVE DATE & TIME: 01/05/2018 11:46:35 AM

USER NAME: Ashling.Mulcahy
ISSUING OFFICE: BURNABY GIS



Terrain Unit Letter Notation

surficial material — surface expression
texture — gFt

Composite Units

Cv / Mb	The component (Cv) above the symbol stratigraphically overlies the one below (Mb)
Mb/R	The component (Mb) in front of the symbol is more extensive than the one that follows (R)

Surface Expression

- b blanket (>1 metre)
- f fan
- h hummocky
- p plain
- r ridged
- s steep slope (>35°)
- t terraced
- v veneer (<1 metre)

Textures

- c clay
- $ silt
- s sand
- g gravel = granual to pebble
- k cobble
- b boulder
- d diamicton

Surficial Materials

- C colluvial
- F fluvial
- F^G glaciofluvial
- L lacustrine
- L^G glaciolacustrine
- M morainal
- O organic
- R bedrock
- W marine
- W^G glaciomarine

MINISTRY OF ENVIRONMENT
STAGE II DETAILED MAPPING STUDY

SURFICIAL GEOLOGY

Date: 09-JAN-19	Drawn by: AM	Edited by: AM	App'd by: ZH

British Columbia Ministry of Environment and Climate Change Strategy

Advisian WorleyParsons Group

WorleyParsons Project No. 307071-01251

FIG No 8 REV 0

Legend

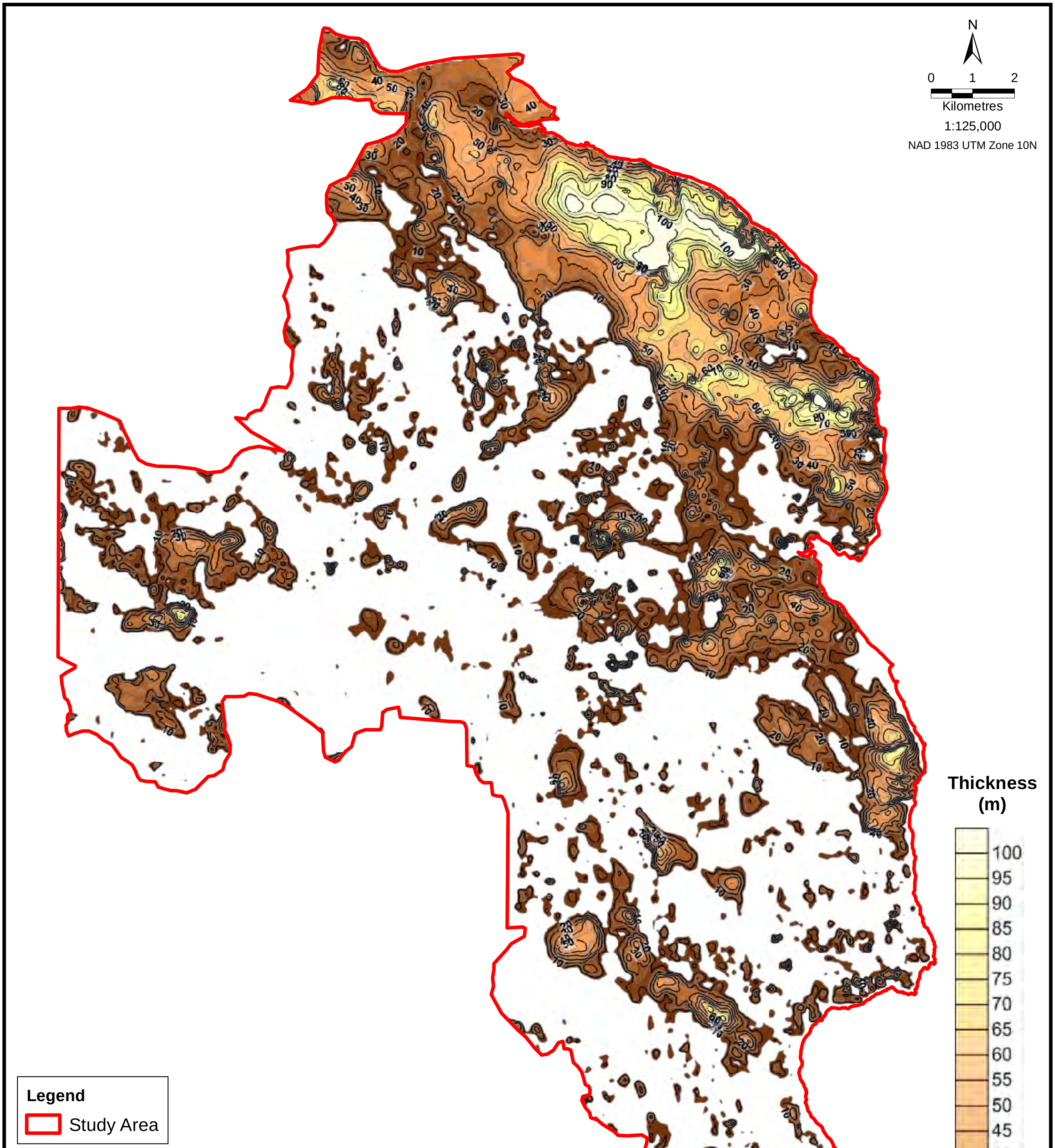
- Study Area
- Lake
- Stream

Source: Freshwater Atlas, Ministry of Energy and Mines

FILE LOCATION: U:\YVR\307071\01251_BCME_GeoInAq\Ma\10_Eng\16_Geomatics\01_Mxd\StageII_Detailed_Mapping_Study\2018-02-21_Fig8_Surficial_Geology.mxd

SAVE DATE & TIME: 01/05/2018 11:45:16 AM

USER NAME: Ashling.Mulcahy
ISSUING OFFICE: BURNABY GIS



MINISTRY OF ENVIRONMENT
STAGE II DETAILED MAPPING STUDY

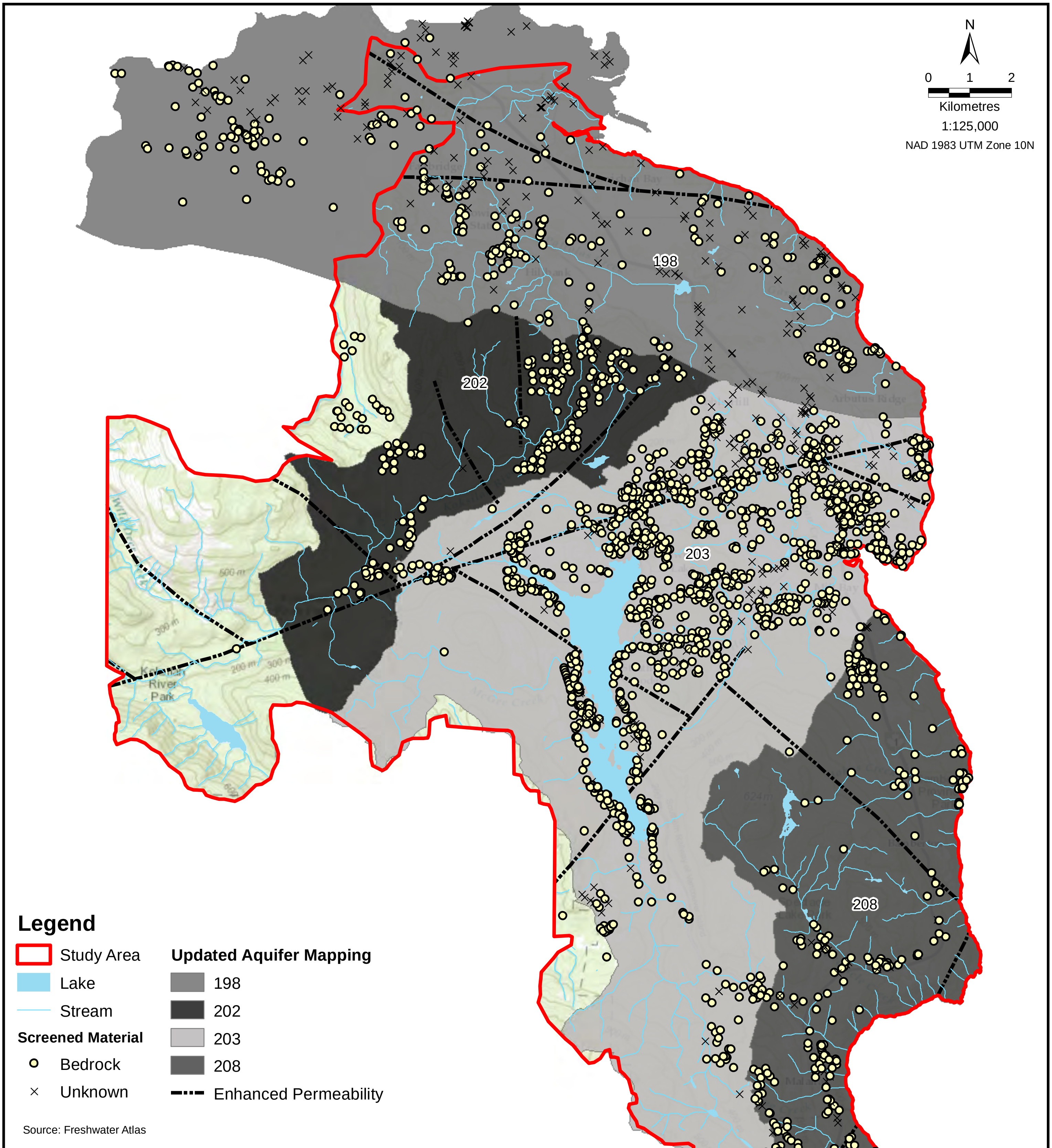
SURFICIAL MATERIAL ISOPACH

Date: 01-MAY-18	Drawn by: AM	Edited by: AM	App'd by: ZH
Advisian WorleyParsons Group		WorleyParsons Project No. 307071-01251	
		FIG No 9	REV 0

British Columbia Ministry of Environment and Climate Change Strategy

FILE LOCATION: U:\YVR\307071\01251_BCME_GeoInAqfMa\10_Eng\16_Geomatics\01_Mxd\StageII_Detailed_Mapping_Study\2018-03-05_Fig9_Surficial_Material_Isopach.mxd

SAVE DATE & TIME: 01/05/2018 10:14:25 AM
USER NAME: ashing.mulcahy
ISSUING OFFICE: BURNABY GIS



MINISTRY OF ENVIRONMENT
STAGE II DETAILED MAPPING STUDY

UPDATED BEDROCK AQUIFERS

Date: 22-APR-19	Drawn by: AM	Edited by: KR	App'd by: ZH

BRITISH COLUMBIA Ministry of Environment and Climate Change Strategy

Advisian WorleyParsons Group

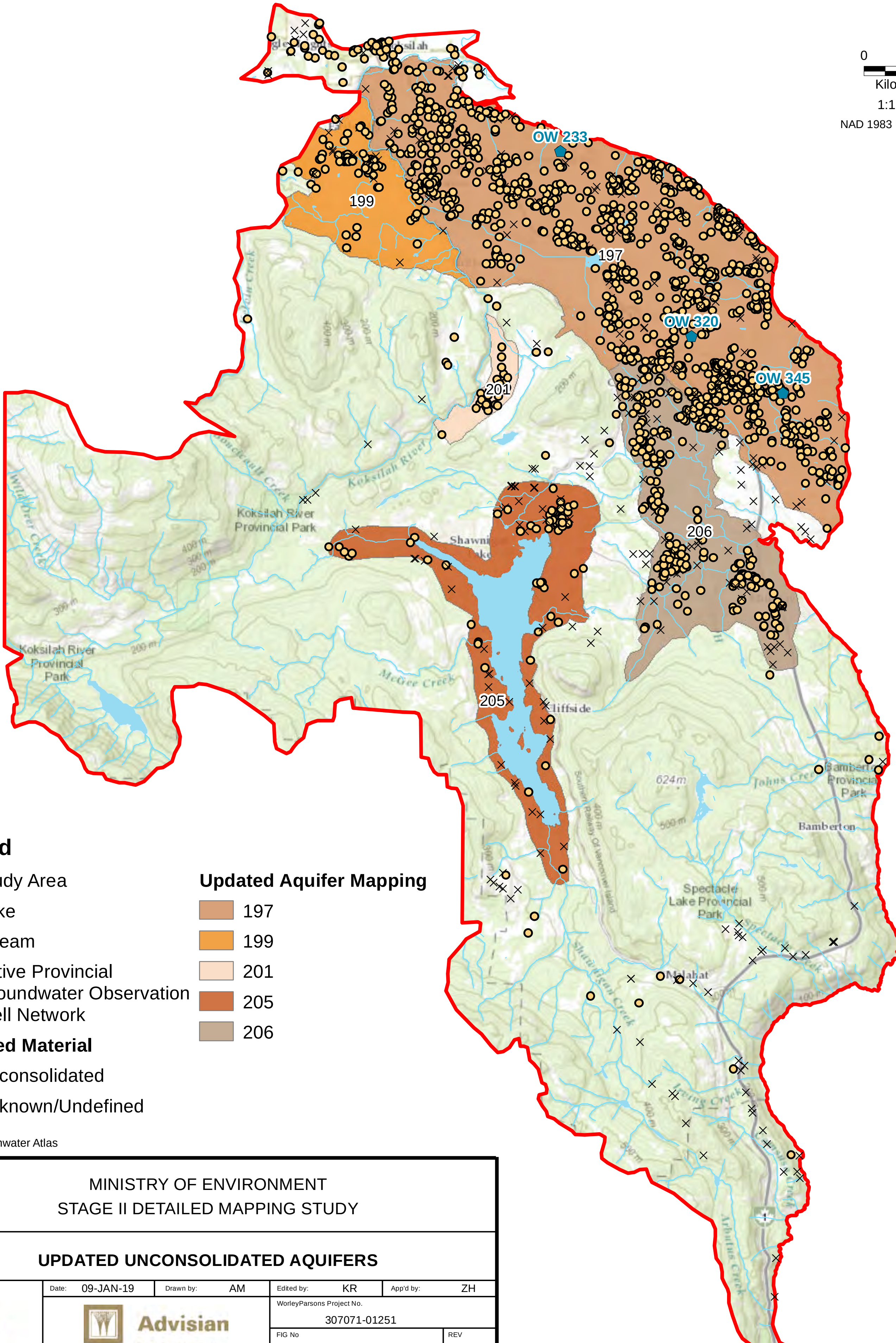
WorleyParsons Project No. 307071-01251

FIG No 10 REV 0

FILE LOCATION: U:\YVR\307071\01251_BCME_GeoInAqfMat\10_Eng\16_Geomatics\01_Mxd\StageII_Detailed_Mapping_Study\2019-01-04_Fig10_Updated_BDCK_Aquifers104.mxd

SAVE DATE & TIME: 22/04/2019 1:14:19 PM

USER NAME: Kenneth.W.Ritchie
ISSUING OFFICE: BURNABY GIS



Legend

- Study Area
- Lake
- Stream
- Active Provincial Groundwater Observation Well Network

Screened Material

- Unconsolidated
- Unknown/Undefined

Updated Aquifer Mapping

- 197
- 199
- 201
- 205
- 206

Source: Freshwater Atlas

MINISTRY OF ENVIRONMENT
STAGE II DETAILED MAPPING STUDY

UPDATED UNCONSOLIDATED AQUIFERS

Date: 09-JAN-19	Drawn by: AM	Edited by: KR	App'd by: ZH
		WorleyParsons Project No. 307071-01251	
		FIG No 11	REV 0

British Columbia Ministry of Environment and Climate Change Strategy

Advisian WorleyParsons Group

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FILE LOCATION: U:\YVR\307071\01251_BCME_GeoInAqfMa\10_Eng\16_Geomatics\01_Mxd\StageII_Detailed_Mapping_Study\2019-01-04_Fig11_Updated_UNC_Aquifers104.mxd

SAVE DATE & TIME: 09/01/2019 11:11:48 AM

USER NAME: Ashling.Mulcahy
ISSUING OFFICE: BURNABY GIS

APPENDIX A. BEDROCK CROSS-SECTIONS


N
S
63364
68758
85134
84011
88930
79365
84800
65078
79431
69059
73409
33439
20547
83827
83831
81976
38233
96128
38228
63355
85109
69095
38351
105772
109058
53807
106005
112219
85309
89253
111276
111278
91265
81988
83822
0
10000
20000
Elevation (m asl)
Intersection with BWE1
Kelvin Creek
Koksilah River
Intersection with BWE3
Shawnigan Lake
San Juan Fault
McGee Creek
Intersection with BWE4
Shawnigan Creek
Shawnigan Creek
Lithology
fill
other
undefined
unconsolidated
boulder
clay
gravel
peat
sand
sand & gravel
silt
till
bedrock
sedimentary
argillite
conglomerate
limestone
sandstone
shale
siltstone
metamorphic
marble
schist
quartz
quartzite
igneous
diorite
granite
volcanic
basalt
Easting (m)
Northing (m)
Stratigraphy
Bonanza Group
Buttle Lake Group - Mount Mark Formation
Island Plutonic Suite
Leech River Complex
Leech River Complex - Survey Mountain Volcanics
Nanaimo Group
Sicker Group - Duck Lake Formation
Vancouver Group - Karmutsen Formation
Vancouver Group - Quatsino Formation
Westcoast Crystalline Complex
Major fault
Water level
Borehole fracture zone
Vertical exaggeration: 11
This cross-section shows interpreted geology based on data from discrete locations and professional judgement. Deviations in the type and location of material are expected.
BRITISH COLUMBIA MINISTRY OF ENVIRONMENT
STAGE II DETAILED AQUIFER MAPPING STUDY
SHAWNIGAN LAKE AREA, VANCOUVER ISLAND, B.C.
HYDROGEOLOGIC CROSS-SECTION BNS1
Date: 26-Mar-19
Drawn by: T.L.
Edited by: Z.H.
App'd by: A.H.
WorleyParsons Project No. 307071-01251
FIG No BNS1
REV 1
OneWay to zero harm
Advisian WorleyParsons Group
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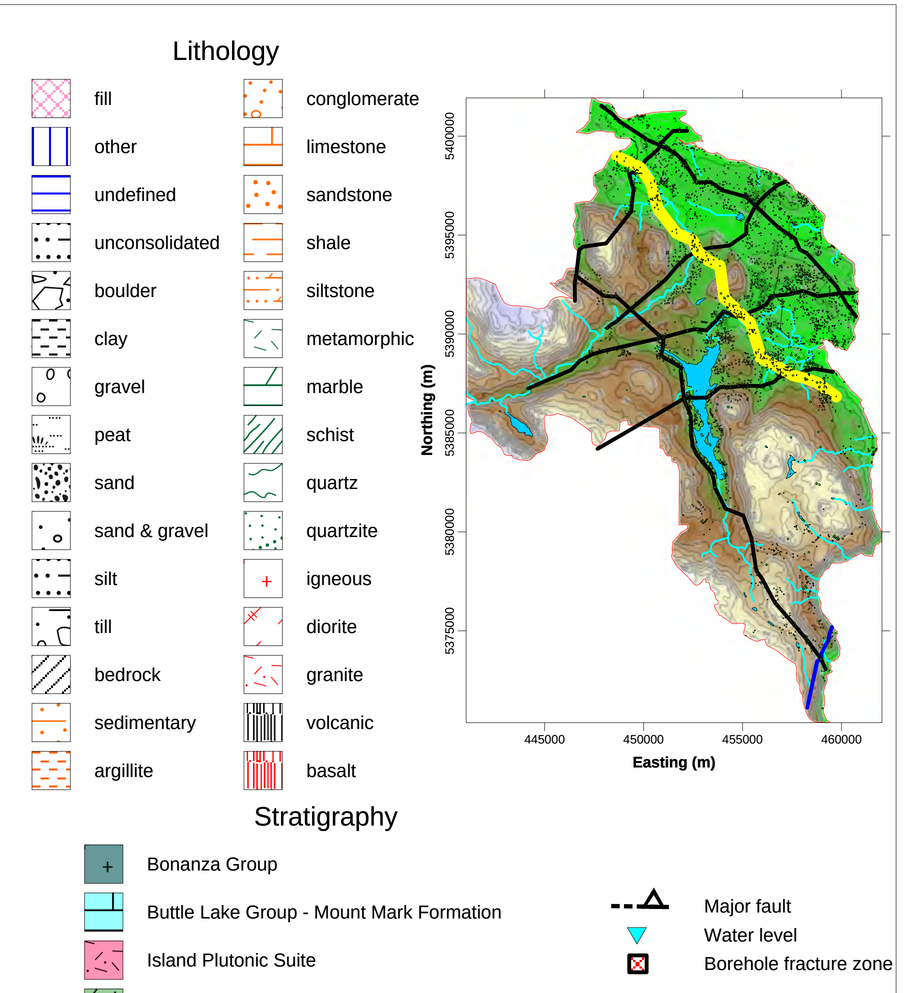

Vertical exaggeration: 8

This cross-section shows interpreted geology based on data from discrete locations and professional judgement. Deviations in the type and location of material are expected.

