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Preliminary Assessment of Hydraulic Connection for the Chilliwack Area

Tim Sivak and Mike Wei

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Cover Photograph: Vedder Canal Dike at Keith Wilson Road, looking northeast toward Chilliwack Mountain (Western Water Associates Ltd., 2023)

Acknowledgements

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EXECUTIVE SUMMARY

Likelihood of hydraulic connection in the Chilliwack area is of interest to the Ministry of Water, Land and Resource Stewardship (WLRS) to inform licensing of groundwater and attributing licensed pumping demand to streams. Under contract no. GS24LMN0006, Western Water Associates Ltd. (WWAL) assessed the likelihood of hydraulic connection for 859 wells in a study area that contained 30 mapped aquifers (23 unconsolidated and 7 fractured bedrock aquifers). To map likelihood of hydraulic connection, the study area was sub-divided into four distinct physiographic sub-areas: 1) the Fraser-Sumas Floodplain, 2) Columbia Valley-Cultus Lake, 3) Chilliwack River Valley, and 4) Ryder Uplands. In each sub-area, the likelihood of hydraulic connection was inferred by mapping the groundwater flow directions, the presence/absence of a vadose zone and low permeability confining layer directly beneath the streams, and then connecting wells to open stream reaches.

Of the 859 wells assessed in the study area, hydraulic connection to streams were inferred for 783 wells. Nearly half (47%) of the wells were connected to more than one stream; fractional pumping demand for these wells were attributed to multiple streams. Connection to streams could not be inferred for 76 wells. This was because those wells were either completed into fractured bedrock aquifers where overlying streams are perched (disconnected) or in confined, unconsolidated aquifers in the Ryder Uplands sub-area where the hydrogeology and aquifer boundaries are not well understood. Hydraulic connection to streams also could not be inferred for wells completed into Aquifer 1197, a deep, confined, unconsolidated aquifer in the Fraser River floodplain. Instead, windows in the confining unit separating Aquifer 1197 and the over-lying shallow unconfined aquifers were identified to infer where connection between aquifers occurs.

For the wells that are inferred to be hydraulically connected to streams, the distance between the well and the connected stream(s) allowed the Stream Depletion Factor (SDF) to be calculated. In calculating the SDFs, representative transmissivity and storativity values were used for Aquifers 6, 8, 21, 1199, 9, and 1206 based on limited pumping tests for the study area. For the other aquifers, default transmissivity and storativity values from Lepitre and Beebe (2019) were used. Calculated SDFs for most of the wells assessed in the study area range from <1 day to 30 days, indicative of quick, responsive flow systems. This suggests taking action to curtail both surface water and groundwater uses to protect streamflow during drought is feasible. Only Aquifer 20 in the Columbia Valley had SDFs of greater than one year because of the relatively long distances between many wells up the valley to connected streams at Cultus Lake, suggesting curtailment of groundwater use from the more distant wells (e.g., with SDFs of >90 days or >one year) to protect streamflow during drought would not likely be effective because of the longer response times.

Understanding of the aquifers and likelihood of hydraulic connection enabled conceptual models to be formulated regarding the sources of inflow, outflow and capture for the aquifers, to provide insight into what some of the major allocation considerations could be. For the shallow, unconsolidated aquifers, streamflow depletion is expected to be a major groundwater allocation consideration. For small unconsolidated aquifers, aquifer storage depletion is another allocation consideration. For the bedrock aquifers, decrease in discharge to connected streams (not many) and aquifer storage depletion are the main allocation considerations. Despite the uncertainties inherent in this preliminary study, the study provides a systematic and larger-scale context to inform future studies and authorization of groundwater use in the Chilliwack area.

The following are recommendations arising from this study:

- Extend the preliminary hydraulic connection mapping to the Sumas Prairie, and up the Chilliwack River Valley to Chilliwack Lake.

- Within the study area, prioritize aquifers for further assessment where there is already significant groundwater use from non-domestic sources or ongoing plans for development of additional non-domestic groundwater sources is proposed by licence applications.
- Install observation wells in bedrock Aquifers 890 and 899, and one of the confined, unconsolidated aquifers in the Ryder Uplands sub-area to better understand the local hydrogeology.
- Install multi-level observation wells in Aquifer 1197 and the overlying shallow unconsolidated aquifers in the Fraser River floodplain, as well as in Aquifers 1206 and 9 along the Chilliwack River to better understand hydraulic connection between those aquifers.
- Explore why the boundary of Aquifer 20 does not extend to Cultus Lake.
- Seek opportunities to update the surficial and soils mapping for the study area, especially in the Ryder Uplands.
- Continue to compile aquifer hydraulic parameters into the GWELLS database and include hydraulic connection maps into the BC Water Resource Atlas and iMapBC to facilitate improved studies in support of managing groundwater use.
- Delineate groundwater management areas to assist with water allocation decisions, especially for aquifers experiencing a higher degree of non-domestic groundwater use and around fully allocated streams.

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Separate digital file

ACRONYMS AND ABBREVIATIONS

DEM	Digital Elevation Model
EFN	Environmental flow needs
ENV	Ministry of Environment and Climate Change Strategy
GIS	Geographic Information System
GWELLS	B.C. government’s water well database
MBR	Mountain block recharge
PoHC	Point of hydraulic connection
SDF	Stream depletion factor
WLRS	Ministry of Water, Land and Resource Stewardship
WSA	*Water Sustainability Act*
WTN	Well tag number

1. BACKGROUND

In the Chilliwack area, surface water and groundwater are used for a variety of purposes, including agricultural and municipal uses. The area is subject to a variety of land base development, such as farming, rural residential, forestry, industry, and recreation. The local streams also provide aquatic habitat for Chinook, Coho, Chum, Steelhead, as well as a resident population of Cutthroat and Rainbow trout. The Chilliwack area is part of the Lower Mainland that experienced drought level 5 (Exceptionally Dry) over the summer of 2023. Regulatory action, such as curtailment of water use may occur in response to critical low streamflow conditions that can arise during drought levels 4 or 5. Several of the local streams have been observed to be dry in the summer months. Determining the likelihood of hydraulic connection between groundwater in aquifers and water in streams in the study area is vital to timely protection of environmental flows and access to water for users.

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 and use of groundwater may affect environmental flow needs (EFNs) of a stream (Section 15 of the WSA); and,
- Curtail water uses, including groundwater uses that are hydraulically connected to streams 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 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. One primary method to determine likelihood of hydraulic connection is to map open reaches of streams where water moves freely between the aquifer and the surface water body, and such stream reaches do not have an unsaturated (vadose) zone below the streambed or low-permeability confining sediments (e.g., clay, silt, till).

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 study area. Another goal is to begin to understand how quickly well pumping may be expected to affect the streams by use of a simple indicator called *streamflow depletion factor (SDF)* (Jenkins, 1968).

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

2. SCOPE OF WORK

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

- Compiling available information to develop a conceptual hydrogeological model and understanding of the study area.
- Mapping and contouring the groundwater elevations and inferring groundwater flow directions in the various aquifers.
- Mapping where hydraulic connection between wells and streams in the study area are expected to occur. For this study, the Ministry of Water, Land and Resource Stewardship (WLRS) provided a list of 859 wells to be assessed for likelihood of hydraulic connection.
- Calculating SDFs for the wells to estimate the approximate length of time effects from well pumping are expected to be felt on streams.
- Identifying where direct hydraulic connection between surface water and groundwater cannot be reasonably inferred. This was a significant aspect of the project compared to the studies completed in recent years on the east coast of Vancouver Island (WWAL, 2019; 2022; 2023).
- Compiling data into an Excel spreadsheet.
- Summarizing the work of this study in a report (this report).

3. STUDY AREA

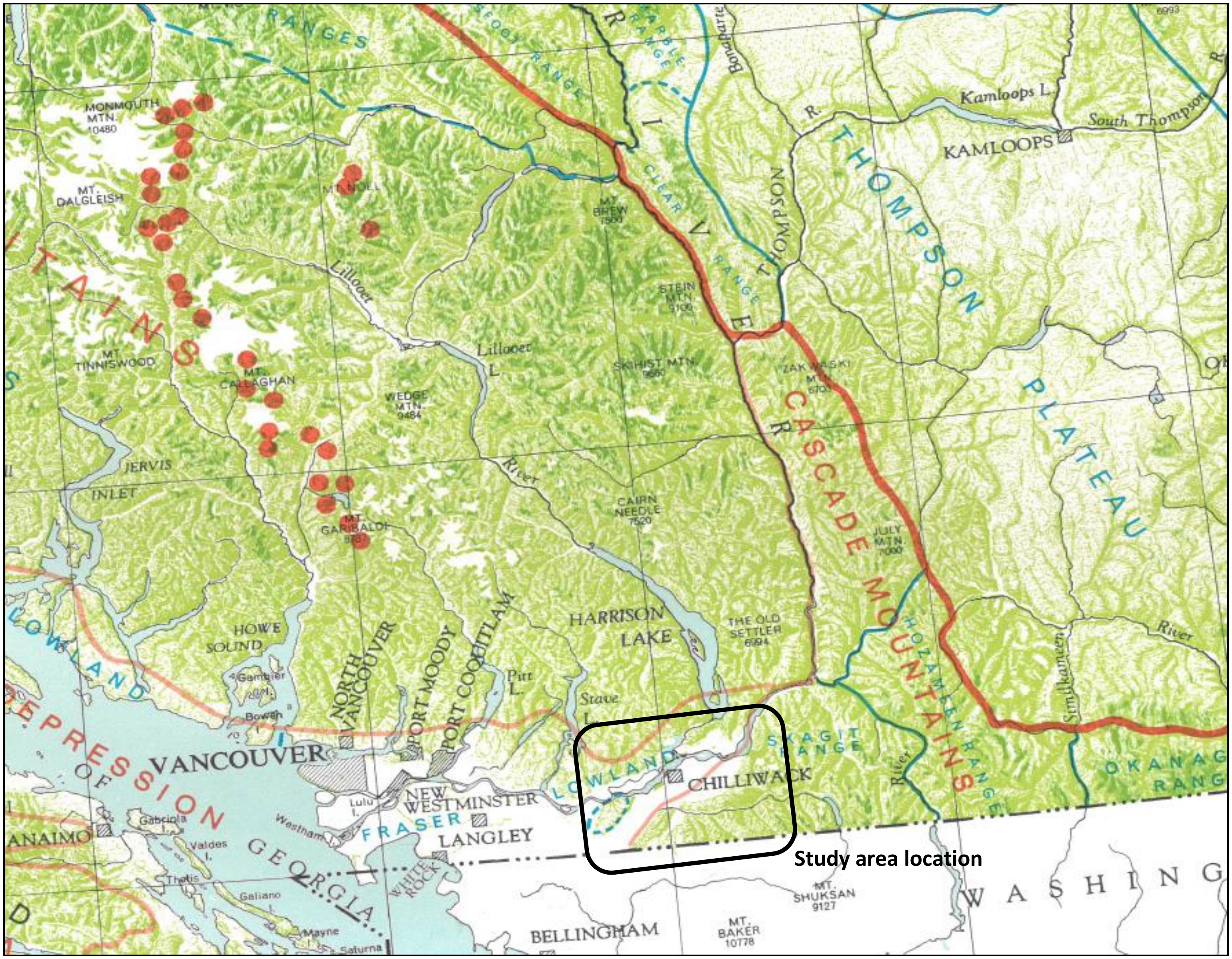
3.1 Watershed Setting and Physiography

The study area is situated along the boundary of the Fraser Lowland and Cascade Mountains physiographic regions (Holland, 1976). The City of Chilliwack is located in the study area, and is roughly 28 km east of Abbotsford, B.C. (Figure 1). The Fraser River flows westward along the north boundary of the study area, and ultimately discharges into Georgia Strait, in Richmond and Delta. The southern boundary of the study area is the Canada-USA border, and the western boundary is Sumas Prairie.

Figure 1 shows the study area and relevant features. The study area occupies a total area of about 60,000 ha, and has a topographic relief of about 2000 m. The study area is bisected by the front of the Cascade Mountains, which runs from southwest to northeast from the Canada-USA border to the Cheam Slide, based on Holland (1976) and digital physiographic boundaries from GeoBC (2015). The southern half of the study area is located within the Cascade Mountains with high topographic relief, and has a median elevation of about 320 m. The northern half of the study area is characterized by lower topographic relief and has a median elevation of only 16 m and a roughly north facing aspect towards the Fraser River.

The major physiographic features within the study area are shown in Figure 2 and include:

- The Cascade Mountains (including Elk Mountain, Liumchen Mountain, and Mount McGuire);
- The Chilliwack River and Cultus Lake;
- The Vedder Fan and Elk Creek Fan (where the Chilliwack River and Elk Creek drain from the Cascade Mountains into the Fraser River floodplain);
- The Fraser River floodplain (where the Fraser River has historically flooded and overtopped its banks, including sloughs and abandoned channels of the River);
- The Cheam Slide, located at the far east end of the study area;
- The Sumas Prairie, located west and south of the Vedder River, which represents a lacustrine basin that was drained in the 20th century for agricultural purposes; and,
- Sumas and Chilliwack Mountains.



Study area location

Figure 1. Physiographic regions of southwest B.C. and study area location (from Holland, 1976).

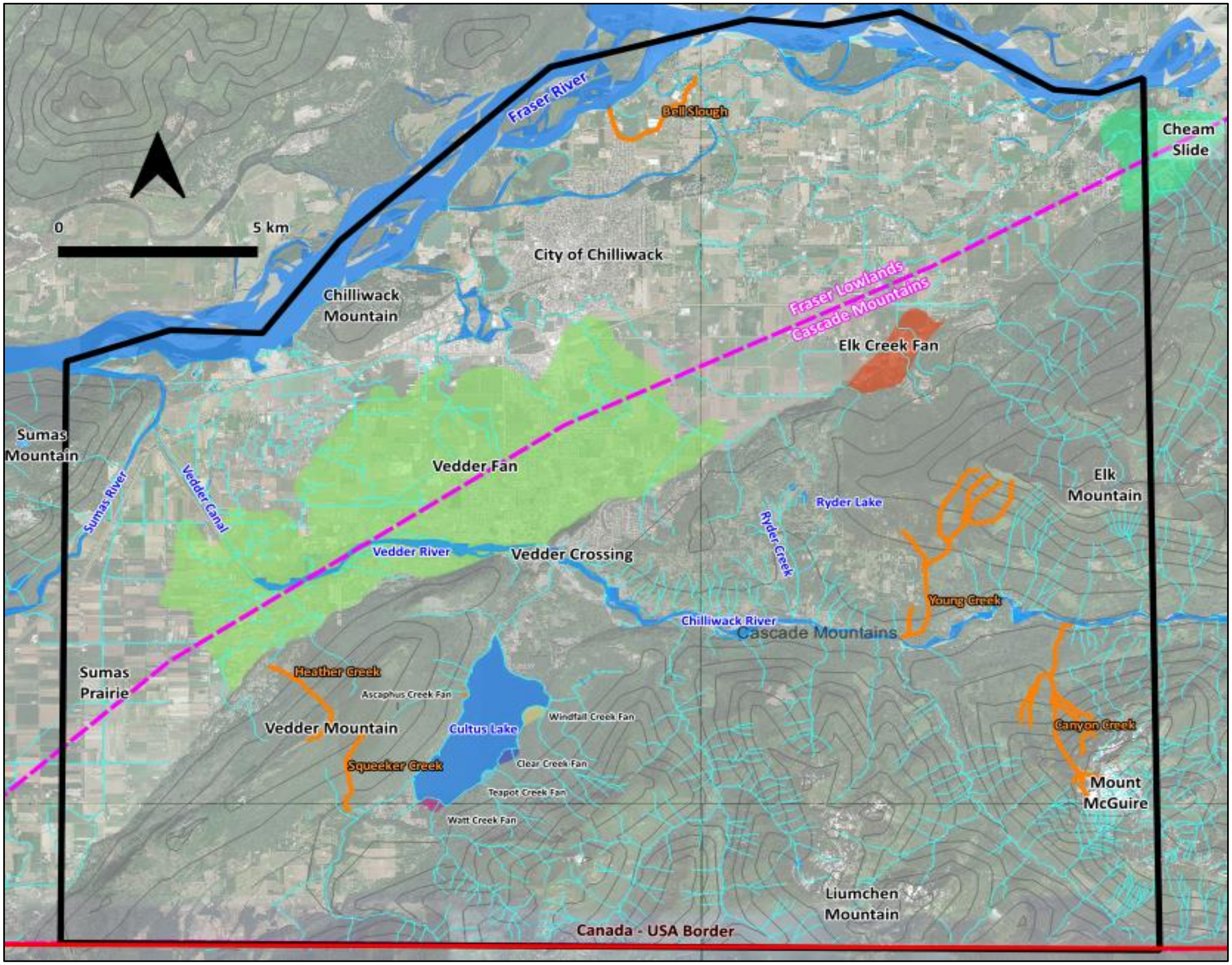


Figure 2. Study area and major physiographic features (fully recorded streams in orange).

The overall drainage direction of the study area is northward toward the Fraser River. Many of the streams are perennial in the study area, indicating that there is baseflow from groundwater in the summer months. Conversely, some streams have been observed dry during the summer.

It is worth noting that seasonal flooding is fairly common in low-lying areas in and near Chilliwack and the area was subjected to widespread flooding during the November 2021 “atmospheric river” rainfall event.

Within the study area, only five streams have been designated as fully recorded (Table 1 and Figure 2): Youngs Creek, Canyon Creek, Bell Slough, Heather Creek, and Squeeker Creek. The Fully Recorded notation is a WLRS operational term taken to mean that there is no more water available to be allocated for licensed use. These notations inform the statutory decision maker regarding water allocation constraints for specific streams that need to be considered in deciding whether or not to grant additional water licences. These notations also imply the likelihood of these specific streams in triggering curtailment of water use during drought to protect stream flows.

Most streams upstream of the Vedder Crossing are subject to an Office Reserve notation. The proposed water reserve was established in 1991 for future use by the City of Abbotsford for waterworks purposes.

There are currently no water allocation notations associated with any aquifers within the study area.

Table 1. Summary of fully recorded streams in the study area.

Stream	**Notation ID**	**Year**	**Notation**	**Comment**
Youngs Creek	NO42659	2001	FR	FULLY RECORDED 2002280
Canyon Creek	NO73778	1996	FR	FULLY RECORDED 2002123
Bell Slough	NO42202	1986	FR	FULLY RECORDED 200801
Heather Creek	NO42612	1960	FR	FULLY RECORDED; 0220776. REFUSED NO WATER; 0230008
Squeeker Creek	NO71309	1994	FR	FULLY RECORDED – 2001784 OCTOBER 18 1994

3.2 Subareas

The variation in physiographic setting allowed us to subdivide the study area into four sub-areas, for the purpose of discussing the hydrogeology and mapping the likelihood of hydraulic connection. The four subareas are listed and described in further detail below in Table 2 and shown in Figure 3; Table 2 summarizes their relevant physiographic attributes and aquifer types.

Table 2. Description of sub-areas.

Physiographic Region	Sub-area	Major Physiographic features	Major Aquifer types
Fraser Lowland*	Fraser-Sumas Floodplain	• Vedder Alluvial Fan, Fraser River and Sumas River (and associated floodplains), Sumas Prairie (former lacustrine basin), and Cheam Slide. • Slopes draining towards the valley bottom and associated alluvial and colluvial fans.	1a – Unconfined sand and gravel – large river system 3 – Unconfined sand and gravel – alluvial or colluvial fan 4a – Unconfined sand and gravel – late glacial outwash 4b – Confined sand and gravel – glacio-marine 6b – Fractured crystalline bedrock
Cascade Mountains	Chilliwack River Valley**	• Liumchen Mountain, Mount McGuire, Elk Mountain, and the slopes draining towards the valley bottom. • Chilliwack River and associated floodplain.	1b – Unconfined sand and gravel aquifer – medium stream system 4b – Confined sand and gravel – glacial 5a – Fractured sedimentary rock
	Columbia Valley - Cultus Lake	• Southeastern and western slopes of Vedder and Liumchen Mountains, respectively. • Cultus Lake and alluvial fans along its perimeter (Windfall Creek, Clear Creek, Teapot Creek, Watt Creek, and Ascaphus Creek Fans).	4a – Unconfined sand and gravel – late glacial outwash 3 – Unconfined sand and gravel – alluvial or colluvial fan 5a – Fractured sedimentary rock
	Ryder Uplands	Southern slopes of Elk Mountain, Ryder Lake, and the slopes draining towards Chilliwack River.	4b – Confined sand and gravel – glacial 5a – Fractured sedimentary rock 6b – Fractured crystalline bedrock

*For this study, the Fraser Lowland region includes the Cascade Mountains that directly slope to the Fraser River floodplain.

**The boundary of Aquifer 1206 underlies both the Chilliwack River Valley sub-area and the Ryder Uplands sub-area. The boundary between the Chilliwack River Valley and Ryder Uplands sub-areas was a balance between having all of the Points of Hydraulic Connections of the wells to be assessed for Aquifer 1206 located in the Chilliwack River Valley sub-area versus not extending the Chilliwack River Valley sub-area too far uphill from the valley bottom.

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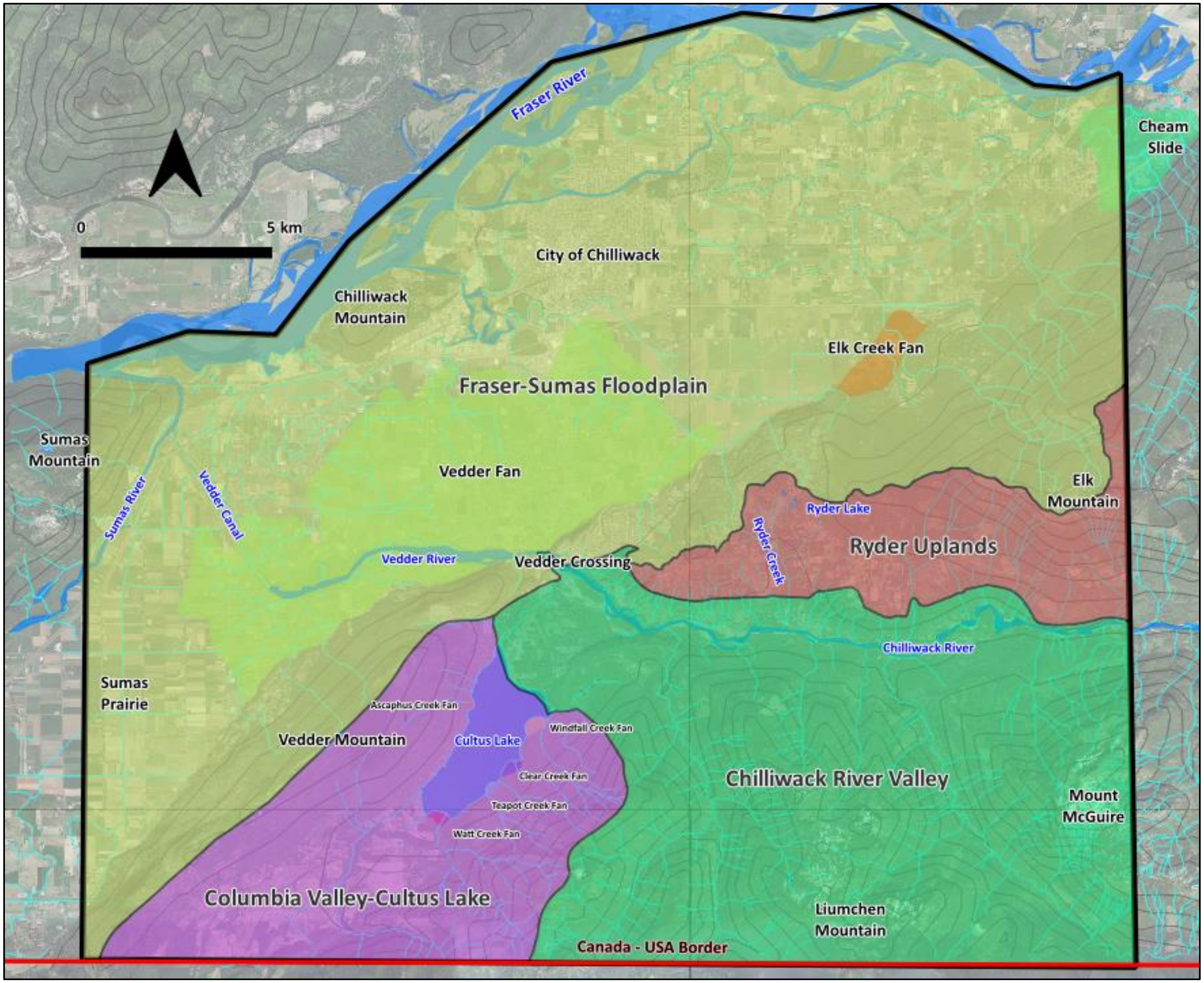


Figure 3. Overview of sub-areas and relevant physiographic features.

