WATER SCIENCE SERIES

Aquifers 178 & 1287 Complex, Cowichan Valley, B.C. Stratigraphy and Characterization

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July 2024

BRITISH COLUMBIA

No. 2024-10

The **Water Science Series** are scientific technical reports relating to the understanding and management of B.C.'s water resources. The series communicates scientific knowledge gained through water science programs across B.C. government, as well as scientific partners working in collaboration with provincial staff. For additional information visit: http://www2.gov.bc.ca/gov/content/environment/air-land-water/water/water-science-data/water-science-series.

ISBN: 978-1-0399-0107-0

Citation:
van Everdingen, D., Barroso, S.L. and Wainwright, M. 2024. Aquifer 178/1287 Complex, Cowichan Valley B.C. - Stratigraphy and Characterization. *Water Science Series*, WSS2024-10. Province of British Columbia, Victoria.

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Cover Photograph:
Left: Folded, subvertical bedded shale with sandstone interbeds outcropping in Cowichan River at Marie Canyon;
Right: Bedrock to Unconsolidated contact at Marie Canyon (Wainwright, M. 2021)

Acknowledgements

Thank you to those who contributed to and reviewed this work, including Jessica Doyle (WLRS), Klaus Rathfelder (WLRS) and Mike Wei (Hydro-Geo-Logic). Funding for this work was provided by FLNR.

EXECUTIVE SUMMARY

A detailed characterization of groundwater conditions and stratigraphy was completed for an unconsolidated aquifer complex found on the north side of Cowichan River, east of Lake Cowichan, B.C. This assessment was completed to revise aquifer polygon mapping, and to improve understanding of groundwater conditions, including the hydraulic connectivity between the aquifers and adjacent surface water bodies, for the purpose of groundwater allocation decisions in this area.

The study area geology was summarized as Quaternary glacio-marine sediments overlying a sequence of glacio-lacustrine and glacio-marine sediments in turn overlying pre-glacial gravel overlying Nanaimo Group sandstone/shale bedrock. Based on geology, water well lithology data cross-sections were developed which helped to recognize two confined sand and gravel aquifers within the Quaternary sediments, one shallow (AQ178) and one deeper (AQ 1287).

Isopach maps based on limited water well lithology data were prepared to provide unit thicknesses for the two aquifers and over- and underlying confining units as well as bedrock topography. The area is underlain by a shale bedrock aquifer which has not been mapped but is likely an unmapped extension of AQ 945.

Average groundwater elevation in AQ 178 is 163 masl and that in AQ 1287 is 139 masl.

A provincial government observation well (OW) is in each aquifer: OW 429 in AQ 178 and OW 428 in AQ 1287. Water level measurements in the observation wells have the following characteristics: a downward directed vertical hydraulic gradient and the deeper OW 428 responds quickly to precipitation events whereas a median delay of 31 days is apparent in the data from OW 429 in AQ 178.

Groundwater flow is generally to the southwest toward the Cowichan River. The two aquifers are likely recharged from the uplands to the north and discharge from seeps along the north bank of the Cowichan River. There is potential for hydraulic connectivity between the two aquifers where the intervening confining unit thins as well as possibly to Mayo Creek where it may be incised into the material overlying the upper aquifer, AQ 178.

Next steps towards further hydrogeological characterization within the study area are identified to support sustainable groundwater management:

- Continued monitoring of the provincial observation wells, OW 428 and OW 429 to further help interpretation of the resulting water level patterns.
- Conduct a survey of streams in the study area to ascertain which if any are hydraulically connected to the shallow aquifer (AQ 178).
- Aquifer mapping to identify the bedrock aquifer beneath the study area as more bedrock wells are installed providing lithologic data would help to reconcile the AQ 182 and AQ 945 boundary beneath the study area.

CONTENTS

1. BACKGROUND

1.1 Introduction

The aquifer 178/1287 unconsolidated complex is located on the northern border of Cowichan River, approximately 9 km east of Cowichan Lake (Figure 1). Historical aquifer mapping had identified a confined aquifer (AQ 178) which was the source of water for most private domestic wells in this area. Several groundwater exploration programs in the 1990's to 2000's identified a deeper confined aquifer that was proposed as a source of water for new residential developments. The deeper aquifer has been mapped as Aquifer 1287 (AQ 1287) as part of this study (Appendices A and B contain the mapping reports for AQ 178 and AQ 1287, respectively; provincial aquifer mapping reports and fact sheets; Province of B.C., 2023a and Province of B.C., 2023b).

1.2 Objective

This work was undertaken to describe the stratigraphy and interrelationships between the layered unconsolidated aquifers and the deeper bedrock aquifer found in the study area. The potential hydraulic connection between the aquifers and the Cowichan River is also explored.

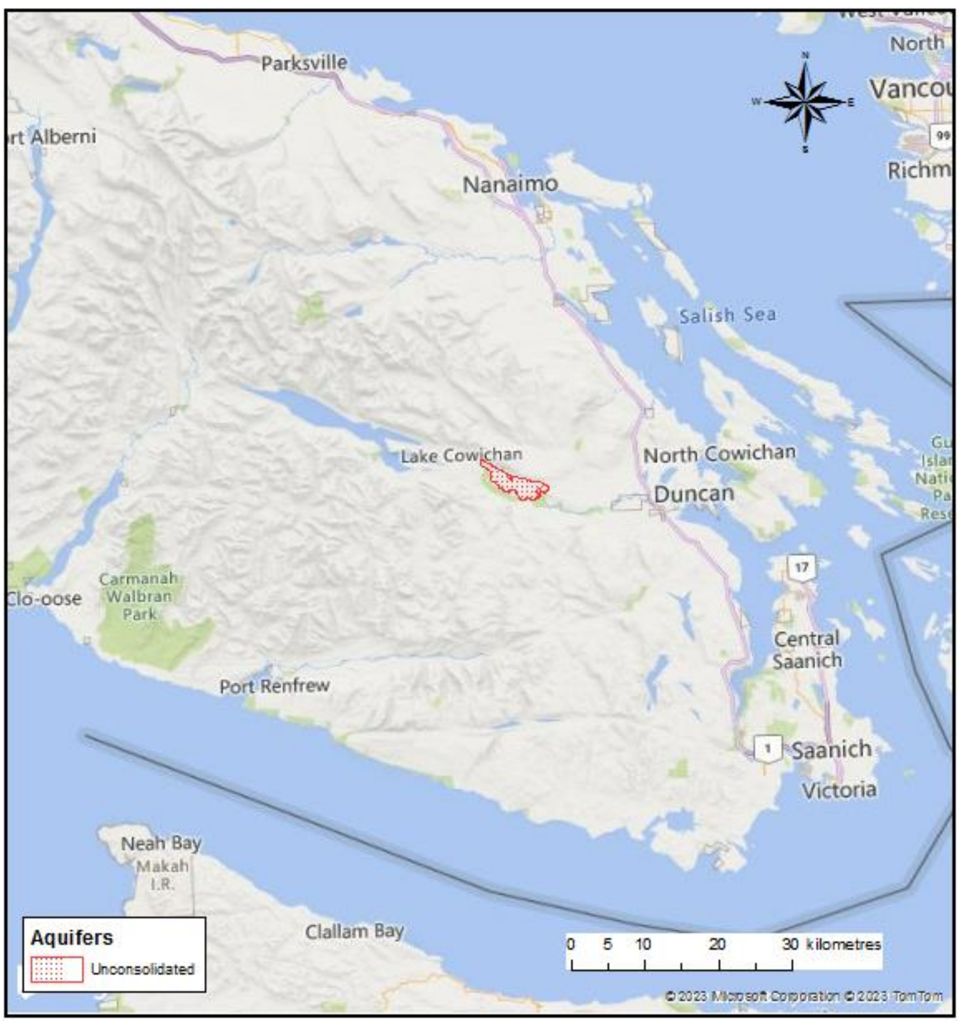

Figure 1: Aquifer location map on Vancouver Island. AQ 178 shown in red.

1.3 Background

Based on available well construction records and provincial surficial geology mapping, the aquifers in the Skutz Falls (Paldi) area are conceptualized as consisting of two layered unconsolidated, coarse sand and gravel aquifers within a glaciofluvial terrace north of Cowichan River (Guthrie, 2005; Province of B.C., 2023a).

A study by LHC (2017) of the well log records identified two separated water-bearing zones. The upper zone is confined to partially confined and lies at 18 to 45 m depth in the region. The lower zone is at approximately 55 to 96 m depth and is confined by a thick clay and silt layer.

2. METHODS

2.1 Data Sources

The primary data source for aquifer mapping is the GWELLS database, the provincial resource for groundwater well and mapped aquifer information. Information on the geologic history of the area was obtained from Geological Survey of Canada publications. Other datasets used in this study are listed in Table 1 below.

Table 1: Summary of data sources.

Data Type	Description/Title	Reference
Map	Surficial Geology of Duncan and Shawnigan Map-Areas	Halstead, 1966
Map	Digital Geology Map of British Columbia: Whole Province	Massey et al., 2005
Spatial dataset	Groundwater Wells and Aquifers database (GWELLS)	https://apps.nrs.gov.bc.ca/gwells/
Spatial dataset	Provincial mapped aquifers	B.C. Data Catalogue: WHSE_WATER_MANAGEMENT.GW_AQUIFERS_CLASSIFICATION_SVW
Spatial dataset	Water information in the BC Freshwater Atlas	Province of BC GeoBC 2023 (https://catalogue.data.gov.bc.ca/)
Spatial 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.
Spatial dataset	Topography and drainage (1:20,000)	Terrain Resource Information Management (TRIM) mapping
Spatial dataset	Digital elevation model (DEM) NRCAN 2011	The scale of this modified data is 1:250,000 which was captured from the original source data which was at a scale of 1:20,000 https://ftp.maps.canada.ca/pub/nrcan_rncan/elevation/cdem_mnec
Spatial Dataset	DEM from Cowichan Valley Regional District (CVRD)	Compiled by CVRD

The GWELLS database contains inconsistencies in terms of lithology, depths and well construction details requiring checking of the uploaded driller's logs for each of the wells to ensure the wells were assigned to the correct aquifer and to facilitate aquifer boundary mapping.

A general search of scientific literature was performed to obtain additional information on water resources and management within the watershed, including a search of the Province's EcoCat Ecological Reports Catalogue and a review of water licensing information provided by provincial water management staff.

2.2 Data Processing

Groundwater information was prepared for analysis by the following steps:

- Assigned ground elevation to wells using the DEM information (LiDAR data were not available for this area at the time of data processing);
- Simplified and standardized the lithology to facilitate interpretation between boreholes;
- Selected cross-section line locations based on areas where coverage of groundwater well information was adequate; and
- Produced three cross-sections to develop a conceptual model of hydro-stratigraphy.

A total of 77 well records currently exist in the study area from the Groundwater Wells and Aquifers database (GWELLS). 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 a DEM compiled by the Cowichan Valley Regional District. Raw lithology descriptions were processed into lithology keywords descriptors.

Well record information from GWELLS was uploaded into BH_Log (Mount Pleasant software, 2012) to generate cross-sections used to develop a hydrostratigraphic conceptual model for the study area. Unconsolidated aquifers were delineated based on topography, the interpolated thickness of unconsolidated material from borehole lithology, overlying/underlying units, water levels, and the physical location of deposits within the study area.

3. PHYSIOGRAPHY

3.1 Climate

The climate of the area is typical of the southern west coast of British Columbia with cool and wet fall and winters and warm and drier spring and summer periods. The Cowichan Valley is within the West Coast Temperature Zone, with an average annual precipitation in Cowichan Lake of 2,022 mm, of which 1,934 mm falls as rain and 88.5 cm falls as snow (based on 1981-2010 climate normals for Environment Canada (2019) Cowichan Lake Station (EC1012055)). The rainy season is generally between October to March where precipitation averages greater than 200 mm per month. Between July and August, precipitation is typically less than 45 mm per month.

There is a strong precipitation gradient decreasing from west to east because of the rain shadow effect of the Vancouver Island Mountains with total annual precipitation at Lake Cowichan and Duncan recorded at 2,018 mm and 1,051 mm, respectively (Foster, 2014). The average precipitation in the mountains in the western part of the watershed is estimated to be up to 4,500 mm annually.

The coldest months are typically between November and February where daytime highs are 5 to 8 °C and lows between -0.2 to 2 °C. From June to September, daytime temperatures typically average 15 °C.

3.2 Land Use

Land use in the study area consists primarily of rural residential and undeveloped forested land, where each non-vacant lot relies on water from a private domestic well or surface water diversion.

3.3 Topography and Drainage

The study area is located within a gently sloping region of moderate to low relief that borders the Georgia Strait from Saanich Inlet to Cowichan Bay. Watersheds within the study area are shown on Figure 2.

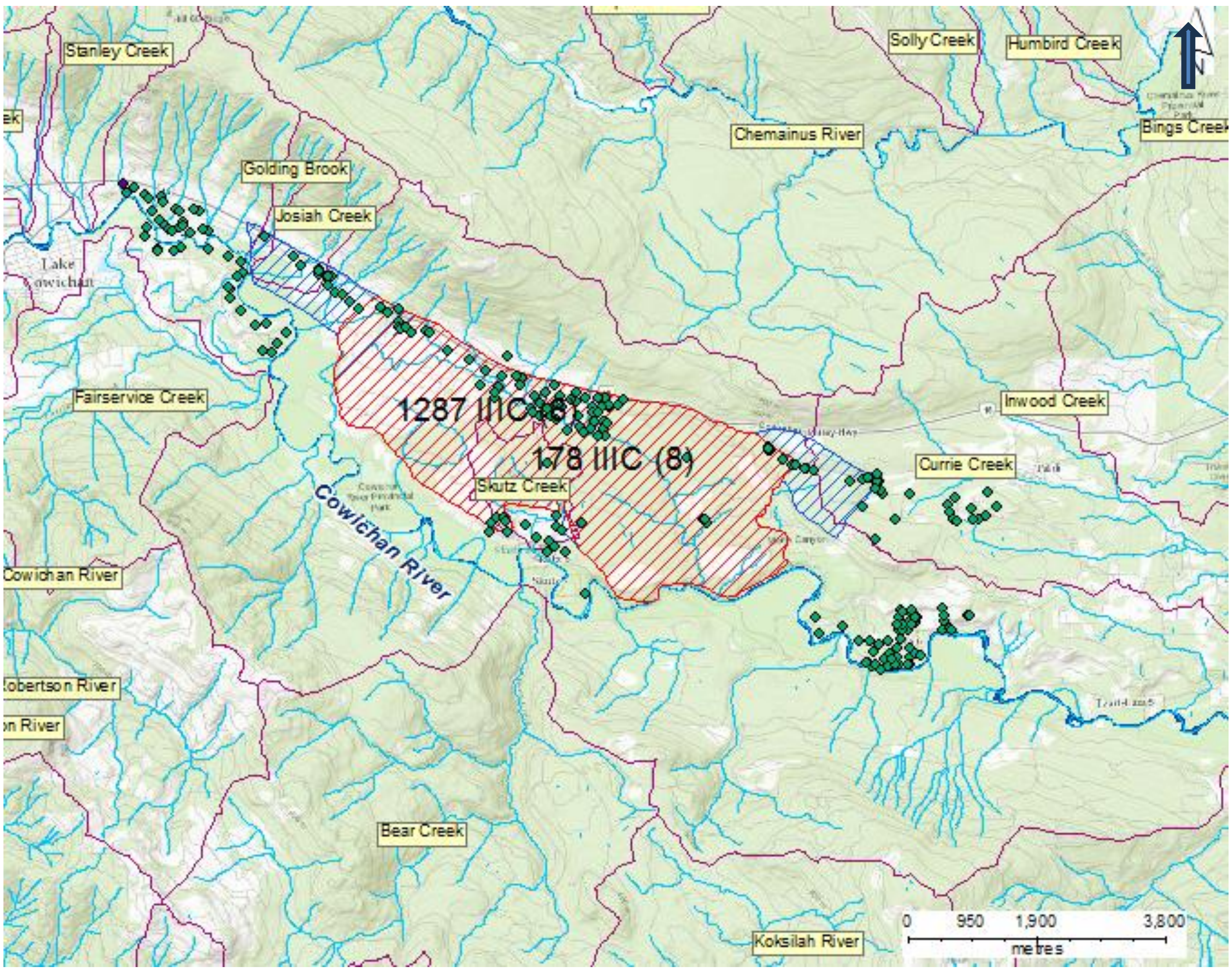

Figure 2: Watersheds (boundaries marked by purple lines) in the study area. Aquifers shown for context. Diagonal-lined blue polygon is Aquifer 178; diagonal-lined red polygon is Aquifer 1287; Green circles are water well locations (from GWELLS).

The study area consists of a moderately sloping to strongly rolling topography. Most surface water likely flows from the uplands in the north to the southwest, toward the nearest creek eventually flowing into the Cowichan River. The area consists of forested land sloping down to the south-west.

Physiographic units consist of Nanaimo Lowland (elevation range 0 to 600 metres above sea level (masl)) in the east bounded to the west by the Vancouver Island Ranges (over 1000 masl). The elevation range within the study area ranges from 70 masl in the southeast along the Cowichan River to 750 masl to the northwest.

The Cowichan River is the largest river in the valley and flows from the headwaters at Cowichan Lake eastward for nearly 45 km to the estuary in Cowichan Bay near Duncan. Numerous streams flow from the uplands in the north to the Cowichan River in the south of the area.