BRITISH COLUMBIA MINISTRY OF ENVIRONMENT
STAGE II DETAILED AQUIFER MAPPING STUDY
SHAWNIGAN LAKE AREA, VANCOUVER ISLAND, B.C.

HYDROGEOLOGIC CROSS-SECTION BNS2

Date: 26-Mar-19	Drawn by: T.L.	Edited by: Z.H.	App'd by: A.H.
		WorleyParsons Project No. 307071-01251	
		FIG No BNS2	REV 1

OneWay to zero harm

Advisian WorleyParsons Group

Vertical exaggeration: 8

This cross-section shows interpreted geology based on data from discrete locations and professional judgement. Deviations in the type and location of material are expected.

BRITISH COLUMBIA MINISTRY OF ENVIRONMENT
STAGE II DETAILED AQUIFER MAPPING STUDY
SHAWNIGAN LAKE AREA, VANCOUVER ISLAND, B.C.

HYDROGEOLOGIC CROSS-SECTION BNS3

Date: 26-Mar-19	Drawn by: T.L.	Edited by: Z.H.	App'd by: A.H.
OneWay to zero harm	Advisian WorleyParsons Group	WorleyParsons Project No. 307071-01251	
		FIG No **BNS3**	REV 1


W
E
67756
67767
68693
81669
44990
30975
38908
51323
90038
52228
109770
16153
64140
56954
0
5000
10000
Elevation (m asl)
640
600
560
520
480
440
400
360
320
280
240
200
160
120
80
40
0
-40
-80
-120
Intersection with BNS1
Kelvin Creek
Intersection with BNS2
Koksilah River
Intersection with BNS3
Koksilah River
Lithology
fill
other
undefined
unconsolidated
boulder
clay
gravel
peat
sand
sand & gravel
silt
till
bedrock
sedimentary
argillite
conglomerate
limestone
sandstone
shale
siltstone
metamorphic
marble
schist
quartz
quartzite
igneous
diorite
granite
volcanic
basalt
Northing (m)
5400000
5395000
5390000
5385000
5380000
5375000
445000
450000
455000
460000
Easting (m)
Stratigraphy
Bonanza Group
Buttle Lake Group - Mount Mark Formation
Island Plutonic Suite
Leech River Complex
Leech River Complex - Survey Mountain Volcanics
Nanaimo Group
Sicker Group - Duck Lake Formation
Vancouver Group - Karmutsen Formation
Vancouver Group - Quatsino Formation
Westcoast Crystalline Complex
Major fault
Water level
Borehole fracture zone
Vertical exaggeration: 5
This cross-section shows interpreted geology based on data from discrete locations and professional judgement. Deviations in the type and location of material are expected.
BRITISH COLUMBIA MINISTRY OF ENVIRONMENT
STAGE II DETAILED AQUIFER MAPPING STUDY
SHAWNIGAN LAKE AREA, VANCOUVER ISLAND, B.C.
HYDROGEOLOGIC CROSS-SECTION BWE1
Date: 26-Mar-19
Drawn by: T.L.
Edited by: Z.H.
App'd by: A.H.
OneWay to zero harm
Advisian
WorleyParsons Group
WorleyParsons Project No.
307071-01251
FIG No BWE1
REV 1
"This drawing is prepared for the use of our customer as specified in the accompanying report.
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W
E
112848
91044
96100
36792
63446
84515
54307
70222
34278
24920
77097
85452
74803
52783
39445
84163
0
5000
10000
640
600
560
520
480
440
400
360
320
280
240
200
160
120
80
40
0
-40
-80
-120
Elevation (m asl)
Koksilah River
Koksilah River
Intersection with BNS2
Intersection with BNS3
Lithology
fill
other
undefined
unconsolidated
boulder
clay
gravel
peat
sand
sand & gravel
silt
till
bedrock
sedimentary
argillite
conglomerate
limestone
sandstone
shale
siltstone
metamorphic
marble
schist
quartz
quartzite
igneous
diorite
granite
volcanic
basalt
Northing (m)
445000
450000
455000
460000
Easting (m)
Stratigraphy
Bonanza Group
Buttle Lake Group - Mount Mark Formation
Island Plutonic Suite
Leech River Complex
Leech River Complex - Survey Mountain Volcanics
Nanaimo Group
Sicker Group - Duck Lake Formation
Vancouver Group - Karmutsen Formation
Vancouver Group - Quatsino Formation
Westcoast Crystalline Complex
Major fault
Water level
Borehole fracture zone
Vertical exaggeration: 6
This cross-section shows interpreted geology based on data from discrete locations and professional judgement. Deviations in the type and location of material are expected.
BRITISH COLUMBIA MINISTRY OF ENVIRONMENT
STAGE II DETAILED AQUIFER MAPPING STUDY
SHAWNIGAN LAKE AREA, VANCOUVER ISLAND, B.C.
HYDROGEOLOGIC CROSS-SECTION BWE2
Date: 26-Mar-19
Drawn by: T.L.
Edited by: Z.H.
App'd by: A.H.
OneWay to zero harm
Advisian
WorleyParsons Group
WorleyParsons Project No. 307071-01251
FIG No BWE2
REV 1
"This drawing is prepared for the use of our customer as specified in the accompanying report. WorleyParsons Canada Services Ltd. assumes no liability to any other party for any representations contained in this drawing."

Vertical exaggeration: 8

This cross-section shows interpreted geology based on data from discrete locations and professional judgement. Deviations in the type and location of material are expected.

BRITISH COLUMBIA MINISTRY OF ENVIRONMENT
STAGE II DETAILED AQUIFER MAPPING STUDY
SHAWNIGAN LAKE AREA, VANCOUVER ISLAND, B.C.

HYDROGEOLOGIC CROSS-SECTION BWE3

Date: 26-Mar-19	Drawn by: T.L.	Edited by: Z.H.	App'd by: A.H.
OneWay to zero harm	Advisian WorleyParsons Group	WorleyParsons Project No. 307071-01251	
		FIG No BWE3	REV 1


W
E
83827
86109
63518
47142
50449
47130
81886
80860
97014
42311
85243
46810
85204
16123
Elevation (m asl)
640
600
560
520
480
440
400
360
320
280
240
200
160
120
80
40
0
-40
-80
-120
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000
12000
McGee Creek
Intersection with BNS1
Shawnigan Lake
Hollings Creek
Intersection with BNS2
Handysen Creek
Shawnigan Fault
Lithology
fill
other
undefined
unconsolidated
boulder
clay
gravel
peat
sand
sand & gravel
silt
till
bedrock
sedimentary
argillite
conglomerate
limestone
sandstone
shale
siltstone
metamorphic
marble
schist
quartz
quartzite
igneous
diorite
granite
volcanic
basalt
Stratigraphy
Bonanza Group
Buttle Lake Group - Mount Mark Formation
Island Plutonic Suite
Leech River Complex
Leech River Complex - Survey Mountain Volcanics
Nanaimo Group
Sicker Group - Duck Lake Formation
Vancouver Group - Karmutsen Formation
Vancouver Group - Quatsino Formation
Westcoast Crystalline Complex
Major fault
Water level
Borehole fracture zone
Northing (m)
Easting (m)
Vertical exaggeration: 6
This cross-section shows interpreted geology based on data from discrete locations and professional judgement. Deviations in the type and location of material are expected.
BRITISH COLUMBIA MINISTRY OF ENVIRONMENT
STAGE II DETAILED AQUIFER MAPPING STUDY
SHAWNIGAN LAKE AREA, VANCOUVER ISLAND, B.C.
HYDROGEOLOGIC CROSS-SECTION BWE4
Date: 26-Mar-19
Drawn by: T.L.
Edited by: Z.H.
App'd by: A.H.
OneWay to zero harm
Advisian WorleyParsons Group
WorleyParsons Project No. 307071-01251
FIG No BWE4
REV 1
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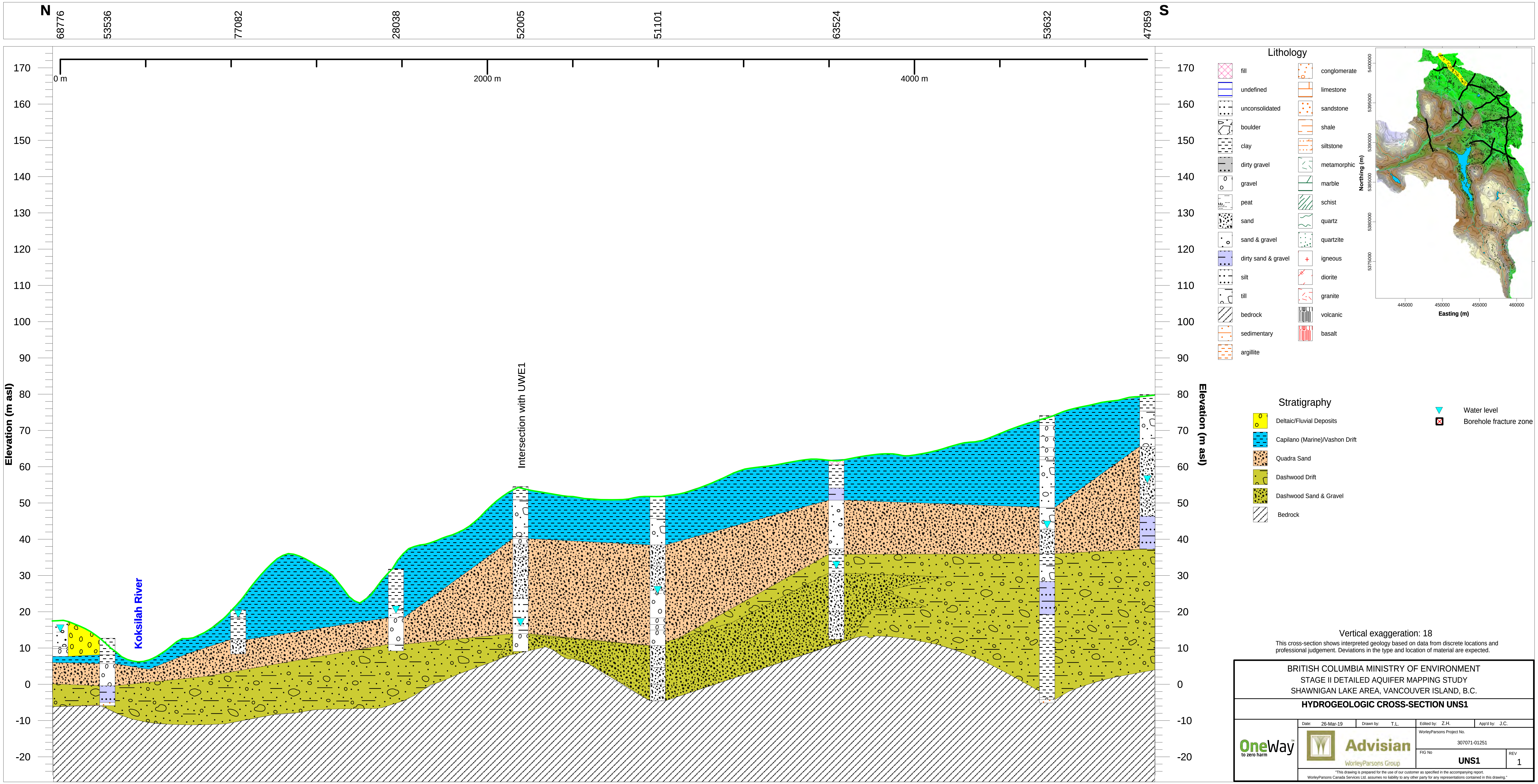
APPENDIX B. UNCONSOLIDATED CROSS-SECTIONS


