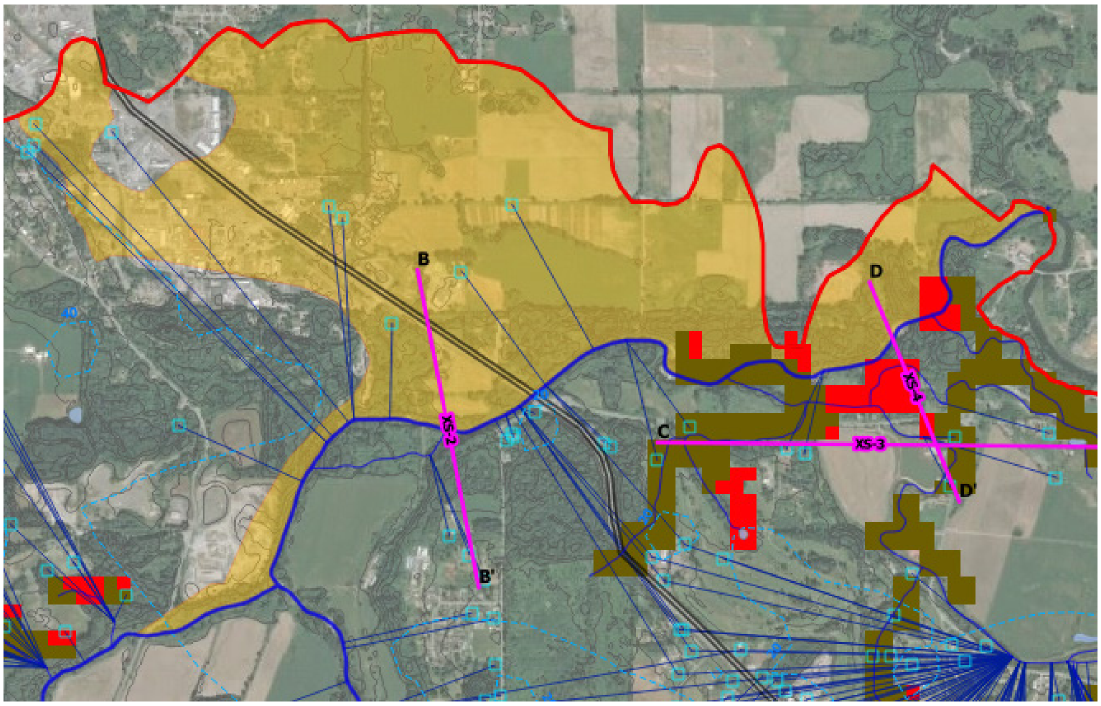
WATER SCIENCE SERIES

Koksilah River Watershed: Preliminary Assessment of Hydraulic Connection

Tim Sivak and Mike Wei



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Cover Photographs:
Screen shot of points of connection of reported wells to streams in the Koksilah watershed.

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EXECUTIVE SUMMARY

Koksilah River is an unregulated stream on the east coast of Vancouver Island that has 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 Koksilah watershed is vital to effective management of environmental flows and access to water for users. Four types of aquifers exist within the Koksilah watershed:

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

This desktop study identified stream reaches within the Koksilah watershed where hydraulic connection with underlying aquifers and depletion of streamflow from well pumping can most likely be expected to occur. These stream reaches were identified by mapping where the stream is not perched nor directly underlain by confining sediments (i.e., by till, silt, or clay), based on available well records from GWELLS, digital stream and topographic elevation data, as well as from published geological mapping. Mapping from this study suggests discharge of groundwater to streams from the unconsolidated and bedrock aquifers in the study area is expected to be restricted to within the Koksilah watershed and hydraulic connections can likely be made for most, if not all, wells in the Koksilah watershed to streams within the watershed. Hydraulic connection and depletion of streamflow from well pumping can be expected mostly along the mainstem of Koksilah River, the upper portion of Patrolas Creek, the lower reach of Kelvin Creek, and short sections along Glenora Creek.

Points of hydraulic connection (PoHCs) were made for 1187 (the vast majority of) reported wells to streams in the Koksilah watershed; PoHCs could not be made for 134 wells because well completion details were not reported or the well was decommissioned. If the reach of stream closest to a well is not perched nor directly underlain by confining sediments, the point of hydraulic connection (PoHC) was made to the closest point on the stream. If the stream closest to the well is perched or directly underlain by confining sediments, the PoHC was made further downstream or down-gradient to a reach where the stream is not perched nor directly underlain by confining sediments.

Stream depletion factors (SDFs), a relative measure of how quickly streamflow depletion can occur from well pumping, were calculated for wells determined to be likely hydraulically connected to streams in the Koksilah watershed. Preliminary calculations suggest wells completed into confined, unconsolidated sediments and into crystalline bedrock tend to have the lowest SDF values (values range up to a few weeks), while wells completed into unconsolidated, unconfined sediments and into the Nanaimo Group sedimentary bedrock have markedly higher SDF values (values range up to years). Streamflow depletion from well pumping and recovery from streamflow depletion after pumping stops are expected to occur more quickly where the SDF is smaller.

Priority recommendations to improve on the preliminary understanding of the nature of hydraulic connection of wells to streams in the Koksilah watershed include:

- Field work during the dry season to verify local geology and identify stream reaches with groundwater inflow where streamflow depletion is most likely to occur;
- Update the 2018 Koksilah watershed curtailment model with results from this study;
- Develop a water balance for the Koksilah watershed using hydrometric data collected near the mouth of Koksilah River mainstem;

- Establish multilevel monitoring wells near streams to verify the hydraulic connection between the unconsolidated and fractured bedrock aquifers and streams with greater certainty;
- Promote the use of observation wells (where feasible) when conducting pumping tests, to obtain more site-specific values of S, S_y, and T.
- Survey critical reaches of Koksilah River and its main tributaries to determine more accurate stream elevations; and,
- Consider requiring specific licensees diverting groundwater to measure and report quantities diverted and monthly static water levels from their wells.

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ACRONYMS AND ABBREVIATIONS

ASL	above sea level
B.C.	British Columbia
BCGS	British Columbia Geographical System
DEM	Digital Elevation Model
EcoCat	Ecological Reports Catalogue (B.C. ENV)
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
SDF	stream depletion factor
URL	uniform resource locator (website address)
WSA	*Water Sustainability Act*
WSS	Water Science Series
WTN	well tag number

1. BACKGROUND

Koksilah River is an unregulated stream on the east coast of Vancouver Island (Figure 1) that has been identified as vulnerable to low flows during the dry season, which may affect the habitat and survival of aquatic life. Koksilah River has unique cultural and economic importance to local First Nations including the Cowichan Tribes, and historically has provided essential habitat for anadromous fish species including Chinook, Coho, Chum and Steelhead salmon, as well as resident Rainbow and Cutthroat Trout. Concerns regarding diminishing river discharge during the dry season and fish population declines were recognised in the early 1980's, at which time a restriction on additional surface water licences was instituted. Well drilling and groundwater use has increased significantly since that time, effectively doubling the water demand within the basin. At the present time, it is estimated that, approximately half of the water use in the basin comes from groundwater.

Since 2017, the Ministry of Forests, Lands, Natural Resource Operations and Rural Development (FLNRORD) have been monitoring and evaluating the low flow conditions within Koksilah River, and working with the community and water users to reduce the impacts of surface and groundwater withdrawals on stream health.

In response to concerns over low flows, Barroso and Wainwright (2018) developed a groundwater curtailment model to identify water use that might be curtailed as part of regulatory action aimed at increasing streamflow during critical low flow periods. One data gap that was identified in the development of the model was information on the likelihood of hydraulic connection of individual wells to streams, and the degree to which well pumping may impact flows on streams in the Koksilah watershed.

The British Columbia (B.C.) *Water Sustainability Act* (WSA) (Province of BC, 2016a) 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 the likelihood of hydraulic connection is necessary to enable surface water and groundwater to be managed together as a single resource. Specifically, determining the likelihood of hydraulic connection between an aquifer and a stream allows decision makers under the WSA 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 on the stream from hydraulically connected points of groundwater diversion; and
- Consider hydraulically connected groundwater users when flow in a stream becomes critically low (Sections 87 and 88 of the WSA).

While the WSA refers to hydraulic connection as existing between an aquifer and a stream, in reality, only certain reaches of a stream may be effectively open to hydraulic connection to an aquifer. It is also along those reaches that depletion of streamflow (streamflow depletion) can be most influenced by well pumping. Identifying where well pumping is occurring in relation to where the stream may be open to connection is key to protecting EFNs and managing rights of users.

Therefore the main goal of this study is to identify, based on available data, where hydraulic connection likely occurs and where pumping of wells may affect streams within the Koksilah watershed. Another goal is to begin to understand how quickly well pumping may be expected to affect the streams.

In the WSA, "stream" includes springs. However, information on the source of springs within the Koksilah watershed 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 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 not within the scope of this study.

Finally, as a note of convention for this report, “Koksilah watershed” is used to refer to the overall watershed. Where we are referring to sub-watersheds within the Koksilah watershed, we include: “River” or “Creek” in the reference (i.e., Koksilah River watershed, Patrolas Creek watershed, Kelvin Creek watershed, and Glenora Creek watershed).

2. SCOPE OF WORK

The main components of the work completed as part of this study include:

- Compiling available information into a conceptual hydrogeological model;
- Mapping and contouring the groundwater elevations and inferring groundwater flow directions;
- Assessing where hydraulic connection between wells and streams in the Koksilah watershed are expected to occur;
- Compiling data into an Excel spreadsheet;
- Calculating stream depletion factors (SDFs) for the wells to estimate the approximate length of time effects from well pumping are expected to be felt on streams; and
- Summarizing the work of this study in a report and other data outputs.

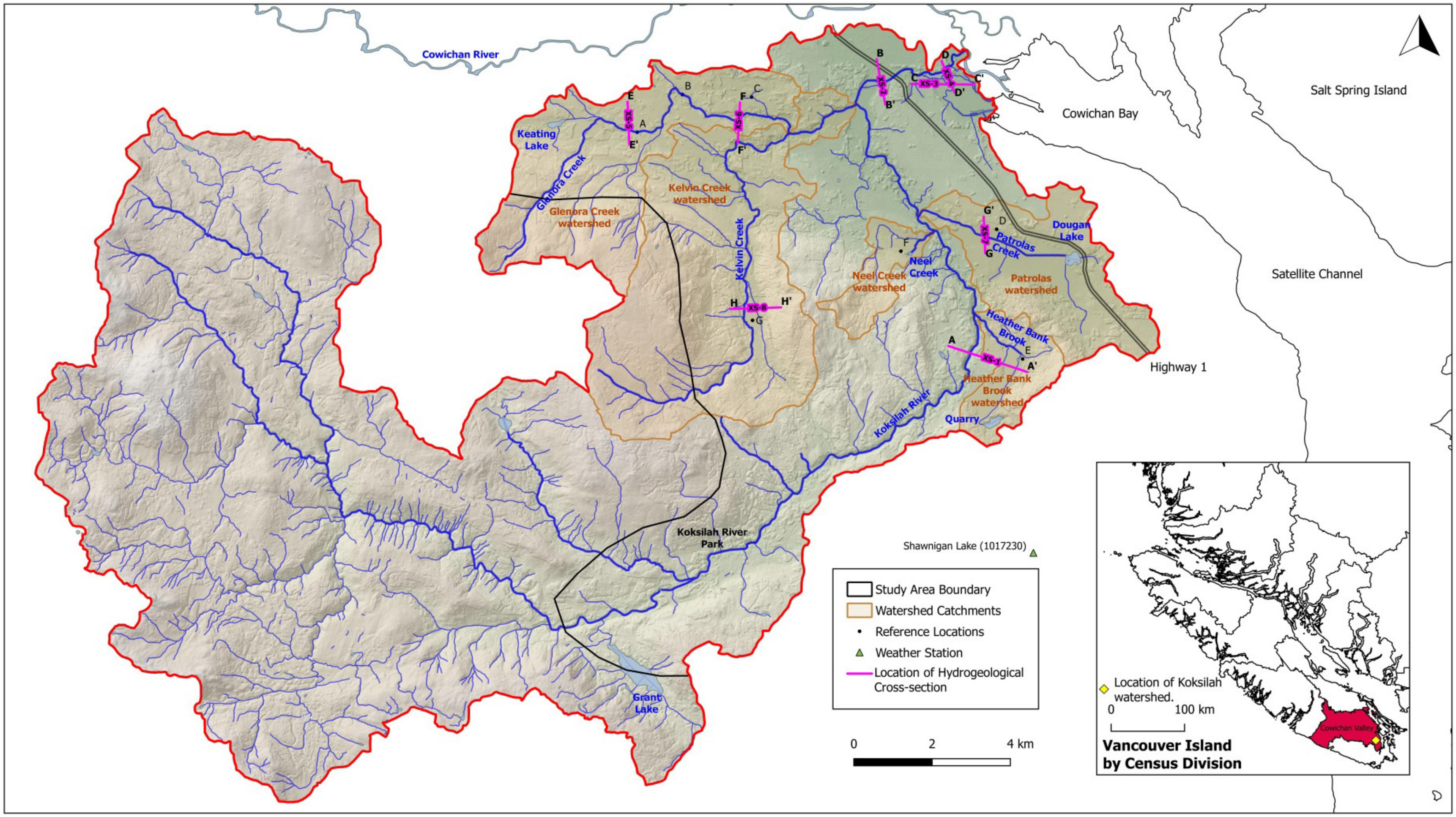
3. STUDY AREA

3.1 Koksilah Watershed Setting

The Koksilah watershed occupies an approximate area of 31,000 hectares and is situated within the Nanaimo Lowland physiographic region (Holland, 1976) on the southeast side of Vancouver Island (see Figure 1). The watershed is located about 32 km northwest of Victoria, B.C. and 10 km south of Duncan, B.C. The study area, delineated based on the distribution of available well data, is located within Koksilah watershed and is outlined in black in Figure 1.

Shawnigan Lake Climate Station (Climate ID: 1017230) climate normals (1981 to 2010) show average total annual precipitation of 1250.0 mm, and average monthly temperatures ranging between 3.1 °C and 17.9 °C. Shawnigan Lake Climate Station is located about 3 km south of the Koksilah watershed boundary (Figure 1).

The watershed has an east-facing aspect, with a total relief of 930 m. The primary watercourses within the watershed include Koksilah River, Patrolas Creek, Kelvin Creek, and Glenora Creek. Dougan Lake, Grant Lake and the unnamed quarry in the Heather Bank Brook watershed are the largest freshwater lakes in the watershed (see Figure 1). Eighty percent of land use in the upper watershed is privately managed forest land, while agricultural, rural residential and industrial development is concentrated within the lower third of the watershed. The most significant use of surface and groundwater by volume in the watershed is for agriculture, including seasonal irrigation.



Koksilah Watershed Hydraulic Connectivity Assessment	TITLE **Figure 1.** Site overview of Koksilah watershed		
western water ASSOCIATES LTD	DRAWN Tim Sivak	DATE March 29, 2019	PROJECT NO. 19-005-01VC
	CHECKED Mike Wei	SCALE See Bar Scales	DWG NO.
	REVIEWED	FILE NO.	FIGURE VERSION NO.

Data Sources: Base plan from Google Maps (2019), DataBC (2018), water features from GeoBC (2010), wells from GWELLS (2019), FLNR (2019).
Contour interval: -
Map Projection: NAD83 UTM Zone 10.
Other notes: See Appendix A for hydrogeological cross-sections.

Figure 1: Site overview of Koksilah watershed.

3.2 Geologic Setting

3.2.1 Surficial geology

The surficial geology in the Koksilah watershed area is interpreted as mixtures 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 described in detail by Hammond et al. (2019), WWAL (2018), Harris and Usher (2017), Blythe et al. (1992; 1993), and Halstead (1965). Figure 2 illustrates the surficial geology of the watershed area, based on digital terrain inventory mapping by Forest Renewal B.C. (1992).

3.2.2 Bedrock geology

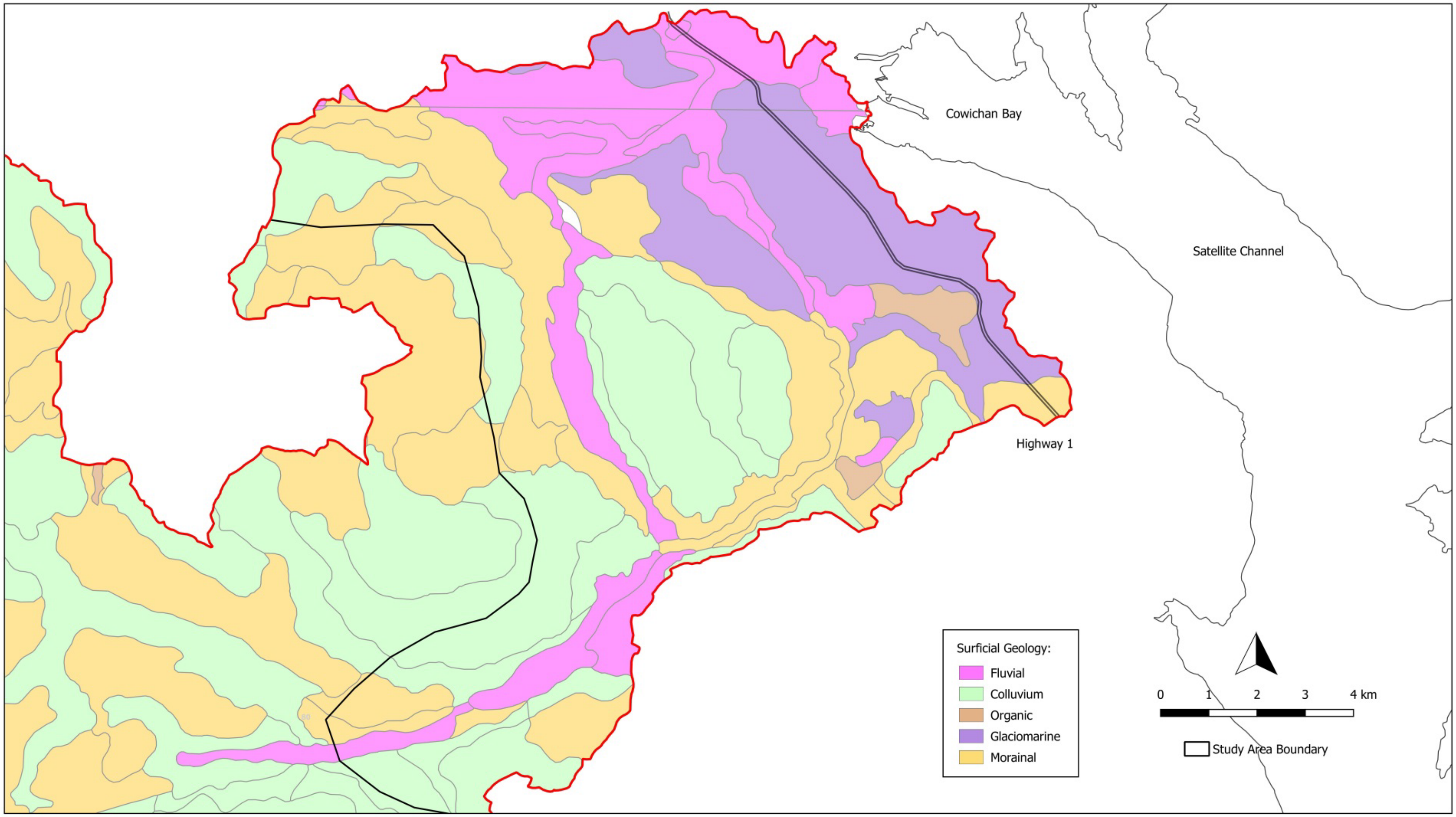
The bedrock geology of the area has been mapped by Massey et al. (1994, 1988) and Muller (1980) and digitally compiled by Cui et al. (2017) (see Figure 3). The bedrock map compiled by Cui et al. (2017) depicts the northern half of the study area as comprising undivided sedimentary rocks of the Upper Cretaceous Nanaimo Group. The southern half of the study area comprises crystalline rock from the Westcoast Crystalline Complex (oldest - Cambrian), Sicker Group, Karmutsen Formation and Island Plutonic Suite (youngest – Jurassic). Late Paleozoic-aged limestone from the Buttle Lake Group is also present in the southern half of the study area.

