



ASSESSMENT OF GROUNDWATER ALLOCATION LIMITS FOR AQUIFER 566 (EAST SECHELT DELTA)

Prepared for:

MINISTRY OF FORESTS
102 INDUSTRIAL PLACE
PENTICTON, BC
V2A 7C8

Prepared by:

HATFIELD CONSULTANTS LLP
#200 - 850 HARBOURSIDE DRIVE
NORTH VANCOUVER, BC
CANADA V7P 0A3
TEL: 1.604.926.3261 • WWW.HATFIELDGROUP.COM

MARCH 2023

MINFO11805-NV
VERSION 3.0

TABLE OF CONTENTS

LIST OF TABLES	iii
LIST OF FIGURES.....	iii
ACKNOWLEDGEMENTS.....	iv
1.0 BACKGROUND	1
2.0 DATA.....	3
3.0 SETTING.....	4
3.1 PHYSIOGRAPHY	4
3.2 CLIMATE	4
3.3 HYDROLOGY	5
3.4 LAND USE	5
3.5 GEOLOGY AND HYDROSTRATIGRAPHY	9
4.0 AQUIFER CHARACTERISTICS.....	10
4.1 AQUIFER GEOMETRY.....	10
4.2 GROUNDWATER FLOW.....	10
4.2.1 Lateral Groundwater Flow	10
4.2.2 Vertical Groundwater Gradients	15
4.2.3 Time Series Groundwater Levels	15
4.3 AQUIFER HYDRAULIC PROPERTIES.....	16
4.4 LIKELIHOOD OF HYDRAULIC CONNECTION WITH CHAPMAN CREEK.....	18
5.0 WATER USES AND WATER RIGHTS.....	20
5.1 SURFACE WATER.....	20
5.2 GROUNDWATER	22
6.0 AQUIFER WATER BALANCE.....	25
6.1 CONCEPTUAL WATER BUDGET	25
6.1.1 Aquifer Inflows	25
6.1.2 Aquifer Outflows	25
6.1.3 Water Budget.....	25
6.2 ESTIMATION OF WATER BUDGET COMPONENTS	25
6.2.1 (R_p) Recharge from Precipitation.....	25
6.2.2 (Q^{GW}_{in}) Groundwater Inflow (Mountain Block Recharge)	26
6.2.3 (Q^{SW}_{out}) Surface Water Outflow (Groundwater Baseflow).....	26
6.2.4 (Q^{GW}_{out}) Groundwater Outflow (Marine Environment).....	26
6.2.5 ($Q^{GW_{pump}_{out}}$) Groundwater Pumping.....	27
6.2.6 Overall Water Budget	27

7.0	ESTIMATING ALLOCATION LIMITS	28
7.1	ALLOCATION LIMIT CONSTRAINED BY STREAM DEPLETION	28
7.2	ALLOCATION LIMIT BY PERCENTAGE OF ANNUAL GROUNDWATER FLUX.....	30
7.3	ALLOCATION LIMIT CONSTRAINED BY PERCENTAGE OF MEAN ANNUAL RECHARGE.....	30
7.4	ALLOCATION LIMIT BASED ON AVAILABLE DRAWDOWN	31
7.5	DISCUSSION OF RESULTS	31
	7.5.1 Aquifer Scale Allocation Limits	31
	7.5.2 Potential Aquifer Management Areas.....	32
7.6	APPLICATION OF APPROACH TO OTHER TYPE 4A AQUIFERS	33
8.0	REFERENCES.....	37

LIST OF TABLES

Table 1	Monthly climate statistics for 1991-2021 from ClimateBC (Wang et al 2016).	6
Table 2	Mapped geologic units, and corresponding mapped aquifers.	9
Table 3	Construction and monitoring details of the PGOWN wells.	15
Table 4	Main hydrogeological properties of Aquifer 566.	17
Table 5	Reported water licenses on Chapman Creek downstream of PD61040.	20
Table 6	Reported wells in Aquifer 566.	23
Table 7	Reported wells in Aquifer 564.	24
Table 8	Water use by groundwater pumping application for entire aquifer.	27
Table 9	Summary of water budget range estimations.	27
Table 10	Streamflow depletion thresholds for Chapman Creek.	30
Table 11	Possible allocation limits for Aquifer 566 based on different methods.	31
Table 12	Possible allocation limits for Allocation Management Areas.	32

LIST OF FIGURES

Figure 1	Mapped aquifers and watersheds.	2
Figure 2	Climate for 1991-2021 reference period from ClimateBC (Wang et al 2016).	7
Figure 3	Long term climate data from 1971-2021 from ClimateBC (Wang et al 2016).	8
Figure 4	Location of hydrogeologic cross-sections.	11
Figure 5	North-south cross-section A-A'.	12
Figure 6	West-East cross-section B-B'.	13
Figure 7	Inferred aquifer 566 groundwater elevation contours.	14
Figure 8	Depth to groundwater for PGOWN wells near Chapman Creek.	16
Figure 9	Inferred confining layer and vadose zone thickness.	19
Figure 10	Location of surface water licenses.	21
Figure 11	Quantity of water withdrawals in Chapman Creek by water source and purpose.	22
Figure 12	Estimated mean monthly flows for Chapman Creek near Wilson Creek (1959-1970).	28
Figure 13	Proposed aquifer allocation management areas.	34

ACKNOWLEDGEMENTS

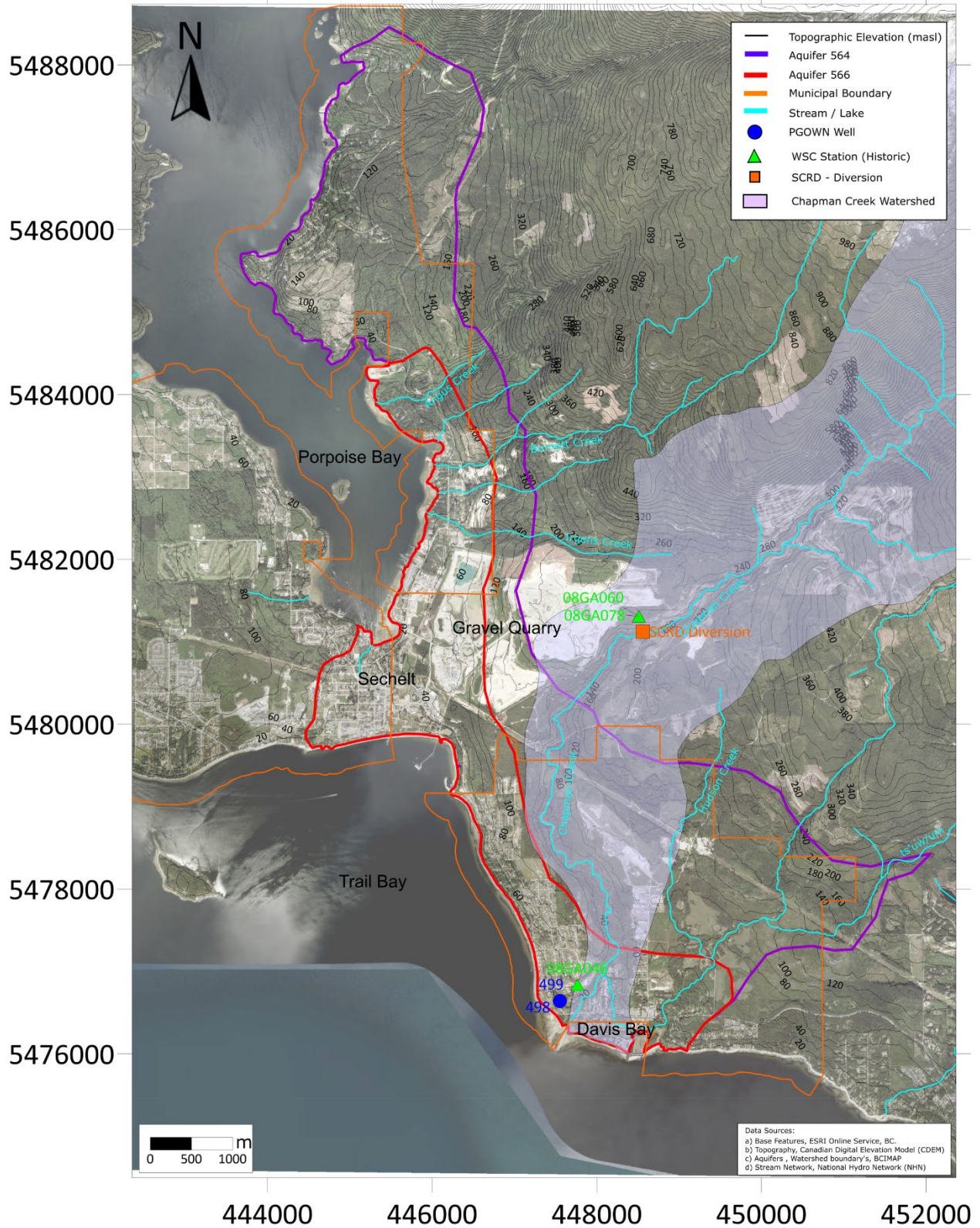
Hatfield contributors to this report include Jessica Warrack, Jacob Nunn, Alex Cassidy and Jos Beckers. We would like to acknowledge the comments from Ministry of Forests personnel that helped improve this document.

1.0 BACKGROUND

The East Sechelt Delta aquifer, aquifer 566, is a 9.7 km² type 4a, mostly unconfined aquifer along the Sunshine Coast, near Sechelt, BC. The aquifer is primarily located in the Carlson Creek watershed (358 km²), but also spans the Chapman Creek (73 km²) and Wilson Creek (45 km²) watersheds. Aquifer 566 overlays aquifer 564, a type 6b fractured crystalline bedrock aquifer. Boundaries of both aquifers are shown in Figure 1.

A desktop assessment case study was completed to estimate the groundwater allocation limits of a type 4a aquifer. The East Sechelt Delta aquifer was a good candidate for study because there have been limited studies completed in the area, but climate change and water scarcity issues have led to an increased interest in groundwater extraction. The Sunshine Coast Regional District (SCRD) operates a surface water diversion license on Chapman Creek, a designated sensitive stream under the *Water Sustainability Act* (WSA). The SCRD surface water intake on Chapman Creek (Point of Diversion 45088) is located 6.6 kms upstream of the mouth of Chapman Creek (Triton, 2006), upslope from the aquifer (Figure 1). Additionally, there are groundwater users in the area and aquifer 566 is within the area of a foundation agreement with shíshálh Nation (self-governing since 1986) meaning this case study will be useful to inform review of batched applications for groundwater extraction in this area.

Figure 1 Mapped aquifers and watersheds.



2.0 DATA

To complete the desktop study, data was collected from the following sources:

- LiDAR BC: 2019 digital elevation model (Ministry of Forests, 2022);
- iMAPBC: aquifer boundaries, water use licenses, soil polygons (Province of British Columbia, 2022b);
- GWELLS: wells, water rights, geological and aquifer mapping (Province of British Columbia, 2022a)
- Climate BC: climate data (Wang et al, 2016); and
- Environment Canada: historical hydrometric data (Government of Canada, 2022).

The assessment was completed through a review and interpretation of available data and should be considered preliminary. No physical observations or field data were collected to confirm the data used in the desktop study.

3.0 SETTING

3.1 PHYSIOGRAPHY

East Sechelt Delta (Aquifer 566) is contained within the Sunshine Coast Regional District (SCRD). The surface elevation begins at sea level by the Strait of Georgia in the south and Sechelt Inlet in the north and increases to a maximum elevation of 129 masl moving inland towards the Coast Mountains, which have a maximum elevation greater than 1,600 masl.

Irgens Creek flows east to west in the northern region of the aquifer and meets Porpoise Bay (southern portion of Sechelt Inlet) at the western boundary of the aquifer (Figure 1). Burnet Creek and Angus Creek, both of which are north of Irgens Creek, similarly terminate in Porpoise Bay. Chapman Creek flows through the southern part of the aquifer area and begins at an elevation of roughly 1,800 masl in the Tetrahedron Plateau. Chapman Creek is the primary water storage supply for the SCR D's Chapman water system.

3.2 CLIMATE

Climatic conditions in the study area are represented using ClimateBC (Wang et al., 2016) which facilitates users to obtain climate data for specific locations (including consideration for orographic and other effects) and for consistent climate normal periods. A reference period from 1991-2021 was used to represent current climate conditions. Average monthly precipitation and temperature for the 1991-2021 reference period is displayed in Figure 2 and Table 1. Mean annual precipitation is around 1,106 mm, the majority of which falls as rain (accumulation of snowpack is uncommon). The driest months of the year typically occur around May to August which together account for approximately 14% of the annual precipitation. The wettest month is typically November which accounts for 15% of the annual precipitation. The mean annual temperature is around 10°C. Average daily temperatures are typically near 4.5°C in mid-winter (December and January) and reach an annual maximum of 18°C in the summer months (July and August). ClimateBC was also used to calculate reference evapotranspiration (ET_0) through the Hargreaves equation (Hargreaves et al., 1985). ET_0 is potential evapotranspiration (PET) for a reference crop (grass). Average ET_0 in the study area was estimated at 605 mm, with ET_0 typically reaches its peak in June and July and is lowest in November to February. Potential for groundwater recharge predominantly occurs for those months where ET_0 is below monthly precipitation (i.e., when there is a water surplus).

The ClimateBC generated long-term data for the study area is displayed from 1971-2021 in Figure 3, a longer period is used to assess long term climate trends compared to 1991-2021 current conditions (reference period). Figure 3 indicates seasonal shifts in precipitation since 1971, with a decline seen in summertime precipitation (June to September) and increases in precipitation in fall and early winter. There is no significant long-term trend evident in annual precipitation across the watersheds (Figure 3). The long-term data for the study area also indicates that temperature has risen about 2-3 degrees from 1971 (Figure 3).

The current long-term trends of increasing temperatures, decreasing precipitation in summertime and increased winter precipitation are generally in-line with what is expected with climate change in south and coast of BC (Lemmon et al 2008). It's also possible that extreme events (extreme precipitation events/droughts) may become more common (Bonsal et al., 2019). Statistically downscaled climate scenarios by

the Pacific Climate Impacts Consortium (PCIC, 2019) can be used to help assess the impact of climate change. Outputs for the PCIC12 ensemble (an average of 12 climate models) indicate an increase in temperature of ~ 1.5 to 2 degrees in the study area by the 2040-2069 reference period for moderate and high emission scenarios (RCP 4.5 and RCP 8.5, respectively). Generally, a 3-5% increase in PET may be expected for each degree change in temperature (e.g., Yates and Strzepek, 1994).

