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Chemainus and Bonsall Watersheds: Preliminary Desktop Assessment of Hydraulic Connection

Tim Sivak and Mike Wei

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Author's Affiliation:
Tim Sivak, M.GISA., P.Geo..
Western Water Associates Ltd.
301-1095 McKenzie Ave
Victoria, BC V8P 2L5

Mike Wei, M.Sc., P.Eng.
Hydro Geo Logic
882 Canterbury Road
Victoria, BC V8X 3E6

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Photo of Chemainus River at Banon Creek provided by West Coast Region Water Authorizations (FLNRORD).

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EXECUTIVE SUMMARY

The Chemainus River and Bonsall Creek on the east coast of Vancouver Island have been identified as vulnerable to low flows during the dry season, which may affect the habitat and survival of aquatic life. Determining the likelihood of hydraulic connection of wells to streams in the Chemainus and Bonsall watersheds is vital to effective management of environmental flows and access to water for users. Four types of aquifers exist within the study area:

- Unconfined sand and gravel along streams (unconsolidated, unconfined);
- Confined sand and gravel (unconsolidated, confined);
- Fractured sedimentary bedrock of the Nanaimo Group; and
- Crystalline bedrock.

In this study, the aquifers were more simply treated as unconsolidated or bedrock. This desktop study identified stream reaches within the Chemainus and Bonsall watersheds where hydraulic connection with underlying aquifers and depletion of streamflow from pumping from those aquifers is most likely to occur. These connected stream reaches were identified by mapping the likely locations of a vadose zone and low--permeability sediments (i.e., till, silt, or clay) underneath streams using available well records, digital stream and topographic elevation data, as well as from published geological mapping. Mapping shows long stretches of Chemainus River in the study area to be likely connected and only the extreme lower reach of Bonsall Creek and the reach between the confluences with Whitehouse Creek and Sollys Creek are likely connected. The stream's tributary to the Chemainus River and Bonsall Creek in the study area appear to be mostly disconnected.

Mapping in this study also suggests that connection exists between the unconsolidated and bedrock aquifers. Vertical hydraulic gradients between the aquifers exist within the study area and interflow between aquifers can occur where low permeability sediments are absent.

Preliminary groundwater management areas, based mostly on groundwater elevation mapping, were delineated in the study area for the Chemainus River and Bonsall Creek for both the unconsolidated and bedrock aquifers. Groundwater management areas identify the portion of the unconsolidated and bedrock aquifers that potentially contributes to streamflow depletion from well pumping upstream and upgradient of specific points along Chemainus River and Bonsall Creek and serves as a tool to inform allocation of water and management of groundwater use within the study area. For the Chemainus River, groundwater management areas were delineated upstream/upgradient of the river near River Road, at the Chemainus Road bridge and at the mouth. For Bonsall Creek, groundwater management areas were delineated for the upper reach of the creek and at the mouth.

The following are recommendations derived from this study to improve on the preliminary understanding of the nature of hydraulic connection of wells to streams in the study area:

- Conduct field work during late summer (low-flow period) to:
    - check if tributary streams exhibit ephemeral or perennial flow; mapping suggests much of the tributary stream reaches to the Chemainus River and Bonsall Creek are disconnected from the underlying water table and therefore may not receive significant baseflow from groundwater.
    - Identify stream reaches where hydraulic connection is likely by measuring, for example, stream temperatures and electrical conductivity along the streams.
- Conduct a level survey of the wells and groundwater level elevations to more accurately characterize groundwater elevations and flow in the lower reach of the Chemainus River and Bonsall Creek.

- Confirm well locations in the Whitehouse Creek to Sollys Creek area to more accurately map groundwater elevations to assess hydraulic connection of Bonsall Creek in that local area.
- Establish multilevel observation well(s) in the unconsolidated and bedrock aquifers near Bonsall Creek above the confluence with Sollys Creek, between Richardson's Brook and Whitehouse Creek and near Observation Well No. 355 to verify vertical gradients between the aquifers, obtain aquifer hydraulic parameters to better understand the hydraulic connection between the unconsolidated and bedrock aquifers in the study area.
- Consider installing shallow piezometers (monitoring wells) at up to a dozen locations along Chemainus River and Bonsall Creek to assess whether those stream reaches are gaining or losing and to confirm local geology.
- If opportunity arises, consider developing a numerical model to quantify the nature of hydraulic connection between the streams and aquifers within the study area.
- Confirm the locations of the points of delineation for the groundwater management areas in the field.
- Consider requiring, as a condition of a water licence, measuring and reporting of monthly quantities diverted and static water level elevations for the larger licensed groundwater users (above a threshold limit, capacity of licensee to comply).
- Establish critical environmental flow thresholds for the Chemainus River and Bonsall Creek to protect streamflows.
- Explore options on how FLNRORD can document points of hydraulic connection for unlicensed domestic wells.
- Initiate an on-going program to raise awareness of water users diverting water from streams and wells in the watershed to promote efficiency of water use and to preserve groundwater levels and protect streamflows.

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ACRONYMS AND ABBREVIATIONS

asl	above sea level
DEM	Digital Elevation Model
EFN	environmental flow needs
ENV	Ministry of Environment and Climate Change Strategy
FLNRORD	Ministry of Forests, Lands, Natural Resource Operations and Rural Development
FWA	Freshwater Atlas
GIS	Geographic Information System
GWELLS	B.C. government’s water well database
PoHC	point of hydraulic connection
WSA	*Water Sustainability Act*

1. BACKGROUND

The Chemainus watershed supports important fisheries and aquatic habitat as well as development on the land base. Under the British Columbia (B.C.) *Water Sustainability Act* (WSA) (Province of BC, 2016a), new groundwater authorizations must consider hydraulic connection to stream(s) and environmental flow needs if determined to be hydraulically connected. The Ministry of Forests, Lands, Natural Resource Operations and Rural Development (FLNRORD) is looking to find efficiencies in assessing hydraulic connection between groundwater and surface water to support the application of the WSA.

The WSA considers groundwater in an aquifer and water in a stream to be hydraulically connected if the test of “reasonably likely (i.e., more likely than not)” is met. Determining where along a stream hydraulic connection likely occurs and the corresponding portion of the aquifer that participates in flow to those connected stream reaches is necessary to enable surface water and groundwater to be managed together as a single resource to allow decision makers to:

- Consider how diversion of groundwater may affect environmental flow needs (EFNs) of a stream (Section 15 of the WSA);
- Operationally account for the demand of water from points of groundwater diversion along the stream; and
- Consider hydraulically connected groundwater users when flow in a reach of stream becomes critically low (protection orders in Sections 87 and 88 of the WSA).

Identifying where effects that pumping wells may have on connected streams helps to inform management of user water rights in times of scarcity or when streamflow reaches critically low levels.

The main goals of this study are to:

- use available data to identify stream reaches where hydraulic connection between surface water and groundwater is more likely; and
- delineate groundwater management areas associated with those major connected stream reaches.

In the WSA, the definition of “stream” includes springs. However, information on the source of springs is not available, so assessment of hydraulic connection of aquifers to springs is not feasible within the scope of this study. Sections 46, 47, 59 and 60 of the WSA also require the water manager to consider hydraulic connection between an aquifer and a stream from the perspective of contamination. Hydraulic connection in this sense requires understanding of specific contaminant pathways and is also beyond the scope of this study.

Finally, as a note of convention for this report, in reference to watersheds and sub-watershed, only the name of the stream is used (e.g., “Chemainus watershed” not “Chemainus River watershed”, “Whitehouse sub-watershed” not Whitehouse Creek sub-watershed). Watersheds within the Chemainus watershed and Bonsall watershed are referred to as sub-watersheds.

2. SCOPE OF WORK

The main components of the work completed as part of this study include compiling available information to:

- Map the groundwater elevations and infer groundwater flow directions;
- Map the overburden thickness and low-permeability-sediment thickness;

- Identify stream reaches where hydraulic connection is likely and where connection is unlikely;
- Delineate groundwater management areas associated with major connected stream reaches; and
- Summarize the work of this study in a report and other data outputs.

3. STUDY AREA

3.1 Watershed Setting

The Chemainus River and Bonsall Creek watersheds occupy a total approximate area of 39,000 hectares and are situated within the Nanaimo Lowland physiographic region (Holland, 1976) on the southeast side of Vancouver Island (see Figure 1). The watersheds are located about 50 km northwest of Victoria, B.C. and 10 km north of the City of Duncan, B.C. The study area is a small subset of the Chemainus and Bonsall watersheds, covering only the area in the watershed where water well data are available (study area is outlined in black in Figure 1).

The study area enjoys a relatively wet and mild climate typical of coastal B.C. and is wetter than Victoria but considerably drier than other parts of Vancouver Island. The Duncan Kelvin Creek Climate Station (Climate ID: 1012573) climate normal (1981 to 2010) shows average total annual precipitation of 1,361.2 mm, and average monthly temperatures ranging between 3.3 °C and 17.9 °C. Duncan Kelvin Creek Climate Station is located about 17 km south of the study area boundary. Note that past climate data are provided here for context only and climate change forecasts for B.C. (PCIC, 2012) point to shifts in climate toward slightly warmer and wetter winters and longer, drier summers. This change is expected to result in longer periods of low stream flow as well as more frequent higher intensity rainfall during the wet season.

The study area has an east-northeast facing aspect, with a total relief of 518 m. The primary streams within the study area include the Chemainus River, Bonsall Creek, and Whitehouse Creek. Sollys Lake is the largest freshwater lake in the study area (see Figure 1).

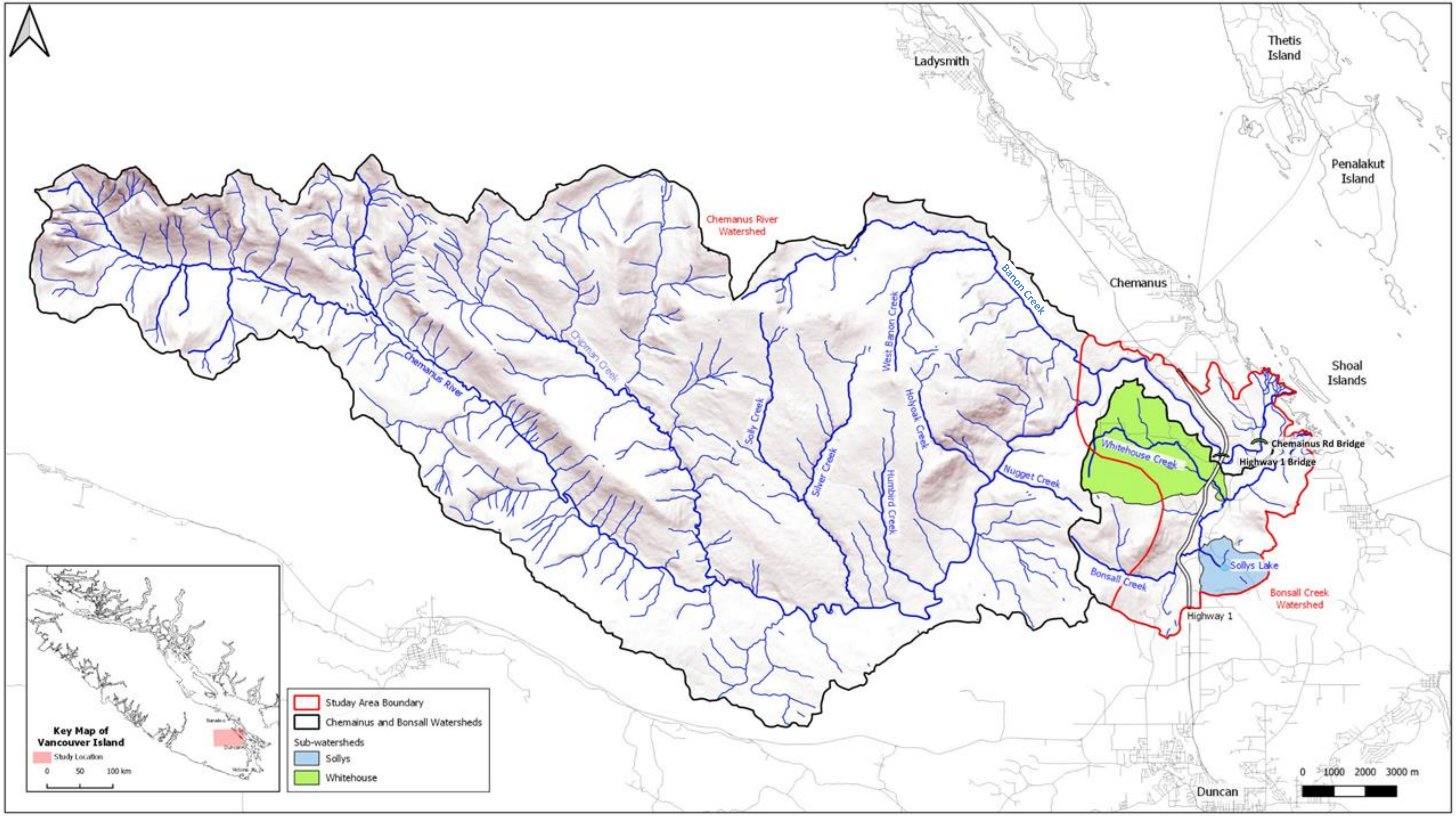
3.2 Geologic Setting

3.2.1 Surficial geology

The surficial geology in the study area comprises a mix of glaciofluvial and till-like deposits and marine deposits from the waning stage of the last period of glaciation (10,000 to 14,000 years ago). The surficial geology of the area has been mapped in detail by Halstead (1965). Digital terrain mapping data compiled by Forest Renewal BC (1992) is also available, which shows the low-lying parts of the study area as comprised of marine and fluvial deposits and upland areas comprised of till and/or colluvium overlying bedrock. Figure 2 illustrates the surficial geology of the watershed area as mapped by Halstead (1965).

