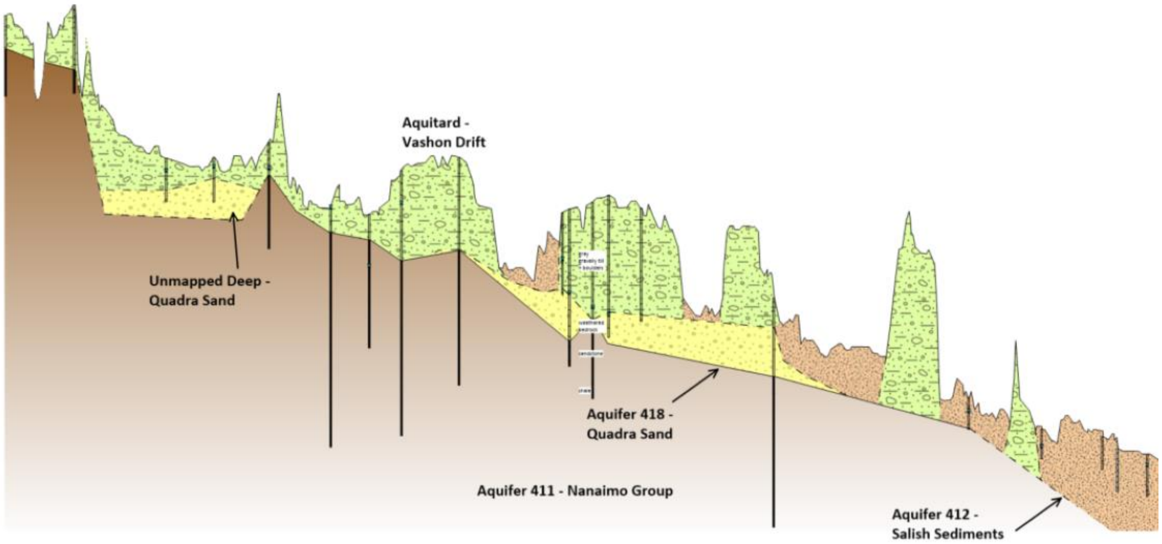
WATER SCIENCE SERIES

Oyster River and Black Creek Watersheds: Preliminary Desktop Assessment of Hydraulic Connection

Tim Sivak and Mike Wei



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Cross-section along Oyster River (adapted from Figure A4).

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EXECUTIVE SUMMARY

Oyster River and Black Creek, two fully recorded streams located on the east coast of Vancouver Island between the communities of Courtenay and Campbell River, support important fisheries and aquatic habitats. Determining the likelihood of hydraulic connection of wells to streams in the Oyster River and Black Creek watersheds is vital to effective management of environmental flows and access to water for users.

In this desktop GIS-based study, we developed a conceptual understanding of the main aquifers within the watersheds and how and where hydraulic connection to Oyster River and Black Creek (and their tributary streams) likely occurs. This understanding was then applied to delineate preliminary Groundwater Management Areas (GWMAs) within the watersheds to allow any streamflow depletion impacts from well pumping to be managed in sub-areas related to key stream reaches.

Seven aquifers exist within the study area. The hydrostratigraphic units are tabulated below, from youngest (and shallowest) to oldest (and deepest):

Hydrostratigraphic unit	Brief description
Aquifers associated with Salish Sediments and Capilano Sediments	• Aquifer 412 (Salish Sediments) is an unconfined sand and gravel aquifer underlying the floodplain in the lower reach of the Oyster River. • Many older wells are dug into shallow sediments (Capilano Sediments comprising clay, silt, sand, but may be also shallow till that is part of the Vashon Drift); these wells are interpreted to intercept limited quantities of shallow groundwater.
Vashon Drift (aquitard)	• Mostly till, with some silt, sand and gravel. • Underlies much of the study area.
Quadra Sands aquifers	• Includes mapped Aquifers 408, 418 and two unmapped aquifers near Enns Road and near York Road. • Aquifer 408 extends south to Courtenay and is well confined within the study area. • Aquifer 418 and the two unmapped aquifers appear limited in areal extent.
Pre-Quadra sediments, possibly comprising Cowichan Head Formation (aquitard)	• May not be present everywhere but appears to occur in the southern portion of the study area.
Nanaimo Group fractured sedimentary bedrock aquifer	• Underlies the entire study area. • Provides limited quantities of groundwater to landowners. • Relied upon where overlying unconsolidated aquifers are absent.

GIS mapping of the water table in the Aquifer 412 and shallow unconsolidated “aquifer” unit indicate that hydraulic connection is likely for many stream reaches. Therefore, well pumping in these two shallow aquifers is expected to impact the closest stream reach. GIS mapping shows that confining sediments (till, silt, and clay) underlie almost every stream reach in the study area restricting hydraulic connection with the deeper confined Quadra Sands aquifers and Nanaimo Group sedimentary bedrock aquifer. Hydraulic connection appears likely only along three reaches of the Oyster River: near the mouth, downstream of the confluence with the Little Oyster River, and upstream of Doyle Road. These open stream reaches are where depletion of streamflow from well pumping can occur.

GIS mapping of groundwater elevations in the shallow (Aquifer 412 and shallow unconsolidated "aquifer" unit), Quadra Sands aquifers and the underlying bedrock aquifer suggest that there is significant inflow of groundwater from the Tsolum River watershed immediately to the west and outflow to the ocean beyond the watershed boundary to the east. Groundwater elevation mapping suggests groundwater flow is not only influenced by the local topography but also regional topography.

We identified preliminary GWMAs for the shallowest aquifers (Aquifer 412 and the shallow, unconsolidated "aquifer" unit), and for the deeper Quadra Sands aquifers (Aquifer 408, 418 and the two unmapped aquifers) and Nanaimo Group sedimentary bedrock aquifer (Aquifer 411). The GWMA delineation corresponds to those reaches of the Oyster River having likely hydraulic connection to adjacent aquifers. For the Black Creek area, only one GWMA was delineated for the Quadra Sands and one for bedrock, mostly to separate the Black Creek area from the Oyster River GWMAs; significant portions within the study area have been excluded from GWMA delineation for these confined aquifers because hydraulic connection to streams seems unlikely, with groundwater likely exiting (flowing out) of the watershed.

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

- Conduct field work to:
  - Supplement field observations by Fyles (1960) and Zubel (1981) by checking for additional locations along the banks of streams where downcutting of the stream has exposed the underlying Quadra Sands and Nanaimo Group sedimentary bedrock aquifers.
  - Inspect tributary stream reaches to check if they exhibit ephemeral or perennial flow to assess the reliability of the mapping of where stream reaches are connected or disconnected. Disconnected or perched streams should not receive significant baseflow from groundwater along those reaches. Observations of the presence/absence of water in a stream channel can be recorded using, for example, a phone application like StreamTracker.
  - Verify stream reaches where hydraulic connection is likely by measuring, for example, stream temperatures and electrical conductivity along the streams.
  - Survey levels in groundwater wells to better determine the groundwater levels and flow gradient in the Quadra Sands and fractured bedrock to inform the GWMA boundaries.
- Inform the groundwater elevation mapping using a high-resolution DEM. We understand that a 1 m resolution DEM may become available within the current year.
- Formally map the two unmapped aquifers identified in this study, which comprise primarily of Quadra Sands.
- Engage with local landowners and watershed societies to explore the feasibility for a citizen-based observation well network for the wells completed in the shallow "aquifer" unit.
- Drill observation wells in key locations in the watershed to address data gaps in groundwater levels and stratigraphy. Obtain aquifer hydraulic parameters to better understand the hydraulic connection between the unconsolidated and bedrock aquifers in the study area. Recommended locations include (but are not limited to):
  - Aquifer 408 in the south part of the study area; and,
  - Aquifer 411 to the west near Northy Lake.
- Confirm the location of the points of delineation for the groundwater management areas in the field. Preferably, the points of delineation should be located where the stream channel is stable so streamflow measurements can be made there. This includes points of delineation at:

    - The confluence of Black Creek and the unnamed tributary to Black Creek near Gladstone Road and the confluence of the Oyster River at its confluence with Little Oyster River (shallow unmapped "aquifer" unit); and,
    - Along the open reaches of the Oyster River northeast of Heather Road (Quadra Sands and Nanaimo Group).
- Establish critical environmental flow thresholds for the Oyster River and Black Creek to protect streamflow.
- Consider requiring, as a condition of a water licence, measuring and reporting of monthly quantities diverted and static water level elevations for the larger licensed groundwater users in the study area (above a threshold limit).
- Consider including term limits for licences to allow evolving understanding of the local hydrogeology to inform subsequent diversion and use of water.
- Initiate an on-going program to raise awareness of water resources management and to engage water users diverting water from streams and wells in the watershed to promote efficiency of water use to preserve groundwater levels and streamflow.

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ACRONYMS AND ABBREVIATIONS

DEM	Digital Elevation Model
EFN	Environmental Flow Needs
ENV	Ministry of Environment and Climate Change Strategy
FOR	Ministry of Forests
FWA	Freshwater Atlas
GIS	Geographic Information System
GWELLS	B.C. government's water well database
GWMA	Groundwater Management Area
MOTI	Ministry of Transportation and Infrastructure
PoHC	Point of Hydraulic Connection
WSA	*Water Sustainability Act*

1. BACKGROUND

Oyster River and Black Creek, located on the east coast of Vancouver Island between the Cities of Courtenay and Campbell River, support important fisheries and aquatic habitats. Both streams are home to Chum, Pink, Coho and Chinook Salmon, Steelhead, Rainbow and Cutthroat Trout, and Dolly Varden Char. Adequate flows are critical for resident, rearing and spawning fish (Oyster River and Black Creek Watersheds – Your Living Resource, accessed February 17, 2021). Both watersheds are also subject to development on the land base. Activities in the lower watersheds include farming, rural residential, forestry, industry, and recreation.

Black Creek and Oyster River have long been considered fully recorded except for some water uses (since 1983 and 1984, respectively). Fully recorded is a Ministry of Forests (FOR) operational term taken to mean that there is no more water available to be allocated. Records of groundwater use in the watersheds date back to earlier than 1950, however, unlike stream water, groundwater use was not regulated under a licensing system until 2016 when the *Water Sustainability Act* (WSA) came into effect. In managing water rights under the WSA (Province of B.C., 2016a), the statutory decision maker must consider the likelihood of hydraulic connection between groundwater and water in a stream.

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

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

The main goals of this study are to:

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

2. SCOPE OF WORK

In the WSA, the definition of “stream” includes springs. However, information on the source of springs is not available, so assessment of hydraulic connection of aquifers to springs is not feasible within the scope of this study. However, in most cases a natural, free-flowing spring can be assumed to be a point of natural groundwater discharge to surface, implying the source of springs is some type of aquifer. Sections 46, 47, 59 and 60 of the WSA also require the water manager to consider hydraulic connection between an aquifer and a stream from the perspective of contamination. Hydraulic connection in this sense requires understanding of specific contaminant pathways and is also beyond the scope of this study.

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

- Identify the main aquifers in the watersheds;
- Map groundwater elevations and infer groundwater flow directions;
- Map overburden thickness, and low permeability sediment thickness;
- Identify stream reaches where hydraulic connection is likely and where connection is unlikely;
- Delineate groundwater management areas associated with major connected stream reaches; and
- Summarize the work of this study in a report and other data outputs.

3. STUDY AREA

3.1 Watershed Setting

The Oyster River and Black Creek watersheds occupy a total approximate area of 42,500 hectares and are situated within the Nanaimo Lowland physiographic region (Holland, 1976) on the east side of Vancouver Island (see Figure 1). The watersheds are located about 22 km equidistant between Campbell River and Courtenay, B.C.

The study area is a subset of the Oyster River and Black Creek watersheds, covering only the area in the watershed where water well data are available (upstream limits of the study area is outlined by a dashed black line in Figure 1). Furthermore, all wells located within about 1 km beyond the watershed boundary and within Aquifer 412 are included as part of the study area, to better characterize the subsurface geology and groundwater elevations along the watershed boundary.

The study area has an east facing aspect, with a total relief of 180 m. The primary higher order streams within the study area include the Oyster River, Woodhus Creek, Little Oyster River, and Black Creek. Northy Lake is the largest freshwater lake in the study area (see Figure 1). The Tsolum River watershed, which drains the much higher slopes of Mt. Washington, occupies the land immediately to the west of the study area. Land draining into smaller creeks occupy the area east of the study area, to the ocean.

The study area enjoys a relatively wet and mild climate typical of coastal B.C. and is wetter than Victoria but considerably drier than other parts of Vancouver Island. The Courtenay Meadowbrook Climate Station (Climate ID: 102JR88) climate normal (1981 to 2010) shows average total annual precipitation of 1455.8 mm, and average monthly temperatures ranging between 3.0 °C and 17.9 °C. Courtenay Meadowbrook Climate Station is located about 20 km south of the study area boundary. Past climate data are provided here for context only and climate change forecasts for B.C. (PCIC, 2020) point to shifts in climate toward slightly warmer and wetter winters and longer, drier summers. This change is expected to result in longer periods of low streamflow as well as more frequent higher intensity rainfall during the wet season, potentially causing an increased need for water conservation and storage (PCIC, 2020).

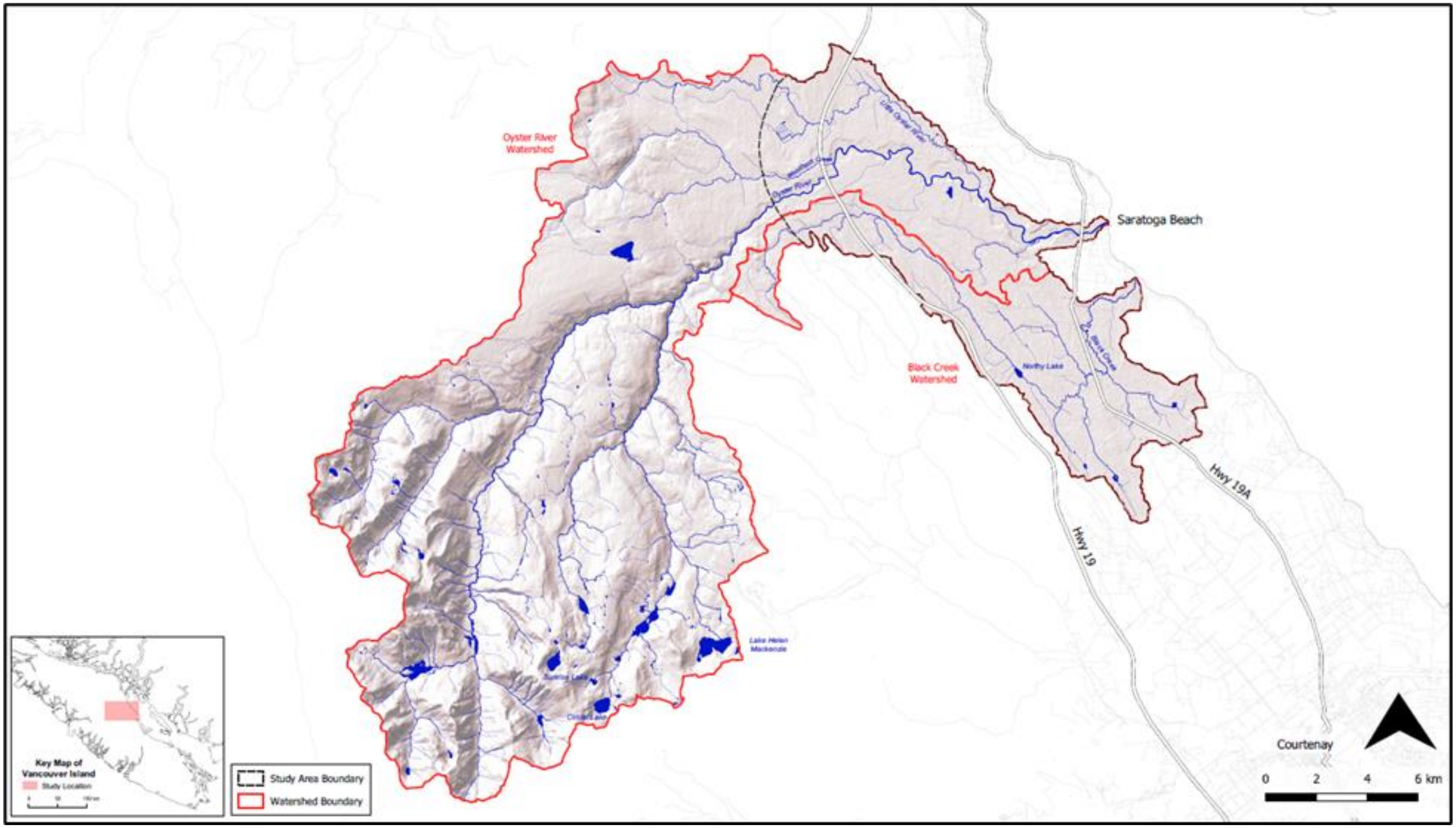

Figure 1: Watershed and study area overview.