N
68776
53536
77082
28038
52005
51101
63524
53632
47859
S
0 m
2000 m
4000 m
Elevation (m asl)
Intersection with UWE1
Koksilah River
Lithology
fill
undefined
unconsolidated
boulder
clay
dirty gravel
gravel
peat
sand
sand & gravel
dirty sand & gravel
silt
till
bedrock
sedimentary
argillite
conglomerate
limestone
sandstone
shale
siltstone
metamorphic
marble
schist
quartz
quartzite
igneous
diorite
granite
volcanic
basalt
Northing (m)
Easting (m)
Stratigraphy
Deltaic/Fluvial Deposits
Capilano (Marine)/Vashon Drift
Quadra Sand
Dashwood Drift
Dashwood Sand & Gravel
Bedrock
Water level
Borehole fracture zone
Vertical exaggeration: 18
This cross-section shows interpreted geology based on data from discrete locations and professional judgement. Deviations in the type and location of material are expected.
BRITISH COLUMBIA MINISTRY OF ENVIRONMENT
STAGE II DETAILED AQUIFER MAPPING STUDY
SHAWNIGAN LAKE AREA, VANCOUVER ISLAND, B.C.
HYDROGEOLOGIC CROSS-SECTION UNS1
Date: 26-Mar-19
Drawn by: T.L.
Edited by: Z.H.
App'd by: J.C.
WorleyParsons Project No. 307071-01251
FIG No UNS1
REV 1
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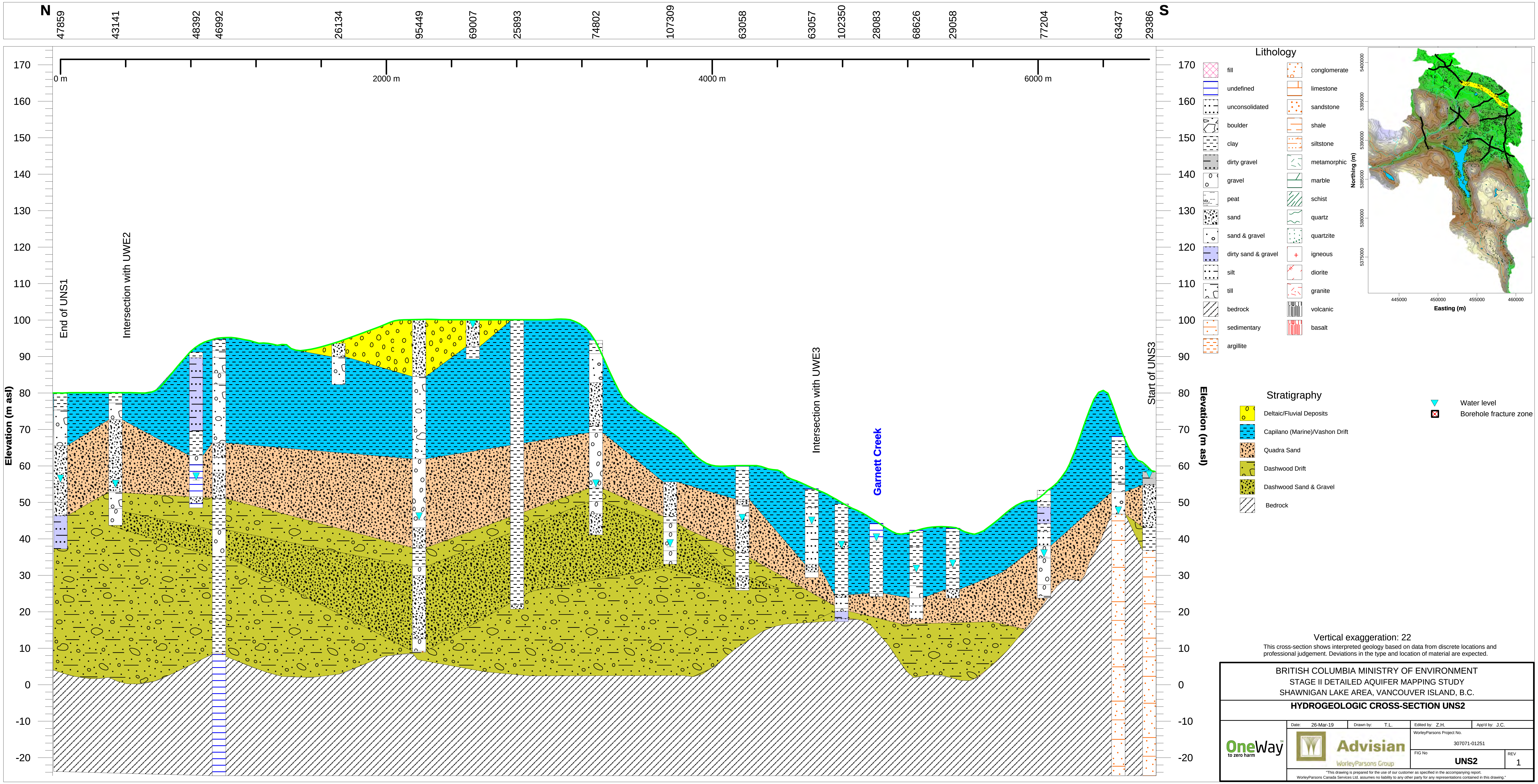
N
S
47859
43141
48392
46992
26134
95449
69007
25893
74802
107309
63058
63057
102350
28083
68626
29058
77204
63437
29386
0 m
2000 m
4000 m
6000 m
Elevation (m asl)
End of UNS1
Intersection with UWE2
Intersection with UWE3
Garnett Creek
Start of UNS3
Lithology
fill
undefined
unconsolidated
boulder
clay
dirty gravel
gravel
peat
sand
sand & gravel
dirty sand & gravel
silt
till
bedrock
sedimentary
argillite
conglomerate
limestone
sandstone
shale
siltstone
metamorphic
marble
schist
quartz
quartzite
igneous
diorite
granite
volcanic
basalt
Northing (m)
Easting (m)
Stratigraphy
Deltaic/Fluvial Deposits
Capilano (Marine)/Vashon Drift
Quadra Sand
Dashwood Drift
Dashwood Sand & Gravel
Bedrock
Water level
Borehole fracture zone
Vertical exaggeration: 22
This cross-section shows interpreted geology based on data from discrete locations and professional judgement. Deviations in the type and location of material are expected.
BRITISH COLUMBIA MINISTRY OF ENVIRONMENT
STAGE II DETAILED AQUIFER MAPPING STUDY
SHAWNIGAN LAKE AREA, VANCOUVER ISLAND, B.C.
HYDROGEOLOGIC CROSS-SECTION UNS2
Date: 26-Mar-19
Drawn by: T.L.
Edited by: Z.H.
App'd by: J.C.
WorleyParsons Project No.
307071-01251
FIG No
UNS2
REV
1
OneWay to zero harm
Advisian
WorleyParsons Group
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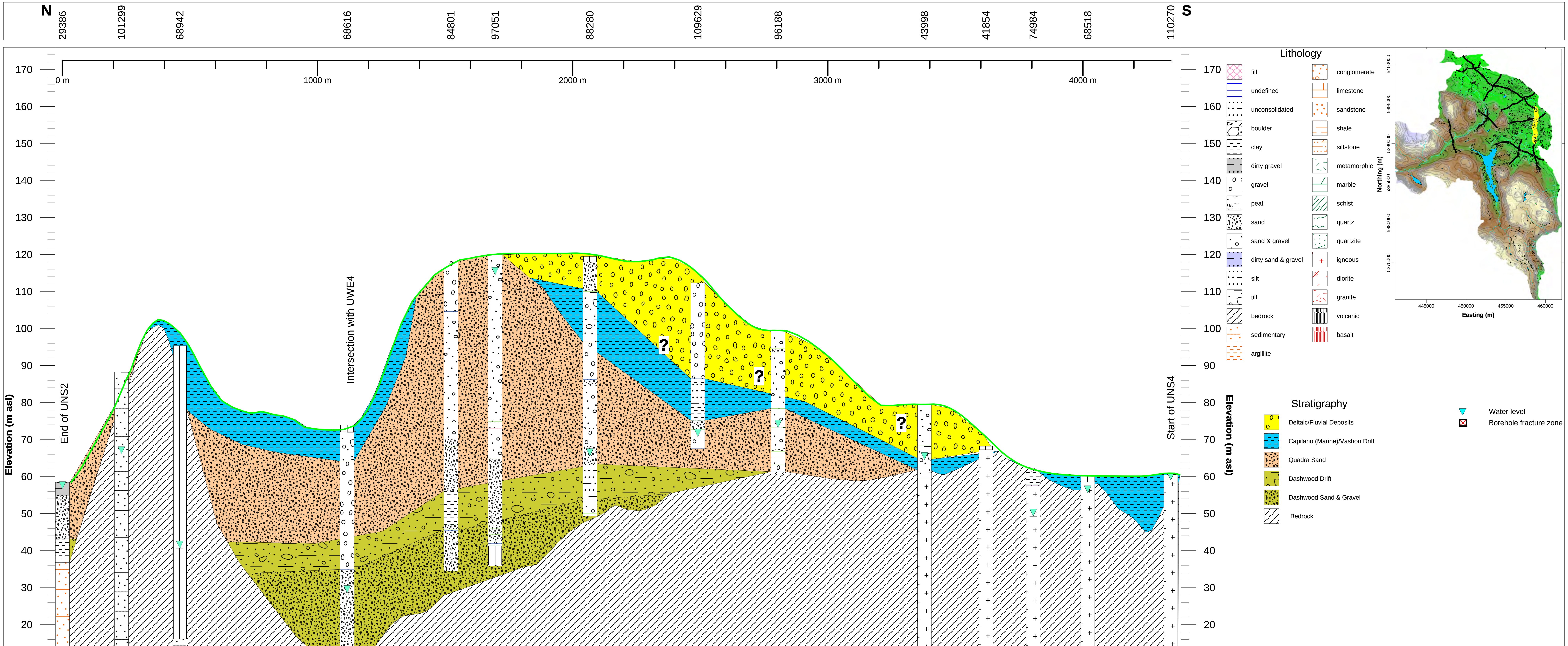


Vertical exaggeration: 14

This cross-section shows interpreted geology based on data from discrete locations and professional judgement. Deviations in the type and location of material are expected.

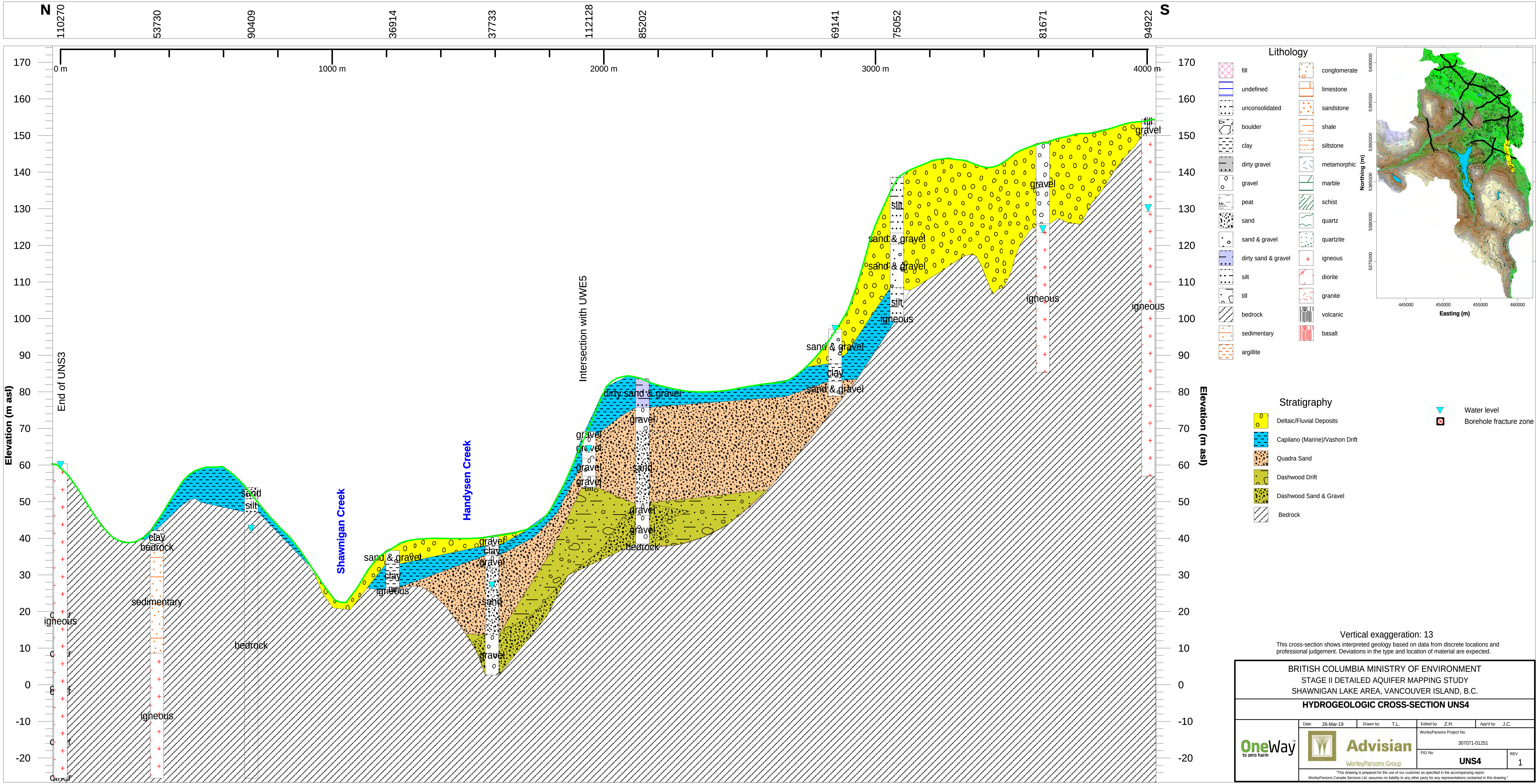
BRITISH COLUMBIA MINISTRY OF ENVIRONMENT
STAGE II DETAILED AQUIFER MAPPING STUDY
SHAWNIGAN LAKE AREA, VANCOUVER ISLAND, B.C.

HYDROGEOLOGIC CROSS-SECTION UNS3

Date: 26-Mar-19	Drawn by: T.L.	Edited by: Z.H.	App'd by: J.C.
		WorleyParsons Project No. 307071-01251	
		FIG No UNS3	REV 1

OneWay to zero harm

Advision WorleyParsons Group



Vertical exaggeration: 13

This cross-section shows interpreted geology based on data from discrete locations and professional judgement. Deviations in the type and location of material are expected.

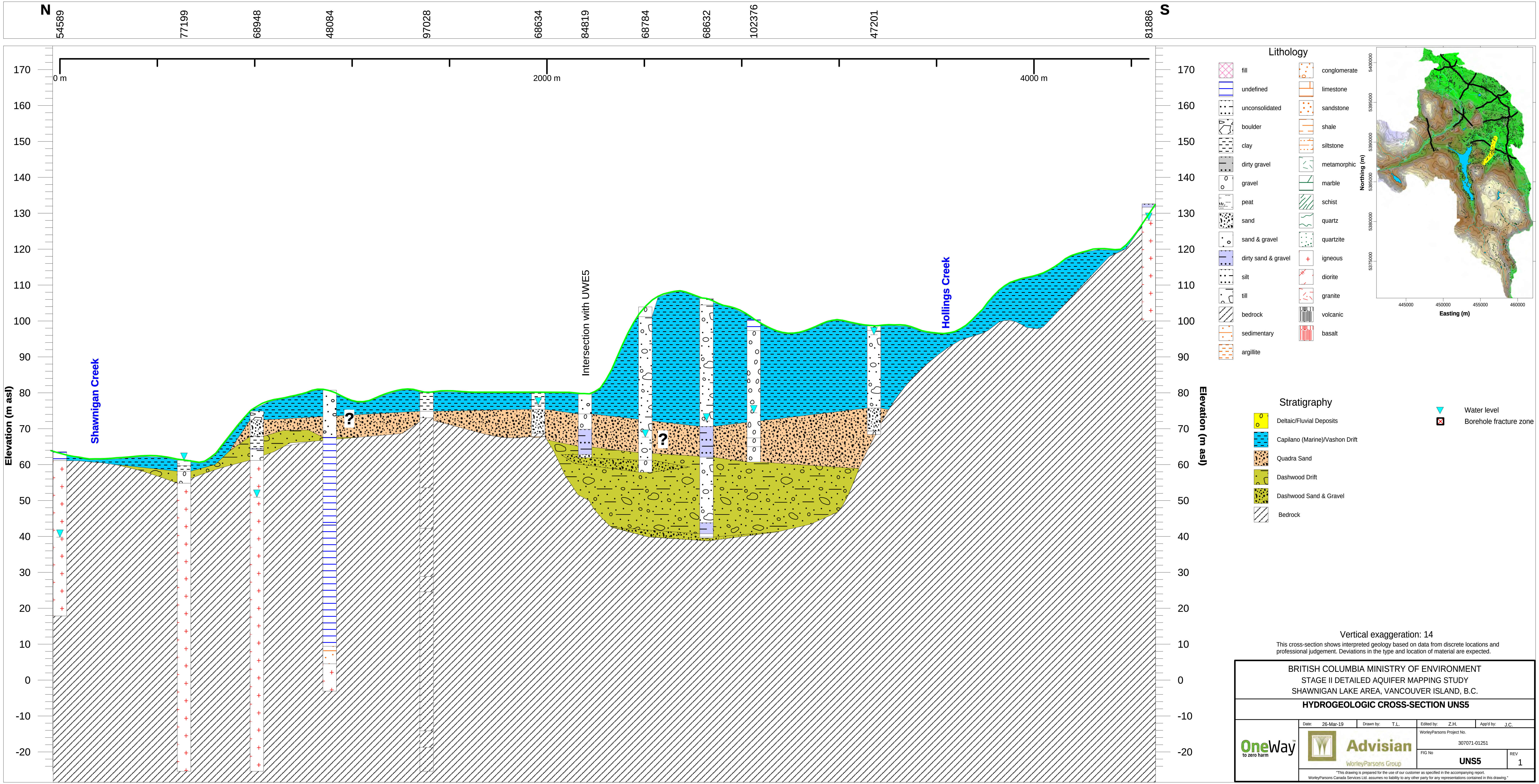
BRITISH COLUMBIA MINISTRY OF ENVIRONMENT
STAGE II DETAILED AQUIFER MAPPING STUDY
SHAWNIGAN LAKE AREA, VANCOUVER ISLAND, B.C.

HYDROGEOLOGIC CROSS-SECTION UNS4

Date: 26-Mar-19	Drawn by: T.L.	Edited by: Z.H.	App'd by: J.C.

WorleyParsons Project No. 307071-01251

FIG No **UNS4** REV 1



N
S
54589
77199
68948
48084
97028
68634
84819
68784
68632
102376
47201
81886
0 m
2000 m
4000 m
Elevation (m asl)
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
Shawnigan Creek
Intersection with UWE5
Hollings Creek
?
?
Lithology
fill
undefined
unconsolidated
boulder
clay
dirty gravel
gravel
peat
sand
sand & gravel
dirty sand & gravel
silt
till
bedrock
sedimentary
argillite
conglomerate
limestone
sandstone
shale
siltstone
metamorphic
marble
schist
quartz
quartzite
igneous
diorite
granite
volcanic
basalt
Northing (m)
Easting (m)
445000
450000
455000
460000
5400000
5395000
5390000
5385000
5380000
5375000
Stratigraphy
Deltaic/Fluvial Deposits
Capilano (Marine)/Vashon Drift
Quadra Sand
Dashwood Drift
Dashwood Sand & Gravel
Bedrock
Water level
Borehole fracture zone
Vertical exaggeration: 14
This cross-section shows interpreted geology based on data from discrete locations and professional judgement. Deviations in the type and location of material are expected.
BRITISH COLUMBIA MINISTRY OF ENVIRONMENT
STAGE II DETAILED AQUIFER MAPPING STUDY
SHAWNIGAN LAKE AREA, VANCOUVER ISLAND, B.C.
HYDROGEOLOGIC CROSS-SECTION UNS5
Date: 26-Mar-19
Drawn by: T.L.
Edited by: Z.H.
App'd by: J.C.
WorleyParsons Project No.
307071-01251
FIG No
UNS5
REV
1
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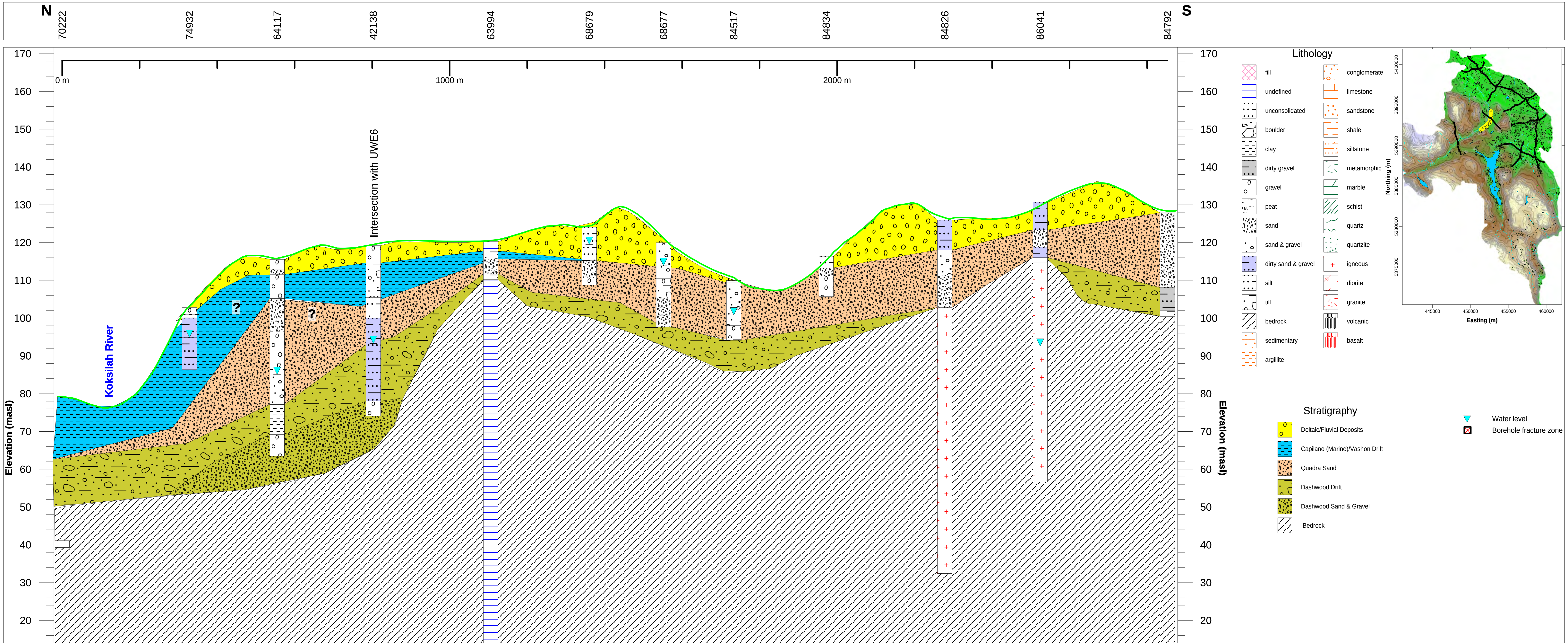


Vertical exaggeration: 10

This cross-section shows interpreted geology based on data from discrete locations and professional judgement. Deviations in the type and location of material are expected.