3.3 Geologic Setting

3.3.1 Surficial Geology

The surficial geology in the study area is a consequence of glacial and post-glacial processes. Vast amounts of rock and sediment was removed by glaciers during the last glaciation and deposited in the study area. After about 15,000 years ago, glaciers began to retreat north up the Strait of Georgia and east across the Fraser Lowlands. Unconsolidated sediments in the region were deposited during the late Quaternary Period, specifically the late Pleistocene to Holocene epochs, from about 50,000 to 10,000 years ago.

This section briefly describes the surficial geology and major stratigraphic units as they pertain to the objectives of the study. Table 3 on the following page summarizes the glacial history during the Pleistocene and Holocene adapted from Armstrong (1981) and Monahan et al. (2019). In terms of groundwater development and hydraulic connection, most of the mapped unconsolidated aquifers were deposited in the late Pleistocene from about 25,000 years ago to present during the late Wisconsin period. For additional information on the surficial geology, the reader should refer to Monahan et al. (2019).

3.3.2 Bedrock Geology

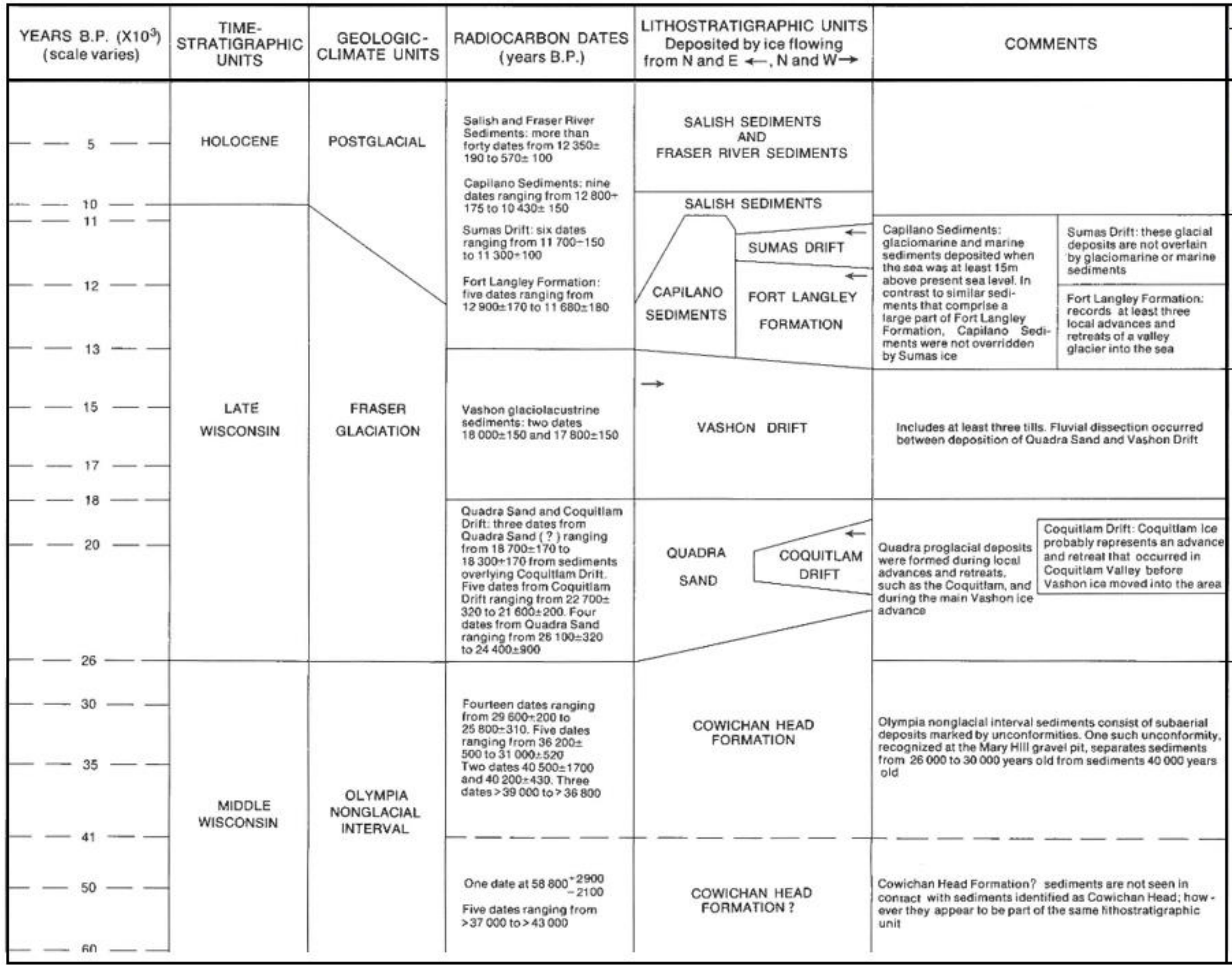
Figure 4 shows the bedrock geology mapping as compiled in Cui et al. (2017). The bedrock underlying the study area is comprised primarily of sedimentary bedrock.

The Chilliwack Group and Cultus Formation underly much of the Chilliwack River Valley, Ryder Uplands, and Columbia Valley-Cultus Lake sub-areas. The Chilliwack Group comprises undivided sedimentary rocks described as undifferentiated pelite, sandstone, minor conglomerate, mafic and felsic volcanics, and carbonate (Cui et al., 2017). The Cultus Formation is described as argillite, sandstone, siltstone, and minor carbonate. The southeast slope of Vedder Mountain, draining towards the Columbia Valley is mapped as conglomerate and coarse clastic sedimentary rocks of the Kent Formation, described as conglomerate, sandstone and argillite.

The Vedder Fault follows the top of Vedder Mountain and trends towards the Cheam Slide in the northeast corner of the study area. An unnamed thrust fault is mapped along the eastern side of the study area separating the Chilliwack Group and Cultus Formation, extending northward from the Canada-USA border truncating against the Vedder Fault. The Vedder Metamorphic Complex is mapped along the northwest slope of Vedder Mountain draining into the Fraser-Sumas Floodplain. This bedrock unit is described as lower amphibolite/kyanite grade metamorphic rocks.

Bedrock in the Fraser-Sumas Floodplain is mapped as sedimentary rocks of the Cultus Lake Group, and towards the Fraser River as volcanic rocks from the Harrison Lake Group and unnamed intrusive rocks. Bedrock in the floodplain is buried by thick deposits of unconsolidated sediments at least several hundred meters thick; the true thickness of the unconsolidated sediments is based on only a few wells.

Table 3. Quaternary stratigraphy (from Armstrong, 1981) and associated mapped aquifers in the four sub-areas.



YEARS B.P. ($\times 10^3$) (scale varies)	TIME-STRATIGRAPHIC UNITS	GEOLOGIC-CLIMATE UNITS	RADIOCARBON DATES (years B.P.)	LITHOSTRATIGRAPHIC UNITS Deposited by ice flowing from N and E ←, N and W →	COMMENTS	Subarea			
						Fraser-Sumas Floodplain	Columbia Valley-Cultus Lake	Chilliwack River Valley	Ryder Uplands
5 10	HOLOCENE	POSTGLACIAL	Salish and Fraser River Sediments: more than forty dates from 12 350± 190 to 570± 100 Capilano Sediments: nine dates ranging from 12 800+ 175 to 10 430± 150	SALISH SEDIMENTS AND FRASER RIVER SEDIMENTS SALISH SEDIMENTS		8, 1196, 1198 6, 21, 1199	1200, 1201, 1202, 1203	9	
11 12 13	LATE WISCONSIN	FRASER GLACIATION	Sumas Drift: six dates ranging from 11 700−150 to 11 300+100 Fort Langley Formation: five dates ranging from 12 900±170 to 11 680±180	CAPILANO SEDIMENTS ← SUMAS DRIFT ← FORT LANGLEY FORMATION	Capilano Sediments: glaciomarine and marine sediments deposited when the sea was at least 15m above present sea level. In contrast to similar sediments that comprise a large part of Fort Langley Formation, Capilano Sediments were not overridden by Sumas ice Sumas Drift: these glacial deposits are not overlain by glaciomarine or marine sediments Fort Langley Formation: records at least three local advances and retreats of a valley glacier into the sea	1206, 1213, 1210	20		1211, 1212
15 17 18			Vashon glaciolacustrine sediments: two dates 18 000±150 and 17 800±150	→ VASHON DRIFT	Includes at least three tills. Fluvial dissection occurred between deposition of Quadra Sand and Vashon Drift	1197, 1208			
20 26			Quadra Sand and Coquitlam Drift: three dates from Quadra Sand (?) ranging from 18 700±170 to 18 300+170 from sediments overlying Coquitlam Drift. Five dates from Coquitlam Drift ranging from 22 700± 320 to 21 600±200. Four dates from Quadra Sand ranging from 26 100±320 to 24 400±900	QUADRA SAND ← COQUITLAM DRIFT	Quadra proglacial deposits were formed during local advances and retreats, such as the Coquitlam, and during the main Vashon ice advance Coquitlam Drift: Coquitlam Ice probably represents an advance and retreat that occurred in Coquitlam Valley before Vashon ice moved into the area			1206	1207, 1208, 1209
30 35 41	MIDDLE WISCONSIN	OLYMPIA NONGLACIAL INTERVAL	Fourteen dates ranging from 29 600+200 to 25 800±310. Five dates ranging from 36 200± 500 to 31 000±520 Two dates 40 500±1700 and 40 200±430. Three dates >39 000 to >36 800	COWICHAN HEAD FORMATION	Olympia nonglacial interval sediments consist of subaerial deposits marked by unconformities. One such unconformity, recognized at the Mary Hill gravel pit, separates sediments from 26 000 to 30 000 years old from sediments 40 000 years old				
50 60			One date at $58\,800^{+2900}_{-2100}$ Five dates ranging from >37 000 to >43 000	COWICHAN HEAD FORMATION ?	Cowichan Head Formation? sediments are not seen in contact with sediments identified as Cowichan Head; however they appear to be part of the same lithostratigraphic unit				

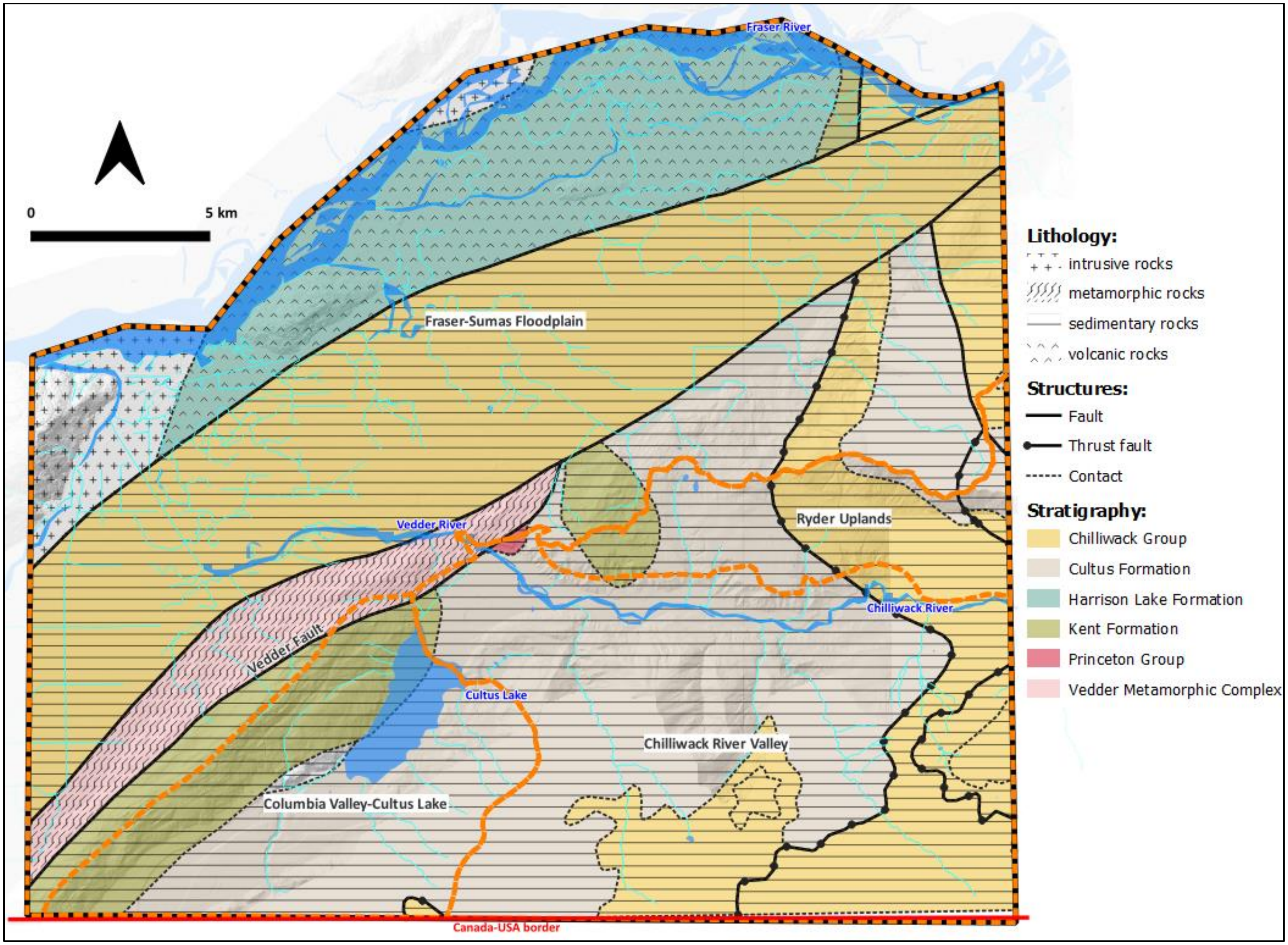


Figure 4. Bedrock geology from Cui et al. (2017) in the study area (sub-area boundaries are in orange).

3.4 Mapped Aquifers

There are thirty mapped aquifers in the study area. Table A1 (in Appendix A) summarizes the main attributes of the aquifers. Twenty-three are unconsolidated aquifers; their correlation to mapped lithostratigraphic units is inferred in Table 3. Seven are bedrock aquifers, comprising a mix of sedimentary (Aquifers 890, 1217 and 1218) and crystalline (Aquifers 899, 1214, 1215, and 1216) bedrock. For all bedrock aquifers, groundwater occurrence and flow are expected to be primarily via fractures in the rock. The relevant hydrogeologic characteristics of the mapped aquifers are discussed within each sub-area in the Results and Discussions section (Section 6).

4. HYDRAULIC CONNECTION

If an aquifer and a stream are hydraulically connected, well pumping may affect the flow in the stream (process known as streamflow 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.

The 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 stream reach must not be perched or disconnected (i.e., a significant thickness of vadose zone separating the stream and the water table exists); and
2. The stream or stream reach must not be directly underlain by low permeability (i.e., till, silt or clay) confining sediments that impede groundwater flow between the aquifer and the stream.

Interception is expected to be the dominant process of streamflow depletion, especially where the pumping well is not near a connected stream to induce infiltration from the stream.

A perched or disconnected stream, or the presence of confining sediments underlying a stream, will essentially restrict hydraulic connection and streamflow depletion along that reach of the stream. However, streamflow depletion from well pumping may still be felt further along at a reach of stream that is not perched nor directly underlain by confining sediments. For example, in steeper terrains (like in the Cascade Mountains) a stream can be perched except along its lowest reaches, near the local base level. Mapping of groundwater flow is, therefore, important to identify where streamflow depletion by interception can occur. Within the Fraser-Sumas Floodplain sub-area, groundwater pumping may also impact open stream reaches up-gradient of the well because the ground surface is flat and the groundwater levels are generally high, so the presence of confining sediments directly underlying streams is expected to be the dominant factor in governing hydraulic connection (as opposed to the direction of groundwater flow or the disconnection of the stream via the presence of a significant vadose zone).

Our main approach was to use available information 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 5.6.2 discusses confining sediments in this study). Reaches where the stream is not perched nor directly underlain by confining sediments are considered open stream reaches where streamflow depletion due to well pumping can potentially occur.

In the study area, there are three common scenarios that pose a challenge to inferring hydraulic connection of groundwater to specific streams because some aquifers may be indirectly connected to streams. Some aquifers may only be connected to adjacent aquifers that are connected to streams. These scenarios are presented below:

Aquifer 1197 (Greendale Deep Aquifer) in the Fraser River floodplain: This confined, unconsolidated aquifer in the Fraser-Sumas Floodplain is overlain by shallower Aquifer 6 (Chilliwack-Rosedale Aquifer). The confined nature and depth of Aquifer 1197 imply direct hydraulic connection to overlying streams, including the Fraser River is unlikely (Monahan et al. (2019)'s cross-sections 2O, 1 to 3 suggest depth of Aquifer 1197 is 50-60 m below sea level). Groundwater pumping from within Aquifer 1197 is expected to ultimately affect streams at the land surface via windows between Aquifer 1197 and overlying Aquifer 6 because windows are locations of higher diffusivity through which pumping stress can more easily propagate.

Aquifer 1206 (Chilliwack River Subtill Aquifer): The confined, unconsolidated aquifer in the Chilliwack River Valley sub-area is overlain by Aquifer 9 (Chilliwack River Shallow Aquifer). Due to the narrowness of the valley, and direction of flow of the Chilliwack River, pumping from within this aquifer is expected to affect Chilliwack River (or Vedder River) further downstream. However, the likely location of pumping impact to the river (the Point of Hydraulic Connection) will depend on if and where windows in the till separating Aquifer 9 and Aquifer 1206 exist, and they are large and permeable enough to transmit significant groundwater through them.

Bedrock aquifers in the study area: A sufficiently thick vadose zone appears to exist underneath many of the low-order mountainous streams that flow over the steeply sloping bedrock. These perched or disconnected streams typically enter the valley-bottom and continue to flow over unconsolidated aquifers. In this scenario, groundwater pumping from the bedrock aquifer is not expected to deplete the overlying perched stream but will likely intercept groundwater flowing downgradient to the unconsolidated aquifers in the valley bottom, which may deplete flow in streams further downgradient. Without a better understanding of the hydrogeology of the study area, hydraulic connection between adjacent bedrock and unconsolidated aquifers may be as far as we can infer. Section 5.2 describes our methodology for identifying areas of hydraulic connection between aquifers.

5. METHODS

An overview of the approach taken is described in subsections 5.1 and 5.2. Detailed descriptions of the data and methods applied to each step are described further in subsections 5.3 to 5.10.

5.1 Identifying where Hydraulic Connection between Groundwater and Streams is Likely

We completed the following subtasks to identify where hydraulic connection between groundwater and surface water is more likely to occur. Where it was determined that streams are likely hydraulically connected, we assessed which hydrostatigraphic units each stream reach was likely connected to.

- Compiled data from multiple sources (Sections 5.3, 5.4, and 5.5).
- Divided the hydrogeology into two settings: a) unconsolidated sediments and b) fractured bedrock.

- Mapped and contoured the groundwater elevations for each grouping, inferred the likely direction of groundwater flow in each setting, and estimated the depth of the groundwater surface below the streams (Section 5.6.1).
- Mapped the thickness and extent of the confining sediments (i.e., till, silt and clay) that directly underlie the streams (Section 5.6.2).
- Reviewed well logs and cross-sections to characterize the non-aquifer units as confining or non-confining, and identified locations where the confining non-aquifer units separating stacked aquifers may be absent.
- Verified interpretations of where a stream is either open or closed to hydraulic connection by reviewing available cross-sections and/or by constructing cross-sections in specific parts of the study area.

It should be noted that mapping directions of groundwater flow and depth of groundwater below streams to infer likelihood of hydraulic connection, as we have done in this project, produces a static picture of these conditions. Actual conditions are dynamic. Lowering of groundwater levels as a result of well pumping can alter direction of groundwater flow and lengthen disconnected stream reaches with time. However, given the preliminary nature of this study and limitations of the sources of data, we believe the mapping methods described herein are reasonable and appropriate.

Once we assessed the likely connection between streams and hydrostratigraphic units, we determined the connections between each well within those units and open stream reaches (described further in Section 5.8). 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 open reach of the stream. The PoHC is the point on the stream where streamflow depletion from pumping of the well is expected to occur. For wells connected to multiple streams, the fractional pumping demand was determined for each stream using the inverse distance equation (Province of BC, 2016b), as described in Section 5.8.1.

Understanding how quickly streamflow 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) proposed by Jenkins (1968) is a relative measure of how quickly streamflow depletion may occur. It is based on the distance between the well and the corresponding PoHC, the aquifer transmissivity, and the aquifer storativity (or specific yield if the aquifer is unconfined). As described in Section 5.10, we calculated the SDF for all wells assessed to have a PoHC to a stream (see Section 5.8 of this report). We then developed maps of the PoHCs and calculated SDF values for the unconsolidated and for the fractured bedrock aquifers in the study area.

5.2 Identifying Areas where Hydraulic Connection between Adjacent Aquifers is more Likely

Section 4 presented three common scenarios where some aquifers in the study area may not be directly connected to streams. In those scenarios, we attempted to identify where connection occurs between those aquifers and adjacent aquifers with a direct connection to streams. In these cases, the PoHC is assumed to extend from the well, downgradient to the valley bottom unconsolidated aquifer, and not to any specific stream.

For Aquifer 1197 in the Fraser-Sumas Floodplain, we reviewed the hydrogeologic cross-sections in Monahan et al. (2019), as well unpublished cross-sections by Monahan (c 2019) and well records, to infer where windows between Aquifer 1197 and overlying Aquifer 6 (Chilliwack-Rosedale Aquifer) may occur. Windows are areas where the low-permeability confining layer separating Aquifer 1197 and Aquifer 6 is interpreted to be absent (see, e.g., Figure 13a [left hand side] and Figure 13c [right half of cross-section] in Monahan et al. 2019). Pumping within Aquifer 1197 would most likely affect the overlying Aquifer 6 and ultimately streams at the land surface through these windows.

For Aquifer 1206 in the Chilliwack River Valley, we also reviewed the hydrogeologic cross-sections in Monahan et al. (2019), as well as unpublished cross-sections by Monahan (c 2019) and well records, to infer where the till separating Aquifer 1206 and overlying Aquifer 9 (Chilliwack River Shallow Aquifer) may be absent. The Point of Hydraulic Connection (PoHC) to the Chilliwack River is assumed to be to the closest window of the subject well.