3.2.3 Mapped aquifers

According to the current B.C. Ministry of Environment aquifer mapping (ENV, 2019), there are eight mapped surficial or bedrock aquifers within the Koksilah watershed. Mapped aquifers in the Koksilah watershed are classified by subtype (from Wei et al., 2009) as follows:

- Subtype 1b and 1c: Unconfined sand and gravel along mid-sized and small-sized streams, respectively;
- Subtype 4b: Confined, sand and gravel of glacial or pre-glacial origin;
- Subtype 5a: Fractured sedimentary bedrock aquifers; and,
- Subtype 6b: Crystalline bedrock aquifers.

For the purpose of the study, aquifers in the Koksilah watershed were categorized in the subtypes above for calculating *Stream Depletion Factors* (SDFs), discussed in greater detail in Section 4.8.



Koksilah Watershed Hydraulic Connectivity Assessment	TITLE **Figure 2.** Surficial geology of Koksilah watershed					Data Sources: Digital surficial geology from Forest Renewal BC (1992), water features from GeoBC (2010), wells from GWELLS (2019), FLNR (2019). Contour interval: - Map Projection: NAD83 UTM Zone 10. Other notes: -
western water ASSOCIATES LTD	DRAWN Tim Sivak	DATE March 29, 2019	PROJECT NO. 19-005-01VC			
	CHECKED Mike Wei	SCALE See Bar Scale	DWG NO.			
	REVIEWED	FILE NO.	FIGURE VERSION NO.			

Figure 2: Surficial geology of Koksilah watershed.

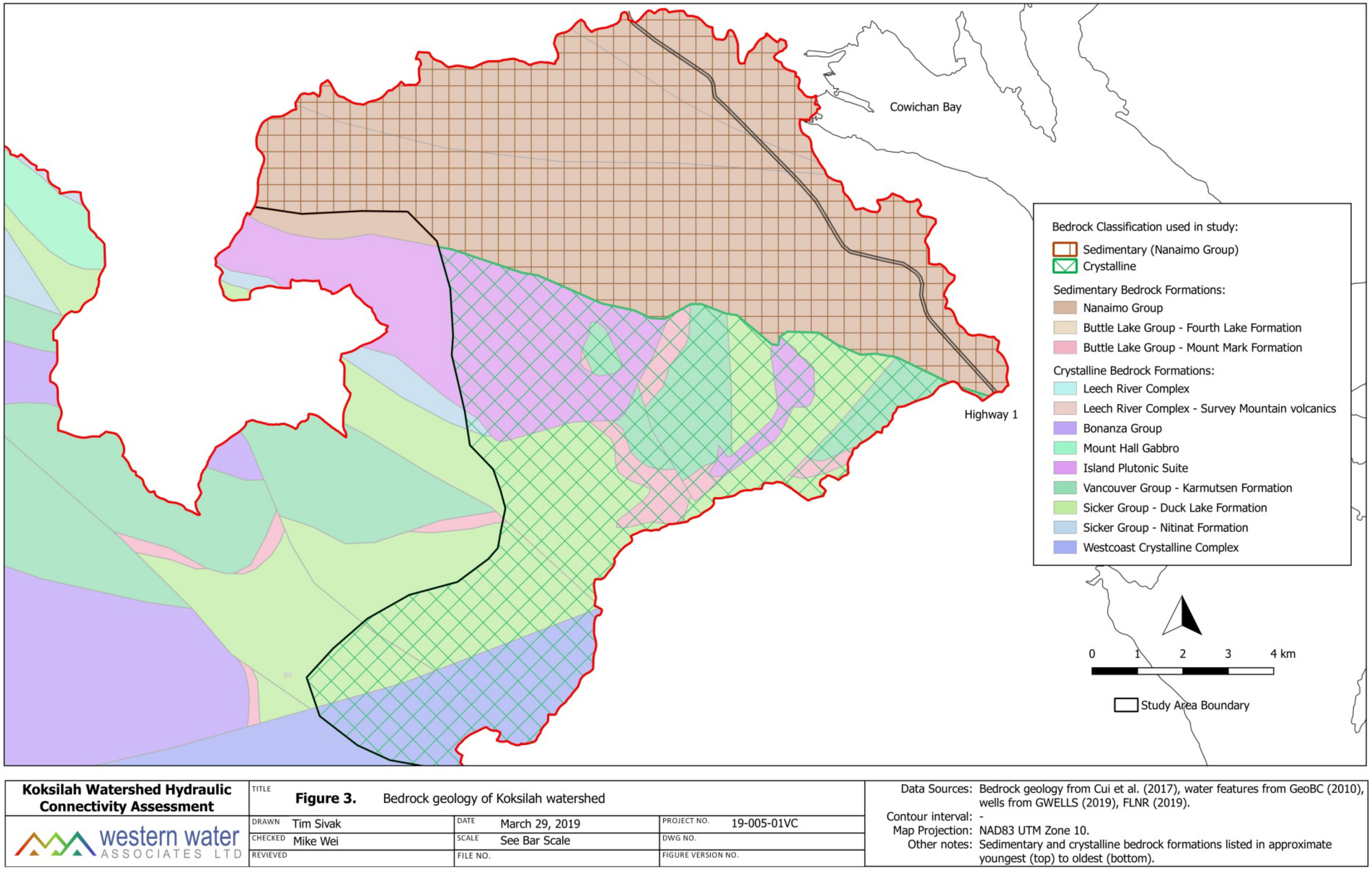


Figure 3: Bedrock geology of Koksilah watershed.

4. METHODS

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

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).

A USGS publication by Barlow and Leake (2012) presents and discusses these two processes in detail. The Water Science Series reports: *Determining the likelihood of hydraulic connection – guidance for the purpose of apportioning demand from diversion of groundwater on streams* (Province of BC, 2016b) and *Modelling tools for estimating effects of groundwater pumping on surface waters* (Province of BC, 2016c) describe key principles that were also considered in this study.

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:

1. The stream or reach of the stream must not be perched; and
2. The stream or reach of the stream must not be directly underlain by low permeability (i.e., till, silt or clay) confining sediments.

A perched stream, or the presence of confining sediments underlying a stream, will essentially restrict hydraulic connection and stream depletion along that reach of the stream. However, any depletion from well pumping may still be felt further down-gradient (by the process of interception) at a reach of stream that is not perched nor directly underlain by confining sediments. Depending on the setting, the downgradient depletion may not affect the stream reach nearest to the pumping well, but rather a reach further downstream or down-gradient of the direction of groundwater flow or even a water body the stream drains to (e.g., larger stream, lake, ocean).

The main approach of this study was to use available lithological information in water well records, topographic information, and stream locations (including elevations) to identify where streams are likely perched and not perched, and where confining sediments likely underlie or are likely absent directly underneath the stream. (Section 4.4.4 defines confining sediments in this study.) Reaches where the stream is not perched nor directly underlain by confining sediments are considered stream reaches where streamflow depletion due to well pumping can potentially occur.

In doing this, we:

- Divided up the hydrogeology into two settings: 1) unconsolidated sediments and 2) fractured bedrock;
- Mapped and contoured the groundwater 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 confining 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.

Since the study approach relied on characterizing basic hydrogeological characteristics associated with the different aquifer subtypes, reference to classified aquifers was not necessary.

From the process described above, reaches along a stream where the stream is neither perched nor directly underlain by confining sediments were identified as where streamflow depletion from well pumping can be expected to occur. If a given well was determined to be hydraulically connected to a stream (including to minor and unnamed tributaries), a point of hydraulic connection (PoHC) was made to the nearest reach of the stream, or to the nearest reach down-gradient, if the closest stream reach to the well is perched or directly underlain by confining sediments. The PoHC is the point on the stream at or below which streamflow depletion from pumping of the well can occur. If a well was located roughly equidistance between two streams, a PoHC was made to both streams and the percentage of the total pumping demand apportioned to both streams (based on inverse distance squared; see section 3.2 of Province of BC, 2016b). If a PoHC could not be made for a well to any stream in the Koksilah watershed, the PoHC for that well was made to the mouth of Koksilah River, signifying that depletion would occur at a reach of Cowichan River or Cowichan Bay.

The distance between the well and the corresponding PoHC and the transmissivity and storativity (or specific yield if the aquifer is unconfined) of the aquifer are major factors governing how quickly depletion may occur due to pumping of a well. Understanding of how quickly depletion may occur is helpful in assessing depletion from seasonal pumping or in curtailing groundwater use during a period of temporary water shortage. The *Stream Depletion Factor* (SDF) is a relative measure proposed by Jenkins (1968) of how quickly streamflow depletion may occur and is based on the distance of the well to the point of connection, and the aquifer's transmissivity and storativity (or specific yield if the aquifer is unconfined. The SDF was calculated for all wells having a PoHC to the stream (see Section 4.8 of this report). Maps of the PoHC and calculated SDF values were presented for the unconsolidated/unconfined, unconsolidated/confined sediments and for fractured bedrock.

Results of this work were summarized in an MS Excel spreadsheet. The interpretation of where the stream is perched or is directly underlain by a confining unit was verified by constructing cross-sections. The following subsections present the data sources in more detail and how the maps, cross-sections and spreadsheets 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.

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. The results were reviewed manually and cross-referenced against available terrain inventory and surficial geology mapping (see Table 2 below). Bedrock type was assigned to each well completed into bedrock by referencing the well's location to the digital bedrock geology mapping compiled by Cui et al. (2017).

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 (2019)
Koksilah Watershed Boundary	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 (2019)
Digital Surficial Geology	Shapefile	1:50,000	Used to refine geological data from GWELLS.	Forest Renewal BC (1992)
Digital Bedrock Geology	Shapefile	1:50,000 to 1:250,000	Used in hydraulic connectivity assessment to assign bedrock types to each well point.	Cui et al. (2017)

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” “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, boulders
Volcanic; granite; basalt, shale	-	Bedrock
Wood; peat; organics	O (Organic)	Peat

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 determine the likely point of hydraulic connection (PoHC) between streams and wells (see Section 4.7 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 (overburden) sediments and for bedrock to infer direction of horizontal groundwater flow in both those settings (see Figure 4). Groundwater elevation contours were constructed by grouping wells from the GWELLS database into unconsolidated sediments and fractured bedrock categories. 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 4.6). The groundwater elevations between well points were interpolated in GIS. In calculating groundwater elevations, well stick-up above ground surface was assumed to be zero. Groundwater elevations were contoured based on the values at individual well locations.

4.4.2 Identifying where stream is perched and not perched

To assess if a stream is perched or not perched, 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. Due to the limited accuracy of well, stream and ground elevations associated with the datasets, we imposed a tolerance value of 3 m to help reduce the possibility of mis-identifying reaches where a stream is likely perched. The groundwater elevation surface had to be more than 3 m beneath the elevation of the stream for the stream to be considered perched. If the groundwater elevation surface was less than 3 m beneath the stream elevation, then the stream was not considered perched. A visual comparison using tolerance values ranging between 1 m and 5 m was conducted, and only minor differences were observed in perched locations.

4.4.3 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 all sediment types (sand and gravel, till, silt, clay) and is not the total thickness of unconsolidated materials 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 (R), the unconsolidated thickness was assumed to be < 1 m. Unconsolidated thickness is presented in Figure 5.

4.4.4 Mapping confining sediment thickness

Confining sediments are described as likely low permeability unconsolidated sediments that are expected to impede groundwater flow. Till is comprised of a broad range of 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. In this study, sediments classified as ‘till’, ‘silt’ or ‘clay’, are considered confining sediments, meaning that they are expected to be low permeability and therefore impede groundwater flow. Confining thickness is presented in Figure 6.

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. For wells not drilled into bedrock, any confining sediments that exist below the depth of the well would not be recorded or mapped.

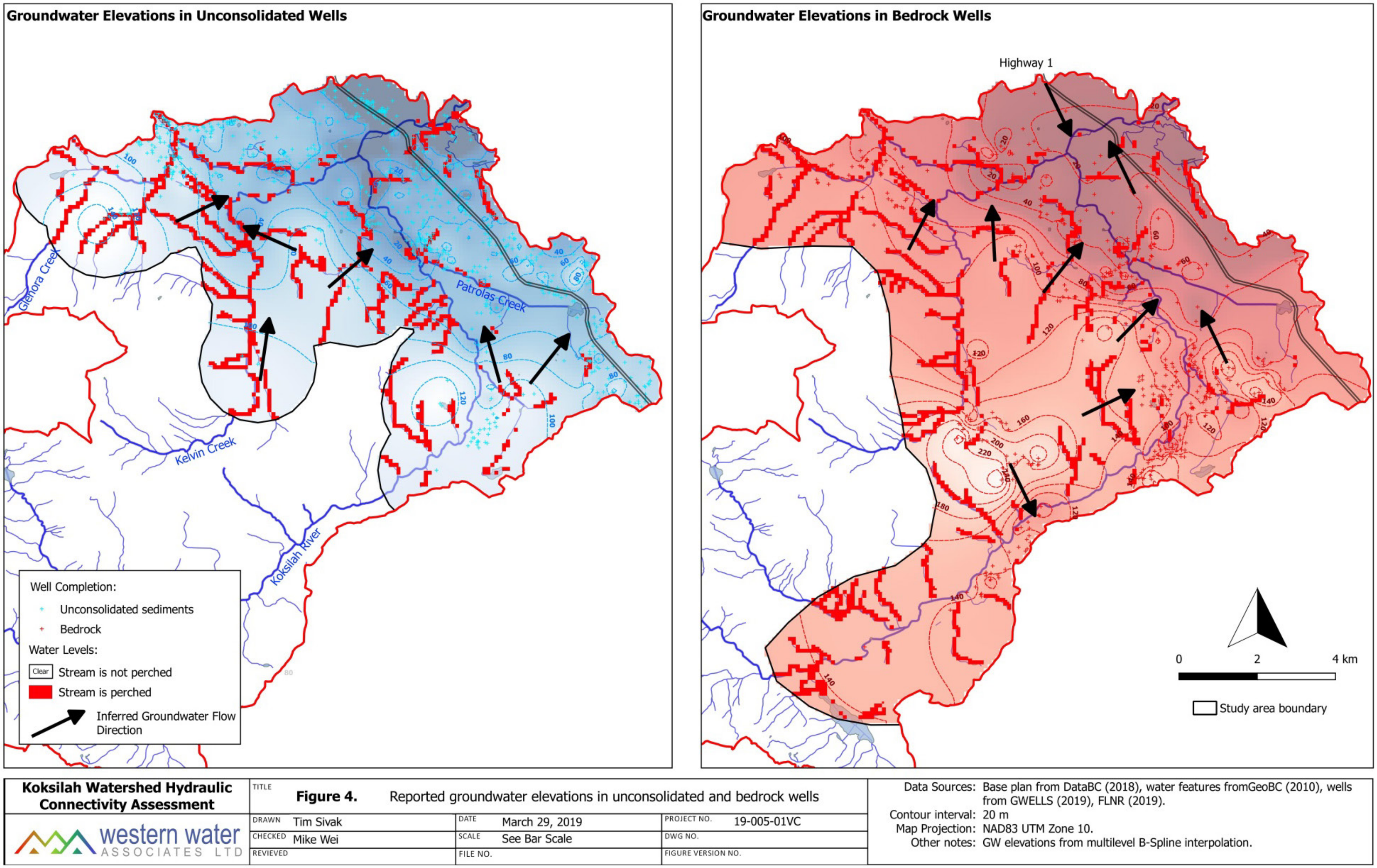
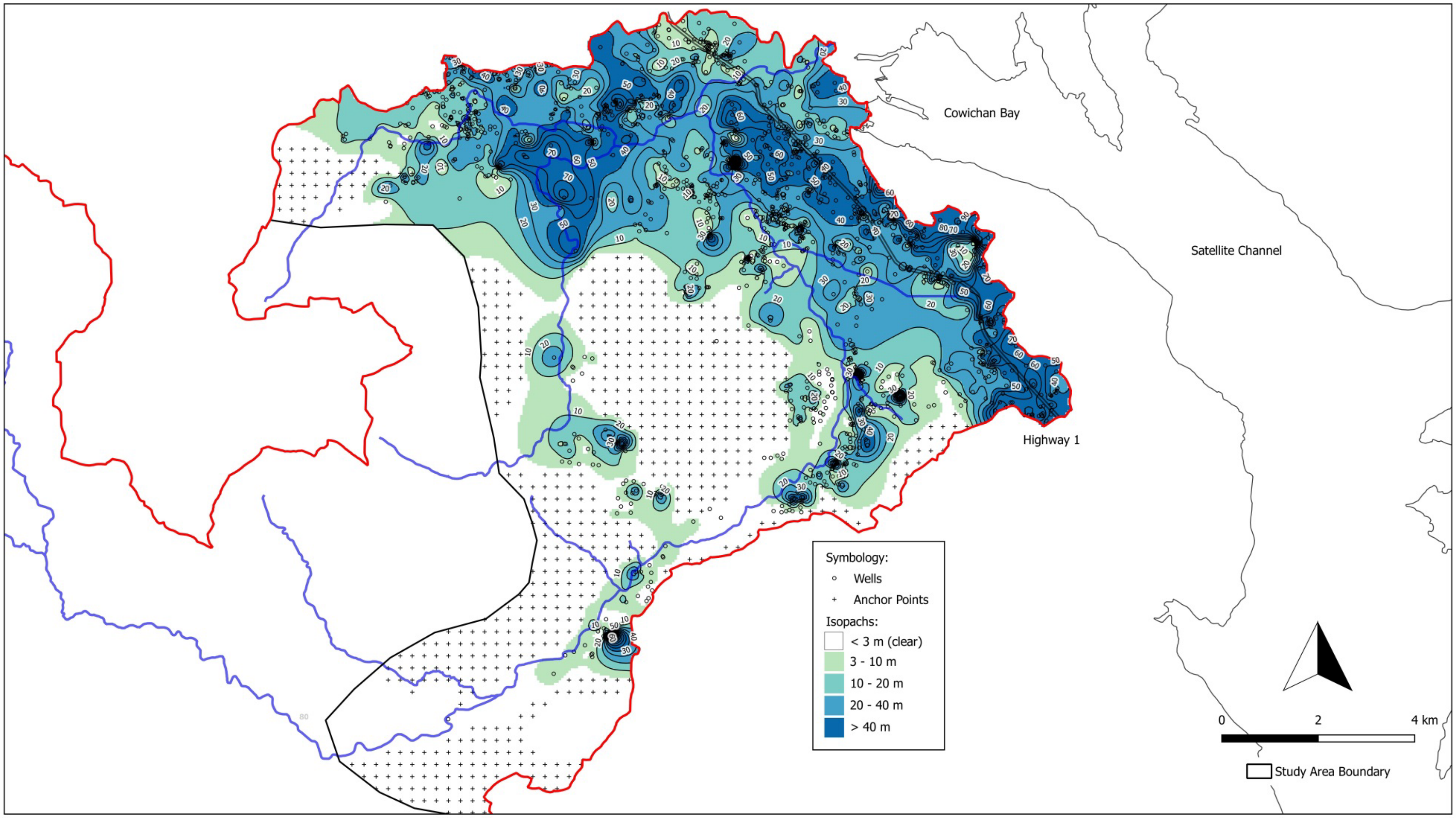