3.2.2 Bedrock geology

The bedrock geology of the area has been mapped by Muller (1980) and digitally compiled by Cui et al. (2017) (see Figure 3). The bedrock map compiled by Cui et al. (2017) depicts the northern part of the study area as comprising undivided sedimentary rocks of the Upper Cretaceous Nanaimo Group. The southern part of the study area comprises crystalline rock from the Sicker Group, Mount Hall Gabbro, and Island Plutonic Suite (youngest – Jurassic). Sicker Group and Island Plutonics are also present in the very northwest corner of the study area. Late Paleozoic-aged chert, siliceous argillite and siliciclastic rocks from the Buttle Lake Group are also present in the eastern part of the study area.

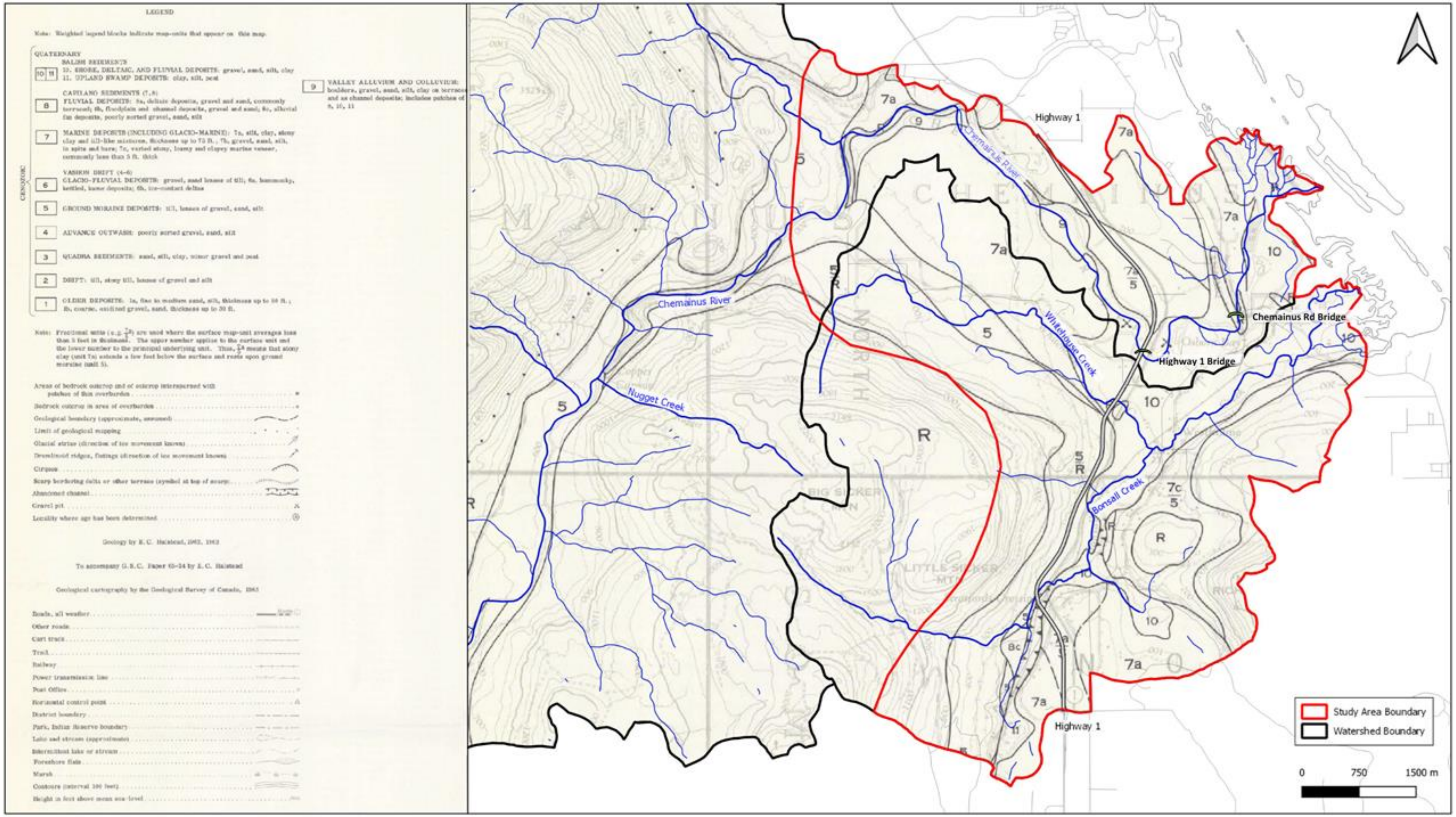


Chemainus and Bonsall Watersheds Assessment of Hydraulic Connection	TITLE **Figure 1:** Site Overview of Chemainus River and Bonsall Creek Watershed		
western water ASSOCIATES LTD	DRAWN Nic Williams	DATE March 27, 2020	CLIENT FLNRORD
	REVIEWED T. Sivak, GIT.; M. Wei, P.Eng.	PROJECT NO. 19-121-01VC	REVISION NO. B

Data Sources: Base plan DataBC (2018), water features from GeoBC (2010), wells from GWELLS (2019), MFLNRO (2019).

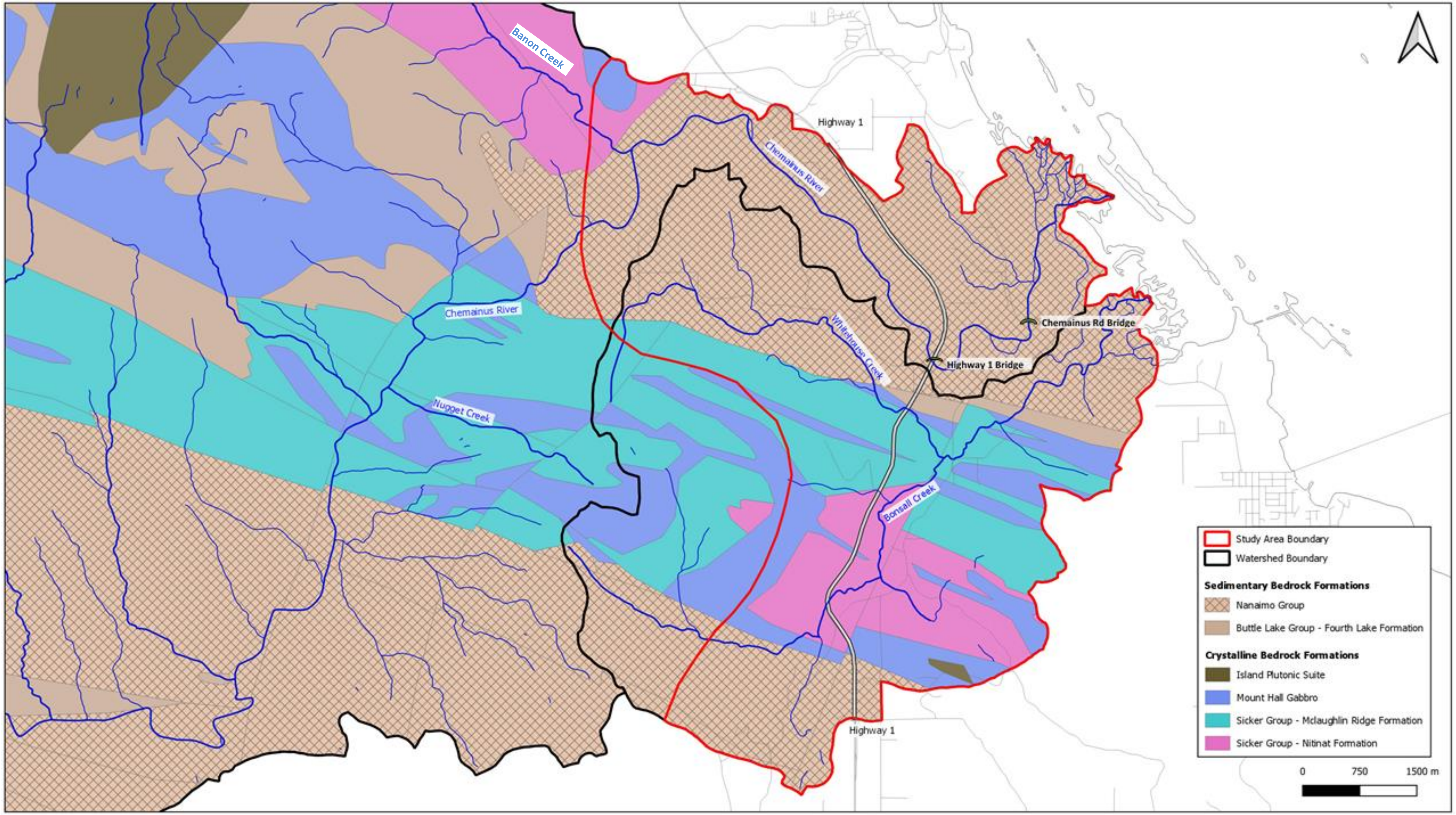
Contour interval: -
Map Projection: NAD83 UTM Zone 10.
Other notes:

Figure 1: Site overview of Chemainus River and Bonsall Creek watersheds.



Chemainus and Bonsall Watersheds Assessment of Hydraulic Connection	TITLE **Figure 2:** Surficial Geology of Chemainus and Bonsall Watershed			Data Sources: Surficial geology from Halstead (1965)
western water ASSOCIATES LTD	DRAWN Nic Williams	DATE March 27, 2020	CLIENT FLNRORD	Contour interval: -
	REVIEWED T. Sivak GIT., M. Wei P.Eng.	PROJECT NO. 19-121-01VC	REVISION NO. B	Map Projection: NAD83 UTM Zone 10. Other notes:

Figure 2: Surficial geology of study area.



Chemainus and Bonsall Watersheds Assessment of Hydraulic Connection

western water ASSOCIATES LTD

TITLE **Figure 3:** Bedrock Geology of Chemainus and Bonsall Watersheds

DRAWN Nic Williams

DATE March 27, 2020

CLIENT FLNRORD

REVIEWED T. Sivak GIT., M.Wei P.Eng.

PROJECT NO. 19-121-01VC

REVISION NO. C

Data Sources: Bedrock geology from BC Digital Geology Cui et al. (2017), water features from GeoBC (2010)

Map Projection: NAD83 UTM Zone 10.

Other notes: Sedimentary and crystalline bedrock formations listed in approximate youngest (top) to oldest (bottom).

Figure 3: Bedrock geology of study area.

3.2.3 Mapped aquifers

In the study area, residents and businesses rely on groundwater for supply. There are five mapped surficial or bedrock aquifers within the study area (ENV, 2019a to e). Mapped aquifers in the study area are classified by subtype (from Wei et al., 2009) as follows:

- Aquifer 172 – Subtype 1b: Unconfined sand and gravel along mid-sized and small-sized streams, respectively. Reported as 'likely' hydraulically connected to surface water (ENV, 2019a);
- Aquifer 174 – Subtype 4b: Confined, sand and gravel of glacial or pre-glacial origin. Reported as 'not likely' hydraulically connected to surface water (ENV, 2019b);
- Aquifers 171 and 175 – Subtype 5a: Fractured sedimentary bedrock aquifers. Reported as 'not likely' hydraulically connected to surface water (ENV, 2019c; ENV, 2019d); and,
- Aquifer 173 – Subtype 6b: Crystalline bedrock aquifers. Reported as 'not likely' hydraulically connected to surface water (ENV, 2019e);

The majority of groundwater use is for private domestic and irrigation in lower reaches of the watershed. The most significant use of groundwater by volume in the watershed is for local waterworks providers and a hatchery, diverting groundwater from Aquifer 172. Previous work conducted in the area suggested that there was a hydraulic connection between these users at some nearby location, but not likely in the immediate vicinity of the respective well fields (WWAL, 2017). Other than the Environmental Assessment Office mandated annual monitoring and reporting associated with these uses, groundwater use currently is not as well known because licensing of groundwater use is new and most of the groundwater use has not yet been authorized.