3.2 Geologic Setting

3.2.1 Surficial geology

The surficial geology has been mapped and described by Fyles (1960; 1963), Clague (1976), and Bednarski (2015). The stratigraphy in the area is (from youngest to oldest):

- Salish Sediments (predominantly sand and gravel),
- Capilano Sediments – fluvial deposits (predominantly gravel, sand, minor silt) and marine/glaciomarine deposits (predominantly silt, clay, stony clay),
- Vashon Drift (predominantly till with gravel, sand and silt lenses),
- Quadra Sands (with minor gravel and silt), and
- Cowichan Head Formation (predominantly clay, silt and sand).

The surficial geology in the study area is shown in Figure 2.

The Cowichan Head Formation was deposited during the Olympia nonglacial period, which preceded the most recent glaciation. The Cowichan Head Formation is composed of marine clay, silt and sand, and gravel, depending on depositional environment. The Cowichan Head Formation appears to occur at depth and only in the southern part of the study area where surficial sediments are thickest.

The Quadra Sands formed as stratified glacial outwash deposited by streams emanating from advancing glaciers from about 29,000 to 15,000 radiocarbon years ago (Clague, 1976; Bednarski, 2015; Hinnel et al., 2020). The Quadra Sands are composed of well-sorted horizontally cross-stratified, glaciofluvial sands and gravels, and in some areas reaches thicknesses of about 75 m. Within the study area, the Quadra Sands are confined above by Vashon Drift and overlie the Cowichan Head Formation or bedrock. The Quadra Sands form productive and important confined aquifers in the area (Aquifers 408 and 418 and two additional unmapped aquifers).

The Quadra Sands were overridden by advancing glaciers, and the sediments were incorporated into the Vashon Drift, which overlies the Quadra Sands (Hinnel et al., 2020; Clague, 1976). The Vashon Drift is interpreted to be surface till and ice-proximal and morainal deposits (Bednarski, 2015). The Vashon Drift is composed of grey, compact, gravel, sand, silt and clay and is up to about 60 m thick. Humphrey (2000) notes that the weathered surface of the Vashon Drift may yield small amounts of water suitable for domestic use.

The Capilano Sediments (marine/glaciomarine sediments) are a postglacial deposit and overlie the Vashon Drift forming a shallow, near-surface unit in the area. They are a veneer of fine-grained cohesive sediment (clay, silt), a result of sea level rise and inundation of coastal areas prior to isostatic adjustment of the land surface. Their thickness ranges from a few centimeters to approximately 9 m thick (Fyles, 1960; Humphrey, 2000).

The Capilano Sediments (fluvial) were deposited during the last glacial recession when the sea level was higher than current levels (Humphrey 2000). The Capilano Sediments form productive aquifers in the Parksville area (see aquifer 665 (ENV, 2020a)); however, they remain relatively unexplored within the study area. Within the study area they are terraced and composed primarily of sand and gravel likely associated with glaciofluvial outwash.

The Salish Sediments are recent shore, deltaic and fluvial deposits composed of mostly sand and gravel with some silt and clay. This deposit occupies beach areas and the lower floodplain of the Oyster River; Salish Sediments in the lower Oyster River floodplain form a productive unconfined aquifer (Aquifer 412).

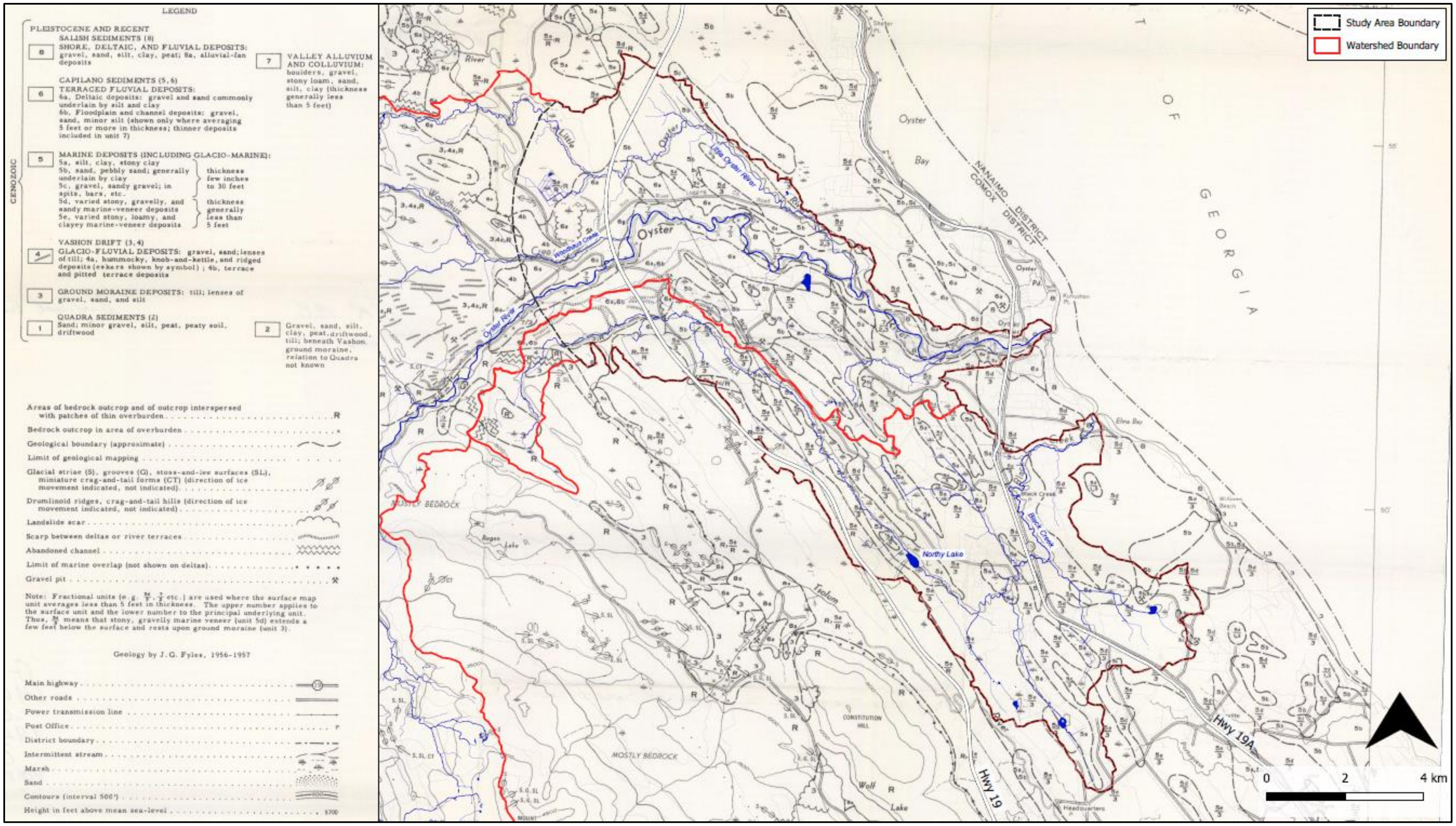

Figure 2: Surficial geology of the study area.

3.2.2 Bedrock geology

The bedrock geology of the study area as compiled by Massey et al. (1994) and Cui et al. (2017) comprises undivided sedimentary rocks of the Upper Cretaceous Nanaimo Group. The bedrock formation is described as boulder, cobble and pebble conglomerate, coarse to fine sandstone, siltstone, shale and coal. Faults in the bedrock are mapped at the foot of Mt. Washington and Constitution Hill striking NW to SE, parallel with the regional geological structure. The bedrock mapping is shown in Figure 3. The Nanaimo Group sedimentary bedrock forms a fractured bedrock aquifer of limited productivity in the local area (Aquifer 411).

3.2.3 Mapped aquifers

In the study area, residents, agricultural landowners and businesses rely on groundwater for supply. There are four mapped surficial or bedrock aquifers within the study area, shown on Figure 4. Mapped aquifers in the study area are classified by subtype (from Wei et al., 2009) as follows, from youngest to oldest:

- Aquifer 412 – Aquifer type 2: Unconfined sand and gravel associated with a delta at the mouth of a stream or river. Reported as 'likely' hydraulically connected to surface water (ENV, 2019a). Aquifer 412 is associated with the Salish Sediments.
- Aquifer 408 – Aquifer subtype 4b: Glaciofluvial sand and gravel of glacial or pre-glacial origin. Reported as 'likely' hydraulically connected to surface water (ENV, 2020b). Hinnel et al. (2020) appeared to lump the shallow and deep wells together for this aquifer. Our interpretation in this study, based on a review of the well records and cross-sections is that Aquifer 408 is associated with the Quadra Sands and is confined beneath till. The shallow wells in the same area are interpreted as belonging to a shallower, unmapped "aquifer" unit.
- Aquifer 418 – Aquifer subtype 4b: Confined glaciofluvial sand and gravel aquifers underneath till, in between till layers, or underlying glaciolacustrine deposits. Reported as 'not likely' hydraulically connected to surface water (ENV, 2000). The aquifer material is composed of layers of sands, gravel and silt interpreted by others to be the Quadra Sands (ENV, 2009).
- Aquifer 411 – Aquifer subtype 5a: Fractured sedimentary bedrock aquifers. Reported as 'not likely' hydraulically connected to surface water (ENV, 2019b; ENV, 2019c). Associated with the Nanaimo Group.

In addition to the above mapped aquifers in the study area, at least two additional confined sand and gravel aquifers and one shallow, unconsolidated "aquifer" unit were identified through this study. The conceptual understanding of the mapped and unmapped aquifers and hydrogeology is presented in Section 5.1 and 5.3.

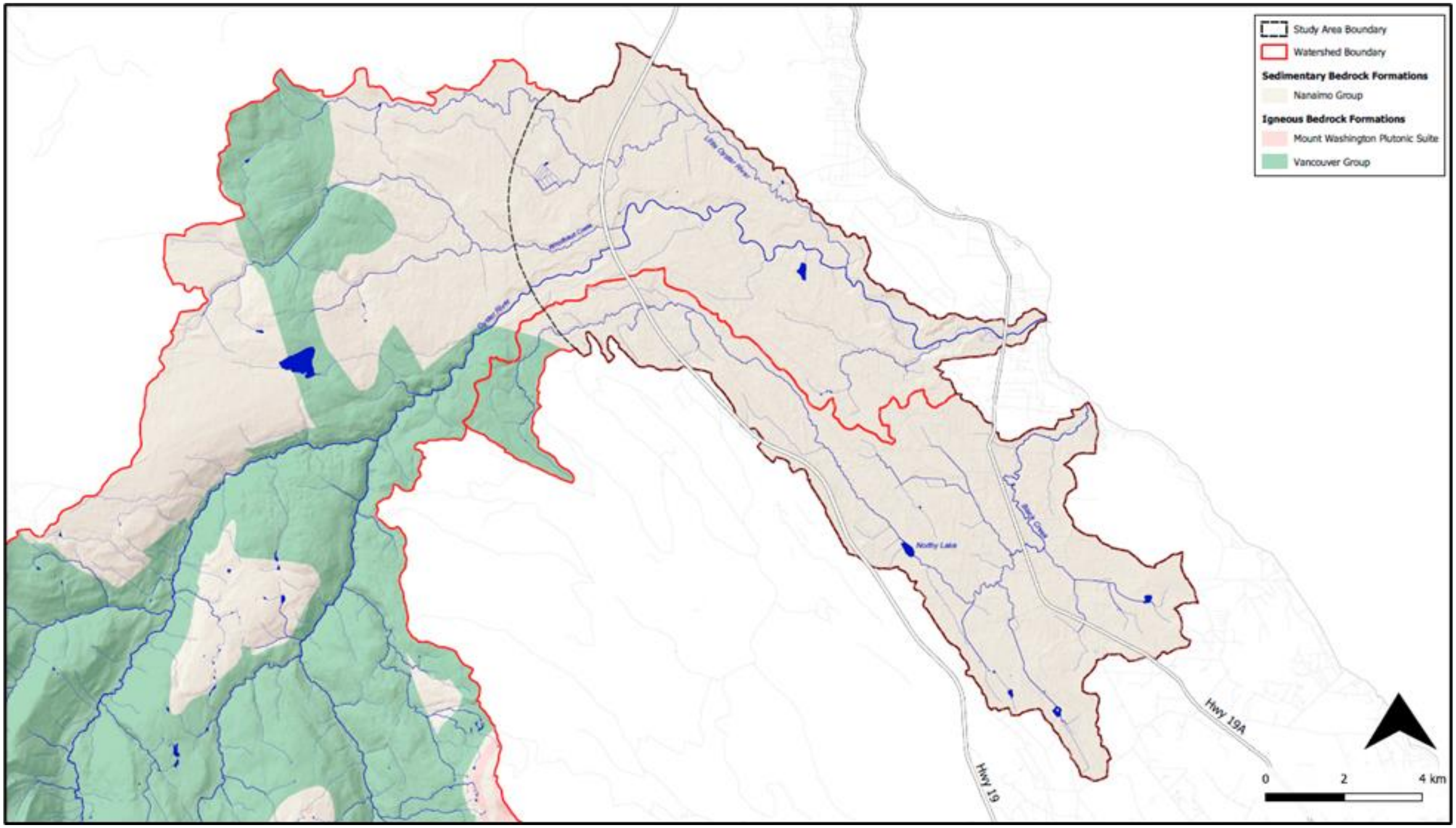

Figure 3: Bedrock geology of the study area.

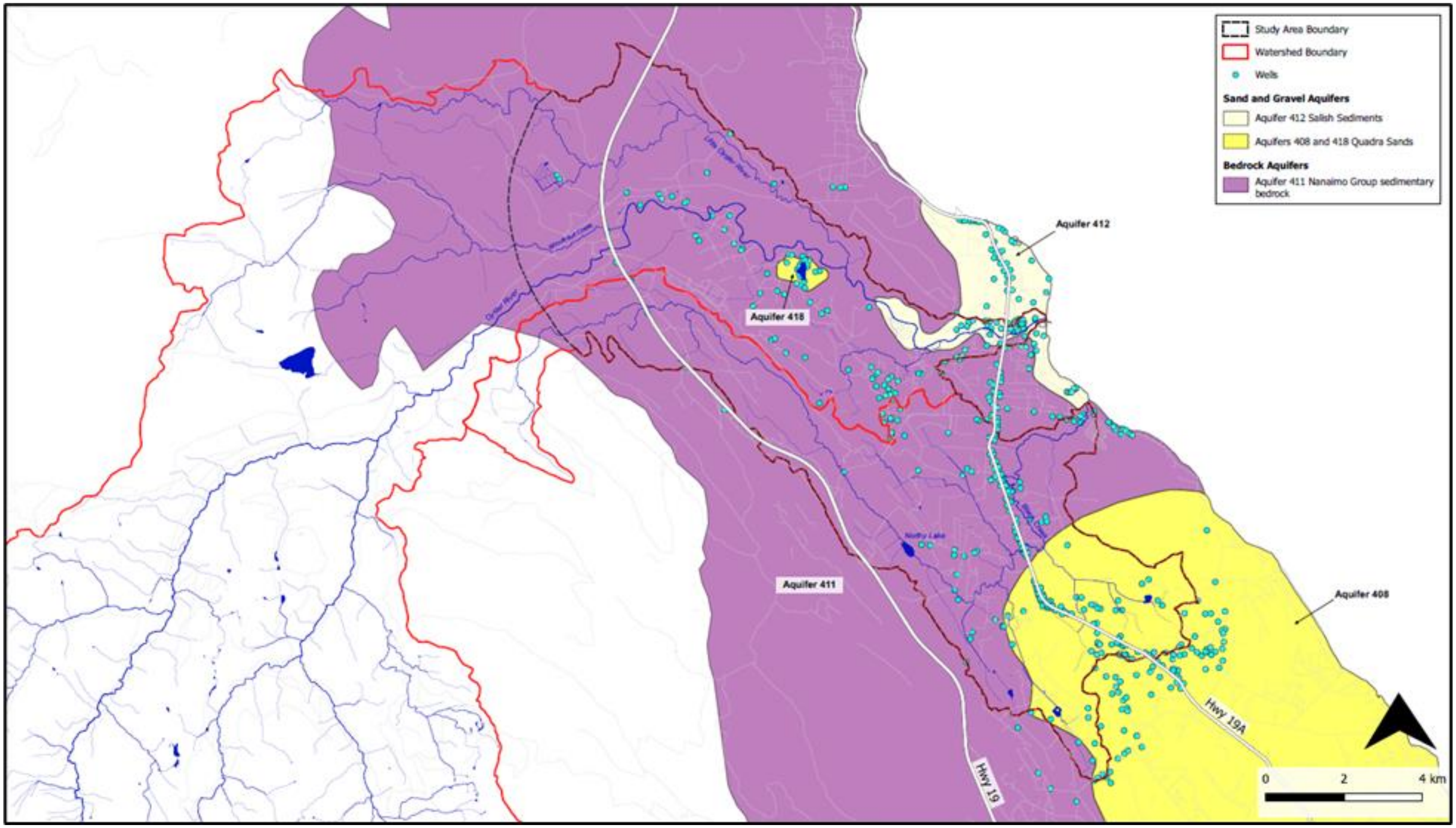

Figure 4: Mapped aquifers in the study area.