3.3 HYDROLOGY

Streamflow in Chapman Creek is influenced by heavy precipitation in the winter months (November and December) and a spring freshet influenced by snowmelt in April, May, and June (Staats, 2014). During the summer months (July to September), water from Chapman Lake is released into the creek through an impoundment structure while during the rest of the year, water flows into the creek under natural conditions. The SCR D has a hydrometric monitoring station located below the Chapman Lake intake which records streamflow every three minutes with a record beginning in 2003 (Triton, 2006). This data is not publicly available and is therefore not included in this report.

There have been three historical Water Survey of Canada (WSC) hydrometric stations located between Chapman Lake and the termination of Chapman Creek on the western boundary of Aquifer 566 into Davis Bay (Figure 1). Two upstream stations were placed immediately upstream (08GA078) and immediately downstream (08GA060) of the Sechelt Diversion (Figure 1). The furthest downstream hydrometric station (08GA046) was located within the boundary of Aquifer 566 approximately 400 m from the termination of the creek and has a data record from 1959 to 1970.

3.4 LAND USE

Land cover in the Sechelt region is primarily broadleaf/coniferous forests in inland areas with urban developed land bordering the Strait of Georgia and Sechelt Inlet (GeoBC, 2022). There is a 2.5 km² aggregate (sand and gravel) mine partially located within the boundary of the northern extent of Aquifer 566 (Heidelberg Materials, 2015), shown in Figure 1. The population of the District of Sechelt, including the Sechelt Indian government district, was 11,561 in 2021. Although tourism contributes significantly to the economy of the Sunshine Coast Regional District, which includes Sechelt, it is not expected that tourists contribute to excessive water use in the area as water usage in the region did not correlate with increased tourist activity (Wise, 2022).

Table 1 Monthly climate statistics for 1991-2021 from ClimateBC (Wang et al 2016).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Daily Average (°C)	4.5	4.9	6.6	9.3	12.9	15.3	17.8	17.9	14.9	10.3	6.6	4.3	10.4
Daily Max (°C)	6.6	7.7	9.8	13.1	17.0	19.3	22.1	22.2	18.8	13.2	9.1	6.4	13.8
Daily Min (°C)	2.4	2.2	3.4	5.4	8.8	11.4	13.5	13.6	11.0	7.3	4.2	2.2	7.1
Total Precipitation (mm)	158.2	104.6	101.4	70.2	51.9	42.8	26.2	32.2	70.1	118.1	169.6	160.7	1106.2 ^a
Total Rain (mm)	150.3	99.7	98.9	69.1	51.7	42.8	26.2	32.2	69.5	117.7	163.2	153.2	1074.5 ^a
Total Snow (cm)	7.9	4.9	2.5	1.1	0.2	0.0	0.0	0.0	0.6	0.4	6.5	7.5	31.6 ^a
Reference Evapotranspiration (mm) ¹	10.7	17.9	35.2	58.1	85.3	94.2	104.8	89.8	56.9	29.0	13.5	9.0	604.6

¹Monthly Reference Evapotranspiration calculated using the Hargreaves 1985 method by ClimateBC.

^aTotal annual.

Figure 2 Climate for 1991-2021 reference period from ClimateBC (Wang et al 2016).

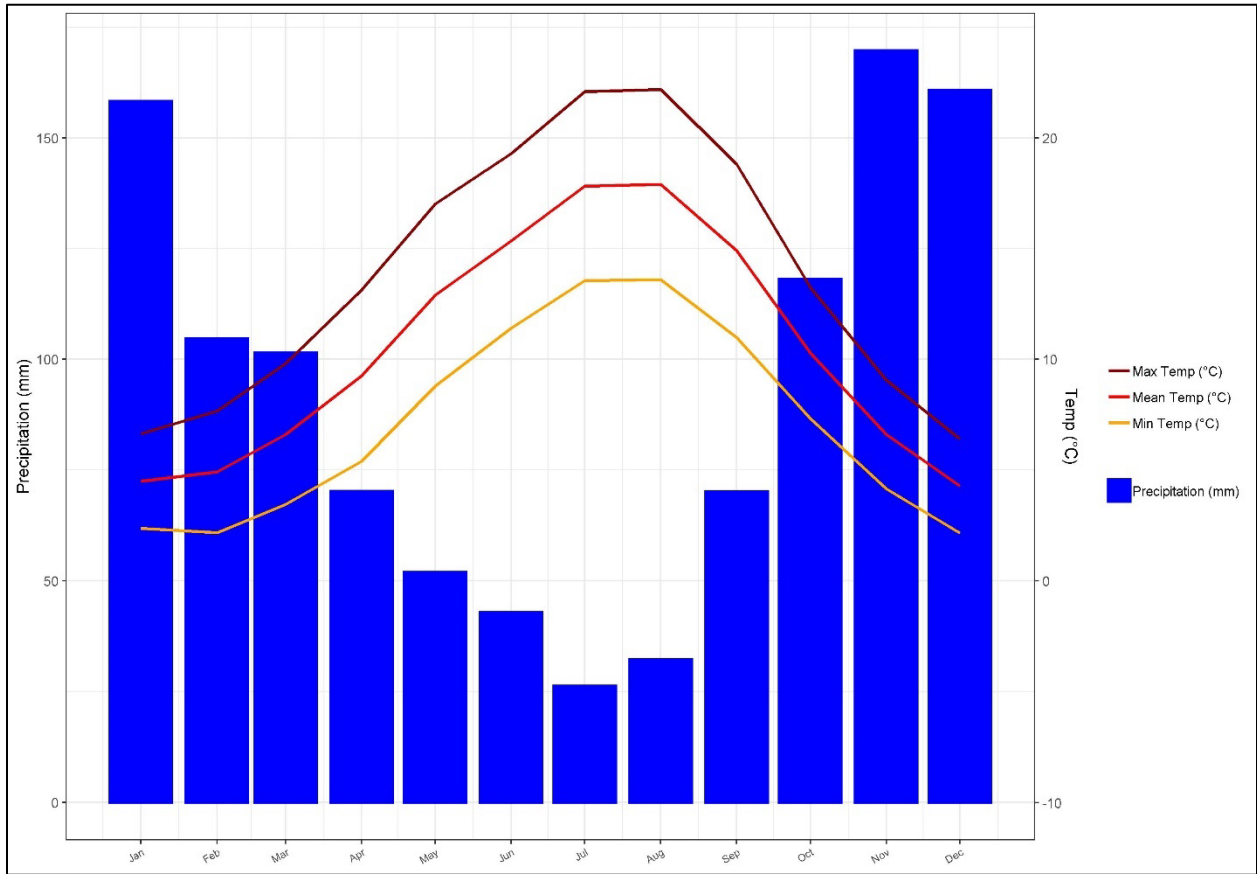
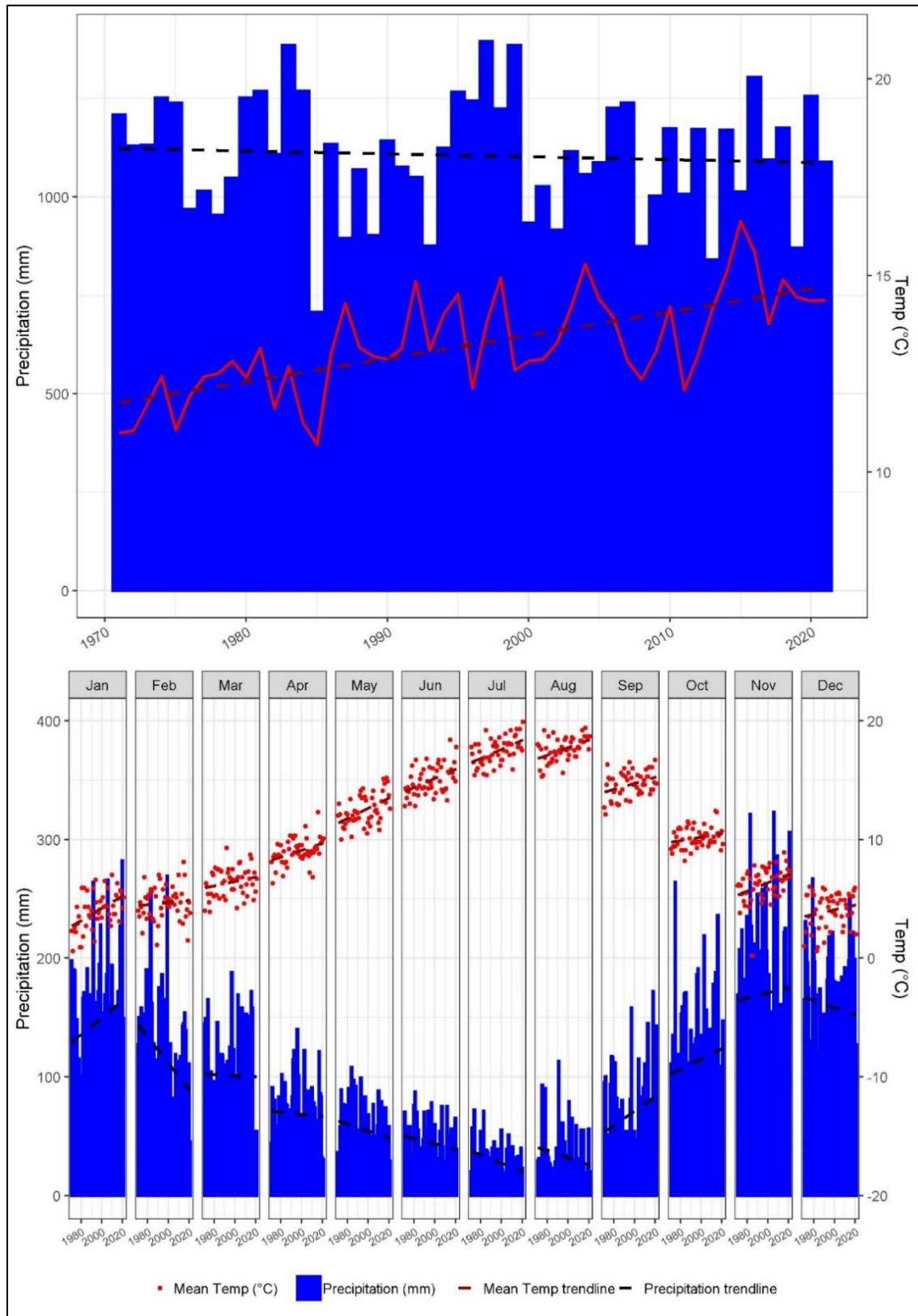


Figure 3 Long term climate data from 1971-2021 from ClimateBC (Wang et al 2016).



3.5 GEOLOGY AND HYDROSTRATIGRAPHY

Table 2 shows the general geology and hydrostratigraphic sequence of the study area, as discussed further below.

Table 2 Mapped geologic units, and corresponding mapped aquifers.

	Deposit	Corresponding mapped aquifer
Surficial geology	Deltaic fluvial fan complex interbedded with well-draining gravel and sand	Aquifer 566
Bedrock geology	Coast Plutonic Complex (Cui et al., 2017)	Aquifer 564

McCammom et al. (1977) mapped the area as primarily as a deltaic fluvial fan, and glacio-marine and marine deposits. Aquifer 566 is made up mostly of sands and gravels. The most westerly extents of the aquifer approach a bedrock outcrop and the eastern and northern boundaries of the aquifer are on Capilano fluvial, deltaic deposits. The aquifer boundary follows the coastlines of the Strait of Georgia and Sechart Inlet. Well lithology records within the aquifer extent indicate most wells are limited to a depth of 100 m and the material overlying the aquifer primarily consists of fine sands. There are limited areas where permeable deposits found at the surface are underlain by till and clay (Hammond and Hinnell, 2018).

Bedrock mapping (Cui et al., 2017) indicates the area is underlain by the intrusive igneous rocks of the Coast Plutonic Complex, described as variability foliated granodiorite, comprising bedrock aquifer 564.

4.0 AQUIFER CHARACTERISTICS

4.1 AQUIFER GEOMETRY

Cross-sections were created using information contained in the GWELLS database for wells installed in Aquifer 566 and underlying Aquifer 564, with cross-section locations shown in Figure 4. Wells used in the cross sections are selected based on a 150 m buffer radius from the cross-section locations. Gaps in electronic well lithology data were manually filled based on data provided in original well logs. Professional judgement was used to simplify lithological materials and to determine if well data was potentially incorrect. Inconsistent wells were removed from cross-sections. The cross-sections generally indicate mostly interbedded sand and gravel layers materials overlying bedrock, with discontinuous silt/clay and till lenses that may act as local confining layers were present (Figure 5 and Figure 6).

Near the shoreline (north and south extents of cross-section A-A'), unconsolidated material extend to a depth of about -50 m asl (i.e., below sea level) while bedrock may be encountered at higher elevation away from the shoreline (central portion of cross-section A-A' and cross-section B-B'). Cross-section B-B' suggests that in the southeast portion of aquifer 566 the unconsolidated deposits become thinner and finer grained and bedrock is close to ground surface.

In the south-east portion of aquifer 566 (i.e., the Chapman Creek area, the water table appears to be encountered at relatively shallow depth (about 10 m bgs) but may be located at greater depth at higher topographic elevations further to the north (i.e., suggesting presence of a thick unsaturated zone). Hammond and Hinnell (2018) suggest that upgradient of the aquifer, perched groundwater conditions may also exist within discontinuous deposits overlying till or clay.

4.2 GROUNDWATER FLOW

4.2.1 Lateral Groundwater Flow

Figure 7 illustrates inferred groundwater contours and lateral groundwater flow directions for Aquifer 566. Groundwater elevations (m asl) are based on static water level depths (m bgs) recorded in the GWELLS database and ground elevations in digital elevation model (DEM; Ministry of Forests, 2022), and are displayed in Figure 7. Static water level depths were recorded directly after well construction, therefore reflect conditions for different time periods, and may not accurately represent current groundwater levels. There are 18 wells in Aquifer 566 that have available groundwater level data.

Based on the groundwater elevations (hydraulic head) shown in Figure 7, lateral groundwater flow in Aquifer 566 is inferred to be toward the coast of the Strait of Georgia and Sechart Inlet which delineate the western edge of the southern portion and the northern portion of Aquifer 566, respectively. Groundwater elevations have a steep gradient that generally follows surface topography. The horizontal hydraulic gradient ranges from 0.001 to 0.06 m/m with a mean of 0.008 m/m. AE (2019) use a hydraulic gradient of 0.02 m/m for capture zone analysis for the SCRD Dusty Road test well near Ingres Creek.