For the purpose of this study, we treated the unconsolidated aquifers as one because it was conceptually simpler. The confined unconsolidated Aquifer 174 also only occurs in the upper part of the Bonsall watershed study area. We also treated the bedrock aquifers as one because:

- Groundwater flow in all three aquifers are the same, via fractures;
- Aquifers 171 and 175 comprise the same rock type and their identity as separate aquifers appears based on differences in location only; and,
- Differences in transmissivity or hydraulic conductivity between the crystalline and sedimentary bedrock aquifers will affect groundwater flux and rate of stream depletion but this is beyond the scope of the study.

4. METHODS

4.1 General Approach: Primary Considerations in Assessing Hydraulic Connections to Streams

For this assignment, we used a modified methodology based on previous work conducted in Koksilah watershed (Sivak and Wei, 2019). In this study, the likely points of hydraulic connection (PoHC) were established at the downstream end of major open stream reaches within each groundwater management area (see Section 4.4.7). Further discussions on data and limitations of this report are located in Section 4.5.

If an aquifer and a stream are hydraulically connected, well pumping may affect the flow in the stream (process known as stream depletion) in one of two ways:

1. By intercepting groundwater that would have eventually made its way to the stream to supply baseflow to the stream (interception); and

2. By causing water in the stream to infiltrate into the aquifer towards the pumping well (induced infiltration or induced recharge).

The USGS publication by Barlow and Leake (2012) presents and discusses these two processes in detail.

Our working hypothesis in this study is that for hydraulic connection to be possible between an aquifer and a stream, two primary conditions are necessary (Figure 4):

1. Vadose zone (unsaturated zone), and
2. Low-permeability unit (i.e., till, silt, or clay), must not directly underlie the stream (to disconnect the aquifer from the stream).

The presence of a vadose zone or low-permeability sediments below a stream and above the aquifer in question will essentially restrict hydraulic connection and stream depletion along that reach of the stream. However, depletion from well pumping may still occur further downgradient (by the process of interception) at a connected reach of stream. Depending on the setting, pumping may not affect the disconnected stream reach nearest to the well, but rather a reach further downstream or downgradient of the direction of groundwater flow. In this report, if a vadose zone or low permeability sediment layer does not underlie a reach of stream, that reach is considered connected.

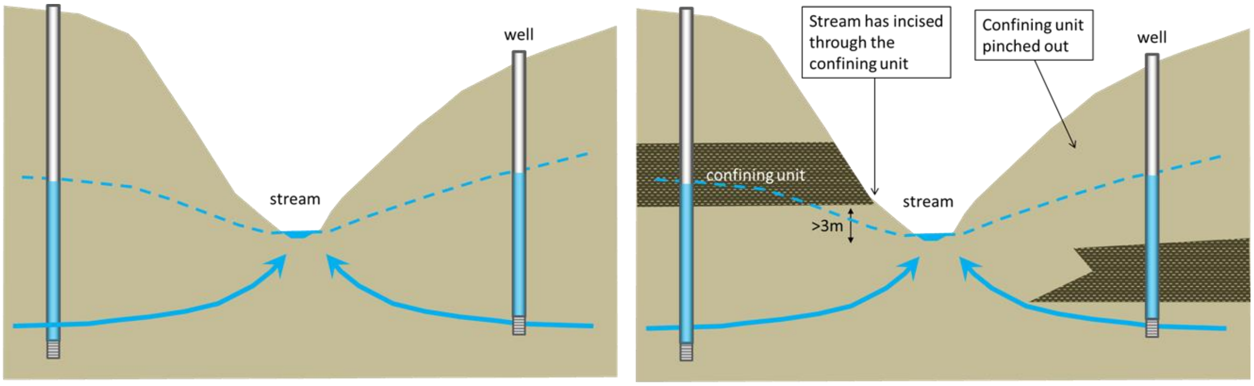


Figure 4: Primary conditions that allow hydraulic connection.

The main approach of this study was to use available lithological information in water well records, digital elevations, and stream locations (including elevations) to identify where the presence of a vadose zone or low-permeability sediments likely exist directly underneath the stream to disconnect the stream from the aquifer (Section 4.4.5 defines low permeability sediments in this study).

In doing this, we:

- Divided up the hydrogeology into two settings: 1) unconsolidated sediments and 2) fractured bedrock;
- Mapped the groundwater level elevations in both the unconsolidated sediments and the fractured bedrock to infer the likely direction of groundwater flow in both settings; and
- Mapped the thickness and extent of low permeability sediments (i.e., till, silt and clay), as well as elevation of the known bottom depth of the confining sediments relative to the stream elevation.

If the elevation of the stream was greater than 3 m above the groundwater levels, the stream was considered to be disconnected above the local water table. If confining low permeability sediments underlying the stream were greater than 1 m thick, then vertical flow between surface water and groundwater were considered to be impeded (or “blocked”) by those sediments. If the groundwater elevations in the stream reach indicate a vadose zone or driller lithologies indicate low-permeability sediments directly underlie the stream reach, then hydraulic connection along the reach is considered to be unlikely.

Once major connected reaches of streams are identified, groundwater management areas can be delineated for the unconsolidated and bedrock aquifers in the study area, based on these hydraulically connected reaches. Specific points along the Chemainus River and Bonsall Creek were selected to delineate the groundwater management areas. Section 5.5 describes groundwater management areas within the Chemainus and Bonsall watersheds.

The following subsections present the data sources in more detail, the uncertainties associated with the data, and how the maps were developed.

4.2 Spatial Data Sources

In completing the analyses herein, we incorporated a series of spatial datasets in various data formats and scale, as summarized in Table 1 below.

Table 1. Summary of spatial datasets used in study.

Dataset	Format	Scale	Purpose	Reference
GWELLS well lithology	Shapefile	-	Lithology and water levels used in hydraulic connection determinations.	ENV (2020)
Chemainus River and Bonsall Creek Watershed Boundaries	Shapefile	1:20,000	Used to constrain study area.	BC Freshwater Atlas from GeoBC (2010)
Watercourses	Shapefile	1:20,000	Used in hydraulic connection determinations.	BC Freshwater Atlas from GeoBC (2010)
Digital Elevation Model	.ASC	10 m resolution	Used to extract elevations to well points and watercourses.	FLNRORD (2020)
Digital Surficial Geology	Shapefile	1:50,000	Used to refine geological data from GWELLS.	Forest Renewal BC (1992)

4.3 Well Lithology

Well data from the GWELLS database formed a primary lithological and groundwater level input dataset for this study. Well data were compiled and used to develop the conceptual hydrogeological model for the watershed and to determine where hydraulic connection is expected to occur. Lithology key words were used to systematically refine the lithology from the GWELLS database using a script to standardize the terminology. Wells were classified as completed in unconsolidated sediments or bedrock based on the refined lithology spreadsheet. The results were reviewed manually and cross-referenced against available terrain inventory and surficial geology mapping (see Table 2 below).

Table 2. Summary of classification methodology for well lithology data.

Lithology Keyword	Dominant Terrain Polygon Descriptor:	Interpreted Lithology:
Till-like material described as “grey till”, “hard till”, “hardpan” “till”, “clay till”,	M (Morainal)	Till
Clay; blue clay; silt; blue silt	W^G (Glaciomarine) W (Marine)	Clay, Silt
Gravel; sand & gravel sand; cobbles, boulders	F^G (Glaciofluvial) F or F^A (Fluvial or Active Fluvial) C (Colluvium)	Gravel, sand & gravel, sand, cobbles, boulders
Volcanic; granite; basalt, shale	-	Bedrock
Wood; peat; organics	O (Organic)	Peat

Shallow wells with poor well records but indicated to be “Excavated” or “Dug” were categorized as unconsolidated. Data from partially complete well records were included in the hydrogeological conceptual model (if possible) but were classified as having unknown well completion details.

4.4 Geographical Information System (GIS) Analysis

This study used a Geographic Information System (GIS) to compile spatial data and conduct spatial analysis (predominantly using the QGIS® platform). GIS was used to clip spatial data to the appropriate study area dimensions and to assign elevation data to well and stream features.

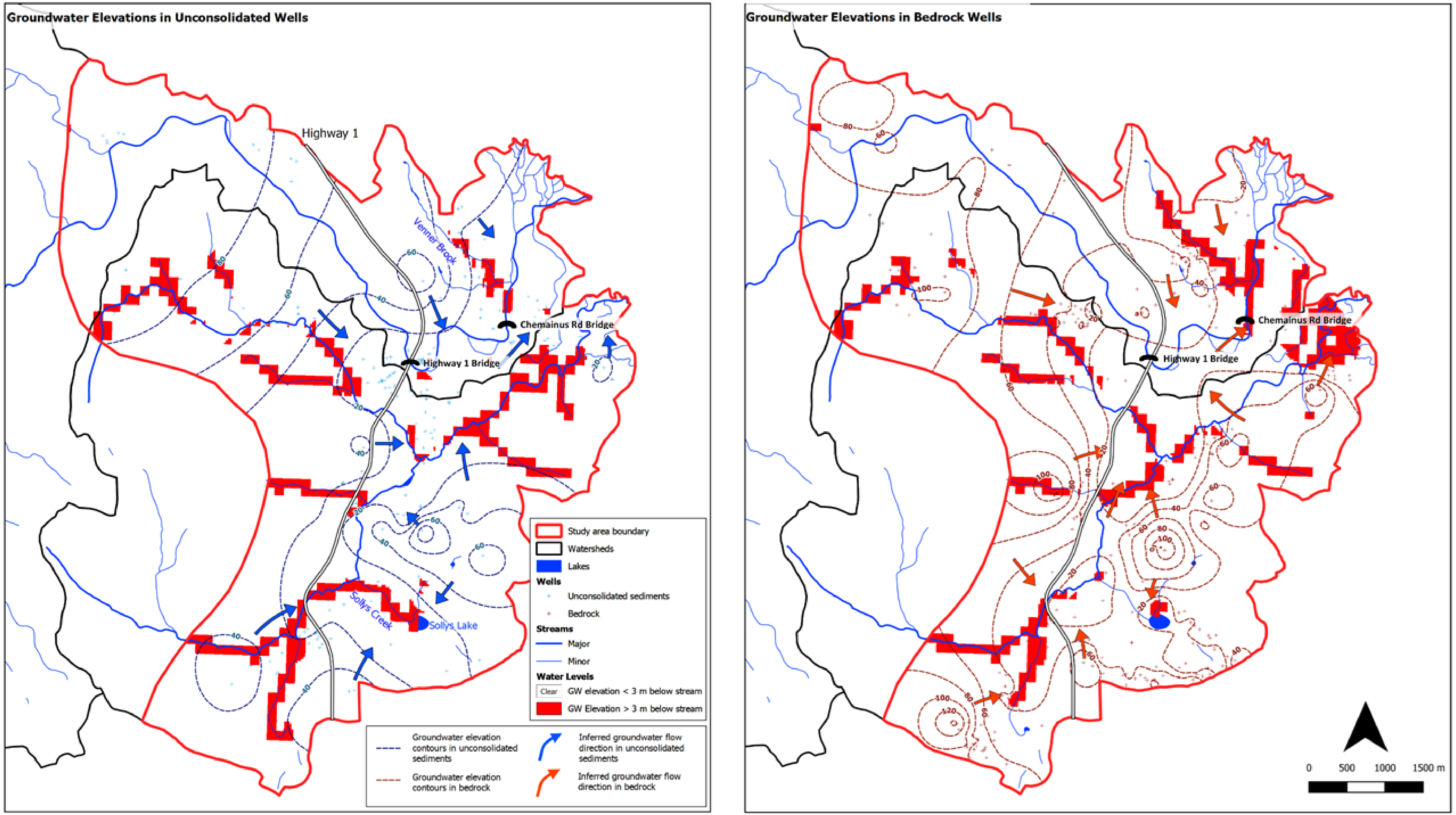
To develop isopach maps, anchor points were placed within terrain polygons where material thicknesses were expected to be <1 m. The anchor points were placed on a grid spaced at regular intervals within these terrain polygons. The multilevel B-spline method (Lee et al., 1997) was used to interpolate between data points for mapping groundwater elevations, and for isopach maps.

GIS was also used to support delineating the groundwater management zones using the PoHC between streams and wells (see Section 5.4.2 for more detail on PoHC determinations).

4.4.1 Mapping groundwater elevation in unconsolidated and bedrock wells

Groundwater elevation maps were constructed separately for unconsolidated sediments and for bedrock to infer direction of horizontal groundwater flow in both those deposits (see Figure 5). Groundwater elevation contours were constructed by grouping wells from the GWELLS database into unconsolidated sediments and fractured bedrock categories. For each category, the ground-surface-elevation value from the digital elevation model (DEM) was then extracted for each well location. The DEM has a horizontal accuracy of about 10 m, and elevation is expressed relative to mean sea level. The groundwater elevation at each well location was calculated by subtracting the reported static water level depth in the well from the DEM ground elevation (limitations of using reported static water levels are discussed in Section 4.5). The groundwater elevations between well points were interpolated and contoured in GIS. In calculating groundwater elevations, well stick-up above ground surface was assumed to be zero.