Figure 4: Reported groundwater elevations in unconsolidated and bedrock wells.



Koksilah Watershed Hydraulic Connectivity Assessment	TITLE **Figure 5.** Reported unconsolidated unit thickness in groundwater wells.			Data Sources: Water features from GeoBC (2010), wells from GWELLS (2019), FLNR (2019). Contour interval: 10 m Map Projection: NAD83 UTM Zone 10. Other notes: Isopachs from multilevel B-Spline interpolation.
western water ASSOCIATES LTD	DRAWN Tim Sivak	DATE March 29, 2019	PROJECT NO. 19-005-01VC	
	CHECKED Mike Wei	SCALE See Bar Scale	DWG NO.	
	REVIEWED	FILE NO.	FIGURE VERSION NO.	

Figure 5: Reported unconsolidated thickness in groundwater wells.

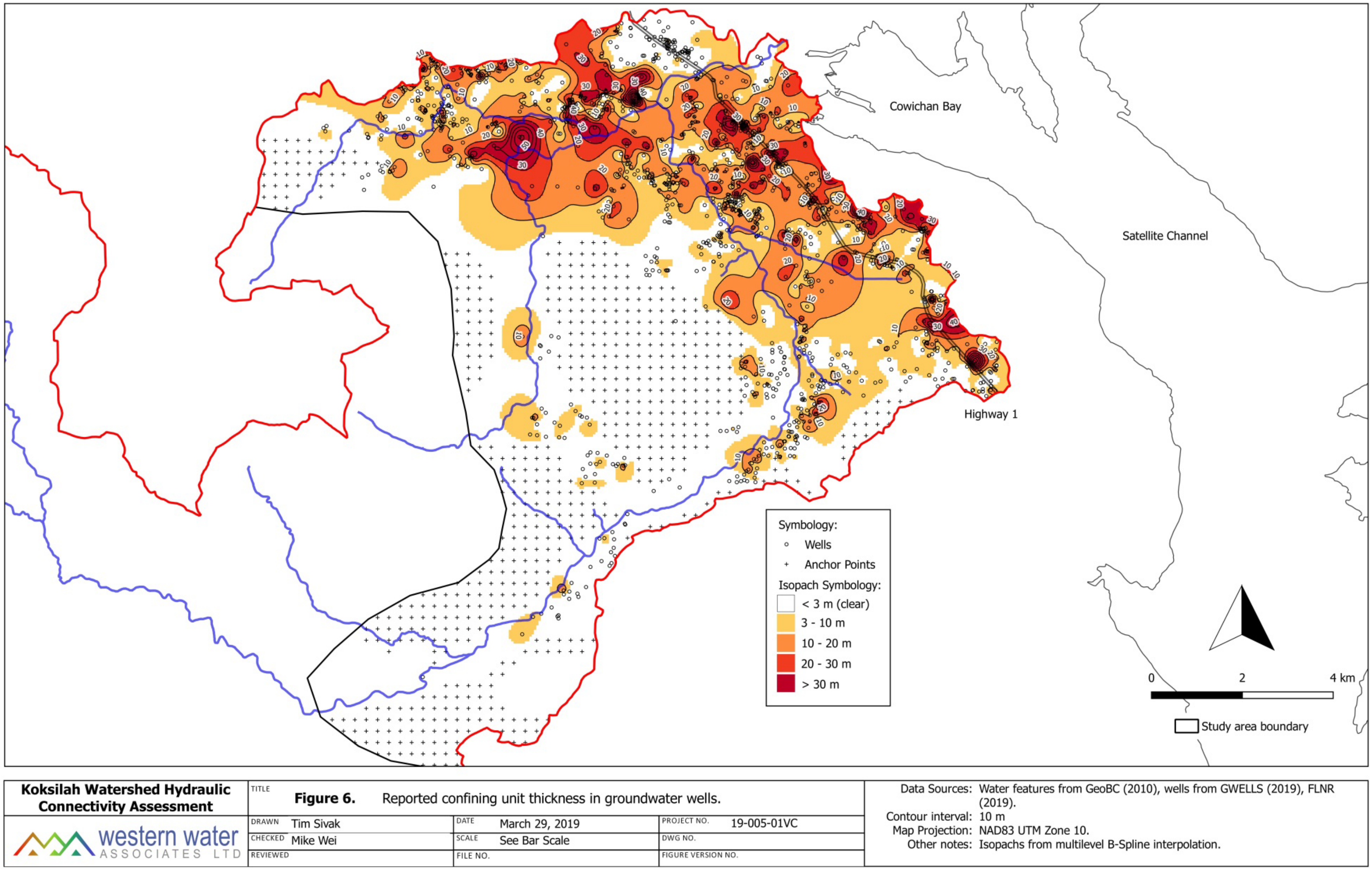


Figure 6: Reported confining sediment thickness in groundwater wells

4.4.5 Identifying where the stream is or is not directly underlain by confining sediments

To assess if a stream had completely down-cut through the confining sediments or not, or if confining sediments pinch out at a stream, the elevation of the stream was compared to the elevation of the bottom of the confining sediments for wells within 100 m of the streams. Where the stream elevation was below the elevation of the lowest confining layer, the stream was considered to have either down-cut through the confining layer or that confining sediments did not extend to the stream. In either case, the stream at that location was considered not directly underlain by confining sediments. Similar to the reasoning in Section 4.4.2 with respect to limited accuracy of the well, stream and ground elevations of the datasets, we imposed a tolerance value of 3 m to help reduce the possibility of mis-identifying reaches where a stream is directly underlain by confining sediments. Where the stream elevation was greater than 3 m above the lowest confining layer below which the wells are screened, the stream was considered to be directly underlain by confining sediments.

For wells within 100 m of streams with no reported confining sediments, an elevation for the "bottom of confining layer" still had to be specified for contouring. These elevations for "bottom of confining layer" were originally anchored to the local ground elevations but the resultant map erroneously interpolated confining sediments to be present in areas not indicated by the confining sediment isopach map. The "bottom of confining layer" for these wells were anchored ranging from 0 m to 20 m above local elevation and it was found that by using an anchor elevation of between 10 m and 20 m, the extent of the confining sediments matched with the confining sediment thickness isopach map (Figure 6). An anchor of 20 m above the well was ultimately selected for those wells within 100 m of streams with no reported confining sediments.

4.5 Hydrogeological Cross-Sections

Hydrogeological cross-sections were developed at key locations primarily to help verify and illustrate where confining sediments do or do not directly underlie streams. The cross-sections were developed using GIS and Microsoft Excel. The terrain profile for each section line was extracted from the DEM and imported into MS Excel. Wells were plotted on the section line based on distance and extrapolated elevation (based on a horizontal accuracy of about 10 m from the DEM). Interpreted lithology was transferred to the cross-sections, and checked against GWELLS and digital surficial and bedrock geology. Eight hydrogeological cross-sections were developed to visually illustrate the local stratigraphy at key locations within the Koksilah watershed and support the interpretations. All cross-sections look downstream and are referred to in subsequent sections of the text.

4.6 Data & Analysis Limitations

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 perched or directly underlain by confining sediments (Sections 4.4.2 and 4.4.5).

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, which is spatially variable. 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 inaccurate well location. Also, 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. 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. Vertical groundwater flow within the unconsolidated sediments and within bedrock was also not characterized in this study.

The scale and desktop nature of the study and the fact that the hydrogeological data is from well records mean smaller groundwater sources may have been overlooked. The maps of groundwater elevations and sediment thicknesses (and cross-sections) are based on drillers' observations and measurements and spatial density of the well data. 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 Koksilah watershed, even to streams mapped as being perched above the main water table.

4.7 Determining the Likely Point of Hydraulic Connection (PoHC) from a Well to the Stream

Once the groundwater elevation contours in the unconsolidated sediments and fractured bedrock were mapped, we assessed the following:

1) Estimated groundwater elevation along the streams and tributaries in the Koksilah watershed to identify reaches of streams that are perched and not perched; and
2) For perched streams, inferred the down-gradient direction of groundwater flow to see where else hydraulic connection can possibly occur.

Mapping the elevations of the bottom of the confining sediments (till, silt and clay) along the streams allowed us to assess which reach of stream may be directly underlain by confining sediments that restrict hydraulic connection with groundwater. Hydraulic connection to the stream was inferred to be more likely significant where the stream is not perched nor directly underlain by confining sediments.

Figure 7 below illustrates the general approach used to determine the PoHC for wells in the Koksilah watershed. The approach can be summarized as follows:

- For each well, if the reach of the stream nearest the well was not perched nor directly underlain by confining sediments, the PoHC would be made to the shortest distance to the stream;
- If the reach of stream nearest the well was either perched or directly underlain by confining sediments, we looked downstream or down-gradient to where the stream (or another stream) was not perched nor directly underlain by confining sediments and made the PoHC to the first clear reach downstream or down-gradient. As long as there was a stream reach further downstream or down-gradient that was not perched nor directly underlain by confining sediments, hydraulic connection to downstream stream reaches was likely because groundwater flow in both unconsolidated and fractured bedrock aquifers was towards the mouth of the watershed; and,

- In the lower portion of the Koksilah watershed, if there were no reaches further downstream that were not perched nor underlain by confining sediments, the well was considered not connected to streams in the Koksilah watershed and the PoHC was made at the mouth of Koksilah River.

The approach described immediately above was also applied to wells completed into unconsolidated confined aquifers. A reach of stream not directly underlain by confining sediments indicates that any confining layer encountered in the well is not present along that reach of stream either because:

- The stream has down-cut through the confining layer; or
- The confining sediments do not extend to the stream bank (pinch out).

The approach was also applied to wells completed into fractured bedrock. The modelling work by Welch and Allen (2012) suggests that much of the groundwater occurring in fractured crystalline bedrock in mountainous areas provides baseflow to tributary streams via topographically driven groundwater flow. Wells completed into the Nanaimo Group of sedimentary bedrock in the northern portion of the Koksilah watershed were also treated in the same way, even though the Nanaimo Group is stratified, because groundwater flow within the Nanaimo Group also appears topographically driven (see Section 5.2).

There is inherent uncertainty in making the PoHC either to be the closest point on the nearest stream or the first reach downstream or down-gradient where the stream is not perched nor directly underlain by confining sediments. This approach assumes any depletion of the stream will occur at the closest possible location from the well. However, given the lack of information that depletion could occur at locations farther away, this assumption was deemed reasonable as a start.

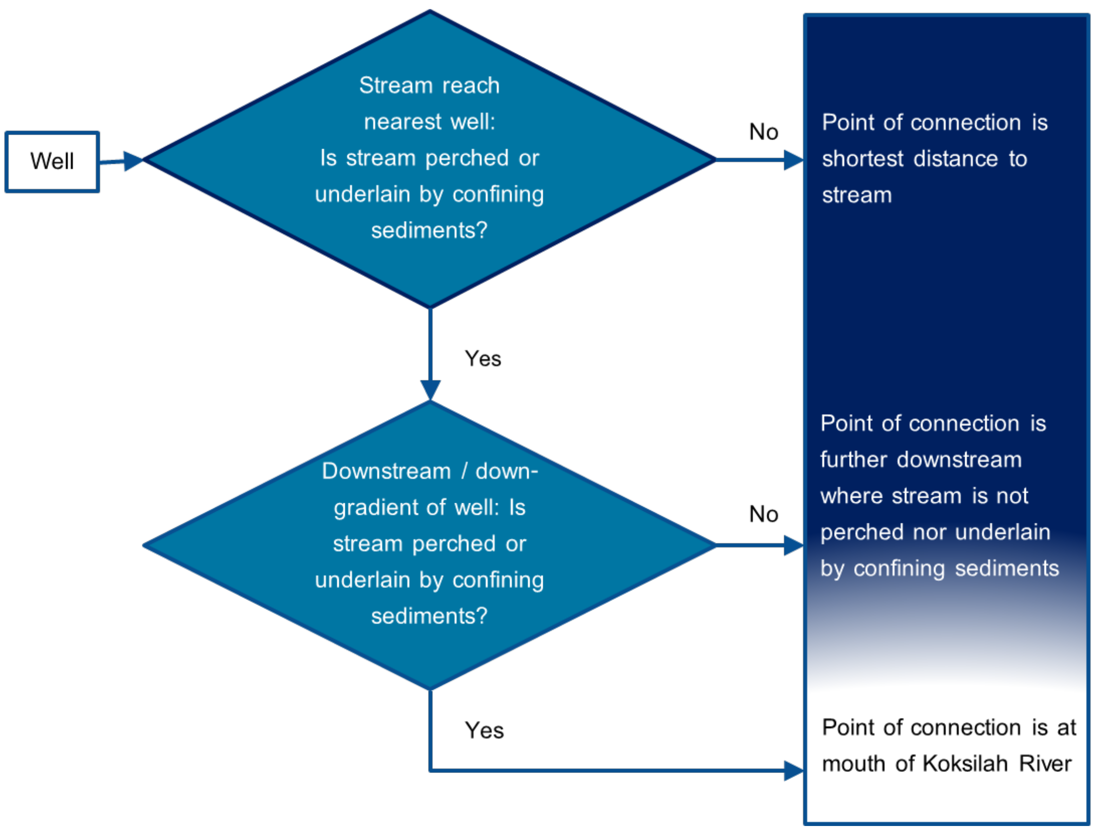


Figure 7: Approach for determining the likely point of hydraulic connection from a well to the stream.

4.8 Calculating Stream Depletion Factor (SDF) for Wells

The *Stream Depletion Factor* is calculated as:

$$SDF = d^2 \times \frac{S}{T}(\text{confined}) \;\; or \;\; SDF = d^2 \times \frac{S_y}{T}(\text{unconfined}) \qquad \text{Equation [1]}$$

where:

d is the distance in metres between the well and the nearby stream (or distance from the well to the PoHC);

S is the aquifer storativity (if aquifer is confined) and S_y is the aquifer specific yield (if aquifer is unconfined), whichever is the predominant case; both values are dimensionless; and

T is the aquifer transmissivity in square metres/day.

The SDF has units of time (e.g., days) and is a relative (not necessarily absolute) measure of how fast streamflow depletion occurs in response to well pumping. Jenkins (1968) defines SDF as the time required for the ratio between the rate of depletion and the rate of well pumping to reach 48%, assuming the aquifer is homogeneous and isotropic and the stream is fully penetrating and has no streambed materials that impeded flow. For a confined aquifer, storativity, S, is used in Equation [1] and for an unconfined aquifer, specific yield, S_y, is used. Equation [1] assumes the aquifer transmissivity and storativity or specific yield are constant throughout the aquifer. As more information on the aquifer hydraulic parameters becomes available in the future, T, S, S_y representative of sub-regions within aquifers can be used.

There are limited data on aquifer hydraulic parameters (T, S, S_y) within the Koksilah watershed. Yet to facilitate preliminary calculations of SDFs for connected wells, representative values for aquifer hydraulic parameters for each aquifer subtype were used and homogeneity within the aquifer subtypes was assumed. Table 3 summarizes the representative T, S, S_y values assigned to each aquifer subtype in the Koksilah watershed for calculating the SDFs.

Table 3: Transmissivity (T), storativity (S) and specific yield (Sy) values assigned to each subtype of aquifer in the Koksilah watershed.