4. GEOLOGY

4.1 Bedrock Geology

The study area, east of Lake Cowichan and on the north side of the Cowichan River is entirely underlain by Nanaimo Group sedimentary rocks (Figure 3). The Nanaimo Group consists of alternating layers of conglomerate, sandstone, siltstone and mudstone (Massey et al., 2005) shown on the report cover photo, deposited as submarine fan deposits (Earle, 2007).

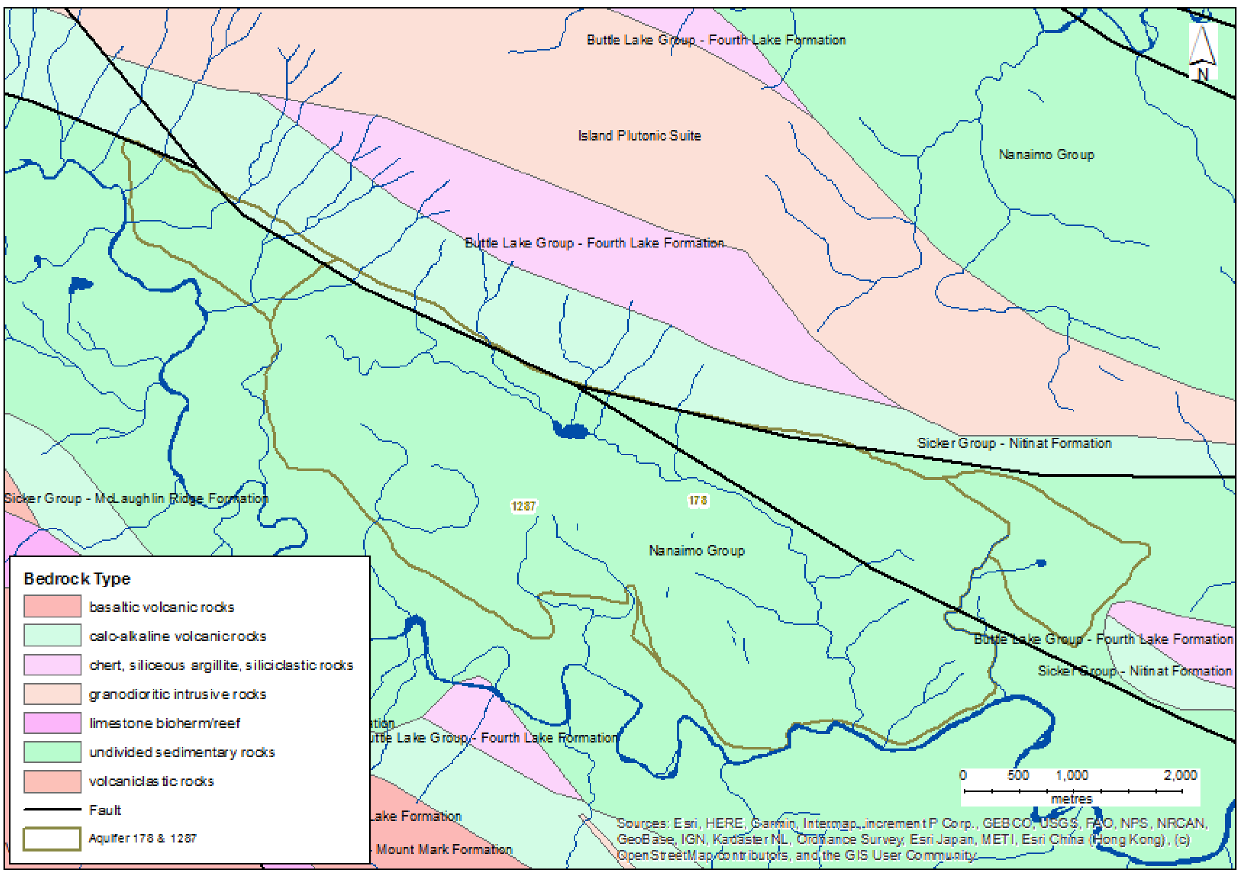

Figure 3: Bedrock geology showing thrust faults along northern edge of Cowichan Valley (after Cui et al., 2017).

North of the study area and south of the Cowichan River are granitic (igneous intrusive granodiorite, quartz diorite, diorite and gabbro) rocks of the Island Plutonic suite. In the Cobble Hill area toward the south-western portion of the study area are found volcanic-type rocks, including those associated with the Vancouver Group/Karmutsen Formation (basalt pillowed flows, tuff, breccia with limestone lenses), Buttle Lake Group/Mount Mark Formation (limestone, chert, siltstone, marble), and Sicker Group/Duck Lake Formation (pillowed and massive basalt flows, basalt breccia, chert, jasper, felsic tuff).

Several major faults (e.g., north-east dipping South Cowichan thrust fault) intersect and define the contacts between the various bedrock units.

Review of the well log records in the area and the data collected in the field suggest the area of study is located within a small, buried valley. This channel is estimated to range up to 3 km wide from north to south, and would likely discharge to the Cowichan River.

Bedrock units in the map area (Figure 3) from youngest to oldest are listed in Table 2.

The stratigraphic bedrock sequence in the area is repeated because of the northwest-southeast trending, north-east dipping South Cowichan thrust fault along the edge of the mountains north of the Cowichan River. Prior to thrust faulting the bedrock was folded into a synclinal structure.

Table 2: Bedrock units in the map area (Muller and Yorath, 1977; Massey, 1992; Massey and Friday, 1987; Cui et al., 2017).

Group or Formation	Material	Stratigraphic Age	Age Range
Nanaimo Group	undivided sedimentary rocks	Upper Cretaceous	65-97 Ma
Island Plutonic Suite	granodioritic intrusive rocks	Middle Jurassic	157-208 Ma
Buttle Lake Group (subdivided)			
Fourth Lake Fm.	chert, siliceous argillite, siliciclastic rocks	Mississippian - Pennsylvanian	290-362 Ma
Mount Mark Fm.	limestone, bioherm reef	Mississippian - Lower Permian	255-323 Ma
Sicker Group (subdivided)			
Nitnat Fm.	calc-alkaline volcanic rocks	Middle - Upper Devonian	362-377 Ma
McLaughlin Ridge Fm.	basaltic volcanic rocks	Middle - Upper Devonian	362-377 Ma
Duck Lake Fm.	volcaniclastic rocks	Middle - Upper Devonian	362-386 Ma

4.2 Quaternary Geology

The Cowichan Valley lowland is located within the Georgia Depression Physiographic subdivision and is flanked by the Insular Mountains of Vancouver Island. The valley has been carved by glaciers that scoured the Nanaimo Group sedimentary rocks. The most recent glacial events have also backfilled the valley with glacial till, outwash sand and gravel, and glacial lake unconsolidated deposits. There is a succession of layered deposits with till or lacustrine deposits alternating with outwash sand and gravel layers. In the study area and other nearby locations there is evidence of three glacial advances and retreats. The evidence is three distinct sand and gravel layers separated by till and/or clay/till layers. The glacier in the valley has been called the Cowichan Valley Ice Tongue as it was a very small segment of the Georgia Depression Glacier(s).

Unconsolidated sedimentary deposits in this area are the result of pre-glacial, glacial and more recent geologic events (Blyth et al., 1993). The Cordilleran ice sheet reached an elevation of 2,300 masl and was more than 2,000 m thick in major valleys (Ryder et al., 1991). Most of the unconsolidated deposits are related to the last major glaciation occupying Vancouver Island to a depth of 1,500 metres. The highest mountains in the area (i.e., Mt. Coronation and Mt. Hall) at elevations of more than 1,300 metres above sea level (masl) were covered by the ice sheet (Fyles, 1955 and Halstead, 1966).

Surficial deposits are generally found below an elevation of 150 masl, elsewhere bedrock is exposed or covered by only thin deposits of glacial or alluvial materials (Halstead, 1966). The lateral extent of quaternary sediments within the study area is shown (in yellow) on Figure 4.

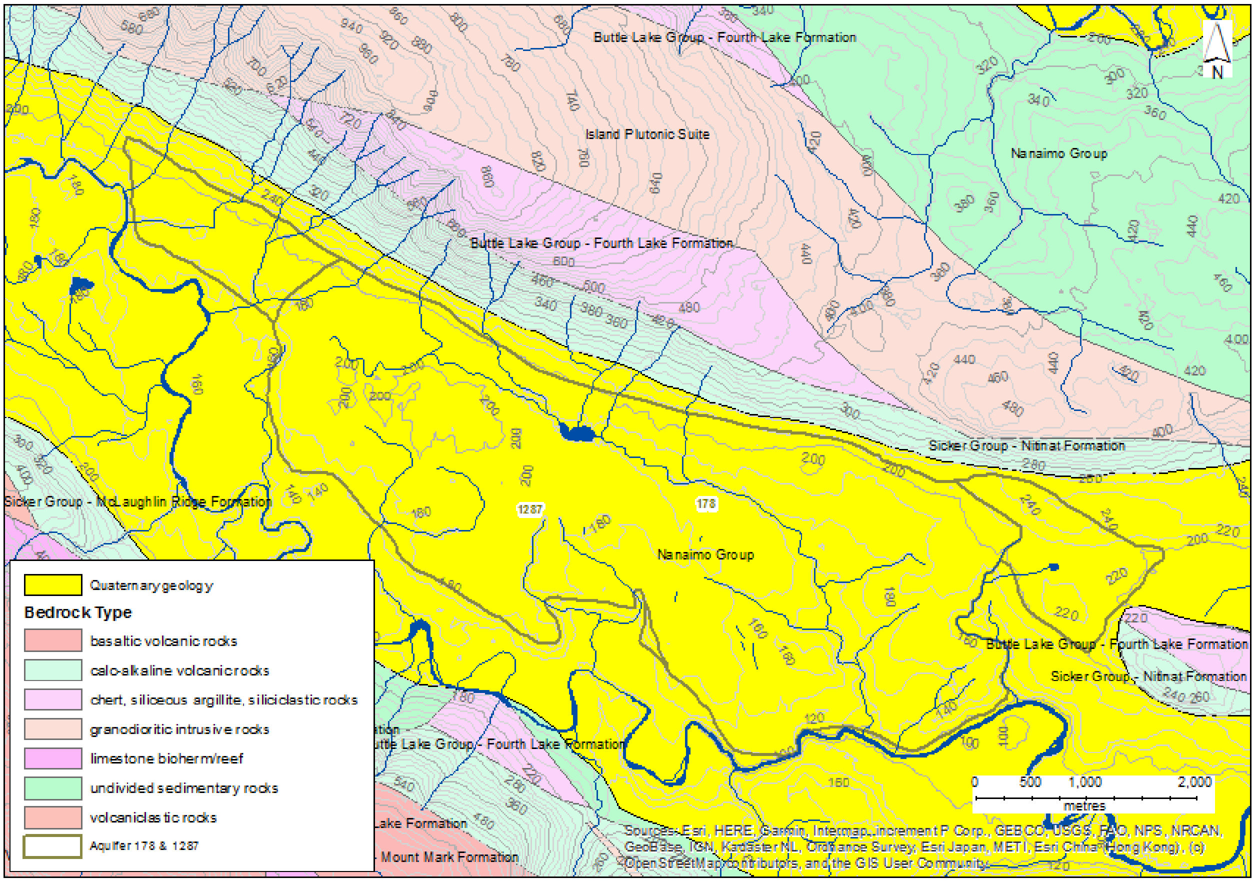

Figure 4: Extent of Quaternary deposits in the study area.

The surficial geology of the study area, shown in Figure 5, is based on terrain classification for Vancouver Island (Ministry of Environment, 2016).

Most of the northern part of the study area is overlain by sediments described as glacio-marine in origin, which were deposited overlying glacial and inter-glacial sediments during the period of higher sea level following the end of the Fraser Glaciation approximately 13,000 years ago. Glaciomarine deposits include poorly sorted to stratified sands, silts and clays. Moraine deposits such as diamicton or till (sand and rock debris within a clay or silt matrix) are found at the surface in the area around and south of Cobble Hill. Fluvial deposits are found within the Cowichan River delta and estuary at the northern boundary of the study area, while organic materials are noted in the west-central area around Dougan Lake and along Shawnigan Creek to the south. Localized deposits of marine sediments (i.e., marine clay) are mapped <1 km from the coast, in the area around Cherry Point. The surficial geology mapping represents a simplified summary of regional characteristics; at a site-scale deposits such as till can vary in presence/absence, and thickness.

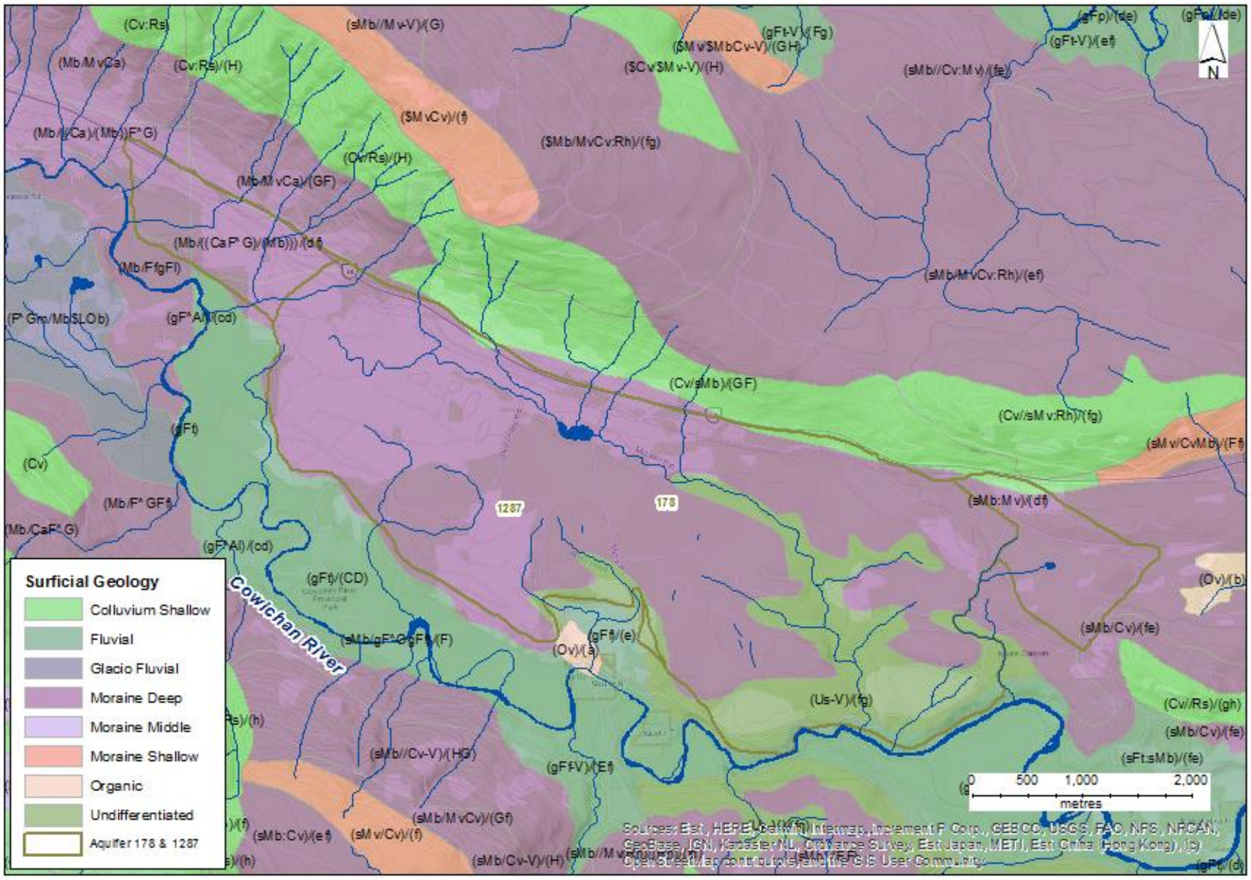

Figure 5: Surficial geology map of the study area (BC Ministry of Environment, 2016).

The Quaternary stratigraphy, from oldest to youngest upwards from bedrock, consists of a pre-glacial gravel with a fining upward sequence, followed by glacio-lacustrine sand and clay (base carbon dated to 24,000 years BP), followed by gravel which may have resulted from a lake draining episode, then another glacio-lacustrine sequence and finally a till originating during the last glaciation period (Brent Ward, SFU pers. Comm. 2024-Jan-18) (Figure 6).

11: Upland swamp clay, silt, peat	Salish Sediments
10: Shore, deltaic & fluvial gravel, sand , silt, clay	Salish Sediments
9: Valley alluvium & colluvium: boulders, gravel, sand, silt, clay – terraces, channel deposits (includes 8,10,11)	
8: Fluvial deposits: 8a: deltaic, terraced gravel and sand; 8b: floodplain and channel gravel and sands; 8c: alluvial fan poorly sorted gravel, sand, silt	Capilano Sediments
7: Marine deposits: 7a: silt, clay, stony clay, till to 23 m; 7b: gravel, sand, silt in spits and bars; 7c: stony, loamy and clayey marine veneer less than 2 m	Capilano Sediments
6. Glacio-fluvial deposits: gravel, sand lenses of till; 6a: hummocky, kettled, kame deposits; 6b: ice-contact deltas	Vashon Drift
5. Ground moraine deposits: till, lenses of gravel, sand, silt	Vashon Drift
4. Advance outwash: poorly sorted gravel, sand, silt	Vashon Drift
3. Quadra sediments: sand, silt, minor gravel and peat	
2. Drift: till, stony till, lenses of gravel and silt	
1. Oldest Deposits: 1a: fine to medium sand & silt to 24 m; 1b: coarse gravel, sand to 10 m	

Black text indicate map units present in study area

Figure 6: Quaternary stratigraphy in study area (based on Halstead, 1966).