In relying on the reported static water levels in the well records, we assume they represent average conditions over the time period of the data.



Chemainus and Bonsall Watersheds Assessment of Hydraulic Connection	TITLE	**Figure 5:** Reported groundwater elevations in unconsolidated and bedrock wells				Data Sources: Base plan DataBC (2018), water features from GeoBC (2010), wells from GWELLS (2019), FLNR (2019
western water ASSOCIATES LTD	DRAWN	Nic Williams	DATE	March 27, 2020	CLIENT FLNRORD	Contour interval: 20 m Map Projection: NAD83 UTM Zone 10.
	REVIEWED	T. Sivak GIT, M.Wei P.Eng.	PROJECT NO.	19-121-01VC	REVISION NO. D	Other notes: GW elevations from multilevel B-Spline interpolation.

Figure 5: Reported groundwater elevations and flow directions in unconsolidated and bedrock wells.

4.4.2 Mapping inferred vertical groundwater gradient

Relative vertical hydraulic gradient direction between overburden and bedrock within the study area is depicted in Figure 6. Figure 6 was created by subtracting the cell values from the unconsolidated groundwater elevation surface from those from the bedrock groundwater elevation surface. The groundwater elevations between well points are interpolated using a multilevel B-Spline interpolation method in GIS. Figure 6 depicts zones of upward gradient in purple, and downward gradient in yellow. While the direction of vertical gradient can be mapped, the magnitude cannot be quantified because bedrock wells are typically open hole, and therefore open to water-bearing fractures at multiple depths.

Upward groundwater flow is inferred to occur in areas where the static water elevation in bedrock is greater than the static water elevation in overburden (purple areas), and vice versa for downward groundwater flow (yellow areas). The arrows on Figure 6 depict the relative direction of vertical groundwater flow.

4.4.3 Identifying where the presence of a vadose zone exists beneath a stream

To assess if a vadose zone exists beneath a stream, we compared the contoured groundwater elevations to stream elevations. The elevations of streams were determined by extracting elevation data from the DEM along the stream nodes from the Freshwater Atlas dataset. A vertical tolerance value of 3 m was imposed to help reduce the possibility of mis-identifying the presence of a vadose zone beneath a stream reach. Therefore, the groundwater elevation surface had to be more than 3 m beneath the elevation of the stream for a vadose zone to be considered to exist beneath the stream. A visual comparison using tolerance values ranging between 1 m and 5 m was conducted, and only minor differences were observed as to the mapped location of a vadose zone beneath streams.

4.4.4 Mapping unconsolidated thickness

Unconsolidated sediment thickness was described as the thickness of unconsolidated sediments encountered in wells. This is the thickness encountered during drilling and includes a variety of sediment types (sand and gravel, till, silt, clay) and is not the total thickness of unconsolidated sediments at a given location, i.e., the well may not be drilled all the way through the overburden to bedrock. Unconsolidated thickness was determined at each well from the GWELLS database. In terrain polygons where the dominant materials are described as veneer of surficial material (e.g., Mv or Cv) or bedrock, the unconsolidated thicknesses were assumed to be < 1 m. Unconsolidated thickness is presented in Figure 7.

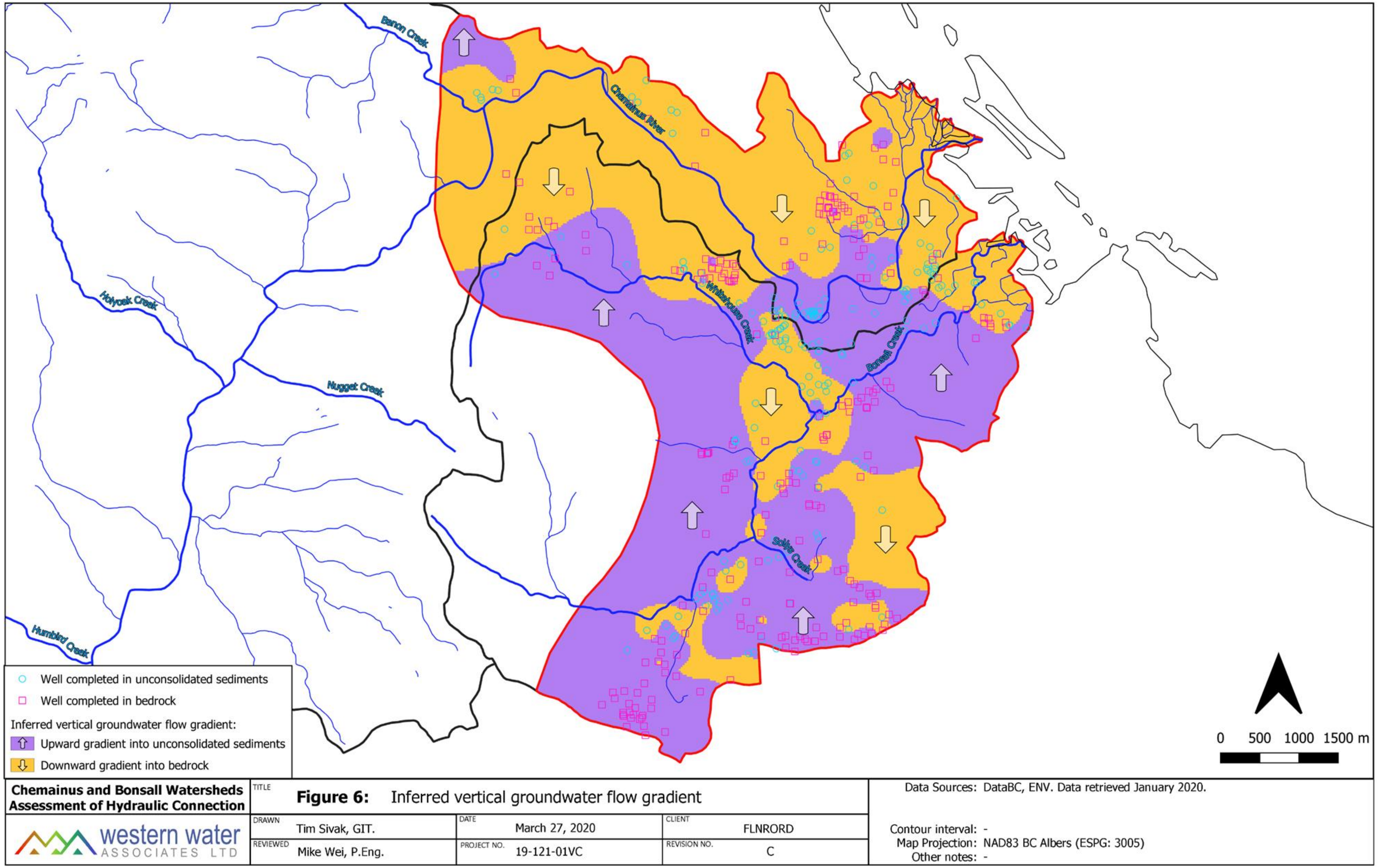


Figure 6: Inferred vertical groundwater flow gradient.

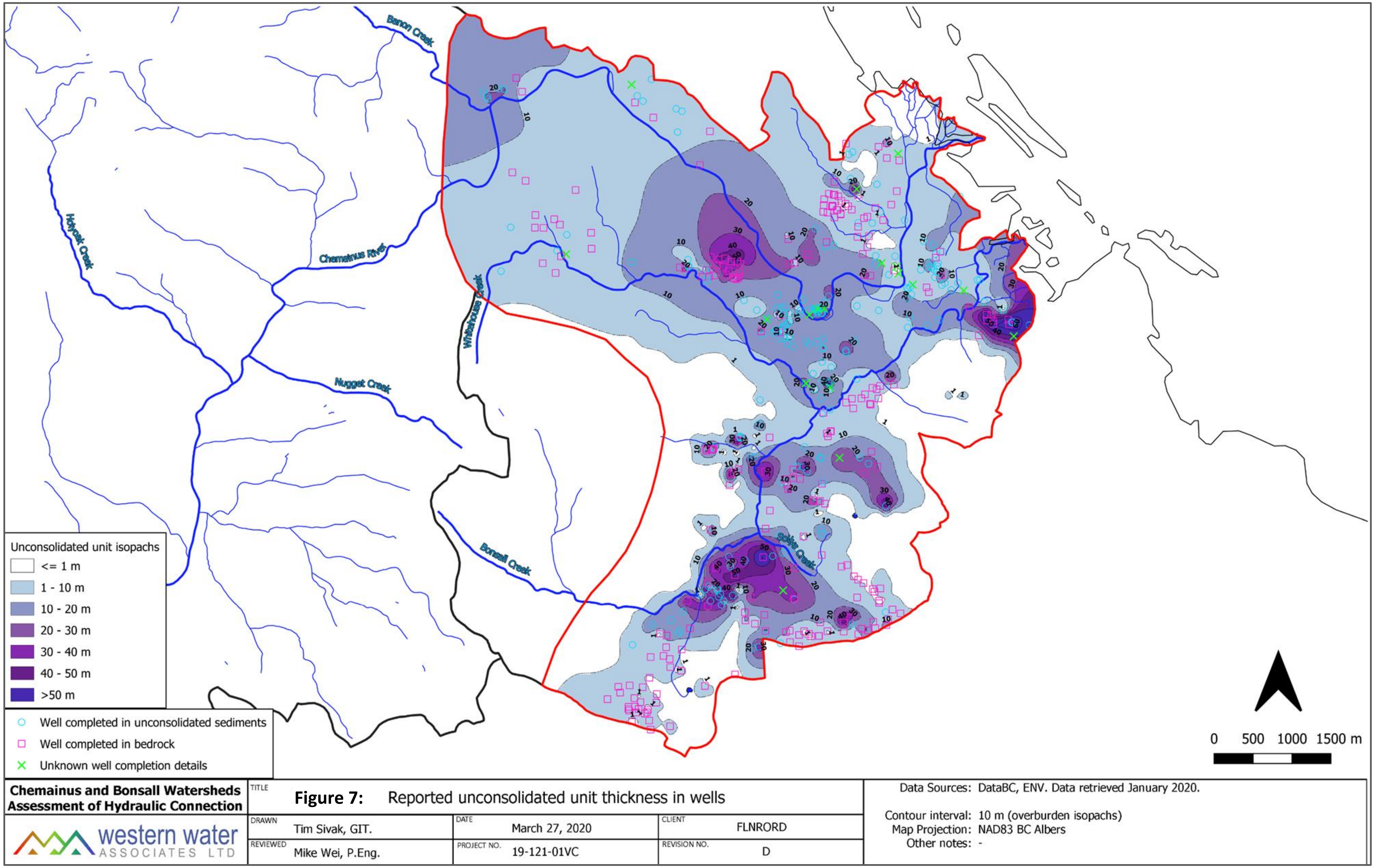


Figure 7: Reported unconsolidated thickness in wells.

4.4.5 Mapping low permeability sediment thickness

Low permeability unconsolidated sediments that are expected to impede groundwater flow include glacial till, clay and silt. Till is comprised of a broad range of glacially-derived materials which reflect depositional history and geological setting. Till can impede the flow of groundwater and act as a confining sediment if it contains appreciable amounts of silt and clay. Clay and silt deposits in the absence of coarser materials typically form in quiet-water environments such as lakes. In this study, sediments classified as 'till', 'silt' or 'clay', are considered confining sediments, meaning that they are expected to have low permeability and therefore impede groundwater flow. Confining thickness is presented in Figure 9.

Confining sediment thicknesses for each well point were contoured using multilevel B-spline method using the anchor point method (described in Section 4.4 above). The confining sediment isopachs are based on material thicknesses encountered during drilling. Confining sediments were lumped together into a single overall thickness at each well point; it was not feasible to correlate individual layers between wells.

To consider if a stream had completely down-cut through the confining sediments or not, only confining sediments located above the well screen or final completed well depth were used in the mapping. For wells not drilled into bedrock, any confining sediments that exist below the depth of the well would not be recorded or mapped.

4.4.6 Identifying stream reaches where hydraulic connection is likely and unlikely

We used the groundwater elevations contoured from wells completed in unconsolidated sediments and bedrock as well as low permeability sediment thickness isopachs, to delineate stream reaches where hydraulic connection is likely. As noted above, hydraulic connection is considered likely along stream reaches where mapping indicates an absence of a vadose zone and low permeability sediments beneath a stream.

The data limitations and associated uncertainty are described in Section 4.5, and further explanation of the methodology is described in Section 5.4.