4. APPROACH

4.1 Primary Criteria in Assessing Hydraulic Connections to Streams

In general, 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).

Barlow and Leake (2012) present and discuss these two processes in detail.

4.1.1 Hydraulic connection governed by presence/absence of a vadose zone or low-permeability unit beneath a stream

Our working hypothesis in this study is that for hydraulic connection to be likely between an aquifer and a stream, there must be an absence of a:

1. Vadose zone (unsaturated zone), and
2. Low-permeability sediments (i.e., till, silt, or clay), beneath the stream (to disconnect the aquifer from the stream).

The presence of a vadose zone or low permeability sediments beneath a stream and above the aquifer in question will essentially restrict hydraulic connection and stream depletion along that reach of the stream. However, depletion from well pumping may still occur further down-gradient (by the process of interception) at a connected reach of stream. Depending on the setting, pumping may not affect the disconnected stream reach nearest to the well, but more likely a reach further downstream or down-gradient of the direction of groundwater flow. In this study, if a vadose zone or low permeability sediment layer does not underlie a reach of stream, that reach is considered likely connected (Figure 5).

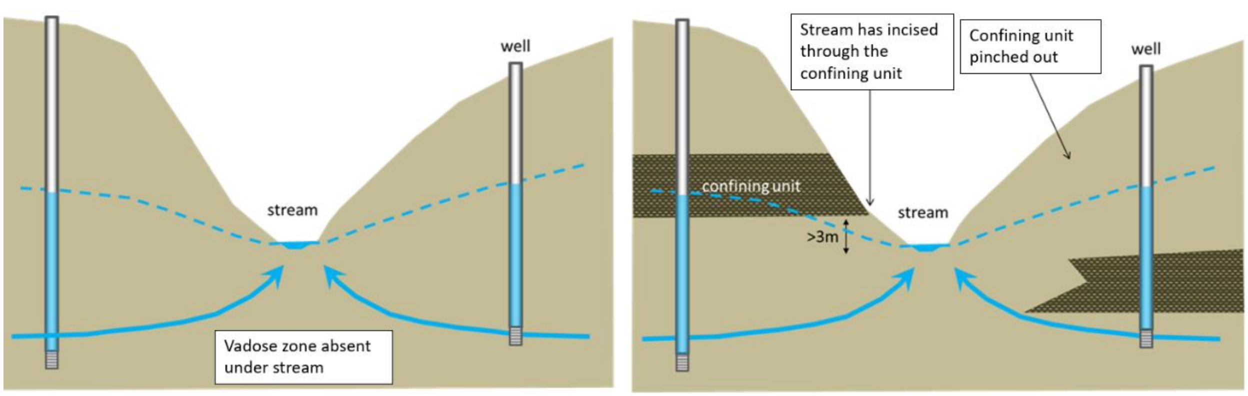

Figure 5: Primary conditions that allow hydraulic connection between water in a stream and an aquifer to occur – no vadose zone and no confining sediments underlying the stream.

4.1.2 *Depth/stratigraphic considerations*

The evaluation of the presence/absence of a vadose zone and a low-permeability unit beneath a stream was applied for each aquifer identified in the study area. However, since the different aquifers in the study area occur at different depths, the stratigraphic position of each aquifer had to be taken into account (see Table 1 for the mapped aquifers).

Table 1: How an aquifer's stratigraphic position affects the presence/absence of low permeability units separating an aquifer from a stream.

Aquifer (from youngest to oldest)	Relative depth	Low-permeability sediments above the aquifer?
Aquifer 412 (Salish Sediments)	Shallowest	Generally unconfined
Aquifers 408 and 418 (Quadra Sands)	Deeper	Vashon Drift
Aquifer 411 (Nanaimo Group sedimentary bedrock)	Deepest	Vashon Drift and, if identified in well records, any low-permeability Cowichan Head Formation sediments underneath the Quadra Sands but above bedrock

4.2 Spatial Data Sources

The following subsections present the data sources and construction of the maps and cross-sections in more detail, and the uncertainties associated with the data. In completing the analyses herein, we incorporated a series of spatial datasets in various data formats and scale. These datasets are summarized in Table 2 below. The data limitations and associated uncertainty are described in Section 4.5.

Table 2: Summary of spatial datasets used in the study.

Dataset	Format	Scale	Purpose	Reference
GWELLS well lithology	Shapefile	-	Lithology and water levels used in hydraulic connection determinations.	ENV (2020c)
Select, deeper geotechnical boreholes	.PDF	-	Lithology and water levels used in hydraulic connection determinations.	MOTI (2020)
Oyster River and Black Creek Watershed Boundaries	Shapefile	1:20,000	Used to constrain study area.	B.C. Freshwater Atlas from GeoBC (2010)
Watercourses	Shapefile	1:20,000	Used in hydraulic connection determinations.	B.C. Freshwater Atlas from GeoBC (2010)
Canadian Digital Elevation Model	.TIF	~20 m horizontal resolution	Used to extract elevations to well points and watercourses.	NRCan (2011)
Digital Surficial Geology	Shapefile	1:50,000	Used to refine geological data from GWELLS and refine hydrogeological conceptual model.	Forest Renewal B.C. (1992)
Digital Bedrock Geology	Shapefile	1:50,000 to 1:250,000	Used to refine hydrogeological conceptual model.	Cui et al. (2017)

4.3 Well Lithology

Well data from GWELLS formed the primary lithological and groundwater level input dataset for this study. Well data were compiled and used to develop the conceptual hydrogeological model for the watershed and to determine where hydraulic connection is expected to occur. Lithology key words were used to systematically refine the lithology from the GWELLS database using a script to standardize the terminology (see Table 3 below). Wells were classified as completed into the various unconsolidated aquifer units or bedrock based on the refined lithology spreadsheet. The results were reviewed manually and cross-referenced against available terrain inventory and surficial geology mapping.

Table 3: Summary of classification methodology for well lithology data.

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

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

4.4 Geographical Information System (GIS) Analysis

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

Anchor points were used to control where sediment thicknesses are expected to be < 1 m (based on available geological mapping). To develop isopach maps, anchor points were placed where material thicknesses were expected to be <1 m. This includes:

- Terrain polygons which show thin veneers of sediment above bedrock or bedrock exposures at surface. The anchor points were placed on a grid spaced at 100 m intervals within these terrain polygons;
- Field observations of bedrock outcrops mapped by Fyles (1960) and Zubel (1981); and,
- Other areas where sediment thicknesses are inferred to be marginal, informed by the hydrogeological cross-sections.

The multilevel B-spline method (Lee et al., 1997) was selected to interpolate between data points for mapping groundwater elevations and for isopach maps due to the clustered and irregular nature of the data points. A summary on the data limitations and sources of uncertainty are discussed in Section 4.5.

GIS was also used to support delineating the groundwater management zones using the Point of Hydraulic Connection (PoHC) between streams and wells.

4.4.1 Well-aquifer correlation

The available well logs were systematically reviewed and correlated to the mapped (and unmapped) aquifers. As previously noted in Section 3.1 above, the study incorporates all wells located within 1 km of the Oyster River and Black Creek watershed boundaries and all wells located within the boundary of Aquifer 412 (part of Aquifer 412 occurs outside of the watershed area). The expanded study area was defined to enhance the hydrogeological conceptual model, because many well logs within the Oyster River and Black Creek watersheds are of low quality. This study documented 491 well records and 63 geotechnical borehole and test pit records (MOTI, 2020) as available in this expanded study area. We used the geotechnical data provided by MOTI (2020) to supplement the mapping (see Sections 4.4.3to 4.4.6 below).

The correlation of wells and aquifers involved importing the data into Microsoft Excel spreadsheet. The records within the expanded study area were reviewed to update information that was not entered or that was entered incorrectly from the scanned well cards (for example, static water level, and final well depth). The aquifer correlations were cross-referenced using lithology and well construction details, aquifer mapping, surficial geology mapping, and the hydrogeological cross sections completed for this study (see Section 4.4.2 below). The updated well-aquifer correlations are shown on Figure 6.

4.4.2 Hydrogeological cross-sections

We constructed six hydrogeological cross-sections at key locations in the study area, to aid in visualization and interpretation to understand the aquifers and the extent and role of confining units in the study area. The locations of the cross-sections are shown in Figure 6. The cross-sections were drafted in Golden Software™ Strater using the GWELLS and geotechnical data provided by MOTI (2020). The terrain profile for each section line was extracted from the DEM and imported into Strater. The raw lithology descriptions from GWELLS and dominant lithology unit from MOTI (2020) were transferred to the cross-sections and checked against surficial and bedrock geology mapping. The cross-sections helped to guide well-aquifer correlations and infer the spatial extents of the main aquifer units in the study area.

4.4.3 Mapping groundwater elevation

Groundwater elevation maps were constructed separately for each aquifer unit to infer direction of horizontal groundwater flow within those units (see Figure 7a through c). For a description of all the aquifer units, see section 5.1. The water table elevation map of the uppermost aquifer unit was also used to infer presence/absence of a vadose zone beneath streams. Groundwater elevation contours were constructed by grouping wells from the GWELLS database into three aquifer unit categories as follows:

- Water table elevation of Aquifer 412 and the other shallow, unconsolidated “aquifer” unit (Figure 7a): includes wells completed in the Salish and Capilano Sediments, and those completed at shallow depth, into the Capilano Glaciomarine and Vashon Drift (<10 m depth);
- Groundwater elevation of the Quadra Sands aquifers (Figure 7b): includes wells completed in the Quadra Sands, and deep wells completed into sand and gravel layers in the Vashon Drift; and,
- Groundwater elevation of Aquifer 411 (Figure 7c): includes only wells completed in the Nanaimo Group of sedimentary bedrock.

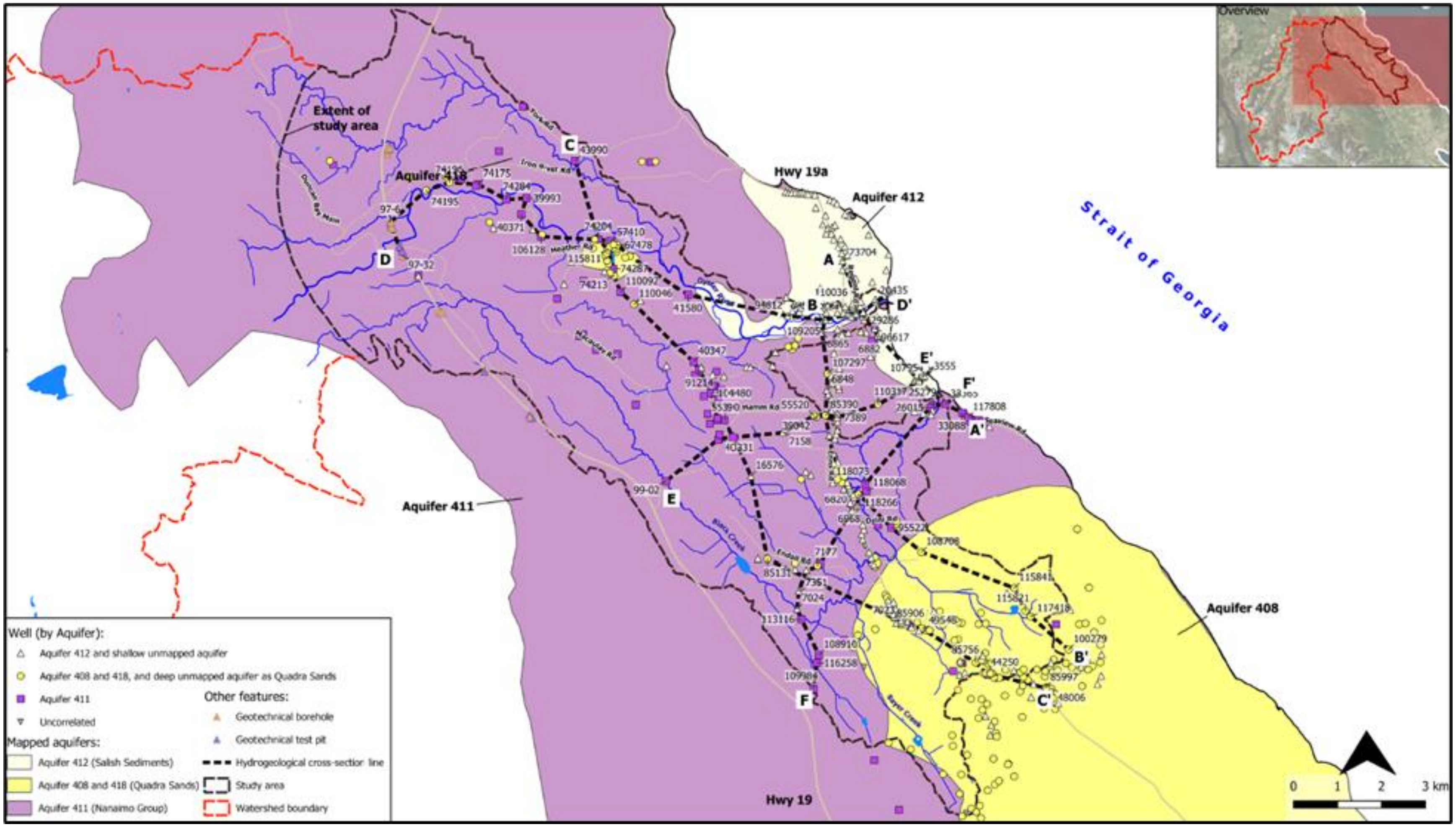

Figure 6: Updated well-aquifer correlations in the study area.