With respect to the steep, mountainous bedrock aquifers, the following criteria informed us of the need to identify where hydraulic connection of groundwater between the bedrock aquifer and an adjacent valley-bottom unconsolidated aquifer was likely:

1. Wells located near a mountainous stream that flows into the valley bottom may not be located within the watershed area of the mountain stream. According to Welch (2012), groundwater within these "triangular facets" that are located in between the watershed boundaries of neighbouring tributary mountain streams would tend to flow directly downgradient to the valley-bottom unconsolidated aquifer (as mountain block recharge).
2. Even if wells are located within the watershed boundary of a mountainous stream, if the stream is inferred to be perched along its entire length to the valley-bottom, groundwater in the bedrock is interpreted to flow underneath the stream to the valley-bottom unconsolidated aquifer(s).

Where there are stacked unconsolidated aquifers in the valley bottom (e.g., in the Fraser-Sumas Floodplain and Chilliwack River Valley sub-areas), PoHC could not be extended from the well to a specific unconsolidated aquifer. The downgradient direction is either inferred from hydraulic head elevation contours if sufficient data from bedrock wells are available, or more crudely from topography (assuming topographically driven groundwater flow in the bedrock).

Results of this work are also summarized in a Microsoft Excel spreadsheet (attached in Appendix D and described in 5.10). The following subsections present the data sources in more detail and how the maps, cross-sections and spreadsheets were developed.

5.3 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 4 below.

5.4 Site Visit

The senior author visited the study area for a full day in late January 2024 focusing on the Fraser-Sumas floodplain area, roughly the area between the Fraser River and the Cascade mountain front. The weather conditions during the site visit were cool and cloudy. While on site the senior author confirmed shallow soil conditions by viewing soil exposures along the roads and ditches and digging shallow test pits with a shovel.

Significant precipitation occurred on the days preceding the site visit, resulting in high water levels in the ditches and ponding water on the ground surface in local topographic lows. The senior author recorded the locations where significant ponding water was observed at surface due to the recent precipitation event. We infer that the ponded water observed during the traverse is likely due to poorly draining soils at these locations.

The field locations were recorded with a handheld GPS, and the observations were used to validate soil conditions to infer the presence or absence of confining sediments underneath the streams.

Table 4. Summary of spatial datasets used in study.

Dataset	Format	Scale	Purpose	Reference
Groundwater wells	Shapefile	-	Well construction data, lithology and water levels used in hydraulic connection determinations.	ENV (2024a)
Mapped aquifer boundaries	Shapefile	-	Mapped aquifer boundaries	ENV (2024b)
Watershed boundaries	Shapefile	1:20,000	Used to constrain sub-area boundaries	BC Freshwater Atlas from GeoBC (2010)
Watercourses and lakes	Shapefile	1:20,000	Used in hydraulic connection determinations.	BC Freshwater Atlas from GeoBC (2010)
Digital Elevation Model	.TIFF	1 m resolution	Used to extract elevations to well points and watercourses.	GeoBC (2019)
Canadian Digital Elevation Model	.TIFF	20 m resolution	Used to extract elevations to well points and watercourses, where GeoBC (2021) is not available	NRCan (2011)
Digital soil survey mapping	Shapefile	1:24,000	Used to map where confining sediments are present under streams	CANSIS (2010)
Leapfrog Model	Scene	-	Used to visualize hydrostratigraphic units from Monahan et al. (2019) in 3D	ENV (2024c)

5.5 Well Data from GWELLS

We relied on the hydrostratigraphic framework developed by Monahan et al. (2019) to inform our conceptual understanding of the hydrogeological setting of the study area. Well data from GWELLS (ENV, 2024a), and geotechnical boreholes from Monahan et al. (2019) were used for lithological and groundwater level input for this study.

Hydrogeological cross-sections and a Leapfrog Scene from Monahan et al. (2019) and ENV (2024c), respectively, and well logs were systematically reviewed to verify the lateral extent, thickness, and composition of the non-aquifer units overlying the aquifers. Figure 5 shows the locations of the hydrogeological cross-sections used in this study. From the cross-sections, we identified areas where aquifers appear to be well-confined and where confining units are thin or absent. We developed one additional cross-section (Figure 9) to help assess the stratigraphic relationship between Aquifers 9, 1206, and 8.

5.6 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 and to assign elevation data to well and stream features.

GIS was used to map the extent of the confining layers, based on soil properties and parent material. The multilevel B-spline method (Lee et al., 1997) was used to interpolate groundwater elevations between data points to guide the groundwater elevation contouring. GIS was also used to determine the likely point of hydraulic connection (PoHC) between streams and the wells (see Section 5.8 for more detail on PoHC determinations).

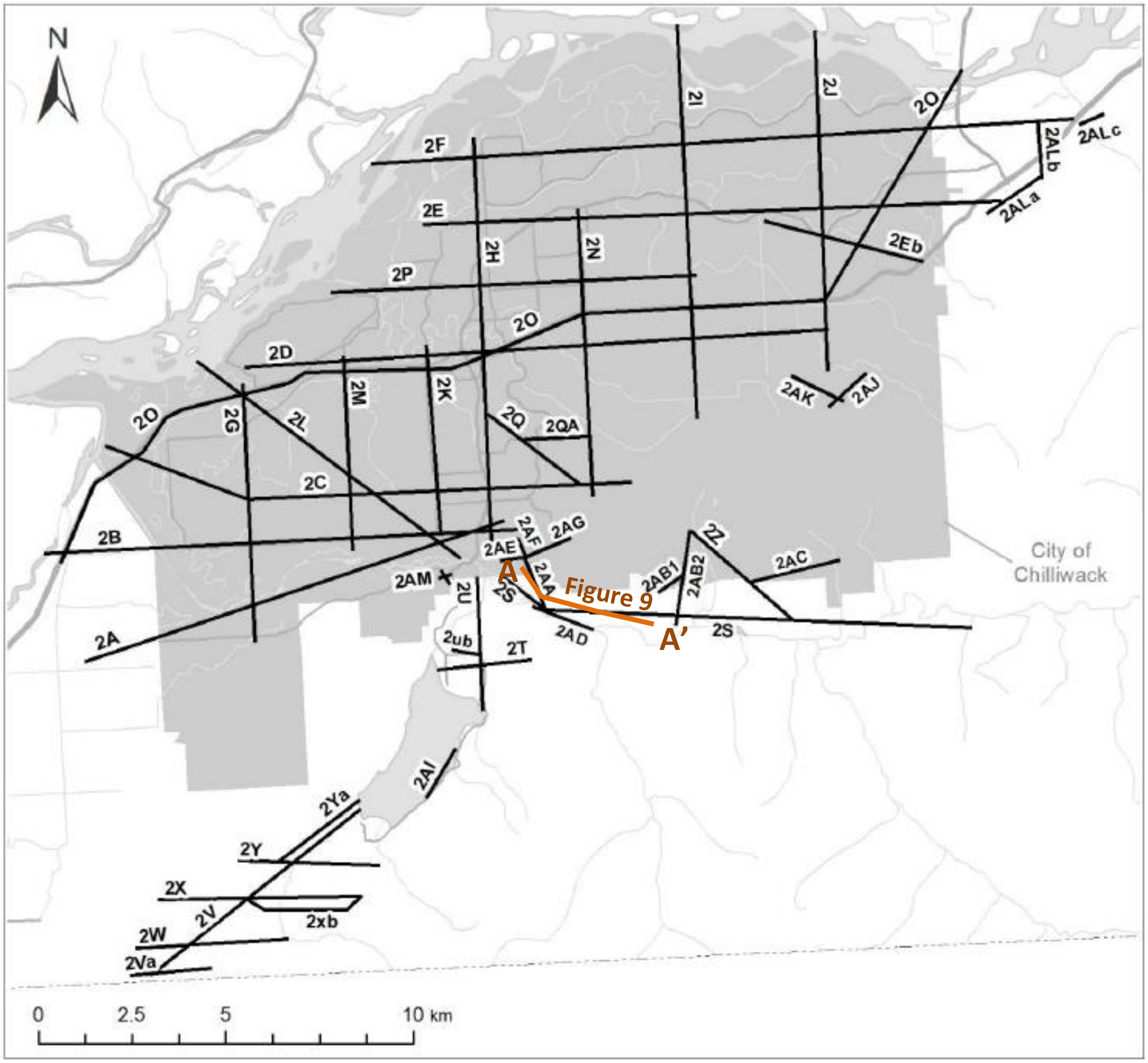


Figure 5. Hydrogeological cross-sections from Monahan et al. (2019) and for current study.

5.6.1 Mapping Groundwater Elevation in Unconsolidated and Bedrock Units

Groundwater elevation maps were constructed separately for unconsolidated (overburden) sediments for each sub-area, and for bedrock aquifers over the entire study area to infer direction of horizontal groundwater flow in these settings.

The groundwater elevations between well points were interpolated in GIS in the valley bottoms and contoured manually in the upland areas and along the slopes draining into the valley. This is due to the uneven spatial distribution of well data in the study area. There are fewer wells located in the upland areas, and where present, they are often clustered together where development has occurred. Contouring was completed in areas where there are reported wells. While manual contouring is believed to be more physically realistic, contouring could only be done in areas with sufficient well water level data.

Due to lithologic and hydrostratigraphic similarities (but also lack of data), we found it necessary to lump data from some unconsolidated aquifers in mapping groundwater elevations. Data from Aquifers 6, 8, 21 and 1199 in the Fraser-Sumas Floodplain subarea were lumped together to map groundwater elevation and to infer regional groundwater flow direction. In the extreme east part of the Fraser-Sumas Floodplain sub-area, data from Aquifer 1198 was also included in the mapping of groundwater flow. Lumping of data was also done for Aquifers 9 and 1206 in the Chilliwack River Valley sub-area. Groundwater elevation data from the unconsolidated aquifers in the Ryder Uplands sub-area were also used together to infer direction of groundwater flow there.

Ground elevations were represented by a topographic surface generated from publicly available Digital Elevation Models (DEMs) from GeoBC (2019) and NRCan (2011) with grid sizes of approximately 1 m and 20 m, respectively, 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 5.7). In calculating groundwater elevations, well stick-up above ground surface was assumed to be zero. 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 nodes placed at 25 m intervals along the centerline of the streams from the Freshwater Atlas dataset. Higher confidence was placed where mapping indicated existence of a vadose zone in 4 or more consecutive grid cells (~100 m) along a stream reach.

The results of this study indicate that groundwater levels are typically within 2 m of the streams in the Fraser-Sumas Floodplain. We imposed a tolerance value of 2 m as a conservative measure, to help reduce the possibility of mis-identifying reaches where a stream is likely perched. The tolerance limit was included because the groundwater level data is based on single measurements made on wells drilled over many years and different seasons. There is also some uncertainty in whether well levels were measured from ground surface or top of casing. This study assumed water levels in depth below ground.

In summary, the estimated or contoured groundwater elevation surface had to be greater than 2 m beneath the elevation of the stream for the stream to be considered perched or disconnected. If the groundwater elevation surface was less than 2 m beneath the stream elevation, then the stream was not considered connected.

Due to lack of groundwater level data, groundwater elevation could not be mapped for Aquifers 1197 (deep, confined aquifer), Aquifers 1200 to 1204 in the Columbia Valley-Cultus Lake sub-area (small alluvial fans), Aquifers 1208, 1209, and 1211 in the Ryder Uplands sub-area, and bedrock Aquifer 1215.

5.6.2 Mapping Confining Sediment Thickness Directly Beneath Streams

Confining sediments are defined as low permeability unconsolidated sediments that are expected to significantly impede groundwater flow. In this study, sediments such as ‘till’, ‘silt’ or ‘clay’, are considered confining sediments. Till can comprise a broad range of materials but can impede groundwater flow if it contains appreciable amounts of silt and clay.

Given the unique depositional environment of the Fraser-Sumas Floodplain sub-area, we approached mapping of confining sediment thicknesses differently than in previous hydraulic connection studies we conducted on the east coast of Vancouver Island (WWAL 2019; 2022; 2023). In those studies, we estimated the presence and thickness of confining sediments directly under the streams based on contouring confining sediment thicknesses determined from well records. The lithological contrast (e.g., till or glaciomarine clay versus sand and gravel) in the well records allowed confining sediments to be more obviously identified. In those studies, we further applied a buffer (minimum interpolated thickness of a few metres) to address uncertainties in contouring thicknesses using limited well data.

Within the Fraser River floodplain and Sumas Prairie, however, much of the area is underlain by Fraser River Sediments or Salish Sediments of lacustrine origin within the same geological time period and under similar depositional (slow to stillwater) environment. The lithologic variability can be subtle but significant from a permeability perspective (e.g., silty sand [permeable] versus clay [low permeability]). Due to the subtle nature of these deposits and impreciseness of the drillers' description of clayey and silty sediments, distances between wells, and size of the area, we did not interpolate the confining sediment thickness using the lithological descriptions from the well data.

Instead, we relied primarily on information from the B.C. Soil Survey Map from CANSIS (2010) to identify and map the presence of confining sediments to infer their occurrence directly underneath the streams. The soils map shows the geographical distribution of various soils in the study area and is spatially comprehensive. Polygons related to the soil surveys can comprise up to three different soil types. The dataset includes relevant soil characteristics (i.e., soil type, drainage, texture), and the percentage of mapped soil types within each respective polygon.

We identified soil polygons where at least 20%, 30%, and 40% of the polygon comprises silty clay loam or silty loam, poorly or very poorly draining soils, or both. This resulted in nine possible scenarios (3x3 matrix) that show how the extent of the uppermost confining sediment unit can be mapped based on soil composition and drainage characteristics. The matrix is shown below in Figure 6. The extent of the upper confining layer was checked against published and unpublished hydrogeological cross-sections from Monahan et al. (2019) and Monahan (c. 2019), respectively, well logs (ENV, 2024a), the Leapfrog model (ENV, 2024c), and observations from the site visit (e.g., observed ponded areas from the site visit are also shown in Figure 6). Relying only on soil type (panel on the left in Figure 6) implies streams in virtually all of the Fraser River floodplain and Sumas Prairie are underlain by confining sediments, resulting in longer distances from wells to PoHCs on open stream and greater streamflow depletion factors. Relying on silty clay and silty loam soil types and poorly and very poorly draining soil conditions increases the potential for hydraulic connection to more nearby stream reaches (panel on the right in Figure 6). Greater potential for hydraulic connection to nearby streams also reflects a generally more responsive flow system (shorter distances between well and PoHC on stream, lower SDF). For this study, we inferred that the upper confining sediments are best represented by soil polygons where at least 30% of the polygon is occupied by poorly or very poorly draining silt clay loam or silt loam (see red cell in Figure 6).

In using this approach, we assumed where confining sediments are mapped as present beneath a stream and of sufficient thickness to provide hydraulic resistance to significantly impede groundwater flow to the stream (no minimum interpolated thickness was applied). The soils map also shows where streams in the Fraser River floodplain likely incised through the confining sediments to expose more permeable sediments underneath, allowing hydraulic connection to occur. This approach was applied to the entire study area because soils mapping was available.

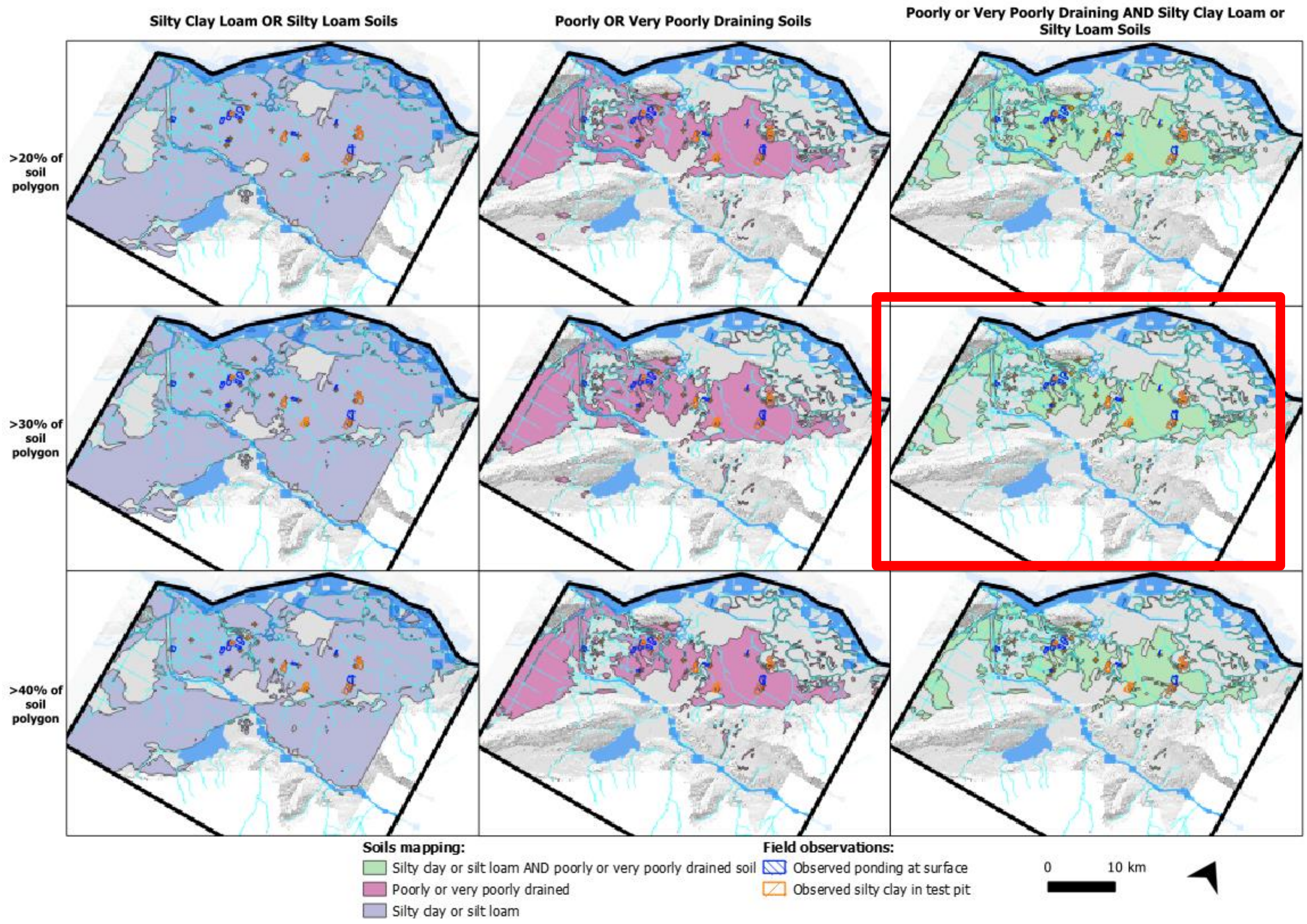


Figure 6. Mapping extent of confining sediments. Selected soil properties from the B.C. Soil Survey to represent the upper confining layer are indicated by red cell.

5.7 Data & Analysis Limitations

A large amount of geospatial data previously compiled by others formed the basis of this desktop study. The scope of work did not include 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 5.6.1 and 5.6.2).

GIS-based maps of information derived from water well records, such as groundwater elevations and sediment thicknesses, can create the illusion of a high degree of accuracy. The contour maps were developed using raster surfaces depicting confining sediment thickness and groundwater elevation at 25 m grid resolution to produce smooth contours. The “bullseye effect” observed in some contours are likely indicative of poor data quality and coverage in GWELLS (discussed in further detail below). The maps were based on available data (a total of 1992 well records and 67 geotechnical boreholes), whose distribution is variable spatially and with depth. The information on the maps was better constrained in areas of higher well density, and more uncertain in areas of lower well density.

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

Some static water levels recorded in bedrock wells may still have been recovering when measured by the driller at the end of well development and the true static water level at the completion of drilling may be under-estimated, at least for some bedrock wells, making the bedrock water level data more uncertain than overburden well data.

Static water levels were also compiled from records of wells drilled over decades in time, in different seasons and to varying depths. In relying on the reported static water levels in the well records, we assume they represent average conditions over the time-period of the data (<1950 to present), and there is sufficient topographic relief for regional trends in groundwater flow to show itself. The groundwater elevation maps produced in this study represent a composite 2-dimensional steady-state picture over time and seasons. Any temporal trends in groundwater elevations would not be discernable from the groundwater elevation maps.

The scale and desktop nature of the study and the fact that the hydrogeological data are mainly from well records, soils mapping, and geological mapping mean smaller scale geological changes within the aquifers and underneath streams could not be incorporated. We assumed that all streams are perennial; however, anecdotal information from FOR (2024) indicates that some may not be. The maps of groundwater elevations represent a picture at the sub-watershed scale but not local site scale (Figures B1 through B5). Well records may not record groundwater perched locally above the main water table. Locally perched groundwater can supply flow to streams, even in the dry season. Saturated and permeable sediments of limited extent may also exist and provide flow to streams, but these sediments may not be mappable because of the limited density of wells and scale of the study. These sources of groundwater may be localized but can play an important role in providing local baseflow to streams in the study area, even to streams mapped as being perched (disconnected) above the main water table.

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

Once the groundwater elevation contours were mapped for the various aquifers, we assessed the following:

1. Estimated groundwater elevation along the streams and tributaries to identify reaches of streams that are perched and not perched; and
2. For perched (or disconnected) streams, where else along the stream hydraulic connection can likely occur.

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

1. 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;
2. If the reach of stream nearest the well was either perched or directly underlain by confining sediments, we looked beyond the well to where the stream (or another stream) was not perched nor directly underlain by confining sediments and made the PoHC to that open reach, if that open reach occurred above the same aquifer.

The approach was also applied to wells completed into fractured bedrock. However, 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.

1. Groundwater in bedrock would be connected to the lower reaches of a tributary stream in the downgradient flow direction if that lower reach is not perched nor underlain by a confining unit.
2. Otherwise, the groundwater in the bedrock would flow to (and wells would intercept groundwater flow to) the unconsolidated deposit at the valley bottom.

This approach assumes any depletion of streamflow will occur at the closest possible location from the well. However, given the lack of information that depletion could occur at locations farther away or might not occur at all, but this assumption was deemed reasonable, as a start.

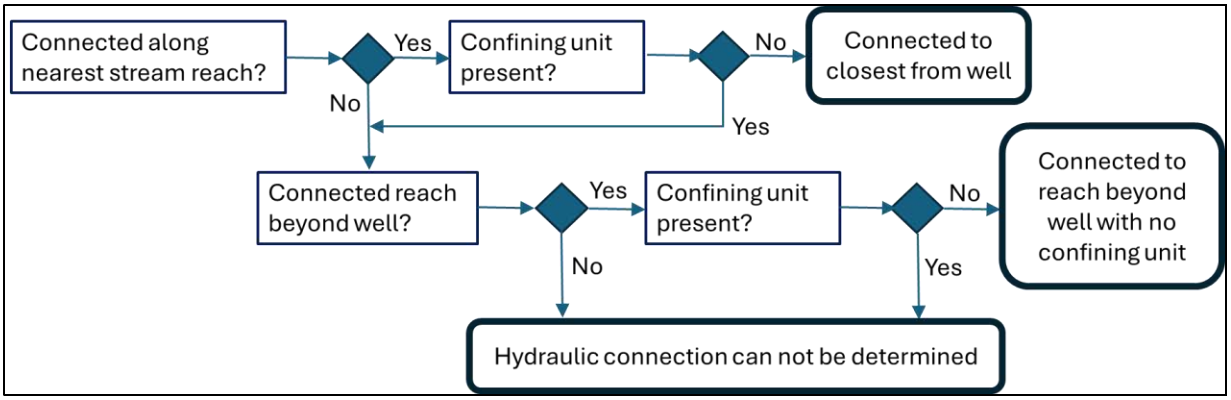


Figure 7. Approach for determining the likely point of hydraulic connection from a well to the stream.

5.8.1 Apportioning Pumping Demand to Multiple Streams

It is common that pumping can deplete flow in more than one stream (the well has more than one PoHC). In those situations, pumping demand would be apportioned to the additional streams using the inverse distance formula:

$$f_i = \frac{\frac{1}{d_i^m}}{\sum_{j=1,n}\frac{1}{d_i^m}} \qquad \text{Equation [1]}$$

where,

f_i is the fraction of total pumping demand attributed to stream i
d_i is the distance from the subject pumping well to the PoHC to stream i
n is the number of streams hydraulically connected to the pumping well
m is the weighting factor (Province of B.C., 2016b).