4.4.7 Delineating groundwater management areas

Groundwater management areas help inform allocation and management of water rights within the Chemainus and Bonsall watersheds. GIS mapping, using available well records, help identify reaches of the streams within the study area that are believed to be essentially disconnected from water in the underlying unconsolidated and bedrock aquifers.

Groundwater management areas were delineated separately for the unconsolidated and bedrock aquifers, by establishing a point of delineation at the downstream end of major open stream reaches. A major reach of connected stream can include short (<500 m in length) disconnected reaches (e.g., although short disconnected reaches occur along the Chemainus River between the Chemainus Road bridge and approximately 1 km upstream of the Highway 1 bridge, that entire reach is considered connected). Points of delineation were established along the mainstem of the Chemainus River and Bonsall Creek because major connected stream reaches occur there and not in the tributaries. Groundwater elevation contours in the unconsolidated and bedrock aquifers were used to guide the area delineation.

Along the Chemainus River, three points were established to delineate three management areas: 1) in the upper reach near River Road, 2) near the Chemainus Road bridge, and 3) at the mouth. These same three points were used to delineate management areas for both the unconsolidated and bedrock aquifers.

In the Bonsall watershed, two points of delineation were established for delineating two management areas for each of the unconsolidated and bedrock aquifers. The point at the mouth of Bonsall Creek was used to delineate management areas for both aquifers. But further upstream, the points of delineation for the unconsolidated and bedrock aquifers were established at slightly different locations. For the unconsolidated aquifer, the point of delineation was established upstream of the confluence with Whitehouse Creek because that is the lowest point along the open stream reach. For the bedrock aquifer, the point was established slightly upstream at the confluence with Richardson Brook because mapping indicated that the stream reach between Whitehouse Creek and Richardson Brook may be disconnected from the groundwater in the bedrock. The physical basis for why the stream reach below Richardson Brook is disconnected from the bedrock aquifer may need further exploration, beyond the scope of this desktop study. For example, the location accuracy of bedrock wells in an area with steep slopes may affect the interpretations of mapped groundwater elevations in bedrock in a local area.

In the lowest reaches of Chemainus River and Bonsall Creek, the hydraulic gradient is so flat and there is not enough data to define the groundwater elevation contours with any degree of confidence. The groundwater management area boundaries here were delineated based simply on the mid-distance between open reaches of Chemainus River and Bonsall Creek (described in more detail in Section 5.5).

4.5 Data & Analysis Limitations, and Sources of Uncertainty

A large amount of geospatial data previously compiled by others formed the basis of this desktop study. It was not part of the scope of work to conduct any validation or quality control checks on the spatial datasets provided; unless otherwise stated, the spatial datasets were taken at face value for analysis and interpretation. Combining geospatial datasets generated at different scales can also produce errors in positional accuracy and precision. To partially address the limited accuracy in well, stream and ground elevations, tolerance limits were imposed in assessing where streams are separated from the underlying aquifer by a vadose zone or low permeability sediments (Sections 5.1 and 5.4).

GIS-based maps of information derived from water well records, such as groundwater elevations and sediment thicknesses, can create an illusion of a high degree of accuracy. However, the maps were based on available data (a total of 457 well records), whose distribution is variable spatially and with depth. The information on the maps was better constrained in areas of higher well density, and more uncertain in areas of lower well density.

As noted above, the GWELLS database formed our main hydrogeological data source. A limitation of the well dataset is that the well data contain records that are incomplete and/or contain missing or erroneous data, including incomplete lithology, missing static water level and inexact well location. As mentioned in Section 4.4.7 above, in steeply sloping bedrock areas, imprecise well locations could also affect calculation and mapping of groundwater elevations.

In relying on the reported static water levels in the well records, we assume they represent average conditions over the time period of the data. Static water levels recorded in bedrock wells may still have been recovering when measured by the driller at the end of well development and the true static water level at the completion of drilling may be under-estimated, at least for some bedrock wells, making the bedrock water level data more uncertain than overburden well data. Static water levels were also compiled from records of wells drilled over decades in time, in different seasons and to varying depths. The groundwater elevation maps produced in this study represent a composite 2-dimensional steady-state picture over time and seasons. Any temporal trends in groundwater elevations would not be discernable from the groundwater elevation maps. The relative vertical groundwater gradient between (and within) the unconsolidated sediments and bedrock was characterized in this study to support our hydrogeological conceptual model; however, quantifying the magnitude of vertical flow was out of the scope of the study. The reader should keep in mind that the groundwater management areas were largely delineated based on groundwater elevation contours of available data. The areas are subject to future modifications as more groundwater elevation data become available within the watershed.

The scale and desktop nature of the study and the fact that the hydrogeological data is from well records mean smaller scale geological changes within the aquifers and underneath streams will be overlooked. The maps of groundwater elevations and sediment thicknesses represent a picture at the sub-watershed scale but not local site scale. Well records may not record groundwater perched locally above the main water table. Locally perched groundwater can supply flow to streams, even in the dry season. Saturated and permeable sediments of limited extent may also exist and provide flow to streams, but these sediments may not be mappable because of the limited density of wells and scale of the study. These sources of groundwater may be localized but can play an important role in providing local baseflow to streams in the study area, even to streams mapped as being perched above the main water table.

5. RESULTS AND DISCUSSIONS

5.1 Groundwater Elevation Maps

Groundwater elevations for unconsolidated sediments and for bedrock are shown separately in Figure 5. Groundwater flow directions in both the unconsolidated sediments and in bedrock (inferred from the groundwater elevation contours) are generally from topographic highs to topographic lows, towards the mouths of the Chemainus River and Bonsall Creek. The highest groundwater elevations are found in the upstream part of the study area. Two other areas of high groundwater elevations are the ridge south of Fuller Lake and the steep rocky slopes of Mount Richard north of Sollys Lake. The other areas of localized groundwater elevation anomalies are likely artifacts from contouring data spanning over years and seasons.

Groundwater elevations within the unconsolidated sediments range from over 80 m above sea level (asl) in the headwaters of the Whitehouse Creek watershed and 80 m asl on the rocky slope north of Sollys Lake to ~0 m asl near the mouths of Chemainus River and Bonsall Creek (see Figure 5). Wells completed in unconsolidated sediments are clustered primarily around Highway 1 near the community of Westholme and along the valley bottom.

Groundwater elevations within bedrock range from over 80 m asl in the upper part of the Chemainus watershed (within the study area) and over 140 m asl in the headwaters of the Bonsall watershed to ~ 0 m asl near the mouths of the Chemainus River and Bonsall Creek (Figure 5). More of the bedrock wells are located in topographically higher areas than the wells in overburden.

Figure 8 graphically shows what Figure 5 indicates; that the relationship between the ground surface elevation and the groundwater elevation at the wells is strongly correlated. The coefficient of determination (r^2) for this relationship was calculated to be between about 0.86 and 0.92. Groundwater elevations are subdued representations of topography and groundwater flow in the unconsolidated sediments and fractured bedrock appear to be topographically driven.

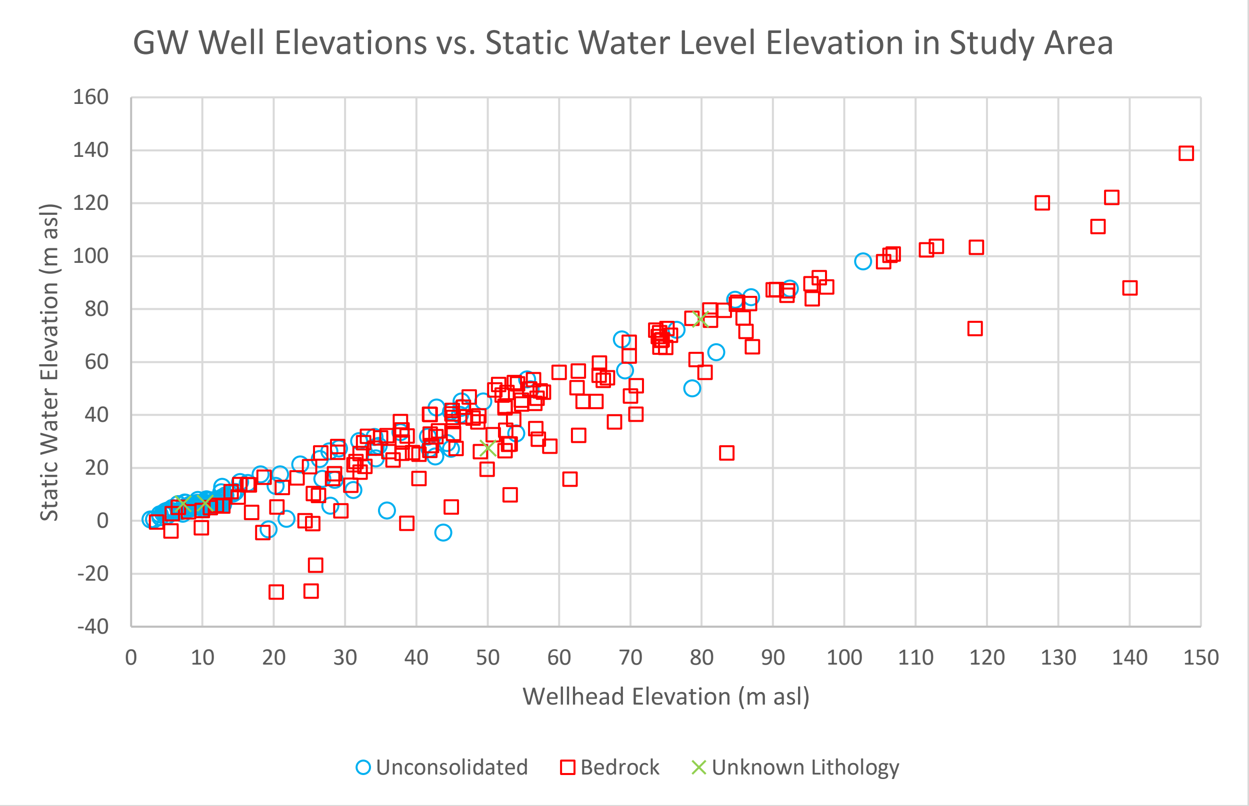


Figure 8: Well elevations vs. static water level elevations in the study area.

A comparison of the groundwater elevations in unconsolidated sediments and bedrock (Figure 5) shows that within much of the Bonsall watershed except at the mouth, groundwater elevations are typically higher in bedrock than in the unconsolidated sediments, indicating a propensity of upward groundwater flow from the underlying bedrock to the overlying unconsolidated sediments. In much of the Chemainus watershed within the study area, the reverse appears to be true. The groundwater elevations in bedrock appear to be lower than in unconsolidated sediments along most of the Chemainus River (excluding the segment of the Chemainus River from just upstream of the highway to just downstream of the rail bridge) indicating a downward direction of groundwater flow gradient along the Chemainus River. This is not surprising given the much higher relief of the bedrock hills in the Bonsall watershed than in the Chemainus watershed.

The direction of groundwater flow in the lower part of the study area (i.e., northeast of the junction of Mt. Sicker Road and Chemainus Road) is difficult to infer from the groundwater contours because of the impreciseness of the DEM and reported groundwater levels and the flat topography of the floodplain. Surveyed elevations of the wells and groundwater levels measured over the same time period are needed to map groundwater elevations in this part of the study area.

5.2 Presence of a Vadose Zone Beneath Stream Reaches

Figure 5 also shows areas where the elevations of the streams are significantly above the mapped groundwater elevations in unconsolidated sediments and bedrock (reaches of the water courses shaded in red). A vadose zone is inferred to exist beneath the stream reaches where the groundwater elevations beneath the stream are deeper (>3 m) than the stream. Along these stream reaches the groundwater and the water in the stream are disconnected.

5.2.1 Chemainus watershed

Within the study area, a vadose zone does not appear to exist underneath much of the main stem of the Chemainus River. Mapping suggests a vadose zone exists along much of Venner Brook that flows into the Chemainus River near Ashcroft Road and Chemainus Road.

5.2.2 Bonsall watershed

Mapping shows that a vadose zone exists along much of Bonsall Creek except at its mouth and along a reach upstream of the confluence with Whitehouse Creek. A vadose zone does not appear to exist in the reach of Bonsall Creek between the confluence of Sollys Creek and Whitehouse Creek. However, the reach between Richardson Brook and Whitehouse Creek appears disconnected based on groundwater elevations in bedrock wells being lower than the stream along that reach.

Mapping also shows that a vadose zone exists underneath significant lengths of Whitehouse Creek and all first order tributaries within the Bonsall watershed.

The absence and presence of a vadose zone along the Bonsall mainstem can not be explained with certainty at this time. The change from absence to presence may reflect changes in gaining and losing stream reaches. For example, where Bonsall Creek emerges from a relatively narrow valley at Richardson Brook and Whitehouse Creek into the broader Chemainus-Bonsall valley, groundwater flow underneath Bonsall Creek may diverge to the north and northwest to fill the alluvial sediments of the broader valley resulting in the existence of a vadose zone underneath that reach of Bonsall Creek.