4.3 Cross-Sections

Three cross-sections were drawn and interpreted based on available water well lithology data from GWELLS. Each section was constructed with a 20-times vertical exaggeration to aid in interpretation.

Cross-section A-A’ (Figure 7) was drawn parallel to the mountain front north of the Cowichan River and approximately parallel to the Cowichan Valley Highway; it has a length of 8 km. Numerous streams sourced in the mountainous are to the north cross the section line (marked in light blue text). This section shows that the shallow aquifer (AQ 178) extends further to the northwest and southeast than the deeper AQ 1287 does. Both aquifers appear to be confined beneath a till unit. There is some thinning in the till unit between the two aquifers at well WTN108006. A shale bedrock aquifer, likely an unmapped extension of AQ 945 underlies the entire length of the cross-section. Based on borehole lithology, updated mapping of AQ 945, and as more data become available, will likely show the aquifer extends beneath the study area.

Cross-sections B-B’ and C-C’ intersect A-A’ toward the eastern end of the cross-section.

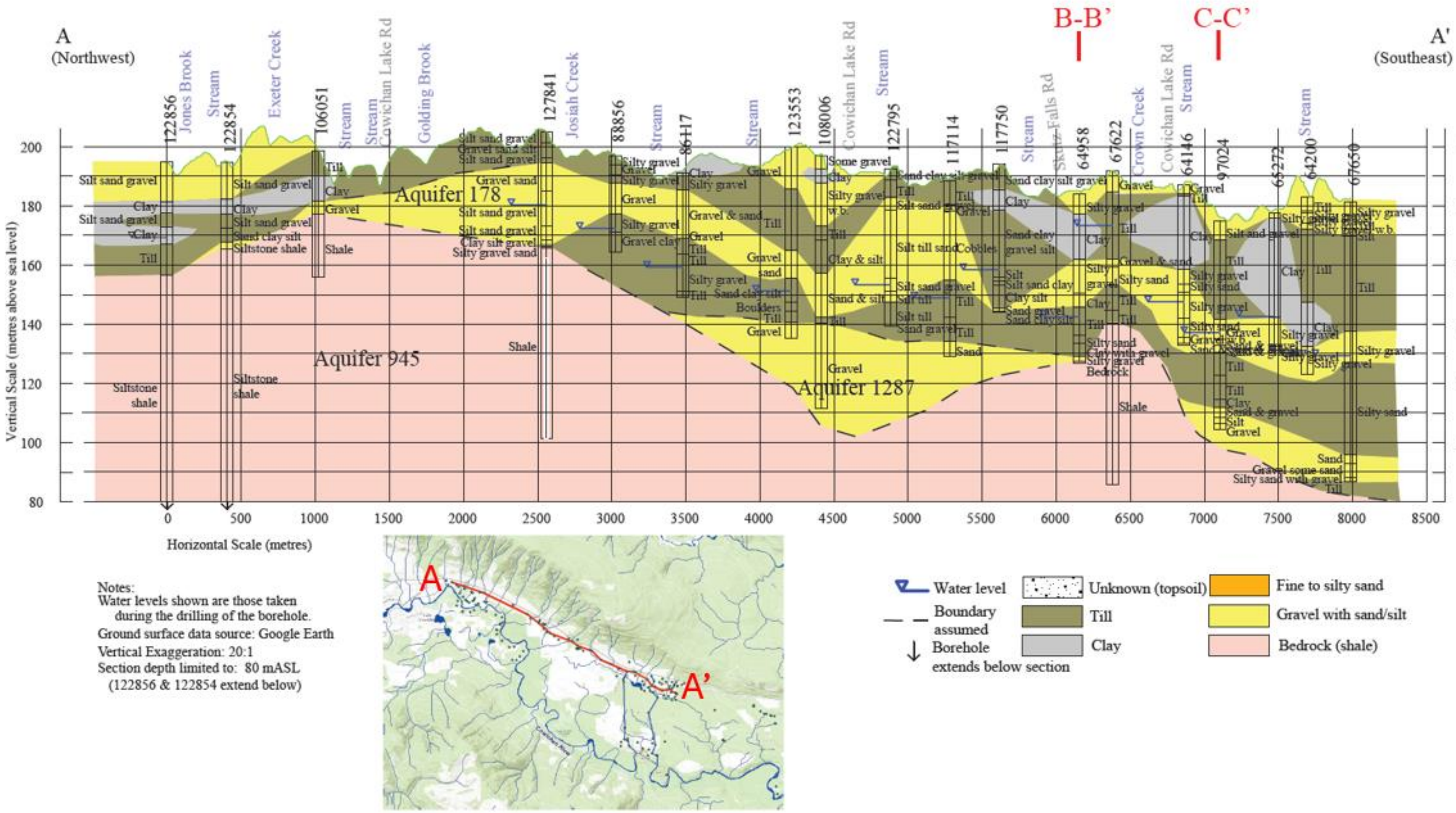

Figure 7: Northwest-southeast trending cross-section A-A'.

Cross-section B-B’ (Figure 8), length 2.5 km shows that both unconsolidated aquifers (AQ 178 and AQ 1287) outcrop (‘daylight’) in the south along the step bank of the Cowichan River forming seepage faces. A shale bedrock aquifer, likely an unmapped extension of AQ 945 forms the base of the river. Near well WTN64143 the clay unit separating the two unconsolidated aquifers is interpreted to become thinner below that well. None of the overlying streams cut far into the surficial gravels or till unit.

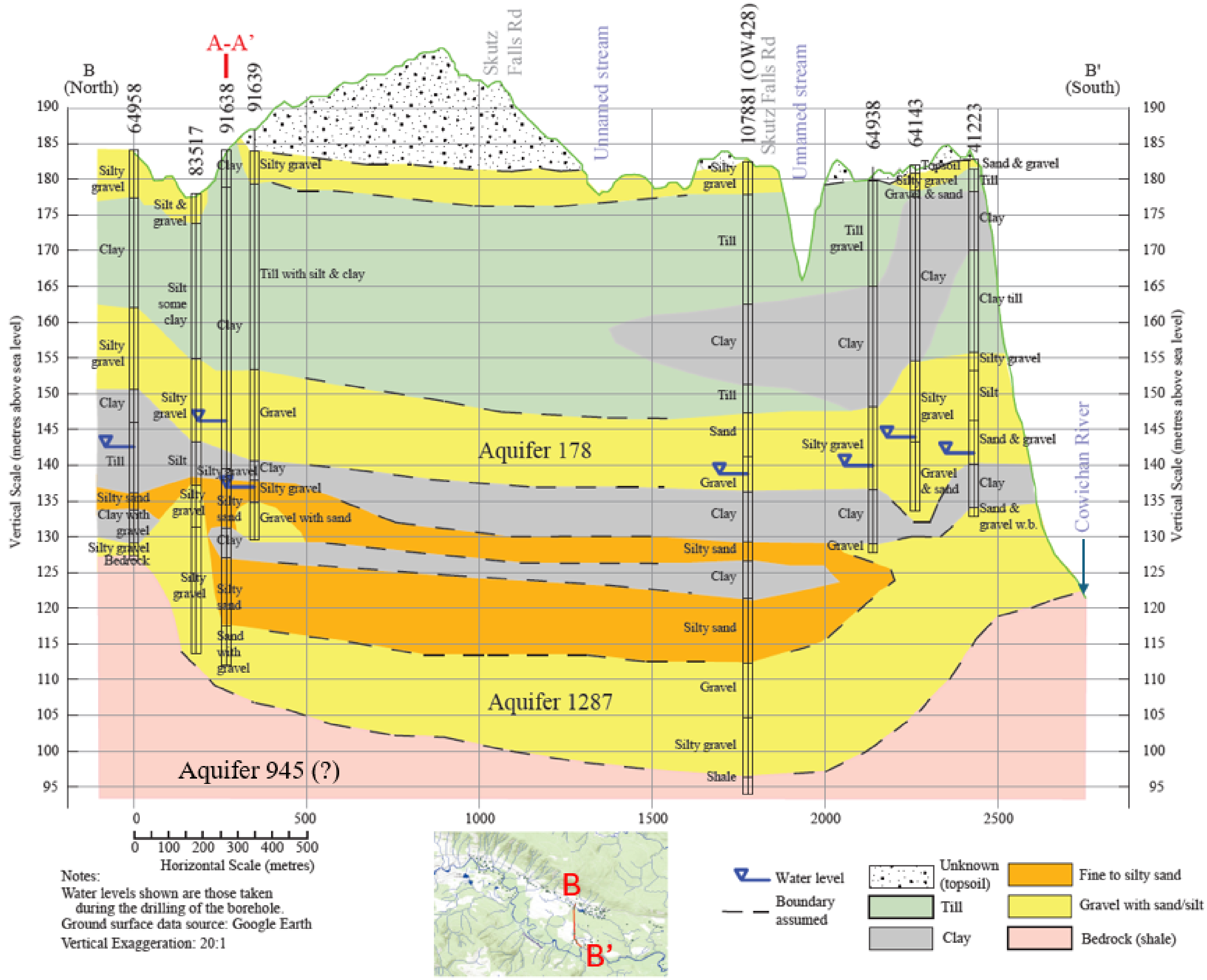

Figure 8: North-south trending cross-section B-B'.

Cross-section C-C’ (Figure 9), length 3 km shows that neither unconsolidated aquifer (AQ 178 and AQ 1287) outcrop near the Cowichan River likely because of the interpreted high in bedrock elevation at that location. A shale bedrock, likely the unmapped extension of aquifer AQ 945 forms the base of the river. None of the streams cut far into the surficial gravels or till unit.

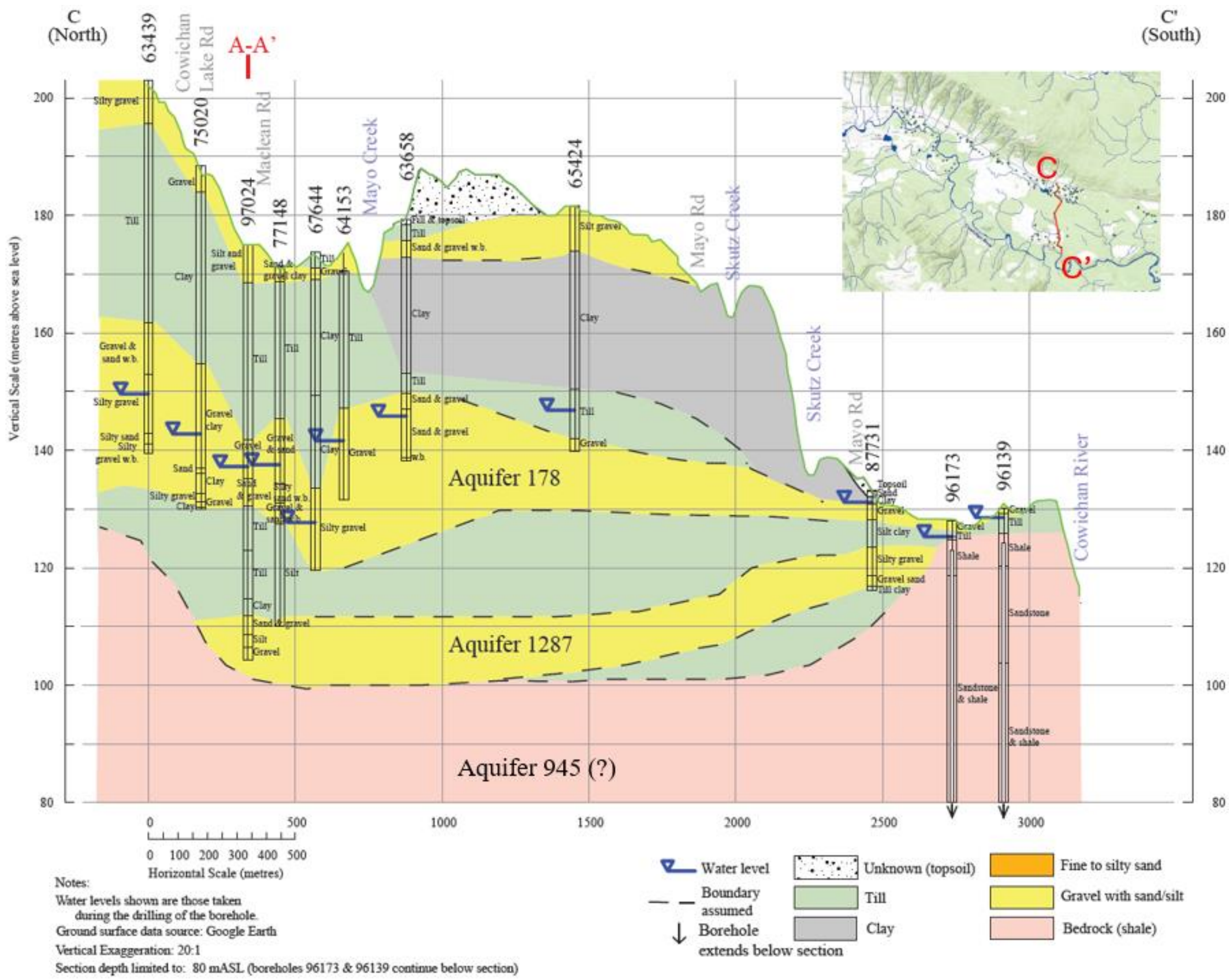

Figure 9: North-south trending cross-section C-C'.

5. <u>HYDROGEOLOGY</u>

5.1 Hydrostratigraphy

Unconsolidated stratigraphy is based on Quaternary units described in Section 4.2. Hydrostratigraphic units with permeable deposits have been designated as aquifers whereas non-permeable deposits are inferred to be aquitards.

5.2 Aquifer Mapping

The sub-type of both aquifers is 4b (confined glacio-fluvial sand and gravel aquifers) (Wei et al., 2009) because they originated from pre-glacial and glaciofluvial processes that contain deposited and reworked alluvial materials from erosion of the adjacent mountains to the north, and river deposits in the historical Cowichan River floodplain. Low permeability layers of clay (till), silt, and silty fine sand are found above, and separate the two aquifers from each other and from the underlying confined bedrock aquifer.

The confining layer between the two unconsolidated aquifers varies in occurrence and thickness; however, well testing in the area indicates there may be a hydraulic connection between the two aquifers, and leakage likely where the confining materials thin or pinch out (described in more detail in Section 5.4). In the upper aquifer, there is evidence of highly permeable gravel seams or lenses within an overall lower permeability sequence of silty till. It is expected there will be outwash channels and preferential flow paths that increase permeability but that are laterally discontinuous.

5.2.1 Aquifer Location and Spatial Extent

LHC (2017) inferred that the deeper aquifer (AQ 1287) is similar in spatial extent to the footprint of the upper aquifer (AQ 178).

Wells constructed in AQ 1287 have a depth of approximately 54 m or greater. Most logs (with some exceptions) indicate the wells intercept two higher permeable zones, described as wet or water-bearing coarse sand or gravel. The unconsolidated materials comprising both aquifers thin or pinch out toward the east where surficial materials are thinner overlying the bedrock. Cowichan River may represent a groundwater divide towards the northwest. Most wells in the study area are constructed in the upper, confined unconsolidated aquifer (AQ 178). Fewer wells are constructed in the deeper, confined, unconsolidated aquifer (AQ 1287) and it appears to be slightly smaller in spatial extent compared to AQ 178. Records also include dug wells and shallow drilled wells that were constructed historically in the surficial sediments or upper unconfined aquifer overlying AQ 178. A smaller number of wells constructed in the bedrock aquifer within the footprint of AQ 178 are also noted and this may indicate zones where the unconsolidated materials are less permeable, or where the aquifer materials thin or pinch out.

The hydrostratigraphic units in the area consist of:

a) upper layer of shallow, unconfined surficial sediments;
b) moderate to deep unconsolidated aquifer, that is confined or leaky-confined, and made up of up to two units, referred to as upper and lower aquifers; and
c) deep, confined bedrock system.

Unconsolidated materials close to the ground surface that provide water to excavated wells are combined into one unit with low permeability materials comprising the shallowest confining layer and is not mapped as an aquifer. The shallow, confined to partially confined aquifer is considered aquifer AQ 178, and the deeper, underlying, confined aquifer is referred to as AQ 1287. Bedrock geology mapping indicates the presence of sedimentary bedrock (e.g., shale) beneath aquifer AQ 178 and AQ 1287 and this is assumed to be associated with aquifer AQ 182 or AQ 945.

Conceptually the stratigraphy, and by inference, the hydro-stratigraphy is as shown in Figure 10 and isopach maps of unconsolidated material thickness are shown in Figure 11 to Figure 16. The two aquifer units are in yellow whereas the till confining materials are in green and the clay/silt confining units are in grey/orange. Note this is the colour scheme followed in the cross-sections (Figure 7 through Figure 9). The cross-sections show that, across the study area, there is a consistent confining layer of lower permeability material between the two aquifers.