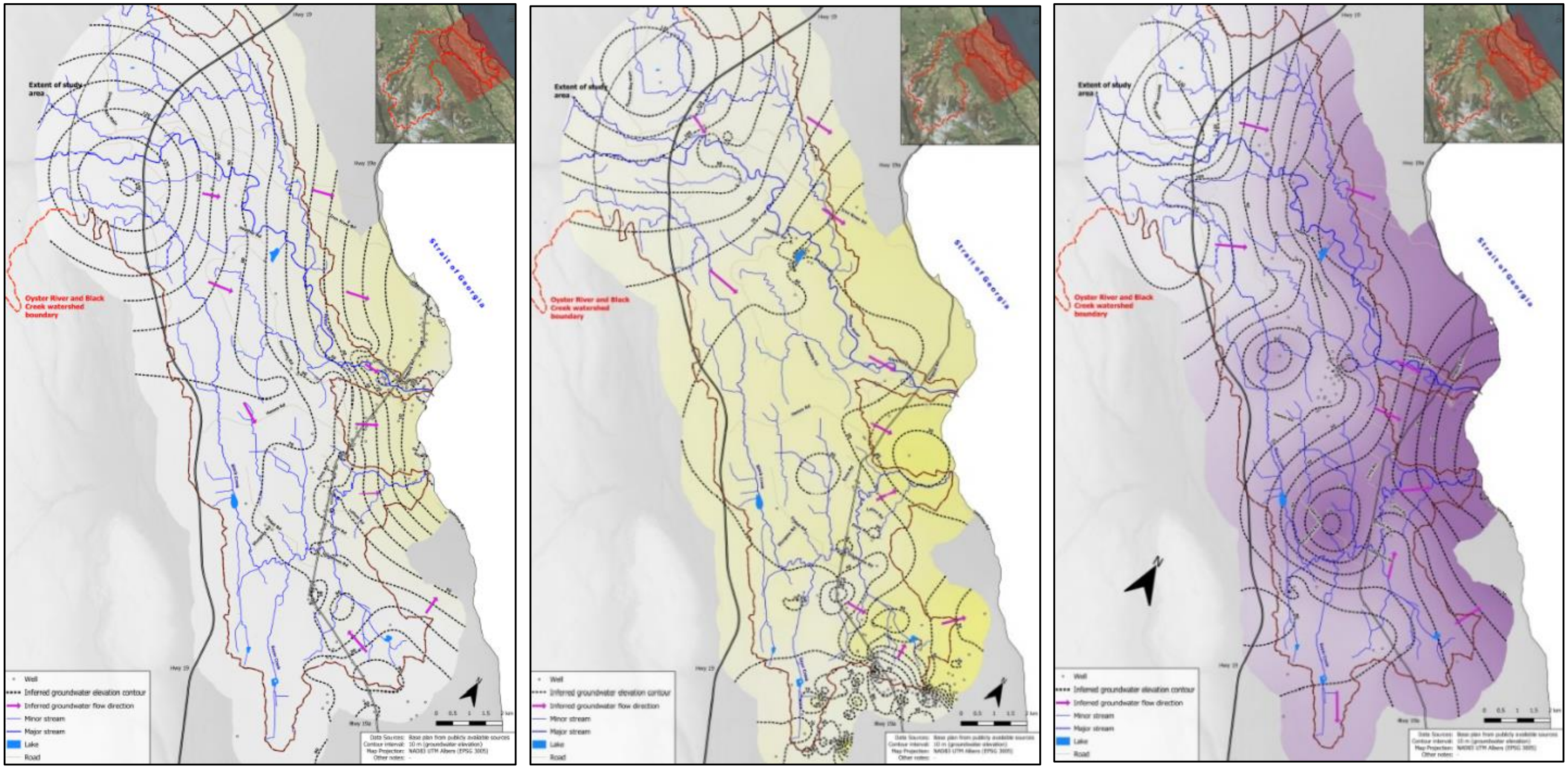

Figure 7: Reported groundwater elevations and flow directions in Aquifer 412 and the unconsolidated unmapped "aquifer" unit (a; left); reported groundwater elevations and flow directions in the Quadra Sands aquifers (b; middle); and reported groundwater elevations and flow directions in Nanaimo Group fractured bedrock aquifer (c; right).

The ground surface elevation at each well location was extracted from the digital elevation model (DEM). The DEM has a horizontal accuracy of about 20 m, and elevation is expressed relative to mean sea level. The groundwater elevation at each well location was calculated by subtracting the reported static water level depth in the well from the DEM ground elevation (limitations of using reported static water levels are discussed in Section 4.5). The groundwater elevations between well points were interpolated and contoured in GIS. In calculating groundwater elevations, well stick-up above ground surface was assumed to be zero.

In relying on the reported static water levels in the well records, we assume they represent average conditions over the period of the dataset (<1950 to present).

4.4.4 Mapping inferred vertical groundwater gradient

Relative vertical hydraulic gradient direction between deposits within the study area is depicted in Figure 8. Figure 8 was created by subtracting the cell water table elevation values for the shallow unconsolidated deposits (<10 m or 30 ft thick) from those for the fractured bedrock. Groundwater elevations from wells interpreted to be completed in the deeper Quadra Sands deposits were excluded because of limited data (see Section 5.3 for more details).

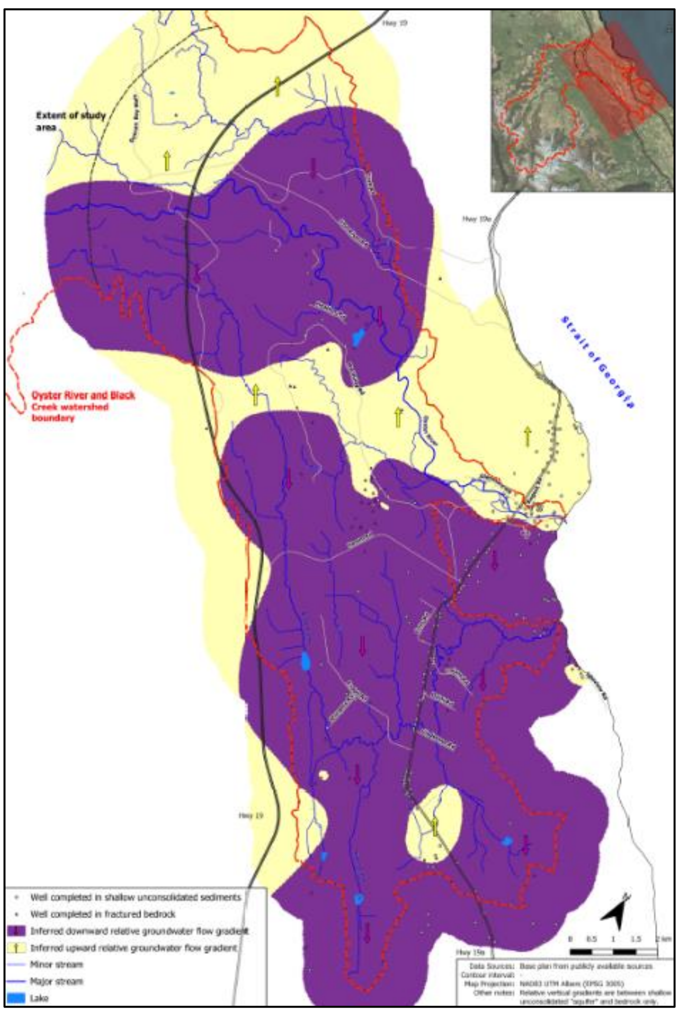

Figure 8: Relative vertical groundwater flow gradient between unconsolidated sediments and fractured bedrock.

The groundwater elevations between wells are interpolated using a multilevel B-Spline interpolation method in GIS. Figure 8 depicts inferred zones of upward gradient in purple, and downward gradient in yellow. Whereas the direction of vertical gradient can be mapped, the magnitude cannot be accurately quantified because bedrock wells are typically open hole, and therefore open to water-bearing fractures at multiple depths.

Upward directed groundwater flow is inferred to occur in areas where the static water elevation in the underlying aquifer unit (bedrock) is greater than the static water elevation in the overlying deposit (yellow areas), and vice versa for downward groundwater flow (purple areas). The arrows on Figure 8 depict the relative direction of vertical groundwater flow.

4.4.5 Inferring the presence/absence of a vadose zone beneath a stream

To assess if a vadose zone exists beneath a stream, we compared the contoured water table elevation map for the uppermost aquifer units (Aquifer 412 and the shallow unconsolidated “aquifer” unit – Figure 7a) to stream elevations. The elevations of streams were determined by extracting elevation data from the DEM along the stream nodes from the Freshwater Atlas dataset. A vertical tolerance value of 3 m, for the difference between stream and groundwater elevation, was imposed to help reduce the possibility of a false positive identification of a vadose zone beneath a stream reach. Therefore, the groundwater elevation surface had to be more than 3 m beneath the elevation of the stream for a vadose zone to be considered to exist beneath the stream. Higher confidence was further placed where mapping indicated existence of a vadose zone in 10 or more consecutive grid cells (~ 250 m) along a stream reach.

A visual comparison using different tolerance values ranging between 1 m and 5 m was conducted, and differences were observed as to the mapped location of a vadose zone beneath streams for the shallow aquifer. This is because the groundwater elevations for these wells are close to ground surface due to the shallow nature of these wells. A tolerance value of 3 m was selected because it is a conservative approach.

4.4.6 Mapping low permeability sediment thickness and inferring its presence/absence beneath a stream

Low permeability unconsolidated sediments that typically impede groundwater flow include till, clay and silt. Till is composed of a broad range of glacially derived materials which reflect depositional history and geological setting. Till can impede the flow of groundwater and act as a confining material if it contains appreciable amounts of silt and clay. Clay and silt deposits in the absence of coarser materials typically form in quiet-water environments such as lakes. In this study, sediments classified as ‘till’, ‘silt’ or ‘clay’, are considered confining sediments, meaning that they are expected to have low permeability and therefore impede groundwater flow. In this study, the confining thickness was mapped relative to specific aquifer units. Figure 9a represents the sum of confining thickness above the Quadra Sands and Figure 9b represents the sum of the confining thickness above the bedrock.

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

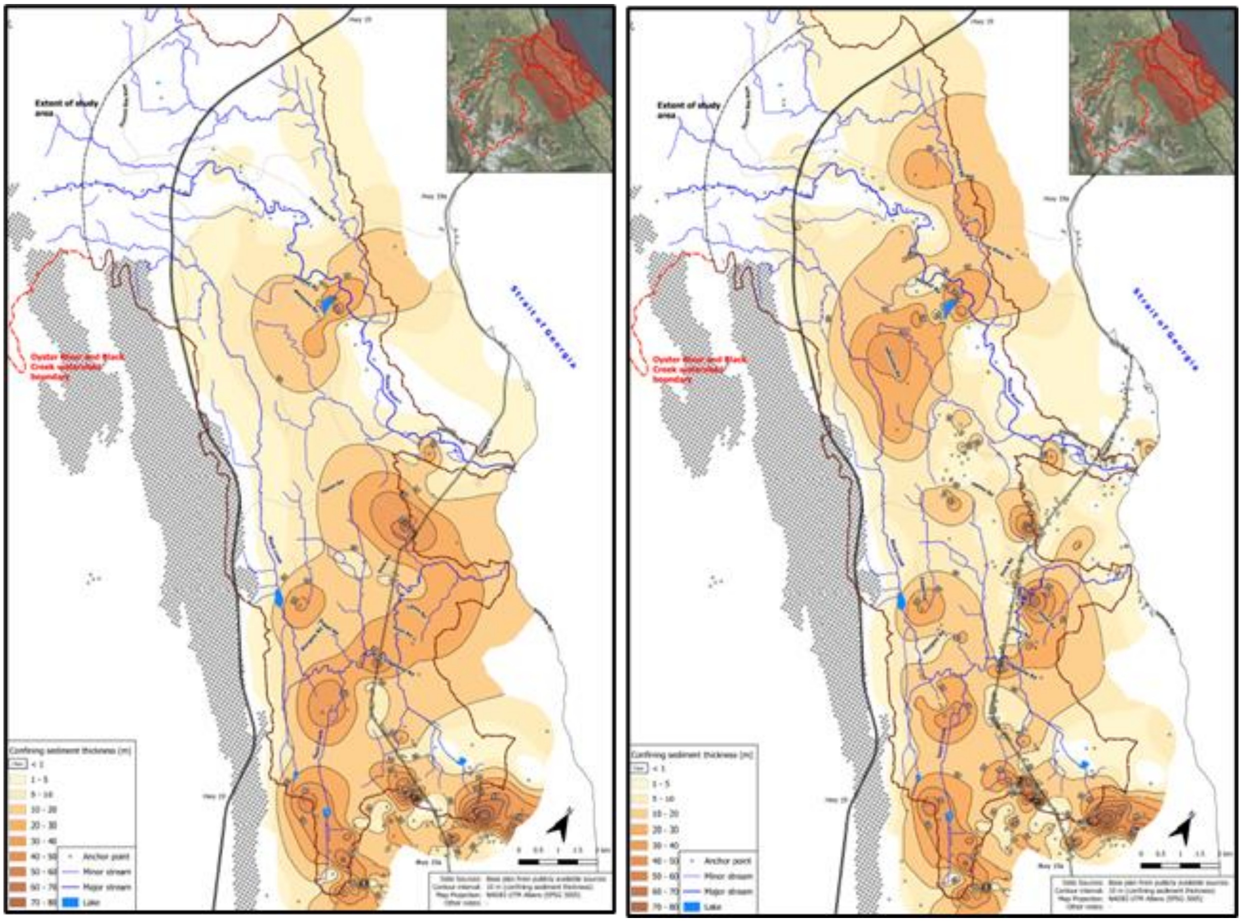

Figure 9: Confining sediment thickness in wells completed in the Quadra Sands aquifers (a; left) and confining sediment thickness in wells completed in the Nanaimo Group (b; right).

The wells were grouped by formation into the same three categories as described above in Section 4.4.3. To consider if a stream had completely down-cut through the confining sediments or not, only confining sediments located above the well screen or final completed well depth were used in the mapping. For wells not drilled into bedrock, any confining sediments that exist below the depth of the well could not be included.

- Confining sediment thickness above the Quadra Sands (Figure 9a) - the thickness of confining sediments encountered during drilling above the screen or final completed well depth was used; and,
- Confining sediment thickness above bedrock (Figure 9b) – the entire thickness of confining sediments encountered above bedrock was used.

As prescribed by FOR, the presence of a low-permeability unit beneath a stream was inferred to exist only where the low-confining sediment thickness was more than 1 m thick.

4.4.7 Identifying stream reaches where hydraulic connection is likely and unlikely

We used the water table elevations contoured from wells completed in Aquifer 412 and the other shallow "aquifer" unit (Figure 7a), as well as the confining sediment thickness isopach map for the Quadra Sands and bedrock aquifers (Figures 9a and 9b) to delineate stream reaches where hydraulic connection is likely. As noted above, hydraulic connection is considered likely along stream reaches where a mapping indicates an absence of a vadose zone and low permeability sediments beneath a stream.

4.4.8 Delineating groundwater management areas (GWMAs)

Once major connected reaches of streams are identified, groundwater management areas can be delineated for the unconsolidated and bedrock aquifers in the study area, based on these hydraulically connected reaches and on the groundwater elevation mapping. Groundwater management areas help inform allocation and management of water rights within the Oyster River and Black Creek watersheds.

Groundwater management areas were delineated separately for the three types of unconsolidated and bedrock aquifers (shallow, Quadra Sands and Nanaimo Group sedimentary bedrock), by establishing a delineation point at the downstream end of major open stream reaches. The GWMAs were delineated upgradient of the delineation point, guided by the groundwater elevation contours. A major reach of connected stream can include short (<500 m in length) disconnected reaches. Points of delineation were established along the mainstem of the Oyster River and Black Creek.

4.5 Data and Analysis Limitations, and Sources of Uncertainty

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

GIS-based maps of information derived from water well records, such as groundwater elevations and sediment thicknesses, can create the illusion of a high degree of accuracy. The contour maps were developed using raster surfaces depicting confined 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 in areas where the bullseyes are present (discussed in further detail below). The maps were based on available data (a total of 491 well records and 63 geotechnical boreholes and test pits), 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 the well data contain records that are incomplete and/or contain missing or erroneous data, including incomplete lithology, missing static water level and inexact well locations. In steeply sloping areas, imprecise well locations could also affect calculation and mapping of groundwater elevations.

In relying on the reported static water levels in the well records, we assume they represent average conditions over the time-period of the data (<1950 to present). 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. The groundwater elevation maps produced in this study represent a composite 2-dimensional steady-state picture over time and seasons. Any temporal trends in groundwater elevations would not be discernable from the groundwater elevation maps. The relative vertical groundwater gradient between (and within) the unconsolidated sediments and bedrock was characterized in this study to support our hydrogeological conceptual model; however, quantifying the magnitude of vertical flow was out of the scope of the study. The reader should keep in mind that the GWMAs were largely delineated based on groundwater elevation contours of available data. The areas are subject to future modifications as more groundwater elevation data become available within the watershed.

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

5. RESULTS AND DISCUSSIONS

Describing how groundwater enters, flows through and exits the subsurface is facilitated using conceptual models. A conceptual hydrogeological model is a qualitative representation of a study area, which is used to describe the occurrence and flow of groundwater through the subsurface. Conditions bounding the system are identified, including: established groundwater levels, surface water bodies and watercourses, barriers to flow, and areas of groundwater recharge and discharge. Groundwater flow patterns are identified based on the interpreted hydraulic gradients. The hydrostratigraphic units are defined in Section 5.1. The well-aquifer correlations are described in Section 5.2. The groundwater flow directions are described in 5.3.