BRITISH COLUMBIA MINISTRY OF ENVIRONMENT
GEOLOGICAL INTERPRETATION AND AQUIFER MAPPING
SHAWNIGAN LAKE, UCLUELET AND HAIDA GWAII

HYDROGEOLOGIC CROSS-SECTION UNS6

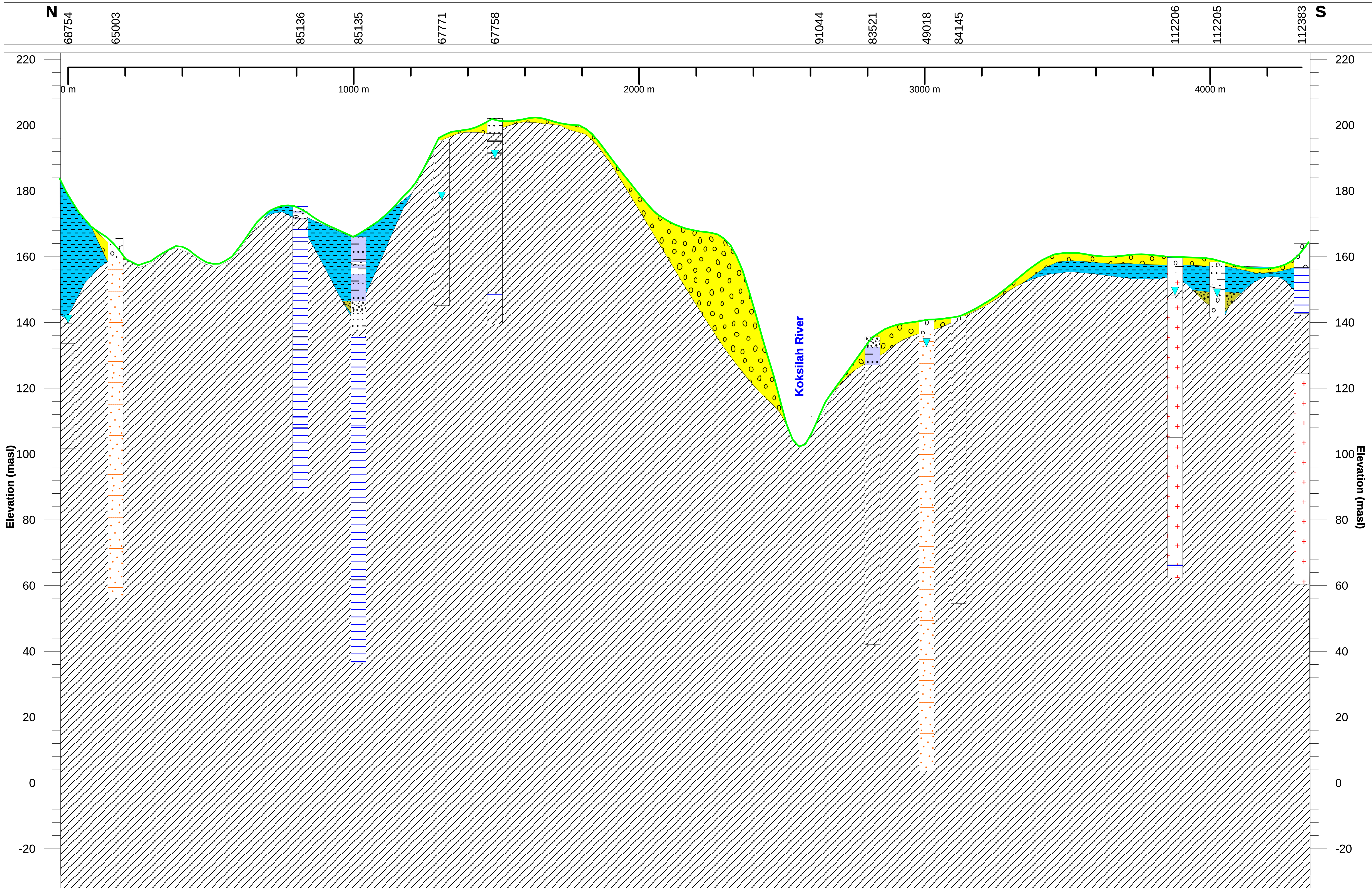
Date: 26-Mar-19	Drawn by: T.L.	Edited by: Z.H.	App'd by: J.C.

OneWay to zero harm

Advisian WorleyParsons Group

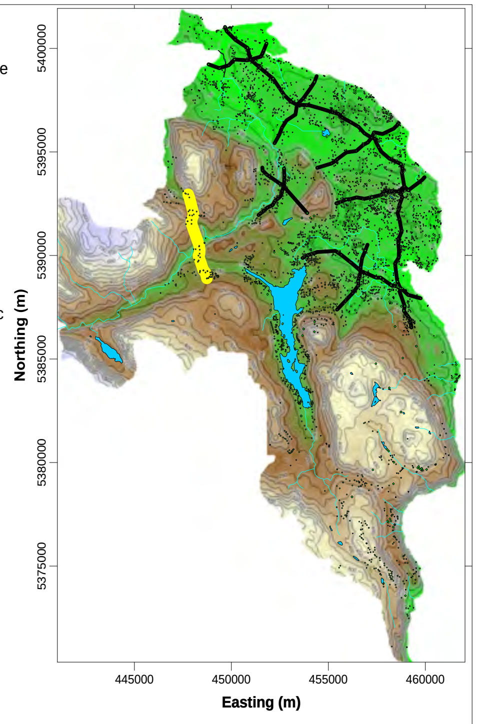
WorleyParsons Project No. 307071-01251

FIG No UNS6 — REV 1



Lithology

fill
undefined
unconsolidated
boulder
clay
dirty gravel
gravel
peat
sand
sand & gravel
dirty sand & gravel
silt
till
bedrock
sedimentary
argillite
conglomerate
limestone
sandstone
shale
siltstone
metamorphic
marble
schist
quartz
quartzite
igneous
diorite
granite
volcanic
basalt



Stratigraphy

Deltaic/Fluvial Deposits
Capilano (Marine)/Vashon Drift
Quadra Sand
Dashwood Drift
Dashwood Sand & Gravel
Bedrock

Water level
Borehole fracture zone

Vertical exaggeration: 11

This cross-section shows interpreted geology based on data from discrete locations and professional judgement. Deviations in the type and location of material are expected.

BRITISH COLUMBIA MINISTRY OF ENVIRONMENT
STAGE II DETAILED AQUIFER MAPPING STUDY
SHAWNIGAN LAKE AREA, VANCOUVER ISLAND, B.C.

HYDROGEOLOGIC CROSS-SECTION UNS7

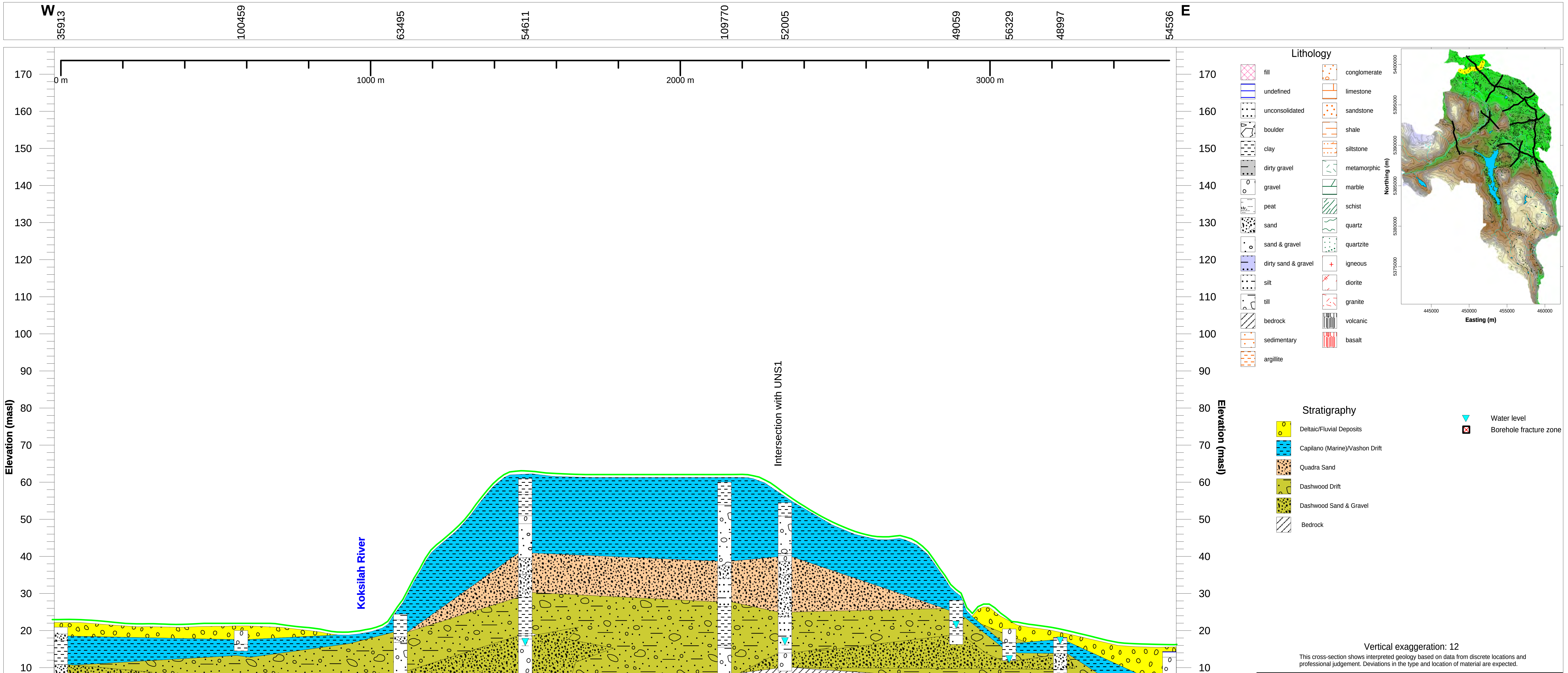
Date: 26-Mar-19	Drawn by: T.L.	Edited by: Z.H.	App'd by: J.C.

OneWay to zero harm

Advisian WorleyParsons Group

WorleyParsons Project No. 307071-01251

FIG No UNS7 — REV 1



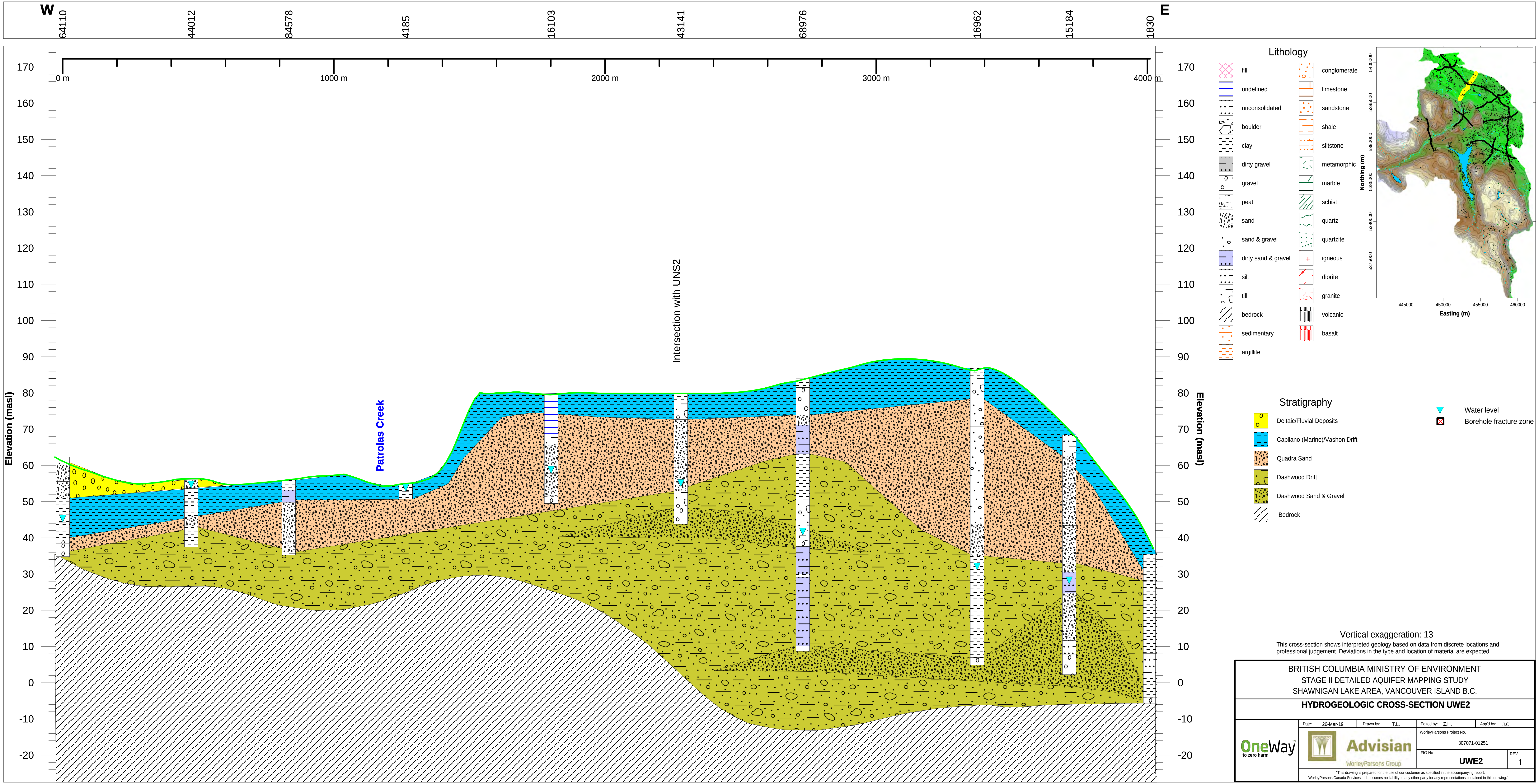
BRITISH COLUMBIA MINISTRY OF ENVIRONMENT
STAGE II DETAILED AQUIFER MAPPING STUDY
SHAWNIGAN LAKE AREA, VANCOUVER ISLAND, B.C.

HYDROGEOLOGIC CROSS-SECTION UWE1

Date: 26-Mar-19	Drawn by: T.L.	Edited by: Z.H.	App'd by: J.C.

WorleyParsons Project No. 307071-01251

FIG No **UWE1** REV 1



Vertical exaggeration: 13

This cross-section shows interpreted geology based on data from discrete locations and professional judgement. Deviations in the type and location of material are expected.

BRITISH COLUMBIA MINISTRY OF ENVIRONMENT
STAGE II DETAILED AQUIFER MAPPING STUDY
SHAWNIGAN LAKE AREA, VANCOUVER ISLAND B.C.

HYDROGEOLOGIC CROSS-SECTION UWE2

Date: 26-Mar-19	Drawn by: T.L.	Edited by: Z.H.	App'd by: J.C.
WorleyParsons Project No. 307071-01251			
FIG No **UWE2**		REV 1	