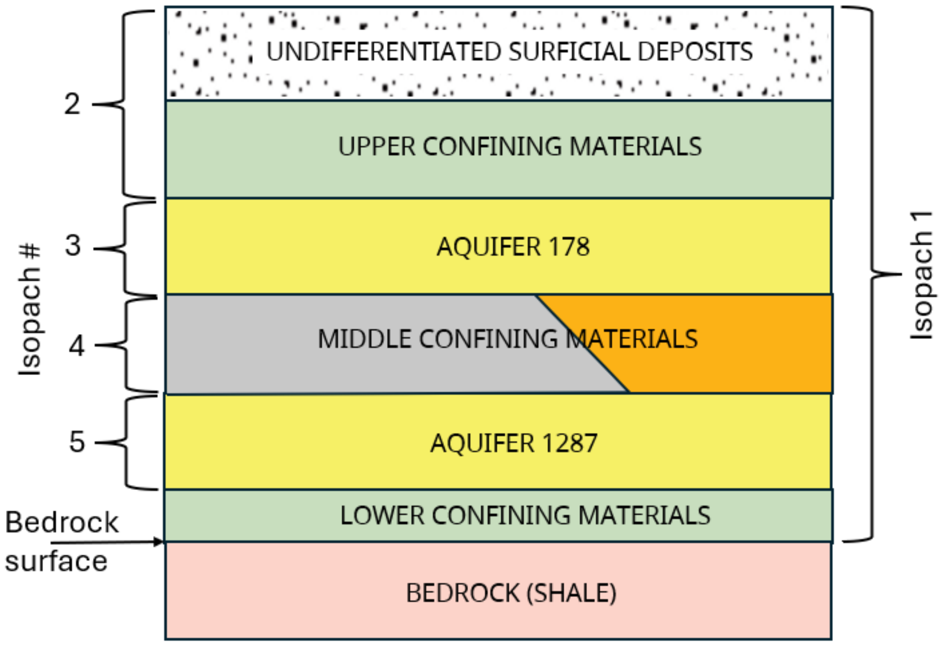

Figure 10: Conceptual diagram of subsurface stratigraphy in the study area. Isopach # refers to hydrostratigraphic units (e.g., Isopach 1 refers to entire column of unconsolidated materials, Isopach 3 refers to Aquifer 178).

Whereas the isopach figures (Figure 11 through Figure 15) are based on sparse water well data concentrated along the highway and a few wells nearer the Cowichan River, they provide a general sense of the distribution of materials. There are limited subsurface data on the southwest side of the aquifers adjacent to the Cowichan River to verify the geology, and therefore the isopach maps do not provide detail in this zone. Further development in the area with accompanying well drilling may serve to refine these.

The total unconsolidated materials package is thickest in two areas separated by a thinner assemblage in the south-central portion of the study area (Figure 11).

The unconsolidated materials overlying AQ 178 consisting of surficial deposits and the upper confining materials (Figure 10) ranges in thickness from 0 m (along the northern uplands) to 50 m (Figure 12).

AQ 178 varies in thickness from 0 to 3 m in the west to more than 20 m in the central portion of the aquifer (Figure 13).

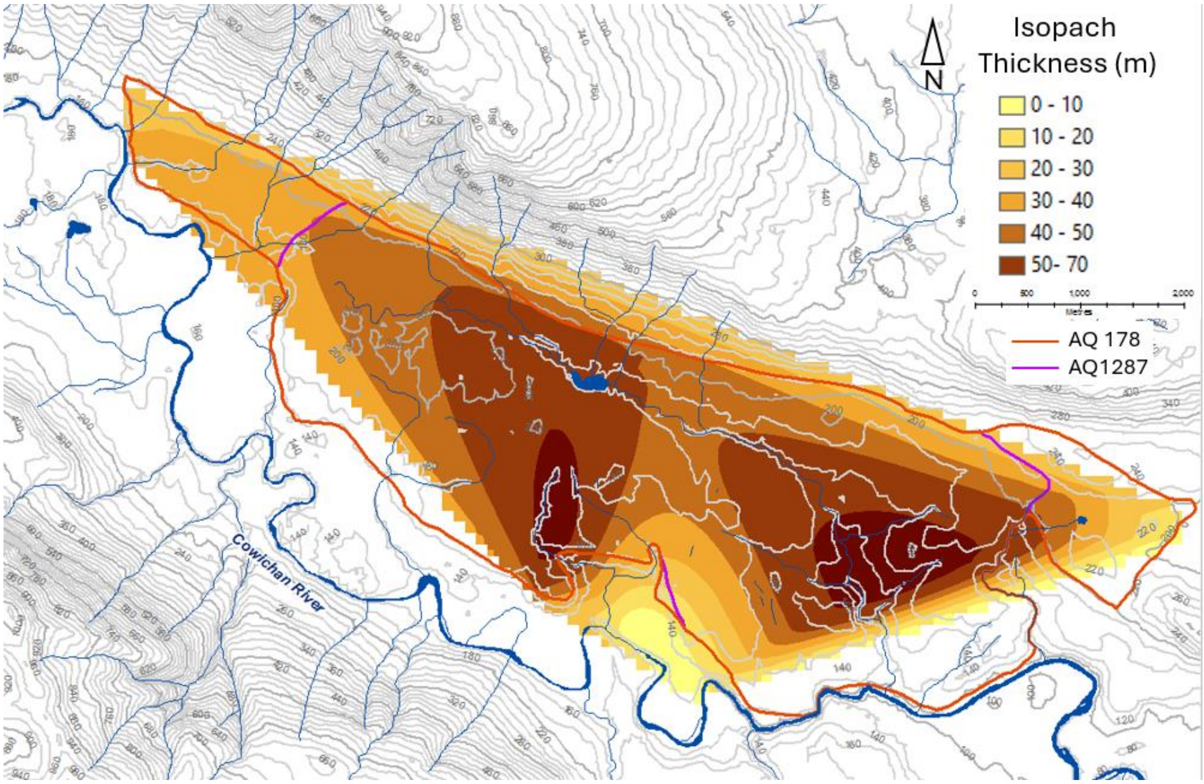

Figure 11: Material thickness of unconsolidated deposits (Isopach 1 on Figure 10).

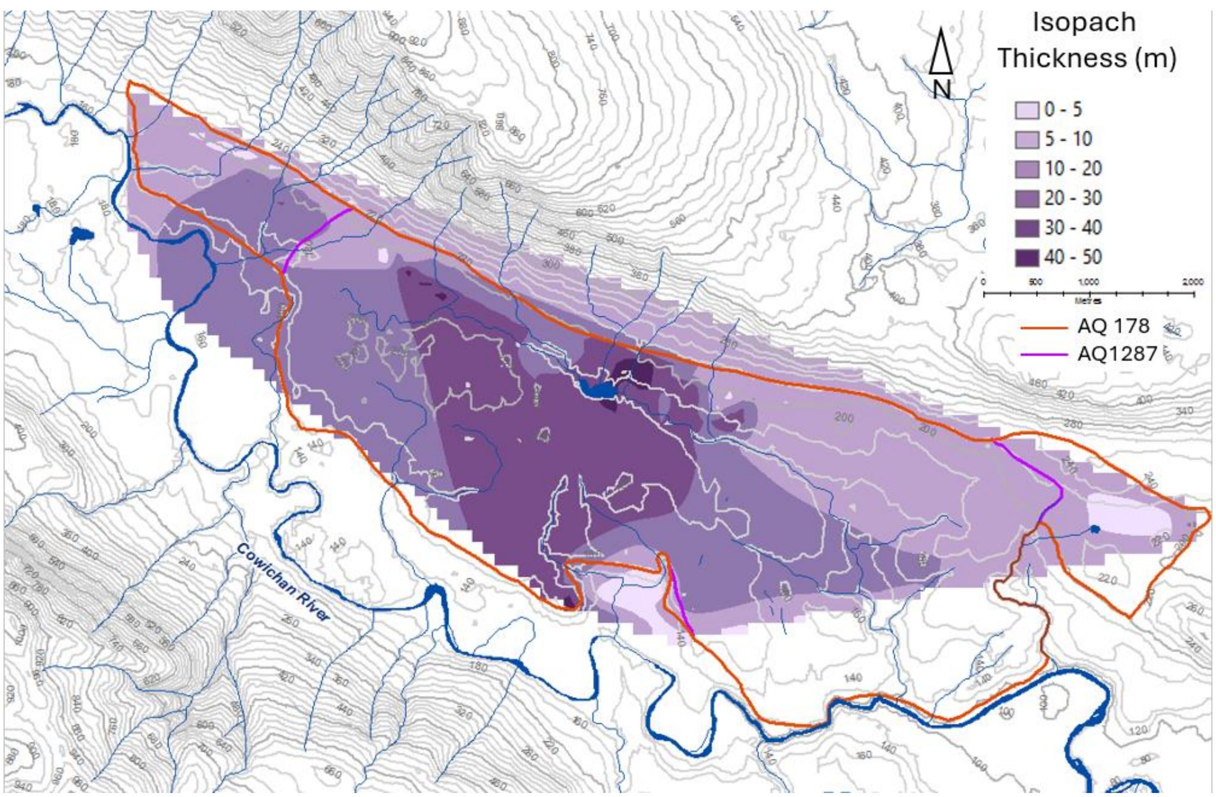

Figure 12: Material thickness of surficial sediments and upper confining layer (Isopach 2 on Figure 10).

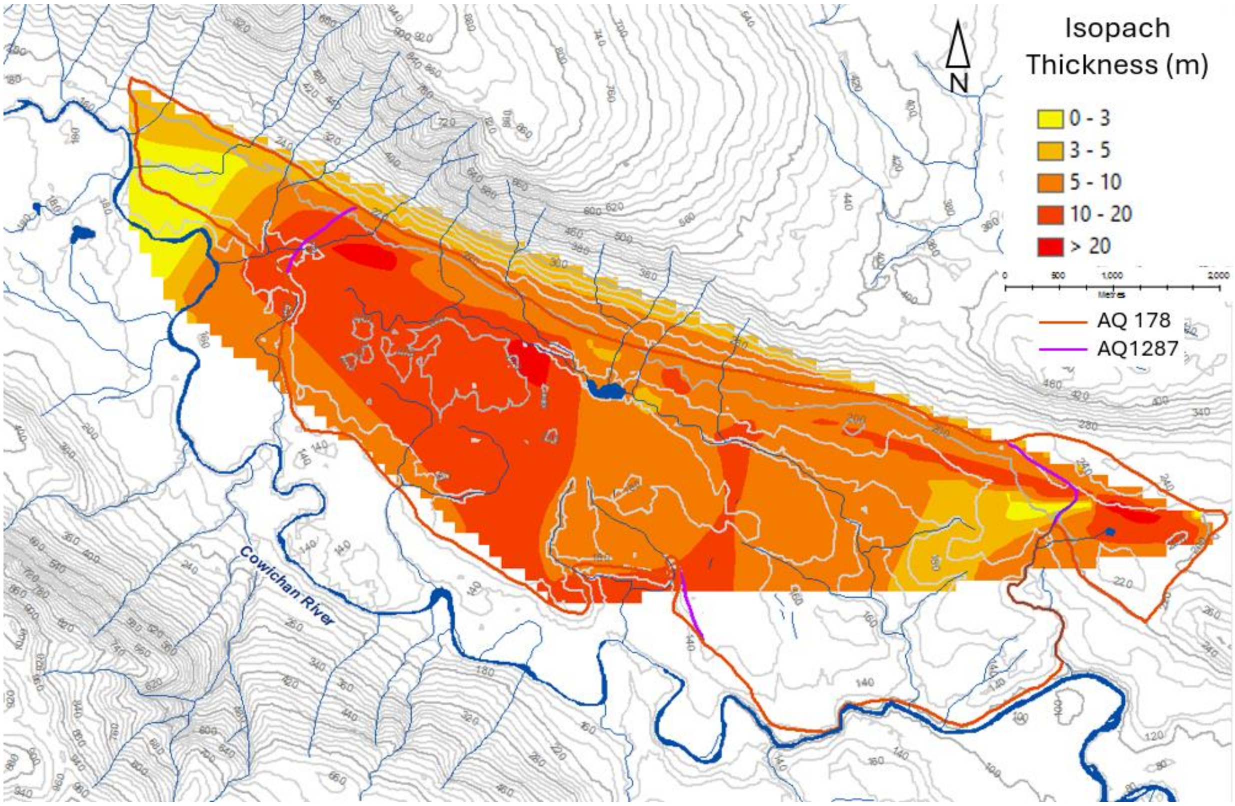

Figure 13: Material thickness of AQ 178 (Isopach 3 on Figure 10).

Figure 14 shows that the thickness of the confining materials between AQ 178 and AQ 1287 ranges up to 40 m thick. Lack of deeper wells meant that this unit could not be delineated in the western portion of the study area.

Directly underlying the middle confining unit of clay and silt is AQ 1287 which thins against the edge of the upland in the north and thickens to more than 20 m in the central portion of the study area (Figure 15).

There were not enough data to separately define an isopach for the lower confining materials overlying the bedrock.

Shale bedrock elevation (Figure 16) is highest in the north toward the upland area and lowest in the southeast toward the Cowichan River where the bedrock forms outcrops at the base of the river.

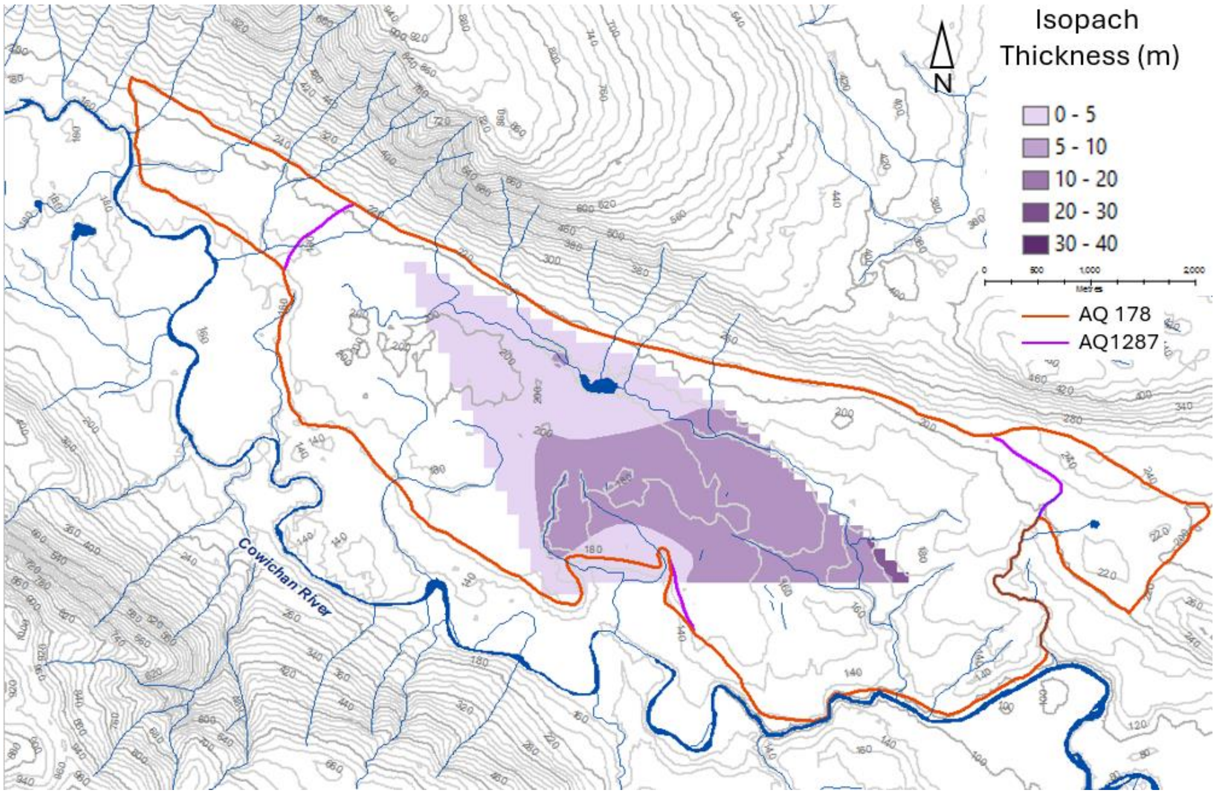

Figure 14: Material thickness of middle confining unit (Isopach 4 on Figure 10).