Type of aquifer	**T (m^2/day)**	**S (-)**	**Sy (-)**
Unconsolidated, unconfined (subtype 1b-lower reaches of the watershed; subtype 1c elsewhere)	1300 (subtype 1b), 200 (subtype 1c)	N/A	0.15
Unconsolidated, confined (subtype 4b)	200	$5(10^{-4})$	N/A
Fractured bedrock-Nanaimo Group (subtype 5a)	0.3	$5(10^{-5})$	N/A
Fractured bedrock-undifferentiated crystalline rocks (subtype 6b) (note: limestone of the Buttle Lake Group has been grouped into the crystalline bedrock, distinct from the Nanaimo Group of sedimentary bedrock)	3	$5(10^{-5})$	N/A

Transmissivity values were assigned based on:

- Our understanding of the local surficial and bedrock geology; and
- T values calculated by Carmichael (2014) for the aquifer types and from Wei et al (2009).

Storativity (S) was assigned based entirely on whether confining sediments were encountered at the well or not. S and S_y values were based on representative values for the aquifer subtypes. In calculating SDF, we assumed the nature of aquifer confinement along the distance between the well and the stream does not change.

4.8.1 SDF for wells completed into unconsolidated, unconfined sediments

No data were available within the study area for the unconsolidated, unconfined sediments in the lower reach of Koksilah River that is part of the main Cowichan River floodplain, therefore a representative T value of 1300 m^2/day was used (see Table 1 in Wei et al, 2009). For other unconsolidated, unconfined sand and gravel in the Koksilah watershed which comprise smaller (presumably thinner) fluvial, outwash and colluvial deposits, a T value of 200 m^2/day was assigned. An S_y value of 0.15 was assigned to calculate SDFs for all wells completed into unconsolidated, unconfined sand and gravel based on professional judgement.

4.8.2 SDF for wells completed into unconsolidated, confined sediments

The T value for unconsolidated, confined sand and gravel was assigned 200 m^2/day, which is close to the geometric mean value from Carmichael (2014) for subtype 4b (confined, glaciofluvial sand and gravel) aquifers. An S value of $5(10^{-4})$ was assigned based on Carmichael's results. In using an S value for unconsolidated, confined wells, hydraulically confined conditions were assumed for this preliminary calculation because:

- Use of an S value results in smaller SDF values which implies streamflow depletion would occur more quickly (conservative case); and
- At lower elevations where the confining sediments generally occur, the static water level in confined wells should be relatively shallow, suggesting conditions are hydraulically confined.

4.8.3 SDF for wells completed into fractured bedrock

A T value of 3 m^2/day was assigned for crystalline bedrock. This is similar to the geometric mean value from Carmichael (2014) for type 6b (crystalline bedrock) aquifers. The value of 3 m^2/day is also similar to T values calculated for fractured bedrock in the Mill Bay Waterworks District just to the south (WWAL, 2018). Because of the age and lack of data of the limestone of the Buttle Lake Group, this group of sedimentary rocks has been grouped into the crystalline bedrock category for calculating SDFs. For wells completed into fractured bedrock of the Nanaimo Group, a T value of 0.3 m^2/day was assigned, similar to the geometric mean value from Carmichael (2014) for type 5b (sedimentary bedrock) aquifers. For both types of bedrock, an S value of $5(10^{-5})$ was assigned because experience shows that water in individual fractures is typically under pressure regardless of whether the bedrock aquifer is lithologically confined or unconfined.

4.9 Summary Excel Spreadsheet

To facilitate analysis of the SDF, we developed a series of worksheets using Microsoft Excel to consolidate the lithology, GIS, and hydraulic connection data. The spreadsheet tools calculate the *Stream Depletion Factor* and when applicable apportion demand between streams. The Excel spreadsheet includes 13 worksheets as shown in Table 4 below.

Table 4: Summary of MS Excel spreadsheet.

Worksheet Name	Description
Hydraulic Connection:	Summary table that provides most of the hydraulic connection data. It is used to consolidate well lithology and GIS data for wells in the study area.
Lithology:	Summary table that provides a list of stratigraphic units for the study area, organized by well WTN.
Well Output for GIS:	Summary table that consolidates well data compiled using the Hydraulic Connection and Lithology tabs for output into a GIS.
Wells <100 m:	Summary table that consolidates well data for wells located within 100 m of streams in the watershed.
UU HC Data:	GIS output of hydraulic connection interpretations for unconsolidated, unconfined (UU) wells.
UC HC Data:	GIS output of hydraulic connection interpretations for unconsolidated, confined (UC) wells.
BU HC Data:	GIS output of hydraulic connection interpretations for bedrock, unconfined (BU) wells.
BC HC Data:	GIS output of hydraulic connection interpretations for bedrock, confined (BC) wells.
Till Thickness:	Determinations of till thickness for each well where stratigraphic information is available, organized by well WTN.
Clay & Silt Thickness:	Determinations of clay & silt thickness for each well where stratigraphic information is available, organized by well WTN.
Stream Nodes:	GIS output of stream node data, used to relate PoHC to stream.
FLNRORD Data:	Raw GIS data provided by FLNRORD and used as part of this assessment.
Validation Tables:	Contains data validation tables used in summary tables.

5. RESULTS AND DISCUSSION

5.1 Hydrogeological Conceptual Model

Describing how groundwater enters, moves through and exits the subsurface is facilitated by the use of conceptual models. A conceptual hydrogeological model is a qualitative representation of a study area, which is used to describe the occurrence and flow of groundwater through the subsurface. Conditions bounding the system are identified, including: established groundwater levels, surface water bodies and watercourses, barriers to flow, and areas of groundwater recharge and discharge. Groundwater flow patterns are identified based on the interpreted hydraulic gradients. Hydrostratigraphic units are defined based on hydrogeological parameters and relative material properties.

For the purpose of this study, hydrogeological conceptual model development focused on describing key relationships as needed to assist in PoHC determinations and SDF calculations. The hydrostratigraphy of the Koksilah watershed is composed of sequences of interbedded unconsolidated sediments of likely high permeability (e.g., sand and gravel, gravel, sand) and low permeability (e.g., till, silt, clay) of variable thickness and distribution. These sequences are contained in the lithology spreadsheets developed for this study. A total of 1321 reported wells are currently located within the study area. The wells were classified for this study as either unconsolidated, unconfined (UU), unconsolidated, confined (UC), bedrock, unconfined (BU) or bedrock, confined (BC) based on reported well completion details. Data from partially complete well records were included in the hydrogeological conceptual model (if possible), but were classified as Does Not Meet Test (DNMT) in the spatial attribute tables (see Appendix B).

The unconsolidated sediments are composed of variable mixtures of sand and gravel, and clay, silt, or till, overlying fractured sedimentary or crystalline bedrock. Groundwater flow directions are discussed in Section 5.2 and are depicted in Figure 4. The geometry and distribution of the total unconsolidated sediment and confining sediment thicknesses are described below in Section 5.3 and are depicted in Figures 5 and 6, respectively. The local hydrostratigraphy is illustrated on hydrogeological cross-sections located in Appendix A of this report (see Figure 1 for cross-section locations):

- Section A-A' across Koksilah River and Heather Bank Brook (XS-1);
- Section B-B' across Koksilah River (XS-2);
- Section C-C' across Koksilah River mouth (W-E) (XS-3);
- Section D-D' across Koksilah River mouth (N-S) (XS-4);
- Section E-E' across Glenora Creek near Waters Road (see Point A on Figure 1) (XS-5);
- Section F-F' across Glenora Creek near McLay Road (see Point B on Figure 1) (XS-6);
- Section G-G' across Patrolas Creek (XS-7); and,
- Section H-H' across Kelvin and Unnamed Creek (XS-8).

5.2 Groundwater Elevation Maps

Groundwater elevations for reported wells completed into unconsolidated sediments and into bedrock are shown separately in Figure 4. Groundwater flow directions in both the unconsolidated sediments and in bedrock (inferred from the groundwater elevation contours) are generally to the north and northeast, towards the mouth of Koksilah River, reflective of topographically driven groundwater flow. The "islands" of groundwater elevation contours are likely artifacts from contouring data compiled over years and seasons.

Groundwater elevations within the unconsolidated sediments range from over 140 m above sea level (asl) in the Glenora Creek watershed to less than 20 m asl near the mouth of Koksilah River. While there are pockets of unconsolidated sediments in the upper portion of the Kelvin Creek watershed (location G in Figure 1) and middle portion of the Koksilah River watershed (see Figure 5), there are very few unconsolidated wells to allow groundwater elevations in unconsolidated sediments to be contoured there.

Groundwater elevations within bedrock range from over 240 m asl between Kelvin Creek and Koksilah River watershed boundaries to less than 20 m asl near the mouth of Koksilah River. Groundwater elevation is likely higher further up the Koksilah watershed but there are currently no wells to verify this.

A visual comparison of the groundwater elevations in unconsolidated sediments and bedrock (Figure 4) shows that groundwater elevations are typically higher in bedrock than in the unconsolidated sediments in much of the study area, indicating a propensity of upward groundwater flow from the underlying bedrock to the overlying unconsolidated sediments. However, below about 60-40 m land elevation, groundwater elevations in the unconsolidated sediments appear higher than the groundwater elevations in bedrock, suggesting a downward direction of groundwater flow in the lower portions of the Koksilah River watershed, the Patrolas Creek watershed, the Kelvin Creek watershed and the Glenora Creek watershed.

Figure 8 (see below) graphically shows what Figure 4 indicates; that the relationship between the ground surface elevation and the groundwater elevation at the well is strongly correlated. The coefficient of determination (r^2) for this relationship was calculated to be between about 0.74 and 0.89. Groundwater elevations are subdued representations of topography and groundwater flow in the unconsolidated sediments and fractured bedrock appear to be topographically driven. This provides the basis for our working assumption that groundwater in the Koksilah watershed largely discharges within the watershed and hydraulic connection of the wells should be made to streams within the watershed. To assess the significance of groundwater discharge beyond the Koksilah watershed and implications on hydraulic connection of wells to streams, a water balance and information on vertical flow (3d) are required.

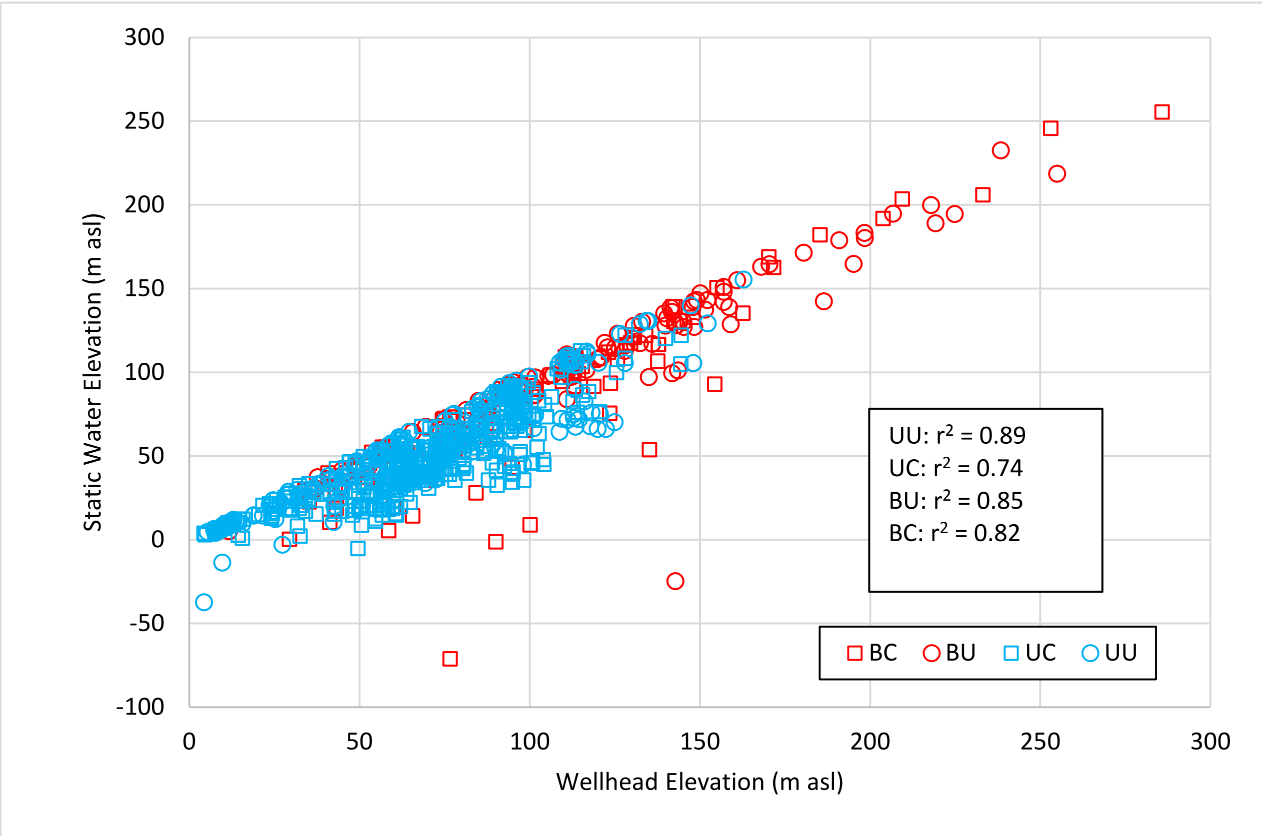


Figure 8: Well elevations vs. static water level elevations in Koksilah watershed.

5.3 Perched and Unperched Stream Reaches

Figure 4 also shows where streams within the Koksilah watershed are inferred to be likely perched (red) and not perched (clear) in relation to groundwater elevations in unconsolidated sediments and bedrock. Note that two figures were developed because the condition of where streams are perched or not were inferred from groundwater levels in unconsolidated sediments and bedrock separately, but the results are similar.

5.3.1 Koksilah River watershed

Within the study area, the mainstem of Koksilah River does not appear to be perched. With respect to tributaries within the Koksilah River watershed:

- Heather Bank Brook that drains the limestone quarry appears to largely not be perched;
- The lower reaches of Neel Creek and the three unnamed creeks immediately to the south appear to not be perched; and
- Sections of the unnamed creek immediately north of Neal Creek appear to not be perched.

Otherwise, first-order tributary streams within the study area appear to be perched.

5.3.2 Patrolas Creek watershed

The upper portion of Patrolas Creek is not perched, but the lower portion of Patrolas Creek appears to be perched, at least in places.

5.3.3 Kelvin Creek watershed

Most of the streams in the Kelvin Creek watershed appear to be perched except for the reach from the confluence with Koksilah River to ~1 Km upstream of the confluence with Glenora Creek, and at one location in the upper portion of the watershed near the junction of Hawthorne and Mountain Roads (location G in Figure 1).

5.3.4 Glenora Creek watershed

Streams in the Glenora watershed appear to be largely perched except for a few short reaches:

- Immediately downstream of Keating Lake (see Figure 1);
- At Waters Road (see location A in Figure 1);
- At Marshall Road and Glenora Road (see location B in Figure 1); and
- At McLay Road (see location C in Figure 1).

5.4 Thickness of Unconsolidated Sediments

Figures 5 and 6 show the thickness of unconsolidated sediments and thickness of likely low permeability confining sediments in the study area, respectively, based on reported well data. Unconsolidated sediments underlie the Koksilah watershed in the tributary valleys and lowlands below about 200 m asl. Unconsolidated sediment thickness reaches up to 80-90 m in the Kelvin Creek and Patrolas Creek watersheds and up to 60 m in the lower portion of the Koksilah River watershed (see cross-sections B-B', C-C' and D-D' in XS-2 through XS-4). Sediments up to 60 m thick occur in isolated patches of limited areal extent in the middle portion of the Koksilah River watershed. Above 200 m elevation, unconsolidated sediments are generally <3 m thick or absent (see Figure 5).

Confining sediments from about 120-200 m asl comprise mostly till; confining sediments below about 120 m elevation include significant amounts of silt and clay. The confining sediments are generally thickest in the Kelvin Creek watershed, where thicknesses range up to 50 m. Patches apparently absent of confining sediments around isolated wells as shown in Figure 6 may indicate the aquitards are not continuous, or may reflect the limited depth of drilling at that location (e.g., well was not drilled through the confining sediments), or lack of descriptive lithology in older well records. The one notable exception where confining sediments are absent in the lower portion of the Koksilah watershed is the northern most tip of the Koksilah watershed along Highway 1 where Koksilah River enters into the main Cowichan River valley (see Figure 1). In that area, sand and gravel directly underlie the local area (see cross-sections C-C' and D-D' in XS-3 and XS-4, respectively).

Figures 9 to 11 infer which reach of stream is directly underlain by confining sediments (i.e., till, silt, clay), superimposed over reaches of streams that appear to be perched. The resultant maps show those reaches of streams that are neither perched nor directly underlain by confining sediments (clear reaches in Figures 9 to 11). Those clear stream reaches are where significant hydraulic connection is expected to occur. Within the Koksilah watershed, those reaches are presented and briefly discussed below.

5.4.1 Koksilah River watershed

The mainstem of Koksilah River (to the edge of the study area) and tributaries at the mouth (see cross-sections in XS-1 through XS-4) appear to not be perched nor directly underlain by confining sediments;

the mainstem is underlain by fluvial (sand and gravel) deposits to beyond the edge of the study area (see surficial geology in Figure 2). Heather Bank Brook, near Thain Road (see location E in Figure 1, and cross-section A-A' (XS-1)), and the lower reach of Neel Creek and the three un-named creeks immediately to the south near the junction of Mines Road and Riverside Road (see location F in Figure 1), also appear to not be perched nor directly underlain by confining sediments.

5.4.2 Patrolas Creek watershed

The upper portion of Patrolas Creek has largely been mapped as not perched nor directly underlain by confining sediments, except at the very upper-most reach. The middle to lower reaches (downstream of location D in Figure 1) appear to by underlain by a thin layer of clay (see cross-section G-G' (XS-7)).

5.4.3 Kelvin Creek watershed

The lower reach of Kelvin Creek appears to not be perched nor directly underlain by confining sediments; this lower reach is underlain by fluvial (sand and gravel) deposits (see surficial geology in Figure 2). Another short reach that does not appear to not be perched nor directly underlain by confining sediments is near the junction of Hawthorne Road and Mountain Road (see location G in Figure 1, and cross-section H-H' (XS-8)).