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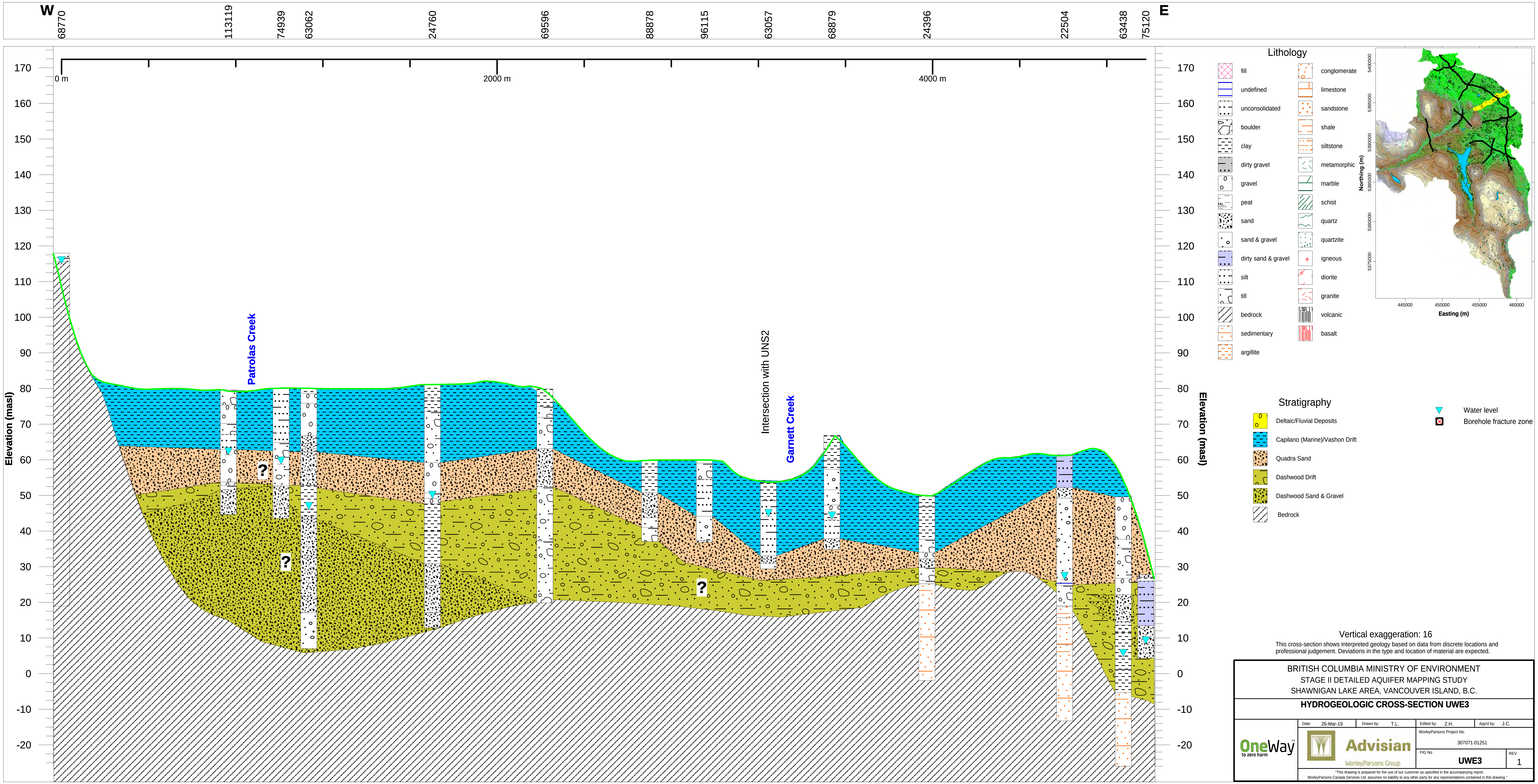
W
E
68770
113119
74939
63062
24760
69596
88878
96115
63057
68879
24396
22504
63438
75120
0 m
2000 m
4000 m
Elevation (masl)
Patrolas Creek
Intersection with UNS2
Garnett Creek
?
Lithology
fill
undefined
unconsolidated
boulder
clay
dirty gravel
gravel
peat
sand
sand & gravel
dirty sand & gravel
silt
till
bedrock
sedimentary
argillite
conglomerate
limestone
sandstone
shale
siltstone
metamorphic
marble
schist
quartz
quartzite
igneous
diorite
granite
volcanic
basalt
Northing (m)
Easting (m)
Stratigraphy
Deltaic/Fluvial Deposits
Capilano (Marine)/Vashon Drift
Quadra Sand
Dashwood Drift
Dashwood Sand & Gravel
Bedrock
Water level
Borehole fracture zone
Vertical exaggeration: 16
This cross-section shows interpreted geology based on data from discrete locations and professional judgement. Deviations in the type and location of material are expected.
BRITISH COLUMBIA MINISTRY OF ENVIRONMENT
STAGE II DETAILED AQUIFER MAPPING STUDY
SHAWNIGAN LAKE AREA, VANCOUVER ISLAND, B.C.
HYDROGEOLOGIC CROSS-SECTION UWE3
Date: 26-Mar-19
Drawn by: T.L.
Edited by: Z.H.
App'd by: J.C.
WorleyParsons Project No. 307071-01251
FIG No UWE3
REV 1
OneWay to zero harm
Advisian WorleyParsons Group
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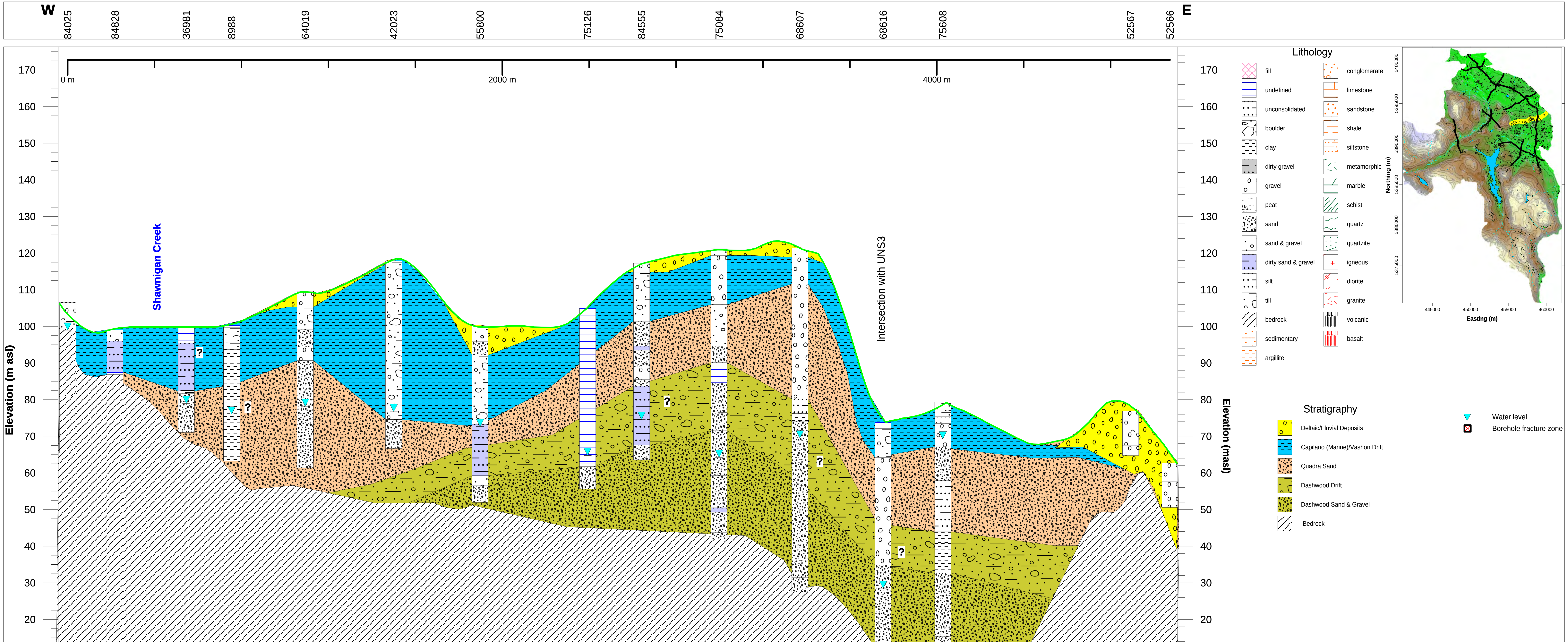


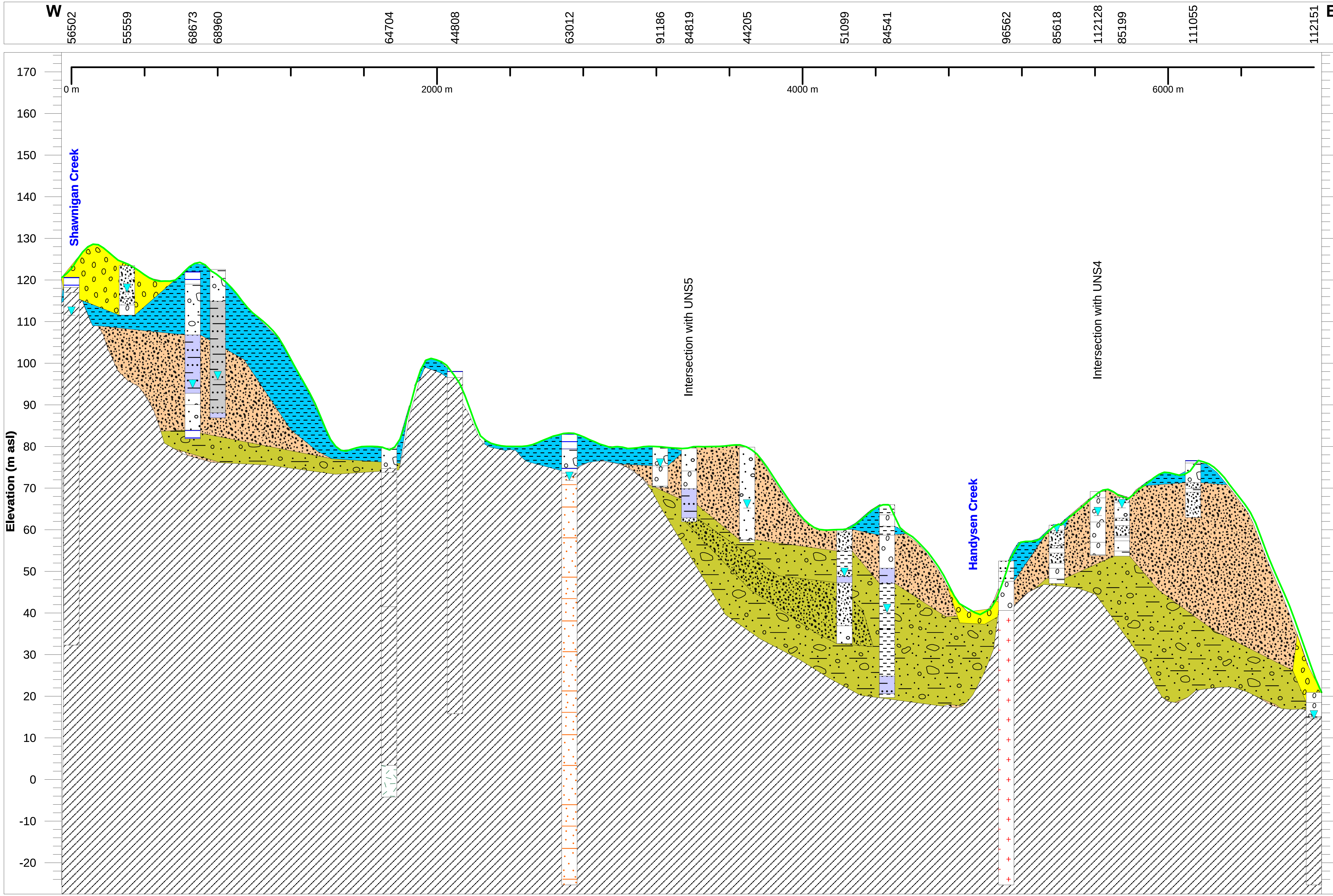
Vertical exaggeration: 17

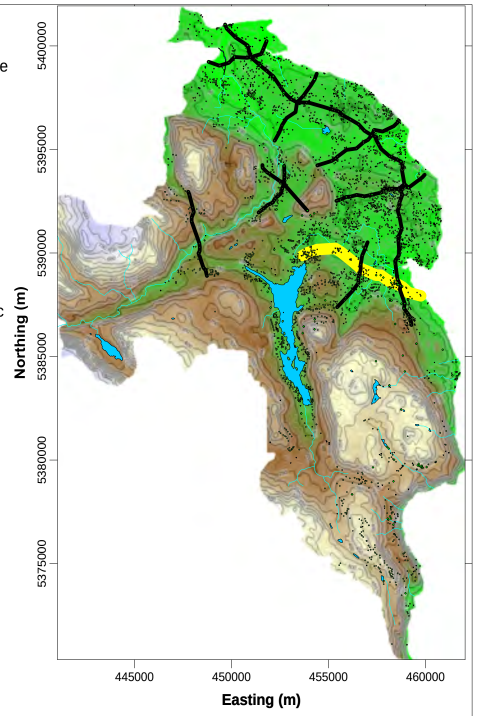
This cross-section shows interpreted geology based on data from discrete locations and professional judgement. Deviations in the type and location of material are expected.

BRITISH COLUMBIA MINISTRY OF ENVIRONMENT
STAGE II DETAILED AQUIFER MAPPING STUDY
SHAWNIGAN LAKE AREA, VANCOUVER ISLAND, B.C.

HYDROGEOLOGIC CROSS-SECTION UWE4

Date: 26-Mar-19	Drawn by: T.L.	Edited by: Z.H.	App'd by: J.C.
OneWay to zero harm	Advisian WorleyParsons Group	WorleyParsons Project No. 307071-01251	
		FIG No UWE4	REV 1





Lithology

fill, undefined, unconsolidated, boulder, clay, dirty gravel, gravel, peat, sand, sand & gravel, dirty sand & gravel, silt, till, bedrock, sedimentary, argillite, conglomerate, limestone, sandstone, shale, siltstone, metamorphic, marble, schist, quartz, quartzite, igneous, diorite, granite, volcanic, basalt

Stratigraphy

Deltaic/Fluvial Deposits
Capilano (Marine)/Vashon Drift
Quadra Sand
Dashwood Drift
Dashwood Sand & Gravel
Bedrock

Water level
Borehole fracture zone

Vertical exaggeration: 23

This cross-section shows interpreted geology based on data from discrete locations and professional judgement. Deviations in the type and location of material are expected.

BRITISH COLUMBIA MINISTRY OF ENVIRONMENT
STAGE II DETAILED AQUIFER MAPPING STUDY
SHAWNIGAN LAKE AREA, VANCOUVER ISLAND, B.C.

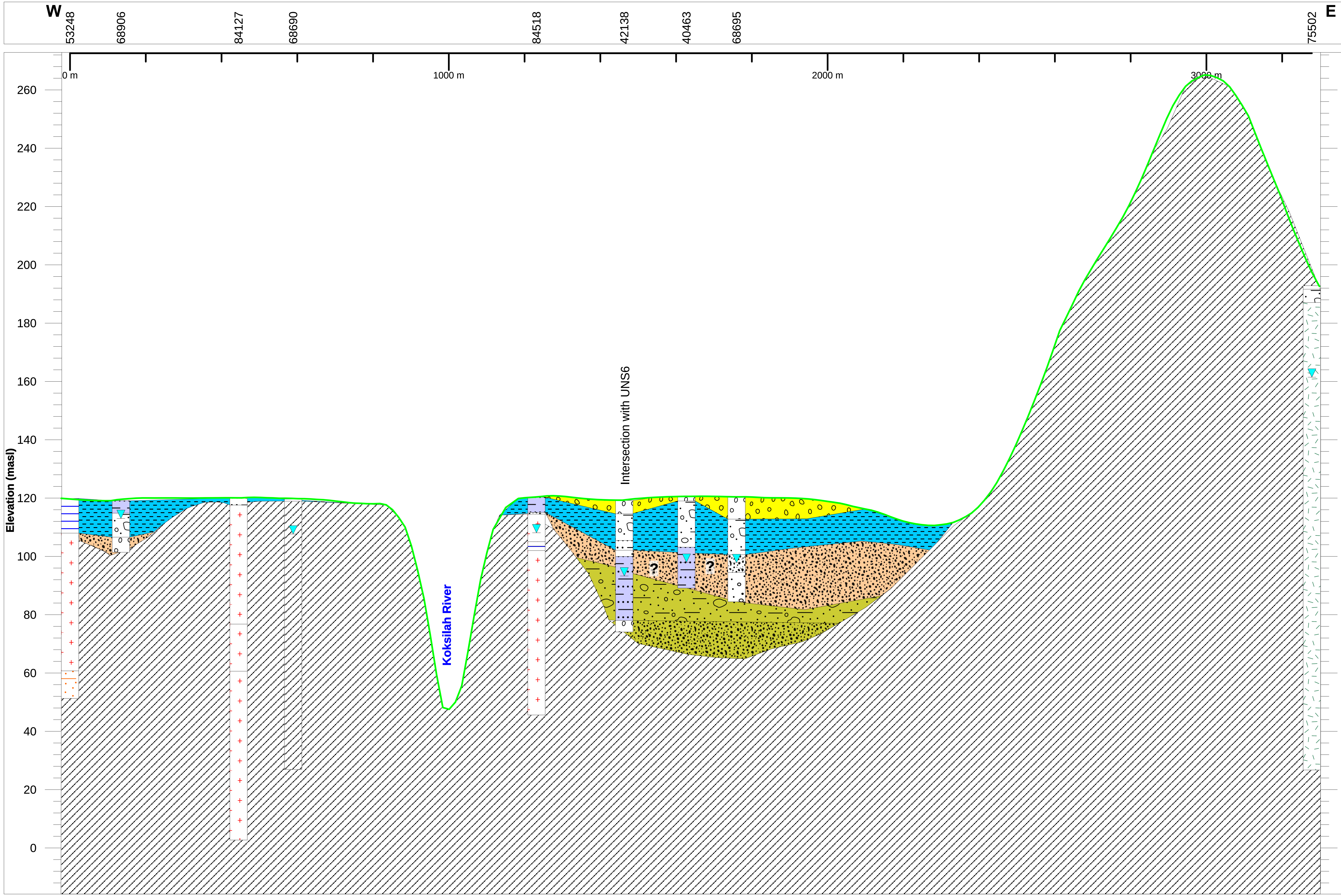
HYDROGEOLOGIC CROSS-SECTION UWE5

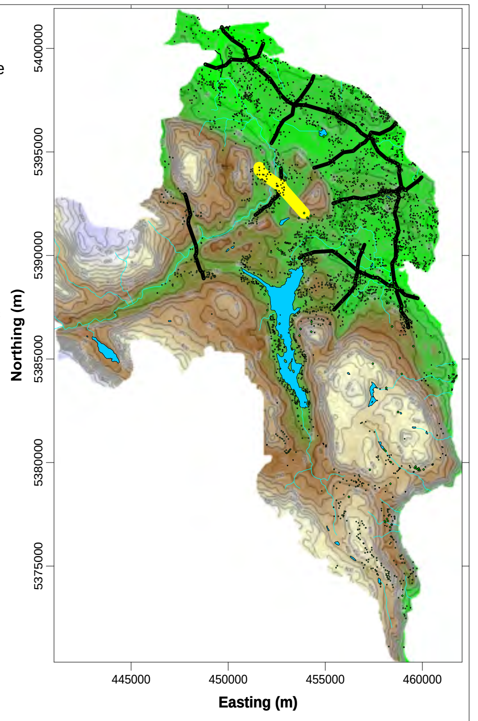
Date: 26-Mar-19	Drawn by: T.L.	Edited by: Z.H.	App'd by: J.C.

OneWay to zero harm
Advisian WorleyParsons Group

WorleyParsons Project No. 307071-01251

FIG No **UWE5** REV 1





Lithology

- fill
- undefined
- unconsolidated
- boulder
- clay
- dirty gravel
- gravel
- peat
- sand
- sand & gravel
- dirty sand & gravel
- silt
- till
- bedrock
- sedimentary
- argillite
- conglomerate
- limestone
- sandstone
- shale
- siltstone
- metamorphic
- marble
- schist
- quartz
- quartzite
- igneous
- diorite
- granite
- volcanic
- basalt

Stratigraphy

- Deltaic/Fluvial Deposits
- Capilano (Marine)/Vashon Drift
- Quadra Sand
- Dashwood Drift
- Dashwood Sand & Gravel
- Bedrock

- Water level
- Borehole fracture zone

Vertical exaggeration: 8

This cross-section shows interpreted geology based on data from discrete locations and professional judgement. Deviations in the type and location of material are expected.

BRITISH COLUMBIA MINISTRY OF ENVIRONMENT
STAGE II DETAILED AQUIFER MAPPING STUDY
SHAWNIGAN LAKE AREA, VANCOUVER ISLAND, B.C.

HYDROGEOLOGIC CROSS-SECTION UWE6

Date: 26-Mar-19	Drawn by: T.L.	Edited by: Z.H.	App'd by: J.C.

WorleyParsons Project No. 307071-01251

FIG No **UWE6** REV 1

APPENDIX C. AQUIFER MAPPING REPORTS

1. AQUIFER DESCRIPTION FOR AQUIFER 198

Aquifer Name: Cowichan Bay

Date of Mapping: November 2018

1.1 Conceptual Understanding of Hydrostratigraphy

1.1.1 Aquifer Extents

The aquifer is bound in the north by the Cowichan River. The western aquifer boundary follows the lower watershed extents for Holt Creek and Glenora Creek (Freshwater Atlas). The southern extent aligns with the mapped geologic boundary between Wrangellian rocks and Nanaimo Group sedimentary rocks (Cui et al. 2017). Bedrock aquifer extents assume near-surface flow within the bedrock to justify the use of topographical features.