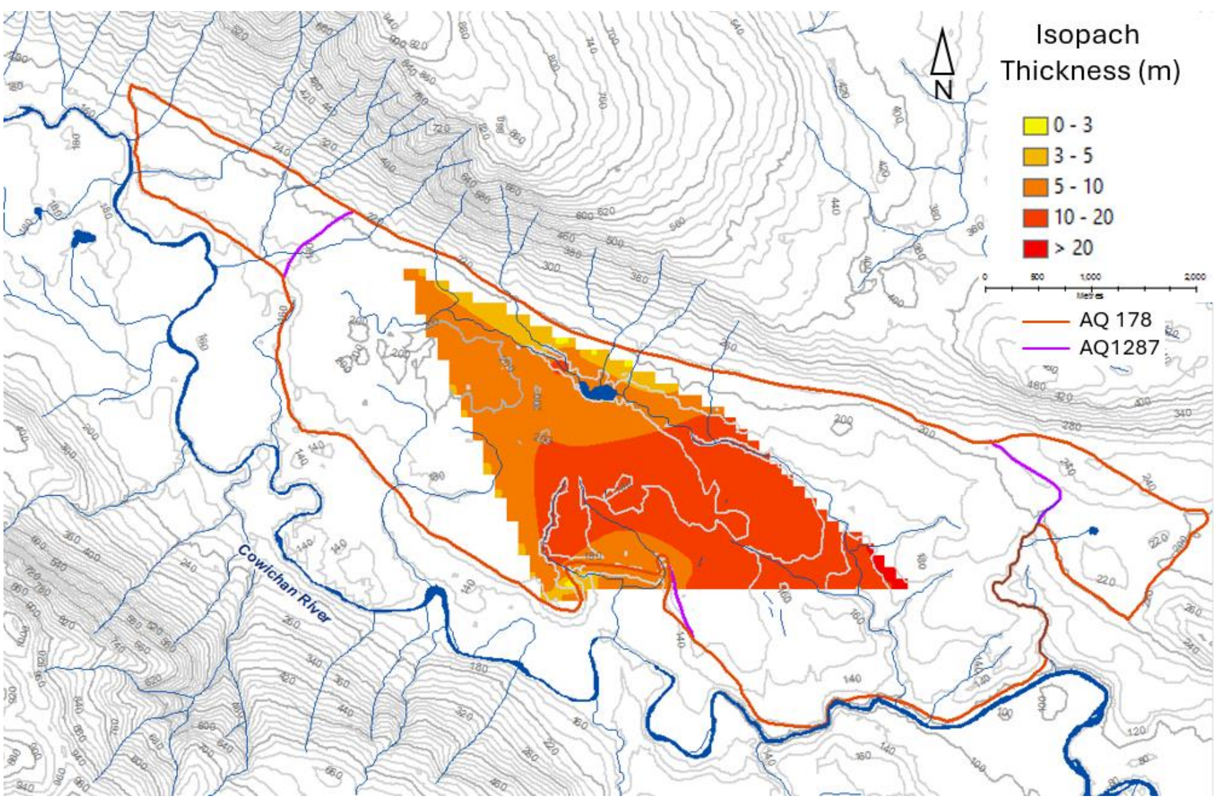

Figure 15: Material thickness of AQ 1287 (Isopach 5 on Figure 10).

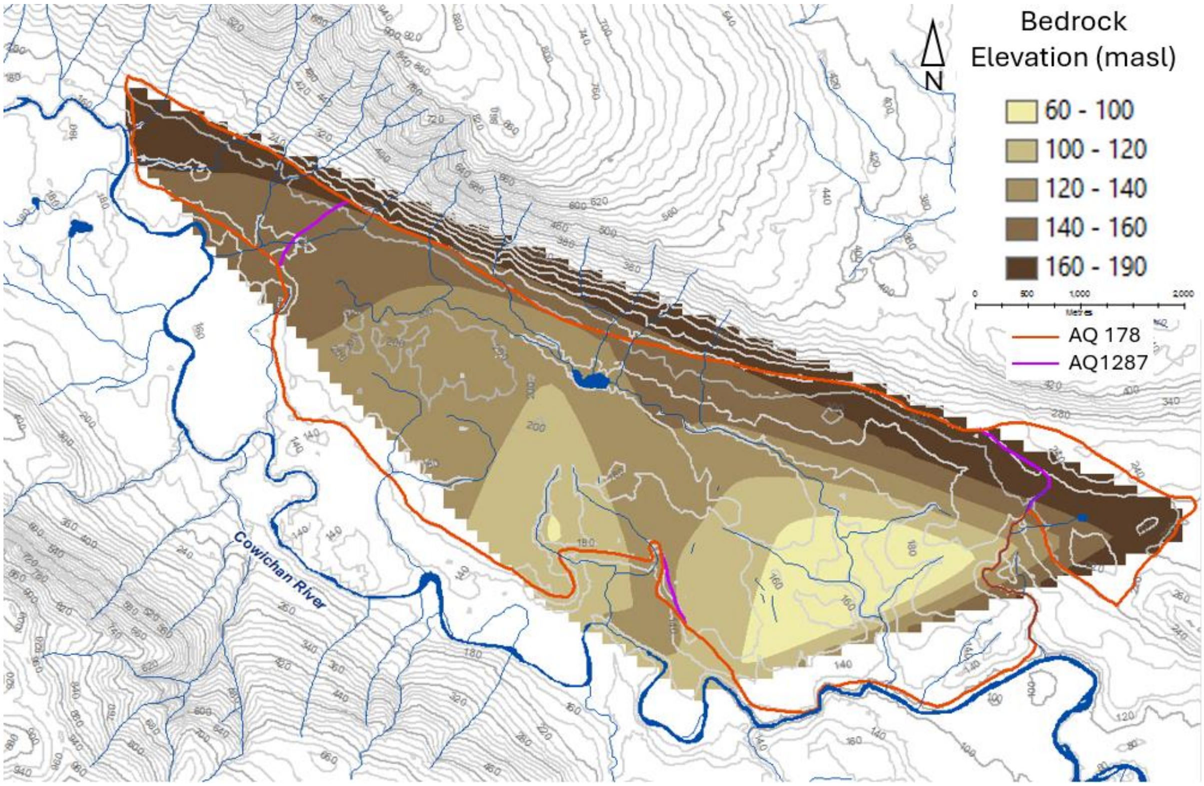

Figure 16: Bedrock elevation (Layer 6 on Figure 10).

5.2.2 Unconsolidated Aquifers

Based on the well lithology data, summarized in Table 3, used to prepare the cross-sections (Figure 7 to Figure 9) and isopach maps (Figure 10 to Figure 16), the boundaries defining AQ 178 are shown in Figure 17; those for AQ 1287 are shown in Figure 18.

Table 3: Summary of well information from identified aquifers/stratigraphic units.

Aquifer	# of Wells	Average well depth [m]	Minium well depth [m]	Maximum well depth [m]	Average non-pumping water level [masl] (# of records with data)	Aquifer area [km^2]	Median thickness [m]
Surficial	14	5.88	0*	13.11	168.5 (9)	17.9	27.4
178	54	37.31	8.23	54.25	162.6 (44)	17.9	11.5
1287	22	66.71	53.95	96.32	139.3 (21)	16.6	9.2
Bedrock	14	91.52	32	212.4	152.0 (12)	NC	NC
Total wells	104						

*Zero value indicates where no depth information were available in the well record

NC = not calculated

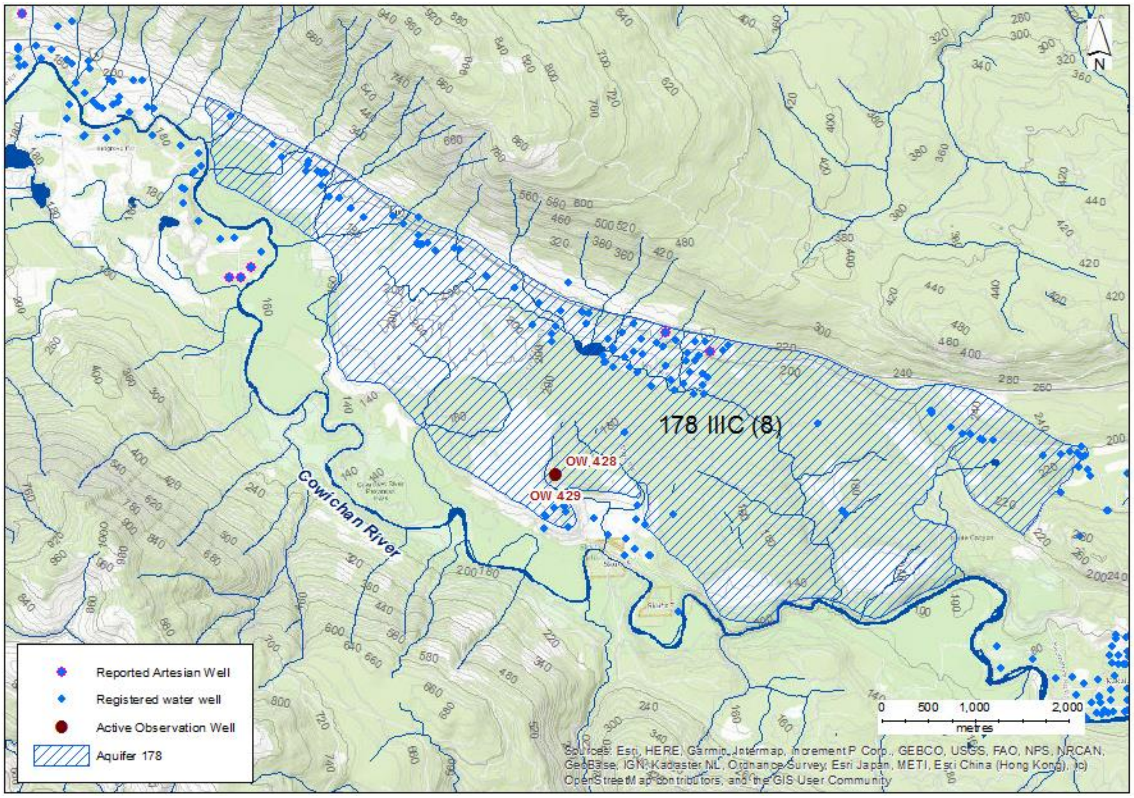

Figure 17: Aquifer 178 extents (blue hatching).

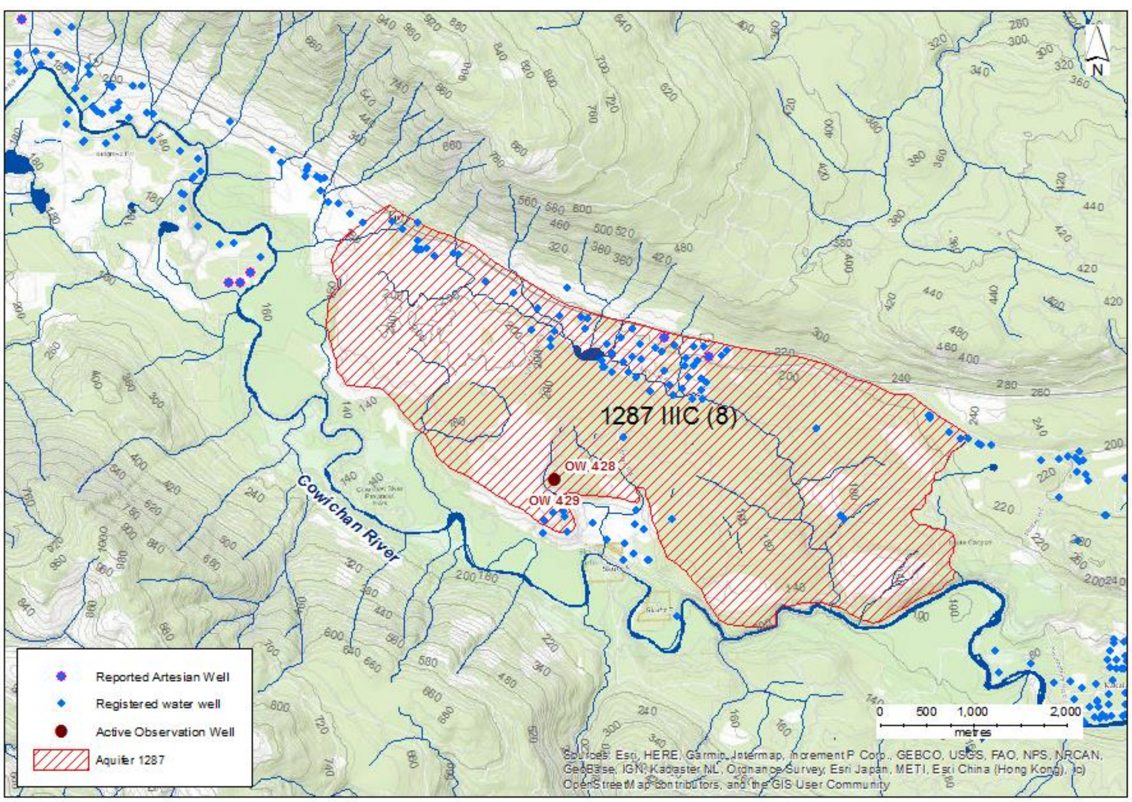

Figure 18: Aquifer 1287 location (red diagonal lines).

Table 4 summarizes the main characteristics of AQ 178 and AQ 1287.

Table 4: Aquifer mapping summary.

Aquifer Number	178	1287
Aquifer Name	Skutz Falls – Shallow	Skutz Falls – Deep
Area	17.9 km^2	16.6 km^2
Lithostratigraphic Unit	Vashon Drift; likely advance glacial outwash	Vashon Drift; likely advance glacial outwash
Descriptive Location	Skutz Falls, Lake Cowichan, Paldi	
Vulnerability	Low	Low
Subtype	4b - Confined sand and gravel – glacial	4b - Confined sand and gravel – glacial
Material	Sand and Gravel	Sand and Gravel
Quality Concerns	None	None
Productivity	Moderate	Moderate
Artesian Conditions	Not noted	Not noted
Observation Well	OW 429	OW 428

5.2.3 Bedrock Aquifers

Although bedrock occurs beneath the study area, no bedrock aquifer mapping has been completed in the study area beneath AQ 178/AQ 1287.

Bedrock aquifer AQ 182, primarily to the southwest of AQ 178, is mapped up to the eastern boundary of AQ178. Bedrock aquifer AQ 945 is mapped to the northwest of AQ 178. Both bedrock aquifers are mapped as shale and sandstone; AQ 182 as Duncan Formation of the Nanaimo Group and AQ 945 as shale and sandstone of the Nanaimo Group without differentiation to a specific formation. Future mapping could re-evaluate the relationship between the mapped aquifers and whether they should be combined into a single unit.

The bedrock underlying the surficial materials, likely similar to AQ 182 and AQ 945, is not further discussed except as it relates to further discussion around AQ 178 and AQ 1287.

5.3 Aquifer Properties

5.3.1 Transmissivity and Storativity

Available information suggests AQ 178 water diversions are mainly for domestic use. Of the shallow wells completed in AQ 178, none are licensed and as a result, there have been no recorded pumping tests conducted in this aquifer. Existing use groundwater applications to date have not provided any additional pumping test data. Future development may result in hydrogeologic assessments involving pumping tests for this aquifer.

Pumping test estimates of transmissivity and storativity for AQ 1287 are listed in Table 5. AQ 1287 has a high transmissivity, with estimated values ranging from 140 to 550 m^2/day (Turner, 1995) based on a pumping test in WTN 67650 and three observation wells in AQ 1287. LHC (2017) calculated transmissivity as ranging from 212 to 713 m^2/d. The median transmissivity was estimated as 227 m^2/d.

The median hydraulic conductivity, based on the aquifer thickness at the well location was 19.3 m/d.

The median storativity was 1.2 x10^{-3}, ranging from 1.1 x 10^{-4} to 4.6 x 10^{-2} (Turner, 1995), higher than the LHC (2017) estimate of 2.2 x10^{-6} using Theis/Cooper-Jacob methods as well as distance-drawdown plot method.

The largest calculated values of storativity may be suggestive of specific yield (i.e., for an unconfined aquifer) but apparently the water level during the pumping test was drawn below the confining layer suggesting transition to local, temporary, unconfined conditions not reflective of the whole aquifer (BC Groundwater, 2011)

Table 5: Pumping test estimates of transmissivity and storativity for AQ 1287.

Well name	WTN	Transmissivity (m^2/d)	Storativity (no units)	Reference and notes
PW 95-3	67650	225		Turner (1995)
OW 94-6	UNK	150	1.2E-03	Turner (1995)
OW 94-6	UNK	165		Turner (1995)
OW 94-7	67612	140	4.6E-02	Turner (1995)
OW 94-7	67612	155		Turner (1995)
Molnar	108006	550	1.1E-04	Turner (1995)
TH 95-2	100212	Not reported		Lowen (June 2006)
Paldi 10"	86087	193	2.3E-04	Lowen (December 2006)
PW 95-3	67650	213		Lowen (November 2017), PW drawdown
PW 95-3	67650	713	2.2E-06	Lowen (November 2017), OW distance-drawdown plot
PW 95-3	67650	499		Lowen (November 2017), PW recovery
PW 95-3	67650	166		S. Barroso re-analysis Lowen (2017), min PW drawdown
PW 95-3	67650	200		S. Barroso re-analysis Lowen (2017), max PW drawdown
OW1	67612	143	1.0E-02	S. Barroso re-analysis Lowen (2017) OW recovery
OW1	67612	446	1.7E-01	S. Barroso re-analysis Lowen (2017) OW drawdown
PW 95-3	67650	227		S. Barroso re-analysis Lowen (Nov 2017) median (all)
PW 95-3	67650		1.3E-04	S. Barroso re-analysis Lowen (Nov 2017) obs well distance-drawdown plot
	Median	200	7.2E-04	
	Minimum	140	2.2E-06	
	Maximum	713	1.7E-01	

5.3.2 Potential Well Interference

The confining layer between AQ 178 and AQ 1287 likely varies in thickness and presence over the study area, allowing leakage and vertical groundwater movement to occur between the units. The northern edge of the aquifer is bounded by a steep bedrock slope. The southern boundary of the unconsolidated aquifer complex is intercepted by a bedrock ridge along Cowichan River west of Marie Canyon, which was interpreted from field and air photo imagery and well construction information.

Groundwater in AQ 1287 is under confining pressure, and hydraulic connection and interference between wells within the aquifer can extend over a significant distance; for example, during a pumping test of a well in AQ 1287 in September 2017 (LHC, 2017) water level drawdown of nearly 3 m was observed in provincial OW428 located 2.9 km away from the pumping well.