5.1 Hydrostratigraphic Units

The study area geology is composed of complex unconsolidated sediment sequences deposited over time from the last glaciation and the underlying fractured sedimentary bedrock (see Section 3.2 above). These sequences are contained in the lithology spreadsheets developed for this study. Groundwater flow directions are discussed in Section 5.3 and are depicted in Figure 7a through 7c. The geometry and distribution of the confining sediment thicknesses are described below in Section 5.4 and are depicted in Figure 9a and 9b, respectively. The local hydrostratigraphy is illustrated on hydrogeological cross-sections located in Appendix A of this report (see Figure 6 for cross-section locations):

- Figure A1 – Section A-A’ across Oyster River and Black Creek at the mouth (N-S);
- Figure A2 – Section B-B’ across Oyster River and Black Creek in their middle reaches (N-S);
- Figure A3 – Section C-C’ across Oyster River and Black Creek in their upper reaches (N-S);
- Figure A4 – Section D-D’ up Oyster River (W-E);
- Figure A5 – Section E-E’ up midway between Oyster River and Black Creek (W-E); and,
- Figure A6 – Section F-F’ up Black Creek (W-E).

Within the study area, the following hydrostratigraphic units have been identified, from the shallowest (and youngest) to the deepest (and oldest):

- Aquifer 412 (Salish Sediments) and an unmapped shallow, unconsolidated "aquifer" unit;
- Vashon Drift (aquitard);
- Aquifers 408, 418 (Quadra Sands) and two additional unmapped aquifers comprising predominantly Quadra Sands;
- Older pre-Quadra glaciomarine sediments, possibly comprising Cowichan Head Formation (aquitard in the southern part of the study area); and,
- Aquifer 411 (Nanaimo Group sedimentary bedrock).

Each of these units is discussed below.

5.1.1 Aquifer 412 (Salish Sediments)

Wells completed in the Salish Sediments of Aquifer 412 are located along the coastline and/or at the mouth of the Oyster River near sea level, within the mapped Aquifer 412 polygon. The unit also contains thin clay or silt layers that are laterally discontinuous. These wells are usually located below 20 m above sea level.

5.1.2 Unmapped shallow, unconsolidated "aquifer" unit

Many older, shallow wells (generally <10 m depth) in the study area were dug into "sand", "hardpan" (till), and even "clay" and provide a limited source of shallow groundwater to local landowners. Many of these wells are located along the Hwy 19A between the Oyster River and Surgenor Road (Figure 6). The scanned well records note that some of the wells are dry in the summer which is indicative that water supply may be seasonal. These water-bearing seams likely occur within the Capilano Sediments and even the very top of the Vashon Drift (which may be weathered).

It is not possible to map the individual water-bearing seams in these shallow wells. Instead, we conceptualized the groundwater encountered in these shallow dug wells to be part of an overall shallow groundwater flow system, flowing through a range of sediments. These shallow sediments were lumped into a single shallow, unconsolidated "aquifer" unit. We initially envisioned groundwater flow within this shallow system to be driven completely by the local topography within the study area and thus expected pumping of these shallow wells will deplete the stream immediately downhill from the well via interception. Our understanding of the groundwater flow in this shallow unit was later further informed by the water table elevation map (see Section 5.3).

5.1.3 Vashon Drift

This predominantly till unit forms an extensive confining layer directly overlying the Quadra Sands. If the Quadra Sands and older unconsolidated sediments are absent, then the Vashon Drift directly overlies the sedimentary bedrock. There are some shallow wells that may have been dug into the top of the Vashon Drift. If so, the upper part of the Vashon has not been included here within this hydrostratigraphic unit, but rather has been included with the unmapped shallow, unconsolidated "aquifer" unit above. In addition, some deeper wells may be completed into sand and gravel seams that occur within the Vashon Drift (the contact between the Vashon Drift and Quadra Sands is not always clear from the well records); in those cases, the lower part of the Vashon Drift has also been excluded from this hydrostratigraphic unit and included with the Quadra Sands (see unmapped Quadra Sands below).

5.1.4 Aquifer 408 (Quadra Sands)

Wells are interpreted to be completed in Aquifer 408 if they are located within or near portion of the mapped aquifer boundary that extends into the study area from the south and are completed below confining sediments. Wells completed in Aquifer 408 are in the Black Creek watershed, south of about Gladstone Road and below about 100 m elevation.

Some of the shallow dug wells within the Aquifer 408 polygon area, previously entered in GWELLS as correlated with Aquifer 408, were removed from Aquifer 408 in our analysis. Instead, these shallow dug wells were interpreted to be part of the unmapped shallow unconsolidated “aquifer” unit (see Section 5.1.2).

5.1.5 Aquifer 418 (Quadra Sands)

Aquifer 418 is in the northern part of the study area between Macaulay Road and the Oyster River, near an unnamed lake (near the intersection of Section C-C’ and D-D’). Wells are interpreted to be completed in Aquifer 418 if they are located within or near the mapped aquifer boundary and completed below confining sediments usually interpreted as till. Sections C-C’ and D-D’ (Figures A3 and A4) show Aquifer 418 is of limited areal extent.

5.1.6 Unmapped Quadra Sands Aquifers

Deeper wells that were not correlated to mapped unconsolidated aquifers occur in the study area. Many of these deeper wells are located along Section B-B’, near the intersection with Section F-F’ and along Section D-D’, in the northwest part of the study area. These deeper wells are drilled into or below the Vashon Drift and are interpreted to be completed into the unmapped Quadra Sands. Sections B-B’, D-D’ and F-F’ indicate that these aquifers are also of limited areal extent.

5.1.7 Pre-Quadra Glaciomarine Aquitard

Wells are inferred to have encountered clay deposits underlying the Quadra Sands, located only in the very south part of Sections B-B’ and C-C’ (see Figures A2 and A3) and extending out of the study area. This unit may be related to the Cowichan Head Formation and is inferred to act as an aquitard based on its relative permeability contrast with the overlying Quadra Sands Aquifers.

5.1.8 Aquifer 411

Wells are inferred to be completed in Aquifer 411 if they are completed in fractured bedrock, which underlies the entire study area. Wells completed in Aquifer 411 are located throughout the study area, including near the coastline along Seaview Road, between Macaulay Road and Hamm Road, and the upper reaches of the Oyster River and Black Creek watersheds (Figure 6).

5.2 Well-aquifer correlation

A total of 491 well logs were systematically reviewed and correlated with aquifers within the expanded study area. Overall, the well records are variable in terms of age and quality. Four wells were not correlated because there was insufficient information in the well record. The well-aquifer correlations are shown in Figure 6, and the results are summarized below.

- 94 (19%) wells are completed in Aquifer 412 (Salish Sediments).
- 134 (28%) wells are completed in Unmapped Shallow (Capilano Sediments and some shallow Vashon till)
- 108 (22%) wells are completed in Aquifer 408 (Quadra Sands);
- 19 (4%) wells are completed in Aquifer 418 (Quadra Sands);

- 48 (10%) wells are completed in Unmapped Deep (Quadra Sands, some sand and gravel lenses in Vashon till); and,
- 80 (16%) wells are completed in Aquifer 411 (Bedrock).

5.3 Groundwater Elevation Maps

Groundwater elevations by aquifer units are shown in Figure 7a through 7c. Figure 7a shows the groundwater elevations in Aquifer 412 and the unmapped shallow, unconsolidated “aquifer” unit. Figure 7b shows the groundwater elevation of the Quadra Sands aquifers in the study area (Aquifers 408, 418, and the two unmapped aquifers). Figure 7c shows the groundwater elevation of the Nanaimo Group sedimentary bedrock aquifer. Figures 7a to 7c reveal some key characteristics of groundwater flow in these aquifers. Each groundwater elevation map is discussed below.

5.3.1 Groundwater flow in the shallow aquifers (Aquifer 412 and the unmapped shallow unconsolidated “aquifer” unit)

The water table ranges from 140 m in the northwest part of the study area to sea level along the ocean shore. Closed contours reflect isolated data points. The water table elevation contours generally slope from west to east and in many places do not meet the watershed boundary at right angles. For example, in the southern half of the study area, the 70 m water table elevation contour runs sub-parallel to the western watershed boundary. Along Little Oyster River the water table elevation contours are also sub-parallel to the watershed boundary there. This suggests that groundwater flow in the shallow aquifer units is not entirely constrained by the local topography within the lower watershed study area. The water table contours indicate that groundwater may also enter the study area from the Tsolum River watershed immediately to the west. This is understandable because groundwater levels from Mt. Washington may be much higher, driving groundwater into the lower Oyster River-Black Creek watershed study area. The water table elevation map (Figure 7a) also suggests that shallow groundwater flows out of the watershed towards the ocean, east of Little Oyster River, in the area between the lowest reaches of Oyster River and Black Creek, and to Seaview Road in the southern part of the study area.

5.3.2 Groundwater flow in the Quadra Sands aquifers

The groundwater level map (Figure 7b) for the Quadra Sands is constructed from more spatially skewed data points but show a similar pattern to the unconsolidated shallow aquifer. Again, the closed contours reflect isolated anomalous data points. In addition, whereas the groundwater elevation is mapped for the entire study area, the reader should keep in mind that the groundwater elevation contours are only meaningful where the Quadra Sands aquifers occur.

5.3.3 Groundwater flow in the sedimentary bedrock

The groundwater elevation map for the Nanaimo Group sedimentary bedrock (Figure 7c) also reveals a similar picture of groundwater flow as in the Quadra Sands (Figure 7b) and shallow aquifers (Figure 7a). Again, the closed contours reflect isolated data points. Figure 7c suggests the underlying bedrock receives groundwater inflow from the Tsolum River watershed to the west. Groundwater also appears to flow out of the watershed east of Little Oyster River, in the area between the lowest reaches of Oyster River and Black Creek, and to Seaview Road in the southern part of the study area. Groundwater levels in the bedrock aquifer are influenced by regional (as well as local) topography.

5.3.4 Correlation between groundwater elevation and topographic elevation

Figure 10 graphically shows that the relationship between the ground surface elevation and the groundwater elevation at the wells is strongly correlated. The coefficient of determination (R^2) for this relationship was calculated to be 0.997 for Aquifer 412 and shallow unconsolidated "aquifer" unit and 0.862 for bedrock. Groundwater elevation is poorly to moderately correlated to topography (R^2 = 0.329) for the Quadra Sands. Figure 10 may lead the reader to conclude that groundwater flow in the study area is dictated by the local topography (at least for the shallow aquifer units where R^2 is high). While that may be partially the case, Figures 7a to 7c provide evidence that groundwater into and out of the watershed is occurring and is influenced by more regional topography (Mt. Washington and the ocean). There is no apparent explanation for the poor correlation between groundwater levels in the Quadra Sands and local topographic elevations.

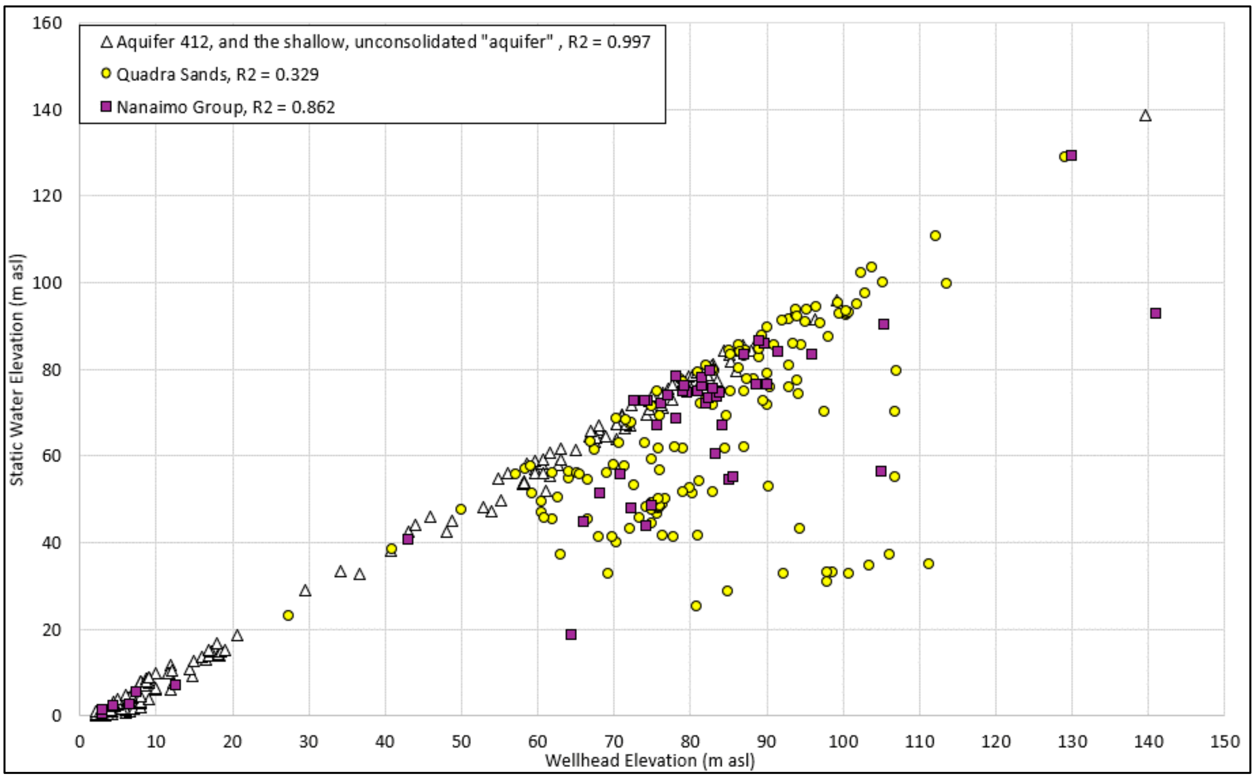

Figure 10: Relationship between wellhead elevations and static water level elevations in the study area.

5.3.5 Vertical groundwater gradients

Figure 8 shows the relative vertical groundwater gradient between the groundwater elevations in uppermost Aquifer 412 and shallow, unconsolidated "aquifer" unit and the bedrock Aquifer 411. Within much of the Oyster River watershed, groundwater elevations are typically lower in bedrock than in the shallow unconsolidated sediments indicating a propensity for downward directed groundwater gradients. Groundwater gradient tends to be upward in the lower portion of the Oyster River watershed.

Mapping in the Black Creek watershed shows that the groundwater elevations in the bedrock are lower than in the deep unconsolidated sediments, except in an area to the east of Sayer Creek. This suggests that groundwater flow potential is downward into the bedrock in most areas in the watershed, except in a localized area along Hwy 19A where upwelling may occur.

5.4 Presence/Absence of a Vadose Zone Beneath Stream Reaches

Figure 11a shows areas where the elevations of the streams are significantly above the mapped water table elevations in the uppermost unconsolidated aquifer units (Aquifer 412 and the shallow, unconsolidated “aquifer” unit). Stream reaches where the mapped water table elevations (from Figure 7a) are more than 3 m below the stream elevation have been shaded in red. Beneath these reaches coloured red, a vadose zone is inferred to exist beneath the stream there. Along these stream reaches the groundwater and the water in the stream are likely to be disconnected, and the stream is said to be “perched”.

5.4.1 Oyster River watershed

<u>Shallow Aquifer (unconsolidated):</u>

Figure 11a shows that vadose zones are inferred to be present only at the mouth, in upper reaches of the Oyster River in the study area west of the Island Highway 19 and along Little Oyster River.

5.4.2 Black Creek watershed

Figure 11a shows that vadose zones are inferred to be present along the major tributaries to Black Creek near Lalum Road and Dzini Road, and in the upper reaches of Black Creek within the study area.

5.5 Presence/Absence of Confining Sediments Beneath Streams

Figures 9a and 9b show the thickness of confining sediments located above the Quadra Sands and fractured bedrock, respectively. Figures 11b and 11c show the stream reaches where there are confining sediments overlying the Quadra Sands and Nanaimo Group sedimentary bedrock, respectively. The presence of confining sediments underneath the stream is expected to impede hydraulic connection between the underlying aquifers and the stream. The stream reaches underlain by confining sediments are classified as not connected and are coloured brown.