It is noted that there is limited data on bedrock groundwater flow for areas upslope of Aquifer 566 and 564. Its possible for steeper groundwater gradients to occur in higher elevations above the study area.

Figure 4 Location of hydrogeologic cross-sections.

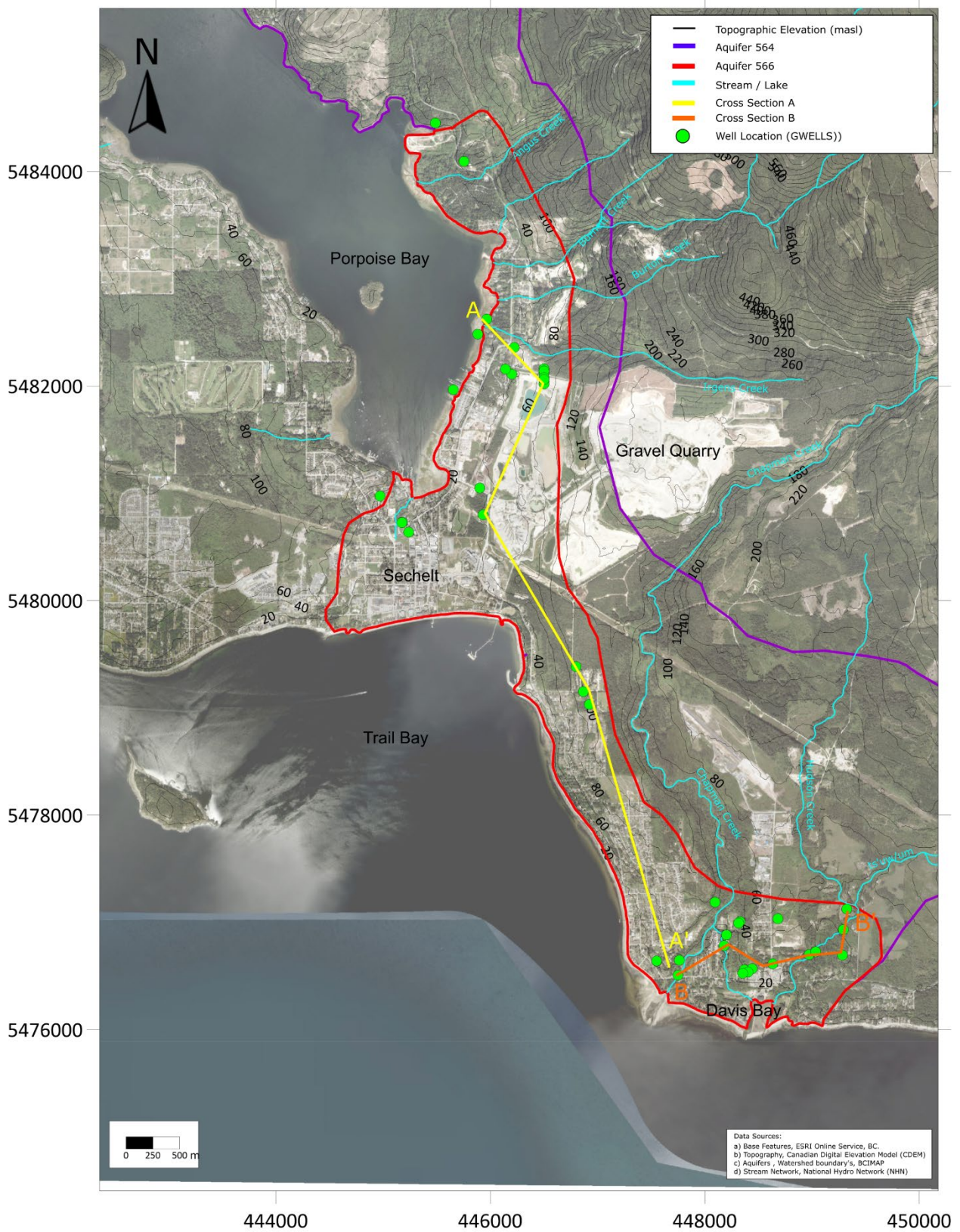


Figure 5 North-south cross-section A-A'.

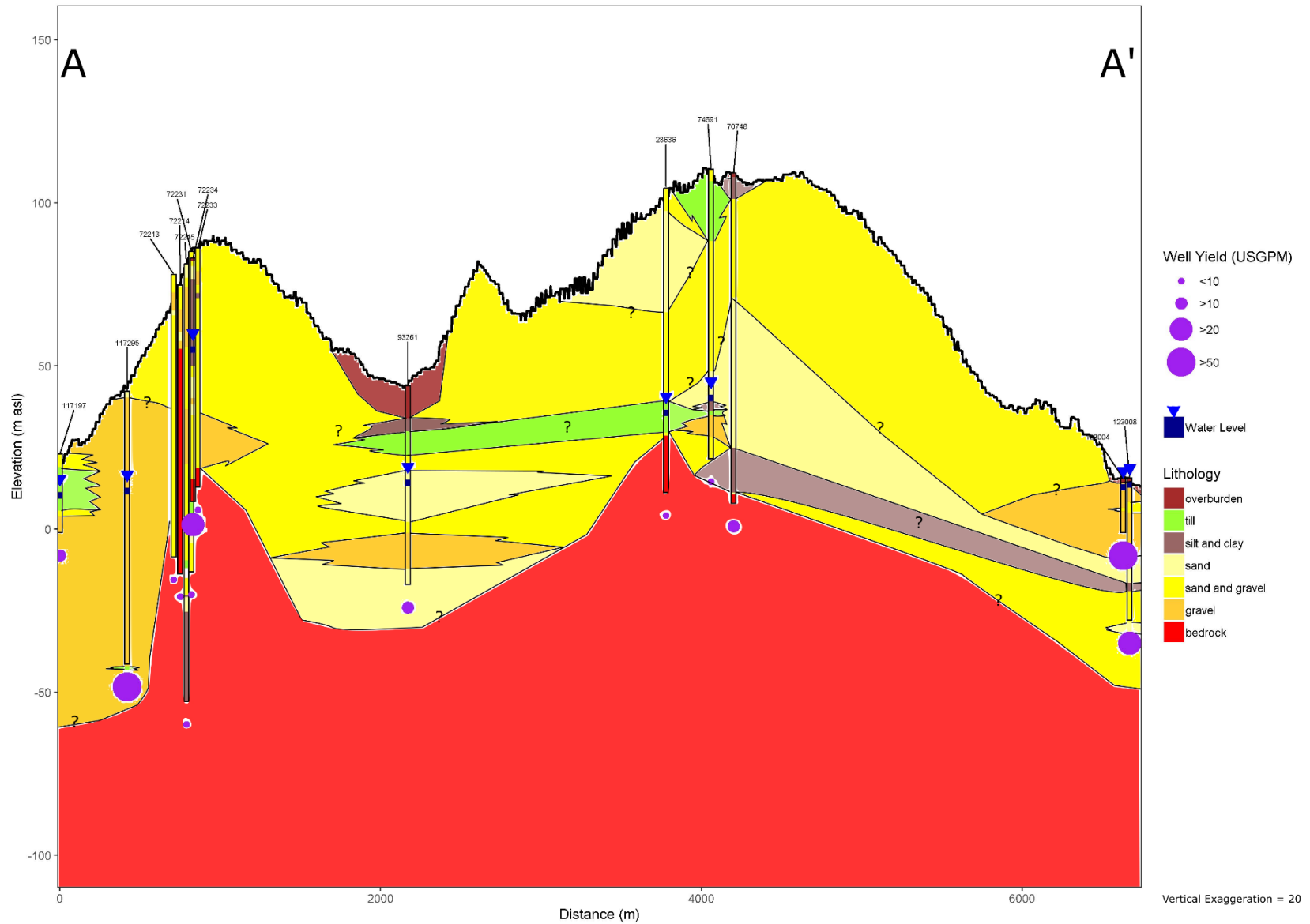


Figure 6 West-East cross-section B-B'.

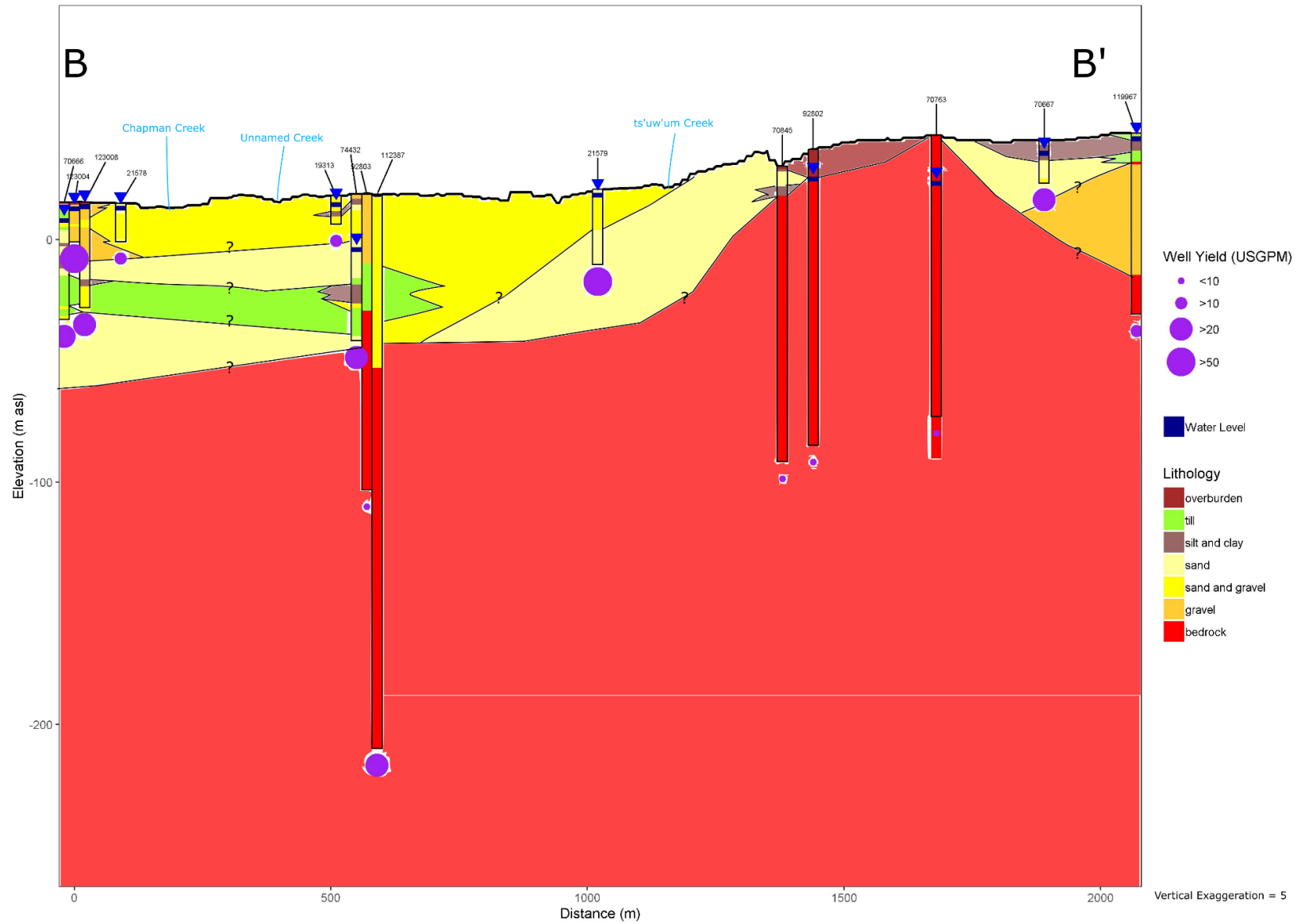
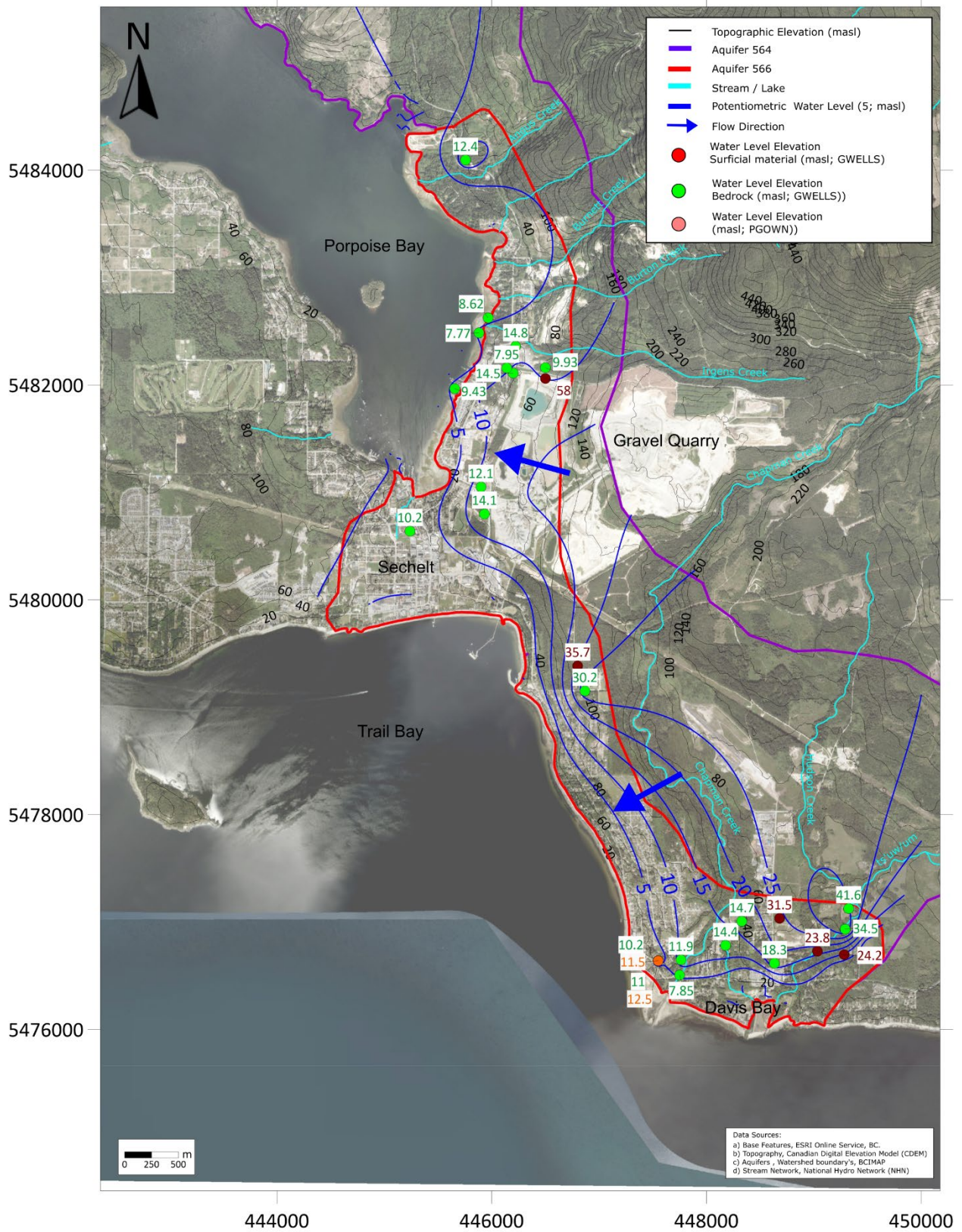


Figure 7 Inferred aquifer 566 groundwater elevation contours.