During a pumping test in AQ 1287 (Turner, 1995), a decline in groundwater levels within four monitored wells constructed in the upper aquifer (AQ 178) was noted, ranging from approximately 0.3 to 0.4 m, suggesting there is a hydraulic connection between the two aquifers. However there did not appear to be a correlation between the distance of the observation well from the pumping well and decline in groundwater level, possibly resulting from heterogeneity of the confining layer thickness and occurrence between the two aquifer units. Drawdown interference was anticipated by Turner to be on the range of 5% of available drawdown within the affected wells in the lower aquifer, and drawdown in the upper aquifer was an order of magnitude less than the drawdown observed within the lower aquifer over the same pumping period.

5.4 Water Levels and Hydraulic Interaction Between the Aquifers

Depth to water was reported for 16 of the 23 wells completed in AQ 178. Reported depth to water table ranges from 0.6 to 50.3 metres (2 to 165 feet). The average depth to water table is 26.2 metres (86 feet), and the median depth to water table is 29 metres (95 feet). The depth to water is considered moderately shallow.

Two artesian wells are noted in the study area, both within AQ 178, WTN 67636 (@ 1 US gpm) and WTN 64963 (noted as 'flowing').

Two provincial groundwater observation network (PGOWN) wells (OW) are present in the area. OW 429 (Cowichan Skutz Falls Shallow, WTN 107882) is completed within in AQ 178 and OW 428 is completed within AQ 1287 (Cowichan Skutz Falls Deep, WTN107881). Both wells were established by the province in 2013. The water level data were downloaded from Province of B.C. (2023). The locations of OW 428 and OW 429 are shown in Figure 17; shown as one dot because the wells are in close proximity.

Hydrograph of water level data for the PGOWN wells (Figure 19) shows the effects of regular pumping impacts (noise) on OW 429 water levels in blue. Overall, there is approximately 0.25 m annual variation; with slightly lower (<0.3 m) levels in 2019 to end of 2021.

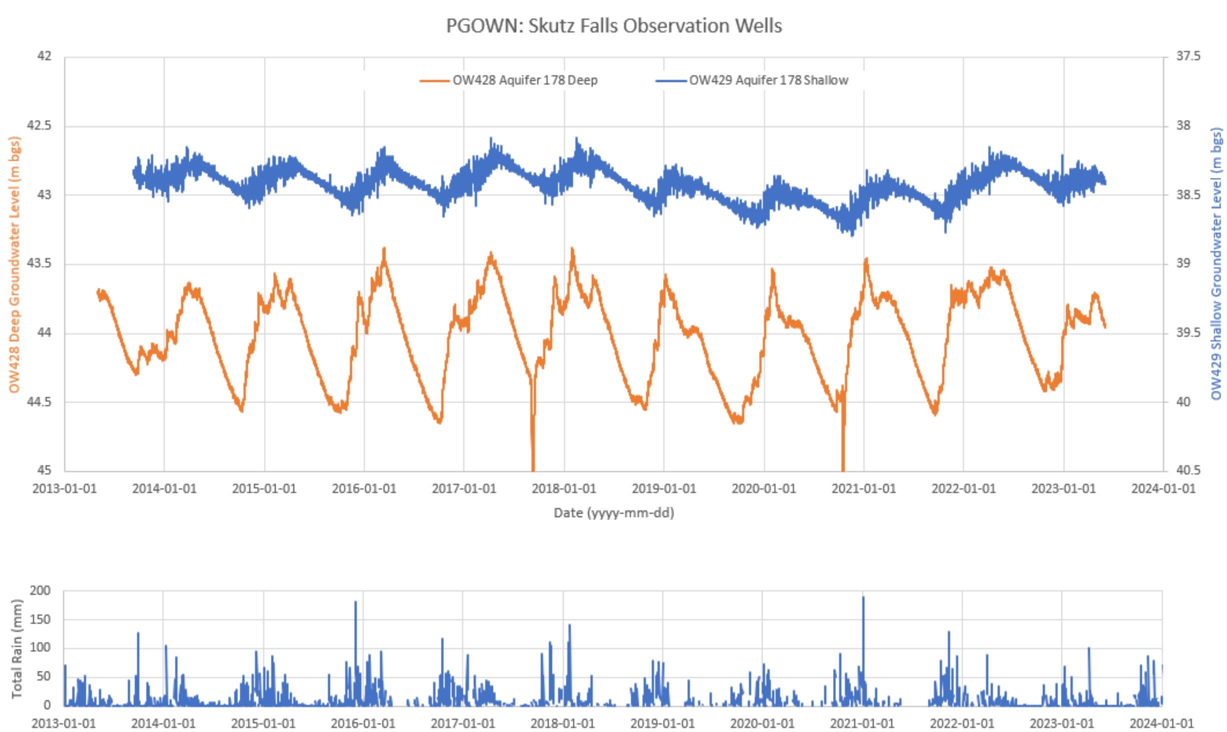

Figure 19: Hydrograph of water level data for OW 428 (orange line) and OW 429 (blue line). Note: vertical axes both display a 3 m range. Lower graph is total rainfall in mm at Cowichan Lake (Climate ID: 1012055).

OW 428, in orange on Figure 19, has no observed effects from pumping impacts. OW428 (AQ 1287) exhibits a seasonal fluctuation of approximately 1 m, with peak groundwater levels in January or February and the lowest levels in September to October (Figure 19). OW428 exhibits a stable long-term trend. The vertical groundwater gradient in vicinity of the observation wells is downward directed, from the shallow toward the deeper aquifer system. The shale bedrock aquifer system beneath the unconsolidated aquifers is not currently monitored.

In both PGOWN wells, hydrograph recession from 2014 to 2021 appears to start earlier from year to year which means less recharge and storage is available to last over the dry summer season. In 2022 the hydrograph recession occurred later in the spring meaning more recharge occurred.

The OW 428 hydrograph shows two unexplained anomalies of lows in water levels less than 45 m below ground (BG): 2017-Sept-12 and 2020-Oct-19. The OW 428 hydrograph shown in this report has been terminated at 45 m BG – to maximize the spread of data points.

Figure 20 shows hydrographs of smoothed data for OW 428 and OW 429. The smoothing used a 2-month window to remove noise. Red vertical lines coincide with winter maximum water levels in OW 428 (AQ 1287). Purple vertical lines coincide with summer minimum water levels in OW 428. A time lag in minima/maxima is apparent. Vertical axes both display a 3 m range (same scale).

The Cowichan Lake climate station (Climate ID: 1012055) precipitation data was compared with the OW 428 water level data. The vertical red lines connect the winter high peaks in the OW 428 hydrograph with the precipitation at the bottom of the figure.

The peaks in the winter high water level in OW 428 coincide reasonably well with peaks in precipitation. This suggests that precipitation events very quickly show up as changes in the deeper OW 428 but are delayed in the shallower OW 429.

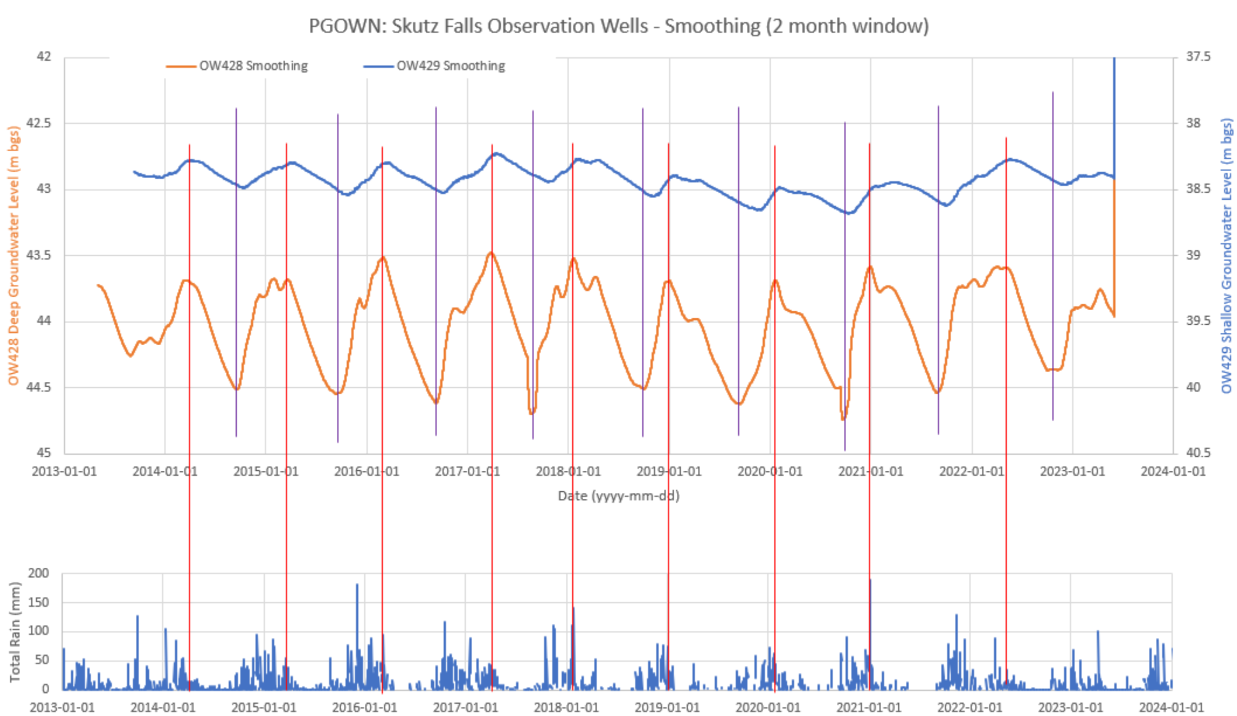

Figure 20: Hydrograph showing smoothed water levels for OW 428 (AQ 1287) and OW 429 (AQ 178). Description in text.

A median lag time for both summer minimum and winter maximum water levels in OW 429 (AQ 178; shallow) behind OW 428 (AQ 1287; deep) is 31 days based on the values in Table 6. This lag time suggests two things:

1. There is a confining layer between the two aquifers, at least at the location of the PGOWN wells and
2. If the majority of recharge comes through mountain block recharge, the transmissivity of AQ 1287 is greater than that of AQ 178.

An alternate interpretation would be that the recharge mechanism is different for each aquifer. In this interpretation, AQ 178 is recharged predominantly through precipitation over the aquifer footprint, which infiltrates through the low permeability confining layer and is therefore slower. Whereas AQ 1287 may be recharged to a greater extent via mountain block recharge. The numerous small tributaries that drain from the slopes to the north side of the aquifer infiltrate into high permeability colluvial (gravity deposited) sediments overlying the bedrock that connect to the deeper aquifer in the valley bottom; a process that occurs more rapidly following precipitation and recharge events.

Table 6: Lag time in summer minima and winter maxima water levels between OW 428 and OW 429.

Summer Minimum Levels		
Deep OW428 Date	Shallow OW429 Date	Difference * # days
2013-08-23	2013-12-19	119
2014-09-14	2014-10-15	31
2015-09-12	2015-10-25	44
2016-09-08	2016-10-09	31
2017-08-24	2017-10-19	56
2018-09-28	2018-10-29	31
2019-09-13	2019-11-21	69
2020-09-22	2020-10-11	19
2021-08-26	2021-09-26	31
2022-11-06	2022-11-25	19

Winter Maximum Levels		
Deep OW428 Date	Shallow OW429 Date	Difference * # days
2014-03-11	2014-04-11	31
2015-01-30	2015-04-08	69
2016-03-05	2016-03-11	6
2017-03-27	2017-04-15	19
2018-01-21	2018-02-09	19
2018-12-25	2019-01-25	31
2020-01-16	2020-02-04	19
2020-12-31	2021-03-22	81
2022-04-08	2022-05-21	44

* - positive value = shallow water levels reach min/max later than deep water levels

Summer Minimum: lag time between deep and shallow varies from 19 to 119 days.
Winter Maximum: lag time between deep and shallow varies from 6 to 81 days.

Figure 21 shows hydrographs of summer minima and winter maxima for OW 428 and OW 429. The hydrographs were plotted using two vertical axes so that the data for the two wells show more detail than if they were on the same axis. Note: vertical scales are the same (3 m range). Note difference in minimum (triangles) and maximum (diamonds) patterns between the two wells.

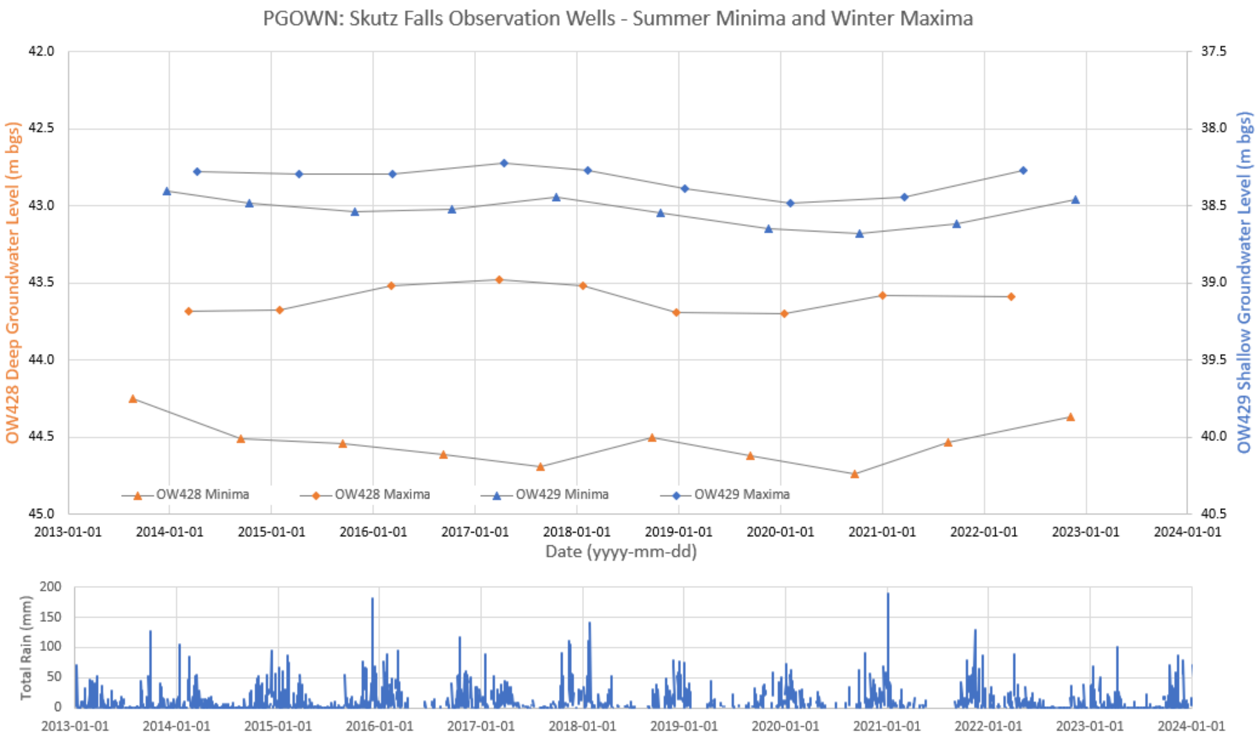

Figure 21: Summer minima and winter maxima for OW 428 (AQ 1287) and OW 429 (AQ 178). Note that water level values in this hydrograph have been shifted by the smoothing process. Lower graph is total rainfall in mm at Cowichan Lake (Climate ID: 1012055).

Summer low and winter high water levels in OW 429 (AQ178) follow a parallel pattern (Figure 21). The offset of approximately 0.25 m between seasonal low and high-water levels in OW 429 is consistent from year to year suggesting that recharge and discharge are balanced on an annual basis.

Summer low and winter high water levels in OW 428 (AQ1287) do not seem related. The offset varies from 0.6 m to 1.2 m. Between 2015 and 2018, summer water level minima are becoming deeper while winter water level maxima are becoming shallower. This is also potentially linked to mountain block recharge and changes in snowpack affecting seasonal patterns of runoff and streamflow in upper Cowichan watershed.

Based on the available data, the following is summarized:

- The water level patterns in OW 428 and OW 429 are different enough that there is no evidence for hydraulic connection between the two aquifers at this location.
- Shallow well (OW 429) water levels lagging 31 days behind deeper well (OW 428) water levels. This means effects of recharge occur earlier or by a different mechanism in the deeper well.
- The variability annually in water levels in the shallow aquifer (AQ178) is less than that in the deep aquifer (AQ 1287) – if recharge was primarily from direct precipitation over the aquifer, the water level fluctuations in the shallow aquifer would normally be greater. Variability in water levels depends on the storage coefficient which is likely smaller in the deeper aquifer.
- Shallow well (OW 429) water level pattern of consistent offset of 0.25 m between minimum and maximum water levels.

- Deep well (OW 428) shows opposite pattern offsets between minimum and maximum water levels varying from 0.6 m to 1.2 m, that is, increasing summer depth in the same year as decreasing winter depth.
- A locally downward directed vertical hydraulic gradient implies that recharge occurs from the shallow to the deep well. It is assumed based on topographic considerations that the downward directed gradient is typical of the aquifer – confirmation based on additional data is required.
- The deeper OW 428 in AQ 1287 responds quickly to precipitation events whereas a median delay of 31 days is apparent in the data from OW 429 in AQ 178.