5.5.1 Oyster River watershed

Low permeability sediments confining the Quadra Sands and Nanaimo Group sedimentary bedrock underlie the Oyster River along most of its reach except from the mouth to the Oyster River Bridge, downstream of the confluence with the Little Oyster River, and upstream of the end of Doyle Road (see Figures 7b and A4). The Oyster River may have eroded through the till at this location, partially exposing the underlying Quadra Sands. Mapping by Fyles (1960) shows that fluvial deposits and other undifferentiated sediments are mapped near these locations. Otherwise, most of the tributaries to the Oyster River in the study area are underlain by low permeability sediments thus having a low likelihood of hydraulic connection.

5.5.2 Black Creek watershed

The mapping shows that in most areas, the low permeability sediments are continuous with thicknesses exceeding 60 m in some locations (Figures 9a and 9b). In other locations the low permeability sediments are apparently thinner, however this may reflect the limited depth of drilling at those locations (e.g., well was not drilled or excavated completely through the confining sediments) or are a result of the lack of descriptive lithology in the well records. The low permeability sediments appear to underlie most of the Black Creek mainstems and their tributaries (Figures 11b and 11c).

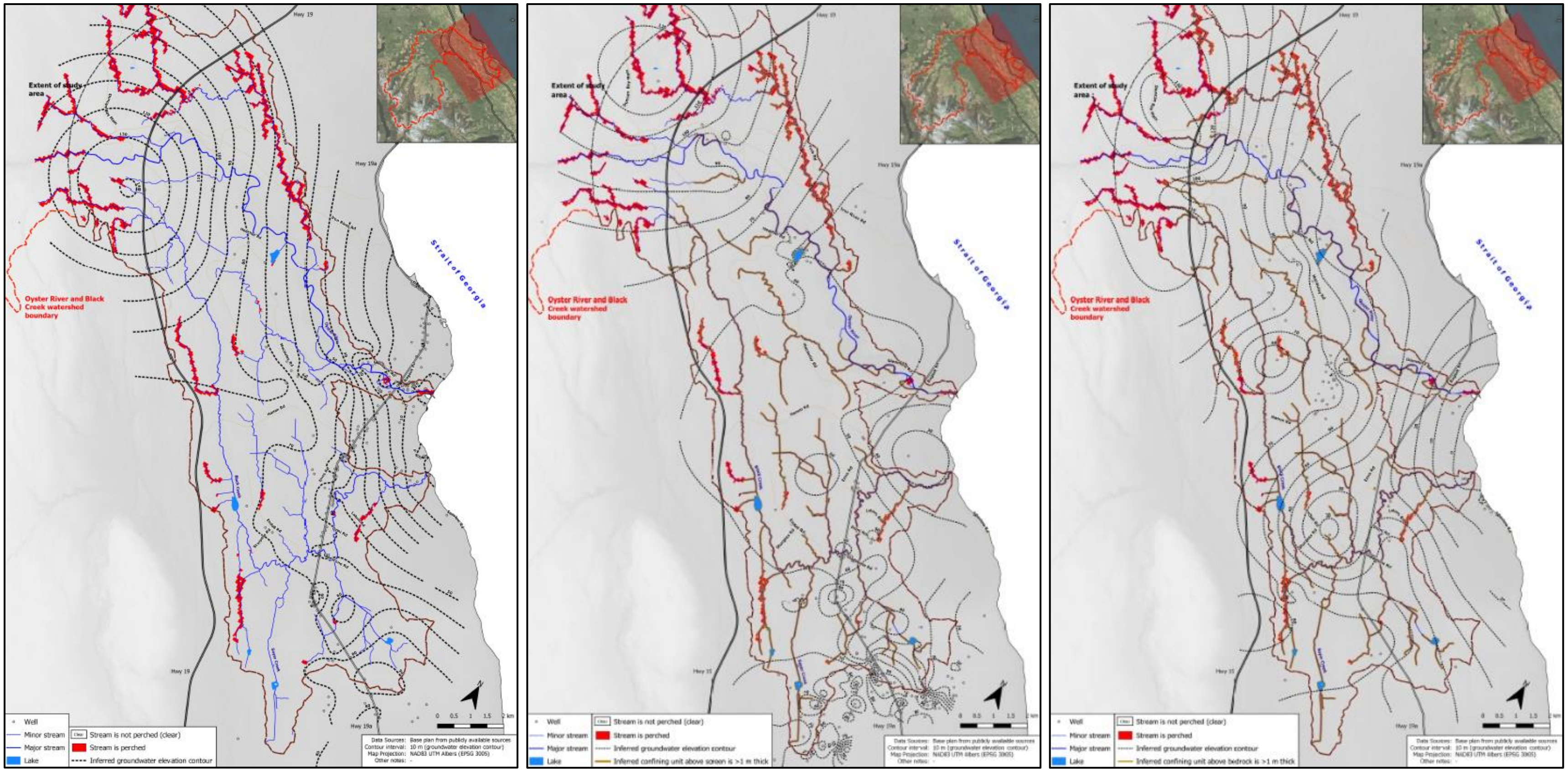

Figure 11: Stream reaches where hydraulic connection is likely for the uppermost aquifer unit (Aquifer 412), and unmapped shallow "aquifer" unit (a; left); stream reaches where hydraulic connection is likely for the Quadra Sands aquifers (b; middle); and stream reaches where hydraulic connection is likely for the Nanaimo Group bedrock aquifer (c; right).

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

Figures 11b and 11c show stream reaches underlain by low permeability sediments greater than 1 m thick (brown), superimposed over the map that show reaches where the mapped groundwater elevation is interpreted to be >3 m below the stream (red grids) to identify stream reaches that are considered disconnected from the underlying groundwater (i.e., where there is brown and/or red shading on the water course); the remaining unshaded reaches show those sections of streams that are connected and where streamflow depletion can occur.

Uppermost aquifer unit (Aquifer 412 and the shallow, unconsolidated "aquifer" unit): For the uppermost aquifer unit, the stream reaches where hydraulic connection is likely or unlikely is determined using the presence or absence of vadose zones only. This is because Aquifer 412 is unconfined and we conceptualized that groundwater flow occurs in the shallow, unconsolidated "aquifer" unit, regardless of the lithology of that shallow unit. Groundwater may discharge to local streams or, where the stream is underlain by confining sediments, flow in the uppermost unit may also discharge along the bank above the stream and flow as surface water to the stream. Pumping of these shallow wells will deplete the stream immediately downhill from the well via interception.

For both the Oyster River and Black Creek mainstems, vadose zones are present in only a few locations, and therefore hydraulic connection between wells completed in the uppermost aquifer unit and streams is likely the shortest distance between the well and stream.

Quadra Sands and Nanaimo Group Sedimentary Bedrock Aquifer Units: The stream reaches where hydraulic connection is likely or unlikely for the Quadra Sands and fractured bedrock is determined using the vadose zone mapping for the shallow aquifer only (Figure 7a); the groundwater elevation maps of the Quadra Sands (Figure 7b) and bedrock (Figure 7c) are piezometric levels of those respective aquifers.

For the Quadra Sands and fractured bedrock aquifer units, hydraulic connection between wells and the Oyster River mainstem likely occurs at the following locations:

- Immediately upstream of the Old Island Highway (Hwy 19A);
- Downstream of the confluence with Little Oyster River; and
- Upstream of the end of Doyle Road.

There are slight differences between Figures 11b and 11c showing the reaches of the Oyster River that are restricted or unrestricted by underlying confining sediments. This slight difference is because wells completed into the Quadra Sands were not used to inform the confining sediment thickness above the sedimentary bedrock.

Mapping shows that hydraulic connection is likely between wells and Black Creek only in the upper reaches of Black Creek within the study area. Hydraulic connection appears to be almost entirely impeded by the extensive till deposit that blankets the Black Creek watershed.

5.6 Conceptual Understanding of Hydraulic Connection within the Study Area

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

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

Pumping of groundwater from the shallow unconsolidated aquifers in the study area can deplete stream flows along the Oyster River and Black Creek where stream reaches are connected (no presence of a vadose zone). Where a well is located along a connected stream reach, streamflow depletion caused by a pumping well is interpreted to occur along that connected stream reach (the location of occurrence is referred to here as the point of hydraulic connection (PoHC)).

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

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

5.6.2 *Hydraulic connection between the unconsolidated and bedrock aquifers*

The existence of vertical gradients in the study area implies that hydraulic connection can also exist between aquifers. Actual interflow between the unconsolidated and bedrock aquifers can occur in areas where mapping shows low permeability sediments are absent (Figures 9a and 9b).

5.7 Preliminary Groundwater Management Areas

The significant influence of groundwater flow into and out of the watershed study area suggests that GWMAs delineated based on groundwater elevation maps can differ significantly in places from sub-watersheds areas delineated from local topography. GWMA delineation for the shallow aquifers, Quadra Sands aquifers and sedimentary bedrock aquifer are presented and discussed below.

5.7.1 *GWMAs for shallow unconsolidated aquifers*

Most of the stream reaches are interpreted to likely be hydraulically connected to shallow groundwater flow. Two GWMAs were delineated for the Oyster River watershed, one being upstream of the confluence with Little Oyster River (OR-Upper) and one downstream from the confluence (OR-Lower). Boundaries of the GWMAs (Figure 12a) were guided by the water table elevation contour map (Figure 7a). No GWMA was defined for the area west of the Island Highway (Hwy 19) in the northern part of the study area because of the paucity of data on which to base the GWMA delineation.

We also delineated two GWMAs for Black Creek (Figure 12a). A GWMA was delineated for a network of unnamed tributary streams at a confluence near Gladstone Road (UN). The other GWMA covers the remainder of the Black Creek area (BC).

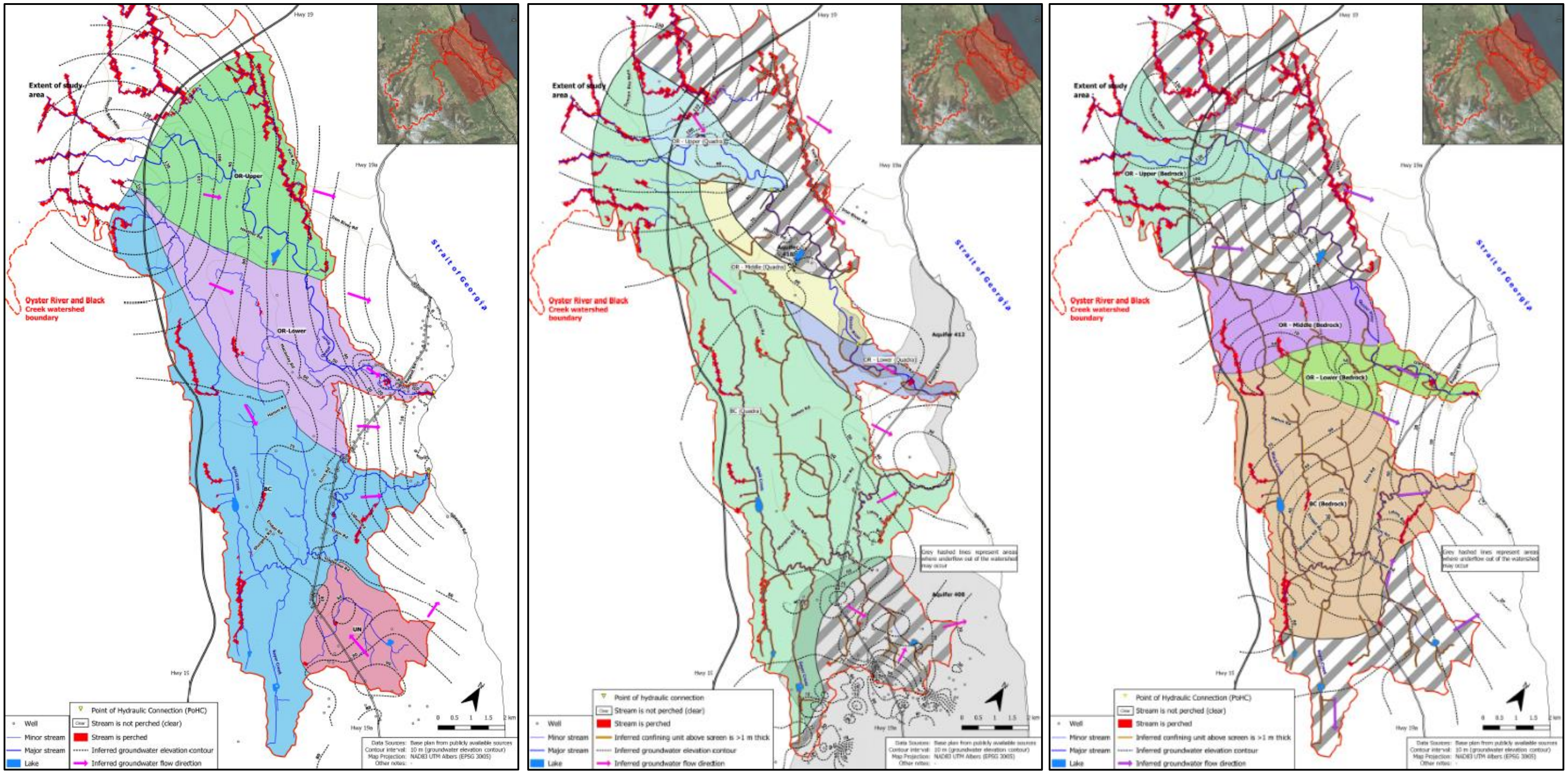

Figure 12: Groundwater management areas in Aquifer 412 and the unconsolidated unmapped "aquifer" unit (a; left); groundwater management areas in the Quadra Sands (b; middle); and groundwater management areas in the Nanaimo Group bedrock aquifer (c; right).

The limited resolution of the water table contours did not allow delineation of GWMAs at a more local scale even though many more tributaries exist. The limited number of GWMAs does not prevent water supply shortages or water conflict problems to be addressed locally, but it may mean that a more localized area would have to be defined at the time using the groundwater elevation contours and presence/absence of vadose zone(s). For example, if water shortages occurred at the Black Creek mainstem just upstream of the confluence at Gladstone Road, a sub-area encompassing the shallow wells directly to the south along the Island Highway and shallow wells at Sturgess and Endall Roads may be included to assess how pumping of the shallow wells may be impacting the stream.

In addition, well pumping within the GWMAs near the watershed boundary may also deplete streams beyond the watershed boundary. This may be the case along the watershed boundary near Little Oyster River, between the lower reaches of Oyster River and Black Creek and in the southeast corner of the study area. Pumping in these areas within the GWMAs could intercept shallow groundwater flow discharging to the ocean or local streams east of the watershed boundary.

5.7.2 GWMAs for the Quadra Sands aquifers

GWMAs were delineated upgradient of those reaches of the Oyster River where hydraulic connection with the underlying Quadra Sands was interpreted to be likely (near the mouth (OR-Lower (Quadra), downstream of the confluence with Little Oyster River (OR-Middle (Quadra), and upstream of Doyle Road (OR-Upper (Quadra)). Figure 12b shows that a large part of the Oyster River watershed in the study area has been excluded, including a part of Aquifer 418. Pumping in this excluded area is not expected to deplete streams within the watershed because the stream reaches are either perched (Little Oyster River) or confining sediments exist between the stream and the Quadra Sands. The excluded area may be part of another (not yet delineated) GWMA beyond the Oyster River watershed to the east.

One single GWMA was delineated for Black Creek (BC (Quadra)). This was mostly done to separate the Black Creek area from the Oyster River GWMAs. Virtually all stream reaches within the Black Creek watershed appear to have confining sediments separating the streams and the Quadra Sands, indicating hydraulic connection as unlikely. The groundwater elevation contours (Figure 7b) suggests pumping in the southern area of the study area occupied by Aquifer 408 may not affect groundwater flowing into Black Creek, but rather groundwater flow to the east beyond the watershed towards Seaview Road and the ocean. This area has also been excluded from GWMA delineation.

Updating the groundwater elevations for wells completed into the Quadra Sands and incorporating mapping the groundwater elevation for all of Aquifer 408 (which lies partly outside of the study area) would help better define the groundwater elevation contours and increase confidence of the GWMA boundaries.