The larger the weighting factor, m, the greater the pumping demand is attributed to the closest stream. The Province of B.C. (2016a) recommends using m=2 as default. Figure 8 shows the influence of the weighting factor on attributing pumping demand to streams that the pumping well is connected to. The specific distances were taken to represent average distances to streams in the Fraser River floodplain. For weighting factors of m>2.5, virtually all of the demand (≥90%) would be attributed to the nearest stream, implying attributing pumping demand to multiple streams to be unnecessary. For this study, a weighting factor of m=2 was used.

Also, for the purposes of this study, fractional pumping demand of <10% was ignored because it may give a false impression of precision to these preliminary estimates. Consequently, the maximum number of streams to which a well was connected to was three.

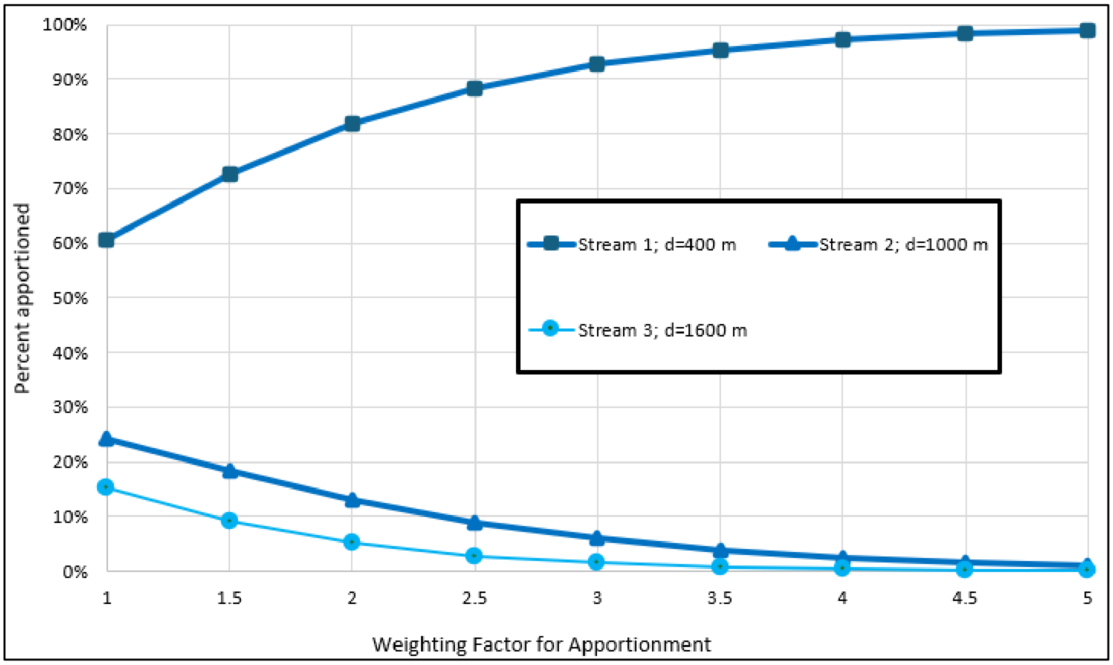


Figure 8. Influence of the weighting factor, m, on fractional pumping demand (the distances to streams 1, 2, and 3 are average distances to three hydraulically connected streams in the Fraser River floodplain).

5.9 Calculating Stream Depletion Factor for Wells

The *Stream Depletion Factor* (SDF) is calculated as:

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

where:

d	is the distance in metres between the pumping 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 measure of how fast streamflow depletion occurs in response to well pumping. Jenkins (1968) defines SDF as the time it takes for the ratio between the rate of depletion and the rate of well pumping to reach 48%. For a confined aquifer, storativity, S, is used in equation [2] and for an unconfined aquifer, specific yield, S_y, is used. Equation [2] assumes the aquifer is homogeneous and isotropic.

There are limited data on aquifer hydraulic parameters (T, S, S_y) within the study area for calculating SDFs. Fourteen historical pumping test reports were made available by WLRS and the City of Chilliwack for the study. These reports described pumping tests in only 7 of the 30 mapped aquifers in the study area:

- Aquifer 6 (Chilliwack-Rosedale Aquifer – 2 reports),
- Aquifer 8 (Vedder River Fan Aquifer – 3 reports),
- Aquifer 9 (Chilliwack River Shallow Aquifer – 1 report),
- Aquifer 899 (bedrock aquifer near Ford Creek – 2 reports),
- Aquifer 1206 (Chilliwack River Subtill Aquifer – 5 reports),
- Aquifer 1216 (Vedder Mountain NW Bedrock Aquifer – 1 report).

Where possible, we applied more aquifer-specific hydraulic parameter values in calculating SDF. Where aquifer-specific data was not available, we used hydraulic parameters based on aquifer type from Lepitre and Beebe (2019). For Aquifers 6, 8, 21, 1199 in the Fraser-Sumas Floodplain, and Aquifers 9 and 1206 in the Chilliwack River Valley, we assigned representative T, S, S_y values based on the pumping test reports, further informed by work done by Rickets (1998) and Scibek and Allen (2005). The same aquifer hydraulic parameters were assigned for Aquifers 6, 8, 21, and 1199 (T = 3000 m^2/day; S or S_y = 0.01). The rationales for this are: the transmissivity values from the available pumping tests for Aquifers 6 and 8 are similar. Aquifers 21 and 1199 were completed into Fraser River Sediments, the same unit as for Aquifer 6. Further, wells completed into Aquifers 6, 8, 21, and 1199 were lumped together to map the hydraulic head contours and infer the direction of groundwater flow in these shallow aquifers.

For the vast majority of unconsolidated aquifers in the study area, we deferred to Lepitre and Beebe (2019) for T, S, and S_y values, corresponding to their aquifer types (3, 4a, 4b, 4c). However, for Aquifer 9, the aquifer hydraulic parameters assigned to Aquifer 8 were adopted for this aquifer (T = 3000 m^2/day; S or S_y = 0.01) because of their hydrostratigraphic similarity. Transmissivity for Aquifer 1206 was also assigned a value of 3000 m^2/day, because this aquifer is lithologically similar to Aquifer 9, however, the storativity (0.005) was taken from Lepitre and Beebe (2019), corresponding to a confined 4b type aquifer.

Due to the limited number of pumping test reports available for bedrock aquifers in the study area (two reports for Aquifer 899 and one report for Aquifer 1216), we deferred to the aquifer hydraulic parameter values (T, S, S_Y) from Lepitre and Beebe (2019) for calculating SDF for all the mapped bedrock aquifers in the study area, corresponding to their aquifer types (5a or 6b).

Table A2 in Appendix A summarizes aquifer hydraulic parameters assigned to each of the aquifers in the study area. One note from Table A2 is that the value for S or S_Y for Aquifers 6 and 8 from Rickets (1998) and Scibek and Allen (2005) seem to be somewhere between typical values for S and S_Y. The reason for this could not be explored within the scope for the project. However, it may be that vertical heterogeneity imparts a more confined nature to these unconfined aquifers, even though in selecting representative aquifer hydraulic parameters for specific aquifers for the purposes of calculating SDF, we are assuming homogeneous, isotropic conditions in the horizontal direction.

5.10 Summary Excel Spreadsheet

To facilitate analysis of the SDF, we developed a series of worksheets using Microsoft Excel to consolidate the hydraulic connection data. The spreadsheet tools calculate the SDF and when applicable apportion demand between streams. The Excel spreadsheet is located in Appendix D and includes the four worksheets as shown in Table 5 below.

Table 5. Summary of Microsoft Excel spreadsheet.

Worksheet Name	**Description**
PoHC and SDF summary	Summary table that provides most of the hydraulic connection data. It is used to summarize the apportioned or fractional pumping demand between up to three PoHC's, and the SDF calculated for each PoHC.
Aquifer and SDF Parameters	Summary table that consolidates the T and S values used to calculate SDF for each established PoHC, and the weighting factor (m) used to apportion pumping demand between streams.
Wells not assessed	Summary table that lists rationale why SDF was not estimated for specific wells.
List of wells for HC assessment	Summary table that lists all wells where detailed assessment of hydraulic connection was requested by WLRS (total of 859 wells).

6. RESULTS AND DISCUSSIONS

This section presents our understanding of the mapped aquifers within each of the sub-areas, based on the aquifer mapping reports, Monahan et al. (2019), and analyses from this study. Discussions in sub-Sections 6.1 to 6.4 focus on our understanding of aquifer geology, groundwater flow where hydraulic connection likely occurs, and the main sources of inflow, outflow and capture for aquifers (or groups of aquifers) within each sub-area. Section 6.5 discusses the streamflow depletion factor results for the assessed wells.

The figures referenced within this section of the report are included in Appendices B and C. Figures B1 to B5 presents the mapped aquifers and inferred groundwater flow direction for each of the four sub areas, with bedrock aquifers presented separately. Figures C1 to C5 present the PoHCs and estimated SDF values for unconsolidated aquifers in each of the four sub areas and for bedrock aquifers across the study area.

6.1 Fraser-Sumas Floodplain Sub-Area

Aquifers in the Fraser-Sumas Floodplain sub-area can be discussed within three categories: 1) unconsolidated aquifers in the Fraser River floodplain and Sumas Prairie, 2) unconsolidated aquifers located adjacent to the Fraser River floodplain and the Cascade Mountains, and 3) bedrock aquifers along the Cascade Mountains and along the Fraser River.

6.1.1 Shallow Unconsolidated Aquifers 6, 8, 21, and 1199

Aquifer geology: The youngest sediments in the Fraser-Sumas Floodplain sub-area are dominated by post-glacial fluvial and lacustrine processes. This includes Holocene fluvial sand and gravel of the Fraser River and also silt and clay flood deposits of up to several meters thick. Lacustrine silt, sand, and clay deposits are located west of the Vedder Fan in the Sumas Prairie, interfingering with the Vedder Fan. The Holocene fluvial sand and gravel deposits form shallow Aquifers 6 (Chilliwack-Rosedale Aquifer), 21 (Sumas Prairie Aquifer), and 1199 (Sumas Prairie North Aquifer). These aquifers are partially confined by a thin unit of clay/silt flood deposits of one or more metres thick.

The Vedder Fan emerges from the Cascade Mountains at Vedder Crossing where the Chilliwack River drains onto the Fraser River floodplain, forming a fourth aquifer (Aquifer 8, type 3). Aquifer 8 is a significant source of groundwater supply in the area and is the main source of supply for the City of Chilliwack.

Regional groundwater flow: In mapping groundwater flow, static water level data from wells completed in Aquifers 6, 8, 21, and 1199 were compiled together. These four aquifers were treated as one unit because they share similar lithologies, degree of confinement and are all of shallow depth. In the extreme east part of the sub-area, data from Aquifer 1198 was also included in the mapping of groundwater flow. Groundwater elevations for Aquifers 1205 and 1210 were separately contoured manually and integrated into Figure B1. Figure B1 shows the regional groundwater flow is generally to the north along the base of the Cascade Mountains and then west and ultimately towards the Fraser River. Groundwater is expected to also flow to local streams and ditches, but this was not possible to show through mapping at this scale. Groundwater flow at the base of the Cascade Mountains may reflect inflows into the unconsolidated aquifers from mountain block recharge and/or infiltration of run-off from the steep hillslope (groundwater elevation contours are parallel to the floodplain/mountain boundary). Hydrologic influence from the Chilliwack River, as it enters into the Fraser River floodplain (and changes name to the Vedder River) and loses water to the Vedder Fan to recharge Aquifer 8 is evident from the groundwater elevation contours. The mounding of groundwater elevation contours at the eastern end of the sub-area may reflect the different surficial geology comprising Aquifer 1198 (Salish Sediments slope deposits) and the more uneven and elevated topography.

Likelihood of hydraulic connection to streams: Figure C1 shows the PoHC to streams for the assessed wells in the Fraser-Sumas Floodplain sub-area. Knowing where hydraulic connection exists allows points of hydraulic connection (PoHCs) to be inferred and the Statutory Decision Maker (SDM) to attribute pumping demand from specific wells to specific stream reaches. The red streamlines in Figure C1 show where stream reaches appear to be perched or disconnected (vadose zone of >2m thick) and where hydraulic connection is inferred to be unlikely. Figure C1 also shows areas underlain by low permeability sediments that would impede groundwater flow to and from streams.

Given the low relief of the floodplain, stream and ditch density, and nature of the floodplain soils, it is common for a well in the floodplain to be connected to and deplete flow from more than one stream. For the wells assessed in this project completed into Aquifers 6, 8, 21, and 1199, over 60% are expected to connect to more than one stream and 20% connect to more than 2 streams.

6.1.2 Deep, Confined, Unconsolidated Aquifer 1197

Aquifer geology: The Greendale Deep Aquifer is formed by deep deltaic sediments, confined by 3-20 m of very fine sand, silt and clay. It underlies the four shallow aquifers (Aquifers 6, 8, 21 and 1199) in the Fraser River floodplain. Due to only 14 wells being correlated to this aquifer, the sparse well data means that the extent of hydraulic connection between this aquifer and the overlying shallow aquifers is not well constrained.

Likelihood of hydraulic connection: The confined nature and inferred depth of Aquifer 1197 (50-60 m below sea level – see Monahan et al. (2019)'s cross-section 2O, 1-3) suggest direct hydraulic connection to overlying streams, including the Fraser River, is unlikely. We expect that impacts from pumping in Aquifer 1197 would propagate more readily through sediments of higher diffusivity via windows in the confining layer to overlying aquifers (and ultimately to streams). Therefore, we focussed on identifying windows in the confining layer separating Aquifer 1197 from the overlying shallow aquifers by reviewing well records and the cross-sections by Monahan et al. (2019). Figure B1 shows where existence of windows is inferred between Aquifer 1197 and the overlying shallow aquifers. The wells that indicated existence of windows include: WTNs 14445, 100138, 103204, 103296, 103318, 107151, 108528, and borehole ID 9999963 from Monahan et al. (2019). The existence of windows is more certain only where there are well records of sufficient depth; additional windows may also exist but cannot be identified presently due to lack of borehole data.

6.1.3 Unconsolidated Aquifers 1205, 1196, 1213, 1198, 1210 and 1208

Aquifer geology: There are four aquifers of limited extent (0.2 to 5.9 Km^2), and sparse water well data in the sub-area.

- Aquifer 1198 (Cheam Slide): Landslide deposits are mapped at the far east end of the study area;
- Aquifer 1196 (Elk Creek Fan): smaller alluvial fans are located along the front of the Cascade Mountains where tributary creeks drain into the Fraser River floodplain;
- Aquifers 1205 and 1213: unconfined sand and gravel that is part of the Sumas Drift.

Unconsolidated Aquifers 1208 and 1210 occur under the northwest-facing hillslope along the Fraser-Sumas Floodplain and Ryder Uplands sub-area boundary. Both these aquifers comprise confined sand and gravel of Sumas Drift or older age. Aquifer 1210 is located mostly in the Fraser-Sumas Floodplain sub-area, but Aquifer 1208 also underlies the Ryder Uplands sub-area. Aquifer 1208 especially is not well understood because only a few reported wells are completed into this aquifer.

Regional groundwater flow: Groundwater elevation contours for Aquifers 1205, 1210, 1196 and 1213 are shown in Figure B1. Groundwater flow in these small aquifers is inferred to be generally to the north, towards the Fraser River floodplain.

Likelihood of hydraulic connection to streams: Figure C1 shows the PoHC for the wells assessed (19 wells) that are completed into Aquifers 1205, 1210, 1196, 1213 and 1198 (aquifer boundaries are not shown in Figure C1 for clarity). PoHCs were generally determined to the nearest open stream reach downhill.

6.1.4 Bedrock Aquifers 890, 899, 1216, 1214 and 1215

Aquifer geology: Two bedrock Aquifers 899 and 890 occur adjacent to each other and underlie the Ryder Uplands and Fraser-Sumas Floodplain sub-areas. The boundary between these two aquifers follows an east-dipping thrust fault line (Monahan et al., 2019). Aquifer 899 comprises crystalline bedrock and occurs higher topographically in the east end of the study area, and Aquifer 890 comprises sedimentary bedrock and underlies the topographically lower area to the west. The aquifer mapping report (ENV, 2019) for Aquifer 890 implies that groundwater flow provides mountain block recharge to unconsolidated Aquifers 6, 8, 1196 in the Fraser-Sumas Floodplain sub-area and Aquifer 1206 in the Chilliwack River Valley sub-area. The aquifer mapping report, as well as Monahan et al. (2019), also question the existence of hydraulic connection between Aquifer 890 and 899 because of the differences in well yields, hydraulic head levels and water chemistry.

Another bedrock aquifer, Aquifer 1216 underlies the north-facing slope of Vedder Mountain. Finally, two other bedrock aquifers exist at the Fraser River. Aquifer 1214 is a fractured crystalline bedrock aquifer that underlies Chilliwack Mountain. The locations of reported wells are skewed to the hillslope overlooking the Fraser River. Aquifer 1215 is a tiny (0.1 Km^2) crystalline bedrock aquifer and appears to be a continuation of the bedrock underlying Chilliwack Mountain (Aquifer 1214).

Regional groundwater flow: Lack of spatial distribution of groundwater level data meant the groundwater elevation of bedrock aquifers had to be manually contoured. Figure B2 shows groundwater flow to be topographically driven, suggesting that recharge from precipitation is a major source of inflow to bedrock aquifers. Groundwater flow directions also indicate the natural outflows are to unconsolidated aquifers at the valley bottom, and where hydraulically connected, to local streams. Groundwater in Aquifer 1214 also flows to the Fraser River.

Likelihood of hydraulic connection to streams: Figure C2 shows that where data is available, streams overlying bedrock aquifers are estimated to be dominantly perched. Limited mapping shows that the majority of streams draining the slopes above Aquifers 1216, 890 and 899 are perched or disconnected. Therefore, for many of the bedrock wells assessed for hydraulic connection in this sub-area, PoHCs have been drawn following the down-gradient groundwater flow direction. Within the north-facing slopes of Aquifers 1216, 890 and 899 (in the Fraser-Sumas Floodplain sub-area) the resultant PoHCs are on the lower reaches of the streams, where they drain into the Fraser River floodplain.

For bedrock Aquifer 1214, no mapped streams exist over the aquifer. The only well assessed for hydraulic connection on the north edge of the aquifer is inferred to be connected to the Fraser River (Figure C2). For the only other bedrock well assessed that is completed into Aquifer 1214, likelihood of hydraulic connection to local streams could not be inferred.

6.1.5 Conceptual Understanding of Potential Sources of Capture

Our conceptual understanding of the most likely sources of input, output and capture[1] for mapped aquifers in this sub-area is summarized in Table 6. Mapping of groundwater flow (Figures B1 and B2) indicates that infiltration of runoff from the steep hillslopes may be a significant source of seasonal inflow to the shallow valley-bottom unconsolidated aquifers. Recharge from precipitation, especially for unconsolidated aquifers underlying the Fraser River floodplain and Sumas Prairie and the bedrock aquifers is likely a major source of seasonal inflow because these aquifers underly a significant portion of the sub-area. However, groundwater pumping in this sub-area is not expected to induce additional infiltration. Mountain block recharge (MBR) to unconsolidated aquifers from Aquifers 890, 899, 1214 and 1216 is also expected, as groundwater flow from bedrock aquifers to the unconsolidated aquifers is inferred from Figures B1 and B2. MBR is not expected to be a major source of capture because the assumed low permeability of fractured bedrock is a limiting factor restricting additional groundwater inflow caused by well pumping. In contrast, streamflow depletion via decreased discharge to streams and induced infiltration locally near streams is expected to be a major source of capture in the shallow,

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[1] During well pumping, groundwater is also yielded from storage in the aquifer but this source of groundwater, by definition (see Konikow and Bredehoeft, 2020), is not “capture”.

unconsolidated aquifers in this sub-area, and therefore a major groundwater allocation consideration. For the smaller unconsolidated aquifers (Aquifers 1205, 1196, 1213, 1198), aquifer storage depletion is another allocation consideration.

Table 6. Summary of the most likely sources of inflows, outflows and capture for mapped aquifers in the Fraser-Sumas Floodplain sub-area.

Aquifer number	**Likely main sources of natural inflows**	**Likely main sources of outflows**	**Likely main sources of capture (depends on location of pumping)**
8, 6, 21, 1199	• Infiltration of precipitation • Infiltration of runoff from hillslope • Seepage loss (via vadose zone) and infiltration (via saturated zone) from streams • Recharge (via mountain front recharge) from Aquifers 890, 899, 1214, 1216	• Discharge to streams • Discharge to wells	• Induced infiltration locally from nearby streams • Decrease in discharge to streams
1196, 1213	• Infiltration of precipitation • Infiltration of runoff from hillslope • Seepage loss (via vadose zone) and infiltration (via saturated zone) from streams • Recharge (via mountain front recharge) from Aquifers 890 and 899	• Discharge to streams • Discharge to wells • For Aquifer 1213, discharge to Aquifer 1196	• Decrease in discharge to streams • For Aquifer 1213, decrease in discharge to Aquifer 1196
1198	• Infiltration of precipitation • Infiltration of runoff from hillslope • Seepage loss from streams • Recharge (via mountain front recharge) from Aquifer 899	• Discharge to streams • Discharge to wells	• Decrease in discharge to streams
1205	• Infiltration of precipitation • Infiltration of runoff from hillslope • Recharge (via mountain front recharge) from Aquifer 1216	• Discharge to Vedder River • Discharge to wells	• Decrease in discharge to Vedder River
1197	• Groundwater inflow from overlying Aquifers 6, 8, 21, 1199 • Recharge (via MFR) from Aquifers 1216, 1214	• Discharge to over-lying aquifers • Discharge to wells	• Increase in groundwater inflow from overlying Aquifers 6, 8, 21, 1199 • Decrease in discharge to overlying aquifers
1210, 1208	• Infiltration of precipitation • Infiltration of runoff from hillslope	• Discharge to streams • Discharge to wells	• Decreased discharge to streams
890, 899, 1214, 1215, 1216	• Infiltration of precipitation	• Discharge to unconsolidated aquifers in the Fraser-Sumas Floodplain and Chilliwack River Valley sub-areas (via MBR) • Discharge to wells • Discharge to some connected tributary streams	• Decrease in discharge to unconsolidated aquifers • Decrease in discharge to some connected tributary streams

For Aquifer 1197, the main sources of inflow are MBR and groundwater inflow from the overlying unconsolidated aquifers. The major source of capture for this aquifer, as a result of well pumping, is decreased discharge to the overlying aquifers. Multi-level monitoring of Aquifer 1197 and the overlying shallow aquifers would increase understanding of the hydraulic connection between these aquifers.

For bedrock aquifers in the sub-area, the decrease in discharge to connected streams (not many) and to the unconsolidated aquifers in the valley bottom are believed to be the major sources of capture as groundwater development continues. Overall, aquifer storage depletion along with site-specific well interference appear to be the main allocation considerations for the bedrock aquifers in this sub-area.

6.2 Columbia Valley – Cultus Lake Sub-Area

The two major geographic features in this sub-area are the Columbia Valley and Cultus Lake. Two types of unconsolidated aquifers occur in this sub-area: an unconfined outwash sand and gravel aquifer in the Columbia Valley (Aquifer 20) and five small alluvial fan aquifers (Aquifers 1200 to 1204) along the shore of Cultus Lake.