A possible explanation of the lag time observed in the shallow aquifer is that the horizontal hydraulic gradient may be greater and the transmissivity may be greater for the deeper aquifer (AQ 1287) because of the topographic gradient from mountain block recharge whereas the MBR recharges the shallower aquifer with a lower horizontal hydraulic gradient. Although data for AQ 178 are lacking, it could be that the shallow aquifer (AQ 178) has a lower diffusivity (T/S ratio) than the deeper aquifer (AQ 1287) resulting in recharge impacting AQ 1287 water levels before those in AQ 178.

It may also suggest that MBR does not contribute as significantly, and that recharge of the upper aquifer originates from other sources which are more delayed, such as infiltration of precipitation over the land surface overlying the confined aquifer. This may manifest as a delayed response in the shallower aquifer (AQ 178).

There is some indication in earlier pumping tests that there may be a hydraulic connection between the two aquifers. A slight decline in groundwater level within wells constructed in the upper aquifer occurred during a pumping test (Turner, 1995) on a well in the lower aquifer, suggesting there was a hydraulic connection between the two aquifers. However there did not appear to be a correlation between observation well distance from the pumping well and amount of water level drawdown, possibly due to heterogeneity of the confining layer thickness and occurrence between the two aquifer units (BC Groundwater Consulting Services Ltd. September 6, 2011; Turner Groundwater Consultants Ltd, April 24, 1995). A later test (LHC, 2017), however, showed no effect due to pumping from the lower aquifer on drawdown within monitoring wells in the upper aquifer (AQ 178).

5.5 Aquifer Recharge

Recharge to the study area is most likely from direct precipitation and infiltrated precipitation to the northeast in the uplands. In this study this upland recharge will be referred to as Mountain Block Recharge (Wilson and Guan, 2004).

Precipitation in the upland areas will infiltrate the shallow soils and the bedrock flowing down and to the southeast toward the Cowichan River. A portion likely recharges the Quaternary sediments in the valley of the Cowichan River. Upland sub-tributaries feed rainfall into the subsurface including colluvial deposits nearest the break in slope (Figure 22).

Based on the above conceptual model, recharge to the upper and lower confined aquifers likely occurs through:

a) Indirect recharge via infiltration of precipitation and leakage through overlying unsaturated and saturated sedimentary layers. Precipitation will infiltrate the upper unsaturated soil and unconfined aquifer layer first, then make its way to deeper aquifers as leakage through the confining layers or where intervening confining layers are absent.
b) Mountain block recharge and lateral flow from the bedrock slopes along the northeast side of the unconsolidated aquifers.

c) Lateral flow from unconsolidated materials/aquifers on the west side of AQ 178, expected to be a minor contribution to potential recharge.

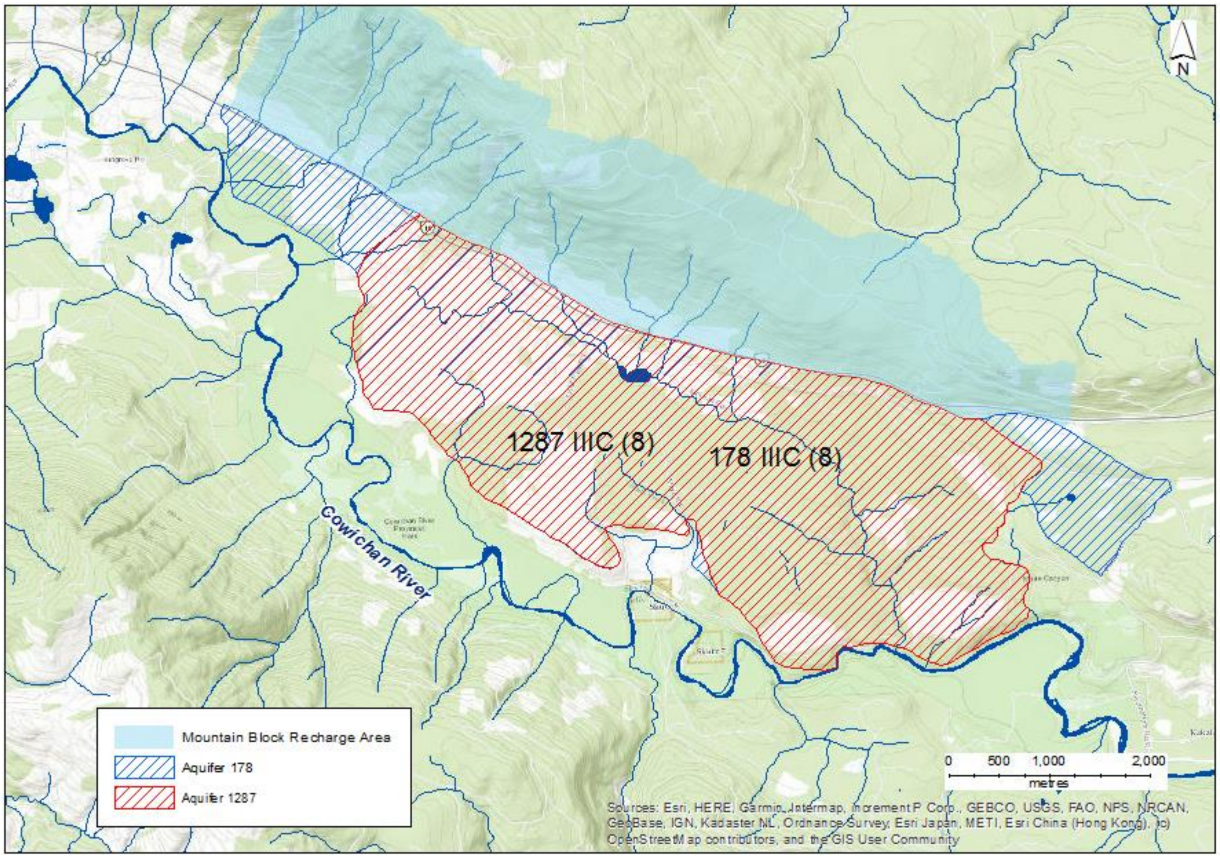

Figure 22: Assumed area of mountain block recharge.

5.6 Aquifer Discharge

Discharge from the upper and lower aquifers is expected to occur via seepage at the bluff face to spring seeps at the toe of the slopes on the north side (left bank) of Cowichan River, or as leakage to the underlying and adjacent sedimentary bedrock units, such as where the Cowichan River is bordered by consolidated materials.

Previous work by Foster and Allen (2015) indicates that the Cowichan River is "gaining" or receiving recharge from the adjacent aquifers in the river reach south of the subject well. The bed of Cowichan River southwest of the study area has eroded into the bedrock underlying the two unconsolidated water-bearing zones. Bedrock outcrops are visible on either side of the river.

Springs and surface seeps are mapped at locations along the north side of the river in this area. East of the bedrock ridge, the unconsolidated bench is exposed along the river as a ~20 m high bluff face. The locations of bedrock or unconsolidated Quaternary sediments along the riverbank and bed are indicated in the report cover photos. The aquifers discharge to the river in the vicinity of Marie Canyon.

5.7 Groundwater Flow Direction

The average static groundwater levels from wells in the study area (Table 3) indicate a downward gradient within the unconsolidated materials, with higher static water levels in the surficial and upper confined aquifer (AQ 178), compared to the deeper, unconsolidated aquifer, AQ 1287. Static water levels within bedrock wells suggest there could be an upward gradient from the bedrock aquifer toward the deeper, unconsolidated aquifer AQ 1287.

Groundwater in the AQ 1287, driven by topographic gradients, flows from north-west to south-east with a hydraulic gradient of approximately 4% (Turner, 1995) (Figure 23).

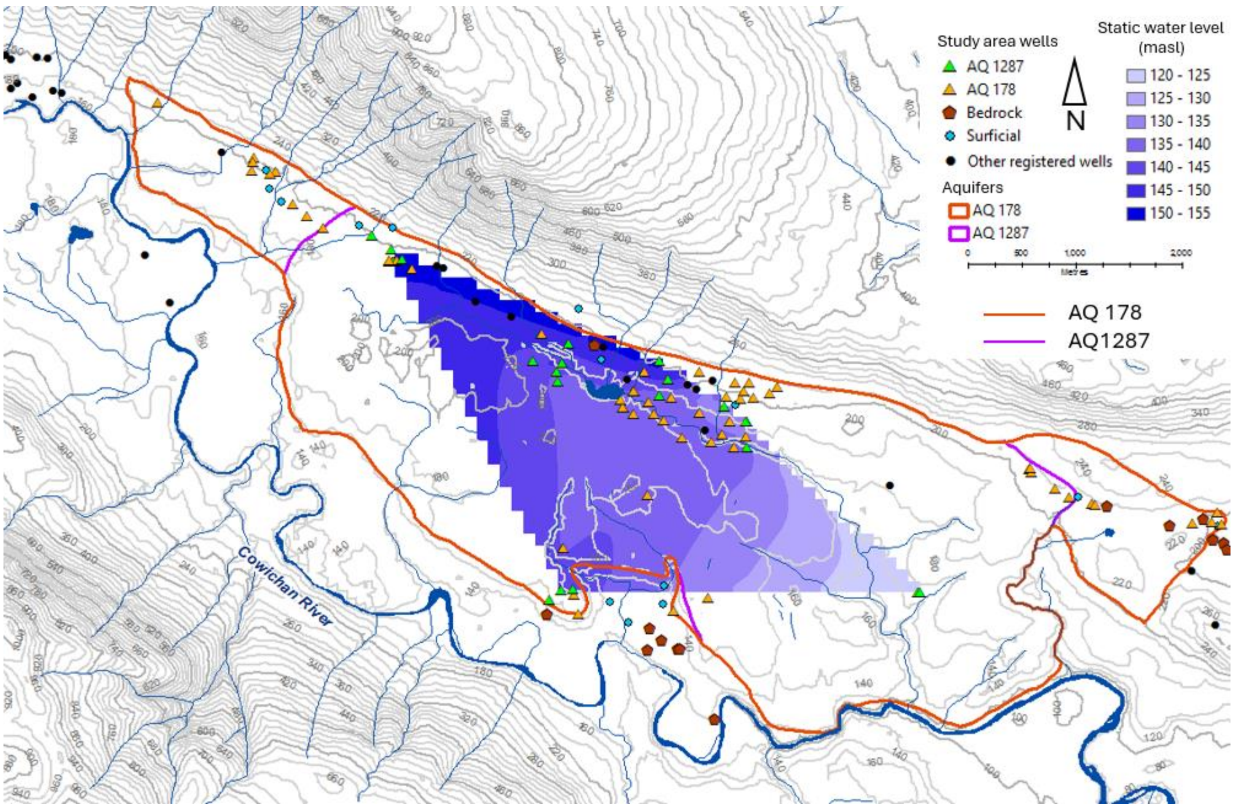

Figure 23: Static water levels and groundwater flow direction in AQ 1287

6. HYDRAULIC CONNECTIVITY TO SURFACE WATER

The guidance document "Determining the Likelihood of Hydraulic Connection" (Province of B.C., 2016), defines hydraulic connection as being: "for the purpose of water allocation and use,… the reasonable likelihood that pumping of groundwater from a well will eventually result in a change in the flow of a stream or spring or change in the level of a lake, pond, wetland that overlies or borders the aquifer, over a time period and to an extent that the decision maker must take into account in considering the environmental flow needs of the stream or whether the rights of other authorized users on the stream are likely to be detrimentally affected."

Overlying tributaries are not thought to be hydraulically connected to the upper aquifer because of the larger vertical separation between the stream and the aquifer (Figure 9). Mayo Creek has the potential to be hydraulically connected where it is incised into the overlying confining materials.

Cowichan River flows during the dry season are primarily determined by regulated discharges from the weir at Cowichan Lake.

Scientific understanding of the effect of long-term groundwater pumping on connected surface waters assumes that over an extended period of pumping, 100% of groundwater withdrawn originates from induced recharge, capture or interception of groundwater that would naturally discharge to surface water sources that are hydraulically connected to the aquifer (Province of B.C., 2016; Barlow & Leake, 2012).

Aquifers of type 4b (confined and comprising unconsolidated, preglacial and glacial sediments) are considered less likely to be hydraulically connected to adjacent surface water bodies if separated from the surface by a continuous confining layer, unless site specific evidence exists to the contrary.

Despite the presence of confining layers above the subject aquifer, there is evidence that erosion along Cowichan River has incised the confining layers, and there may be a hydraulic connection between the unconsolidated aquifers and the river, either discharging directly through streambank seepage and spring discharges, or via leakage with the adjoining sedimentary bedrock which borders the river. The Cowichan River water level is typically below the base of the aquifers (AQ 178 and AQ1287) where they are exposed in the steep riverbank; this means that flow from the river will not be induced into the aquifer because of pumping. The Cowichan River has eroded surficial materials down to the lower permeability bedrock surface in the study area. Groundwater flow from overlying aquifers toward the river would intercept the bedrock surface (a local base level) – pumping in those aquifers would potentially intercept that flow.

Cross-section C-C’ (Figure 9) and to a lesser degree cross-section B-B’ (Figure 8) and description of AQ 178 and the underlying AQ 1287, indicate that there is a bedrock ridge that separates the unconsolidated aquifers from the river south-southeast of the well, and the Marie Canyon area of Cowichan River. This bedrock ridge and the presence of shallow, sedimentary bedrock bordering Cowichan River upstream of Stoltz Bluff are also confirmed in bedrock geology mapping, (Muller, 1983).

Seepage through the fractured shale in areas of the river underlain and bordered by bedrock is another potential source of discharge to the river. However, the degree of interaction between the sedimentary bedrock and adjacent unconsolidated aquifers is not well understood. The various studies to date have not provided a quantitative analysis of impact from well pumping that has been verified by detailed field observations in proximity to the river.

Cowichan River is observed in the field to be disconnected from the steep vertical cliff faces which border the north side of the river west of Stoltz Pool (Cowichan River Park). A decrease in groundwater level or head within the unconsolidated aquifers may result in a decrease in seepage through diffuse flow and concentrated spring seeps on the cliff face and toe of the slope adjoining the river bank, but due to the topography of the area would not be anticipated to reverse the gradient between aquifer and river (i.e. the river is unlikely to contribute to direct recharge of the unconsolidated aquifers on the northern slope bordering the river).

Cowichan Tribes (Craig and Kulchynski, 2016) have long suggested that cold water influx from groundwater discharge as seeps along the upper Cowichan River above Skutz Falls (within the study area) provide cold water refugia for fish during the summer months.

7. DATA GAPS AND UNCERTAINTY

Mapped aquifers extend beyond areas with registered wells; therefore, there is uncertainty in aquifer boundaries, properties, and interpreted water levels. Sources of uncertainty include the following:

- Lack of well data closer to the river. Areas which are forested, non-residential, and within parks lack subsurface information.
- No groundwater level monitoring in the bedrock aquifer system.
- Streamflow monitoring data is limited.
    - Ephemeral tributaries.
    - Streams with perennial/year-round baseflow.
    - The relative contribution of tributaries to Cowichan River flows is unknown.
- Biological importance of groundwater baseflow to microhabitats (e.g. thermal regulation).
- Potential impacts of a major increase in groundwater diversion from the deep undeveloped aquifer are poorly understood.
- AQ 1287's spatial variability and degree of leakiness and hydraulic connection with upper aquifer (AQ 178) and unknown connection to bedrock system.
- Surface water/groundwater interactions from limited information on local variations in the hydraulic conductivity of streambed sediments and underlying geology.

8. CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

This work was undertaken to describe the stratigraphy and interrelationships between the layered unconsolidated aquifers and the deeper bedrock aquifer based on information available at the time. The potential hydraulic connection between the aquifers and the Cowichan River was explored.

The study area geology was summarized as Quaternary glacio-marine sediments overlying a sequence of glacio-lacustrine and glacio-marine sediments in turn overlying pre-glacial gravel overlying Nanaimo Group sandstone/shale bedrock. Based on geology, water well lithology data cross-sections were developed which helped to recognize two confined sand and gravel aquifers within the Quaternary sediments, one shallow AQ 178 and one deeper AQ 1287.

Isopach maps based on limited water well lithology data were prepared to provide unit thicknesses for the two aquifers and over- and underlying confining units as well as bedrock topography. Lack of detailed well logs and a limited number of deeper wells drilled in undeveloped areas prevented creation of isopach maps for the whole aquifer. The area is underlain by a shale bedrock aquifer which has not been mapped but is likely an unmapped extension of AQ 945. Adjacent to the study area there are mapped bedrock aquifers AQ 182 and AQ 945.

Average groundwater elevation in AQ 178 is 163 masl and that in AQ 1287 is 139 masl.

A provincial government observation well is in each unconsolidated aquifer: OW 429 in AQ 178 and OW 428 in AQ 1287. Water levels in the observation wells have the following characteristics:

- The variability annually in OW 429 is less than that in OW 428.
- Water levels in the shallow well (OW 429) varies annually by 0.25 m consistently whereas the deep well (OW 428) shows groundwater levels varying from 0.6 m to 1.2 m.
- Downward directed vertical hydraulic gradient.

- The deeper OW 428 responds quickly to precipitation events whereas a median delay of 31 days is apparent in the data from OW 429 in AQ 178.

The horizontal hydraulic gradient may be greater for the deeper aquifer (AQ 1287) whereas the shallower aquifer recharges with a lower horizontal hydraulic gradient which may manifest as a delayed response in the shallower aquifer (AQ 178).

Groundwater flow is generally to the southwest toward the Cowichan River. The two aquifers are likely recharged from the uplands to the north and discharge from seeps along the north bank of the Cowichan River. There is potential for hydraulic connectivity between the two aquifers where the intervening confining unit thins as well as possibly to Mayo Creek where it may be incised into the material overlying the upper aquifer, AQ 178. This may only occur locally and needs to be confirmed from lithologic descriptions as additional wells are drilled in the area.