5.7.3 GWMAs for the Nanaimo Group sedimentary bedrock aquifer

Figure 12c shows the GWMAs for the bedrock aquifer. Similar to the Quadra, three GWMAs were delineated in the Oyster River watershed study area (OR-Lower (Bedrock), OR-Middle (Bedrock), and OR-Upper (Bedrock)). For Black Creek, one GWMA was delineated (BC (Bedrock)). Rationale for this delineation is similar to rationale for the Quadra Sands. The differences in the GWMAs between the Quadra Sands and the bedrock are controlled by differences in groundwater elevation contours. Two major areas in bedrock have also been excluded from GWMA delineation; pumping in these areas is believed to not affect streams within the watershed but rather beyond it.

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

6. RECOMMENDATIONS FOR FURTHER WORK

We provide the following series of recommendations to improve on the current understanding of the nature of hydraulic connection and protection of the water resource in the study area. Several of the recommendations include involvement of water users and property owners within the study area.

6.1.1 Technical surveys

- Conduct field work to:
  - Supplement field observations by Fyles (1960) and Zubel (1981) by checking for additional locations along the banks of streams where downcutting of the stream has exposed the underlying Quadra Sands and Nanaimo Group sedimentary bedrock aquifers.
  - Inspect tributary stream reaches to check if they exhibit ephemeral or perennial flow to assess the reliability of the desk-top mapping indicating where stream reaches are connected or disconnected. Disconnected or perched streams should not receive significant baseflow from groundwater along those reaches. Observations of the presence/absence of water in a stream channel can be recorded using, for example, a phone application like StreamTracker.
  - Verify stream reaches where hydraulic connection is likely by measuring, for example, stream temperatures and electrical conductivity along transects in the streams.
  - Survey groundwater levels in wells to better determine the groundwater levels and flow gradient in the Quadra Sands and fractured bedrock to inform the GWMA boundaries.
- Inform the groundwater elevation mapping using a high-resolution DEM. We understand that a 1 m resolution DEM may become available within the current year.
- Formally map the two unmapped aquifers identified in this study which primarily comprise Quadra Sands and include them in the Provincial inventory of aquifers.
- Update the aquifer polygon boundaries for Aquifers 408 and 418 within the study area, based on the results of the well-aquifer correlations in this study.
- Engage with local landowners and watershed societies to explore the feasibility for a citizen-based observation well network for the wells completed in the shallow “aquifer” unit.
- Drill observation wells in key locations in the watershed to address data gaps in groundwater levels and stratigraphy. Obtain aquifer hydraulic parameters to better understand the hydraulic connection between the unconsolidated and bedrock aquifers in the study area. Recommended locations include (but are not limited to):
  - Aquifer 408 in the south part of the study area; and,
  - Aquifer 411 to the west near Northy Lake.

6.1.2 Operational

- Confirm the location of the points of delineation for the groundwater management areas in the field. Preferably, the points of delineation should be located where the stream channel is stable so stream flow measurements can be made there. This includes points of delineation at:
    - The confluence of Black Creek and the unnamed tributary to Black Creek near Gladstone Road and the confluence of the Oyster River at its confluence with Little Oyster River (shallow unmapped "aquifer" unit); and,
    - Along the open reaches of the Oyster River northeast of Heather Road (Quadra Sands and Nanaimo Group).
- Establish critical environmental flow thresholds for the Oyster River and Black Creek to protect streamflow.
- Consider requiring, as a condition of a water licence, measuring and reporting of monthly quantities diverted and static water level elevations for the larger licensed groundwater users in the study area (above a threshold limit).
- Consider including term limits for licences to allow evolving understanding of the local hydrogeology to inform subsequent diversion and use of water.
- Initiate an on-going program to raise awareness of water resources management and to engage water users diverting water from streams and wells in the watershed to promote efficiency of water use to preserve groundwater levels and streamflow.

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8. GLOSSARY

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

otherwise flow to the stream (process called interception) or by inducing infiltration of water from the stream into the underlying aquifer to the pumping well (process called induced infiltration).

Till: Primarily a mixture of clay, silt, sand, gravel and boulders ranging widely in size and shape deposited directly by and underneath a glacier.

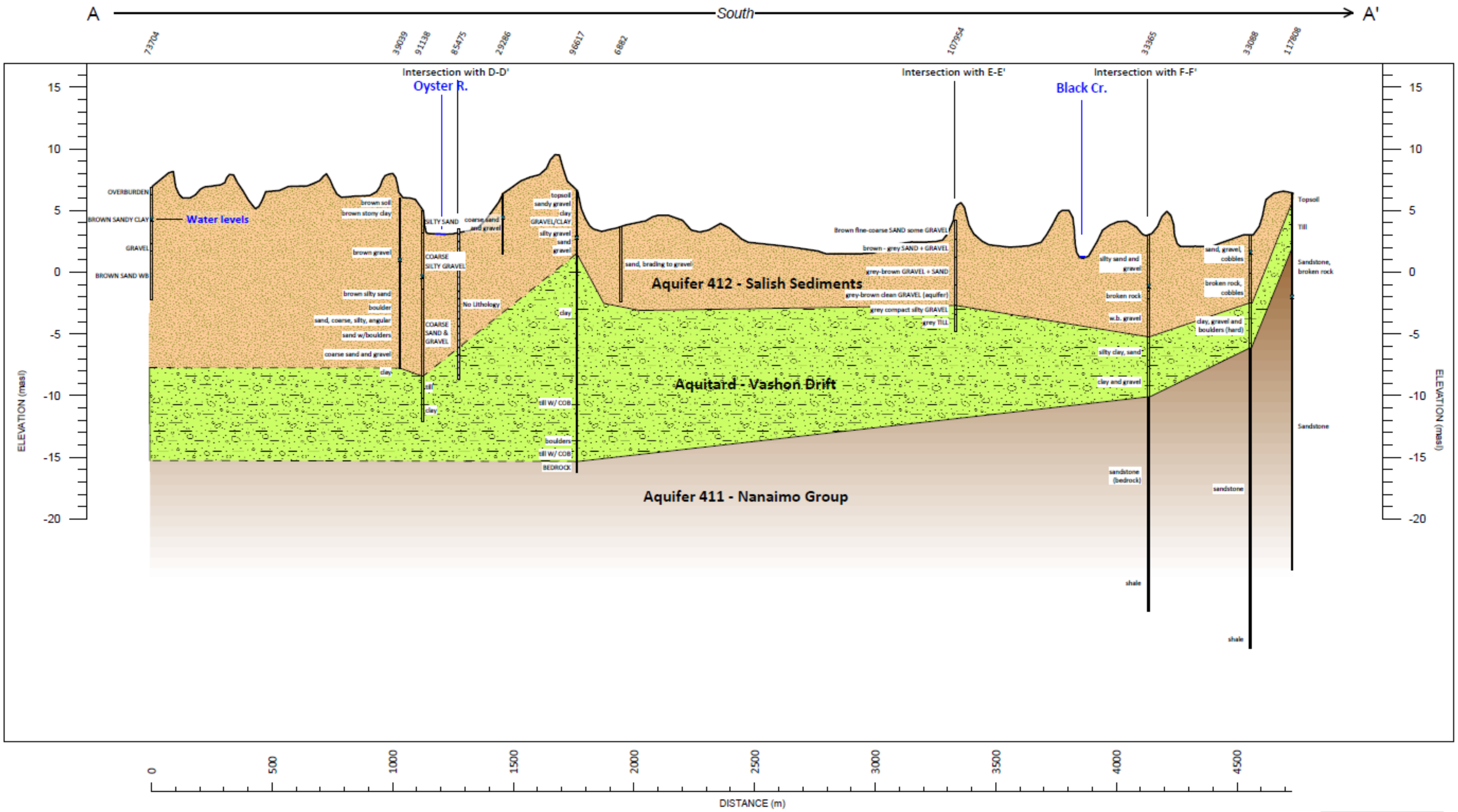
Unconfined aquifer: An aquifer where the top of the aquifer is the water table.

Unconsolidated sediments: A geological material comprising loose sediments, e.g., sand and gravel. Synonymous with “Surficial sediments”.

Vadose zone: The zone beneath the land surface and above the water table where pores are not saturated with groundwater; same as “unsaturated zone”.

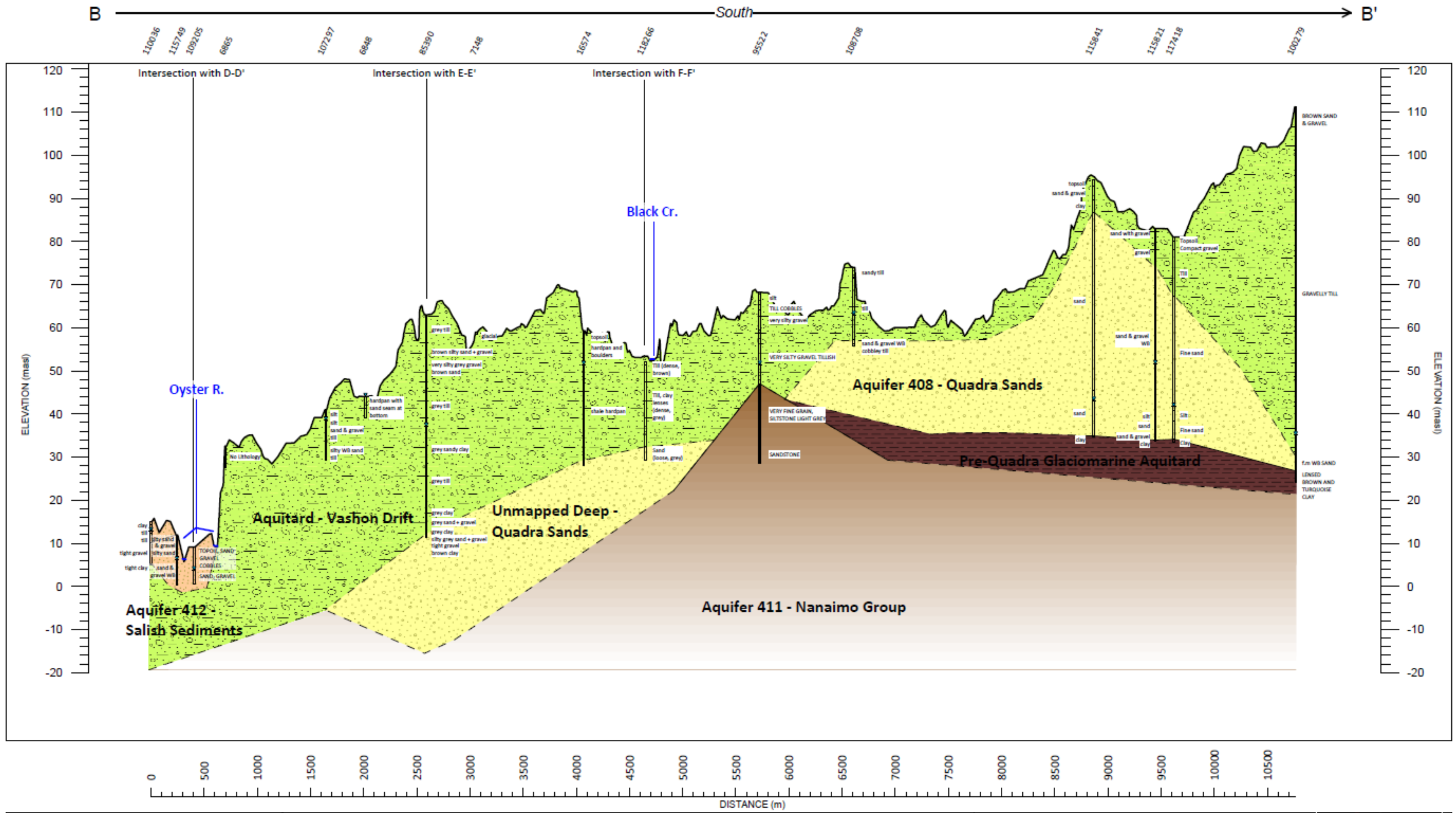
Water table: The top of the saturated zone in the ground where the water pressure is equivalent to atmospheric pressure.

APPENDIX A: HYDROGEOLOGICAL CROSS-SECTIONS



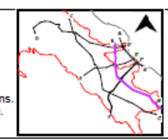
Oyster River / Black Creek Preliminary Assessment of Hydraulic Connection	Figure A1. Section A-A' across Oyster River and Black Creek at the mouth (N-S)			
western water ASSOCIATES LTD	Drawn: Tim Sivak, P.Geo.	Client: MFLNRO		
	Reviewed: Mike Wei, P.Eng.	Project Number: 20-121-01VC		
	Revision: D	Date: April 15, 2021		

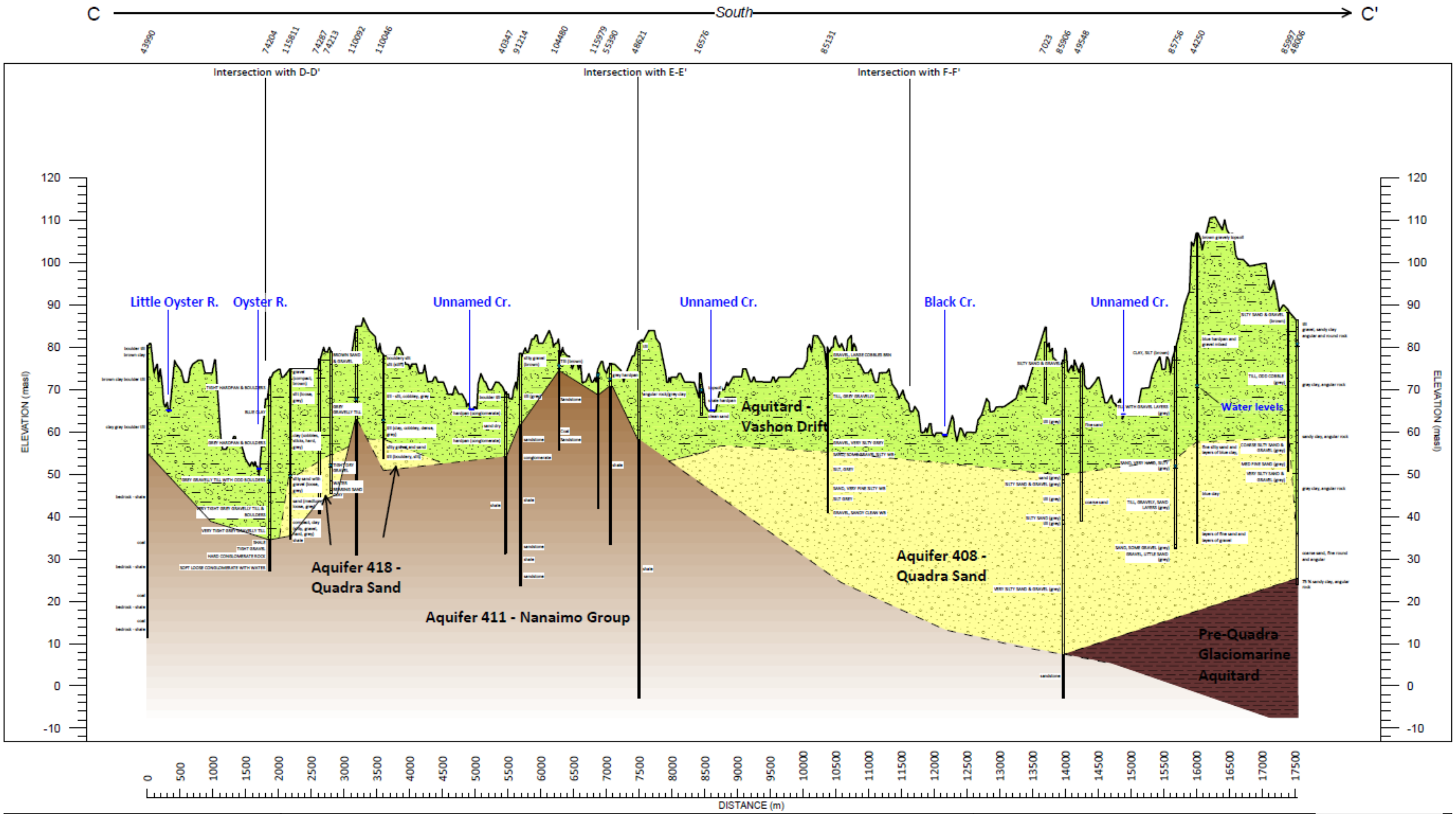
Notes:
1) Map Projection: NAD83 UTM Albers (EPSG: 3005)
2) Vertical Exhaggeration: 51x
3) Lithology descriptions from GWELLS
4) Wells labeled by Well Tag Number (WTN)
5) The hydrostratigraphy shown on this drawing are interpreted from borehole logs and is known with certainty only at the borehole locations. Actual hydrostratigraphy may vary from that indicated on this drawing.