4.2.2 Vertical Groundwater Gradients

Comparing groundwater elevations for wells drilled into Aquifer 566 and underlying bedrock Aquifer 564 allows a basic understanding of vertical groundwater flow between these two aquifers (Figure 7). Due to limited groundwater level data for Aquifer 564, it is only possible to infer vertical groundwater gradients in localized areas with available data. Upward groundwater gradients are suggested in the Chapman Creek area (three bedrock groundwater levels), the Irgens Creek area and the central portion of Aquifer 566 (one groundwater level).

An upward groundwater gradient is also evident in Figure 8 which shows data from two Provincial Groundwater Observation Well Network (PGOWN) wells approximately 250 meters from the coast of the Strait of Georgia in Sechelt Mission Point Park. Installation details of the PGOWN wells are provided in Table 3. Based on available data the magnitude of the upward gradient is interpreted to be about 0.04 m/m.

4.2.3 Time Series Groundwater Levels

Two PGOWN wells were established in 2021 to monitor local groundwater conditions in the developed area, to better understand hydraulic connectivity with Chapman Creek, and to monitor for saltwater intrusion. Their location is shown in Figure 1. Figure 8 shows time series groundwater levels for the two PGOWN wells for 2021 and 2022 which illustrate that groundwater levels are relatively elevated during the winter wet season and relatively low at the end of summer dry period, with an overall variation of approximately 1 m. The groundwater levels therefore appear to respond to seasonal variations in precipitation and possibly Chapman Creek stage. Based on the water level depth data, it is possible that deeper well OW498 may become artesian during the wet season.

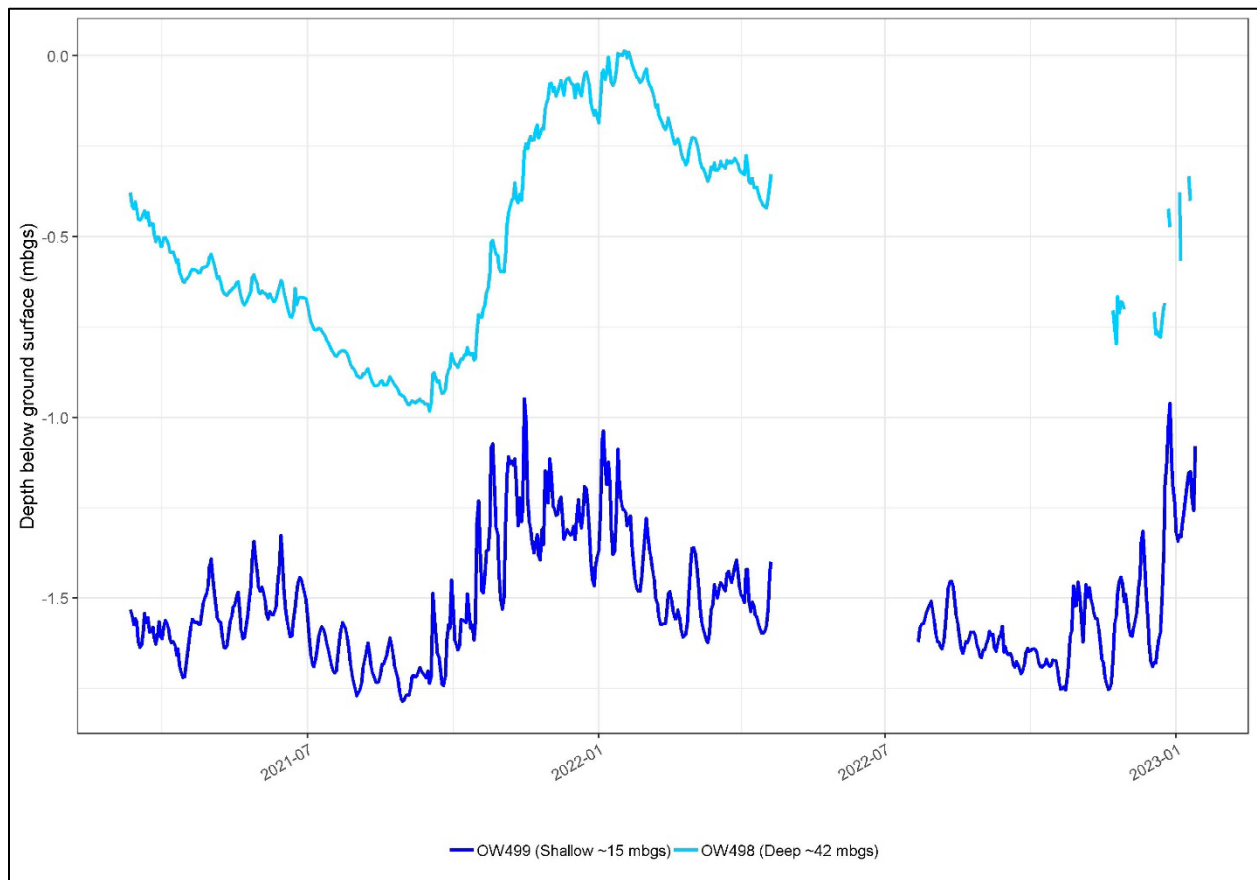
Mean water level values calculated for the PGOWN wells were used in groundwater contouring (Figure 7) in which it is noted that well elevations are based on DEM for the listed well locations (not elevations shown in the electronic well records). This was done for consistency with approach used for GWELLS data. It is noted that the original drill logs appear to list the ground elevation at the wells as 36 feet (which is not matched in electronic well records).

Table 3 Construction and monitoring details of the PGOWN wells.

Well	Easting	Northing	Ground Surface (m asl) ¹	Screened Interval (m bgs)	Aquifer	Start of Monitoring	Mean Water Level Depth Below Ground Surface (m bgs)
OW498	447551	5476640	13.0	40.54 -44.20	566	2021	0.51
OW499	447551	5476639	13.0	14.63-15.24	566	2021	1.52

¹Based on surface elevations from the DEM (Ministry of Forests, 2022)

Figure 8 Depth to groundwater for PGOWN wells near Chapman Creek.



4.3 AQUIFER HYDRAULIC PROPERTIES

There is likely a broad range in intrinsic aquifer properties for Aquifer 566, because of the heterogeneous nature of the aquifer. The hydraulic properties of the aquifer are summarized below to reflect what it thought to be representative for Aquifer 566 as a whole and to support subsequent water budget and allocation assessments:

- **Transmissivity (T):** Transmissivity values were calculated using a relationship with well yield as noted in (Berardinucci and Ronneseth, 2002). Yield ranges from wells in the GWELLS database within Aquifers 566 are mostly in the 1 to 3 L/s range (25th to 75th percentile) with a geometric mean of 1.6 L/s. This indicates a medium yield for the aquifer and corresponding values for transmissivity between 140 m²/day to 430 m²/day, with a geometric mean of 230 m²/day. It was considered whether the yield data may not properly represent aquifer properties and may instead reflect limited yield of wells that have been installed. A silty sand to sand and gravel type aquifer would generally be expected to have a hydraulic conductivity on the order of 10⁻⁵ to 10⁻⁴ m/s. Combined with an approximate 50 m aquifer saturated thickness near the shoreline (Figure 5), this would suggest a transmissivity of 5 x 10⁻⁴ to 5 x 10⁻³ m²/s or 45 to 450 m²/day. It is therefore inferred that the yield data likely reasonably represents aquifer properties. SCRDC commissioned a pumping test on their Dusty Road test well adjacent to Ingres Creek near Porpoise Bay. The calculated sustainable yield for this test well was about 90 L/s (1445 US GPM), which is substantially higher than the range

quoted above. While this would suggest that local areas of higher transmissivity may exist in the aquifer, AE (2019) used a hydraulic conductivity value of 9×10^{-5} m/s and aquifer thickness of 50 m for capture zone analysis of the Dusty Road test well (i.e., similar values to those inferred above).

- **Storativity (S):** given that the aquifer is unconfined, it's response will likely be determined by specific yield (S_y). S_y for sand and gravel aquifers typically ranges from 0.1 to 0.3 (average of about 0.2), based on values quoted by Morris and Johnson (1967), Heath (1983) and Duffield (2019). It is noted that effective values for specific yield at the aquifer scale may be lower than the quoted range but this was not considered herein.
- **Aquifer hydraulic diffusivity:** aquifer diffusivity (D) is calculated by dividing the estimate aquifer transmissivity by the estimated storativity ($D = T/S$)

Diffusivity values for the aquifer may therefore range from 470 m²/day to 4,300 m²/day based on the transmissivity and storativity ranges. Diffusivity estimated using the geomean transmissivity and average specific yield values is about 1200 m²/day.

- **Aquifer response time (days):** The aquifer response time is a measure of how quickly an aquifer responds to a change in hydraulic stress (e.g., from pumping or change in recharge – Wei et al, 2014).

Based on the aquifer area ($A = 9.7$ km²), estimated diffusivity ranges (470 m²/day to 4,300 m²/day), the groundwater response time ($t = A/3D$) is estimated to be 6 to 60 years. These results suggest a response time on the order of years to decades because of the interpreted unconfined nature of the aquifer which has not been substantiated by pumping test data. Furthermore, aquifer scale estimates for response time may not reflect local responses to pumping stresses, which should be evaluated on a case-by-case basis.

Table 4 Main hydrogeological properties of Aquifer 566.

Aquifer attribute	Attribute	Explanation
Material type	Sand and Gravel	(Province of British Columbia, 2022c)
Subtype	4a	(Province of British Columbia, 2022c)
Confined or unconfined	Unconfined	Figure 5, Figure 6, Figure 9, and (Province of British Columbia, 2022c)
Area (km ²)	9.7	(Province of British Columbia, 2022c)
Horizontal hydraulic gradient (-)	0.001 - 0.06	Figure 7
Transmissivity, T (m ² /day)	140 - 430	Yield ranges from GWELLS and PGOWN wells
Specific yield, S_y (-)	0.2 (0.1 – 0.3)	Literature estimates
Hydraulic Diffusivity, D (m ² /day)	470 - 4,300	Estimated based on transmissivity and storativity (specific yield) ranges
Aquifer response time (years)	Years to Decades	Calculated using method proposed by Wei et al. (2014)

4.4 LIKELIHOOD OF HYDRAULIC CONNECTION WITH CHAPMAN CREEK

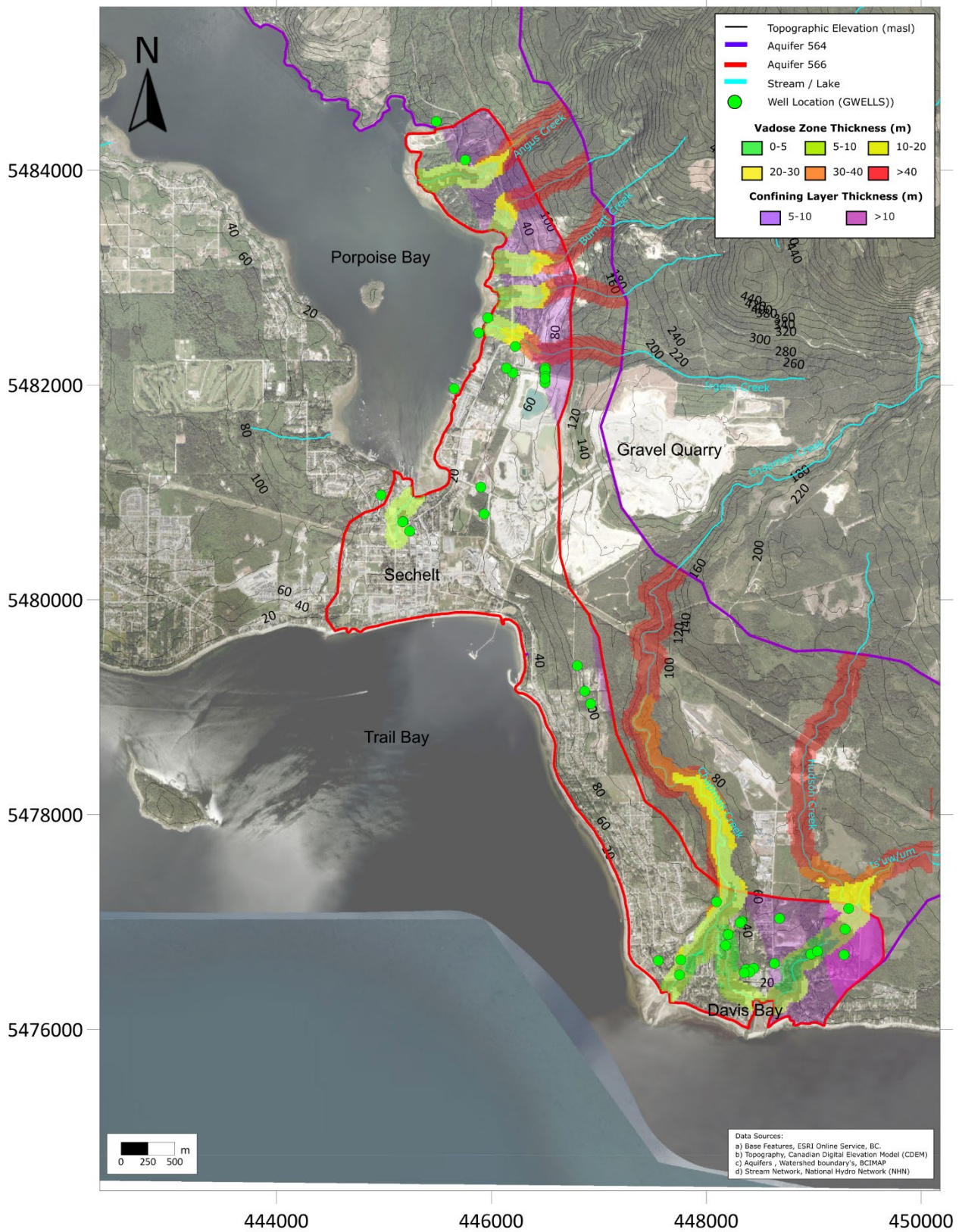
In assessing likelihood of hydraulic connection between Aquifer 566 and local creeks, the methods previously employed by WWAL (2019, 2022) are used. Figure 9 shows the thickness of confining materials above Aquifer 566 and depth to groundwater (i.e., vadose zone thickness) below the streams. Where confining materials are thin or absent and where depth to groundwater is shallow, hydraulic connection between aquifer 566 and the streams is likely to exist. Understanding where connection occurs is important because those stream segments are more susceptible to impacts from groundwater pumping, while others are not.