5.4.4 Glenora Creek watershed

Even though much of Glenora Creek is directly underlain by fluvial (sand and gravel) deposits (see surficial geology in Figure 2), only short reaches along Glenora Creek have been mapped as absent of confining sediments. This is because the upper fluvial unit is thin and wells in the area are mostly completed into sand and gravel underneath till (confining sediments; see cross-sections E-E' and F-F' in XS-5 and XS-6). The clear reaches (no underlying confining units) are:

- The reaches immediately downstream of Keating Lake;
- At Waters Road (location A in Figure 1);
- At Marshall Road and Glenora Road (location B in Figure 1); and
- At McLay Road (location C in Figure 1).

5.5 Points of hydraulic connection (PoHCs) and stream depletion factors (SDFs)

Since groundwater appears to flow to the mouth of Koksilah River (Figure 4) and the mainstem of Koksilah River is not perched nor directly underlain by confining sediments (Figures 9-11), it is reasonable to suggest that the discharge of groundwater to streams in the study area is restricted to streams within the watershed. Therefore, hydraulically connection can likely be made for most, if not all, wells to streams within the watershed. On that premise, points of hydraulic connection were made for 1187 reported wells within the Koksilah watershed. PoHC could not be determined for 134 wells because well completion details were not reported or the well was decommissioned.

The following points summarize the categories for each type of well (based on the above methodology) for which hydraulic connection was determined:

- Unconsolidated, unconfined (UU) wells (258 wells, or 22% of total wells);
- Unconsolidated, confined (UC) wells (531 wells, or 45% of total wells);
- Bedrock, unconfined (BU) wells (205 wells, or 17% of total wells); and
- Bedrock, confined (BC) wells (193 wells, or 16% of total wells).

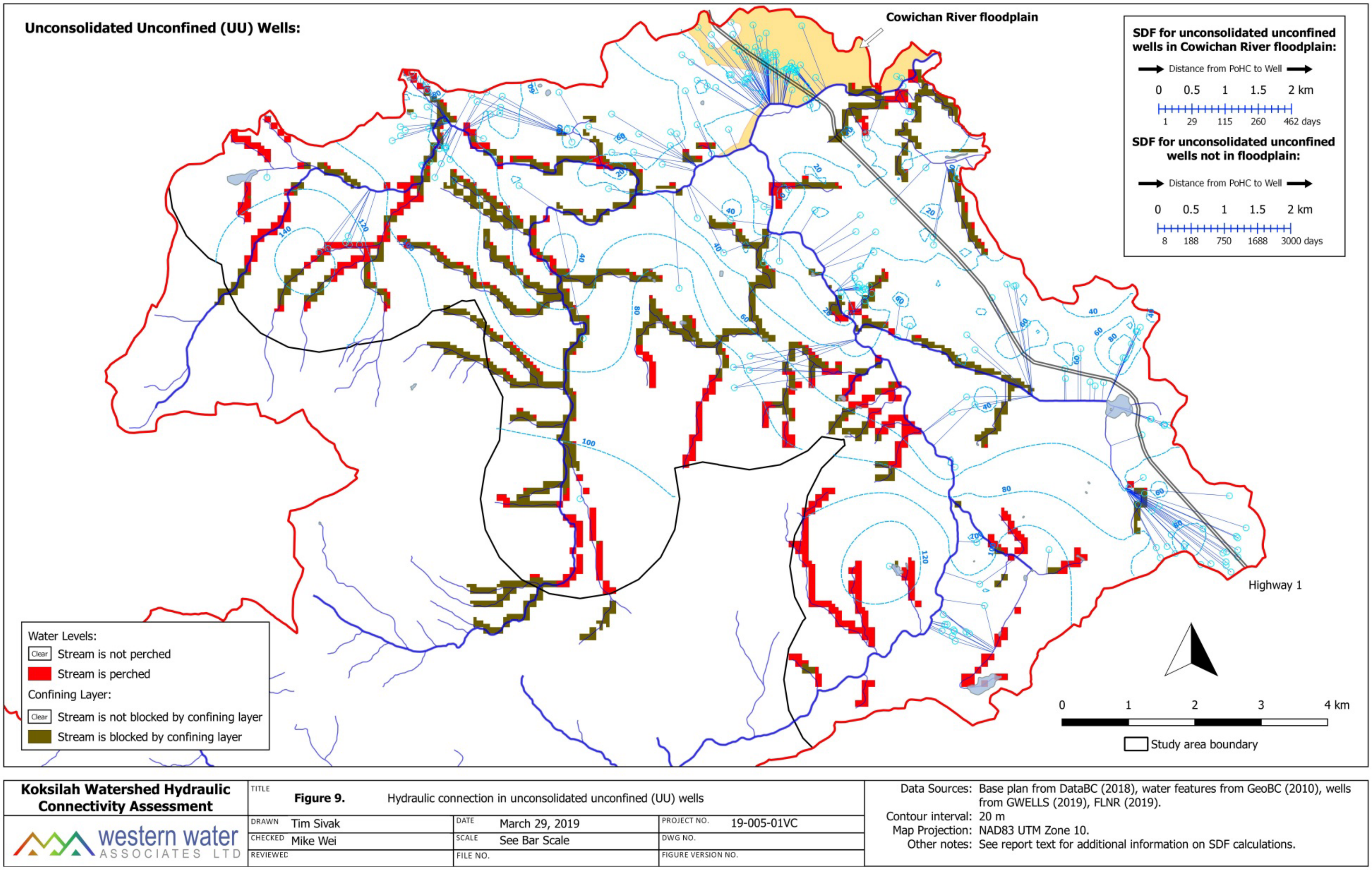


Figure 9: Hydraulic connection in unconsolidated, unconfined (UU) wells.

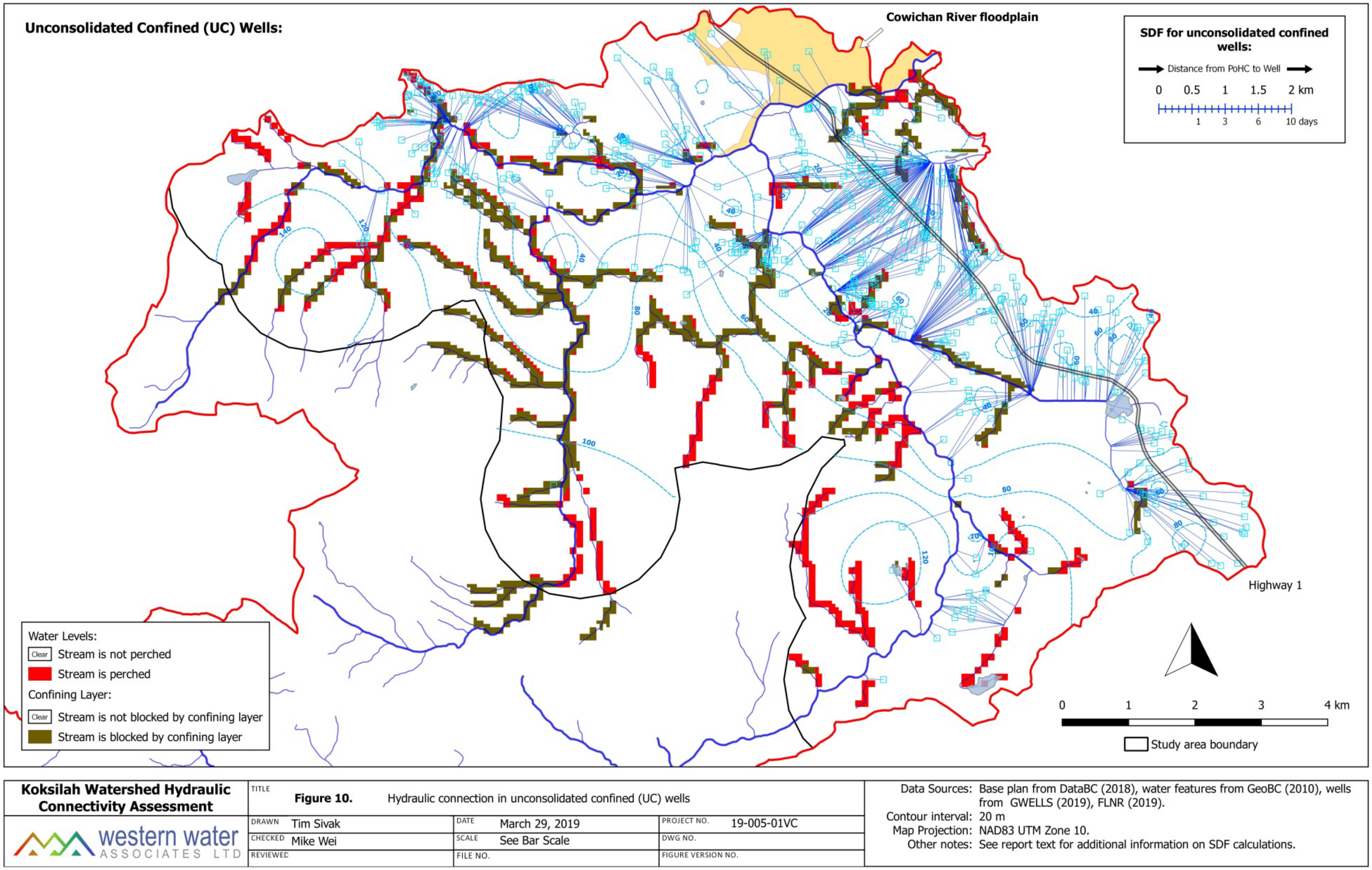
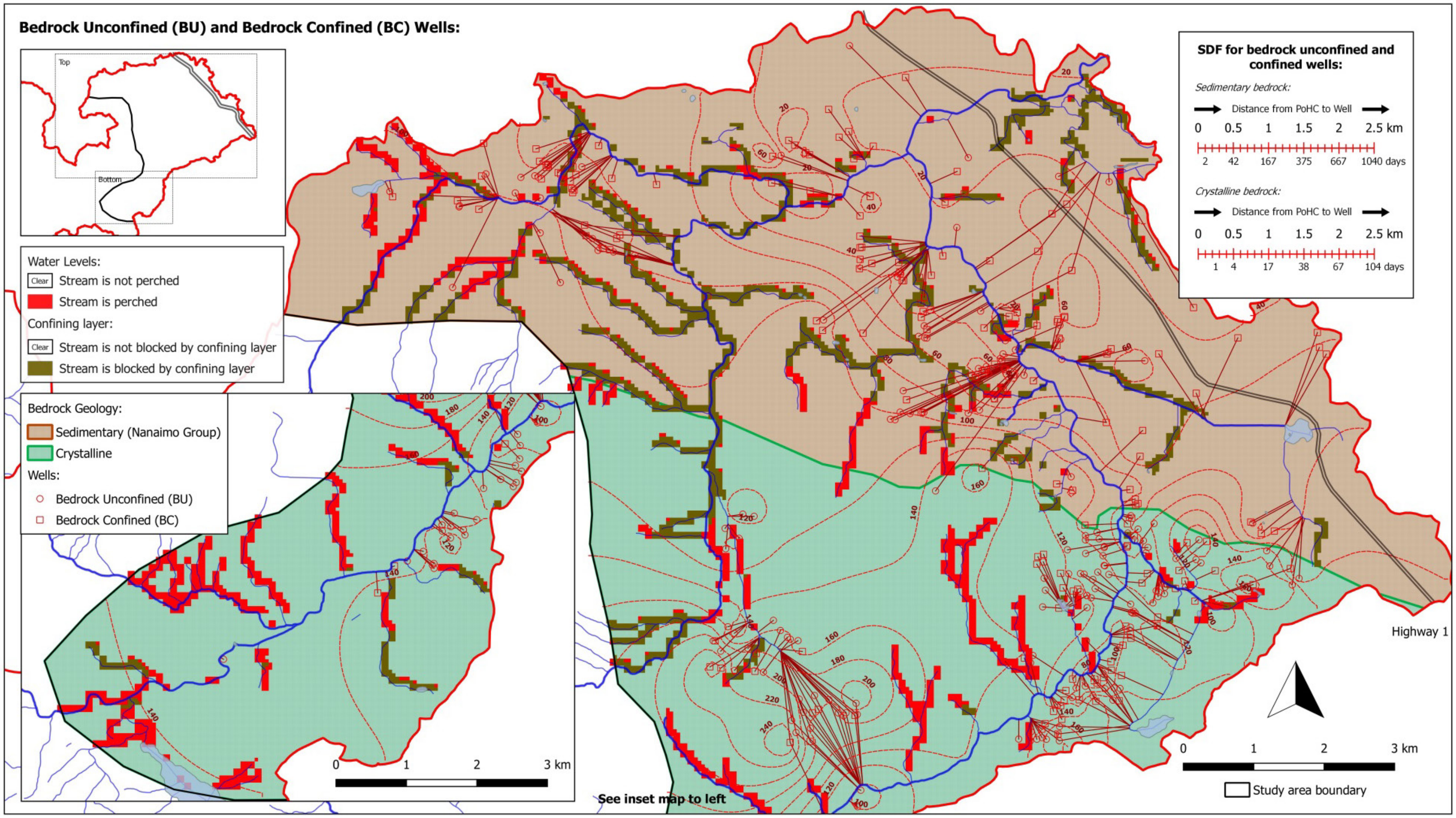


Figure 10: Hydraulic connection in unconsolidated confined (UC) wells.



Koksilah Watershed Hydraulic Connectivity Assessment	TITLE **Figure 11.** Hydraulic connection in bedrock unconfined (BU) and bedrock confined (BC) wells			Data Sources: Base plan from DataBC (2018), water features from GeoBC (2010), wells from GWELLS (2019), FLNR (2019). Contour interval: 20 m. Map Projection: NAD83 UTM Zone 10. Other notes: See report text for additional information on SDF calculations.
western water ASSOCIATES LTD	DRAWN Tim Sivak	DATE March 29, 2019	PROJECT NO. 19-005-01VC	
	CHECKED Mike Wei	SCALE See Bar Scales	DWG NO.	
	REVIEWED	FILE NO.	FIGURE VERSION NO.	

Figure 11: Hydraulic connection in bedrock, unconfined (BU) and bedrock, confined (BC) wells.

5.5.1 *Wells completed into unconsolidated, unconfined sediments*

Figure 9 shows the point of hydraulic connection for wells completed into unconsolidated, unconfined sediments in the Koksilah watershed. For many wells, the point of hydraulic connection (PoHC) is the point on the stream that is the shortest distance from the well.

Where the nearest reach of stream is either perched or directly underlain by confining sediments, we used the map of groundwater elevations (Figure 4) to look down-gradient to find the closest stream reach that is neither perched nor directly underlain by confining sediments; these stream reaches may even be associated with a neighbouring tributary stream. Examples of this are the wells at the end of Waters Road (near location A in Figure 1) in the Glenora Creek watershed. In this area, the unnamed creek closest to the wells is perched. Well pumping here is interpreted to intercept water flowing towards Glenora Creek to the north, and the PoHC is made to the reach of Glenora Creek that is not perched nor directly underlain by confining sediments. One area where the wells' PoHC were made slightly upstream is in middle Patrolas Creek, near Lakeside Road and Wilmot Road (see location D in Figure 1). Here, the reach of stream closest to the wells is underlain by confining sediments. Making the PoHC slightly upstream was deemed acceptable because the direction of groundwater flow is indistinct in this local area, so PoHC was made to the closest reach (which happens to be upstream).

In a number of areas, the PoHC for wells are made to two separate streams. In these areas, depletion to both streams is expected because both reaches are not perched nor directly underlain by confining sediments and the well is located roughly equidistance to both streams. PoHCs were made to no more than two streams, and only if apportionment to the second stream is greater than 10%. The wells between Koksilah mainstem and Heather Bank Brook, Koksilah mainstem and Patrolas Creek, and the wells bounded by Marshall Road, Glenora Road, McLay Road in the Glenora Creek watershed (locations B and C in Figure 1) are examples of wells with a PoHC to two separate streams.

The distribution of wells completed into unconsolidated, unconfined sediments show many of the PoHCs are near the mouth of Koksilah River where it enters the Cowichan River floodplain (north part of Figure 9) and at the upstream portion of Patrolas Creek.

Also shown in Figure 9are two graduated Stream Depletion Factor (SDF) scales. Each SDF scale shows distance on the top part of the scale and corresponding value of SDF on the bottom part of the scale based on the assigned aquifer hydraulic parameters for aquifer subtypes 1b and 1c in Table 4. The SDF scale is used to estimate the time lag between the start of pumping and the onset of streamflow depletion at the PoHC, based on distance and aquifer hydraulic parameters. Figure 9 contains a SDF scale for the wells completed into the unconsolidated, unconfined sediments within the Koksilah watershed that is also within the main Cowichan River valley. This SDF scale is based on a transmissivity (T) value of 1300 m^2/day and a specific yield of 0.15 (aquifer subtype 1b). The second SDF scale in Figure 9 is for the wells completed into the unconsolidated, unconfined sediments in the remaining portion of the Koksilah watershed and is based on a T of 200 m^2/day and S_y of 0.15 (aquifer subtype 1c).

Within the main Cowichan River valley, SDFs for wells completed into unconsolidated, unconfined sediments range up to 8-9 months (the PoHC is up to 1.5 Km away from the well). Within the rest of the Koksilah watershed, SDFs range from 1 week (PoHC is ~100 m away) to over 8 years (some PoHCs up to 2 km away). The relatively high SDF values reflect the unconfined nature of the aquifer (S_y) and the relatively slower rate of streamflow depletion from well pumping as compared to a confined aquifer.

5.5.2 *Wells completed into unconsolidated, confined sediments*

Figure 10 shows the PoHC between wells completed into unconsolidated, confined sediments and streams in the Koksilah watershed. Most wells completed into unconsolidated, confined sediments occur in the low-lying areas of the watershed. PoHCs are based either on the shortest distance to the nearest stream or the distance to the nearest reach downstream or down-gradient that is not perched nor directly underlain by confining sediments. Within the Koksilah watershed, SDFs for wells completed into confined, unconsolidated sediments range from less than one day to up to a couple of weeks and reflect the relatively faster rate of streamflow depletion from well pumping.