1.1.2 Geologic Formation (Overlying Materials)

Glacial sediments from Dashwood Drift, Quadra Sands, Vashon till, and Capilano Sediments overlie the aquifer. Dashwood Drift tills interbedded with lenses of sands and gravels that are inferred to be discontinuous generally overlie bedrock with patchy distribution particularly along the southeastern extent. A large erosional remnant of Quadra Sand with deposits up to 70 m underlies a whaleback-shaped topographic ridge within the central portion of the aquifer. Deposits thin to approximately 10 m in the north and south but increase to 40m along the boundary with Wrangellian rocks. The thickness of marine Capilano Sediments is typically less than 5 m but combined with the Vashon till the total thickness can reach 20 m.

1.1.3 Geologic Formation (Aquifer) –5a Fractured Sedimentary Rock

The aquifer material consists of Nanaimo Group sedimentary rocks deposited in nearshore and marine environments along the east margin of Wrangellia Terrane. Conglomerate, coarse to fine sandstone, siltstone, shale and coal are characteristic of this group (Cui et al. 2017). Nanaimo Group rocks have been folded and faulted subsequent to deposition; however, they have not been subjected to elevated temperatures and pressures, and thus are believed to retain much of their original porosity.

1.1.4 Vulnerability - Low

The DRASTIC method was used to complete intrinsic groundwater vulnerability mapping as part of the Vancouver Island Water Resources Vulnerability Mapping Project (Newton and Gilchrist, 2010). However, this intrinsic vulnerability analysis was applied to the upper-most aquifer which does not apply. As such, aquifer vulnerability was based on thickness and extent of geologic materials above the aquifer, depth to water table (or top of confined aquifer), and aquifer material.

Well lithology records indicate one or more confining units of low permeability material (till, clay) exists across the majority of well locations. The combined thickness of confining units ranges approximately from 1 m to 80 m thick but is typically 10 m thick. The confining layer thins or may be absent along the southern extent of the aquifer. Water-bearing fracture zones are typically 75 m deep based on the median depth of existing wells. The hydraulic conductivity of the aquifer itself is assumed to be relatively low. Based on this description, the vulnerability of the aquifer to surface contamination is low.

The coastal setting of the aquifer makes it vulnerable to saltwater intrusion. Saltwater has been noted in several bedrock wells in this area.

1.2 Conceptual Understanding of Flow Dynamics

1.2.1 Groundwater Levels and Flow Direction

Water levels are considered shallow based on a geometric mean of 10.5 m with a range of 0.06 to 91.4 m. Artesian conditions were noted in a few wells.

Groundwater is inferred to flow east towards Cowichan Bay where a saltwater-freshwater interface is expected to exist. Groundwater flow is expected in the sandstone-dominated formations of the Nanaimo Group predominantly through bedrock deformities (e.g. fractures, bedding planes) and to a lesser extent through intergranular pore spaces.

Mapped faults are inferred as enhanced permeability areas; however, they could potentially reduce permeability and create barriers to groundwater flow or act as combined conduit-barrier systems. Additional studies are required to confirm fault zone hydrogeology.

1.3 Recharge

Regional recharge is likely to occur within the mountainous terrain where precipitation infiltrates through bedrock deformities, such as fractures. Mountain block recharge along the bedrock contact with Quaternary deposits may contribute to some recharge. Leakage from overlying unconsolidated deposits may also occur. Recharge from surface water features may also occur where the thickness of surficial materials is thin (e.g. Koksilah River, Patrolas Creek, and Kelvin Creek).

1.3.1 Potential for Hydraulic Connection

Connection with surface water features may be possible where surficial material coverage is thinner (e.g. Koksilah River, Patrolas Creek). The bedrock surface is inferred to be below sea level in the central portion and along the eastern boundary of the aquifer. The extent of any hydraulic connection with seawater along the coastline, mapped faults, overlying unconsolidated aquifer, and the contact with Wrangellia rocks is unknown.

1.4 Additional Information on Water Use and Management

Based on regional land-use, all groundwater use is expected to be conjunctive (drinking water, commercial/industrial and agricultural). Water quality remarks in a few wells, including salty water, odour, and sulphur issues. Deepening of a few wells is also noted. Mapping of local water systems for the region is available from the Cowichan Valley Regional District (cvrdnewnormalcowichan.ca). Additional water use in the area includes licensed diversion of water from local creeks and springs.

1.5 Additional Assessments or Management Actions:

The following groundwater characterization studies have been completed using analytical methods:

- Carmichael, V., March 2014. Compendium of Re-evaluated Pumping Tests in the Cowichan Valley Regional District, Vancouver Island, British Columbia. Environmental Sustainability Division, Ministry of Environment.
- Harris, M. & S. Usher, October 2017. Preliminary Groundwater Budgets, Cobble Hill/Mill Bay Area, Vancouver Island, BC.
- Ministry of Environment (MOE), February 2006. Shawnigan-Goldstream Water Allocation Plan.
- Ministry of Environment and Parks, September 1986. Cowichan-Koksilah Water Management Plan.

- Newton, P. & A. Gilchrist, April 2010. Technical Summary of Intrinsic Vulnerability Mapping Methods for Vancouver Island.
- van der Gulik, T., Neilsen, D., Fretwell, R. and Tam, S. June 2013. Agricultural Water Demand Model, Report for the Cowichan Valley Regional District. Victoria, BC: BC Ministry of Agriculture and Agriculture and Agri-Food Canada.
  WorleyParsons, February 2009. South Cowichan Water Plan Study: A Preliminary Assessment of Water Supply & Needs within the South Cowichan Region.

1.6 Aquifer References

Blyth, H. E., N.W. Rutter, & L.M. Sankeralli, 1993. Surficial geology of the Shawnigan Lake Area. Victoria, BC: BC Ministry of Energy and Mines.

Cowichan Valley Regional District http://cvrdnewnormalcowichan.ca/water-systems/ - accessed March 2019.

Cui, Y., D. Miller, P. Schiarizza, & L.J. Diakow, 2017. British Columbia digital geology. British Columbia Ministry of Energy, Mines and Petroleum Resources, British Columbia Geological Survey Open File 2017-8, 9p.

Geographic datasets from the BC Data Catalogue, accessed February 2017 https://data.gov.bc.ca/

Hammond, Z.M., A.C. Hinnell, J.J. Clague. 2018. Stage II Detailed Aquifer Mapping Study: Shawnigan Lake Area, Vancouver Island, B.C. Water Science Series, WSS2019-02. Prov. B.C., Victoria B.C.

2. AQUIFER DESCRIPTION FOR AQUIFER 202

Aquifer Name: Koksilah River Valley

Date of Mapping: November 2018

2.1 Conceptual Understanding of Hydrostratigraphy

2.1.1 Aquifer Extents

The northeastern aquifer extent aligns with the mapped geologic boundary between Wrangellian rocks and Nanaimo Group sedimentary rocks (Cui et al. 2017). Mapped limestone units (limited extent) have been grouped with Wrangellian rocks to facilitate groundwater management. The northwestern limits of the aquifer partially follows the Kelvin Creek watershed (Freshwater Atlas) and then continues along the 200 m elevation contour within the Koksilah River valley. The southwestern aquifer boundary coincides with the extent of existing wells. The southeastern aquifer boundary follows the Koksilah River watershed (Freshwater Atlas). Bedrock aquifer extents assume near-surface flow within the bedrock to justify the use of topographical features.

2.1.2 Geologic Formation (Overlying Materials)

A blanket of Vashon till deposits exists in the central portion of the aquifer. Glaciofluvial sands and glaciolacustrine clays/silts are found near the eastern boundary. Near surface bedrock (<1 m) has also been mapped within portions of the aquifer area.

2.1.3 Geologic Formation (Aquifer) – 6b Fractured Crystalline Rock

The Sicker Group (Duck Lake Formation) and Island Plutonic Suite are the primary bedrock units that have been mapped within the aquifer (Cui et. al. 2017). The Duck Lake Formation includes pillowed and massive basalt flows, monolithic basalt breccia and pillow breccia, chert, jasper and cherty tuff, felsic tuffs, massive dacite and rhyolite, magnetite-hematite-chert iron formation. The intrusive rocks of the Island Plutonic Suite include granodiorite, quartz diorite, quartz monozonite, diorite, agmatite, feldspar, feldspar porphyry, as well as minor gabbro and aplite.

A small portion of the aquifer also includes sedimentary rocks from the Buttle Lake Group (Mount Mark Formation) including massive crinoidal limestone, bedded calcirudite and calcerenite, chert, cherty argillite and siltstone, and marble.

Several faults, including the San Juan fault, have been mapped in the area.

2.1.4 Vulnerability - Moderate

The DRASTIC method was used to complete intrinsic groundwater vulnerability mapping as part of the Vancouver Island Water Resources Vulnerability Mapping Project (Newton and Gilchrist, 2010). The intrinsic vulnerability for the majority of the area was classified as low to moderate. Areas classified as high vulnerability may be associated with potential surficial deposits based on existing surficial geology mapping (Blyth et al 1993).

Well lithology records indicate a confining layer of low permeability material (till, clay) exists, ranging from approximately 1 to 55 m thick but typically 5 m thick. However, the confining layer may be laterally discontinuous or localized within the aquifer extents. Water-bearing fracture zones are typically 85 m deep based on the median depth of existing wells. The hydraulic conductivity of the aquifer itself is assumed to be relatively low. Based on this description, the vulnerability of the aquifer to surface contamination is moderate.

2.2 Conceptual Understanding of Flow Dynamics

2.2.1 Groundwater Levels and Flow Direction

Water levels are considered shallow based on a geometric mean of 11.1 m with a range of 0.9 to 167.6 m. Artesian conditions were noted in a few wells.

Groundwater is inferred to flow towards the Koksilah River valley and then easterly along the valley bottom along bedding planes and through bedrock deformities (e.g. fractures). Groundwater flow may also occur at depth and across adjacent surface watersheds.

Mapped faults are inferred as enhanced permeability areas; however, they could potentially reduce permeability and create barriers to groundwater flow or act as combined conduit-barrier systems. Additional studies are required to confirm fault zone hydrogeology.

2.3 Recharge

Regional recharge is likely to occur within the mountainous terrain where precipitation infiltrates through bedrock deformities, such as fractures. Mountain block recharge along the bedrock contact with Quaternary deposits may contribute to some recharge. The Koksilah River could contribute to recharge given that it has deeply incised the bedrock within the valley bottom.

2.3.1 Potential for Hydraulic Connection

The Koksilah River has deeply incised the bedrock along the trajectory of the San Juan fault. Additional studies are required to determine surface water/groundwater interactions. The extent of any hydraulic connection with mapped faults is also unknown.

2.4 Additional Information on Water Use and Management

Based on regional land-use, all groundwater use is expected to be conjunctive (drinking water, commercial/industrial and agricultural). Water quality remarks associated with a few wells noted odour, sulphur and iron.

Mapping of local water systems for the region is available from the Cowichan Valley Regional District (cvrdnewnormalcowichan.ca). Additional water use in the area includes licensed diversion of water from local creeks and springs.

2.5 Additional Assessments or Management Actions:

The following groundwater characterization studies have been completed based on analytical methods:

- Carmichael, V., March 2014. Compendium of Re-evaluated Pumping Tests in the Cowichan Valley Regional District, Vancouver Island, B.C. Environmental Sustainability Division, Ministry of Environment.
- Harris, M. & S. Usher, October 2017. Preliminary Groundwater Budgets, Cobble Hill/Mill Bay Area, Vancouver Island, B.C.
- Newton, P. & A. Gilchrist, April 2010. Technical Summary of Intrinsic Vulnerability Mapping Methods for Vancouver Island.
- Ministry of Environment (MOE), February 2006. Shawnigan-Goldstream Water Allocation Plan.
- Ministry of Environment and Parks, September 1986. Cowichan-Koksilah Water Management Plan.

- van der Gulik, T., Neilsen, D., Fretwell, R. and Tam, S. June 2013. Agricultural Water Demand Model, Report for the Cowichan Valley Regional District. Victoria, B.C.: BC Ministry of Agriculture and Agriculture and Agri-Food Canada.
- WorleyParsons, February 2009. South Cowichan Water Plan Study: A Preliminary Assessment of Water Supply & Needs within the South Cowichan Region.

2.6 Additional Aquifer References

Blyth, H. E., N.W. Rutter, & L.M. Sankeralli, 1993. Surficial geology of the Shawnigan Lake Area. Victoria, BC: BC Ministry of Energy and Mines.

Cowichan Valley Regional District http://cvrdnewnormalcowichan.ca/water-systems/ - accessed March 2019.

Cui, Y., D. Miller, P. Schiarizza, & L.J. Diakow, 2017. British Columbia digital geology. British Columbia Ministry of Energy, Mines and Petroleum Resources, British Columbia Geological Survey Open File 2017-8, 9p.

Geographic datasets from the BC Data Catalogue, accessed February 2017 https://data.gov.bc.ca/

Hammond, Z.M., A.C. Hinnell, J.J. Clague. 2018. Stage II Detailed Aquifer Mapping Study: Shawnigan Lake Area, Vancouver Island, B.C. Water Science Series, WSS2019-02. Prov. B.C., Victoria B.C.

3. AQUIFER DESCRIPTION FOR AQUIFER 203

Aquifer Name: Shawnigan Lake/ Cobble Hill/ Mill Bay

Date of Mapping: November 2018

3.1 Conceptual Understanding of Hydrostratigraphy

3.1.1 Aquifer Extents

The majority of the aquifer extents follow the Shawnigan Creek watershed (Freshwater Atlas). The northeast extent aligns with the mapped geologic boundary between Wrangellian rocks and Nanaimo Group sedimentary rocks (Cui et al. 2017). Mapped limestone units (limited extent) have been grouped with Wrangellian rocks to facilitate groundwater management efforts. A portion of the northeast aquifer boundary also follows the coastline of Saanich Inlet. Bedrock aquifer extents assume near-surface flow within the bedrock to justify the use of topographical features.

3.1.2 Geologic Formation (Overlying Materials)

Overlying material varies from a veneer of colluvium to 60 m thick glacial sediments from the Dashwood Drift, Quadra Sands, Vashon t, and Capilano Sediments. Bedrock outcrops or where bedrock is overlain by a veneer of surficial material have been mapped to the east and west of Shawnigan Lake. Thicker deposits are typically found within the inferred bedrock valley along the eastern extents of the aquifer.

3.1.3 Geologic Formation (Aquifer) – 6b Fractured Crystalline

Bedrock consists of granitic rocks of the Westcoast Crystalline Complex, basaltic volcanic rocks of the Bonanza Group, sedimentary rocks from the Sicker Group, and intrusive igneous rock from the Island Plutonic Suite (Cui et. al. 2017).

A small portion of the aquifer also includes sedimentary rocks from the Buttle Lake Group (Mount Mark Formation) and Vancouver Group (Quatsino Formation) including massive crinoidal limestone, bedded calcirudite and calcerenite, chert, cherty argillite and siltstone, and marble.

There are several faults, including the San Juan fault, within the aquifer boundary.

3.1.4 Vulnerability - Moderate

The DRASTIC method was used to complete intrinsic groundwater vulnerability mapping as part of the Vancouver Island Water Resources Vulnerability Mapping Project (Newton and Gilchrist, 2010). The intrinsic vulnerability for the majority of the area was classified as low to moderate. Areas classified as high vulnerability are associated with potential aquifers in surficial deposits and do not apply to the bedrock aquifer.

Well lithology records indicate a confining layer of low permeability material (till, clay) exists, ranging from approximately 1 to 60 m thick but typically 5 m thick. However, the confining layer may be thin or absent in some areas. Water-bearing fracture zones are typically 80 m deep based on the median depth of existing wells. The hydraulic conductivity of the aquifer material is assumed to be relatively low (i.e. fracture dominated flow in the aquifer). Based on this description, the vulnerability of the aquifer to surface contamination is moderate.

3.2 Conceptual Understanding of Flow Dynamics

3.2.1 Groundwater Levels and Flow Direction

Water levels are considered shallow based on a geometric mean depth to water of 7.1 m with a range of 0.3 to 121.9 m. The wells are predominantly located in the lowland areas near surface water features. Deeper water levels likely occur for wells in the upland areas. Artesian conditions were noted in several wells.

Groundwater is inferred to flow east towards the coastline, with local contributions towards Shawnigan Lake, predominantly through bedrock deformities (e.g. fractures). A saltwater-freshwater interface is expected to exist along the coastline. Groundwater flow may also occur at depth and across adjacent surface watersheds.

Mapped faults are inferred as enhanced permeability areas; however, they could potentially reduce permeability and create barriers to groundwater flow or act as combined conduit-barrier systems. Additional studies are required to confirm fault zone hydrogeology.

3.3 Recharge

Regional recharge is likely to occur within the mountainous terrain where precipitation infiltrates through bedrock deformities, such as fractures. Mountain block recharge along the bedrock contact with Quaternary deposits may contribute to some recharge. Leakage from overlying unconsolidated deposits may also occur. Recharge from surface water features may occur where the thickness of surficial materials is thin (e.g. Shawnigan Creek, Handysen Creek and Hollings Creek).

3.3.1 Potential for Hydraulic Connection

Shawnigan Creek is a significant watershed in the area (MOE 2006). Additional studies are required to confirm/determine surface water/groundwater interactions with Shawnigan Lake and drainage features in the area. The extent of hydraulic connections with seawater along the coastline, mapped faults, and the overlying unconsolidated aquifers are unknown.

3.4 Additional Information on Water Use and Management

Based on regional land-use, all groundwater use is expected to be conjunctive (drinking water, commercial/industrial and agricultural). Water quality remarks in a few well records identified odour, iron, and sulphur issues. Deepening of a few wells was also noted.

Mapping of local water systems for the region is available from the Cowichan Valley Regional District (cvrdnewnormalcowichan.ca). Additional water use in the area includes licensed diversion of water from local creeks and springs.

There are three active Provincial observation wells (OW# 380, 439, and 470).

3.5 Additional Assessments or Management Actions

The following groundwater characterization studies have been completed based on analytical methods:

- Carmichael, V., March 2014. Compendium of Re-evaluated Pumping Tests in the Cowichan Valley Regional District, Vancouver Island, British Columbia. Environmental Sustainability Division, Ministry of Environment.
- Harris, M. & S. Usher, October 2017. Preliminary Groundwater Budgets, Cobble Hill/Mill Bay Area, Vancouver Island, BC.