Reaches where mapping shows a vadose zone existing in one aquifer and not the other may be reflecting artesian conditions (upward gradient) in the bedrock aquifer (e.g., along Sollys Creek where a vadose zone exists in the unconsolidated but not bedrock aquifer) or downward gradient (e.g., between Richardson Brook and Whitehouse Creek where a vadose zone exists in the bedrock but not unconsolidated aquifer).

5.3 Thickness of Unconsolidated Sediments

Figure 7 and Figure 9 show the thickness of unconsolidated sediments and the thickness of (likely low permeability) confining sediments, respectively. Unconsolidated sediments underlie the study area in the tributary valleys and lowlands below a ground elevation of about 150 m asl. Unconsolidated sediment thickness reaches up to about 60 m in the Whitehouse Creek and Sollys Creek areas and up to about 70 m at the mouth of Bonsall Creek. Above ~150 m elevation, unconsolidated sediments are generally <1 m thick or absent (see Figure 7).

Low permeability sediments between ~100-200 m asl comprise mostly till. Low permeability sediments below about 100 m elevation are mostly marine deposits (silt, clay). Mapping suggests that low permeability sediments thicker than 5 m only occur in patches and reach up to about >40 m thick in localized areas within the Chemainus and Bonsall watersheds. Thick pockets of low permeability sediments are present in the area upstream of the confluence of Sollys Creek and Bonsall Creek, along Richardson Brook, at the mouth of Bonsall Creek, and in the area between Whitehouse Creek and Chemainus River (Figure 9).

Mapping shows that within the Bonsall watershed, low permeability sediments of between 1 and 5 m thick underlie much of Whitehouse Creek, Sollys Creek, Richardson Brook as well as a significant length of Bonsall Creek. Low permeability sediments >1 m thick appear absent along Bonsall Creek, in the upper reaches of the study area, along the reach between Richardson Brook and Sollys Creek, and at the mouth.

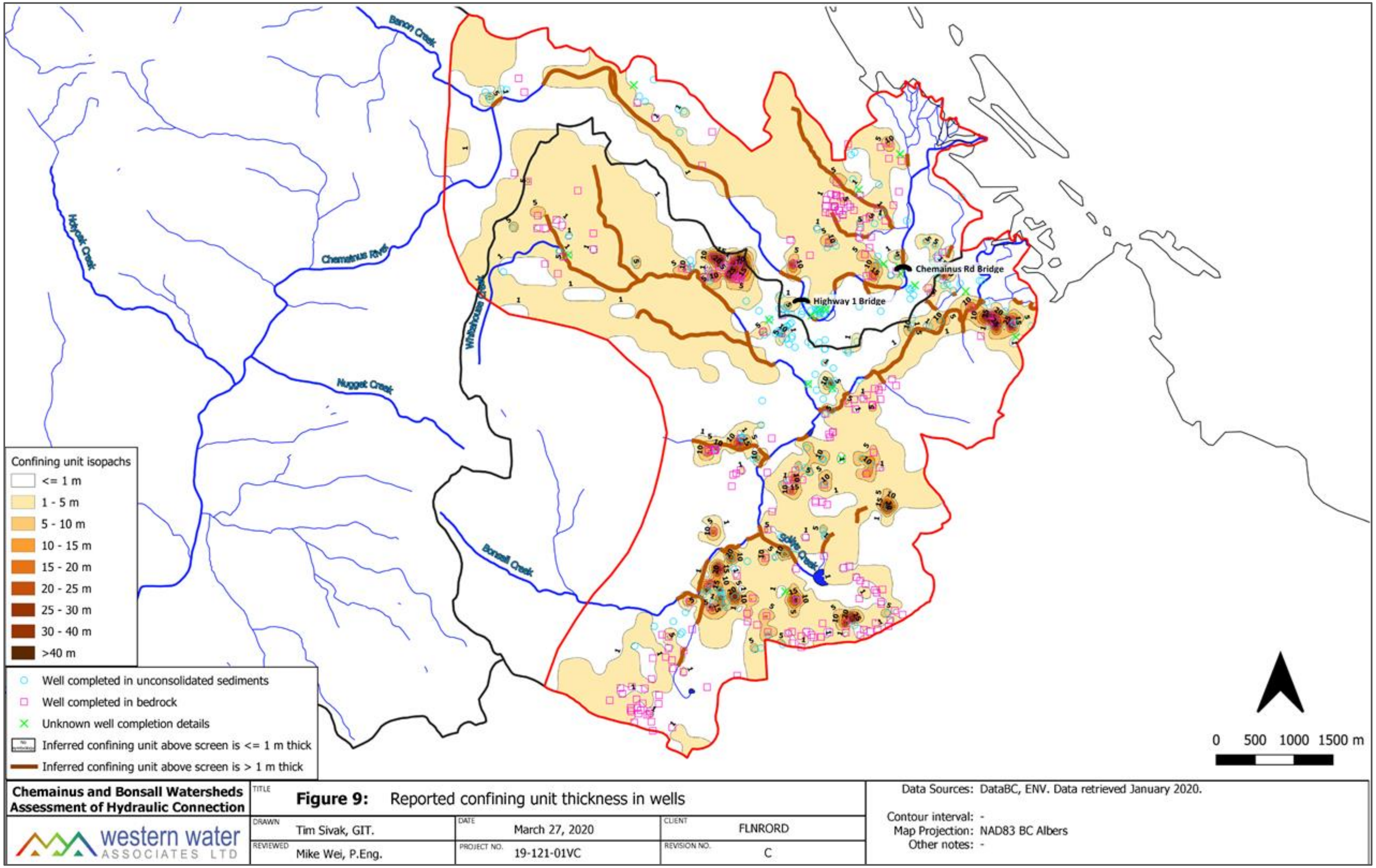


Figure 9: Reported confining sediment thickness in wells.

Patches apparently absent of low permeability sediments around isolated wells shown in Figure 9 may indicate the aquitards are not continuous (i.e., the confining layer is absent), or may reflect the limited depth of drilling at that location (e.g., well was not drilled or excavated/dug to the confining sediments), or are a result of the lack of descriptive lithology in older well records.

5.3.1 Chemainus watershed

Mapping shows the reach of the Chemainus River between River Road and approximately 1 km upstream of the Highway 1 bridge is underlain by low permeability sediments of 1-5 m thickness. Within the study area, the only other locations where low-permeability sediments appear to be beneath the river are short reaches further downstream.

Venner Brook, draining into Chemainus River downgradient of the Chemainus Road bridge, appears to be underlain by low-permeability sediments along much of its length until its confluence with the Chemainus River.

5.3.2 Bonsall watershed

Bonsall Creek is underlain by recent fluvial or alluvial deposits (generally higher permeability) upstream of Westholme, and marine deposits overlying till downstream of Westholme (low permeability), until the mouth where a confining unit is absent. Low-permeability sediments underlie Bonsall Creek upstream of the confluence with Sollys Creek.

Mapping shows low-permeability sediments underlie much of Sollys Creek and Richardson Brook. Even though much of Sollys watershed is directly underlain by fluvial deposits (see surficial geology in Figure 2), only short reaches along Sollys Creek near Sollys Lake have been mapped as absent of low-permeability sediments. This is because the upper fluvial unit is thin and unconsolidated wells in the area are mostly completed into sand and gravel underneath confining sediments.

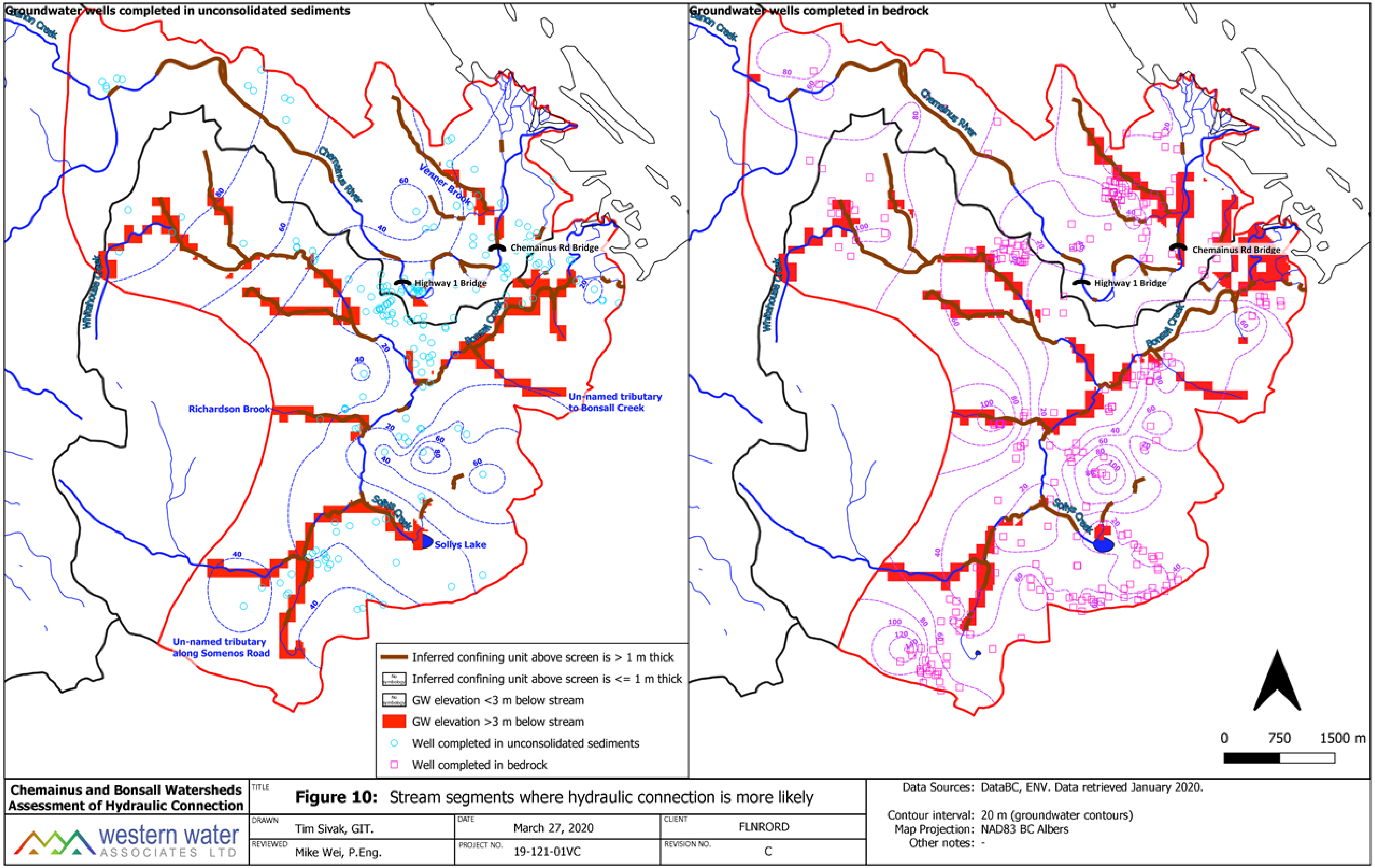
From surficial geology mapping, the mainstem of Whitehouse Creek and its tributaries are underlain by marine deposits, till, and bedrock (see surficial geology in Figure 2) over the majority of its reach. These low-permeability sediments do not appear to underlie Whitehouse Creek in the headwaters of some of its tributaries and other short reaches in the upper watershed.

5.3.3 Stream reaches where hydraulic connection with groundwater is likely and unlikely

Figure 10 shows stream reaches underlain by low-permeability sediments greater than 1 m thick (brown), superimposed over the map that show reaches where the mapped groundwater elevation is interpreted to be >3 m below the stream (red squares) to identify stream reaches that are considered disconnected from the underlying groundwater (i.e., where there is brown and/or red shading on the water course); the remaining unshaded reaches show those sections of streams that are connected and where streamflow depletion can occur.

Within the study area, hydraulic connection is considered unlikely along the following:

- Venner Brook that flows into Chemainus River just downstream of the Chemainus Road bridge;
- Much of Whitehouse Creek;
- The un-named tributary to Bonsall Creek at Bonsall Road;
- Richardson Brook tributary to Bonsall Creek at Hidden Hills Road;
- Sollys Creek and Sollys Lake; and
- Bonsall Creek and the un-named tributary along Somenos Road upstream of the confluence with Sollys Creek.



Chemainus and Bonsall Watersheds Assessment of Hydraulic Connection

western water ASSOCIATES LTD

TITLE **Figure 10:** Stream segments where hydraulic connection is more likely

DRAWN Tim Sivak, GIT.

DATE March 27, 2020

CLIENT FLNRORD

REVIEWED Mike Wei, P.Eng.