The confining layer thickness was determined using all wells in the GWELLS database that had lithology logs. It was assumed that the confining layer thickness was equal to the sum of all low permeability layers (silt and clay layers, as shown in the cross sections in Figure 5 and Figure 6). The result of Figure 9 validates the assumption that Aquifer 566 is largely unconfined with a confining layer thickness that does not exceed 5 m throughout most of the aquifer. Exceptions are the southeast corner of the aquifer and the north portion of the aquifer where confining materials in excess of 5 m are interpreted.

Vadose zone thickness (depth to groundwater) was calculated using the inferred groundwater elevation contours calculated (Figure 7) and the topography obtained from the DEM of the area. It is interpreted that in the north portion of the aquifer, creeks appear perched above the water table where they enter the aquifer (i.e., the creeks are interpreted to locally be losing reaches, providing recharge to the aquifer through the vadose zone) but may become connected to groundwater closer to Porpoise Bay (i.e., creeks could be receiving baseflows from groundwater closer to Porpoise Bay). AE (2019) note that Ingres Creek appears to be perched along much of its reach and that leakage from the creek probably provides recharge to the aquifer. This AE inference potentially highlights limitations of the current vadose zone thickness analysis based on groundwater contouring with limited spatial data coverage. It is also possible that groundwater levels near Ingres Creek have been lowered over time (due to dewatering at the gravel pit, as suggested by AE, 2019) and that this is not captured in the data utilized.

In the southeast portion of Aquifer 566 (i.e., the Chapman Creek area), creeks are likely connected to groundwater across the entire aquifer footprint, except Hudson Creek, where confining material may prevent direct connection. Chapman Creek is therefore interpreted to be directly connected to groundwater with the upward vertical gradient in the BC PGOWN wells suggesting groundwater discharge conditions. This is consistent with inference of hydraulic connection between Chapman Creek and the aquifer made by Hammond and Hinnell (2018).

Figure 9 Inferred confining layer and vadose zone thickness.



5.0 WATER USES AND WATER RIGHTS

5.1 SURFACE WATER

There are a number of surface water licenses on streams across the aquifer 566 footprint as shown in Figure 10. However, the focus of this case study is on Chapman Creek, with water rights shown in Table 5. In addition, upgradient of the study area the SCRDC has a water license for a water intake (C050724; PD61040) located on Chapman Creek (Figure 1). The SCRDC are required to maintain 400 L/s flows (34,560 m³/day) for a period of four hours during nights when there is a flood tide, and when Pink Salmon are confirmed to be holding in the downstream reach of Chapman Creek (Shirley Wang, personal communication, January 11, 2023).

Triton (2006) further indicates that the SCRDC has a total of eight Waterworks and Storage Water Licences on Chapman Creek, Chapman Lake and Edwards Lake; six of these are located above the intake (PD61040), and as such are not shown in Table 5. According to these licences, the SCRDC can withdraw 4.5 million gallons per day from Chapman Creek above the intake (17,000 m³/day). Per Triton (2006), these licenses have effective dates (dates from which license has precedence) of 1929 (authorizing use of 300,000 gallons per day), 1967 (two licenses pertaining to water storage in Chapman and Edward Lake and one authorizing 1 million gallons per day diversion), 1974 (water storage in Chapman Lake), 1988 (authorizing diversion of 3 million gallons per day). Triton (2006) further indicates that annual water use has been rising and that in 2004 the SCRDC consumed 1.08 billion gallons from Chapman Creek (93% of its supply).

Summarised in Table 5 and Figure 11 are the licensed stream users that divert water from Chapman Creek downstream of the SCRDC Intake (PD61040). There are five total licensed water users ranging in quantity from 23 m³/day to 24,466 m³/day. The dominant use types are pond and aquaculture, conservation (construct works), and stream storage (non-power).

Table 5 **Reported water licenses on Chapman Creek downstream of PD61040.**

Water License	POD Number	Purpose	Easting	Northing	Quantity (m ³ /day)
C016599	PD60277	00A - Waterworks: Local Provider	447684	5476733	23
C022345	PD60277	00A - Waterworks: Local Provider	447684	5476733	91
C050724	PD61040	08A - Stream Storage: Non-Power	456252	5492452	2,484
C114222	PD74424	11C - Conservation: Construct Works	447773	5478543	14,679
C121468	PD60275	03B - Irrigation: Private	448030	5477687	34
C129269	PD60276	02E - Pond & Aquaculture	448170	5477436	24,466

Figure 10 Location of surface water licenses.

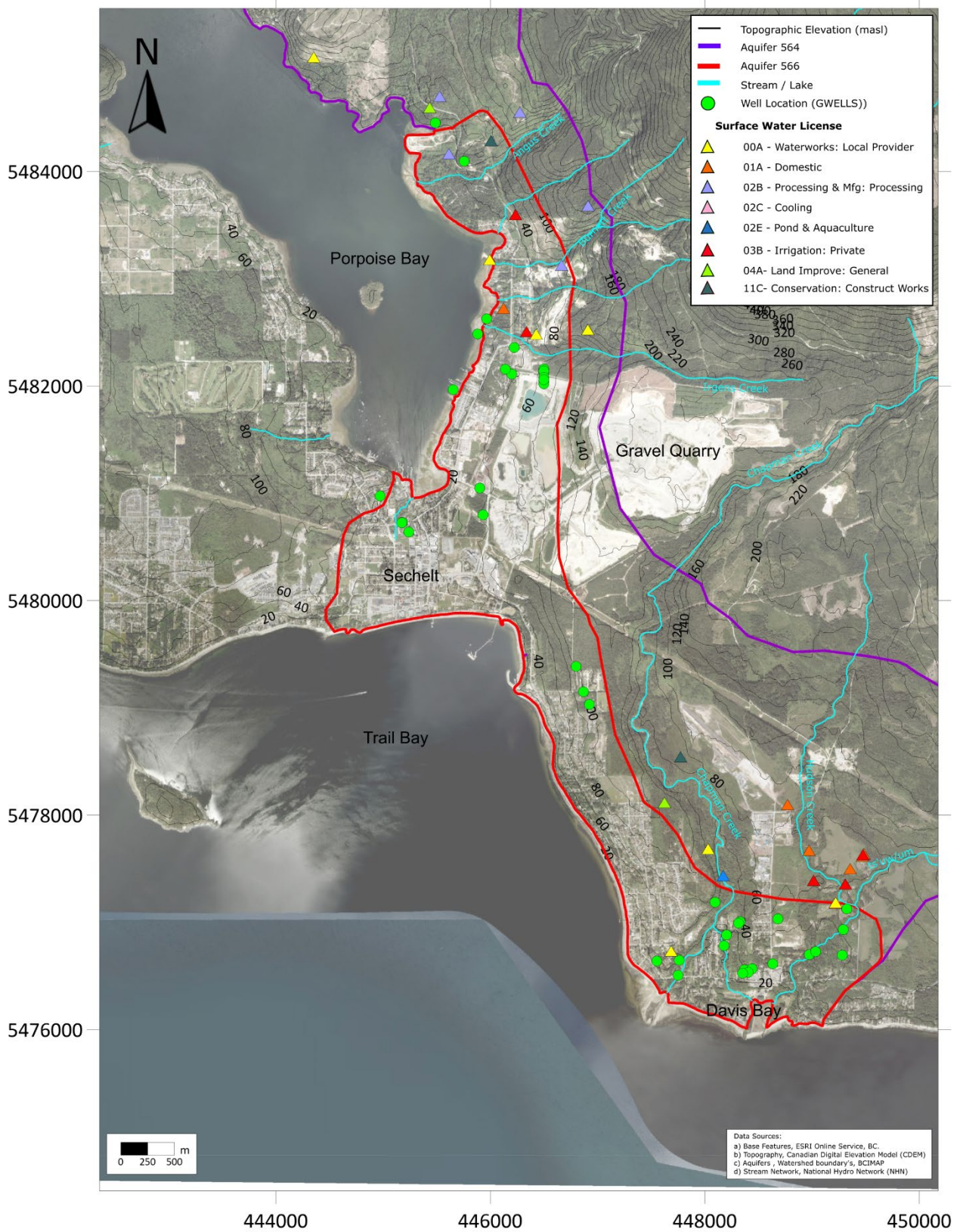
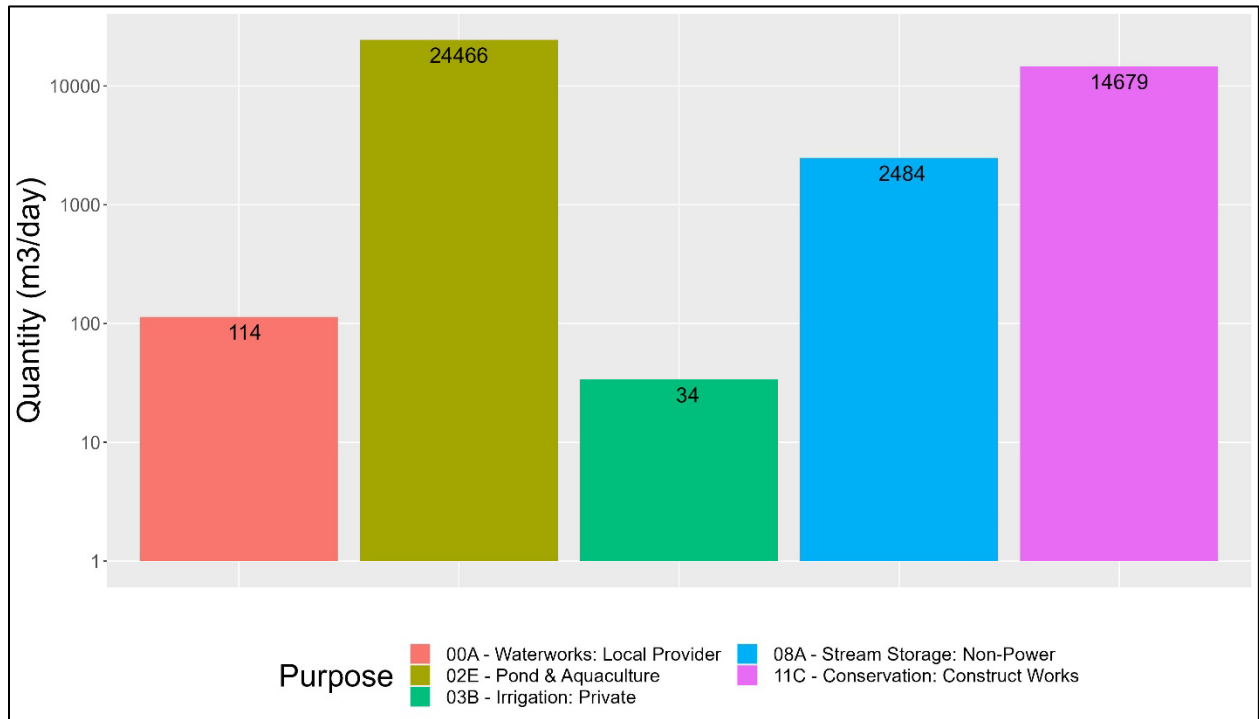


Figure 11 Quantity of water withdrawals in Chapman Creek by water source and purpose.



5.2 GROUNDWATER

There are 24 registered groundwater wells within Aquifer 566 (Table 6) and 12 groundwater wells within underlying bedrock aquifer 564 (Table 7). Currently, there are no licensed groundwater users in aquifer 566 or aquifer 564 although several applications for existing and new groundwater use are in progress.

Table 6 **Reported wells in Aquifer 566.**

Well Tag	Intended Use	Construction Date	Easting	Northing	Finished Depth (m)	Yield (L/s)	Static Water Level (mbgs)
70667	Private domestic	-	449291	5476934	17.68	1.26	5.49
70666	Private domestic	-	447750	5476507	48.46	1.26	7.62
123004	Monitoring well (OW499)	2021-03-11	447551	5476639	16.46	3.15	2.80
123008	Monitoring well (OW498)	2021-03-10	447551	5476640	43.59	1.26	1.95
74432	Not applicable	1992-07-28	448329	5477007	60.35	1.89	22.86
70748	Private domestic	-	446923	5479031	101.19	0.95	-
74691	Private domestic	1987-03-17	446868	5479151	88.70	0.38	70.10
93261	Gravel mine	2002-04-04	445932	5480800	60.96	0.63	29.87
93094	Private domestic	2003-09-27	445900	5481050	49.68	25.24	29.87
93084	Gravel mine	2003-09-27	445900	5481050	49.68	-	29.87
101785	Gravel mine	2001-03-26	446140	5482158	76.81	3.15	35.66
21578	Unknown	1968-06-24	447762	5476647	15.85	1.14	2.13
21579	Unknown	1968-06-24	448633	5476615	31.09	3.79	2.44
19313	Private domestic	1965-07-01	448178	5476783	11.58	0.95	3.66
88780	Commercial and industrial	2006-06-11	445175	5480726	33.53	3.15	-
88753	Private domestic	2006-06-11	445180	5480731	33.53	3.15	-
92425	Private domestic	1996-06-15	445654	5481966	30.48	0.38	8.23
72231	Not applicable	1996-02-07	446500	5482040	98.15	0.00	-
72215	Not applicable	1994-08-27	446500	5482080	104.55	0.00	-
93003	Gravel mine	2004-07-09	446200	5482111	79.25	6.31	35.97
72213	Not applicable	1994-08-11	446500	5482120	86.56	0.00	-
72212	Undeveloped lot	1994-08-17	446500	5482160	101.19	25.24	72.24
27560	Unknown	1973-01-19	445882	5482485	12.50	0.63	11.58
27466	Unknown	1973-01-01	445755	5484095	24.38	2.21	7.62

Table 7 Reported wells in Aquifer 564.