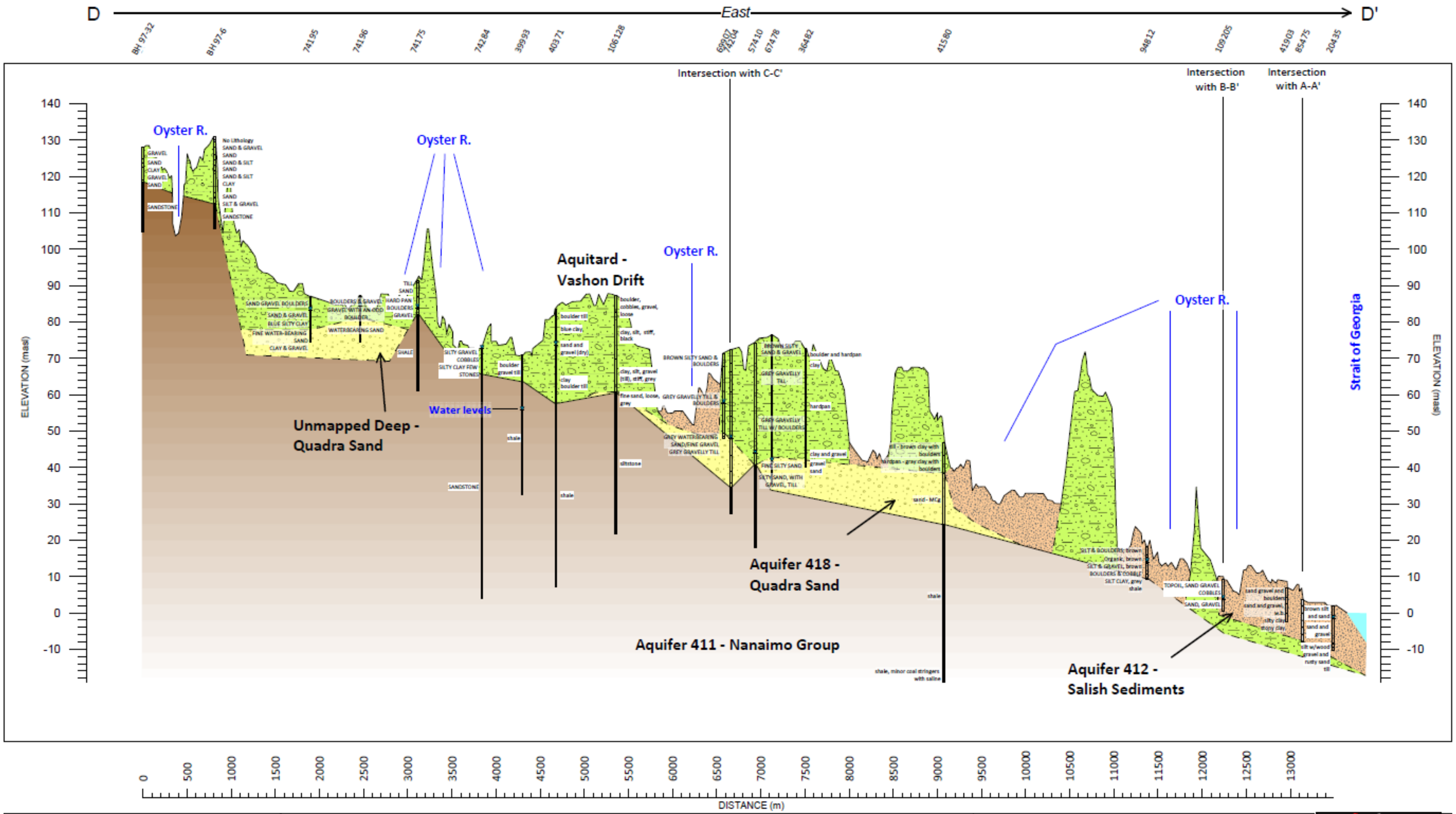
Oyster River / Black Creek Preliminary Assessment of Hydraulic Connection	Figure A2. Section B-B' across Oyster River and Black Creek in their middle reaches (N-S)			
western water ASSOCIATES LTD	Drawn: Tim Sivak, P.Geo.		Client: MFLNRO	
	Reviewed: Mike Wei, P.Eng.		Project Number: 20-121-01VC	
	Revision: D		Date: April 15, 2021	

Notes:
1) Map Projection: NAD83 UTM Albers (EPSG: 3005)
2) Vertical Exhaggeration: 41x
3) Lithology descriptions from GWELLS
4) Wells labeled by Well Tag Number (WTN)
5) The hydrostratigraphy shown on this drawing are interpreted from borehole logs and is known with certainty only at the borehole locations. Actual hydrostratigraphy may vary from that indicated on this drawing.

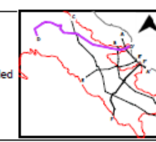


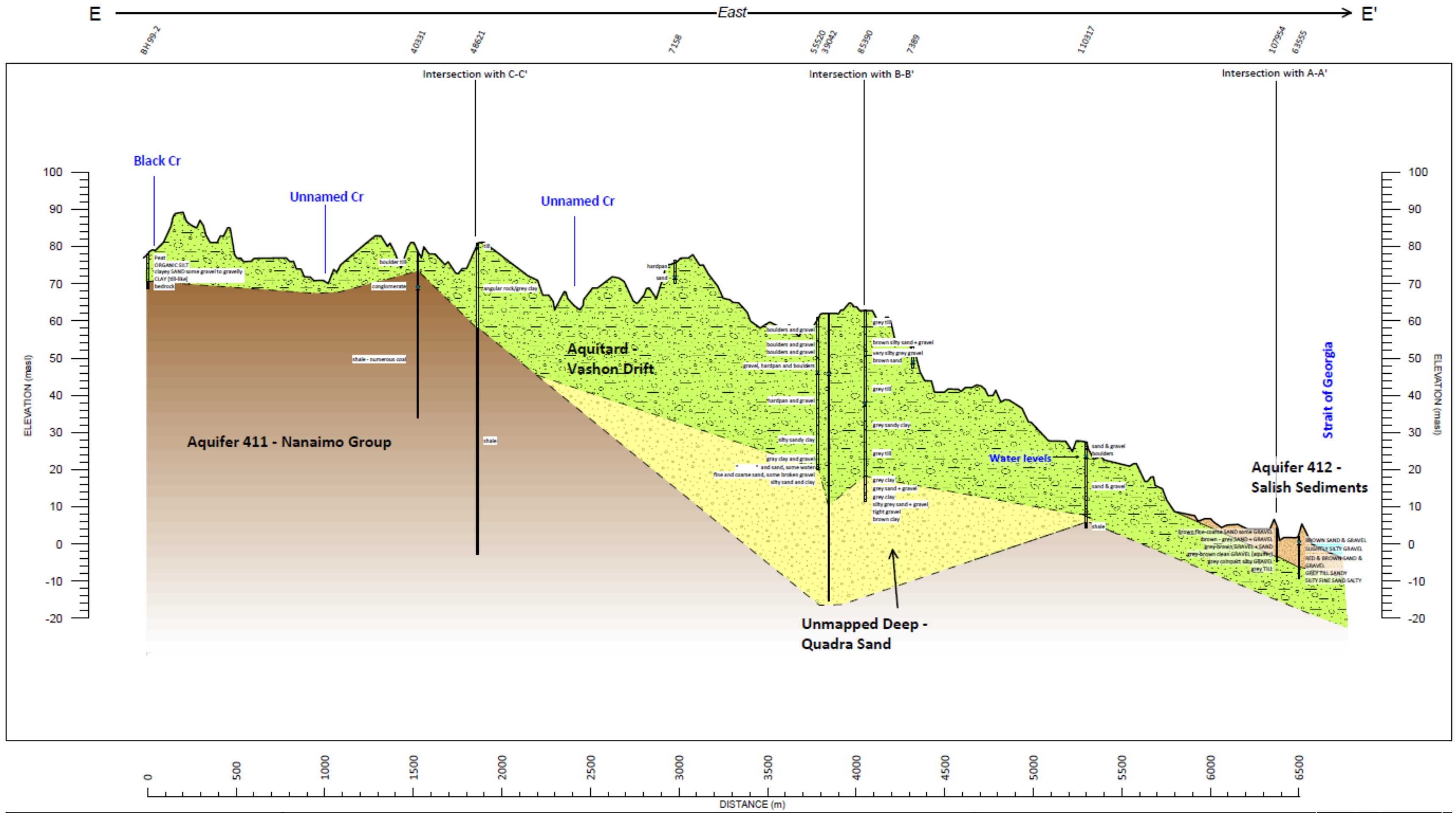


Oyster River / Black Creek Preliminary Assessment of Hydraulic Connection	Figure A3. Section C-C' across Oyster River and Black Creek in their upper reaches (N-S)				Notes:
western water ASSOCIATES LTD	Drawn:	Tim Sivak, P.Geo.	Client:	MFLNRO	1) Map Projection: NAD83 UTM Albers (EPSG: 3005) 2) Vertical Exhaggeration: 65x 3) Lithology descriptions from GWELLS 4) Wells labeled by Well Tag Number (WTN) 5) The hydrostratigraphy shown on this drawing are interpreted from borehole logs and is known with certainty only at the borehole locations. Actual hydrostratigraphy may vary from that indicated on this drawing.
	Reviewed:	Mike Wei, P.Eng.	Project Number:	20-121-01VC	
	Revision:	D	Date:	April 15, 2021	



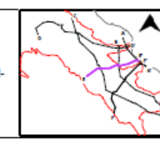
Oyster River / Black Creek Preliminary Assessment of Hydraulic Connection	Figure A4. Section D-D' up Oyster River (W-E)			Notes:
western water ASSOCIATES LTD	Drawn: Tim Sivak, P.Geo.	Client: MFLNRO		1) Map Projection: NAD83 UTM Albers (EPSG: 3005) 2) Vertical Exaggeration: 41x 3) Lithology descriptions from GWELLS and MOTI (2020) 4) Wells labeled by Well Tag Number (WTN); Geotechnical test holes labeled with borehole (BH) prefix. 5) The hydrostratigraphy shown on this drawing are interpreted from borehole logs and is known with certainty only at the borehole locations. Actual hydrostratigraphy may vary from that indicated on this drawing.
	Reviewed: Mike Wei, P.Eng.	Project Number: 20-121-01VC		
	Revision: D	Date: April 15, 2021		

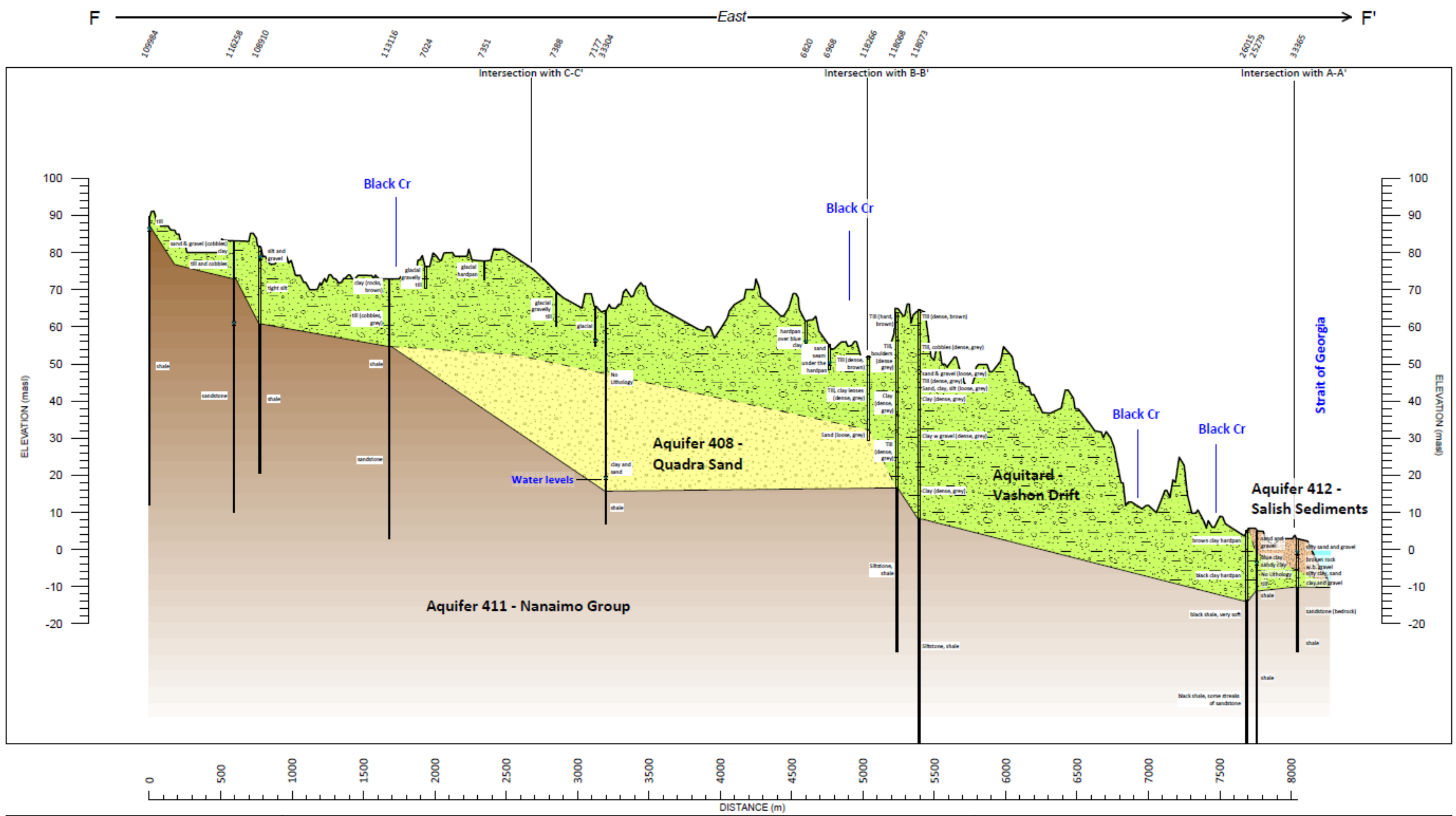




Oyster River / Black Creek Preliminary Assessment of Hydraulic Connection	Figure A5. Section E-E' up midway between Oyster River and Black Creek (W-E)			
western water ASSOCIATES LTD	Drawn: Tim Sivak, P.Geo.		Client: MFLNRO	
	Reviewed: Mike Wei, P.Eng.		Project Number: 20-121-01VC	
	Revision: D		Date: April 15, 2021	

Notes:
1) Map Projection: NAD83 UTM Albers (EPSG: 3005)
2) Vertical Exaggeration: 21x
3) Lithology descriptions from GWELLS
4) Wells labeled by Well Tag Number (WTN); Geotechnical test holes labeled with borehole (BH) prefix.
5) The hydrostratigraphy shown on this drawing are interpreted from borehole logs and is known with certainty only at the borehole locations. Actual hydrostratigraphy may vary from that indicated on this drawing.





Oyster River / Black Creek Preliminary Assessment of Hydraulic Connection	Figure A6. Section F-F' up Black Creek (W-E)			Notes: 1) Map Projection: NAD83 UTM Albers (EPSG: 3005) 2) Vertical Exaggeration: 26x 3) Lithology descriptions from GWELLS 4) Wells labeled by Well Tag Number (WTN) 5) The hydrostratigraphy shown on this drawing are interpreted from borehole logs and is known with certainty only at the borehole locations. Actual hydrostratigraphy may vary from that indicated on this drawing.
western water ASSOCIATES LTD	Drawn: Tim Sivak, P.Geo.	Client: MFLNRO		
	Reviewed: Mike Wei, P.Eng.	Project Number: 20-121-01VC		
	Revision: D	Date: April 15, 2021