6.2.1 Unconsolidated, Unconfined Aquifer 20

Aquifer geology: The Columbia Valley Aquifer[2] (Aquifer 20) occupies the valley bottom and comprises glaciofluvial sediments from the Sumas Drift. These sediments have a maximum thickness of about 150 m and directly overlie bedrock (Monahan et al. 2019). The aquifer is characterized by a deep water table and a 30 to50 m thick vadose zone (Zubel, 2000), except near Cultus Lake where terraces step down closer to lake level. The deeper water table means the streams flowing in the valley bottom from the bedrock hillslopes are likely disconnected from the aquifer except on the lower terrace near Cultus Lake where the depth to the water is shallow.

Regional groundwater flow: Direction of groundwater flow has been mapped towards the thalweg of the valley and then to the northeast towards Cultus Lake (Figure B3). The groundwater elevation contours are sub-parallel to the valley sides, suggesting mountain block recharge and infiltration from run-off from the steep hillslopes are sources of inflows to Aquifer 20.

Likelihood of hydraulic connection to streams: Figure C3 shows streams flowing over Aquifer 20 are disconnected along most of their length. Frosst Creek and Watt Creek appear to be disconnected over Aquifer 20. PoHCs for the assessed wells completed into Aquifer 20 all eventually connect to Spring Creek[3] near Cultus Lake, as well as Cultus Lake itself. Unlike wells in the Fraser-Sumas Floodplain sub-area, the narrowness of Columbia Valley restricts groundwater flow and stream drainage entirely to the northeast direction along the valley and the PoHCs towards Cultus Lake. The length of disconnected streams results in distances to the PoHC for wells located up the Columbia Valley being larger (up to distances of 6.8 Km) compared to distances to PoHC for the assessed wells completed into other unconsolidated aquifers in the study area.

6.2.2 Unconsolidated Alluvial Fan Aquifers 1200 to 1204

Aquifer geology: In the Columbia Valley-Cultus Lake sub-area, the youngest sediments are Holocene stream deposits and the alluvial fans at the mouth of Watt, Teapot, Clear, Windfall, and Ascaphus Creeks along the shore of Cultus Lake. The alluvial fans are comprised of shale gravel, gravel, and sand deposits between 20 m to 70 m thick, generally overlying bedrock. They are mapped as small (<0.2 Km^2), Type 3 unconfined alluvial fan aquifers (1200 to 1204).

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[2] The mapped boundary of Aquifer 20 does not extend to Cultus Lake.

[3] Spring Creek is a creek that originates at the base of a terrace near the lower end of Columbia Valley.

Regional groundwater flow and likelihood of hydraulic connection to streams: There are insufficient wells to help map the direction of groundwater flow in these small fans, however, groundwater flow is most likely from the apex of the fan down to the distal end of the fan at Cultus Lake, possibly with a component of radial flow outward from the apex along more permeable channel deposits within the fans. We estimate that losses from alluvial streams is the main source of recharge to these aquifers and discharge to Cultus Lake the main source of natural outflow. Recharge from precipitation is expected to be secondary source of inflow.

Hydraulic connection between groundwater in the fans and Cultus Lake is likely. Inspection of the individual well records for wells completed into Aquifers 1200, 1201 and 1202, indicated deeper water tables (>14 m) suggesting the tributary streams are mostly perched or disconnected. No wells are competed into Aquifer 1203 and the only well record in Aquifer 1204 had no reported static water level. There were no wells assessed for hydraulic connection completed into these aquifers to specifically map PoHCs and calculate SDFs. Given the small sizes of these aquifers, the distances to PoHC (to Cultus Lake) for wells in these aquifers would be short.

6.2.3 Bedrock Aquifers 1217 and 1218

Aquifer geology: Finally, the steep bedrock slope rising to the northwest and southeast from the valley bottom also form bedrock aquifers (Aquifer 1217 to the northwest and Aquifer 1218 to the southeast). Aquifer 1217 comprises conglomerate, sandstone, and argillite, with lesser amounts of limestone, basalt and schistose chert of the Kent Formation. Aquifer 2018 comprises mudstone and sandstone of the Cultus Formation. Few wells are reported for these aquifers in the sub-area, indicating light groundwater use.

Regional groundwater flow and likelihood of hydraulic connection: Groundwater flow in these bedrock aquifers is not well mapped because of lack of data. However, groundwater flow is interpreted to be in the direction of the topographic slope, towards unconsolidated Aquifer 20 and Cultus Lake in the valley bottom (Figure B2). This interpretation of topographically driven flow implies recharge from precipitation is the main source of inflow for Aquifers 1217 and 1218 and groundwater discharge to Aquifer 20, to Cultus Lake and to the small alluvial fans is the main source of natural outflow.

Figure C2 shows streams flowing over these bedrock aquifers in the sub-area to be perched (disconnected). Therefore, pumping in these aquifers would reduce groundwater discharge to Aquifer 20, Cultus Lake, and the alluvial fans but is not likely to directly deplete flow in the tributary streams.

6.2.4 Conceptual Understanding of Potential Sources of Capture

Our conceptual understanding of the Cultus Lake and Columbia Valley Sub-area is summarized in Table 7, including likely sources of inflows, outflows and capture. Mapping of groundwater flow in Figures B2 and B3 indicates that infiltration of runoff from the steep hillslopes may be a significant source of seasonal inflow to Aquifer 20. Recharge from precipitation, especially for unconsolidated Aquifer 20 and the bedrock Aquifers 1217 and 1218 is also a likely major source of seasonal inflow. However, groundwater pumping in this sub-area is not expected to induce additional infiltration recharge because of the perched nature of the streams. MBR to unconsolidated aquifers from bedrock Aquifers 1217 and 1218 is also expected but is not expected to be a major source of capture because the likely low permeability of fractured bedrock is a limiting factor restricting additional significant groundwater inflow as a result of well pumping. Despite the perched and disconnected nature of streams over Aquifer 20, streamflow depletion by process of interception is expected to be concentrated at Cultus Lake and Spring Creek. In the remainder of Aquifer 20, aquifer storage depletion and increased inflow from

Washington State are expected to be the other main allocation considerations, depending where pumping occurs.

For Aquifers 1200 to 1204 along the shores of Cultus Lake, the main source of inflow is seepage loss from the overlying stream and infiltration of run-off from the steep hillslope. The major source of capture is decrease in discharge to Cultus Lake and induced infiltration locally from Cultus Lake. Decreased aquifer storage is the other possible impact of pumping in these small aquifers, although not defined as capture.

For the surrounding bedrock aquifers 1217 and 1218, decreased discharge to Cultus Lake and to the unconsolidated aquifers are likely the main sources of capture (depending on location of well pumping). Overall, aquifer storage depletion and site-specific well interference are the main allocation considerations for the bedrock aquifers in this sub-area.

Table 7. Summary of the most likely sources of inflows, outflows and capture for mapped aquifers in the Columbia Valley-Cultus Lake sub-area.

Aquifer number	**Likely main sources of inflows**	**Likely main sources of outflows**	**Likely main sources of capture (depends on location of pumping)**
1200, 1201, 1202, 1203, 1204	• Seepage loss from streams via vadose zone • Infiltration of runoff from hillslope • Infiltration of precipitation • Mountain block recharge from Aquifers 1217 and 1218	• Discharge to Cultus Lake • Discharge to wells	• Decrease in discharge to streams • Induced infiltration locally from Cultus Lake
20	• Infiltration of precipitation • Infiltration of runoff from hillslope • Seepage loss from streams via vadose zone • Inflow of groundwater flow from Washington State • Mountain block recharge from Aquifers 1217 and 1218	• Discharge to Cultus Lake and Spring Creek • Discharge to wells	• Induced infiltration locally from Cultus Lake • Decrease in discharge to streams near Cultus Lake • Increase in groundwater inflow from Washington State (pumping near the border)
1217 and 1218	• Infiltration of precipitation	• Discharge to Cultus Lake • Discharge to Aquifers 20, 1200, 1201, 1202, 1203 and 1204 (via MBR) • Discharge to wells	• Decrease discharge to Cultus Lake and Aquifers 20, 1200, 1201, 1202, 1203, and 1204

6.3 Chilliwack River Valley Sub-Area

The Chilliwack River flows through this narrow, mostly mountainous sub-area. In this sub-area, the main unconsolidated aquifers are found at the valley bottom, along the Chilliwack River and underlying the outwash plain between northeast end of Cultus Lake and Chilliwack River.

6.3.1 Unconsolidated Aquifers 9 and 1206

Aquifer geology: Two stacked unconsolidated aquifers occur in this sub-area, constrained laterally by steep hillslopes. Aquifer 9 comprises mostly Salish Sediments of fluvial origin, some colluvial sediments, and minor Sumas Drift outwash deposit. The aquifer is largely unconfined and highly transmissive (see Section 5.9 for a discussion of the aquifer's representative hydraulic parameters). Underlying Aquifer 9, Aquifer 1206 is a glaciofluvial sand and gravel unit that was deposited during the advance of the last glaciation (Monahan et al., 2019 interprets Aquifer 1206 to be of Quadra Sand equivalent). Till separates Aquifer 1206 and Aquifer 9 (see Figure 9). The till layer reaches up to 40 m thick under Coen Ave and Wilson Road but, based on drillers' descriptions and previous interpretations, the till is absent in some places, such as beneath the outwash plain between Cultus Lake and Chilliwack River, near Midgely Creek, Wingfield Creek, and near Slesse Park. Hydraulic connection between Aquifers 9 and 1206, and therefore the Chilliwack River, can occur at these locations where the till is absent.

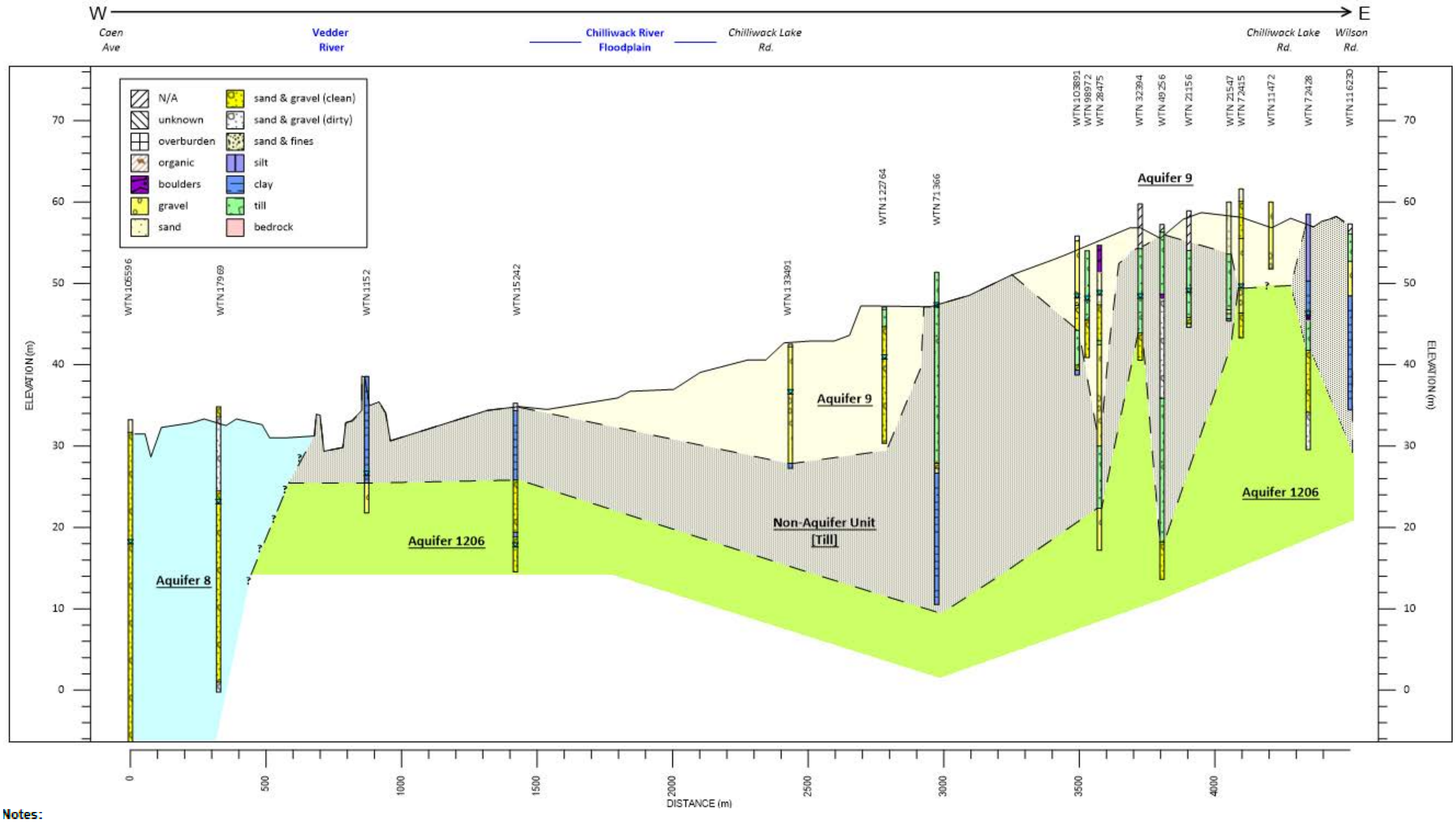
Regional groundwater flow: Static water levels from wells completed in both aquifers were used to map groundwater elevation contours (Figure B4). Groundwater flow in both aquifers is inferred to be to the NE from Cultus Lake and to the NW along the Chilliwack River valley (Figure B4). Note the sub-parallel groundwater elevation contours near the boundary between the Chilliwack River Valley and Ryder Uplands sub-areas suggest mountain block recharge, lateral groundwater inflow to Aquifer 1206, and run-off from the steep hillslope are sources of inflow.

Likelihood of hydraulic connection to streams: Figure C4 shows the Chilliwack River is hydraulically connected to Aquifer 9 along certain reaches of its length. Hydraulic connection between Aquifer 9 and tributaries appears to be unlikely as mapping indicates many of the tributary streams are perched or disconnected.

We reviewed Monahan's (c. 2019) unpublished cross-sections and well records to identify locations where windows in the till between Aquifer 1206 and overlying Aquifer 9 are inferred to exist. These windows are shown in Figure B4, Figure C4, and Figure 9 below, an unpublished cross-section drawn by Monahan (c. 2019). See Figure 5 for the cross-section location for Figure 9. Similar to Aquifer 1197, pumping impact is expected to propagate vertically through these windows where diffusivity of the sediments is high, providing a path for pumping influence on the Chilliwack River. PoHCs for the assessed wells completed in Aquifer 1206 were drawn to the nearest window.

6.3.2 Bedrock Aquifers 1216 and 1218

Aquifer geology, regional groundwater flow and likelihood of hydraulic connection: The bedrock along both sides of the outwash plain are mapped as bedrock Aquifers 1216 and 1218. Additional descriptions of these aquifers are provided in Sections 6.2.3 and 6.1.4. Few wells are reported in these aquifers in this sub-area, indicating light groundwater use. Groundwater flow in these aquifers cannot currently be mapped because of lack of data, however, groundwater flow is expected to follow topography towards the outwash plain and Chilliwack River. We expect that recharge from precipitation is a main source of inflow to the bedrock aquifers. The steep topography suggests streams flowing over the bedrock in this sub-area to be perched (disconnected) and discharge to unconsolidated aquifers in the valley bottom.



Notes:
1) Map Projection: NAD83 UTM Zone 10
2) Vertical Exhaggeration: 30x
3) Lithology descriptions from GWELLS;
4) Topography from GeoBC (2019);
5) The hydrostratigraphy shown on this drawing are interpreted from well logs is known with certainty only at these locations. Actual hydrostratigraphy may vary from that indicated on this drawing.

Figure 9. Hydrogeological cross-section from Vedder Crossing to Wilson Road, looking north.

6.3.3 Conceptual Understanding of Potential Sources of Capture

Conceptual understanding of the Chilliwack River Valley Sub-Area is summarized in Table 8, including likely sources of inflows, outflows, and capture. Infiltration of precipitation and run-off from the steep hillslope, seepage losses from streams, and inflow from Cultus Lake are believed to be major sources of inflows. MBR and lateral groundwater flow from the Ryder Uplands to Aquifer 1206 may also be sources of inflows. However, amongst these sources, inflow from Cultus Lake and decreased discharge to Chilliwack River are likely the main sources of capture under pumping conditions. Increased infiltration, streambed losses, lateral inflows, and MBR are not anticipated to be major sources of capture. Hydraulic connection of Aquifers 9 and 1206 to Chilliwack River and Cultus Lake and potential streamflow depletion are important allocation considerations in this sub-area. For the bedrock aquifers and Aquifer 1206, aquifer storage depletion is also an allocation consideration.

Table 8. Summary of the most likely sources of inflows, outflows and capture for mapped aquifers in the Chilliwack River Valley sub-area.

Aquifer number	**Likely main sources of inflows**	**Likely main sources of outflows**	**Likely main sources of capture (depends on location of pumping)**
9	• Seepage loss (via vadose zone) and infiltration (via saturated zone) from tributary streams • Infiltration from Cultus Lake • Infiltration of precipitation • Infiltration of runoff from hillslope • Inflow from Aquifer 1206 (via windows in the till) • Mountain block recharge from Aquifers 1216 and 1218	• Discharge to streams • Discharge to wells	• Increase in infiltration locally from streams and from Cultus Lake • Decreased discharge to streams • Increase inflow from Aquifer 1206
1206	• Infiltration from Cultus Lake • Infiltration of runoff from hillslope • Inflow from Aquifer 9 (via windows in the till) • Inflow of groundwater from the Ryder Uplands • MBR from surrounding bedrock aquifers	• Discharge to Aquifer 9 (via windows in the till) • Discharge to wells	• Increase inflow from Aquifer 9 (via windows) and infiltration locally from Cultus Lake • Decrease discharge to Aquifer 9 (via windows)
1216 and 1218	• Infiltration of precipitation	• Discharge to Cultus Lake • Discharge to Aquifers 9 and 1206 (via MBR) • Discharge to wells	• Decrease discharge to Cultus Lake and Aquifers 9 and 1206

6.4 Ryder Uplands Sub-Area

6.4.1 Confined, Unconsolidated Aquifers 1207, 1208, 1209, 1211, and 1212

Aquifer geology, regional groundwater flow and likelihood of hydraulic connection: The sediments in the Ryder Uplands sub-area are comprised of thick sequences of glaciolacustrine silts and clays, and tills, with interbedded sands and gravels. Monahan et al. (2019) inferred that the glaciolacustrine and till sediments were deposited during the Late Wisconsin period when the Chilliwack River Valley outlet was dammed by the Cordilleran ice sheet in the Fraser Lowlands, before the Chilliwack River Valley glacier coalesced with the Fraser Lowlands ice sheet. The sand and gravel deposits are up to about 45 m thick. Many of these deposits are water-bearing, as evident by the creeks and springs that emerge from the valley wall between about 250 and 300 m elevations. The glaciolacustrine and till sediments are inferred to as overly advanced phase Fraser Glaciation outwash sands and gravels (Quadra Sand equivalent) that extend northward from the Chilliwack River (Monahan et al. 2019), but this is constrained by records from just a few wells.

The aquifers mapped in the Ryder Uplands are not well characterized. The lateral extents of the unconsolidated aquifers are poorly delineated, as evident by their oval shapes. It is challenging to infer the local hydraulic connection due to limited understanding of aquifer extents, poorly constrained groundwater flow directions (Figure B5), and the mostly confined nature of these aquifers.

6.4.2 Bedrock Aquifers 890 and 899

Two bedrock Aquifers 899 and 890 occur adjacent to each other and underlie the Ryder Uplands and Fraser-Sumas Floodplain sub-areas. Aquifer geology is described in Section 6.1.4. Within the Ryder Uplands, groundwater flow is not well mapped within the bedrock aquifers but is assumed to generally follow topography and flow into the Chilliwack River Valley sub-area (Figure B2). Aquifer 890 likely contributes flow to unconsolidated Aquifer 1206 in the Chilliwack River Valley sub-area (Monahan et al., 2019). Figure C2 shows streams flowing over these bedrock aquifers in the sub-area to be perched (disconnected). Hydraulic connection between Aquifer 890 and 899 is uncertain because of the thrust fault contact and differences in well yields, hydraulic head levels and water chemistry (Monahan et al., 2019).

6.4.3 Conceptual Understanding of Potential Sources of Capture

Our conceptual understanding of the Ryder Uplands is summarized in Table 9, including the likely sources of inflows, outflows and capture. Groundwater flow is not well understood for the unconsolidated aquifers in this sub-area. Based on the limited available information, we estimate that the main source of capture from these aquifers is potentially a decreased discharge to streams. For Aquifers 890 and 899, the likely source of capture is decreased discharge to unconsolidated aquifers. Installing observation wells in both types of aquifers in the Ryder Uplands sub-area would provide better understanding of the recharge-discharge characteristics of these aquifers. Finally, in addition to capture, aquifer storage depletion is another allocation consideration for aquifers in this sub-area.

Table 9. Summary of the most likely sources of inflows, outflows and capture for mapped aquifers in the Ryder Uplands sub-area.

Aquifer number	**Likely main sources of input**	**Likely main sources of output**	**Likely main sources of capture (depends on location of pumping)**
1211, 1212, 1207, 1208, 1209	• Infiltration of precipitation • Infiltration of runoff from hillslope	• Discharge to streams • Discharge to wells	• Decreased discharge to streams
890 and 899	• Infiltration of precipitation	• Discharge to unconsolidated aquifers in the Fraser-Sumas Floodplain and Chilliwack River Valley sub-areas (via MBR) • Discharge to wells	• Decrease in discharge to unconsolidated aquifers

6.5 Points of Hydraulic Connection (PoHC) and Stream Depletion Factors (SDFs)

The Excel file in Appendix D contains the results for the 859 wells assessed for likelihood of hydraulic connection to streams in this study. Of the 859 wells assessed, 783 wells were inferred to be hydraulically connected to streams. Hydraulic connection for 76 of the wells assessed could not be determined. Most of these wells are completed in bedrock aquifers where the overlying streams are perched or disconnected; some of the wells are completed in the confined, unconsolidated aquifers in the Ryder Uplands sub-area where the aquifer boundaries are uncertain. Hydraulic connection for 11 wells completed in Aquifer 1197 could not be assessed because they are completed at depth. Table 10 summarizes the hydraulic connection results by sub-area.

Table 10. Summary of hydraulic connection to streams for wells assessed in this study.

Sub-area	**# of wells assessed**	**# wells connected to streams**	**# wells not connected to streams**	**Notes**
Fraser-Sumas Floodplain	557	532	25	- 11 wells that could not be connected to streams are completed in Aquifer 1197 (Greendale Deep). - 10 bedrock wells where could not connected to streams, - Four wells were not correlated to the correct aquifer.
Columbia Valley-Cultus Lake	116	99	17	- 13 bedrock wells cannot be connected to streams - Four wells are completed in Aquifers 1200 to 1204 (see Section 6.2.2).
Chilliwack River Valley	150	146	4	- Of the four wells where connection to streams cannot be inferred, one is completed in Aquifer 1206, two are completed in bedrock aquifers, and one is completed in Aquifer 1208.
Ryder Uplands	36	6	30	- Limited understanding of aquifer extent and groundwater flow directions make determining likelihood of hydraulic connection to local streams challenging. - Two of the wells where connection to streams cannot be inferred are correlated to the incorrect aquifer (Aquifer 243, which does not exist in study area).
Total	859	783	76	

Of the 783 wells connected to streams, almost half (371 or 47%) were likely connected to multiple streams. The apportionment equation with a weighting factor m=2 was used to assign a percentage of fractional demand to each stream. For demand apportioned to multiple streams, the SDFs and timing of streamflow depletion for each stream will be different, longer for PoHC to more distant streams.