The distribution of wells completed into unconsolidated, confined sediments in the Koksilah watershed shows that most PoHCs for these wells are:

- Along the lower portion of the Koksilah mainstem;
- Along the upper and lower reaches of Patrolas Creek;
- Along the lower reach of Kelvin Creek; and
- At Glenora Road and Marshall Road (see location B in Figure 1) and at McLay Road (see location C Figure 1) in the Glenora Creek watershed.

5.5.3 Wells completed into bedrock

Figure 11 shows the PoHCs for wells completed into bedrock. Wells completed into bedrock are more commonly located in the middle to upper portion of the study area. Again, the PoHCs are either the shortest distance to the nearest stream or if the nearest stream is perched or directly underlain by confining sediments, down-gradient to the nearest stream reach that is not perched nor directly underlain by confining sediments. Wells in the Kelvin Creek watershed and between Koksilah mainstem and Heather Bank Brook have two PoHCs to two separate streams (Koksilah mainstem and headwaters of the unnamed tributary to Kelvin Creek).

Figure 11 shows an SDF scale for wells completed into the Nanaimo Group of sedimentary rocks to the north and an SDF scale for wells completed into the crystalline bedrock to the south. SDF values range from days to up to about 2 years for wells completed into the Nanaimo Group sedimentary rocks (PoHC up to 2 km away). For wells completed into crystalline bedrock, SDF values range up to 3 weeks (PoHC up to over 1 km away). The SDFs for wells completed into crystalline bedrock are much lower than for wells completed into the Nanaimo Group because transmissivity of the crystalline bedrock is estimated to be an order of magnitude greater. This implies that the rate of streamflow depletion from well pumping is faster in crystalline bedrock than in Nanaimo Group sedimentary bedrock, for comparable distances.

5.5.4 Wells near the Koksilah watershed boundary

While not part of this study, it should be noted that wells close to the edge of the Koksilah watershed boundary may also deplete nearby streams in the neighbouring watershed. The proportion of depletion to other streams outside of the Koksilah watershed will depend on the distance to the PoHC to the other stream relative to the distance to the PoHC to the stream in the Koksilah watershed.

5.6 Discussion

The nature of the relief and topography of the Koksilah watershed, limited extent and thickness (except in the lower portion of the watershed) of confining sediments, and the fact that the lower portion of Koksilah and tributary streams have (in areas) down-cut through the confining sediments, all influence which stream reaches are more open to hydraulic connection (i.e., those reaches that are not perched nor directly underlain by confining sediments). The distribution of the wells, then, determines which of those reaches well pumping is expected to affect.

The watershed relief and topography result in groundwater flow that is topographically driven; discharge of groundwater to streams from the unconsolidated and bedrock aquifers in the study area is expected to be restricted to within the Koksilah watershed. Even if there is no hydraulic connection evident along the stream reach closest to a well (and assuming isotropic conditions), groundwater within the Koksilah watershed is expected to flow generally in the down-gradient direction toward either a stream reach further downstream or to another reach in a neighbouring tributary stream. In the case of perched streams or streams directly underlain by confining sediments, the next available reach for hydraulic connection to the pumping well is generally not far away (i.e., because there are usually reaches just downstream where the stream is neither perched nor directly underlain by confining sediments). For example, while streams in the Glenora Creek watershed appear to be perched and directly underlain by confining sediments along much of their lengths, there are "windows" where connection (and depletion) can occur. Similarly, these "windows" in confining sediments allow PoHCs to be made from the well to the stream within the Koksilah watershed for most of the wells in the study and show that connection between streams in the Koksilah watershed and the underlying unconsolidated and fractured bedrock aquifers exist.

Figures 9 through 11 show that most PoHCs are made along the following stream reaches:

- Koksilah mainstem;
- Patrolas Creek; and
- Lower reach of Kelvin Creek.

These are the main reaches where depletion of streamflow from well pumping is expected to occur. However, the magnitude of streamflow depletion can only be quantified once the volume of groundwater diversion is better known.

The discussion of the "windows" in the Glenora Creek watershed above also raises the question of how certain these mapped reaches of streams that are not perched nor directly underlain by confining sediments are. The accuracy of the method depends on the number and spatial distribution of well records within the watershed to map groundwater elevations and extent of confining sediments. Given the accuracy of the digital elevation model and digital stream network, we only considered the stream perched or underlain by confining sediments if the groundwater elevation or bottom of the confining sediments were at least 3 m depth below the stream to reduce likelihood of false-identifying reaches of streams that were not perched nor directly underlain by confining sediments (see Sections 4.4.2 and 4.4.5). Confidence in the locations of the reaches of streams not perched nor directly underlain by confining sediments was higher where the length of the windows is longer. Shorter reaches where a stream is not perched nor directly underlain by confining sediments, like those reaches in the Glenora Creek watershed, could also be affected by contouring. In the example of Glenora Creek, if these short reaches are not actually perched nor directly underlain by confining sediments, the actual PoHCs for wells near those reaches would likely be made further down-gradient, to below the confluence with Kelvin Creek where the "windows" are more certain.

Portions of Koksilah mainstem illustrate where the stream has down-cut to allow hydraulic connection to occur with confined sand and gravel and with the underlying bedrock. For example, in the middle reaches of the Koksilah mainstem near cross-section A-A' (XS-1), it appears the river has down-cut through the unconsolidated sediments to allow hydraulic connection with the underlying bedrock to occur. Near the mouth (near cross-section B-B' (XS-2)), the results show that Koksilah mainstem has also down-cut to below the confining clay to allow hydraulic connection with the confined sand and gravel to occur. Note in the same area (cross-section B-B' (see XS-2)), bedrock is not exposed but hydraulic connection between the Koksilah River and the underlying bedrock can still occur if there is high permeability sand and gravel separating the stream and the bedrock.

Six of the wells that Carmichael (2014) had re-analyzed in her Cowichan Valley Regional District (CVRD) study are located in the Koksilah watershed. However, only four had pumping tests that had suitable drawdown data to provide insight into whether hydraulic connection was evident during the pumping tests. Table 5 (below) shows that drawdown in two of the three wells completed into unconsolidated, confined sediments stabilized during the pumping test. The one bedrock well (well tag number (WTN) 62965) also showed a significant decrease in rate of drawdown after ~1 ½ days into the pumping test. Stabilization (and decrease in drawdown rate) suggests a source of recharge may have been encountered as the drawdown cone expands with pumping time. Drawdown in one well (WTN 54611) did not stabilize. However, the T value calculated by Carmichael (2014) for WTN 54611 was quite low (6-8 m^2/day). Therefore, any depletion to Koksilah mainstem from pumping of WTN 54611 is expected to take much longer than the duration of the pumping test (1-day).

Table 5: Observations of drawdown in four wells located in the Koksilah watershed from Carmichael's (2014) study.

WTN	Aquifer	Point of Hydraulic Connection	Observation
35913	Unconsolidated, confined	Lower reach of Kelvin Creek	Drawdown stabilized during the pumping test.
54611	Unconsolidated, confined	Koksilah mainstem	Drawdown did not stabilize during test (T value was only ~7 m^2/day, possibly due to higher SDF).
23207	Unconsolidated, confined	Koksilah mainstem	Drawdown stabilized during the pumping test.
62965	Bedrock (crystalline)	Koksilah mainstem	Rate of drawdown decreased after 1 ½ days of pumping.

The SDF calculations illustrate that confined aquifers are expected to respond more quickly to well pumping than unconfined aquifers. Within the Koksilah watershed, wells completed into unconsolidated, confined aquifers generally have the lowest SDFs (<1 day to a couple of weeks). In contrast, SDFs for unconsolidated, unconfined sediments and for the likely low permeability Nanaimo Group of sedimentary bedrock yield the largest SDF values (up to years). Figure 12 (see below) shows how values of SDF vary with distance between a well and the PoHC on the stream, for wells completed in the various aquifer subtypes in the Koksilah watershed. For wells completed into unconsolidated, unconfined sediments and into the Nanaimo Group of sedimentary bedrock, the SDF increases relatively quickly with distance away from the stream (slower response with increasing distance); for wells completed into unconsolidated, confined sediments or crystalline bedrock, SDF does not increase nearly as quickly with distance (relatively quick response even if the pumping well is farther away). This means the period of residual depletion (i.e., depletion that occurs after pumping stops) for those connected wells completed into unconsolidated, unconfined sediments or into the Nanaimo Group are expected to be longer than for wells completed into unconsolidated, confined sediments or crystalline bedrock (period of residual depletion should be shorter lived).

From the point of view of considering water rights during a period of temporary water shortage, for example a shortage expected to last 100 days, there may be a distance beyond which curtailing groundwater pumping may have little benefit to recovery of streamflow. For example, a well completed into unconsolidated, unconfined sediments located 1 km from the stream is expected to have a SDF of 1000 days (~3 years), which suggests recovery of streamflow would be much longer than the period of water shortage (100 days) and would not be felt until well after the drought period is over. Conversely, wells completed into unconsolidated, confined sediments or crystalline bedrock located 1 kilometre from the stream have such low SDF values (a few days to a couple of weeks, respectively) that recovery of streamflow is expected in a relatively short time (days to couple of weeks). Province of B.C. (2016d) and Barroso and Wainwright (2018) provide further discussion on a screening tool for guiding management of rights during a temporary water shortage.

Impact of seasonal pumping for wells completed into unconsolidated, confined sediments or crystalline bedrock should also be expected to be felt even if the well is located a couple of kilometers away from the stream; in contrast, the rate of depletion for seasonal pumping from a well completed into unconsolidated, unconfined sediments and into the Nanaimo Group of sedimentary bedrock at the same distance is expected to be much more muted because SDFs for these wells are generally much higher. Note that the lower the SDF, the faster the rate of streamflow depletion; the higher the SDF, the slower the rate of streamflow depletion.

SDF does not account for other factors that affect (e.g., impede) the rate of streamflow depletion, such as low-permeability streambed materials nor the heterogeneous nature of the aquifers in the Koksilah watershed; therefore, SDF values should be viewed as a somewhat conservative measure of response time. SDF also does not consider the magnitude of pumping, which is another important consideration in assessing the magnitude of streamflow depletion from well pumping. We further note that SDF values are calculated based on representative values of T, S and S_Y; actual values will vary spatially because of the heterogeneous nature of aquifers. Therefore, SDF values should be interpreted with these limitations in mind.

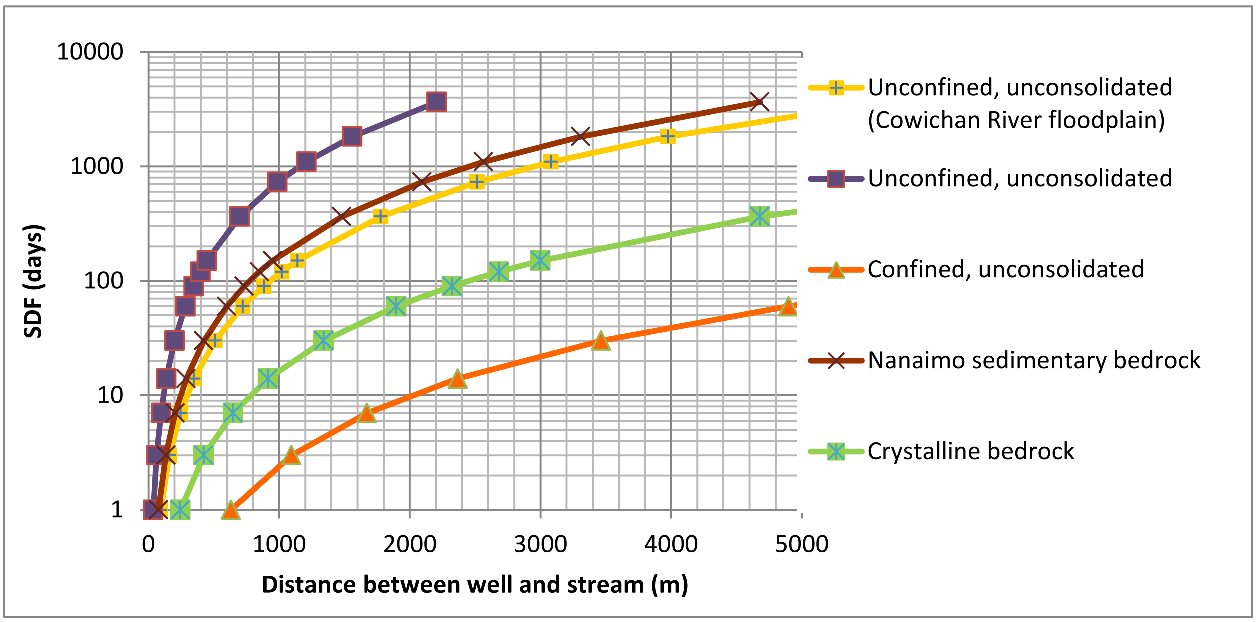


Figure 12: Graph showing SDF values with distance between the well and stream, for the different well types in the Koksilah watershed.

Finally, the results of this preliminary study provide a framework for determining where hydraulic connection is expected for new wells. Once the location of the new well has been determined, Figures 9 through 11 can be used to identify the closest reach of stream that is neither perched nor directly underlain by confining sediments to which a PoHC can then be made.

6. <u>RECOMMENDATIONS FOR FURTHER WORK</u>

6.1 Koksilah Watershed

The following are recommendations to improve on the current understanding of the nature of hydraulic connection in the Koksilah watershed:

6.1.1 Technical studies

- Conduct field work during late summer to:
    - Check local geology;
    - Identify stream reaches with groundwater inflow where streamflow depletion is most likely to occur by collecting stream temperature and electrical conductivity or thermal infrared measurements; and
    - Visually inspect the streambed to verify those reaches of streams in the watershed where hydraulic connection is expected;
    - Conduct field assessments of stream reaches in the upper and middle watershed that were identified as perched to determine if they exhibit ephemeral flow, and therefore may have a lower degree of hydraulic connection to the groundwater flow system.
- Update Barroso and Wainwright (2018)'s curtailment model using the results from this study.
- To assess the reasonableness of the working assumption that discharge of groundwater occurs mostly within the Koksilah watershed, consider establishing a hydrometric station near the mouth of Koksilah River (near Highway 1) to measure streamflow and develop a water balance for the watershed.
- Consider establishing and testing multilevel observation well(s) in aquifers close to streams to verify vertical gradients (3d), aquifer hydraulic parameters, groundwater elevations and hydraulic connection between the fractured bedrock aquifers, layered unconsolidated aquifers and the stream with greater certainty. This would include conducting a pumping test on the observation well(s), monitoring water levels and water temperatures in the observation well(s) and nearby stream(s).
- Promote use of observation wells (where feasible) when conducting a pumping test to obtain more site-specific values of S, S_y and T.
- Survey critical reaches of Koksilah River and main tributaries to determine more accurate stream elevations. Critical reaches are areas with high numbers of PoHC, and where the confining sediments underneath the streams are absent. Based on the results of this study, the critical reaches include areas of Glenora Creek (refer to discussion on Glenora Creek in Section 5.7 above), and Koksilah River near the mouth (refer to discussion on Koksilah River in Section 4.6 above).

6.1.2 Regulatory

- Consider requiring, as a condition of a water licence, measuring and reporting of quantities diverted and monthly static water levels for key wells diverting water for non-domestic use (above a threshold limit, capacity of licensee to comply).

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GLOSSARY

Aquifer:	A geological deposit that is permeable and saturated that allows a sufficient supply of water to flow to wells and to springs.
Aquitard:	A geological deposit that is made up of mainly low permeability sediments like till, silt or clay. Also sometimes referred to as a confining layer.
Coarse-grained:	Sediment composed of larger diameter particles like sand and gravel.
Confined aquifer:	An aquifer that is overlain by confining sediments or confining layer; groundwater in a confined aquifer is commonly under pressure.
Confining sediments:	Sediments composed of typically low permeability sediments like till, silt or clay.
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*).
Homogeneous, homogeneity:	In relation to hydrogeology, where geological characteristics (e.g., permeability, storativity, thickness) do not change spatially.
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.
Perched stream:	A stream that is separated from the underlying groundwater system by an unsaturated zone.
Point of hydraulic connection (PoHC):	The point at which depletion of streamflow 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 depletion factor (SDF):	A measure of how quickly the rate of depletion of the stream occurs, based on the distance of the pumping well to the stream and the aquifer transmissivity and storativity or specific yield:

$$SDF = d^2 \times \frac{S}{T} (confined) or\ SDF = d^2 \times \frac{Sy}{T} (unconfined) \quad \text{Equation [1]}$$

Where:

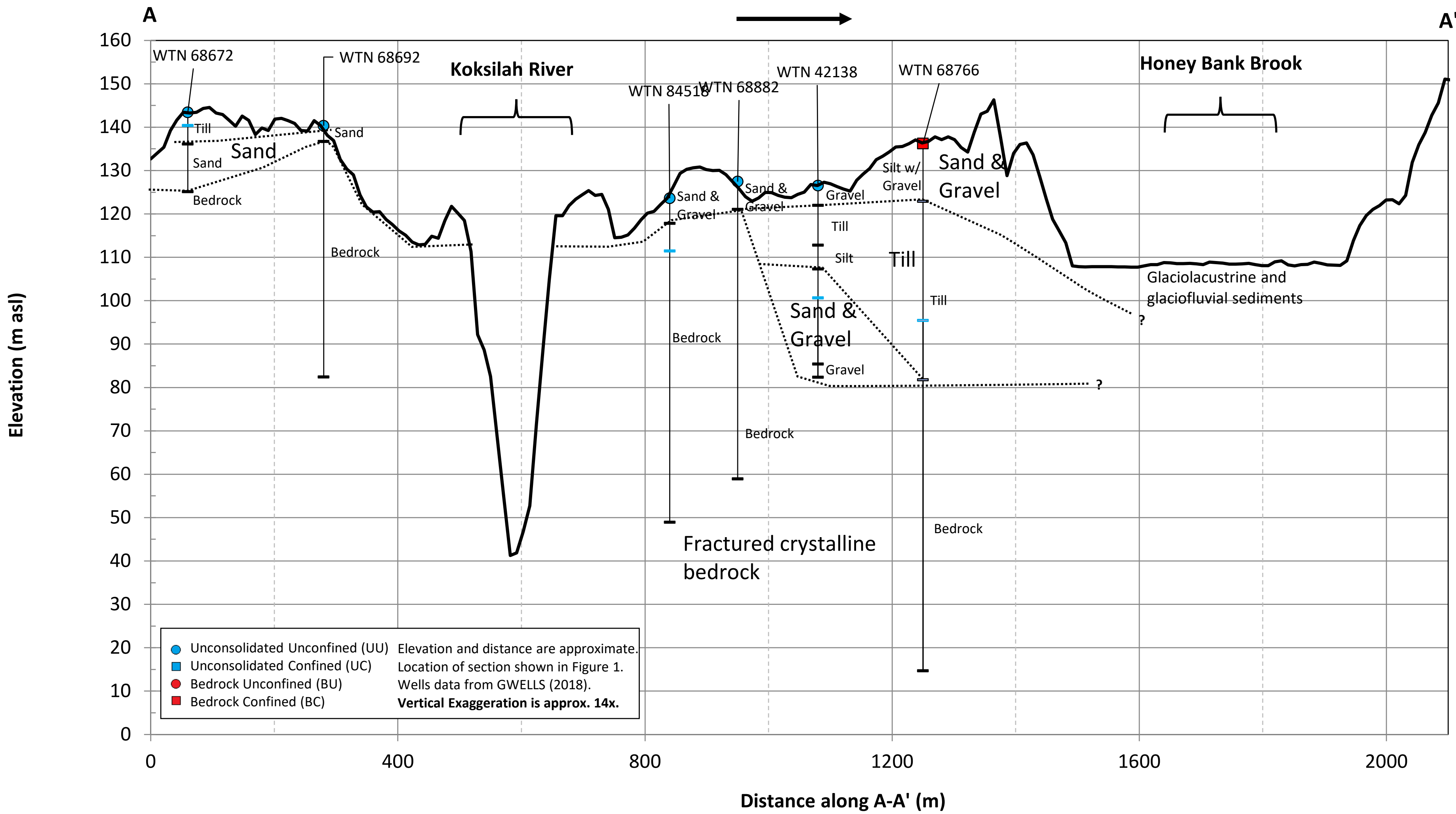
d is the distance between the well and the nearby stream (or distance from the well to the PoHC) ;

S is the aquifer storativity (confined) and S_y is the aquifer specific yield (unconfined), whichever is the predominant case; and

T is the aquifer transmissivity, see definition below.