PROJECT NO. 19-121-01VC

REVISION NO. C

Data Sources: DataBC, ENV. Data retrieved January 2020.

Contour interval: 20 m (groundwater contours)

Map Projection: NAD83 BC Albers

Other notes: -

Figure 10: Stream segments where hydraulic connection is more likely.

In the above stream reaches, well pumping is not expected to affect flows in these streams.

In contrast, the following reaches appear likely to be hydraulically connected to groundwater in the underlying unconsolidated and bedrock aquifers:

Chemainus River

- The Chemainus River at its mouth;
- The stretch of the Chemainus River from just upstream of the confluence with Venner Brook, approximately 1 km upstream of the Highway 1 bridge (this long stretch of the Chemainus does contain short (<500 m) segments where low permeability confining materials >1 m underly the river); and
- Chemainus River upstream of River Road.

Bonsall Creek

- The extreme lower reach of Bonsall Creek at its mouth; and
- The Bonsall Creek mainstem upstream of the confluence with Whitehouse Creek to the confluence with Sollys Creek.

5.4 Conceptual understanding of hydraulic connection within the study area

The results of surficial geology mapping and groundwater flow interpretations allow a conceptual understanding of hydraulic connection within the study area to be developed. As noted previously, groundwater in the study area flows towards the mouth of the Chemainus River and Bonsall Creek, and ultimately discharges to the ocean either directly or via those two streams. The conceptual model of hydraulic connection between groundwater and surface water in the study area is summarized in the following sections.

5.4.1 Hydraulic connection between the unconsolidated and bedrock aquifers

The inferred upward gradient in much of the Bonsall watershed (see Figure 6) suggests groundwater in the bedrock aquifer in the Bonsall watershed may also discharge into the overlying unconsolidated aquifer (hydraulic connection between the aquifers) before reaching the mouth of Chemainus River and Bonsall Creek. The relatively higher groundwater elevations in bedrock are generated from the higher bedrock relief within and beyond the study area. Actual interflow between the unconsolidated and bedrock aquifers can occur in areas where mapping shows low permeability sediments are absent (Figure 9).

5.4.2 Streamflow depletion from well pumping and points of hydraulic connection to streams

Pumping of groundwater from the unconsolidated and bedrock aquifers in the study area can deplete stream flows along the Chemainus River and Bonsall Creek where stream reaches are connected (no presence of a vadose zone nor low permeability sediments directly beneath the stream). Where a well is located along a connected stream reach, streamflow depletion caused by a pumping well is interpreted to occur along that connected stream reach (the location of occurrence is referred to here as the point of hydraulic connection (PoHC)).

Where a well is located near a stream reach that is considered disconnected (presence of a vadose zone or low permeability sediments directly underlying the stream), the PoHC for the well is interpreted to be to the next connected stream reach downgradient. The main reason for extending the PoHC downgradient is because pumping is expected to intercept groundwater that would otherwise be flowing downgradient to a connected stream reach.

For wells in the lower Bonsall watershed where hydraulic connection along much of the lower reach of Bonsall Creek is unlikely, the PoHCs for those wells are interpreted to be at the mouth of Bonsall Creek. For wells in this area located between Bonsall Creek and Chemainus River, another PoHC may be made also to the nearest connected stream reach in the Chemainus River in the adjacent watershed because pumping wells between the Chemainus River and Bonsall Creek in this area could deplete not only Bonsall Creek but the lower reach of the Chemainus River.

With respect to the process of streamflow depletion, Barlow and Leake (2012) notes that depletion of streamflow includes both induced infiltration and interception of groundwater flow to the stream. However, unless a well is adjacent to the stream bank and the pumping drawdown cone extends to the stream to induce infiltration, the main process of streamflow depletion for wells farther away from the stream is expected to be via the process of interception.

5.5 Groundwater management areas

For discussion purposes, we identify three management areas for the Chemainus watershed and two areas for the Bonsall watershed in both the unconsolidated and bedrock aquifers. The management areas are named based on their locations within the Chemainus and Bonsall watersheds. Management areas are shown in Figure 11 and discussed below.

5.5.1 Unconsolidated aquifer

Chemainus upper (CH-UP) (UNC): This area, delineated from a point on the Chemainus River near River Road, covers the upper part of the Chemainus watershed in the study area and includes the upper edge of the Whitehouse sub-watershed. Any wells completed into the unconsolidated aquifer in this area have the potential to deplete Chemainus River to the point at River Road. Delineation was based on only a limited number of groundwater elevation data in the area and can be modified in the future when more groundwater elevation data become available.

Chemainus middle (CH-MID) (UNC): This area, delineated from the CH-UP (UNC) management area to the point at the Chemainus Road bridge, is the largest of the identified groundwater management areas. This area extends into the Whitehouse sub-watershed (part of the Bonsall watershed). The reason for this is because Whitehouse Creek and the middle reach of Bonsall Creek are considered to be largely disconnected from the underlying groundwater. Any wells completed into the unconsolidated aquifer in this area are interpreted to have potential to deplete flow in Chemainus River to the Chemainus Road bridge.

Chemainus lower (CH-LOW) (UNC): This area is delineated from the mouth of the Chemainus River and covers the remaining part of the Chemainus watershed outside of the Chemainus upper CH-UP (UNC) and CH-MID (UNC) management areas. Unconsolidated wells in this area have potential to deplete streams within this management area but not further upstream.

Bonsall upper (BO-UP) (UNC): This area is delineated from a point just upstream of the confluence with Whitehouse Creek, based on groundwater elevation contours. Wells completed into the unconsolidated aquifer in this area can potentially deplete Bonsall Creek upstream of the confluence with Whitehouse Creek.

Bonsall lower (BO-LOW) (UNC): This area is delineated from the mouth of Bonsall Creek and is relatively narrow because groundwater is not likely connected to the middle part of Bonsall Creek. Wells in this area, therefore, are mostly likely connected to the extreme lower reach of Bonsall Creek. Wells west of this area in the Bonsall watershed are interpreted to potentially deplete the Chemainus River by intercepting groundwater flow to it (therefore included in the CH-MID (UNC) management area).

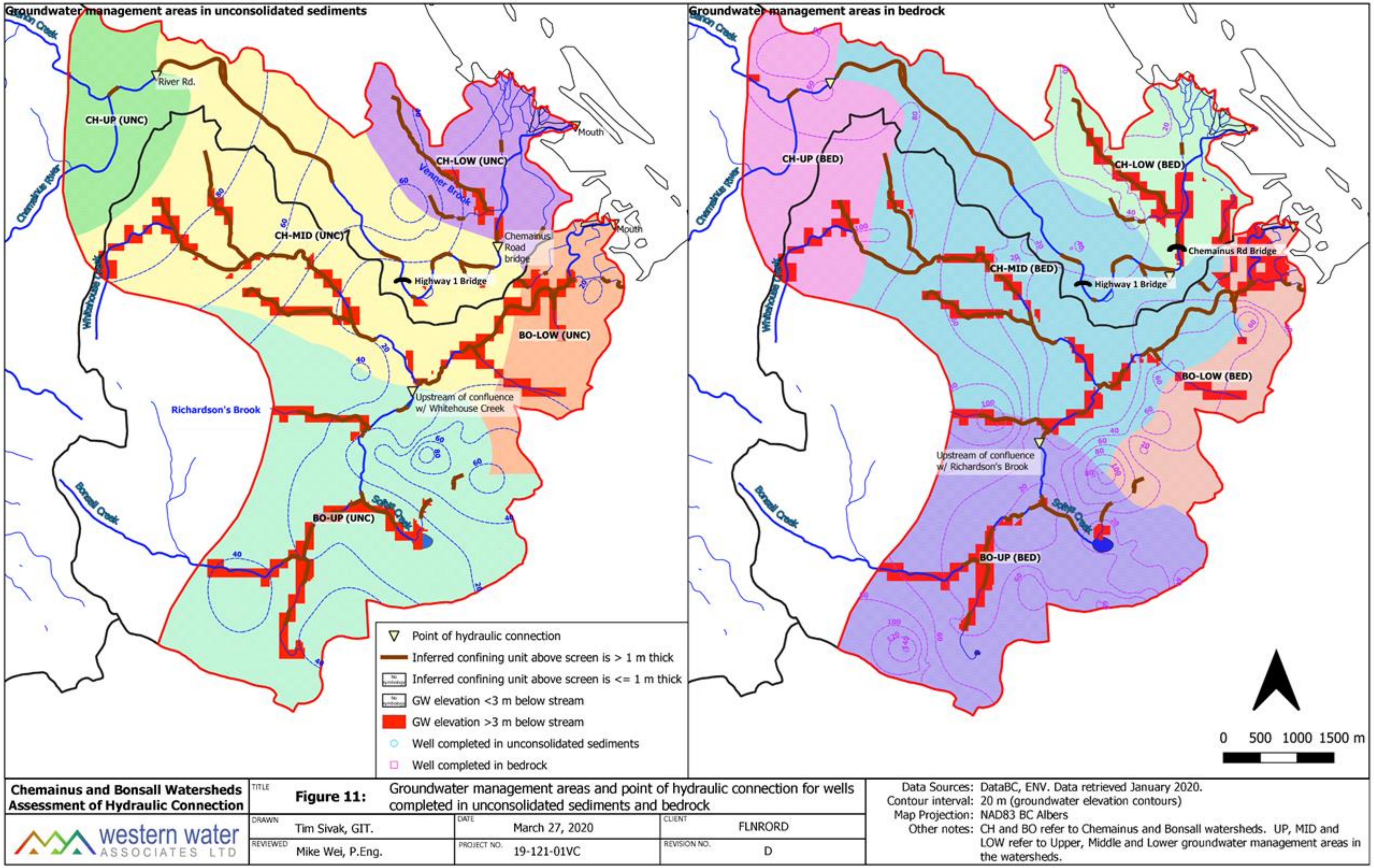


Figure 11: Groundwater management areas and point of hydraulic connection for wells completed in unconsolidated sediments and bedrock.

5.5.2 Fractured bedrock aquifer

Management areas for the bedrock aquifer underlying the Chemainus watershed are delineated using the same PoHCs as for the unconsolidated aquifer (near River Road, Chemainus Road Bridge, and mouth of the Chemainus River. The resultant three zones - CH-UP (BED), CH-MID (BED), and CH-LOW (BED) are similar in shape as CH-UP (UNC), CH-MID (UNC) and CH-LOW (UNC), respectively. The slight difference in areas is because the groundwater elevation contours in the unconsolidated and bedrock aquifers are slightly different, which may in part be due to the spatial distribution of the unconsolidated and bedrock wells and artifact of contouring.

Management areas for the bedrock aquifer underlying the Bonsall watershed are delineated based on two PoHCs, at the mouth of Bonsall Creek and upstream of the confluence with Richardson Brook (at Hidden Hills Road). The latter differing slightly from the PoHC for the unconsolidated aquifer. Again, the different shapes of the management areas for the bedrock aquifer in the Bonsall watershed result from the difference in inferred groundwater flow patterns.

5.5.3 Discussion of Groundwater Management Areas

The nature of the relief and topography of the study area, extent and thickness of low-permeability sediments, presence of a vadose zone, and the fact that the Chemainus River and tributary streams have (in areas) down-cut through the confining sediments, all influence which stream reaches are likely hydraulically connected or not. The distribution of the wells then determines which of those reaches groundwater pumping is expected to affect.

The groundwater management areas delineated for the unconsolidated and bedrock aquifers in the study area provide a basis for viewing which wells may deplete which major reach of Chemainus River and Bonsall Creek. The main reason why the CH-MID (UNC and BED) management areas extend into parts of the Bonsall watershed is because the mapping indicates that a significant length of Whitehouse Creek and middle reach of the Bonsall mainstem are disconnected from the underlying groundwater and groundwater in these parts of the watershed is interpreted to discharge to Chemainus River instead. Because of a lack of data, it was not feasible to consider minor connected and disconnected stream reaches in delineating groundwater management areas.

In the lower part of the study area, the hydraulic gradient is so low that groundwater flow in this part of the watershed has not been well defined. Delineation of groundwater management areas in this part of the watershed is less based on inferred groundwater flow direction and more on distances from connected stream reaches. For example, the boundary between CH-MID (UNC) and BO-LOW (UNC) is based on a line that is approximately mid-way between Chemainus River and the lower reach of Bonsall Creek near its mouth where hydraulic connection is likely. Any wells completed into the unconsolidated aquifer near this boundary may deplete both stream reaches but wells located within the CH-MID (UNC) zone is expected to impact Chemainus River more than Bonsall Creek, and vise versa, simply based on the relative distances between the two reaches of streams where connection is likely.

5.5.4 Interpreting groundwater management areas

The groundwater management areas delineate locations within the watershed upstream or upgradient of a critical point along the Chemainus or Bonsall mainstem where well pumping could affect streamflow to that point on the stream. The management areas for the unconsolidated and bedrock aquifers are similar because of similarities in the groundwater elevation contours and in the same points of delineation, except for in the upper reach of Bonsall Creek.