There are sufficient results to summarize SDF statistically for some of the aquifers. The SDF statistics are summarized in Figure 11 and Table 11. Some interesting observations can be made from the results:

- For most of the unconsolidated aquifers, the distances to the primary connected stream (stream 1) are commonly only a few hundred metres. This means the SDFs range from less than a day to up to 30 days, indicative of a responsive flow system, which, in turn, suggests taking action to curtail both surface water and groundwater uses to protect streamflow during drought is feasible.
- The only unconsolidated aquifer that has a comparatively larger range of SDF is Aquifer 20. 60% of the wells have SDF of 90 days or greater; 32% have SDF of more than 1 year. This is because

the streams are perched or disconnected along much of their length except near Cultus Lake. Groundwater pumping in the southwest end of Aquifer 20 near the Washington State border will still deplete flow in streams near Cultus Lake several kilometres away. Depletion, however, will take a longer time to manifest in the stream (farther way). Similarly, curtailment of groundwater use from the more distant wells (e.g., with SDFs of >90 days or >1 year) to protect streamflow during drought would likely be less effective because of the longer response times.

- For the wells assessed that are inferred to be connected to more than 1 stream, the SDF for (and distance to) to the second-nearest and third-nearest streams is naturally increasingly greater. This means that streamflow depletion caused by well pumping is distributed to multiple streams and will also take longer to manifest to the more distant connected streams.
- The relatively low bedrock storativity and resultant high diffusivity also result in the SDF for most bedrock wells assessed in this study to be 30 days or less, indicative of a responsive flow system, suggesting taking action to curtail both surface water and groundwater use to protect streamflow depletion during drought is feasible.

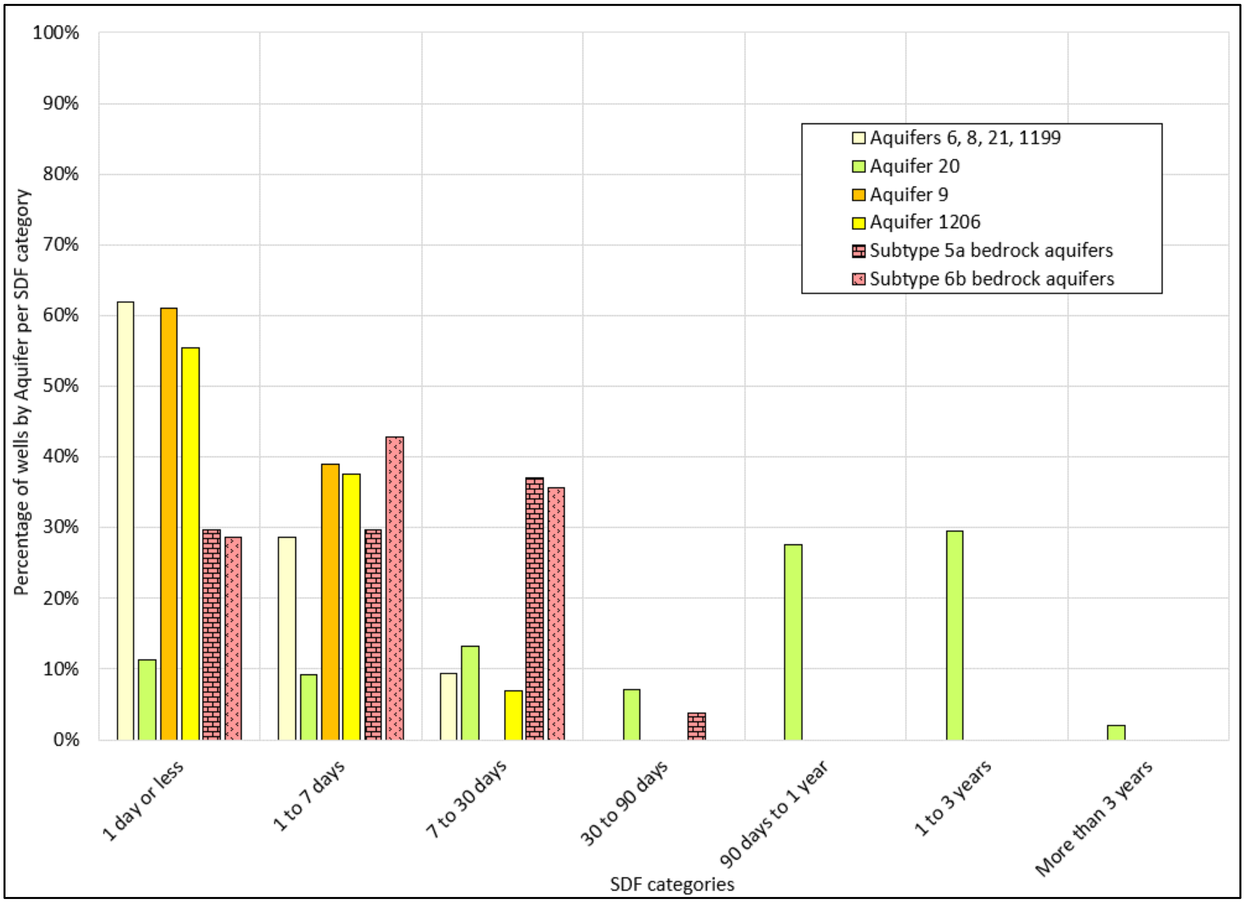


Figure 10. Breakdown of streamflow depletion factors (SDF) for select aquifers and aquifer subtypes in the study area.

Table 11. Summary of streamflow depletion factors for select aquifers and aquifer subtypes in the study area.

Aquifer ID	**T (m^2/day)**	**S or S_y (-)**	**Summary of SDFs for wells assessed in this study for select aquifers**							
			No. of PoHCs to stream 1	**SDF^1_{min} (days)**	**SDF^1_{median} (days)**	**SDF^1_{max} (days)**	**No. of PoHCs to stream 2**	**SDF^2_{median} (days)**	**No. of PoHCs to stream 3**	**SDF^3_{median} (days)**
6, 8, 21, and 1199	3000	0.01	476	<1	0.5	18	281	4	106	8
20	690	0.02	98	<1	183	1341	56	75	0	-
9	3000	0.01	41	<1	0.2	5	21	2	9	9
1206	3000	0.005	105	0.02	0.8	15	0	-	0	-
5a bedrock	4	$3(10^{-5})$	27	0.04	4	30	3	2	0	-
6b bedrock	23	$6.4(10^{-4})$	15	0.03	5	10	8	18	0	-

Notes:
SDF^1 =streamflow depletion factor for the nearest stream.
SDF^2 = streamflow depletion factor for the second-nearest stream.
SDF^3 = streamflow depletion factor for the third-nearest stream.

The implication of using both default and local aquifer hydraulic parameters on calculation of SDF is illustrated in Figure 11 below. The upper band of SDF curves are calculated for the various aquifer types, including crystalline bedrock, using the default values of T and S from Lepitre and Beebe (2019). The reason the SDF curves plot close together is the diffusivity values (ratios of T/S or T/S_Y) for the various aquifer types are relatively similar within a range of ~30,000-50,000 m^2/day (see Table in Appendix B). The salmon-coloured curve is from default values from Lepitre and Beebe (2019) for sedimentary type bedrock. The significantly lower SDF for any given distance is due mostly to the low default S value for the sedimentary bedrock ($3x10^{-5}$). The green and dark red curves at the lower part of the graph are based on aquifer hydraulic parameters from local pumping tests. Use of T and S values from local pumping tests resulted in the higher diffusivity and lowest SDF values by roughly one order of magnitude because the transmissivity values from the local pumping tests are much higher than the default values for the corresponding aquifer type.

The aquifer-specific T and S values were assigned based on only a few pumping tests. Although limited, these values better reflect the local conditions of the study area. The data upon which the representative T and S values were selected in Lepitre and Beebe (2019) are also based on limited data. Therefore, the SDFs calculated in this study should be viewed as preliminary and to provide an order of magnitude estimate only of the time response to streamflow depletion from pumping. SDF estimates can be improved by continually compiling T and S values for the various aquifer subtypes.

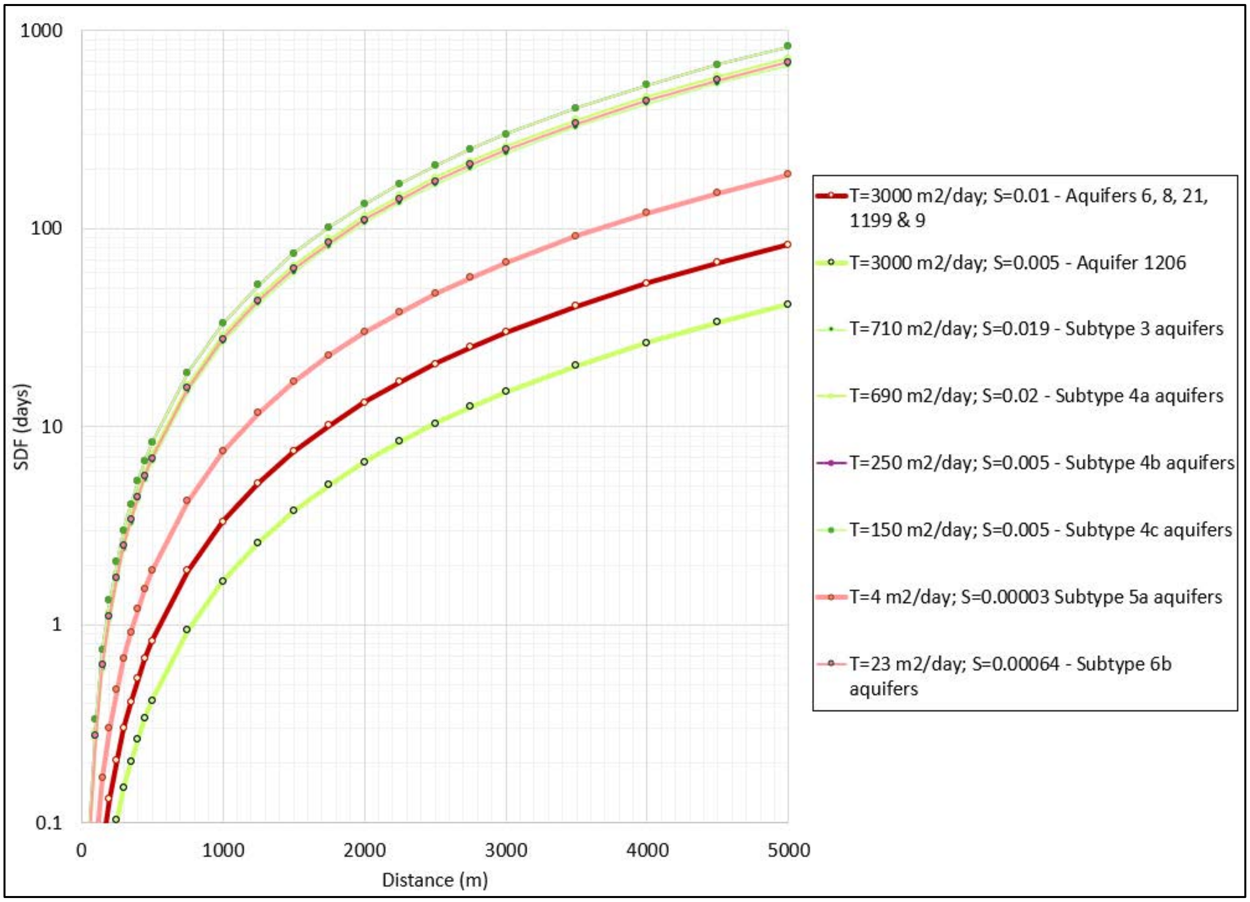


Figure 11. Relationship between streamflow depletion factor and distance from the pumping well to the stream for various aquifers and aquifer subtypes in the study area.

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. SDF values should be viewed as a conservative measure of response time. Therefore, SDF values should be interpreted with these limitations in mind. SDF also does not consider the magnitude of pumping or whether the pumping is on-going or seasonal; these are also important considerations in assessing the magnitude of streamflow depletion from well pumping. These aspects of groundwater use that affect streamflow depletion were not within the scope of this study.

Finally, despite the uncertainties related to the identification of where hydraulic connection likely occurs, the rate and magnitude of streamflow depletion and sources of capture for aquifers in the study area, the results of this preliminary study provide a systematic and larger-scale context to inform future studies and authorization of groundwater use in the Chilliwack area.

7. RECOMMENDATIONS FOR FURTHER WORK

We recommend the following further work to better understanding the nature of hydraulic connection and streamflow depletion in the study area:

- Extend the hydraulic connection mapping into the Sumas Prairie and/or up the Chilliwack River to Chilliwack Lake.
- Within the study area, prioritize aquifers for further assessment where there is already significant non-domestic groundwater use or ongoing plans for further development of non-domestic groundwater use is proposed by licence applications.
- Consider installing observation wells in Aquifers 890, 899 and one of the unconsolidated aquifers in the Ryder Uplands.
- Consider installing multi-level observation wells in Aquifer 1197 and overlying Aquifers 6, 8, 21 or 1199 as well as in Aquifers 1206 and overlying Aquifer 9, to better understand hydraulic connection between these aquifers.
- Explore why the boundary of Aquifer 20 does not extend to Cultus Lake.
- Seek opportunities to update the soils and surficial geology mapping for the study area.
- Continue to compile aquifer hydraulic parameters and enter them into GWELLS database.
- Include hydraulic connection maps into the BC Water Resources Atlas and iMapBC to facilitate improved groundwater studies.
- Consider delineating groundwater management areas to assist with allocation decisions within sub-areas, especially for aquifers with a higher degree of non-domestic groundwater use and around fully allocated streams.

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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.
Capture:	The changes in recharge and discharge caused by pumping and represents water “captured” by the well(s) that otherwise would not have entered the groundwater system or otherwise would have discharged from the groundwater system naturally.
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*).
Diffusivity (D):	A measure of how quickly hydraulic stress propagates through an aquifer. Diffusivity is the ratio of the aquifer’s transmissivity, T (or hydraulic conductivity, K) to the aquifer’s storativity, S (or specific storage, S_s) or specific yield (S_y).
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*).
Hydraulic conductivity (K):	The ability for a fluid to flow through a porous medium under a given hydraulic gradient.
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.
Mountain Block Recharge:	Recharge to the valley-bottom unconsolidated aquifer from groundwater flow in the mountainous bedrock.

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 stream flow as a result of pumping of a well is expected to be first felt.
Relief:	The difference between the highest and lowest point within a watershed.
Specific storage (S_s)	The amount of water an aquifer releases via expansion of water and compaction of aquifer grains as the aquifer depressurizes (e.g., pumped).
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*).
Storativity (S)	Volume of water stored or released from a column of aquifer with unit cross section under unit change in groundwater level.
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: $SDF = d^2 \times \frac{S}{T} (confined) or\ SDF = d^2 \times \frac{Sy}{T} (unconfined)$ 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), which ever 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).
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. MAPPED AQUIFERS AND AQUIFER PARAMETERS

Table A1. Summary of mapped aquifers in study area.

Aquifer ID	Aquifer Name	Sub-area	Location	Subtype	Stratigraphic Unit
6	Chilliwack-Rosedale	Fraser-Sumas Floodplain	Chilliwack Fraser Lowland	1a - Unconfined sand and gravel - large river system	Holocene fluvial sand and gravel
8	Sardis-Vedder	Fraser-Sumas Floodplain	Vedder Alluvial Fan, Vedder Crossing	3 - Unconfined sand and gravel - alluvial or colluvial fan	Holocene alluvial fan
9	Chilliwack River Shallow	Chilliwack River Valley	Chilliwack River; Cultus Lake	1b - Unconfined sand and gravel aquifer - medium stream system	Holocene Fluvial, include Sumas Outwash by Cultus Lake
20	Columbia Valley	Columbia Valley-Cultus Lake	South of Chilliwack	4a- Unconfined sand and gravel - late glacial outwash	Sumas Stade Outwash
21	Sumas Prairie	Fraser-Sumas Floodplain	Sumas Prairie	1a - Unconfined sand and gravel - large river system	Salish Sediments; Fraser River Sediments
890	Mount Tom Bedrock	Fraser-Sumas Floodplain, and Ryder Uplands	Mt Tom area, SE of Chilliwack	5a- Fractured sedimentary rock	Cultus Mudstones (east) to Kent coarse sedimentary (west) / Locally Vedder Complex
899	-	Fraser-Sumas Floodplain, and Ryder Uplands	Ford Creek area, SE of Chilliwack	6b - Fractured crystalline bedrock	Primarily Volcanic rocks of Pennsylvanian to Permian Chilliwack Group
1196	Elk Creek Fan	Fraser-Sumas Floodplain	SE of Chilliwack	3 - Unconfined sand and gravel - alluvial or colluvial fan	Holocene Alluvial Fan
1197	Greendale Deep	Fraser-Sumas Floodplain	Chilliwack – Fraser Lowland	4b - Confined sand and gravel - glacio-marine	Pleistocene, Late Wisconsin Glaciomarine Outwash
1198	Cheam Slide	Fraser-Sumas Floodplain	Chilliwack – Fraser Lowland	3 - Unconfined sand and gravel - alluvial or colluvial fan	Holocene slide debris
1199	Sumas Prairie North	Fraser-Sumas Floodplain	West Chilliwack / East Abbotsford	4b - Confined sand and gravel - glacial	Holocene lacustrine
1200	Cultus Lake Fan Delta A	Columbia Valley-Cultus Lake	Cultus Lake	3 - Unconfined sand and gravel - alluvial or colluvial fan	Alluvial Fan Delta
1201	Cultus Lake Fan Delta B	Columbia Valley-Cultus Lake	Cultus Lake	3 - Unconfined sand and gravel - alluvial or colluvial fan	Alluvial Fan Delta
1202	Cultus Lake Fan Delta C	Columbia Valley-Cultus Lake	Cultus Lake	3 - Unconfined sand and gravel - alluvial or colluvial fan	Alluvial Fan Delta

Aquifer ID	Aquifer Name	Sub-area	Location	Subtype	Stratigraphic Unit
1203	Cultus Lake Fan Delta D	Columbia Valley-Cultus Lake	Cultus Lake	3 - Unconfined sand and gravel - alluvial or colluvial fan	Cultus Lake Fan Delta D
1204	Cultus Lake Dan Delta E	Columbia Valley-Cultus Lake	Cultus Lake	3 - Unconfined sand and gravel - alluvial or colluvial fan	Alluvial Fan Delta
1205	Vedder Crossing	Fraser-Sumas Floodplain	Northeast end of Vedder Mountain	4a - Unconfined sand and gravel - late glacial outwash	Sumas & advance phase Late Wiconsin Outwash, Lower part pre-Wisconsin
1206	Chilliwack River Subtill	Chilliwack River Valley	Chilliwack River Valley	4b - Confined sand and gravel - glacial	advance phase Late-Wisconsin Outwash (Quadra equivalent)
1207	Ryder Upland A	Ryder Uplands	Ryder Upland – Southeast Chilliwack	4b - Confined sand and gravel - glacial	Late-Wisconsin pre-Vashon glaciolacustrine
1208	Ryder Upland B	Ryder Uplands	Ryder Upland – Southeast Chilliwack	4b - Confined sand and gravel - glacial	Late-Wisconsin pre-Vashon glaciolacustrine
1209	Ryder Upland C	Ryder Uplands	Ryder Upland – Southeast Chilliwack	4b - Confined sand and gravel - glacial	Late-Wisconsin pre-Vashon glaciolacustrine
1210	Mount Tom Unconsolidated	Fraser-Sumas Floodplain, Ryder Uplands	Promontory Heights, Southeast Chilliwack	4b - Confined sand and gravel - glacial	Late Wisconsin, Sumas and earlier
1211	Lookout Ridge	Ryder Uplands	Lookout Road – Southeast Chilliwack	4b - Confined sand and gravel - glacial	Late Wisconsin
1212	Elkview Road Shallow	Ryder Uplands	Elkview Road – Southeast Chilliwack	4b - Confined sand and gravel - glacial	Sumas outwash and moraine
1213	Marble Hill Unconsolidated	Fraser-Sumas Floodplain	Eastern Hillsides - Chilliwack	4a - Unconfined sand and gravel - late glacial outwash	Late Wisconsin (Sumas) outwash, and Holocene colluvium
1214	Chilliwack Mountain Bedrock	Fraser-Sumas Floodplain	Northwest Chilliwack	6b - Fractured crystalline bedrock	Pyroclastics and Flows of Jurassic Harrison Lake Formation
1215	Cannor Road North	Fraser-Sumas Floodplain	Northwest Chilliwack	6b - Fractured crystalline bedrock	Pyroclastics and Flows of Jurassic Harrison Lake Formation
1216	Vedder Mountain NW Bedrock	Fraser-Sumas Floodplain	Southwest Chilliwack	6b - Fractured crystalline bedrock	Permian to Triassic Vedder Complex, locally Jurassic to Cretaceous
1217	Vedder Mountain SE Bedrock	Columbia Valley-Cultus Lake	Southwest of Chilliwack	5a - Fractured sedimentary rock	Jurassic to Cretaceous, Kent Formation
1218	East Cultus Columbia Bedrock	Chilliwack River Valley, Columbia Valley-Cultus Lake	East of Cultus Lake and Columbia Valley	5a - Fractured sedimentary rock	Mudstones and Sandstones of Triassic-Jurassic Cultus Formation

Table A2. Representative transmissivity, storativity or specific yield, and diffusivity by aquifer and interpreted geological unit.

Interpreted geological unit	Aquifer number	Aquifer sub-type	Representative T (m^2/day)	Representative S or S_y (-)	Representative Diffusivity (m^2/day)	Notes
Fraser-Sumas Floodplain						
Salish Sediments	8	3	3000*	0.01*	300 000*	Aquifers 6, 8, 21, 1199 are treated as one unit, same as in inferring regional groundwater flow. The representative T, S values were based on the geometric mean of reported values available for this study, but also aligned with T values for Aquifers 9, 1206 (similar lithology).
Fraser River Sediments	6, 21	1a				
Salish Sediments	1199	4b				
Salish Sediments (slope deposits)	1196, 1198	3	710	0.019	37 368	No T or S values were available for Aquifers 1196, 1198, 1205 and 1213 for this study; for simplicity, these aquifers were assigned the same T, S values as for aquifer sub-type 3 from Lepitre and Beebe (2019) (T, S values for aquifer sub-type 4a is very similar).
Sumas Drift	1205, 1213	4a				
Sumas Drift	1210	4b	250	0.005	50 000	No T or S values are available for these aquifers. Aquifers 1207, 1208, 1209, 1210, 1211, and 1212 are the same aquifer sub-type; for simplicity, these aquifers were assigned the same T, S values from Lepitre and Beebe (2019) for this aquifer sub-type.
Pre-Vashon	1208	4b				
Sumas Drift? (post-Vashon?)	1197	4c	150	0.005	30 000	No T or S values were available for aquifer 1197 for this study; for simplicity, this aquifer was assigned T, S values from Lepitre and Beebe (2019) for this aquifer sub-type.
Pre-Tertiary Bedrock	1214, 2015	6b	23	0.00064	35 938	Reported T values available for this study ranged from 0.6 to 1166 m^2/day, with a geomean of 40 m^2/day. S ranged from 0.000001 to 0.03 with a geomean of 0.00031. However, the values came from only 2 aquifers (899 and 1216 – 2

Interpreted geological unit	Aquifer number	Aquifer sub-type	Representative T (m^2/day)	Representative S or S_y (-)	Representative Diffusivity (m^2/day)	Notes
						T, S values from each aquifer). Due to the limited (and range in T, S values), for simplicity, T, S values from Lepitre and Beebe (2019) were assigned for all aquifers of this sub-type.
Pre-Tertiary Bedrock	890	5a	4	0.00003	133 333	No T or S values are available for this study for aquifers 890, 1217 or 1218. These are all the same aquifer sub-types. Representative T, S values from Lepitre and Beebe (2019) were assigned for this aquifer sub-type.
Pre-Tertiary Bedrock	1216	6b	23	0.00064	35 938	Reported T values available for this study ranged from 0.6 to 1166 m^2/day, with a geomean of 40 m^2/day. S ranged from 0.000001 to 0.03 with a geomean of 0.00031. However, the values came from only 2 aquifers (899 and 1216 – 2 T, S values from each aquifer). Due to the limited (and range in T, S values), for simplicity, T, S values from Lepitre and Beebe (2019) were assigned for all aquifers of this sub-type.
Pre-Tertiary Bedrock	899	6b				
Columbia Valley-Cultus Lake						
Salish Sediments	1203, 1200, 1201, 1202	3	710	0.019	37 368	No T or S values are available for these aquifers. Aquifers 1200, 1201, 1202, and 1203 are the same aquifer sub-type; for simplicity, these aquifers were assigned the same T, S values from Lepitre and Beebe (2019) for this aquifer sub-type.
Sumas Drift	20	4a	690	0.02	34500	One set of T, S values is available for this aquifer but we felt that was insufficient to represent the aquifer as a whole. Instead, T, S values from Lepitre and Beebe (2019) were assigned for this aquifer sub-type.