Stream order:	A hierarchy within a stream network where the uppermost streams in the watershed are called first-order streams. A stream attains a higher order when two streams of the same order join. For example, two first-order streams join to become a second-order stream and so on. The order of a stream also reflects the size of a stream; higher order streams are larger than lower-order streams.
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”.
Water table:	The top of the saturated zone in the ground where the water pressure is equivalent to atmospheric pressure.

APPENDIX A: HYDROGEOLOGICAL CROSS-SECTIONS



Koksilah River Watershed Hydraulic Conductivity Assessment

TITLE

XS-1. Section A-A' across Koksilah River and Heather Bank Brook

DRAWN	Tim Sivak	DATE	March 18, 2019	PROJECT NO.	19-005-01VC
CHECKED	Mike Wei	SCALE	N/A	DWG. NO.	N/A
REVIEWED		FILE NO.		FIGURE VERSION NO.	

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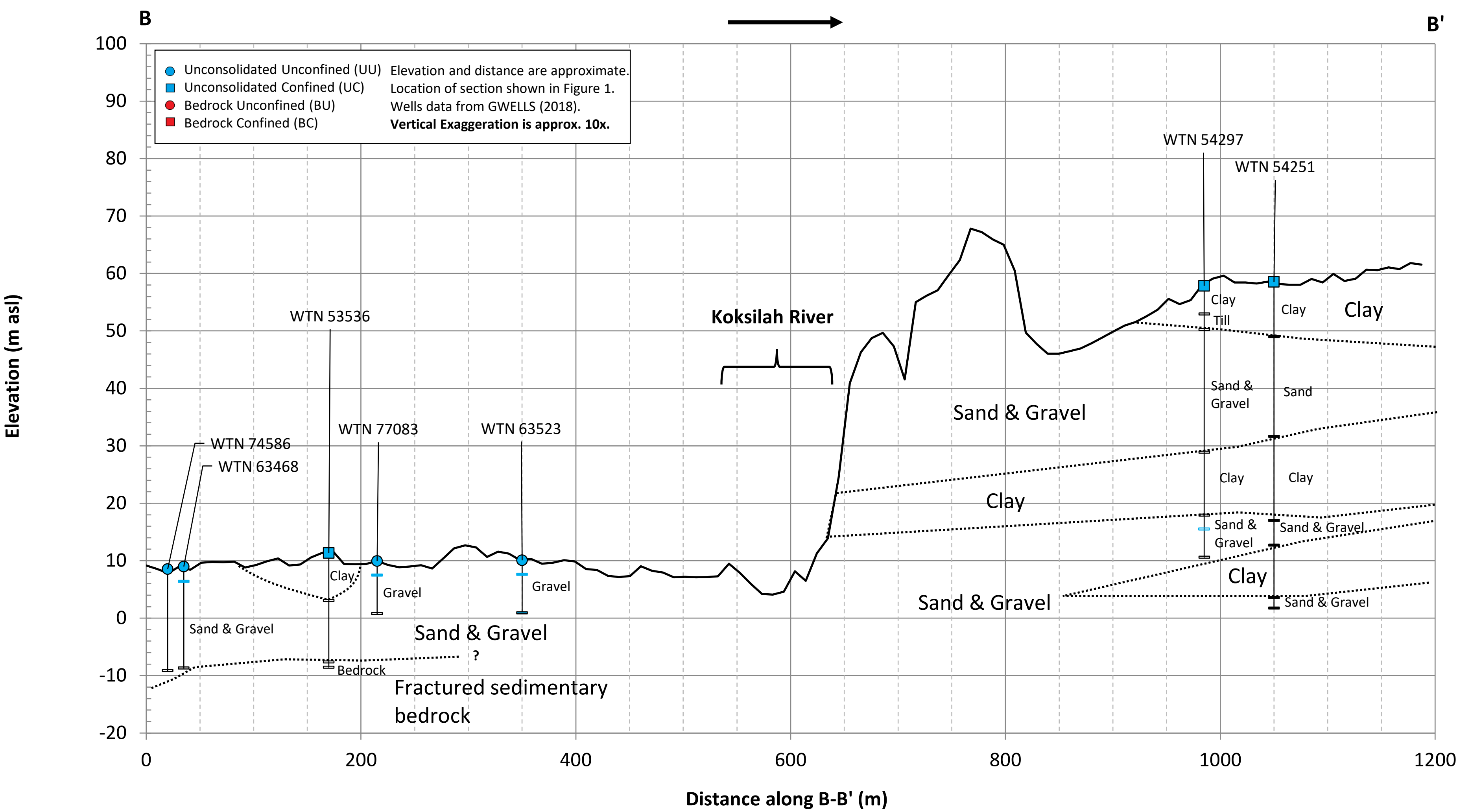
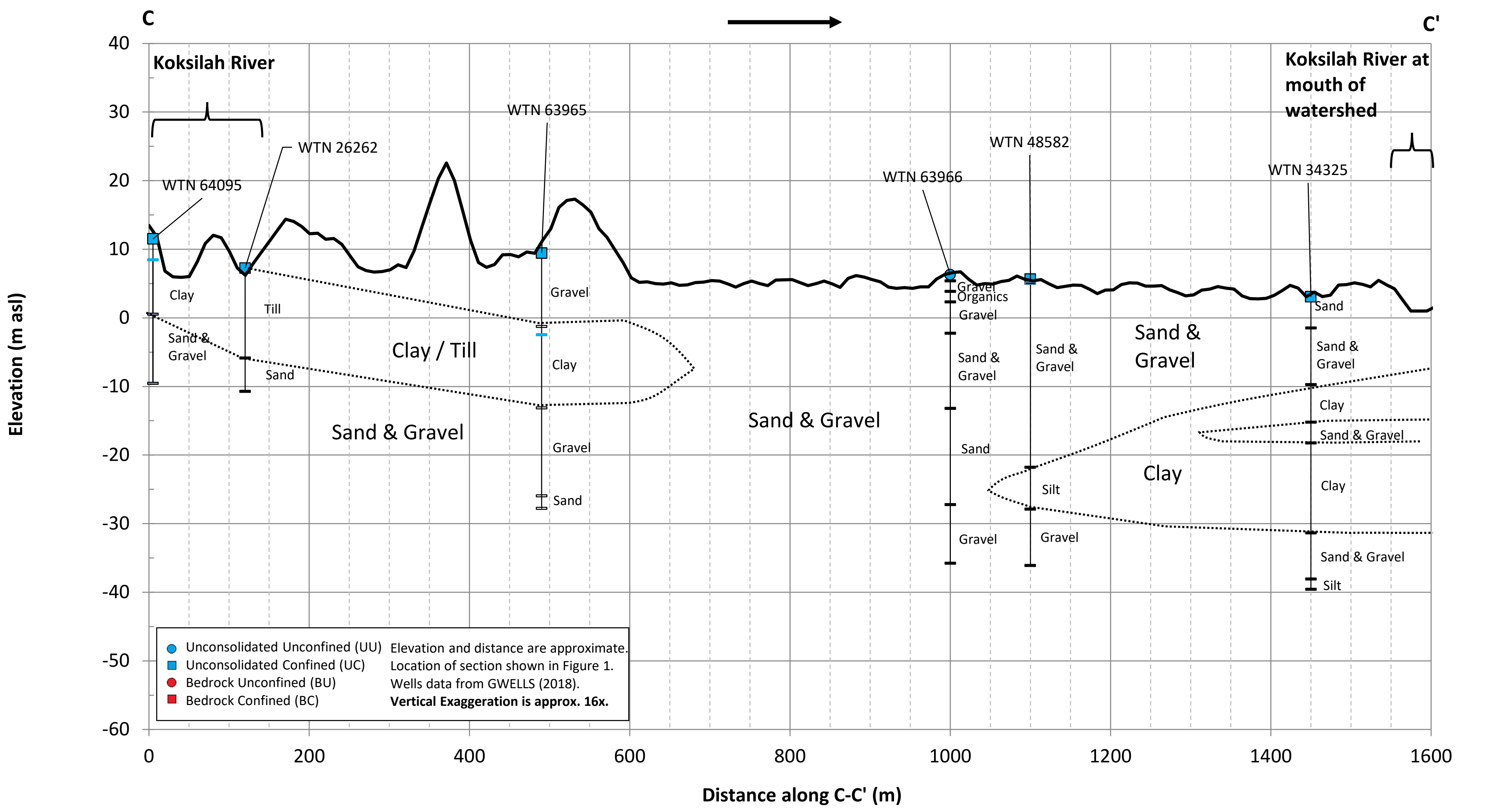
Consultants in Hydrogeology and Water Resources Management



Koksilah River Watershed Hydraulic Conductivity Assessment	TITLE **XS-2. Section B-B' across Koksilah River**				
western water ASSOCIATES LTD Consultants in Hydrogeology and Water Resources Management	DRAWN Tim Sivak	DATE	March 18, 2019	PROJECT NO.	19-005-01VC
	CHECKED Mike Wei	SCALE	N/A	DWG. NO.	N/A
	REVIEWED	FILE NO.		FIGURE VERSION NO.	

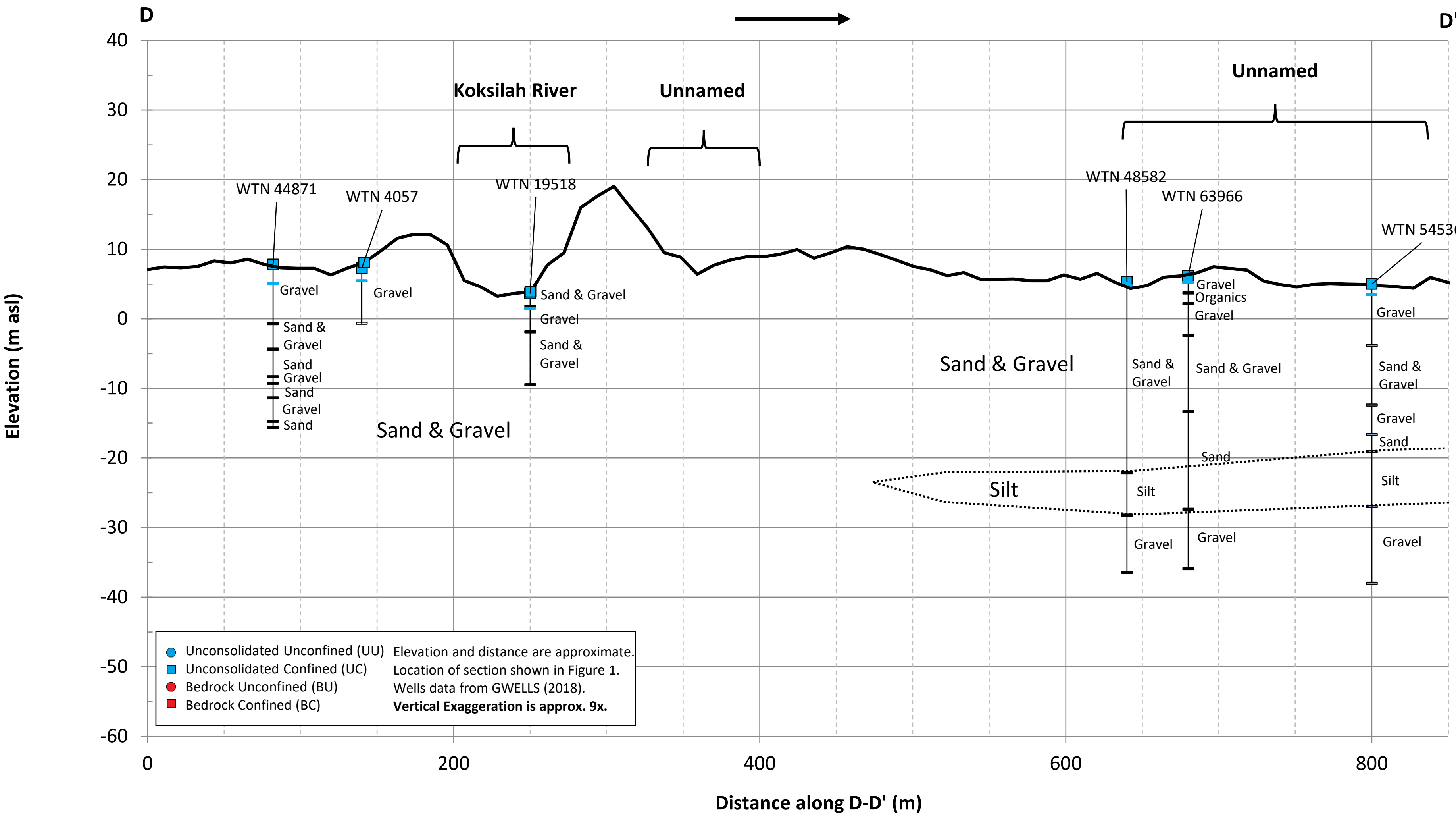


Koksilah River Watershed Hydraulic Conductivity Assessment

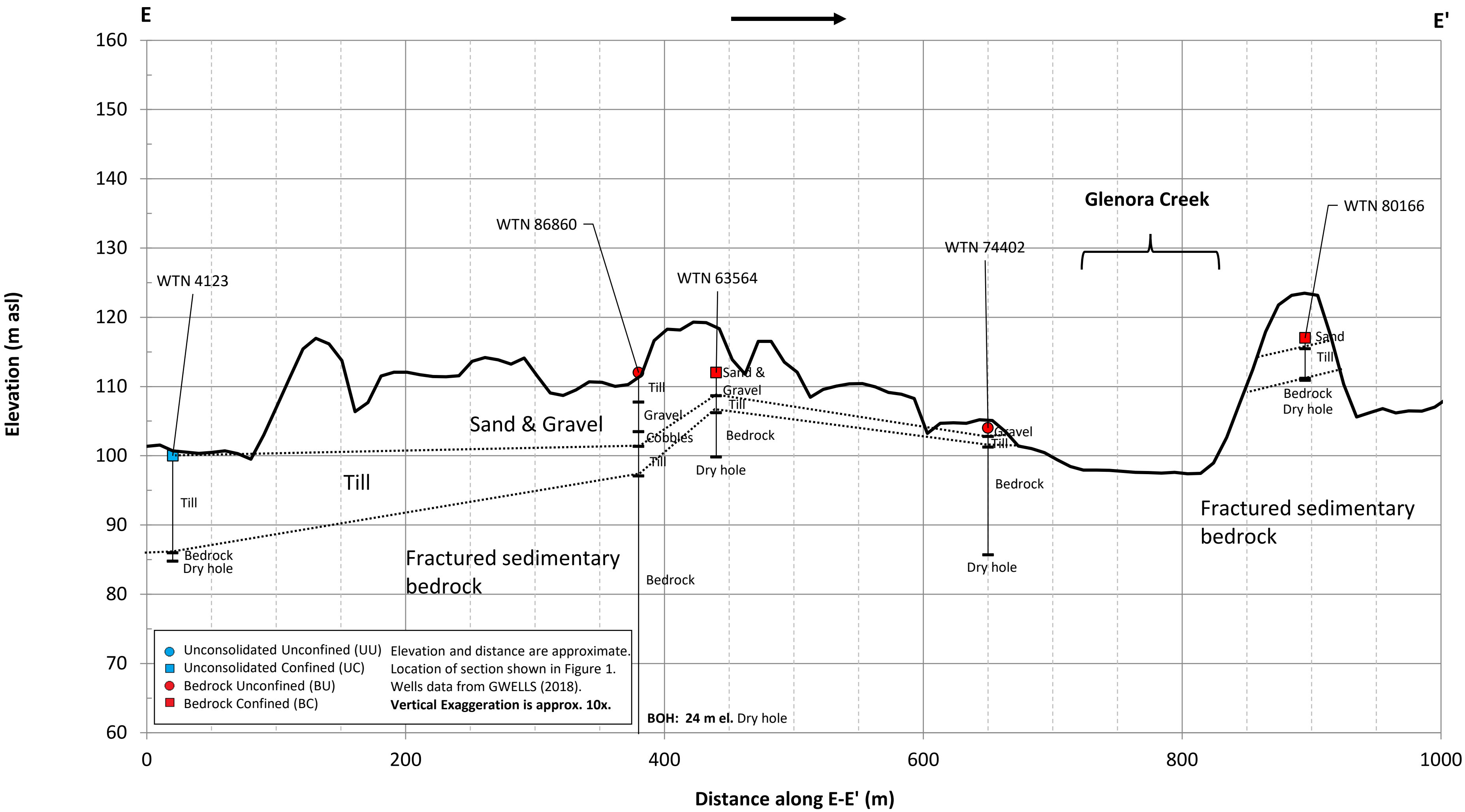
western water ASSOCIATES LTD
Consultants in Hydrogeology and Water Resources Management