Delineating groundwater management areas for both the unconsolidated and bedrock aquifers means, in any given area, pumping of groundwater from both aquifers can deplete streamflow and should be considered. For example, if streamflow depletion from well pumping in the upper Chemainus River near River Road is of interest, area CH-UP (UNC) and CH-UP (BED) both help identify the unconsolidated and bedrock wells located within the management areas that could deplete streamflow in the Chemainus River near River Road.

If the interest of streamflow depletion is further downstream, such as at the Chemainus Road bridge, the wells in zones CH-MID (UNC & BED) and CH-UP (UNC & BED) could potentially contribute to streamflow depletion; interest in streamflow depletion further downstream must take into account pumping from wells in all the management areas upstream.

Understanding that the management zones are largely delineated using groundwater elevation contours allows sub-areas within a management zone to be similarly delineated if streamflow concerns occur anywhere along the Chemainus or Bonsall mainstem. Figure 12 demonstrates how sub-areas are delineated within the study area. If a concern for streamflow depletion develops along the middle reach of the Chemainus River, say just upstream of the Highway 1 bridge, the point of interest shifts upstream from the Chemainus Road bridge and a smaller sub-management zone upstream can be delineated using the groundwater elevation contours and flow lines for both aquifers. The lower boundary of the sub-area is a flow line and not the original boundary line for the management area because the point of interest has shifted upstream. The upgradient management zone, in this case Zone CH-UP, could potentially contribute to streamflow depletion, so it is included in the sub-management zone.

This study identified the main reaches where depletion of stream flow from well pumping is interpreted to occur along the Chemainus River and Bonsall Creek. However, the magnitude of streamflow depletion can only be quantified once the volume of groundwater diversion is known and the aquifer hydraulic properties (transmissivity, storativity, and specific yield) are characterized. In addition, a streamflow depletion factor may also be important if the timing of stream flow depletion is critical.

Finally, the hydraulic connectivity in the factsheets for Aquifers 171 to 175 (ENV, 2019a to e) should be interpreted with care. Firstly, note number 1 in reference to how connectivity was determined is not likely “Based on broad regional assessment”, but rather based on aquifer type. Other than Aquifer 172 (along the Chemainus River), the other four aquifers are noted in the factsheets as being “not likely” connected. While they may not be hydraulically connected to the reach of stream immediately above them, pumping from Aquifers 174, 171, 175 and 173 will likely intercept water to deplete streams further down-gradient.

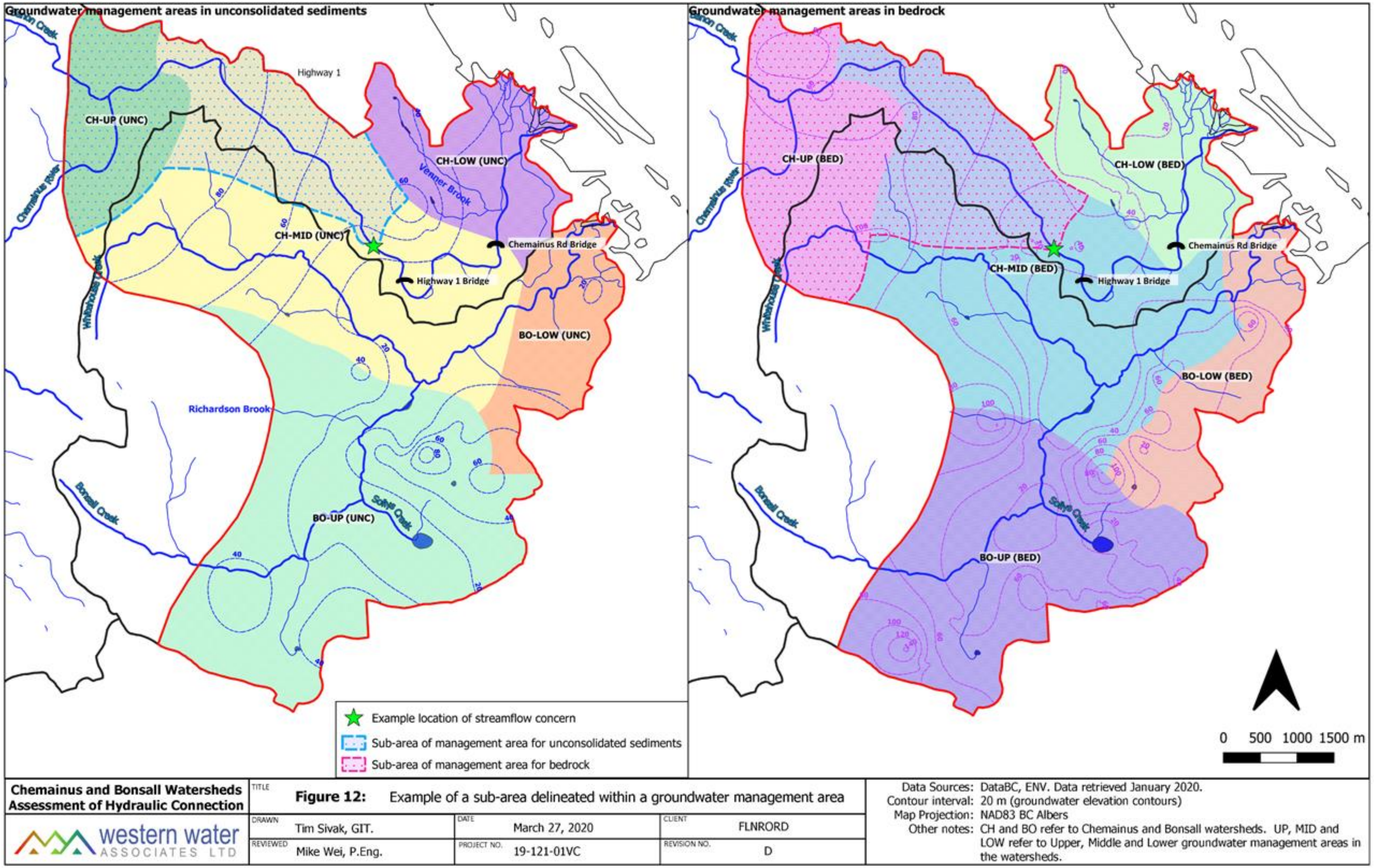


Figure 12: Example of a sub-area delineated within a groundwater management area.

6. RECOMMENDATIONS FOR FURTHER WORK

The following are recommendations to improve on the current understanding of the nature of hydraulic connection and protection of the water resource in the study area.

6.1.1 Technical studies

- Conduct field work during late summer (low-flow period) to:
  - Inspect tributary stream reaches to check if they exhibit ephemeral or perennial flow; mapping suggests much of the stream reaches along tributaries to the Chemainus River and Bonsall Creek are disconnected from the underlying water table and therefore may not receive significant baseflow from groundwater.
  - Identify stream reaches where hydraulic connection is likely by measuring, for example, stream temperatures and electrical conductivity along the streams.
- Conduct a field-based assessment in the lower reach of the Chemainus River and Bonsall Creek, including elevation survey of the wells and measure groundwater levels to more accurately characterize groundwater elevations, flow directions, inflow of groundwater into both streams and significance of groundwater flow between the two watersheds in that lower reach.
- Confirm well locations in the Whitehouse Creek to Sollys Creek area to more accurately map groundwater elevations to assess hydraulic connection of Bonsall Creek in that local area.
- Establish and pump or slug test multilevel observation well(s) in the unconsolidated and bedrock aquifers near Bonsall Creek above the confluence with Sollys Creek, between Richardson's Brook and Whitehouse Creek and near the Province's Observation Well No. 355 to verify vertical gradients between the aquifers. Obtain aquifer hydraulic parameters to better understand the hydraulic connection between the unconsolidated and bedrock aquifers in the study area.
- Consider installing shallow piezometers (monitoring wells) at up to a dozen locations along Chemainus River and Bonsall Creek to assess whether those stream reaches are gaining or losing and to confirm local geology.
- Undertake habitat assessments in management zones or likely hydraulically connected reaches to identify how potential reduction in flows will impact instream conditions for aquatic species.
- If the opportunity arises, consider developing a numerical model to quantify the nature of hydraulic connection between the streams and aquifers within the study area.

6.1.2 Operational

- Confirm the location of the points of delineation for the groundwater management areas in the field. Preferably, the points of delineation should be located where the stream channel is stable so stream flow measurements can be made there.
- Consider requiring, as a condition of a water licence, measuring and reporting of monthly quantities diverted and static water level elevations for the larger licensed groundwater users in the study area (above a threshold limit, subject to the capacity of licensees to comply).
- Establish critical environmental flow thresholds for the Chemainus River and Bonsall Creek to protect streamflows.
- Explore options on how FLNRORD can document points of hydraulic connection for unlicensed domestic wells.
- Initiate an on-going program to raise awareness of water users diverting water from streams and wells in the watershed to promote efficiency of water use and to preserve groundwater levels and protect streamflows.

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8. GLOSSARY

Aquifer:	A geological deposit that is permeable and saturated that allows a sufficient supply of water to flow to wells and to springs.
Confined aquifer:	An aquifer that is overlain by confining sediments or confining layer; groundwater in a confined aquifer is commonly under pressure.
Confluence (of streams):	Where two streams flow into one.
Critical environmental flow threshold:	In relation to the flow of water in a stream, means the volume of water flow below which significant or irreversible harm to the aquatic ecosystem of the stream is likely to occur (legal definition from the *Water Sustainability Act*).
Down-gradient:	The direction of maximum decrease in the groundwater elevation; often inferred as the direction of groundwater flow.
Environmental flow needs (EFNs):	In relation to a stream, means the volume and timing of water flow required for the proper functioning of the aquatic ecosystem of the stream (legal definition from the *Water Sustainability Act*).
Gaining (stream):	Where a stream receives groundwater inflow to the stream (via the streambed).
Induced infiltration:	Infiltration of water from the stream into the underlying aquifer caused by well pumping.
Interception:	In relation to streamflow depletion, the process where well pumping captures water that would otherwise flow to the stream.
Losing (stream):	Where a stream loses water through the streambed to the underlying vadose zone or aquifer.
Low permeability sediments:	Sediments composed of typically low permeability sediments like till, silt or clay.
Permeability	Ability for a porous material to allow water to flow through it.
Point of hydraulic connection (PoHC):	The point at which depletion of stream flow as a result of pumping of a well is expected to be first felt.
Relief:	The difference between the highest and lowest point within a watershed.
Specific yield (S_y):	The volume of water that an unconfined aquifer releases from storage per unit surface area of aquifer per unit decline in the water table.
Static water level (SWL):	Distance (in metres or feet) from the top of the production casing or the surface of the ground to the groundwater level in the well, when the groundwater level is not affected by pumping activities in the well (legal definition from the *Water Sustainability Act*).
Stream reach:	A section of a stream.

Streamflow depletion:	In relation to well pumping, it is the capture of water from a stream by a pumping well. Water can be captured by the pumping well intercepting water that would otherwise flow to the stream (process called interception) or by inducing infiltration of water from the stream into the underlying aquifer to the pumping well (process called induced infiltration).
Storativity (S):	Volume of water stored or released from a column of aquifer with unit cross section under unit change in groundwater level. Storativity determines how quickly (or slowly) an aquifer responds to hydraulic changes and is reported as a dimensionless number (e.g., 0.0001).
Till:	Primarily a mixture of clay, silt, sand, gravel and boulders ranging widely in size and shape deposited directly by and underneath a glacier.
Transmissivity (T):	The rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient. Transmissivity is commonly expressed as metres squared per second or day, feet squared per second or day, or gallons per day per foot. Transmissivity reflects the permeability of the aquifer integrated over the thickness of the aquifer.
Unconfined aquifer:	An aquifer where the top of the aquifer is the water table.
Unconsolidated sediments:	A geological material comprising loose sediments, e.g., sand and gravel. Synonymous with “Surficial sediments”.
Vadose zone:	The zone beneath the land surface and the water table where pores are not saturated with groundwater; same as “unsaturated zone”.
Water table:	The top of the saturated zone in the ground where the water pressure is equivalent to atmospheric pressure.

APPENDIX A: SPATIAL DATA

Spatial Dataset	Format	Description	Comments
Confining thickness	Raster (.TIF)	Confining unit isopach surface.	Thickness in metres.
Unconsolidated thickness	Raster (.TIF)	Confining unit isopach surface.	Thickness in metres.
Bedrock Groundwater Elevations	Raster (.TIF)	Elevation of water surface in bedrock wells.	Elevation in metres asl
Unconsolidated Groundwater Elevations	Raster (.TIF)	Elevation of water surface in wells completed in unconsolidated sediments	Elevation in metres asl
Bedrock surface	Raster (.TIF)	Elevation of bedrock surface.	Elevation in metres asl