Interpreted geological unit	Aquifer number	Aquifer sub-type	Representative T (m^2/day)	Representative S or S_y (-)	Representative Diffusivity (m^2/day)	Notes
Pre-Tertiary Bedrock	1217, 1218	5a	4	0.00003	133 333	No T or S values are available for this study for Aquifers 890, 1217 or 1218. These are all the same aquifer sub-types. Representative T, S values from Lepitre and Beebe (2019) were assigned for this aquifer sub-type.
Chilliwack River Valley						
Salish Sediments (mountain stream sediments)	9	1b	3000*	0.01*	300 000*	No T or S values are available for Aquifer 9 for this study. The representative T and S values assigned for Aquifer 9 are the same as for Aquifers 6, 8, 21, 1199 and 1206 because of their similarity in lithology.
Quadra equivalent	1206	4b	3000*	0.005*	600 000*	The representative T value for Aquifer 1206 is based on reported T values available for this study. A representative S value from Lepitre and Beebe (2019) were assigned for this aquifer sub-type.
Pre-Tertiary Bedrock	1217, 1218	5a	4	0.00003	133 333	No T or S values are available for this study for Aquifers 890, 1217 or 1218. These are all the same aquifer sub-types. Representative T, S values from Lepitre and Beebe (2019) were assigned for this aquifer sub-type.
Ryder Uplands						
Sumas Drift	1211, 1212	4b	250	0.005	50 000	No T or S values are available for these aquifers. Aquifers 1207, 1208, 1209, 1210, 1211, and 1212 are the same aquifer sub-type; for simplicity, the same T and S values were assigned for all these aquifers, adopted from Lepitre and Beebe (2019) for this aquifer sub-type.
Quadra equivalent or per-Vashon	1207, 1208, 1209	4b				

Interpreted geological unit	Aquifer number	Aquifer sub-type	Representative T (m^2/day)	Representative S or S_y (-)	Representative Diffusivity (m^2/day)	Notes
Pre-Tertiary Bedrock	890	5a	4	0.00003	133 333	No T or S values are available for this study for aquifers 890, 1217 or 1218. These are all the same aquifer sub-types. Representative T, S values from Lepitre and Beebe (2019) were assigned for this aquifer sub-type.
Pre-Tertiary Bedrock	899	6b	23	0.00064	35 938	Reported T values available for this study ranged from 0.6 to 1166 m^2/day, with a geomean of 40 m^2/day. S ranged from 0.000001 to 0.03 with a geomean of 0.00031. However, the values came from only 2 aquifers (899 and 1216 – 2 T, S values from each aquifer). Due to the limited (and range in T, S values), for simplicity, T, S values from Lepitre and Beebe (2019) were assigned for all aquifers of this sub-type.

*Representative value based on pumping test reports. See discussion in Section 5.9 of this report.

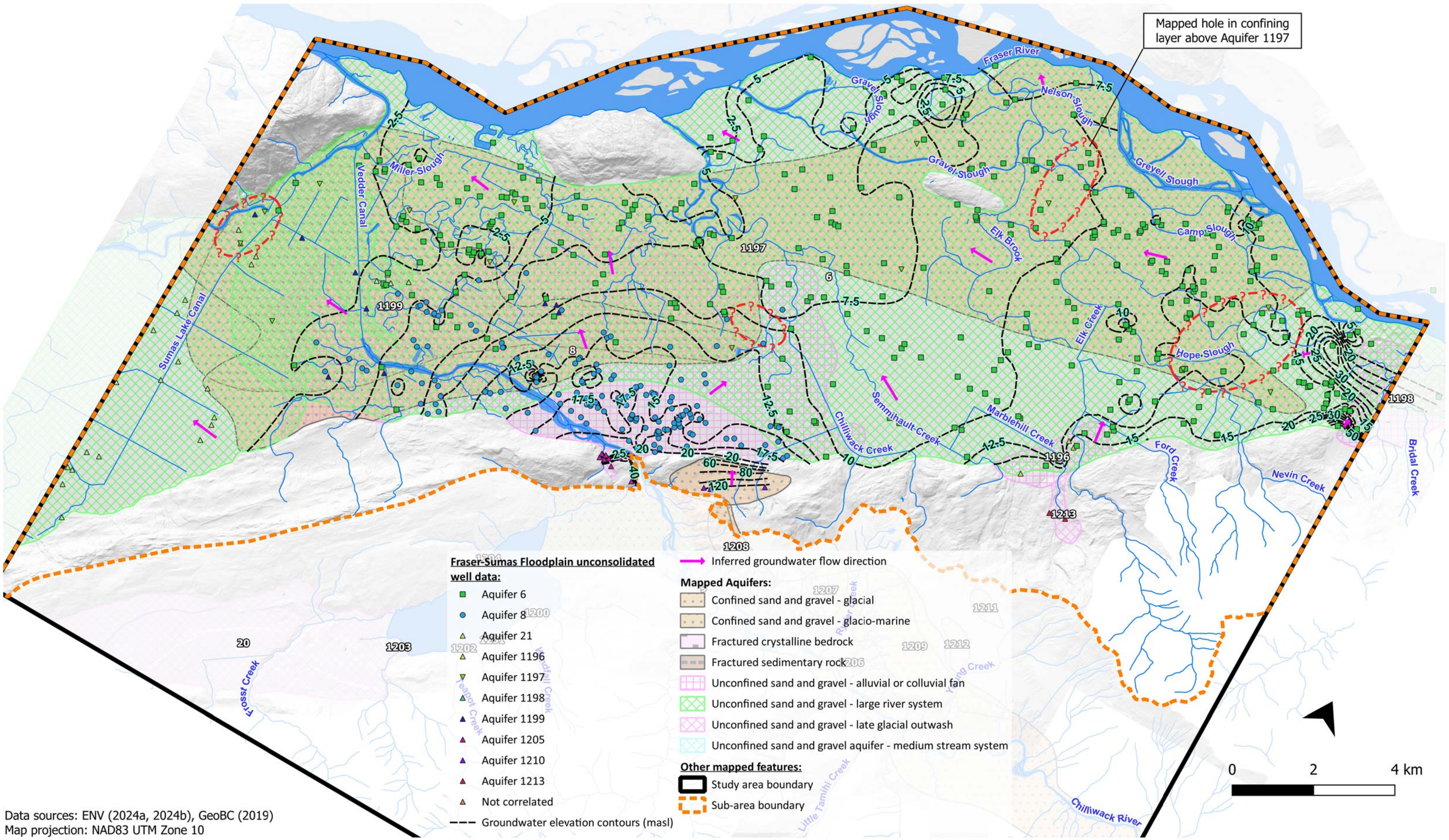
APPENDIX B. INFERRED GROUNDWATER FLOW DIRECTIONS

Chilliwack Preliminary Assessment of Hydraulic Connection

Figure B1. Fraser-Sumas Floodplain Mapped Unconsolidated Aquifers and Inferred Groundwater Flow Direction

Drawn: TJS
Reviewed: MW
Date: May 8, 2024

Client: MOF
Project No. 23-116-01VC
Revision No.: C



Fraser-Sumas Floodplain unconsolidated well data:

- ■ Aquifer 6
- ● Aquifer 8
- △ Aquifer 21
- △ Aquifer 1196
- ▽ Aquifer 1197
- ▲ Aquifer 1198
- ▲ Aquifer 1199
- ▲ Aquifer 1205
- ▲ Aquifer 1210
- ▲ Aquifer 1213
- ▲ Not correlated
- --- Groundwater elevation contours (masl)

→ Inferred groundwater flow direction

Mapped Aquifers:

- ▨ Confined sand and gravel - glacial
- ▨ Confined sand and gravel - glacio-marine
- ▨ Fractured crystalline bedrock
- ▨ Fractured sedimentary rock
- ▦ Unconfined sand and gravel - alluvial or colluvial fan
- ▨ Unconfined sand and gravel - large river system
- ▨ Unconfined sand and gravel - late glacial outwash
- ▨ Unconfined sand and gravel aquifer - medium stream system

Other mapped features:

- ▭ Study area boundary
- ▭ Sub-area boundary

Data sources: ENV (2024a, 2024b), GeoBC (2019)
Map projection: NAD83 UTM Zone 10

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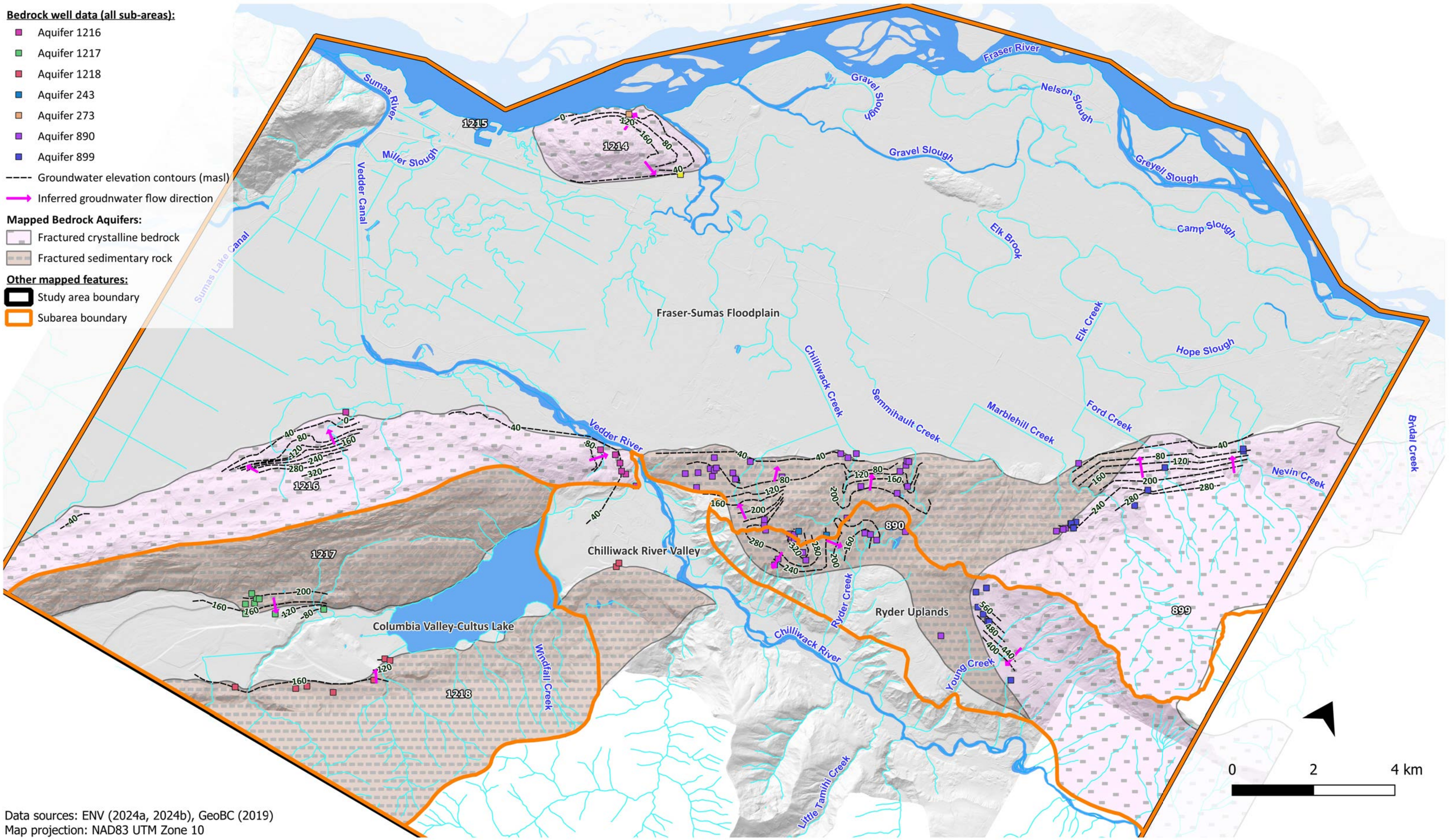
Chilliwack Preliminary Assessment of Hydraulic Connection

Figure B2. Mapped Bedrock Aquifers and Inferred Groundwater Flow Direction

Drawn: TJS
Reviewed: MW
Date: July 4, 2024

Client: MOF
Project No. 23-116-01VC
Revision No.: D



Data sources: ENV (2024a, 2024b), GeoBC (2019)
Map projection: NAD83 UTM Zone 10

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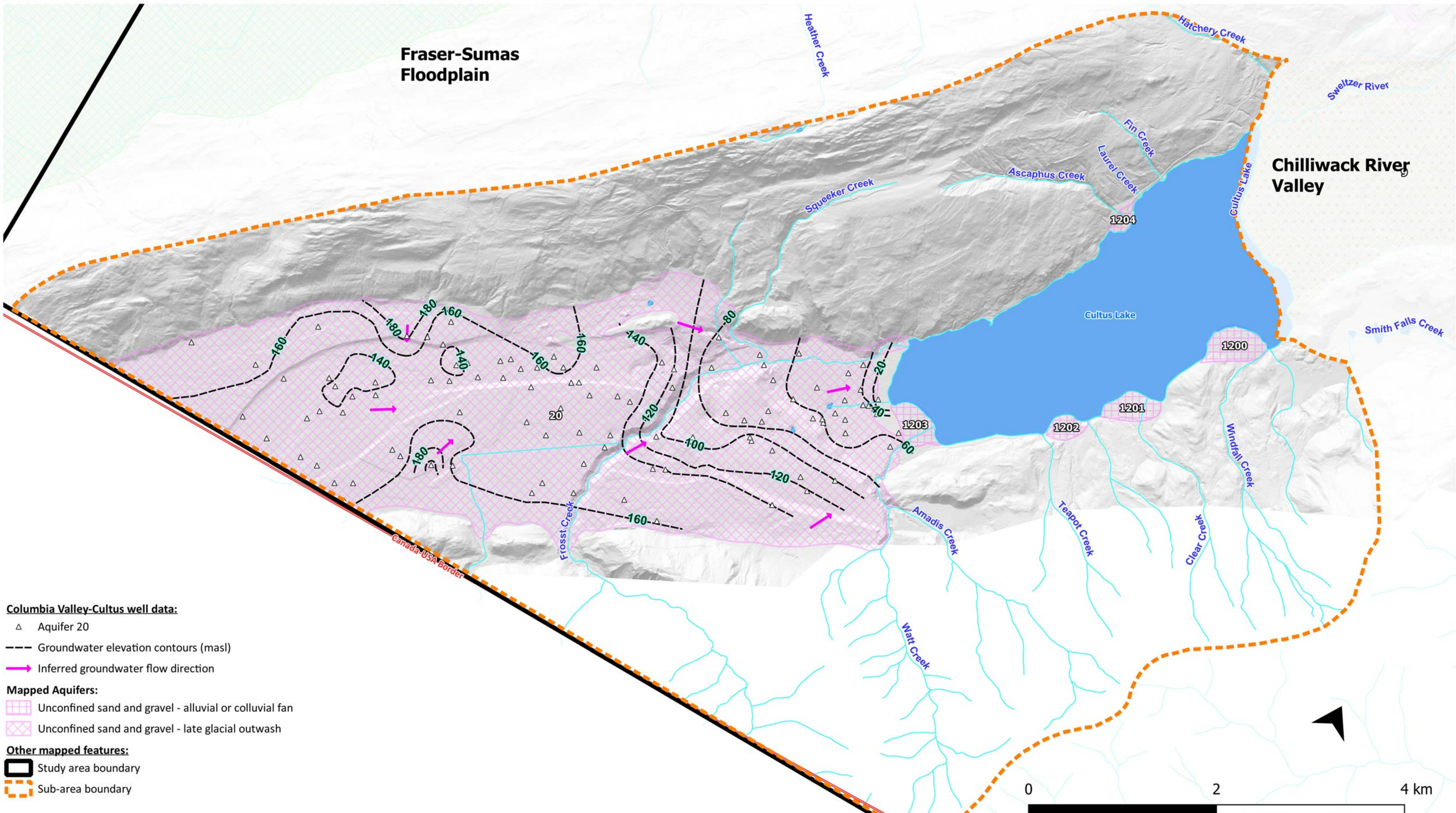
Chilliwack Preliminary Assessment of Hydraulic Connection

Figure B3: Columbia Valley-Cultus Lake Mapped Unconsolidated Aquifer and Inferred Groundwater Flow Direction

Drawn: TJS
Reviewed: MW
Date: May 8, 2024

Client: MOF
Project No. 23-116-01VC
Revision No.: C



Data sources: ENV (2024a, 2024b), GeoBC (2019)
Map projection: NAD83 UTM Zone 10

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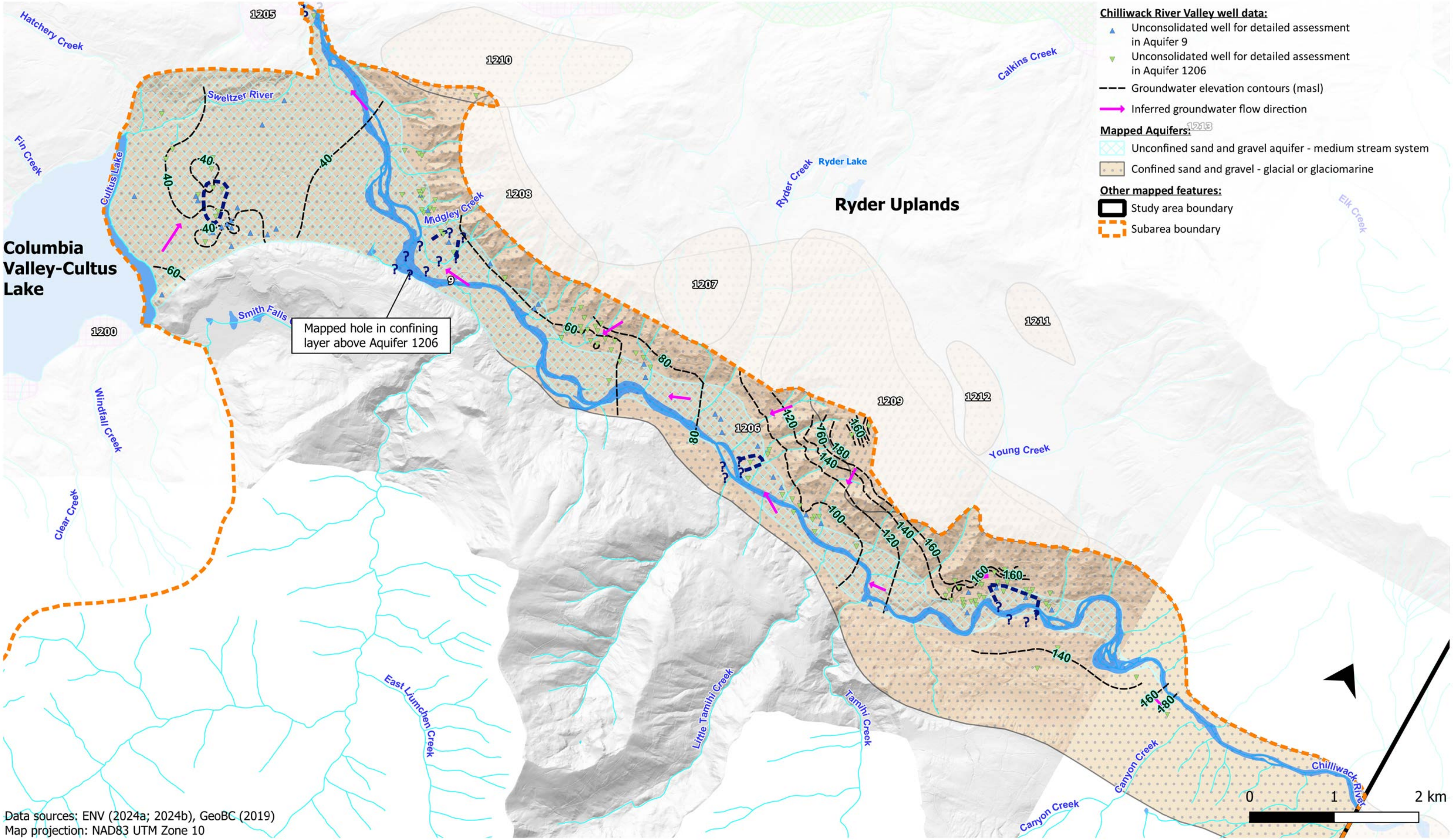
Figure B4. Chilliwack River Valley Mapped Unconsolidated Aquifers and Inferred Groundwater Flow Direction

Drawn: TJS
Reviewed: MW
Date: May 8, 2024

Client: MOF
Project No. 23-116-01VC
Revision No.: C



Data sources: ENV (2024a; 2024b), GeoBC (2019)
Map projection: NAD83 UTM Zone 10

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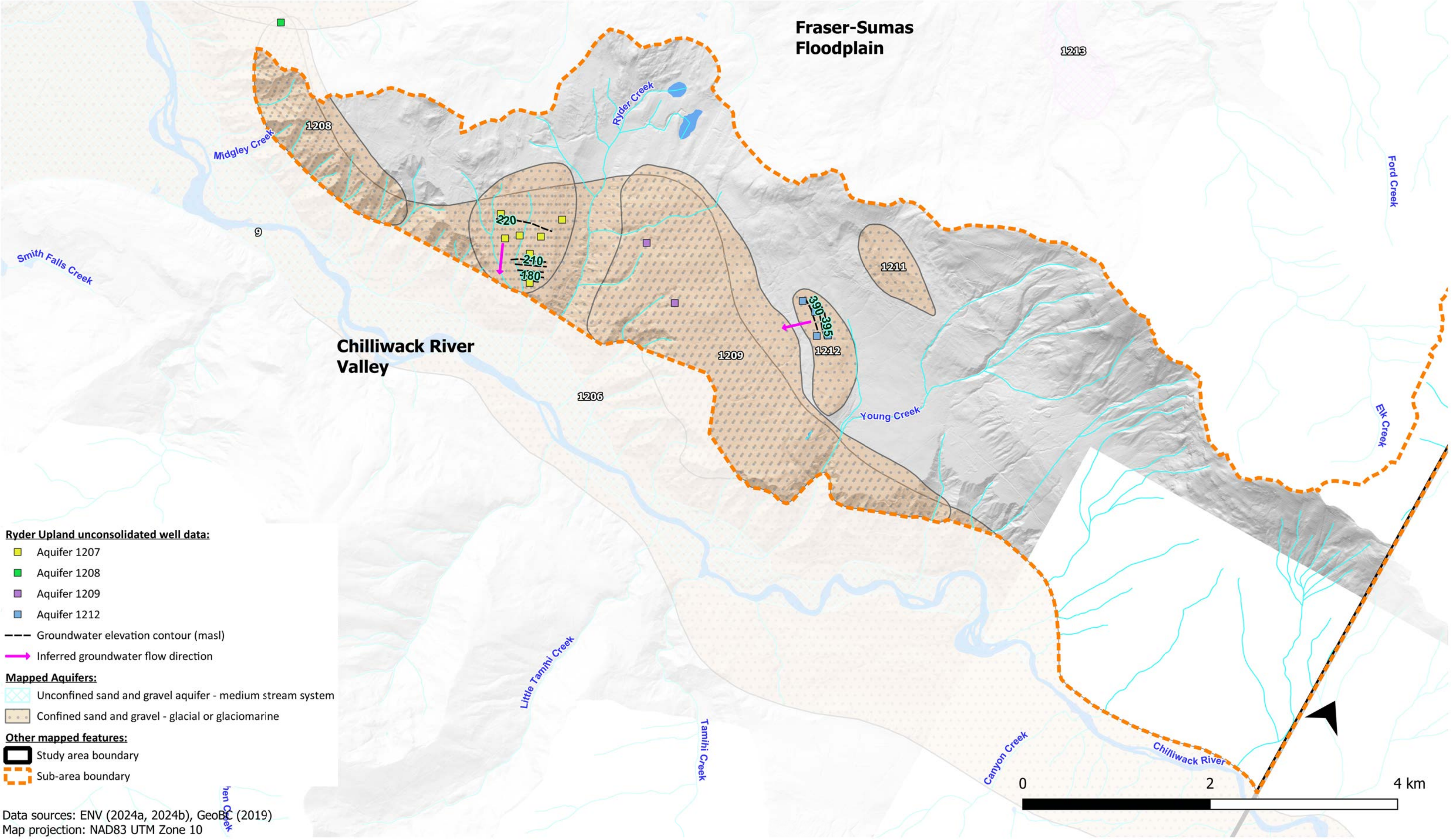
Chilliwack Preliminary Assessment of Hydraulic Connection