8.2 Recommendations

Next steps towards further hydrogeological characterization within the study area are identified below to support sustainable groundwater management.

- According to available information, AQ 178 water diversion is inferred to currently consist mainly of domestic use. As a result, there have been no pumping tests recorded in this aquifer. Existing use groundwater applications to date have not provided pumping test data. New use groundwater applications for future development will likely include pumping test data and analyses which will be helpful to further characterize this aquifer.
- Continued monitoring of the provincial observation wells, OW 428 and OW 429 to further help interpretation of the resulting water level patterns.
- Conduct a survey of streams in the study area to ascertain which if any are hydraulically connected to the shallow aquifer (AQ 178).
- Periodic updating 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.
- A field study designed to better understand the hydraulic connection between the two aquifers, AQ 178 and AQ 1287 and the Cowichan River.
- Aquifer mapping to identify the bedrock aquifer beneath the study area as more bedrock wells are installed providing lithologic data would help to reconcile the AQ 182 and AQ 945 boundary beneath the study area.

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APPENDIX A: AQUIFER MAPPING REPORT FOR AQUIFER 178

A. AQUIFER DESCRIPTION FOR AQUIFER TAG 178

A.1 CONCEPTUAL UNDERSTANDING OF HYDROSTRATIGRAPHY

A.1.1 AQUIFER EXTENTS

Aquifer 178, the Skutz Falls Aquifer, is located near Skutz Falls west of Paldi, Cowichan Valley, B.C. (Figure 1). It is bounded by terrace-like feature of the Cowichan River valley that is situated between mountains to the north and the Cowichan River floodplain to the south. The aquifer area is approximately 17.0 km^2.

The eastern boundary of the Skutz Falls Aquifer is estimated. A bedrock ridge appears in the Stoltz Road area. It is possible that the Skutz Falls Aquifer and the South Sahtlam Aquifer (Aquifer No.179) could be connected by the same flow system because they both occur in a similar geological environment. There are no water well records available to assure a connection between the two aquifers therefore, they are delineated as two separate aquifers with a boundary drawn based on area of development.

NTS Map sheet: 092B/13 and 092C/16. Well location maps: Cowichan Lake and Sahtlam Land Districts. BCGS Mapping Areas: 092B.071.3.3.2; 092B.071.3.3.3; 092B.071.3.3.4; 092B.071.3.4; 092B.071.4.3.1; 092B.071.4.3.3; 092B.081.1.1; 092B.081.1.2.1; 092C.090.2.4.1; 092C.090.2.4.2

A.1.2 GEOLOGIC FORMATION (OVERLYING MATERIALS)

The aquifer is confined by till, clay, lenses of silty, sand and gravel. The overlying material is characterized as ground moraine deposits part of Vashon Drift of the Cenozoic Era.

A.1.3 GEOLOGIC FORMATION (AQUIFER)

Likely ice advance outwash. Poorly sorted gravel, sand and silt. Vashon Drift, Cenozoic Era.

A.1.4 PRODUCTIVITY

Moderate. Reported yields range from 0.13 to 1.26 L/s (2 to 20 gallons per minute; gpm). The geometric mean yield is 0.57 L/s (9 gpm) and the median yield is 0.63 L/s (10 gpm). No wells in this aquifer have had pumping tests conducted to determine the transmissivity and specific capacity of the aquifer.

Depth of wells ranges from 1.8 to 67.4 metres (6 to 221 feet). The geometric mean depth of wells is 22.3 metres (73 feet) and the median depth of wells is 30.5 metres (100 feet).

A.1.5 VULNERABILITY

Low. Depth to water table is moderately shallow. Confined by till and clay. Depth of confining layer averages 8.8 metres (28.8 feet), however the range of confinement varies from 0.3 to 47.2 metres (1 to 155 feet). Degree of confinement is moderately high.

A.2 CONCEPTUAL UNDERSTANDING OF FLOW DYNAMICS

A.2.1 GROUNDWATER LEVELS AND FLOW DIRECTION

Depth to water was reported for 16 of the 23 wells. Reported depth to water table ranges from 0.6 to 50.3 metres (2 to 165 feet). The geometric mean depth to water table is 18.3 metres (60 feet). The average depth to water table is 26.2 metres (86 feet), and the median depth to water table is 29 metres (95 feet). The depth to water is considered moderately shallow.

Flow direction has not been determined. It is probable that the direction of flow is south towards the Cowichan River. Additional water level data are required to confirm the direction of flow.

A.2.2 POTENTIAL FOR HYDRAULIC CONNECTION

Where surface water streams have incised into the unconsolidated materials hydraulic connection is more likely.

A.3 ADDITIONAL INFORMATION ON WATER USE AND MANAGEMENT

Domestic well density is approximately 1.3 wells/km^2. Reliance on source is conjunctive (both surface water and groundwater sources). Several water licenses exist on streams, lakes and springs located within the Skutz Falls Aquifer boundaries. There are no documented conflicts between users; no documented water quantity nor quality concerns.

A.4 ADDITIONAL ASSESSMENTS OR MANAGEMENT ACTIONS:

None.

A.5 AQUIFER REFERENCES

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A.6 REVISION HISTORY

Date	Version	Revision Class	Comments	Author
19951116	1	Major	Initial mapping of aquifer	Unknown
20120325	2	Major	Updated aquifer extents and statistics	Margaret Scott
20231130	3	Minor	Updated extents and well numbers	D. van Everdingen, P.Geo.

A.7 AQUIFER SUMMARY TABLE

Parameter	Value
Aquifer Number	178
Aquifer Name	Skutz Falls – Shallow
Area	17.9 km^2
Lithostratigraphic Unit	Vashon Drift; Likely advance glacial outwash
Descriptive Location	Skutz Falls, Lake Cowichan, Paldi
Vulnerability	Low
Subtype	4b - Confined sand and gravel – glacial
Material	Sand and Gravel
Quality Concerns	None
Productivity	Moderate
Artesian Conditions	Two noted
Obs. Wells	OW 429

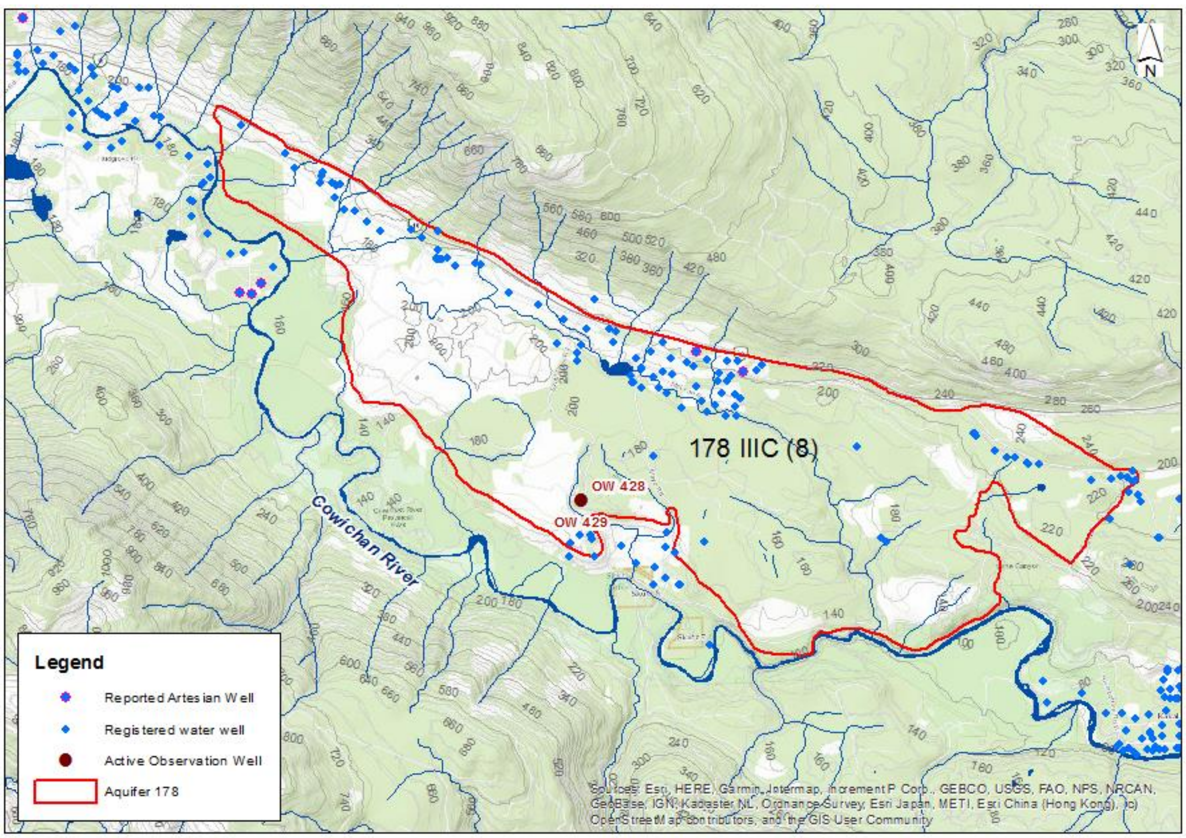

Figure 1: Red outlined polygon - Aquifer 178.

APPENDIX B:

B. AQUIFER DESCRIPTION FOR AQUIFER TAG 1287

B.1 CONCEPTUAL UNDERSTANDING OF HYDROSTRATIGRAPHY

B.1.1 AQUIFER EXTENTS

Aquifer 1287 is bounded by the terrace-like feature of the Cowichan River Valley situated between the mountains to the north and the Cowichan River plain to the south (Figure 1). Its boundary to the west and east is defined by the extent of wells drilled into or through the aquifer. It is located near Skutz Falls west of Paldi, Cowichan Valley. Aquifer area is approximately 16.6 km^2.

B.1.2 GEOLOGIC FORMATION (OVERLYING MATERIALS)

Low permeability confining layers of clay (till), silt, and silty fine sand are found above Aquifer 1287 which separate the overlying Aquifer 178. The confining layer between the two layered unconsolidated aquifers varies in occurrence and thickness. Testing of wells in the area indicates there is a hydraulic connection between the two aquifers, and leakage where the confining materials thin or pinch-out is likely.

B.1.3 GEOLOGIC FORMATION (AQUIFER)

Consists of unconsolidated, coarse sand and gravel within a glaciofluvial terrace originating from pre-glacial and glacio-fluvial processes that have deposited and reworked alluvial materials derived from erosion of the adjacent mountains to the north. Thickness varies up to 20 m with a median thickness of 9.2 m.

Aquifer 1287 is underlain by unmapped fractured shale bedrock belonging to the Nanaimo Group and is likely associated with bedrock Aquifer 182 to the east.

B.1.4 VULNERABILITY

Low. Although depth to the piezometric surface is moderately shallow, the depth to the top of the Aquifer is deep (average 60 m) and is confined by till and clay. Degree of confinement is high.

B.2 CONCEPTUAL UNDERSTANDING OF FLOW DYNAMICS

B.2.1 GROUNDWATER LEVELS AND FLOW DIRECTION

Wells constructed in Aquifer 1287 range in depth from 54 m to 96.3 m. Depth to water was reported for 22 of 23 wells and ranged from 7.3 to 16.2 m below ground. The average depth is 12.9 m. Flow direction has not been determined but is likely to be to the south towards Cowichan River. Aquifer 1287 may be hydraulically connected to the Cowichan River at Stoltz Bluff through aquifer discharge along the steep slopes of the river valley. Recharge is likely from precipitation and snow melt through mountain block recharge from the mountains to the north.

B.2.2 POTENTIAL FOR HYDRAULIC CONNECTION

The smaller tributaries to Cowichan River are not believed to have incised through the low permeability sediments (confining layers) overlying aquifer 1287 and therefore hydraulic connection between these tributaries and the aquifer is considered unlikely.

Despite the presence of confining layers above Aquifer 1287, there is evidence that erosion along Cowichan River has incised the confining layers, and there may be a hydraulic connection between the unconsolidated aquifers and the river, either directly through streambank seepage and spring discharges, or indirectly via leakage through the adjoining sedimentary bedrock which borders the river. Aquifer discharge via seepage, along steep slopes, is small compared to Cowichan River flow.

B.3 ADDITIONAL INFORMATION ON WATER USE AND MANAGEMENT

Domestic well density is approximately 1.4 wells/km^2. Reliance on source is conjunctive (both surface water and groundwater sources are utilized). Several water licenses exist on streams, lakes and springs located within the Skutz Falls Aquifer boundaries. There are no documented conflicts between users; no documented water quantity nor quality concerns.

B.4 ADDITIONAL ASSESSMENTS OR MANAGEMENT ACTIONS:

None.

B.5 AQUIFER REFERENCES

Clapp, C.H. 1918. Duncan Sheet, Vancouver Island Map 42A. Canada Department of Mines, Geological Survey. Memoir 96, No. 80, Ottawa Government Printing Bureau 1918, No. 1192.

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B.6 REVISION HISTORY

Date	Version	Revision Class	Comments	Author
202105	1	Major	Initial mapping of aquifer	Sylvia Barroso, P.Geo
20231130	2	Major	Updated mapping of aquifer, preparation of aquifer mapping report	D. van Everdingen, P.Geo.

B.7 AQUIFER SUMMARY TABLE

Parameter	Value
Aquifer Number	1287
Aquifer Name	Skutz Falls – Deep
Area	16.6 km^2
Lithostratigraphic Unit	Vashon Drift; Likely advance glacial outwash
Descriptive Location	Skutz Falls, Lake Cowichan, Paldi
Vulnerability	Low
Subtype	4b - Confined sand and gravel – glacial
Material	Sand and Gravel
Quality Concerns	None
Productivity	Moderate
Artesian Conditions	Not noted
Obs. Wells	OW 428

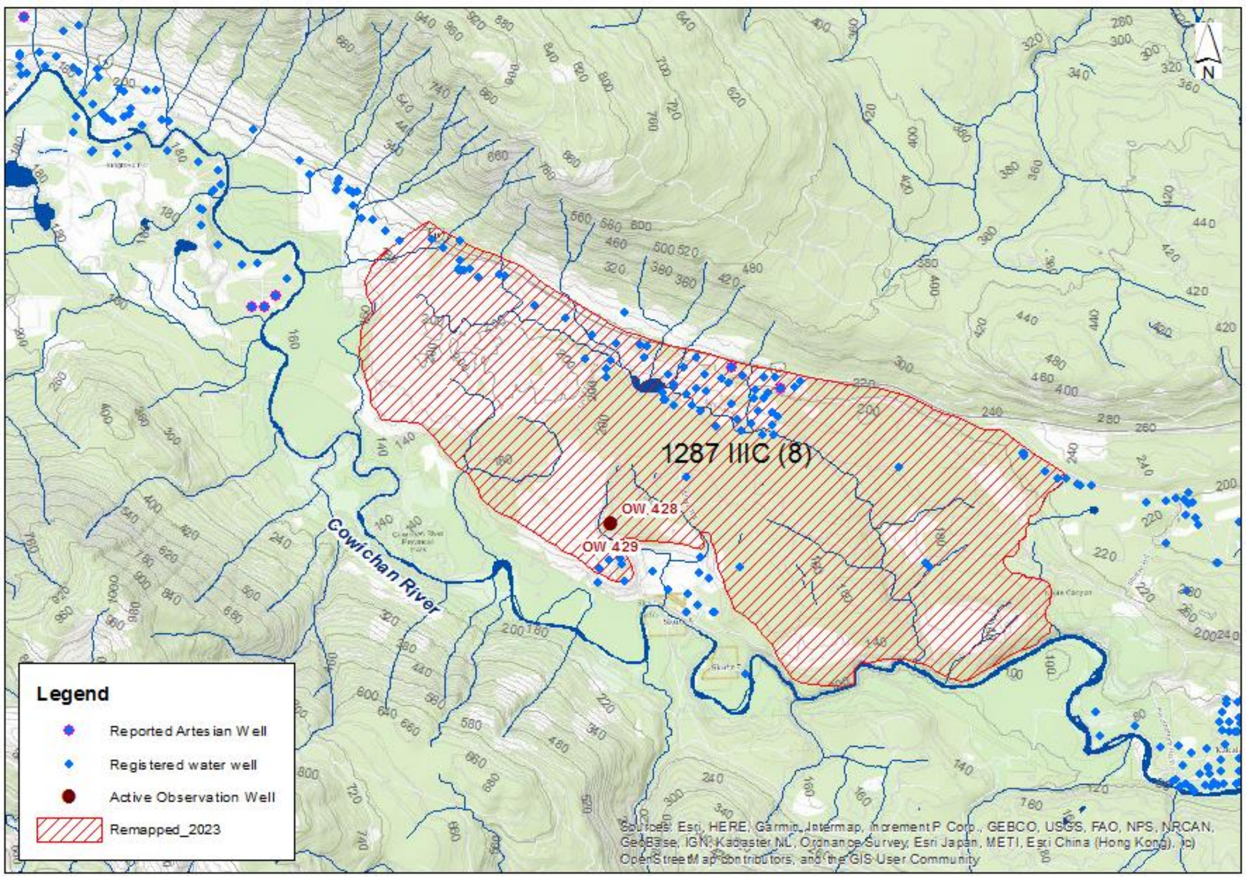

Figure1: Cross-hatched red polygon - Aquifer 1287.