Well Tag	Intended Use	Construction Date	Easting	Northing	Finished Depth (m)	Yield (L/s)	Static Water Level (mbgs)
92802	Gravel mine	2006-10-19	449033	5476728	121.92	0.13	12.19
70763	Private domestic	-	449282	5476696	115.82	0.25	19.81
70845	Unknown	-	448973	5476699	121.92	0.50	-
92803	Gravel mine	2006-10-10	448202	5476883	121.92	0.32	-
112387	Gravel mine	2016-02-01	448314	5476993	228.60	1.58	-
92783	Private domestic	2007-02-12	448680	5477034	121.92	0.13	2.44
87153	Irrigation	2007-05-17	448639	5477748	170.69	-	-
87056	Private domestic	2004-11-28	448856	5478507	91.44	0.50	-
28636	Monitoring well	1973-08-03	446800	5479386	93.27	0.13	68.88
72233	Not applicable	-	446500	5482020	73.15	0.00	-
72234	Not applicable	1996-01-10	446500	5482060	74.68	1.89	28.04
72214	Private domestic	1994-08-07	446500	5482140	88.39	0.00	-
119967	Private domestic	2015-09-10	449323	5477125	74.68	-	-
121178	Commercial and industrial	2015-01-01	448095	5477188	34.60	-	-

6.0 AQUIFER WATER BALANCE

6.1 CONCEPTUAL WATER BUDGET

By understanding the groundwater balance of the study area, potential impacts of groundwater pumping can be better understood. The main aquifers inflows and outflows (conceptual water budget) are discussed in following sections.

6.1.1 Aquifer Inflows

Hammond and Hinnell (2018) indicate that recharge to aquifer 566 is thought to primarily occur through infiltration of precipitation from the surface (R_p). Groundwater inflows from upslope areas and from the underlying bedrock aquifer as mountain block recharge originating from the Tetrahedron Plateau area (Q^{GW}_{in}) are also possible.

As noted by AE (2019), its possible that creeks perched above groundwater also contribute groundwater inflows, but this has not been considered herein with focus of case study on water management challenges in Chapman Creek area where upward groundwater gradients have been noted (Section 4.2.2).

6.1.2 Aquifer Outflows

Predominant aquifer outflows are expected to be to the marine environment (Q^{GW}_{out}), to local creeks (Q^{SW}_{out}) and losses to groundwater pumping (Q^{GWpump}_{out}). For groundwater discharge to creeks, the focus is on Chapman Creek.

6.1.3 Water Budget

The conceptual water budget for type 4a aquifers, simplified to account for the principal aquifer inflow and outflow components discussed above, is described as:

$$R_p + Q^{GW}_{in} = \Delta S^{GW} + Q^{SW}_{out} + Q^{GWpump}_{out} + Q^{GW}_{out}$$

For simplicity, the analysis below assumes that changes in groundwater storage (ΔS^{GW}) are zero, i.e. the aquifer is in long-term equilibrium.

6.2 ESTIMATION OF WATER BUDGET COMPONENTS

6.2.1 (R_p) Recharge from Precipitation

Forstner et al. (2018) did HELP modelling for unconfined aquifers across the Province to estimate groundwater recharge. For the Sechelt area, recharge was estimated as between 40-60% of precipitation (440 – 660 mm/year). For the 9.7 km² aquifer, this gives a recharge range of 11,700 to 17,500 m³/day (average of 14,600 m³/day). These recharge rates may be relatively high considering steep slopes in the area which would tend to lead to relatively high amounts of runoff. However, the potentially high estimates may compensate for the fact that stream losses to groundwater (i.e. where streams are perched above the groundwater system; Figure 9) are not explicitly considered in the water balance.

An annual average recharge rate of 14,600 m³/day was therefore used in the water budget (Section 6.2.6), with confidence bounds of 11,700 to 17,500 m³/day.

6.2.2 (Q^{GW}_{in}) Groundwater Inflow (Mountain Block Recharge)

As a first order estimate of possible MBR contributions to Aquifer 566, the groundwater modelling by Doyle (2013) for the confined Gibsons Aquifer is used as a proxy given that the bedrock geology is similar. Dolye (2013) simulated that 45% of inflows to the Gibsons Aquifer are from MBR representing a contribution of 2,290 m³/day for the model domain, this estimate represents an approximate 2.5 km upgradient interface between bedrock and the Gibsons Aquifer. Doyle (2013) utilized environmental tracers to confirm a significant influence of MBR through environmental tracers, with depleted stable isotope signature in all groundwater samples indicating that a significant component of recharge occurs at high elevations and may have a contribution of snowmelt.

The upgradient interface between bedrock and Aquifer 566 is about 10 km suggesting an MBR contribution on the order of 9,200 m³/day (i.e. prorating the Gibsons Aquifer estimate by length of relative bedrock contributing interface).

6.2.3 (Q^{SW}_{out}) Surface Water Outflow (Groundwater Baseflow)

The groundwater flux directed toward Chapman Creek was estimated using Darcy Flux calculations. Based on the estimated groundwater contours (Figure 7), lateral groundwater gradients in the Chapman Creek area range between 0.014 and 0.025 m/m with a mean of 0.016 m/m. The thickness of the saturated zone contributing flow to the creek is assumed to be 11 m, based on the ground elevation near the creek (14 m) and the estimated groundwater level (25 m) for upslope areas draining towards the creek. The cross-sectional area for groundwater flow was calculated using the estimated saturated thickness and the length of the portion of the aquifer draining to the creek, represented by the length of the eastern edge of the Chapman Creek delta (650 m). Based on the mean groundwater gradient, and using low, geomean and higher aquifer transmissivity values, the calculated surface water outflows range between 320 m³/day and 1,000 m³/day, with a value of 530 m³/day based on the geomean transmissivity value.

As noted in Section 4.4, it is inferred that most of the creeks in the northern portion of Aquifer 566 are indicated to be disconnected from the groundwater system (potentially losing reaches with a significant unsaturated zone), and are not incorporated in the water budget calculations. Furthermore, the inferred groundwater flow direction (Figure 7) is parallel to these creeks, hence the calculation as conducted for Chapman Creek cannot be repeated for the creeks to the north. Only the Chapman Creek estimates are therefore carried forward in the water budget.

6.2.4 (Q^{GW}_{out}) Groundwater Outflow (Marine Environment)

The groundwater outflow to the marine environment was also estimated using Darcy Flux calculations. A representative groundwater gradient was determined to be 0.008 m/m. Aquifer saturated thickness was based on the mean groundwater level for the wells shown in cross-section A-A' (Figure 5) and is calculated to be about 50 m, with significant uncertainty as the depth to bedrock is only known in limited wells. The approximate length of the aquifer along the marine shoreline about 9.7 km. Based on the mean groundwater gradient, and using low, geomean and higher aquifer transmissivity values, the calculated groundwater outflows range between 10,900 m³/day and 33,400 m³/day, with a value of 17,800 m³/day based on the geomean transmissivity value. It is noted that the upper end Darcy Flux estimate exceeds the estimated recharge for the aquifer, indicating considerable uncertainty in the water budget calculations.

6.2.5 ($Q^{GW_{pump}_{out}}$) Groundwater Pumping

Groundwater pumping is estimated from the water use of wells drilled in the aquifer (Table 6) based on Bennett et al. (2021). The total estimated groundwater wells use for the aquifer is 3,970 m³/day, as shown in Table 8.

For the subset of wells located in the Chapman Creek area of the aquifer, six private domestic wells and two groundwater monitoring wells, the total estimated groundwater wells use for the aquifer is only 12 m³/day, which is carried forward in Section 7.0. Existing groundwater use in the Chapman Creek area therefore appears relatively minimal while the bulk of groundwater use in other portions of the aquifer is associated with commercial and industrial activities and dewatering for the gravel pit operation.

Table 8 Water use by groundwater pumping application for entire aquifer.

Area	Private Domestic (m ³ /day)	Commercial and Industrial (m ³ /day)	Gravel Pit (m ³ /day)	Porpoise Bay Park (m ³ /day)	Total (m ³ /day)
Entire aquifer	36	30	3,000	128	3,970
Chapman Creek Area	12	-	-	-	12

6.2.6 Overall Water Budget

The overall estimated annual average water budget for Aquifer 566 is summarized in Table 9 including confidence ranges, based on rationalization provided in preceding sections. There is reasonable agreement between estimated total groundwater inflows and outflows for the aquifer. However, confidence bounds on the outflow component are large and result from uncertainty in the Darcy Flux calculation and underlying aquifer transmissivity ranges. Groundwater discharge to the marine environment is the largest outflow component, followed by groundwater use and baseflow to Chapman Creek.

Table 9 Summary of water budget range estimations.

Water Budget Component	Estimated Inflow (m ³ /day)	Estimated Outflow (m ³ /day)	Percent of Total Outflow	Source
Precipitation	14,700 (11,700-17,500)	-	-	Section 6.2.1
Mountain Block Recharge	9,200	-	-	Section 6.2.2
Baseflow to Chapman Creek	-	530 (320-1,000)	2%	Section 6.2.3
Marine Outflow	-	17,800 (10,900 – 33,400)	80%	Section 6.2.4
Groundwater Use	-	4,000	18%	Section 6.2.5
TOTAL	23,900 (20,900-26,700)	22,330 (15,220-38,400)	100%	

7.0 ESTIMATING ALLOCATION LIMITS

We use the following methods to calculate allocation limits for Aquifer 566:

- ALLOCATION LIMIT CONSTRAINED BY STREAM DEPLETION;
- ALLOCATION LIMIT BY PERCENTAGE OF ANNUAL GROUNDWATER FLUX;
- ALLOCATION LIMIT CONSTRAINED BY PERCENTAGE OF MEAN ANNUAL RECHARGE; and
- Allocation Limit Based on Available Drawdown.

7.1 ALLOCATION LIMIT CONSTRAINED BY STREAM DEPLETION

The focus of the streamflow depletion analysis is on Chapman Creek. Streamflow depletion may also be a consideration further north in the aquifer (e.g., near Ingress Creek) but has not been considered herein. Furthermore, the streams in the northern portion of the aquifer may be perched above groundwater over much of their length (i.e. streams are separated from groundwater by a vadose zone), therefore streamflow depletion calculations would not apply as these assume groundwater-surface water connection.

As discussed in Section 3.3, the SCR D currently monitors Chapman Creek flows below the intake but data is not publicly available. Instead, monthly flows in Chapman Creek were estimated using historical hydrometric data near Wilson Creek (08GA046) with the monitoring location shown in Figure 1. The gauged mean monthly flows are shown in Figure 12.

Figure 12 Estimated mean monthly flows for Chapman Creek near Wilson Creek (1959-1970).

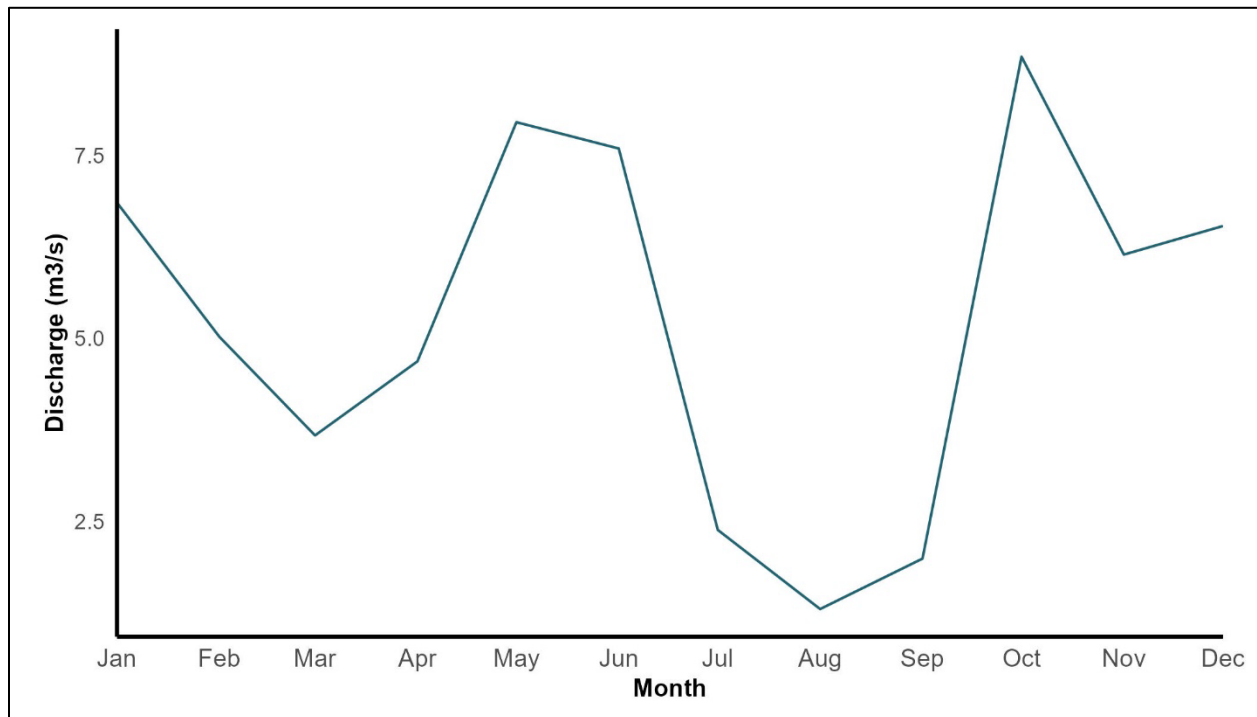


Figure 12 illustrates that recorded mean monthly flows range from about 1.3 m³/s in August to 6.3 m³/s in winter months and 8.0 m³/s (May and June) during freshet inflows from the Tetrahedron Plateau. This seasonal flow pattern and general flow magnitudes matches more recent SCRD monitoring shown in Triton (2006) although recent low flows during the July to September low flow period appear significantly lower (0.1-0.2 m³/s in late summer). While existing water use likely factors into this difference it is also possible that the WSC flow monitoring which occurred in the downstream portion of Chapman Creek (Figure 10) was influenced by tidal effects (i.e. lower flows may have been difficult to estimate) and that monitoring further upstream in the watershed (away from tidal influences) is more reliable. Furthermore, historical data shown in Triton (2006) also indicate significant year-to-year variability in historical monthly flows over the 1970-1988 period. As noted, SCRD is obliged to ensure that a minimum of 400 liters per second (0.4 m³/s) is present in Chapman Creek, for a period of 4 hours during nights when there is a flood tide, and when Pink Salmon are confirmed to be holding in the downstream reach of Chapman Creek; while during stage 4 water restrictions in Sechelt, the SCRD releases 200 L/s (0.2 m³/s) from the dam at Chapman Lake to meet required flows (Chapman Creek Hatchery communication, 2019). SCRD water use and water management, therefore, is the largest influence on gauged flows. The hatchery also holds a large water use license (Table 5), but water is returned to the creek 200 m downstream from their intake. As such hatchery water use was not included in the analysis. There is also a large water storage for conservation license listed in Table 5, which was also not carried forward. Only SCRD water use is therefore considered below. For the stream depletion analysis, the mean monthly flows shown in Figure 12 were assumed to represent natural conditions (because of much smaller SCRD water use at the time) and were carried forward in the analysis (Table 10).