- Kwong, J., January 1987. Summary of field sampling in September 1985 to assess residents ongoing concerns of saltwater intrusion of groundwater sources, Mill Bay Area, Shawnigan Land District. Groundwater Section, 29 pages, NTS Map 092B12.
- Ministry of Environment (MOE), February 2006. Shawnigan-Goldstream Water Allocation Plan.
- Ministry of Environment and Parks, September 1986. Cowichan-Koksilah Water Management Plan.
- Newton, P. & A. Gilchrist, April 2010. Technical Summary of Intrinsic Vulnerability Mapping Methods for Vancouver Island.
- van der Gulik, T., Neilsen, D., Fretwell, R. and Tam, S. June 2013. Agricultural Water Demand Model, Report for the Cowichan Valley Regional District. Victoria, BC: BC Ministry of Agriculture and Agriculture and Agri-Food Canada.
- WorleyParsons, February 2009. South Cowichan Water Plan Study: A Preliminary Assessment of Water Supply & Needs within the South Cowichan Region.

Chloride concentrations ranged from 14 to 209 mg/L in groundwater from bedrock wells in the Mill Bay area based on sampling conducted in 1985 (Kwong 1987). The report concluded saltwater movement occurs in the bedrock aquifers but the source of saltwater was unknown.

3.6 Aquifer References

Blyth, H. E., N.W. Rutter, & L.M. Sankeralli, 1993. Surficial geology of the Shawnigan Lake Area. Victoria, BC: BC Ministry of Energy and Mines.

Cowichan Valley Regional District http://cvrdnewnormalcowichan.ca/water-systems/ - accessed March 2019.

Cui, Y., D. Miller, P. Schiarizza, & L.J. Diakow, 2017. British Columbia digital geology. British Columbia Ministry of Energy, Mines and Petroleum Resources, British Columbia Geological Survey Open File 2017-8, 9p.

Geographic datasets from the BC Data Catalogue, accessed February 2017 https://data.gov.bc.ca/

Hammond, Z.M., A.C. Hinnell, J.J. Clague. 2018. Stage II Detailed Aquifer Mapping Study: Shawnigan Lake Area, Vancouver Island, B.C. Water Science Series, WSS2019-02. Prov. B.C., Victoria B.C.

4. AQUIFER DESCRIPTION FOR AQUIFER 208

Aquifer Name: Malahat Ridge

Date of Mapping: November 2018

4.1 Conceptual Understanding of Hydrostratigraphy

4.1.1 Aquifer Extents

The aquifer is located along the east and southeast slopes of Malahat Ridge. The aquifer is bound along the east by Saanich Inlet. The western aquifer extents follow the watershed boundaries for Shawnigan Creek and Goldstream River (Freshwater Atlas). Bedrock aquifer extents assume near-surface flow within the bedrock to justify the use of topographical features.

4.1.2 Geologic Formation (Overlying Materials)

Near surface bedrock (less than 1 m below surface) has been mapped within the majority of the aquifer area. A blanket of till and clay inferred to be Vashon till exists where surficial materials are present. Capilano Sediments consisting of gravel, sand, and clayey silt may overlie till at elevations below 100 to 150 masl.

4.1.3 Geologic Formation (Aquifer) – 6b Fractured Crystalline Rock

Bedrock belonging to Bonanza Group, Island Plutonic Suite, Westcoast Crystalline Complex, and Leech River Complex have been mapped within the aquifer extents along with several faults (Cui et. al. 2017).

Volcanic rocks of the Bonanza Group (erupted on land) include massive amygdaloidal and pillowed basalt to andesite flows, dacite to rhyolite massive or laminated lava, green and maroon tuff, fledspar crystal tuff, breccia, tuffaceous sandstone, argillite, pebble conglomerate and minor limestone.

The intrusive rocks of the Island Plutonic Suite include granodiorite, quartz diorite, quartz monozonite, diorite, agmatite, feldspar, feldspar porphyry, as well as minor gabbro and aplite.

Intrusive rocks of Westcoast Crystalline Complex include quartz diorite, tonalite, hornblende-plagioclase gneiss, quartz-feldspar gneiss, amphibolite, diorite, agmatite, gabbro, marble, and metasediments.

Volcanic rocks of the Leech River Complex consist of metabasalt, metarhyolite, chlorite schist, ribbon chert, and cherty argillite.

4.1.4 Vulnerability - Moderate

The DRASTIC method was used to complete intrinsic groundwater vulnerability mapping as part of the Vancouver Island Water Resources Vulnerability Mapping Project (Newton and Gilchrist, 2010). The intrinsic vulnerability for the majority of the area was classified as low to moderate.

Well lithology records indicate a confining layer of low permeability material (till, clay) exists, ranging from approximately 1 to 24 m thick but typically 5 m thick. However, the confining layer may be thin or absent in some areas. Water-bearing fracture zones are typically 90 m deep based on the median depth of existing wells. The hydraulic conductivity of the aquifer material is assumed to be relatively low (i.e. fracture dominated flow in the aquifer) Based on this description, the vulnerability of the aquifer to surface contamination is moderate.

4.2 Conceptual Understanding of Flow Dynamics

4.2.1 Groundwater Levels and Flow Direction

Water levels are considered shallow based on an average of 14.3 m with a range of 0.6 to 131.1 m. Groundwater is inferred to flow east towards Saanich Inlet predominantly through bedrock deformities (e.g. fractures). A saltwater-freshwater interface is expected to exist along the coastline. Groundwater flow may also occur at depth and across adjacent surface watersheds.

Mapped faults are inferred as enhanced permeability areas; however, they could potentially reduce permeability and create barriers to groundwater flow or act as combined conduit-barrier systems. Additional studies are required to confirm fault zone hydrogeology.

4.3 Recharge

Recharge is likely to occur where precipitation or runoff infiltrates through bedrock deformities, such as fractures. Lakes and wetlands in the mountainous area to the west may also act as a source of recharge.

4.3.1 Potential for Hydraulic Connection

Significant watersheds in the area include Arbutus Creek, Irving Creek, Johns Creek, and Spectacle Creek (MOE 2006). Additional studies are required to confirm/determine surface-ground water interactions for drainage features in the area. The extent of any hydraulic connections with seawater along the coastline and mapped faults is unknown.

4.4 Additional Information on Water Use and Management

Based on regional land-use, all groundwater use is expected to be conjunctive (drinking water, commercial/industrial and agricultural). Well records indicate a potential for sulphur odour. Deepening of a few wells is also noted.

Mapping of local water systems for the region is available from the Cowichan Valley Regional District (cvrdnewnormalcowichan.ca). Additional water use in the area includes licensed diversion of water from local creeks and springs.

4.5 Additional Assessments or Management Actions

The following groundwater characterization studies have been completed based on analytical methods:

- Carmichael, Vicki, March 2014. Compendium of Re-evaluated Pumping Tests in the Cowichan Valley Regional District, Vancouver Island, British Columbia. Environmental Sustainability Division, Ministry of Environment.
- Harris, M. & S. Usher, October 2017. Preliminary Groundwater Budgets, Cobble Hill/Mill Bay Area, Vancouver Island, BC.
- Ministry of Environment (MOE), February 2006. Shawnigan-Goldstream Water Allocation Plan.
- Newton, P. & A. Gilchrist, April 2010. Technical Summary of Intrinsic Vulnerability Mapping Methods for Vancouver Island.
- van der Gulik, T., Neilsen, D., Fretwell, R. and Tam, S. June 2013. Agricultural Water Demand Model, Report for the Cowichan Valley Regional District. Victoria, BC: BC Ministry of Agriculture and Agriculture and Agri-Food Canada.
- WorleyParsons, February 2009. South Cowichan Water Plan Study: A Preliminary Assessment of Water Supply & Needs within the South Cowichan Region.

4.6 Aquifer References

Blyth, H. E., N.W. Rutter, & L.M. Sankeralli, 1993. Surficial geology of the Shawnigan Lake Area. Victoria, BC: BC Ministry of Energy and Mines.

Cowichan Valley Regional District http://cvrdnewnormalcowichan.ca/water-systems/ - accessed March 2019.

Cui, Y., D. Miller, P. Schiarizza, & L.J. Diakow, 2017. British Columbia digital geology. British Columbia Ministry of Energy, Mines and Petroleum Resources, British Columbia Geological Survey Open File 2017- 8, 9p.

Geographic datasets from the BC Data Catalogue, accessed February 2017 https://data.gov.bc.ca/

Hammond, Z.M., A.C. Hinnell, J.J. Clague. 2018. Stage II Detailed Aquifer Mapping Study: Shawnigan Lake Area, Vancouver Island, B.C. Water Science Series, WSS2019-02. Prov. B.C., Victoria B.C.

5. AQUIFER DESCRIPTION FOR AQUIFER 197

Aquifer Name: Cherry Point

Date of Mapping: November 2018

5.1 Conceptual Understanding of Hydrostratigraphy

5.1.1 Aquifer Extents

The eastern aquifer boundary follows Saanich Inlet. The Cowichan River and Koksilah River respectively constrain the northern boundary and a portion of the western boundary of the aquifer. The other portion of the western boundary follows the extent of surficial geology mapping (Blyth et al. 1993) and a portion of the Shawnigan Lake watershed (Freshwater Atlas). The inland portion of the southern aquifer boundary generally follows an inferred bedrock ridge and corresponds to where surficial geology deposits are inferred to be limited.

5.1.2 Geologic Formation (Overlying Materials)

Vashon till and marine Capilano Sediments overly the aquifer. The thickness of marine Capilano Sediments is relatively thin (< 5 m) but combined with the Vashon till the total thickness can reach 40 m based on regional interpretation of geology (Hammond et al. 2019). In some areas, the aquifer may be also be overlain by clay and till associated with the Dashwood Drift.

5.1.3 Geologic Formation (Aquifer) – 4b Confined glacio-fluvial sand and gravel

The geologic formation of the aquifer generally consists of sand and gravel from Quadra Sand and Dashwood Drift geologic units. A large erosional remnant of the Quadra Sand unit underlies a whaleback-shaped ridge within the central portion of the aquifer extents (topographic high between Cowichan Bay and Cowichan Station). Quadra Sand is interpreted to overlie the Dashwood Drift. Sand and gravel is interbedded within Dashwood Drift or in some places is inferred to be in contact with the Quadra Sand unit.

5.1.4 Vulnerability - Moderate

The DRASTIC method was used to complete intrinsic groundwater vulnerability mapping as part of the Vancouver Island Water Resources Vulnerability Mapping Project (Newton and Gilchrist, 2010). A medium intrinsic vulnerability was calculated for a majority of the aquifer. High vulnerability areas are identified along the Koksilah River and south of Patrolas Creek and Garnett Creek.

Well lithology records indicate one or more confining units of low permeability material (till, clay) exists for the majority of well locations. The combined thickness of confining units ranges approximately from 1 m to 85 m thick but is typically 15 m thick. The confining material is inferred to be aerially extensive but may be thin or absent in some areas (e.g. closer to major drainage features such as Koksilah River). The depth to bottom of the deepest confining unit is typically moderately shallow (15 to 30 m). The hydraulic conductivity of the aquifer itself is assumed to be relatively high. Based on this description, the vulnerability of the aquifer to surface contamination is moderate.

The coastal setting of the aquifer makes it vulnerable to saltwater intrusion.

5.2 Conceptual Understanding of Flow Dynamics

5.2.1 Groundwater Levels and Flow Direction

Water levels are considered moderately shallow based on a geometric mean depth to water of 20.6 m with a range of 0.3 to 93 m. Artesian conditions were noted in a few wells.

Groundwater flow is anticipated to follow surface and/or bedrock topography and drain from areas of higher elevation to areas of lower elevation. Groundwater mounding could occur within the whaleback-shaped ridge (topographic high between Cowichan Bay and Cowichan Station) resulting in radial groundwater flow towards Saanich Inlet, Patrolas Creek/Koksilah River, and Garnett Creek.

Groundwater in the southeastern extent of aquifer likely flows towards Garnett Creek or Saanich Inlet. A number of springs occur in the area of the aquifer and could be associated with zones of groundwater discharge, indicating that groundwater levels are intersecting side slopes and not reaching local topographic low points.

A saltwater-freshwater interface is expected to exist where groundwater flows towards Saanich Inlet.

5.3 Recharge

Infiltration from precipitation and mountain block recharge (runoff from the mountainous terrane that infiltrates along the contact with unconsolidated materials) are expected to be the primary mechanisms for recharge. The presence of an overlying confining layer may limit the infiltration of precipitation or may result in leakage into the aquifer if saturated conditions develop above the confining layer.

5.3.1 Potential for Hydraulic Connection

Garnet Creek, Koksilah River and Patrolas Creek are the major watersheds in the vicinity of the aquifer (MOE 2006; and Ministry of Environment and Parks 1986). Thick clay/till, deposits up to 20 m thick interpreted in the area based on lithology from well records, may prevent direct connection of groundwater with surface water features. Additional studies are required to confirm/determine surface-ground water interactions for drainage features in the area. The extent of any hydraulic connection with seawater along the coastline are also not well understood.

5.4 Additional Information on Water Use and Management

Based on regional land-use, all groundwater use is expected to be conjunctive (drinking water, commercial/industrial and agricultural). Water quality remarks in a few well record identify odour, iron, and sulphur issues. Deepening of a few wells is also noted.

Mapping of local water systems for the region is available from the Cowichan Valley Regional District (cvrdnewnormalcowichan.ca). Additional water use in the area includes licensed diversion of water from local creeks and springs.

Three Provincial observation wells have been installed in this aquifer (OW# 233, 320, and 345).

5.5 Additional Assessments or Management Actions:

The following groundwater characterization studies have been completed based on analytical methods:

- Carmichael, V., March 2014. Compendium of Re-evaluated Pumping Tests in the Cowichan Valley Regional District, Vancouver Island, British Columbia. Environmental Sustainability Division, Ministry of Environment.

- Harris, M. & S. Usher, October 2017. Preliminary Groundwater Budgets, Cobble Hill/Mill Bay Area, Vancouver Island, BC.
- Ministry of Environment (MOE), February 2006. Shawnigan-Goldstream Water Allocation Plan.
- Ministry of Environment and Parks, September 1986. Cowichan-Koksilah Water Management Plan.
- Newton, P. & A. Gilchrist, April 2010. Technical Summary of Intrinsic Vulnerability Mapping Methods for Vancouver Island.
- Thurber Engineering Ltd. 2013. Fisher Road Groundwater Investigation, Cobble Hill, B.C. https://www.cvrd.bc.ca/DocumentCenter/View/9842/Fisher-Road-Groundwater-Investigation-Final-Report-2013.
- van der Gulik, T., Neilsen, D., Fretwell, R. and Tam, S. June 2013. Agricultural Water Demand Model, Report for the Cowichan Valley Regional District. Victoria, BC: BC Ministry of Agriculture and Agriculture and Agri-Food Canada.
- WorleyParsons, February 2009. South Cowichan Water Plan Study: A Preliminary Assessment of Water Supply & Needs within the South Cowichan Region.

5.6 Aquifer References

Blyth, H. E., N.W. Rutter, & L.M. Sankeralli, 1993. Surficial geology of the Shawnigan Lake Area. Victoria, BC: BC Ministry of Energy and Mines.

Cowichan Valley Regional District http://cvrdnewnormalcowichan.ca/water-systems/ - accessed March 2019.

Cui, Y., D. Miller, P. Schiarizza, & L.J. Diakow, 2017. British Columbia digital geology. British Columbia Ministry of Energy, Mines and Petroleum Resources, British Columbia Geological Survey Open File 2017-8, 9p.

Geographic datasets from the BC Data Catalogue, accessed February 2017 https://data.gov.bc.ca/

Hammond, Z.H., A.C. Hinnell, J.J. Clague. 2018. Stage II Detailed Aquifer Mapping Study: Shawnigan Lake Area, Vancouver Island, B.C. Water Science Series, WSS2019-02. Prov. B.C., Victoria B.C.

6. AQUIFER DESCRIPTION FOR AQUIFER 199

Aquifer Name: Fairbridge

Date of Mapping: November 2018

6.1 Conceptual Understanding of Hydrostratigraphy

6.1.1 Aquifer Extents

The northeast boundary of the aquifer follows the Koksilah River. The western aquifer boundary follows the Kelvin Creek watershed (Freshwater Atlas). The southwestern aquifer boundary aligns with surficial geology mapping of glacial fluvial deposits (Blyth et al. 1993).

6.1.2 Geologic Formation (Overlying Materials)

Capilano Sediments consisting of marine silts/clays and Vashon till overlie the aquifer. Holocene fluvial gravel, sand, or silt is found along the Koksilah River.

6.1.3 Geologic Formation (Aquifer) – 4b Confined glacio-fluvial sand and gravel

Aquifer material consists of sand and gravel of the Quadra Sand and/or Dashwood Drift.

6.1.4 Vulnerability - Moderate

The DRASTIC method was used to complete intrinsic groundwater vulnerability mapping as part of the Vancouver Island Water Resources Vulnerability Mapping Project (Newton and Gilchrist, 2010). A medium intrinsic vulnerability was calculated for a majority of the aquifer. High vulnerability areas were identified along the Koksilah River.

Well lithology records indicate a confining layer of low permeability material (till, clay) is present, ranging from approximately 1 to 25 m thick but typically 10 m thick. The confining material is inferred to be aerially extensive but may be thin or absent in some areas (e.g. closer to major drainage features such as Koksilah River). The depth to the bottom of the lowest confining unit is typically shallow (<15 m). The hydraulic conductivity of the aquifer is assumed to be relatively high. Based on this description, the vulnerability of the aquifer to surface contamination is moderate.

6.2 Conceptual Understanding of Flow Dynamics

6.2.1 Groundwater Levels and Flow Direction

Water levels are considered shallow based on a geometric mean depth to water of 7.1 m with a range of 0.3 to 46 m. Artesian conditions were noted at a few wells.

Groundwater flow is inferred to follow surface and/or bedrock topography and drain from areas of higher elevation to areas of lower elevation towards the Koksilah River.

6.3 Recharge

Infiltration from precipitation and mountain block recharge (runoff from the mountainous terrane that infiltrates along the contact with unconsolidated materials) are expected to be the primary mechanisms for recharge. The presence of an overlying confining layer may limit the infiltration of precipitation or may result in leakage into the aquifer if saturated conditions develop above the confining layer.

6.3.1 Potential for Hydraulic Connection

Koksilah River and a few unnamed creeks are located within the aquifer extents. Additional studies are required to confirm/determine the interaction between these features and groundwater in the area.

6.4 Additional Information on Water Use and Management

Based on regional land-use, all groundwater use is expected to be conjunctive (drinking water, commercial/industrial and agricultural).

Mapping of local water systems for the region is available from the Cowichan Valley Regional District (cvrdnewnormalcowichan.ca). Additional water use in the area includes licensed diversion of water from local creeks and springs.