TITLE
XS-3. Section C-C' across Koksilah River mouth (W-E)

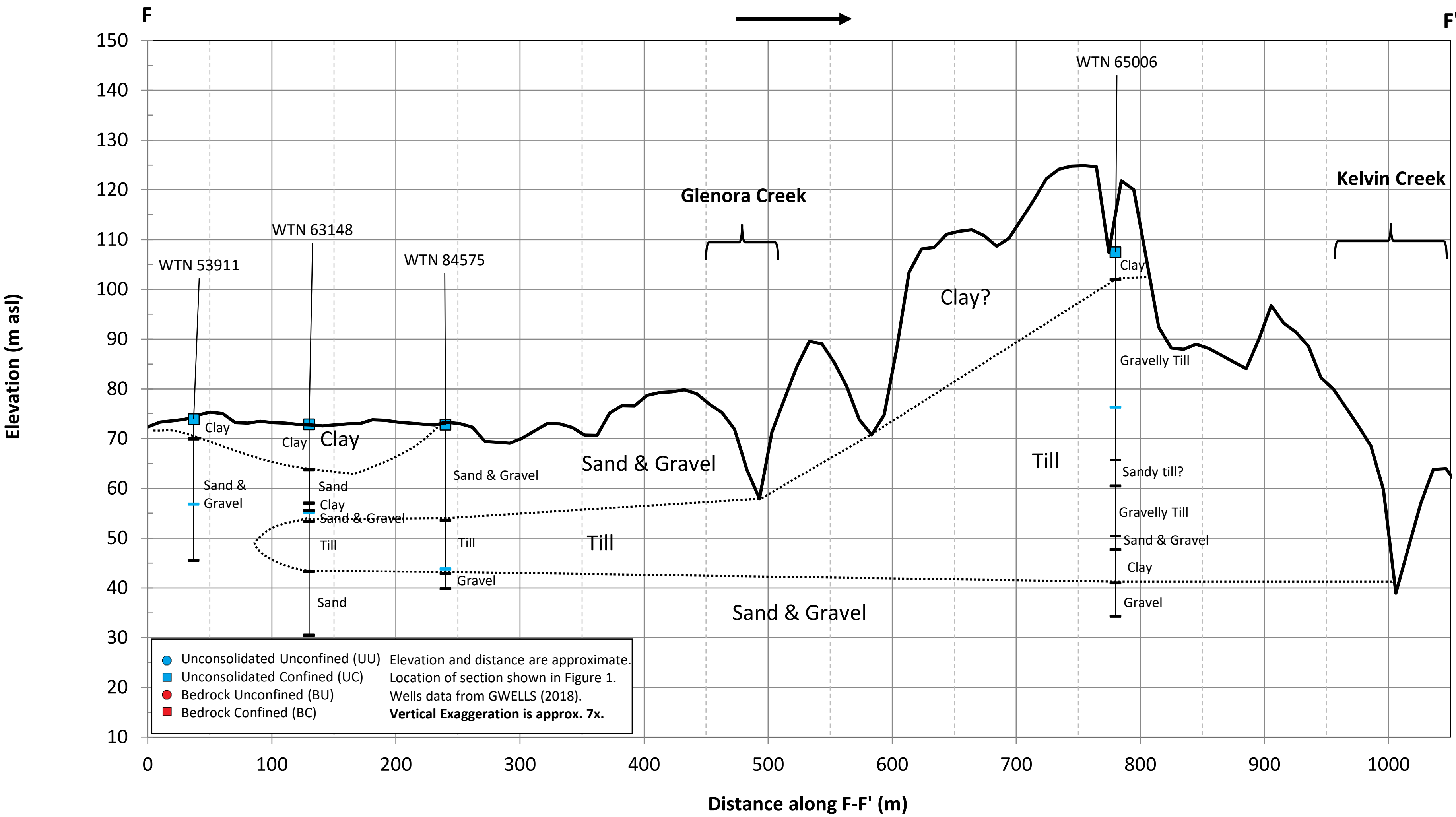
DRAWN	Tim Sivak	DATE	March 18, 2019	PROJECT NO.	19-005-01VC
CHECKED	Mike Wei	SCALE	N/A	DWG. NO.	N/A
REVIEWED		FILE NO.		FIGURE VERSION NO.	



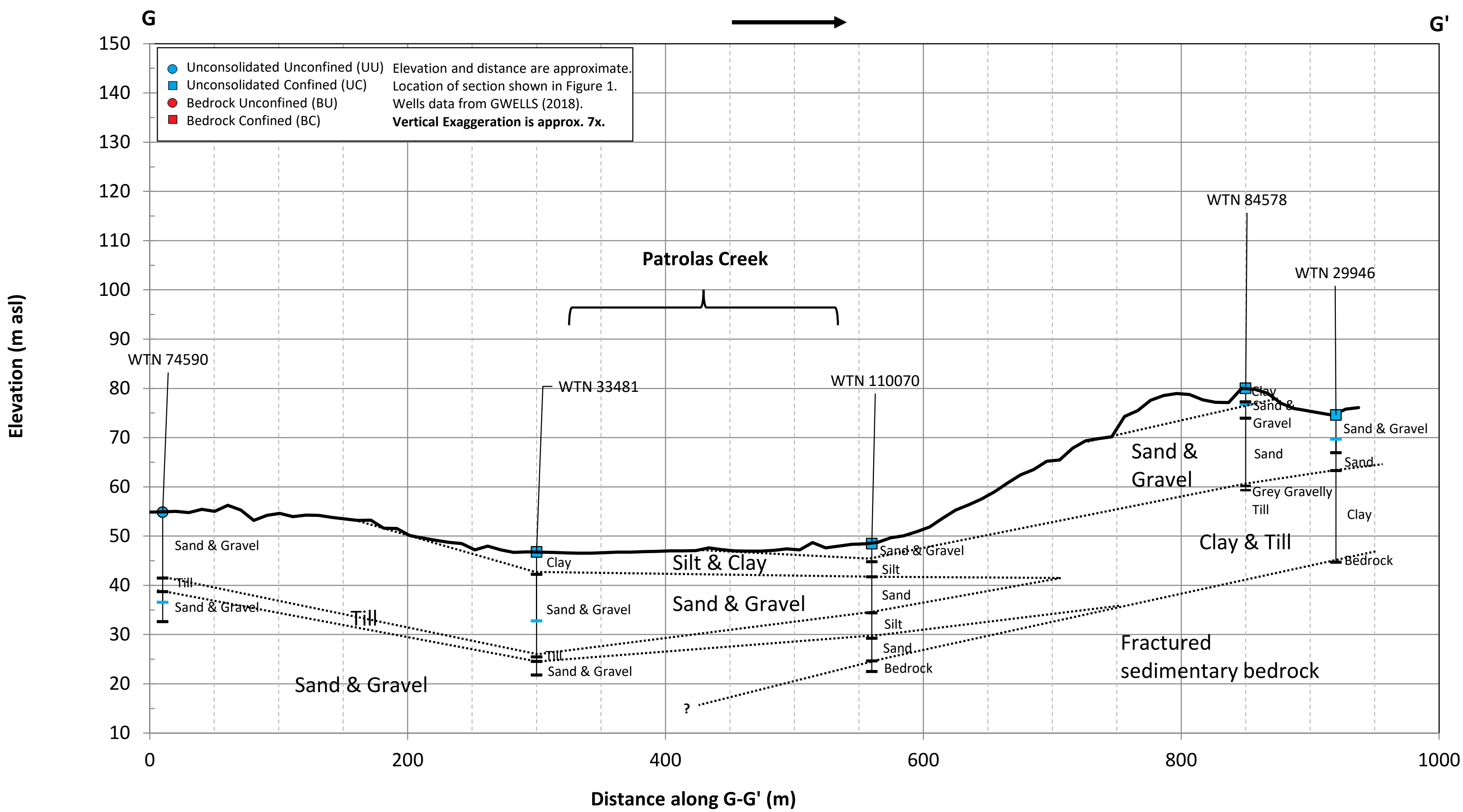
Koksilah River Watershed Hydraulic Conductivity Assessment	TITLE XS-4. Section D-D' across Koksilah River mouth (N-S)		
western water ASSOCIATES LTD Consultants in Hydrogeology and Water Resources Management	DRAWN Tim Sivak	DATE March 18, 2019	PROJECT NO. 19-005-01VC
	CHECKED Mike Wei	SCALE N/A	DWG. NO. N/A
	REVIEWED	FILE NO.	FIGURE VERSION NO.



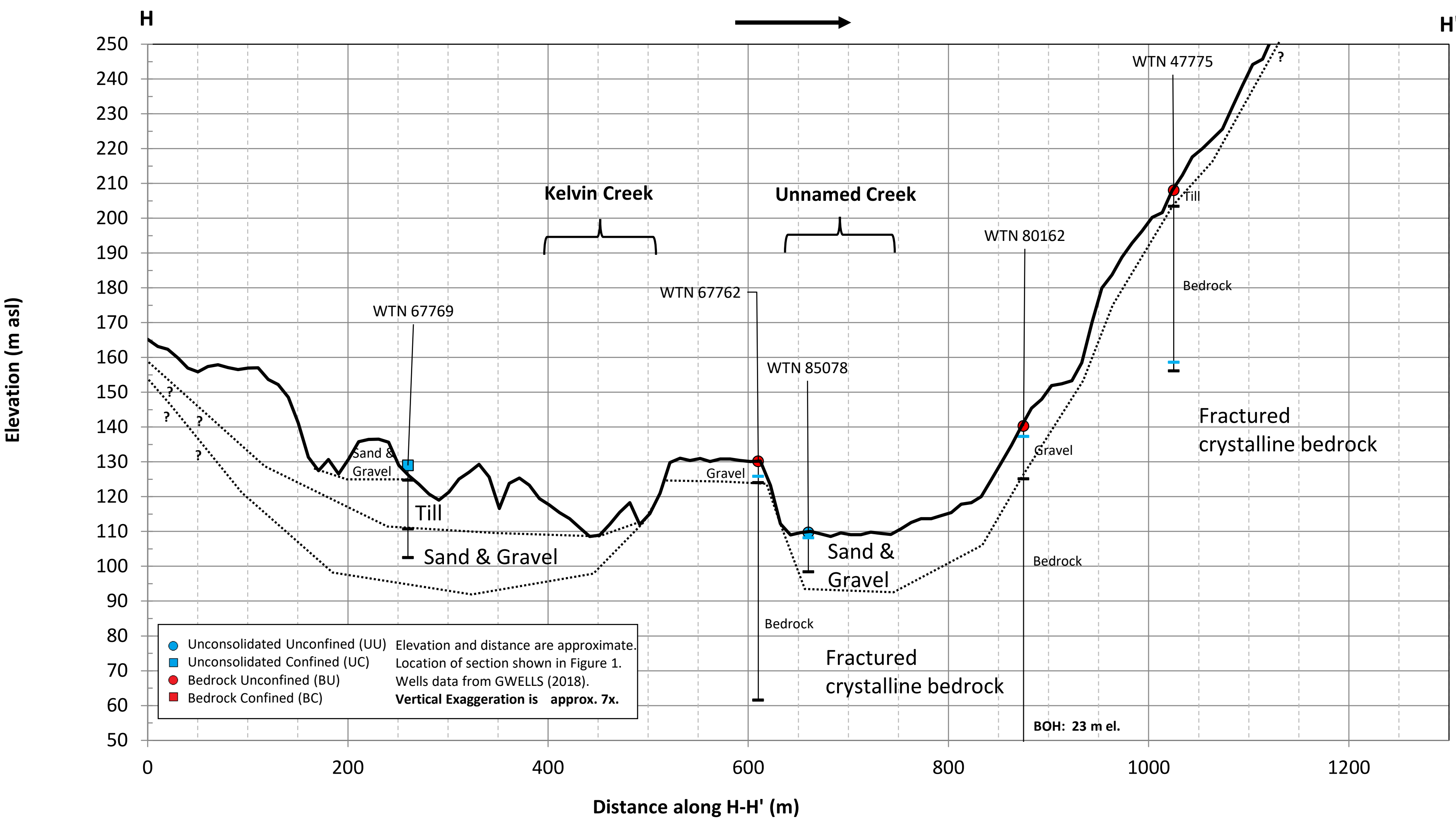
Koksilah River Watershed Hydraulic Conductivity Assessment	TITLE XS-5. Section E-E' across Glenora Creek near Waters Road				
western water ASSOCIATES LTD Consultants in Hydrogeology and Water Resources Management	DRAWN: Tim Sivak	DATE: March 18, 2019	PROJECT NO.: 19-005-01VC		
	CHECKED: Mike Wei	SCALE: N/A	DWG. NO.: N/A		
	REVIEWED:	FILE NO.:	FIGURE VERSION NO.:		



Koksilah River Watershed Hydraulic Conductivity Assessment	TITLE **XS-6. Section F-F' across Glenora Creek near McLay Road**					
western water ASSOCIATES LTD Consultants in Hydrogeology and Water Resources Management	DRAWN	Tim Sivak	DATE	March 18, 2019	PROJECT NO.	19-005-01VC
	CHECKED	Mike Wei	SCALE	N/A	DWG. NO.	N/A
	REVIEWED		FILE NO.		FIGURE VERSION NO.	



Koksilah River Watershed Hydraulic Conductivity Assessment	TITLE: **XS-7. Section G-G' across Patrolas Creek**		
western water ASSOCIATES LTD — Consultants in Hydrogeology and Water Resources Management	DRAWN: Tim Sivak	DATE: March 18, 2019	PROJECT NO.: 19-005-01VC
	CHECKED: Mike Wei	SCALE: N/A	DWG. NO.: N/A
	REVIEWED:	FILE NO.:	FIGURE VERSION NO.:



Koksilah River Watershed Hydraulic Conductivity Assessment	TITLE **XS-8. Section H-H' across Kelvin and Unnamed Creek**				
western water ASSOCIATES LTD Consultants in Hydrogeology and Water Resources Management	DRAWN Tim Sivak	DATE March 18, 2019	PROJECT NO. 19-005-01VC		
	CHECKED Mike Wei	SCALE N/A	DWG. NO. N/A		
	REVIEWED	FILE NO.	FIGURE VERSION NO.		

APPENDIX B: SPATIAL DATA DESCRIPTIONS

Spatial Dataset	Format	Description	Comments
XSectionLines	ESRI Shapefile (.SHP)	Location of cross-section lines from study.	-
CONF_ISO	Raster (.TIF)	Confining unit isopach surface.	Symbolized using discrete interpolation where values <= 3 are transparent.
UNCONSOL_ISO	Raster (.TIF)	Confining unit isopach surface.	Symbolized using discrete interpolation where values <= 3 are transparent.
Confining_Contours_10m	ESRI Shapefile (.SHP)	Contours for confining layer (10 m contour interval).	-
Unconsolidated_Contours_10m	ESRI Shapefile (.SHP)	Contours for unconsolidated layer (10 m contour interval).	-
Conflyr_ste	Raster (.TIF)	Distribution of confining layer under streams.	Symbolized using discrete interpolation where values <= 3 are transparent.
UU HC Connections	ESRI Shapefile (.SHP)	PoHC layer for UU wells.	Field “HubDist” refers to calculated distance from stream node. Field “NODE_ID” identifies node where connection is made.
UC HC Connections	ESRI Shapefile (.SHP)	PoHC layer for UC wells.	Field “HubDist” refers to calculated distance from stream node. Field “NODE_ID” identifies node where connection is made.
BU HC Connections	ESRI Shapefile (.SHP)	PoHC layer for BU wells.	Field “HubDist” refers to calculated distance from stream node. Field “NODE_ID” identifies node where connection is made.
BC HC Connections	ESRI Shapefile (.SHP)	PoHC layer for BC wells.	Field “HubDist” refers to calculated distance from stream node. Field “NODE_ID” identifies node where connection is made.
UNC study area limit	ESRI Shapefile (.SHP)	Spatial extent of wells completed in unconsolidated sediments.	Based on approximate distance between wells.
Bedrock study area limit	ESRI Shapefile (.SHP)	Spatial extent of wells completed in fractured bedrock.	Based on approximate distance between wells.
CowichanR Floodplain	ESRI Shapefile (.SHP)	Location of Cowichan River floodplain.	Derived from Forest Renewal BC dataset (1992).
Koksilah well data	ESRI Shapefile (.SHP)	Compiled well data for wells within Koksilah watershed.	fDepth: Final depth of well. Aquifer: well completion details. Well_El: elevation of well head.

Spatial Dataset	Format	Description	Comments
			SWL_El: elevation of static water level. BR_El: elevation of bedrock. UNC_Thick: total thickness of unconsolidated sediments at well point. TL_Thick: thickness of till (confining) at well point. CLML: thickness of clay and silt (confining) at well point. CONF_thick: total thickness of confining layer at well point. HC_Class: HC classification (UU, UC, BU, BC, or DNMT).
SWL_BR	Raster (.TIF)	Static water elevations in bedrock wells compared to stream elevations.	Symbolized using discrete interpolation where values <= 3 are transparent, and >3 are red.
SWL_UNC	Raster (.TIF)	Static water elevations in wells completed in unconsolidated sediments compared to stream elevations.	Symbolized using discrete interpolation where values <= 3 are transparent, and >3 are red.
SWLbr	Raster (.TIF)	Elevation of water surface in bedrock wells.	-
SWLunc	Raster (.TIF)	Elevation of water surface in wells completed in unconsolidated overburden.	-
Topo_10m	ESRI Shapefile (.SHP)	Topographic contours (10 m contour interval) derived from DEM (10 m resolution).	-
BR Surface	Raster (.TIF)	Elevation of bedrock surface.	-