Based on comparison of mean monthly discharge (MMD) to the MAD (about 5 m³/s, which classifies the creek as a small stream), the inherent sensitivity of Chapman Creek to water withdrawals is considered low throughout the entire year as MMD remains above the 20% MAD threshold in all months. Existing water use was estimated from Triton (2006) who indicate that SCRD can withdraw 17,000 m³/day based on current licenses (Section 5.1) and also indicate a peak water demand in summer months of 250 L/s (22,000 m³/day). This information was used to generate an estimated seasonal water use distribution (Table 10). Existing water use, therefore, comprises between 3% (winter months) and 19% (August) of Chapman Creek flows. Based on the combined consideration of flow sensitivity and existing withdrawals, Chapman Creek, therefore, has a EFN Risk Management Level of 1 for most months except August (risk management level 2). A risk management level of 2 indicates that the aquatic environment may be flow limited.

Based on the inferred low streamflow sensitivity to withdrawals, a 15% percent flow threshold was applied to each month that would correspond to a risk management level of 1 under EFN guidance (i.e., sufficient water for EFN and additional use). Corresponding quantitative monthly flow thresholds were subsequently calculated from the naturalized MMD and available additional water for use was determined through comparison of the calculated flow thresholds with the existing cumulative use estimates. This analysis would suggest that there is additional water available for use except in August when the 15% water use threshold is already exceeded. This inference seems to be at odds with current understanding highlighting flow limitations in downstream Chapman Creek and a more comprehensive hydrometric analysis using recent gauging data is recommended.

Table 10 Streamflow depletion thresholds for Chapman Creek.

	WSC Gauged Flow (m ³ /day)	MMD % MAD	Flow Sensitivity	Existing Water Use (m ³ /day)	Existing Water Use (% MMD)	Risk Management Level	RM1 Flow Threshold (%)	RM1 Flow Threshold (m ³ /day)	Available Use (m ³ /day)
Jan	542,864	125	Low	15,000	3	1	15	81,430	66,430
Feb	401,798	92	Low	15,000	4	1	15	60,270	45,270
Mar	291,233	67	Low	15,000	5	1	15	43,685	28,685
Apr	375,708	86	Low	15,000	4	1	15	56,356	41,356
May	687,001	158	Low	17,000	2	1	15	103,050	86,050
Jun	655,949	150	Low	19,000	3	1	15	98,392	79,392
Jul	206,256	47	Low	22,000	11	1	15	30,938	8,938
Aug	112,982	26	Low	22,000	19	2	15	16,947	-5,053
Sep	172,446	40	Low	19,000	11	1	15	25,867	6,867
Oct	764,230	175	Low	17,000	2	1	15	114,635	97,635
Nov	502,893	115	Low	15,000	3	1	15	75,434	60,434
Dec	519,039	119	Low	15,000	3	1	15	77,856	62,856

7.2 ALLOCATION LIMIT BY PERCENTAGE OF ANNUAL GROUNDWATER FLUX

The following calculations apply to the whole of Aquifer 566. The estimated annual groundwater flux in the aquifer is based on total outflows shown in Table 9 and is 22,330 m³/day, with confidence bounds of 15,220 to 38,400 m³/day. Using a presumptive standard of 10% (WWAL, 2022) of this groundwater flux, the estimated allocation limit is 2,200 m³/day, with confidence bounds of 1,500 to 3,800 m³/day.

7.3 ALLOCATION LIMIT CONSTRAINED BY PERCENTAGE OF MEAN ANNUAL RECHARGE

The following calculations apply to the whole of Aquifer 566. The estimated aquifer recharge is based on Table 9 total inflows and is 23,900 m³/day, with confidence bounds of 20,900 to 26,700 m³/day. Using a presumptive standard of 10% (WWAL, 2022) of this total recharge, the estimated allocation limit is 2,400 m³/day, with confidence bounds of 2,100 to 2,700 m³/day.

Although there is no trend in the amount of annual precipitation over the last 20 years, climate change is likely to impact the amount of evapotranspiration as temperatures increase and summers have been getting drier. As such, the lower estimated allocation limit may be more appropriate as groundwater recharge may be expected to decline because of climate change.

7.4 ALLOCATION LIMIT BASED ON AVAILABLE DRAWDOWN

Per WWAL (2022), this method is applicable to unconsolidated, unconfined (water table) aquifers, a condition that is met for Aquifer 566. WWAL suggest that the *annual* volume of water available for use can be calculated as $(A \times b \times Sy) \times \alpha$ in which A is the aquifer area, b is its saturated thickness (50 m), and in which α is a presumptive standard (assumed 10%). Applying this equation and specific yield values of 0.1, 0.2 and 0.3 (Table 4) suggests available allocation on a daily basis of 27,000 m³/day with confidence bounds of 13,000 to 40,000 m³/day. This approach indicates a much higher allocation limit than other methods and should be approached with caution as effects on groundwater users, EFNs and saltwater intrusion risk could become a concern before the allocation limit is reached.

7.5 DISCUSSION OF RESULTS

7.5.1 Aquifer Scale Allocation Limits

Potential allocation limits for Aquifer 566 as a whole were determined based on estimate groundwater recharge and estimated groundwater fluxes. The best estimate allocation limit from both methods is about 2,200 to 2,400 m³/day (Table 11), which compares to estimated existing groundwater use of 4,000 m³/day (Table 8). A much higher allocation limit based on available drawdown is also provided but its use is presently not recommended. From this assessment it could be concluded that there is no groundwater available for additional use across the aquifer, which seems in conflict with the notion that large portions of Aquifer 566 are relatively undeveloped. This is in part related to the use of a 10% presumptive standard, which may be highly conservative in a setting in which dominant groundwater outflows are to the marine environment, although this was not investigated further. The outcome is also dominated by the inferred and unconfined high existing groundwater use by the gravel pit. Different portions of the aquifer therefore are likely to have different allocation potentials, which is explored further in Section 7.5.2. Seawater intrusion concerns should also be considered for setting Aquifer 566 allocation limits but as noted by WWAL (2022) this should be done on a case-by-case basis and, as such, was not considered in this case study.

Table 11 Possible allocation limits for Aquifer 566 based on different methods.

Method	Allocation limit
	No available allocation in August
Allocation limit constrained by stream depletion (Chapman Creek area)	Between 6,800 m ³ /day to 98,000 m ³ /day available in other months (this assessment may reflect limitations of streamflow data used as discussed in text)
Allocation limit based on a presumptive standard of 10% of Darcy Flux (whole aquifer)	2,200 m ³ /day, with confidence bounds of 1,500 to 3,800 m ³ /day
Allocation limit based on a presumptive standard of 10% of aquifer recharge (whole aquifer)	2,400 m ³ /day, with confidence bounds of 2,100 to 2,700 m ³ /day.
Allocation limit based on available drawdown	27,700 m ³ /day with confidence bounds of 13,000 to 40,000 m ³ /day.

7.5.2 Potential Aquifer Management Areas

The aquifer has been tentatively divided into four separate management areas (Figure 13), as follows:

- Area 1 has limited existing groundwater use; ENF may be a key consideration for aquifer allocation decisions given the presence of a number of creeks.
- Aquifer 2 includes the area of the existing gravel pit with inferred but unconfirmed high groundwater use for dewatering purposes. It also includes Ingres Creek.
- Area 3 has limited existing groundwater use and no creeks.
- Area 4 has limited existing groundwater use (Table 8) but includes Chapman Creek with known water supply limitations.

Possible allocation limits for each of these four management areas are provided in Table 12 based on percent aquifer area (i.e. scaling Table 11 values by these areas, except for EFN).

Table 12 Possible allocation limits for Allocation Management Areas.

Management Area	Aquifer Area (km ²)	Aquifer Area (%)	Groundwater Flux Section 7.2 (m ³ /day)	Recharge Section 7.3 (m ³ /day)	EFN (Section 7.4)
1	1.5	16	340 (230 - 590)	370 (330 - 420)	Not assessed
2	4.2	43	950 (650 - 1600)	1000 (910 - 1200)	Not assessed
3	1.6	16	360 (250 - 630)	400 (350 - 450)	Not applicable
4	2.4	25	540 (370 - 940)	590 (520 - 670)	See Table 10

7.5.2.1 Allocation Management Area #1

In the northern portion of the aquifer, currently there is limited groundwater use. There is some uncertainty of the aquifer stream connection in this area, due to limited data (Section 4.4). Allocation decisions in this portion of the aquifer may be a combination of flux constraints (Darcy Flux, recharge) and ENF depending on inferred groundwater-surface water interactions.

7.5.2.2 Allocation Management Area #2

In the central portion of the aquifer potential for additional allocation may be limited due to larger commercial uses and dewatering occurring at the gravel pit, which may have lowered groundwater levels locally (AE, 2019). In addition there may be ENF concerns surrounding Ingres Creek, where SCR D halted further work on their Dusty Road test well apparently due to concerns of potential for impact on Ingres Creek aquatic habitat (AE, 2019). This may require further investigation.

7.5.2.3 Allocation Management Area #3

The south-central portion of the aquifer, does not appear to have any ENF concerns (no streams present) and existing groundwater use is limited. The allocation decision approaches based on Darcy Flux and

annual recharge are currently recommended as the best initial approximation of possible allocation limits (Table 12), subject to future verification and refinement (e.g., through monitoring efforts).

7.5.2.4 Allocation Management Area #4

In the southern portion of the aquifer, potential for Chapman Creek streamflow depletion is the overriding consideration for determining groundwater allocation limits. Even though existing groundwater use in this area appears minimal (Table 8), existing SRCD withdrawals from the creek have led to well documented water management challenges during the end of summer dry period. A streamflow depletion analysis was completed to estimate potential for additional water use in this area using the EFN risk management framework. From this, it could be concluded that there is additional water available for use except in August. However, this inference seems to be at odds with current understanding highlighting flow limitations in downstream Chapman Creek. A significant limitation of the present analysis was the need to use historical data that does not reflect existing conditions. Smaller streams like Chapman Creek see significant year-to-year variability in flows (Triton, 2006). Given the results of this case study, it may be advisable to limit additional groundwater users in the southern portion of the aquifer around Chapman Creek.

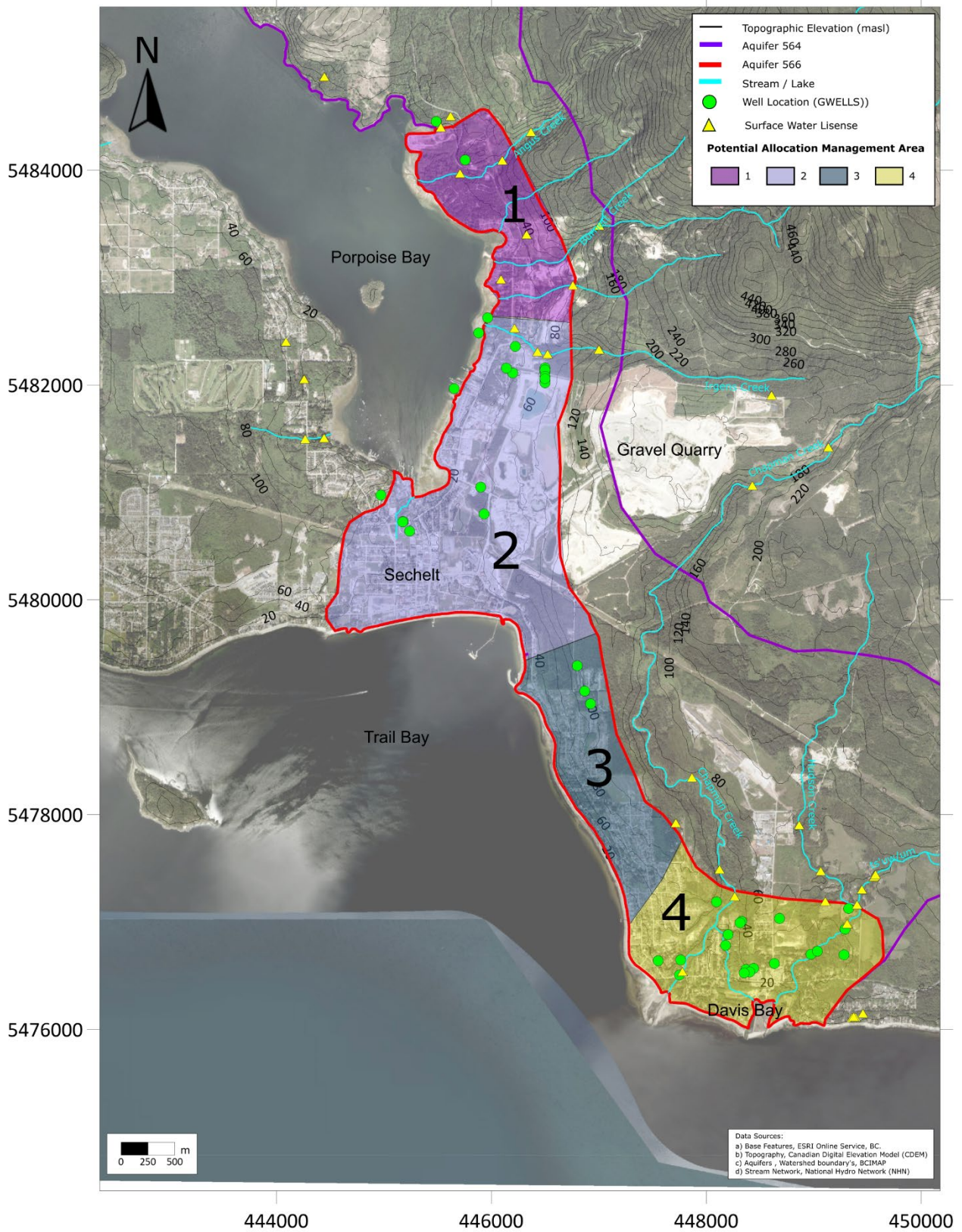
7.6 APPLICATION OF APPROACH TO OTHER TYPE 4A AQUIFERS

This case study is a good proxy to display the complexity of type 4A aquifers in BC and how application of simplified techniques to determining allocation limits may have limitations. The case study provided value in identifying knowledge gaps and recommending a path forward, but should be viewed with caution when setting allocation limits.