6.5 Additional Assessments or Management Actions:

The following groundwater characterization studies have been completed based on analytical methods:

- Harris, M. & S. Usher, October 2017. Preliminary Groundwater Budgets, Cobble Hill/Mill Bay Area, Vancouver Island, BC.
- Ministry of Environment (MOE), February 2006. Shawnigan-Goldstream Water Allocation Plan.
- Ministry of Environment and Parks, September 1986. Cowichan-Koksilah Water Management Plan.
- Newton, P. & A. Gilchrist, April 2010. Technical Summary of Intrinsic Vulnerability Mapping Methods for Vancouver Island.
- van der Gulik, T., Neilsen, D., Fretwell, R. and Tam, S. June 2013. Agricultural Water Demand Model, Report for the Cowichan Valley Regional District. Victoria, BC: BC Ministry of Agriculture and Agriculture and Agri-Food Canada.
- WorleyParsons, February 2009. South Cowichan Water Plan Study: A Preliminary Assessment of Water Supply & Needs within the South Cowichan Region.

6.6 Aquifer References

Blyth, H. E., N.W. Rutter, & L.M. Sankeralli, 1993. Surficial geology of the Shawnigan Lake Area. Victoria, BC: BC Ministry of Energy and Mines.

Cowichan Valley Regional District http://cvrdnewnormalcowichan.ca/water-systems/ - accessed March 2019.

Cui, Y., D. Miller, P. Schiarizza, & L.J. Diakow, 2017. British Columbia digital geology. British Columbia Ministry of Energy, Mines and Petroleum Resources, British Columbia Geological Survey Open File 2017-8, 9p.

Geographic datasets from the BC Data Catalogue, accessed February 2017 https://data.gov.bc.ca/

Hammond, Z.H., A.C. Hinnell, J.J. Clague. 2018. Stage II Detailed Aquifer Mapping Study: Shawnigan Lake Area, Vancouver Island, B.C. Water Science Series, WSS2019-02. Prov. B.C., Victoria B.C.

7. AQUIFER DESCRIPTION FOR AQUIFER 201

Aquifer Name: Heather Bank

Date of Mapping: November 2018

7.1 Conceptual Understanding of Hydrostratigraphy

7.1.1 Aquifer Extents

The aquifer is located within the Koksilah River valley upstream of the river floodplain. The western aquifer boundary is based on surficial geology mapping of glaciolacustrine deposits (Blyth et al. 1993) and well extents. The northern boundary is based on the mapping of near surface bedrock (less than one metre below ground surface) and then extends to Koksilah River based on topography. The western boundary primarily follows the Koksilah River except for a section in the middle that is separated from the river by an inferred bedrock high. The southern boundary is based on well extents, surficial geology mapping and topography.

7.1.2 Geologic Formation (Overlying Materials)

Overlying materials consist of Vashon till and deltaic Capilano Sediments. Marine Capilano Sediments are not expected given that ground surface elevation corresponds to the approximate marine limit before isostatic rebounding (100 to 150 masl).

7.1.3 Geologic Formation (Aquifer) – 4a/4b Semi-confined glacio-fluvial sand and gravel

Aquifer material consists of Dashwood Drift sand and gravel possibly connected to Quadra Sand based on lithology from well records and regional interpretation of geology (Hammond et al. 2019).

7.1.4 Vulnerability - High

The DRASTIC method was used to complete intrinsic groundwater vulnerability mapping as part of the Vancouver Island Water Resources Vulnerability Mapping Project (Newton and Gilchrist, 2010). The intrinsic vulnerability for the aquifer area varied from low to high. The high vulnerability areas are mapped in the central portion of the aquifer.

Well lithology records indicate a confining layer of low permeability material (till, clay) exists at some locations, ranging from approximately 2 to 18 m thick but typically 15 m thick. Overlying aquifer materials are also described as find sands; therefore, the confining material is inferred to be thin or absent in some areas. The depth to water is shallow (<15 m) based on median water level values. The hydraulic conductivity of the aquifer is assumed to be relatively high. Based on this description, the vulnerability of the aquifer to surface contamination is high.

7.2 Conceptual Understanding of Flow Dynamics

7.2.1 Groundwater Levels and Flow Direction

Water levels are considered shallow based on a geometric mean depth to water of 7.2 m with a range of 1.5 to 39.6 m. No artesian conditions were noted.

Groundwater is inferred to flow in an oblique direction to the flow of the Koksilah River. In the central part of the aquifer, groundwater may flow north and/or south around the inferred bedrock high towards the Koksilah River.

7.3 Recharge

Recharge in the form of infiltration from precipitation is expected to be the primary mechanism for recharge. The presence of an overlying confining layer may limit the infiltration of precipitation or may result in "leakage" into the aquifer if saturated conditions develop above the confining layer.

7.3.1 Potential for Hydraulic Connection

The Koksilah River has deeply incised the bedrock along the trajectory of the San Juan fault. The majority of the aquifer is likely hydraulically connected to the Koksilah River with the exception of the section along the inferred local bedrock high. Additional studies are required to determine surface water/groundwater interactions.

7.4 Additional Information on Water Use and Management

Based on regional land-use, all groundwater use is expected to be conjunctive (drinking water, commercial/industrial and agricultural). Water quality remarks in a few well records include high iron.

Mapping of local water systems for the region is available from the Cowichan Valley Regional District (cvrdnewnormalcowichan.ca/water-systems/). Additional water use in the area includes licensed diversion of water from local creeks and springs.

7.5 Additional Assessments or Management Actions:

The following groundwater characterization studies have been completed based on analytical methods:

- Harris, M. & S. Usher, October 2017. Preliminary Groundwater Budgets, Cobble Hill/Mill Bay Area, Vancouver Island, BC.
- Ministry of Environment (MOE), February 2006. Shawnigan-Goldstream Water Allocation Plan.
- Ministry of Environment and Parks, September 1986. Cowichan-Koksilah Water Management Plan.
- Newton, P. and A. Gilchrist, April 2010. Technical Summary of Intrinsic Vulnerability Mapping Methods for Vancouver Island.
- van der Gulik, T., Neilsen, D., Fretwell, R. and Tam, S. June 2013. Agricultural Water Demand Model, Report for the Cowichan Valley Regional District. Victoria, BC: BC Ministry of Agriculture and Agriculture and Agri-Food Canada.
- WorleyParsons, February 2009. South Cowichan Water Plan Study: A Preliminary Assessment of Water Supply & Needs within the South Cowichan Region.

7.6 Aquifer References

Blyth, H. E., N.W. Rutter, & L.M. Sankeralli, 1993. Surficial geology of the Shawnigan Lake Area. Victoria, BC: BC Ministry of Energy and Mines.

Cowichan Valley Regional District http://cvrdnewnormalcowichan.ca/water-systems/ - accessed March 2019.

Cui, Y., D. Miller, P. Schiarizza, & L.J. Diakow, 2017. British Columbia digital geology. British Columbia Ministry of Energy, Mines and Petroleum Resources, British Columbia Geological Survey Open File 2017-8, 9p.

Geographic datasets from the BC Data Catalogue, accessed February 2017 https://data.gov.bc.ca/

Hammond, Z.H., A.C. Hinnell, J.J. Clague. 2018. Stage II Detailed Aquifer Mapping Study: Shawnigan Lake Area, Vancouver Island, B.C. Water Science Series, WSS2019-02. Prov. B.C., Victoria B.C.

8. AQUIFER DESCRIPTION FOR AQUIFER 205

Aquifer Name: Shawnigan Lake

Date of Mapping: November 2018

8.1 Conceptual Understanding of Hydrostratigraphy

8.1.1 Aquifer Extents

The aquifer boundary in contained within the Shawnigan Creek watershed and generally does not extend above an elevation of 150 m based on existing well extents.

8.1.2 Geologic Formation (Overlying Materials)

Marine Capilano Sediments and Vashon till overlies portions of the aquifer but this confining material is typically less than 10 m thick or inferred to be absent in some areas. Marine Capilano Sediments are not expected above an elevation of 150 m which is inferred to be the maximum relative elevation reached by the sea after glacial retreat. However, deltaic or fluvial sands and gravels of the Capilano Sediments may be present.

8.1.3 Geologic Formation (Aquifer) – 4a/b Semi-confined glacio-fluvial sand and gravel

Aquifer material consists of sand and gravel of the Quadra Sand or Dashwood Drift. The aquifer material is of variable thickness due to deposition of glacial sediments within erosional bedrock features.

8.1.4 Vulnerability - High

The DRASTIC method was used to complete intrinsic groundwater vulnerability mapping as part of the Vancouver Island Water Resources Vulnerability Mapping Project (Newton and Gilchrist, 2010). A medium intrinsic vulnerability was calculated for a majority of the aquifer.

Well lithology records indicate a confining layer of low permeability material (till, clay) exists, ranging from approximately 3 to 45 m thick but typically 10 m thick. However, the confining layer may be thin or absent in some areas of the aquifer. The depth to water is shallow (< 15 m) based on median water level values. The hydraulic conductivity of the aquifer is assumed to be relatively high. Based on this description, the vulnerability of the aquifer to surface contamination is high.

8.2 Conceptual Understanding of Flow Dynamics

8.2.1 Groundwater Levels and Flow Direction

Water levels are considered shallow based on a geometric mean depth to water of 14.3 m with a range of 1.5 to 71 m. No artesian conditions were noted.

Groundwater flow is inferred to follow surface and/or bedrock topography and drain from areas of higher elevation to areas of lower elevation, with flow ultimately discharging into Shawnigan Lake.

8.3 Recharge

Infiltration from precipitation and mountain block recharge (runoff from the mountainous terrane that infiltrates along the contact with unconsolidated materials) are expected to be the primary mechanisms for recharge. The presence of an overlying confining layer may limit the infiltration of precipitation or may result in leakage into the aquifer if saturated conditions develop above the confining layer.

8.3.1 Potential for Hydraulic Connection

Key surface water features include Shawnigan Lake, Shawnigan Creek, and McGee Creek. Additional studies are required to confirm/determine surface-ground water interactions.

8.4 Additional Information on Water Use and Management

Based on regional land-use, all groundwater use is expected to be conjunctive (drinking water, commercial/industrial and agricultural). Water quality remarks include high iron and deepening of well at a few locations.

Mapping of local water systems for the region is available from the Cowichan Valley Regional District (cvrdnewnormalcowichan.ca). Additional water use in the area includes licensed diversion of water from local creeks and springs.

8.5 Additional Assessments or Management Actions:

The following groundwater characterization studies have been completed based on analytical methods:

- Harris, M. & S. Usher, October 2017. Preliminary Groundwater Budgets, Cobble Hill/Mill Bay Area, Vancouver Island, BC.
- Ministry of Environment (MOE), February 2006. Shawnigan-Goldstream Water Allocation Plan.
- Ministry of Environment and Parks, September 1986. Cowichan-Koksilah Water Management Plan.
- Newton, P. & A. Gilchrist, April 2010. Technical Summary of Intrinsic Vulnerability Mapping Methods for Vancouver Island.
- van der Gulik, T., Neilsen, D., Fretwell, R. and Tam, S. June 2013. Agricultural Water Demand Model, Report for the Cowichan Valley Regional District. Victoria, BC: BC Ministry of Agriculture and Agriculture and Agri-Food Canada.
- WorleyParsons, February 2009. South Cowichan Water Plan Study: A Preliminary Assessment of Water Supply & Needs within the South Cowichan Region.

8.6 Aquifer References

Blyth, H. E., N.W. Rutter, & L.M. Sankeralli, 1993. Surficial geology of the Shawnigan Lake Area. Victoria, BC: BC Ministry of Energy and Mines.

Cowichan Valley Regional District http://cvrdnewnormalcowichan.ca/water-systems/ - accessed March 2019.

Cui, Y., D. Miller, P. Schiarizza, & L.J. Diakow, 2017. British Columbia digital geology. British Columbia Ministry of Energy, Mines and Petroleum Resources, British Columbia Geological Survey Open File 2017-8, 9p.

Geographic datasets from the BC Data Catalogue, accessed February 2017 https://data.gov.bc.ca/

Hammond, Z.H., A.C. Hinnell, J.J. Clague. 2018. Stage II Detailed Aquifer Mapping Study: Shawnigan Lake Area, Vancouver Island, B.C. Water Science Series, WSS2019-02. Prov. B.C., Victoria B.C.

9. AQUIFER DESCRIPTION FOR AQUIFER 206

Aquifer Name: Mill Bay

Date of Mapping: November 2018

9.1 Conceptual Understanding of Hydrostratigraphy

9.1.1 Aquifer Extents

The aquifer is situated in a bedrock depression infilled by glacial deposits that extends from Shawnigan Lake to Saanich Inlet. The aquifer bottom is defined by the contact with Wrangellian rocks. The western, southern, and a portion of the eastern boundary coincide with the inferred extent of surficial deposits based on lithology from existing wells. A portion of the eastern aquifer boundary follows Saanich Inlet. The northeastern aquifer boundary generally follows an inferred bedrock ridge and groundwater divide.

9.1.2 Geologic Formation (Overlying Materials)

Capilano Sediments consisting of marine silts/clays and Vashon till overlie portions of the aquifer and can be up to 30 m thick but is typically less than 5 m thick or inferred to be absent in some areas. Deltaic or fluvial deposits from the Capilano Sediments are interpreted at the higher elevations between 100 to 150 masl. This corresponds to the interpreted maximum elevation reached by the sea after glacial retreat.

9.1.3 Geologic Formation (Aquifer) – 4a/b Semi-confined glacio-fluvial sand and gravel

The geologic formation of the aquifer generally consists of sand and gravel from Quadra Sand and Dashwood Drift geologic units. Quadra Sand is interpreted to overlie the Dashwood Drift. Sand and gravel is interbedded within Dashwood Drift or in some places may be in contact with the Quadra Sand unit. The aquifer material can be of variable thickness due to deposition of glacial sediments within erosional bedrock features. Deposits within the upper elevations may be laterally discontinuous and separated by local bedrock ridges; however, ultimately the deposits are connected to the bottom valley.

9.1.4 Vulnerability - High

The DRASTIC method was used to complete intrinsic groundwater vulnerability mapping as part of the Vancouver Island Water Resources Vulnerability Mapping Project (Newton and Gilchrist, 2010). A medium intrinsic vulnerability was calculated for a majority of the aquifer. However, high vulnerability areas are identified along the western extent and in the southeast area of the aquifer. Low vulnerability was also calculated typically within the southern portion of the aquifer.

Well lithology records indicate a confining layer of low permeability material (till, clay) exists, ranging from approximately 1 to 60 m thick but typically 10 m thick. However, the confining layer may be thin or absent in some areas of the aquifer. The depth to water is moderately shallow (15 to 30 m) based on median water level values. The hydraulic conductivity of the aquifer itself is assumed to be relatively high. Based on this description, the vulnerability of the aquifer to surface contamination is high.

The coastal setting of this aquifer makes it vulnerable to saltwater intrusion.

9.2 Conceptual Understanding of Flow Dynamics

9.2.1 Groundwater Levels and Flow Direction

Water levels are considered moderately shallow based on a geometric mean water depth of 15.6 m with a range of 0.3 to 61.0 m. Artesian conditions were noted in four wells.

Groundwater flow is interpreted to follow surface and/or bedrock topography and drain from areas of higher elevation to areas of lower elevation. Ultimately groundwater flows towards Saanich Inlet where a saltwater-freshwater interface is expected to exist.

9.3 Recharge

Infiltration from precipitation and mountain block recharge (runoff from the mountainous terrane that infiltrates along the contact with unconsolidated materials) are expected to be the primary mechanisms for recharge. The presence of an overlying confining layer may limit the infiltration of precipitation or may result in leakage into the aquifer if saturated conditions develop above the confining layer.

9.3.1 Potential for Hydraulic Connection

Shawnigan Creek, Hollings Creek, and Handysen Creek are key drainage features. Some small lakes also exist within the aquifer boundary. Additional studies are required to confirm/determine the interactions between these features and groundwater. The extent of any hydraulic connection with seawater along the coastline is not well documented.

9.4 Additional Information on Water Use and Management

Based on regional land-use, all groundwater use is expected to be conjunctive (drinking water, commercial/industrial and agricultural). Water quality remarks include high iron and deepening of a few wells.

Mapping of local water systems for the region is available from the Cowichan Valley Regional District (cvrdnewnormalcowichan.ca). Additional water use in the area includes licensed diversion of water from local creeks and springs.

9.5 Additional Assessments or Management Actions:

The following groundwater characterization studies have been completed based on analytical methods:

- Carmichael, V., March 2014. Compendium of Re-evaluated Pumping Tests in the Cowichan Valley Regional District, Vancouver Island, British Columbia. Environmental Sustainability Division, Ministry of Environment.
- Harris, M. & S. Usher, October 2017. Preliminary Groundwater Budgets, Cobble Hill/Mill Bay Area, Vancouver Island, BC.
- Ministry of Environment (MOE), February 2006. Shawnigan-Goldstream Water Allocation Plan.
- Newton, P. & A. Gilchrist, April 2010. Technical Summary of Intrinsic Vulnerability Mapping Methods for Vancouver Island.
- van der Gulik, T., Neilsen, D., Fretwell, R. and Tam, S. June 2013. Agricultural Water Demand Model, Report for the Cowichan Valley Regional District. Victoria, BC: BC Ministry of Agriculture and Agriculture and Agri-Food Canada.
- WorleyParsons, February 2009. South Cowichan Water Plan Study: A Preliminary Assessment of Water Supply & Needs within the South Cowichan Region.

- Zubel, M., Oct 1985. Maps: Cobble Hill, Static Water Level, Overburden Thickness, Bedrock Elevation, Depth to Water, cross-section Lines.

9.6 Aquifer References

Blyth, H. E., N.W. Rutter, & L.M. Sankeralli, 1993. Surficial geology of the Shawnigan Lake Area. Victoria, BC: BC Ministry of Energy and Mines.

Cowichan Valley Regional District http://cvrdnewnormalcowichan.ca/water-systems/ - accessed March 2019.

Cui, Y., D. Miller, P. Schiarizza, & L.J. Diakow, 2017. British Columbia digital geology. British Columbia Ministry of Energy, Mines and Petroleum Resources, British Columbia Geological Survey Open File 2017-8, 9p.

Geographic datasets from the BC Data Catalogue, accessed February 2017 https://data.gov.bc.ca/

Hammond, Z.H., A.C. Hinnell, J.J. Clague. 2018. Stage II Detailed Aquifer Mapping Study: Shawnigan Lake Area, Vancouver Island, B.C. Water Science Series, WSS2019-02. Prov. B.C., Victoria B.C.