Figure B5. Ryder Uplands Mapped Aquifers and Inferred Groundwater Flow Direction

Drawn: TJS
Reviewed: MW
Date: May 8, 2024

Client: MOF
Project No. 23-116-01VC
Revision No.: C



Data sources: ENV (2024a, 2024b), GeoBC (2019)
Map projection: NAD83 UTM Zone 10

APPENDIX C. PoHC AND ESTIMATED SDF VALUES

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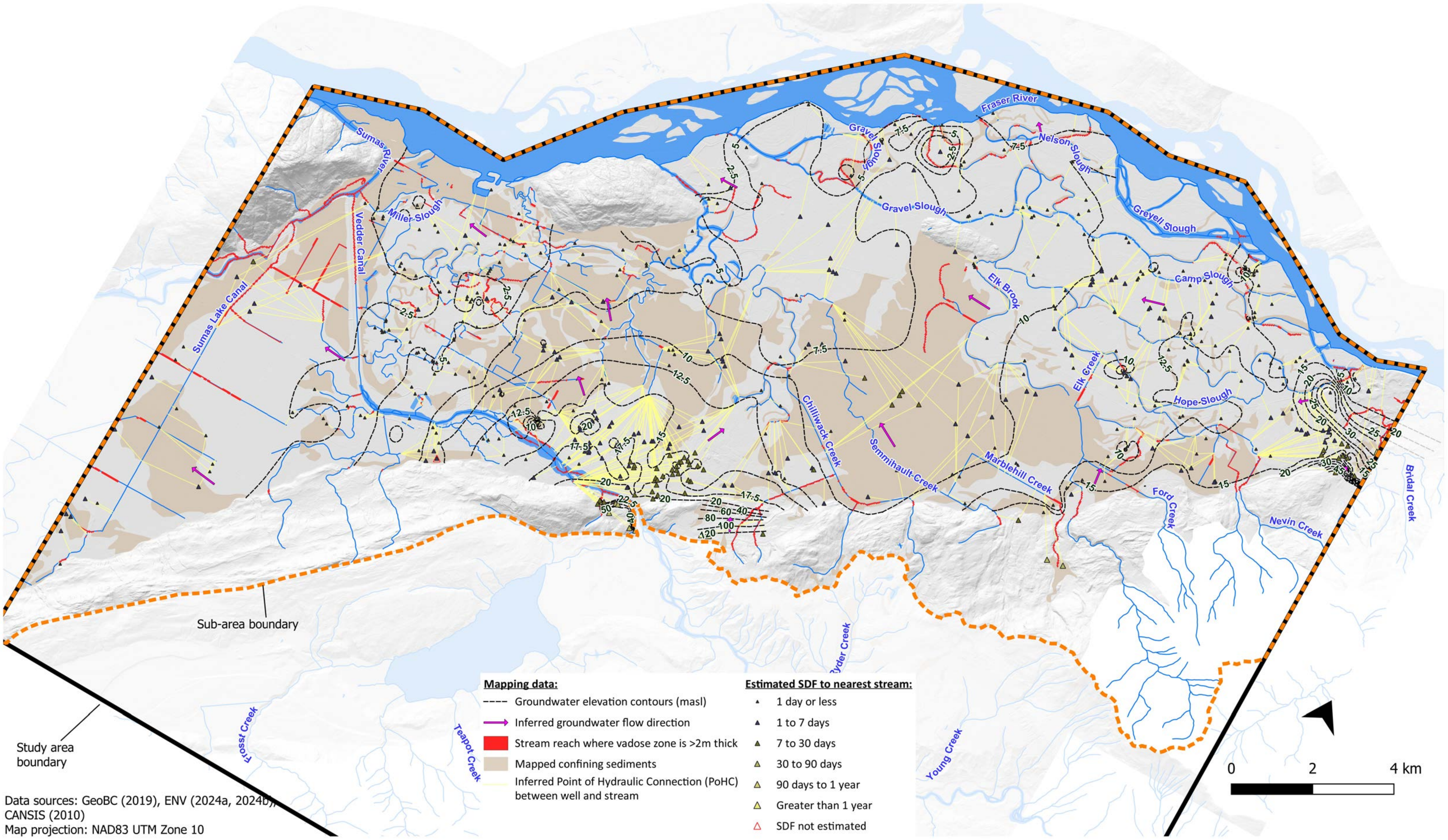
Chilliwack Preliminary Assessment of Hydraulic Connection

Figure C1. Fraser-Sumas Floodplain Points of Hydraulic Connection and Estimated SDF Values

Drawn: TJS
Reviewed: MW
Date: May 8, 2024

Client: MOF
Project No. 23-116-01VC
Revision No.: C



Data sources: GeoBC (2019), ENV (2024a, 2024b), CANSIS (2010)
Map projection: NAD83 UTM Zone 10

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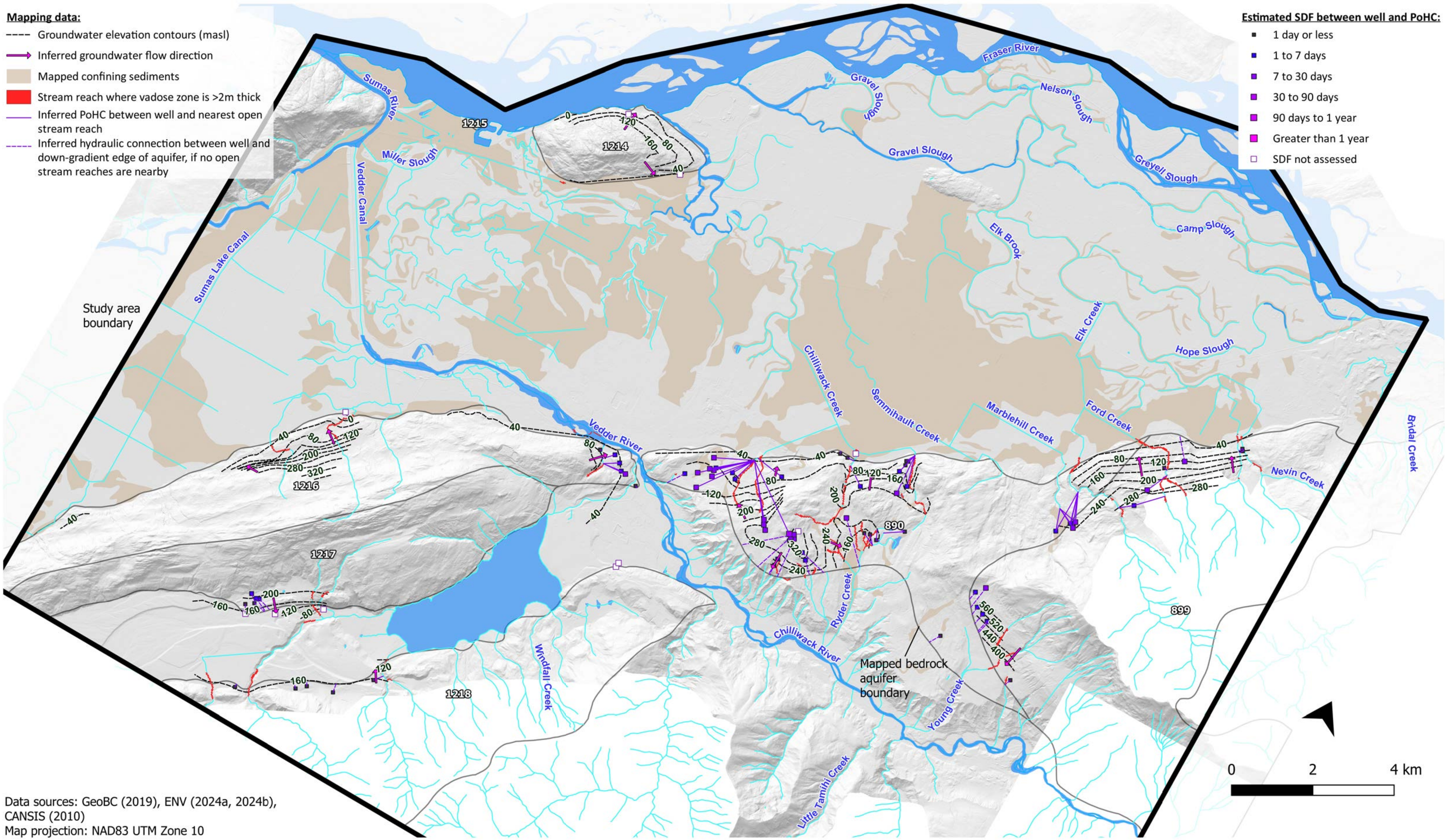
Figure C2. Fractured Bedrock Points of Hydraulic Connection and Estimated SDF Values

Drawn: TJS
Reviewed: MW
Date: May 8, 2024

Client: MOF
Project No. 23-116-01VC
Revision No.: C



Data sources: GeoBC (2019), ENV (2024a, 2024b), CANSIS (2010)
Map projection: NAD83 UTM Zone 10

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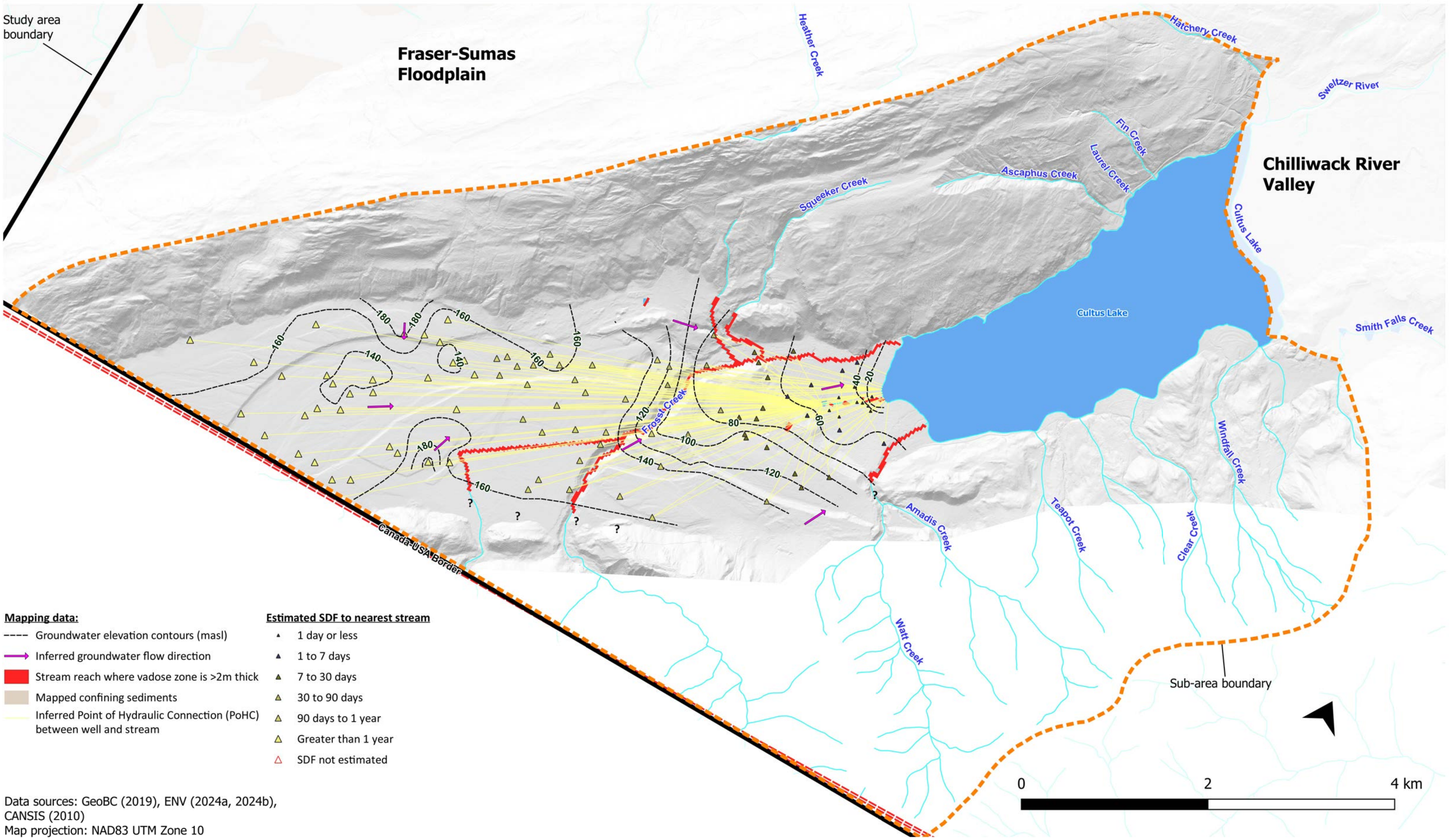
Chilliwack Preliminary Assessment of Hydraulic Connection

Figure C3. Columbia Valley-Cultus Lake Points of Hydraulic Connection and Estimated SDF Values

Drawn: TJS
Reviewed: MW
Date: May 8, 2024

Client: MOF
Project No. 23-116-01VC
Revision No.: C



Data sources: GeoBC (2019), ENV (2024a, 2024b), CANSIS (2010)
Map projection: NAD83 UTM Zone 10

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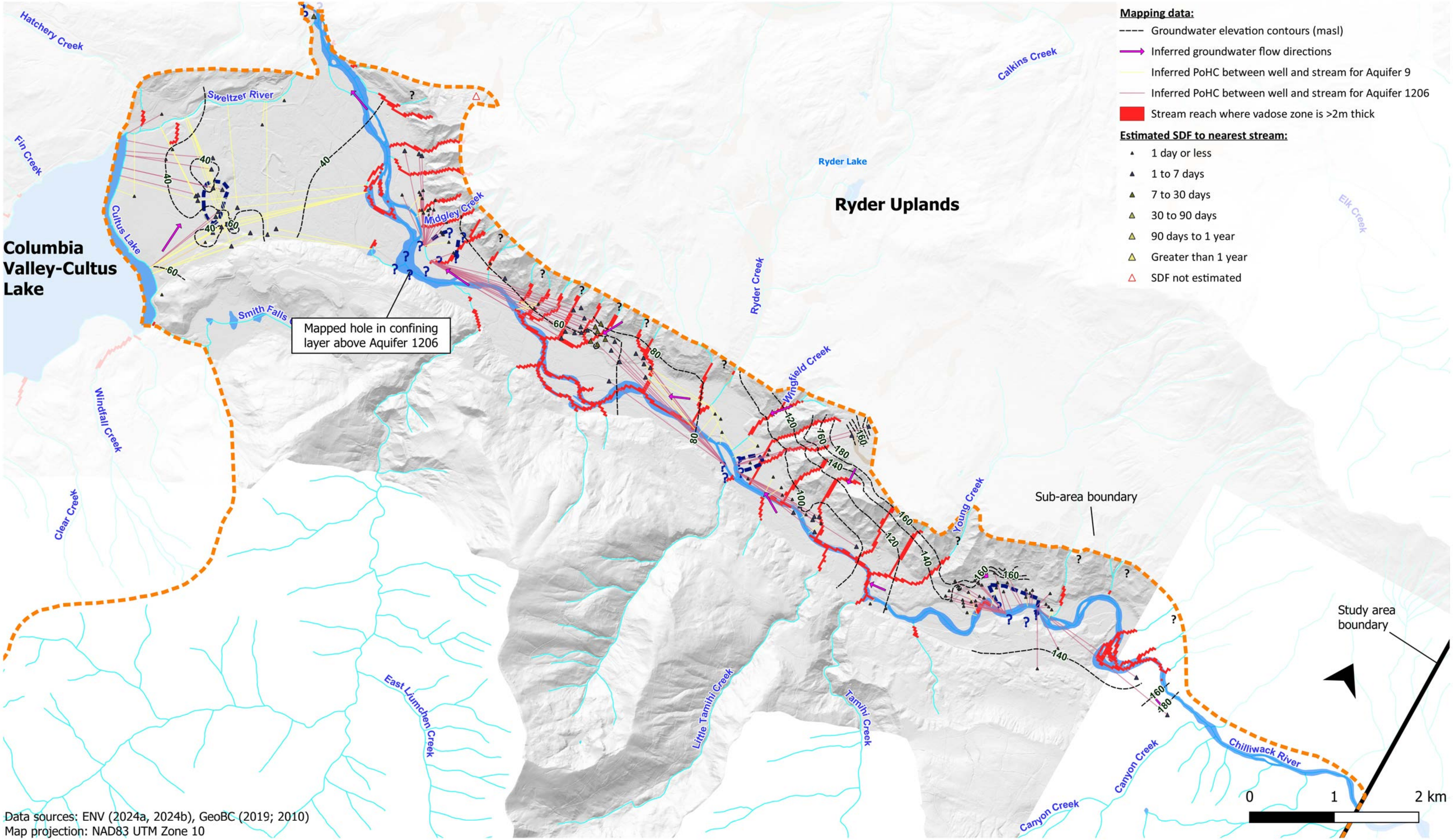
Chilliwack Preliminary Assessment of Hydraulic Connection

Figure C4. Chilliwack River Valley Points of Hydraulic Connection and Estimated SDF Values

Drawn: TJS
Reviewed: MW
Date: May 8, 2024

Client: MOF
Project No. 23-116-01VC
Revision No.: C



Data sources: ENV (2024a, 2024b), GeoBC (2019; 2010)
Map projection: NAD83 UTM Zone 10

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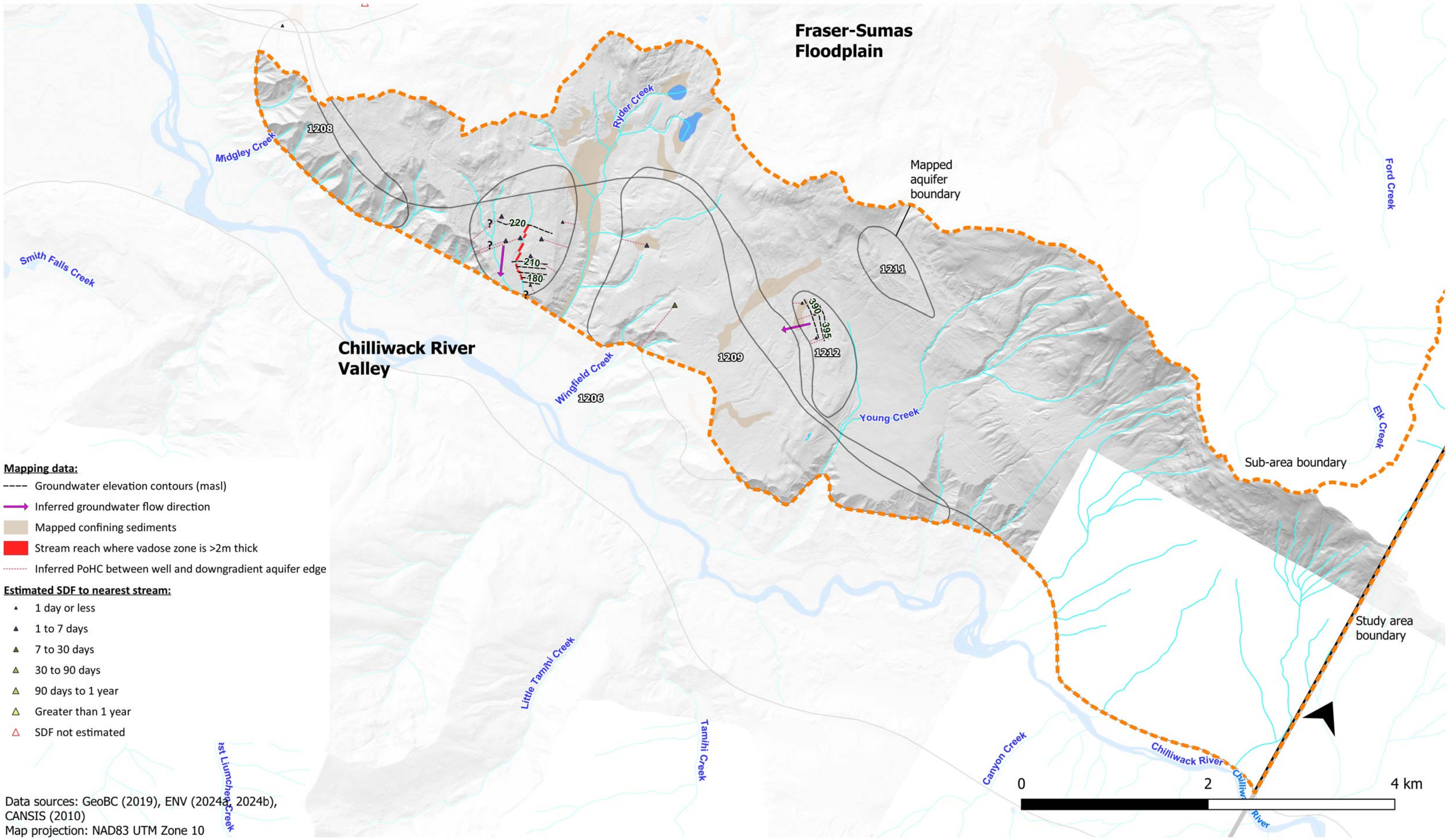
Chilliwack Preliminary Assessment of Hydraulic Connection

Figure C5. Ryder Upland Points of Hydraulic Connection and Estimated SDF Values

Drawn: TJS
Reviewed: MW
Date: May 8, 2024

Client: MOF
Project No. 23-116-01VC
Revision No.: C



Mapping data:

- Groundwater elevation contours (masl)
- Inferred groundwater flow direction
- Mapped confining sediments
- Stream reach where vadose zone is >2m thick
- Inferred PoHC between well and downgradient aquifer edge

Estimated SDF to nearest stream:

- ▲ 1 day or less
- ▲ 1 to 7 days
- ▲ 7 to 30 days
- △ 30 to 90 days
- △ 90 days to 1 year
- △ Greater than 1 year
- △ SDF not estimated

Data sources: GeoBC (2019), ENV (2024a, 2024b), CANSIS (2010)
Map projection: NAD83 UTM Zone 10

APPENDIX D. HYDRAULIC CONNECTION SUMMARY SPREADSHEET

Microsoft Excel Spreadsheet attached as a separate file.