This case study also illustrated that even for a relatively small aquifer, different considerations for setting allocation limits may prevail in different portions of the aquifer. Allocation limits set on an aquifer-scale basis (e.g., such as based on recharge or Darcy Fluxes) should therefore be treated with caution. Based on current understanding, it is recommended that Aquifer 566 is subdivided into four different allocation management areas (Figure 13). Similar considerations are expected to more generally apply to allocation decisions in most aquifer settings.

In WWAL (2022), a list of priority aquifers was developed based on “aquifer demand”, a former aquifer classification category that is no longer in use. There are standardized tools and approaches available to estimate water demand (e.g., Bennett et al., 2021) that were applied in this case study and that could readily be applied across the Province to provide standardized water use estimates and to refine the identification of priority aquifers. High use aquifers (or portions of aquifers) that are not yet monitored should be prioritized for additional PGOWN observation wells to inform the aquifer allocation decision process.

Figure 13 Proposed aquifer allocation management areas.



The case study also highlighted potential limitations with the streamflow depletion approach. Specifically, the approach is heavily reliant on reliable streamflow data, which was lacking for Chapman Creek (the data may now exist through SCRD monitoring but was not available for this case study). Standardized tools and methods to confidently determine streamflow characteristics to support allocation limit calculations should therefore be an integral part of the guidance document (even though it is understood that it is an aquifer-focused document). Lastly, the case study also highlighted potential limitations of the EFN risk management approach in that it may not sufficiently account for hydroclimatic variability (drought conditions) in determining sustainable withdrawal limits.

This case study illustrated that a simplified groundwater balance could be developed for a type 4A aquifer using the tools recommended by WWAL (2022) such as HELP modelling to estimate groundwater recharge and Darcy's Law calculations to estimate groundwater fluxes. While the interpreted confidence bounds on groundwater recharge rates are relatively narrow, the underlying work by Forstner et al. (2018) was not repeated or confirmed. Like Case Study 2 prepared by WWAL, the potential role of stream losses in contributing to groundwater recharge was ignored. While this is conservative, it would become a limitation in aquifer settings where stream losses are the dominant groundwater recharge mechanism. Such settings exist across British Columbia (e.g., alluvial fan aquifers).

In Aquifer 566, a large suspected contributing component to groundwater flow is mountain block recharge. This is challenging to quantify and demonstrates benefits of more detailed analysis like groundwater modelling. In addition, detailed mapping of bedrock units including potential fault and lineament surveys could help identify preferential bedrock groundwater pathways to the unconfined aquifer.

The outflow component of the groundwater balance of Aquifer 566 was largely based on Darcy Flux calculations which have large inherent uncertainty. This uncertainty demonstrates the importance of qualified professional judgement in making allocation decisions. More fundamentally, Bredehoeft (2002) states that the idea that knowing recharge or the groundwater balance of an aquifer is important in determining the size of sustainable groundwater development has no basis in fact. As such the recharge and Darcy Flux based approaches to making allocation decisions are not necessarily scientifically reasonable although per WWAL (2022) they may provide a screening level understanding of possible aquifer allocation limits when combined with conservative presumptive thresholds (as was done in this case study). It is recommended that the recharge and Darcy Flux approaches are tested further for relevance in aquifers where groundwater storage declines are known to exist. PGOWN monitoring data is being analyzed for long-term trends providing indication of aquifers where storage declines are occurring versus aquifers where existing withdrawals have not yet resulted in storage declines. PGOWN groundwater level trends could therefore serve as important data for additional methodology testing, which has not yet occurred. If a PGOWN well is characterized by a long-term declining groundwater level trend, that trend can be used to estimate aquifer storage depletion (change in aquifer storage). Comparison with water use estimates would provide an indication of the degree of over-allocation of the aquifer.

It should also be considered whether PGOWN monitoring could be more formally incorporated into the aquifer allocation decision process, as follows:

- In general, when declining groundwater levels are noted in an aquifer additional groundwater licenses should not be issued although it could be considered whether the application is for an area of the aquifer that is relatively under-utilized (i.e., based on management area considerations). If this concerns a large water use application it would be up to the proponent to demonstrate absence of incremental impact on the aquifer (e.g., through groundwater modelling). In case the license application concerns a smaller use, this decision may be subject to discretion of the statutory decision maker as informed by regional hydrogeologist opinion.
- If a PGOWN well is characterized by a long-term stable groundwater level trend, this would tend to indicate that current groundwater use in the aquifer (or that portion of the aquifer for which the groundwater level data is representative) is sustainable and additional use should be possible, albeit that the additional “room” for use is unknown. To address that uncertainty, if the license application is for a large water use that would substantially increase existing water demand (e.g., a greater than 10% increase in existing demand) it would be up to the proponent to demonstrate absence of incremental impact on aquifer (e.g., through groundwater modelling). In case this concerns a smaller application (e.g., less than 10% of existing use), the license could be approved without detailed study (i.e., alleviating the onus on smaller users) unless the setting where groundwater use is proposed to occur suggests potential for impact. Continued PGOWN monitoring would provide indication whether groundwater use remains sustainable with the added water use, creating an iterative feedback process for subsequent groundwater licensing decisions where monitoring data exists.

Generally, this study and resulting considerations and recommendations highlight the need for a staged approach to making aquifer allocation decisions, progressing from simplified desk top assessments (such as this one) which can be used to identify the risk of aquifer over-allocation and streamflow depletion at a screening level (and which can be used to set preliminary allocation limits), to more advanced aquifer assessments (detailed aquifer mapping and hydrogeologic assessments), and numerical modelling if sufficient data exists and if a need for this is identified.

8.0 REFERENCES

- Associated Engineering (AE), 2019. Groundwater Investigation Phase 2 Project: Final Report and Preliminary Design of Production Wells at Dusty Rd, Mahan Rd, and Church Rd Well Sites.
- Bennett, T., Bystron, I., Lapcevic, P., Wainwright, M., & Diep, T., 2021. Analysis of Current Groundwater Use in the West Coast Region, British Columbia. Water Science Series WSS2021-01, Province of British Columbia, Victoria.
- Berardinucci, J. and Ronneseth, K., 2002. Guide to using the B.C. Aquifer Classification Maps for the protection and management of groundwater. Ministry of Water, Land, and Air Protection. 54 p. [cited 2023Jan30].
- Bonsal, B.R., Peters, D.L., Seglenieks, F., Rivera, A., and Berg, A., 2019. Changes in freshwater availability across Canada; Chapter 6 in Canada's Changing Climate Report, (ed.) E. Bush and D.S. Lemmen; Government of Canada, Ottawa, Ontario, p. 261–342.
- Duffield G, 2019. Representative values of hydraulic properties [Internet]. Hydraulic Properties :. Aquifer Testing 101. HydroSOLVE, Inc. [cited 2023Jan30]. Available from: http://www.aqtesolv.com/aquifer-tests/aquifer_properties.htm
- Doyle, J., 2013. *Integrating environmental tracers and groundwater flow modeling to investigate groundwater sustainability, Gibsons, BC* (T). University of British Columbia. Available from: <https://open.library.ubc.ca/collections/ubctheses/24/items/1.0074249>
- Forstner, T., Gleeson, T., Borrett, L., Allen, D.M., Wei, M., and Baye, A., 2018. [*Mapping aquifer stress, groundwater recharge, groundwater use, and the contribution of groundwater to environmental flows for unconfined aquifers across British Columbia*](#). Water Science Series, WSS2018-04. Prov. B.C., Victoria B.C.
- Gelhar, L. W., and J. L. Wilson, 1974. *Ground-Water Quality Monitoring*. In Ground Water 12(6): 399-408.
- GeoBC, 2022. Landcover Classification of British Columbia [Internet]. Static Maps of B.C. Government of British Columbia; [cited 2023Jan30]. Available from: https://www2.gov.bc.ca/assets/gov/data/geobc/bc_land_cover.pdf
- Government of Canada, 2022. Historical Hydrometric Data [Internet]. Water Level and Flow - Environment Canada. Government of Canada / Gouvernement du Canada [cited 2023Jan3]. Available from: https://wateroffice.ec.gc.ca/search/historical_results_e.html?search_type=station_name&station_name=chapman%2Bcreek&start_year=1850&end_year=2023&minimum_years=&gross_drainage_operator=%3E&gross_drainage_area=&effective_drainage_operator=%3E&effective_drainage_area=
- Hammond Z, Hinnell A, 2018. AQUIFER MAPPING REPORT: AQUIFER 0566 [Internet]. Aquifer 566 Summary. Province of British Columbia; [cited 2023Jan30]. Available from: https://s3.ca-central-1.amazonaws.com/aquifer-docs/00500/AQ_00566_0566_Aquifer_Mapping_Report_2019.pdf
- Hargreaves, G.H., and S.A. Samani. 1985. Reference crop evapotranspiration from temperature. Applied engineering in agriculture 1.2. pp. 96-99.

- Heath, R.C., 1983. Basic ground-water hydrology, U.S. Geological Survey Water-Supply Paper 2220, 86p. [cited 2023Jan30]. Available from: <https://pubs.usgs.gov/wsp/2220/report.pdf>
- Heidelberg Materials, 2015. Sechelt Sand & Gravel Mine [Internet]. Quarry Life Award. Heidelberg Materials [cited 2023Jan11]. Available from: <https://www.quarrylifeaward.com/quarries/north-america/sechelt-sand-gravel-mine>
- Lemmen, D.S., Warren, F.J., Lacroix, J., and Bush, E., editors (2008): From Impacts to Adaptation: Canada in a Changing Climate 2007; Government of Canada, Ottawa, ON, 448 p
- McCammon J et al, 1977. Surficial Geology and Sand and Gravel Deposits of Sunshine Coast Powell River and Campbell River Areas. Victoria British Columbia: Ministry of Mines and Petroleum Resources. [cited 2023Jan30].
- Ministry of Forests, 2022. LIDARBC [Internet]. Province of British Columbia. Province of British Columbia [cited 2023Jan3]. Available from: <https://www2.gov.bc.ca/gov/content/data/geographic-data-services/lidarbc>
- Morris, D.A. and Johnson, A.I., 1967. Summary of Hydrologic and Physical Properties of Rock and Soil Materials, as Analyzed by the Hydrologic Laboratory of the U.S. Geological Survey, 1948-1960. USGS Water Supply Paper: 1839-D. [cited 2023Jan30].
- Pacific Climate Impacts Consortium, University of Victoria, (Feb. 2019). Statistically Downscaled Climate Scenarios. Method: BCCAQ v2." (PCIC12, RCP4.5 and RCP8.5, Lat 48.776 Long -123.430, Tmax and Tmin.; [cited 2023Jan25] Available from https://data.pacificclimate.org/portal/downscaled_gcms/map/
- Province of British Columbia, 2017. Environmental Flow Needs Policy. Ministry of Environment and Climate Change Strategy. Available from: <https://www2.gov.bc.ca/gov/content/environment/air-land-water/water/water-licensing-rights/water-policies/environmental-flow-needs>
- Province of British Columbia, 2022a. Groundwater Wells and aquifers [Internet]. Groundwater Wells and aquifers. Province of British Columbia; [cited 2023Jan3]. Available from: <https://apps.nrs.gov.bc.ca/gwells/>
- Province of British Columbia, 2022b. IMAPBC [Internet]. Web-based mapping. Province of British Columbia [cited 2023Jan3]. Available from: <https://www2.gov.bc.ca/gov/content/data/geographic-data-services/web-based-mapping/imapbc>
- Province of British Columbia, 2022c. Aquifer#566 - S3. Aquifer #566: East Sechelt Delta. Government of British Columbia. [cited 2023Jan30]. Available from: https://s3.ca-central-1.amazonaws.com/aquifer-docs/00500/AQ_00566_Aquifer_Factsheet.pdf

- Statistics Canada, 2022. Census profile, 2021 census of Population: Profile Table [Internet]. Profile table, Census Profile, 2021 Census of Population - Sechelt (Part), Indian government district (IGD) [Census subdivision], British Columbia; Sechelt, District municipality (DM) [Census subdivision], British Columbia. Government of Canada [cited 2023Jan11]. Available from: <https://www12.statcan.gc.ca/census-recensement/2021/dp-pd/prof/details/page.cfm?Lang=E&SearchText=sechelt&DGUIDlist=2021A00055929803%2C2021A00055929011&GENDERlist=1&STATISTIClist=1&HEADERlist=0>
- Staats M, 2014. Water Availability and Climate Change: Chapman Creek Water System, Sunshine Coast, BC [Internet]. Final Project for the professional Masters Degree in Land and Water Systems at the University of British Columbia. [cited 2023Jan30]. Available from: <https://blogs.ubc.ca/mstaats8/methods-2/study-area/>
- Triton, 2006. Chapman Creek Source Assessment.
- Wang T., A. Hamann, D. Spittlehouse, and C. Carroll, 2016. Locally Downscaled and Spatially Customizable Climate Data for Historical and Future Periods for North America. PLoS ONE 11(6): e0156720. doi:10.1371/journal.pone.0156720. Available from: <https://climatebc.ca/>
- Western Water Associates Ltd. (Sivak, T., Wei, M.). 2019. Koksilah River Watershed: Preliminary Assessment of Hydraulic Connection. Water Science Series, [WSS2019-05](#). Prov. B.C., Victoria B.C.
- Western Water Associates Ltd. (Sivak, T., Wei, M., Kohut, A., Geller, D.). 2022. Establishing Groundwater Allocation Limits in B.C
- Wise A, 2022. Letter: Actually, water is part of tourism planning on the Coast [Internet]. Coast Reporter [cited 2023Jan30]. Available from: <https://www.coastreporter.net/opinion/letter-actually-water-is-part-of-tourism-planning-on-the-coast-6054036>
- Yates D, Strzepek K. 1994. Potential Evapotranspiration Methods and their Impact on the Assessment of River Basin Runoff Under Climate Change, Working Paper of the International Institute for Applied Systems Analysis, WP-94-46, July 1994.