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Groundwater Quality Survey of Aquifers in South Wellington, Cassidy and North Oyster, Vancouver Island

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EXECUTIVE SUMMARY

The South Wellington, Cassidy, and North Oyster areas south of Nanaimo, Vancouver Island, rely predominantly on groundwater supply for domestic, agricultural and industrial use. Within the community, concerns had been expressed regarding potential impacts on groundwater quality due to human activities such as heavy industry and historical mining and the high density of septic systems in some areas. A geochemical survey was conducted within four aquifers: the Upper Cassidy (aquifer 161) and Lower Cassidy (aquifer 160), which are made up of unconsolidated materials (sand and gravel), and the South Wellington (aquifer 165) and Cassidy-Nanaimo Airport (aquifer 964), which are made up of fractured sedimentary bedrock (mainly sandstone and shale). The project was completed in partnership between the Ministry of Forests, Lands and Natural Resource Operations (FLNRO) Water Protection Section (Nanaimo), the Regional District of Nanaimo (RDN), Drinking Water and Watershed Protection Program, and the Cowichan Valley Regional District (CVRD), Environmental Initiatives division.

The objective of this work was to survey groundwater quality in the South Wellington-Cassidy (RDN) and North Oyster (CVRD) areas by collecting groundwater samples from residential and water system wells. The study was undertaken in order to (a) describe the geochemistry of groundwater within the four heavily used aquifers in this region; (b) determine if there are any water quality concerns related to human health or potability; (c) establish a baseline from which one may evaluate changes in water quality over time; and (d) provide residents with information on how to maintain and protect their wells.

The sampling was completed in April and June 2011 within the RDN portion of the study area (South Wellington and Cassidy), and in March 2012 in sample sites in the CVRD (the North Oyster area within CVRD Electoral Area H). Groundwater samples were collected from 62 sites, comprising 60 private domestic wells and 2 water supply systems. Access to the wells was provided to FLNRO, RDN, and CVRD by the well owners who volunteered to participate. Field staff also completed an inspection of the well head. The samples were analyzed for field parameters, general chemistry, major ions, trace metals, and bacteria.

The water quality within sampled wells was found to be good overall in both unconsolidated and bedrock aquifers. Samples from unconsolidated wells never exceeded Canadian drinking water quality health or aesthetic guidelines, while a small number of samples from bedrock wells did.

Fluoride, nitrate, and arsenic are three drinking water parameters associated with human health concerns. Fluoride is a naturally occurring element that at elevated concentrations is associated with changes in the composition of bones and teeth (fluorosis). In total, 4 samples (6%) in the study area had fluoride above Maximum Allowable Concentration of 1.5 mg/L; the median concentration of fluoride was 0.21 mg/L in samples from bedrock wells and 0.04 mg/L in samples from unconsolidated wells. The nitrate-nitrogen concentration was below the drinking water guideline of 10 mg/L and very low in the majority of sites, with a median of 0.35 mg/L in samples from all well types. Nitrate was higher in shallow sand and gravel aquifers; the median concentration was 0.63 mg/L in samples from unconsolidated wells and 0.068 mg/L in samples from bedrock wells. The arsenic concentration also was below the drinking water guideline of 10 µg/L in all samples; it was higher in samples from bedrock aquifers compared to unconsolidated wells, with a median of 0.18 µg/L and 0.22 µg/L respectively. Notably, 10% of samples had arsenic between 1 and 6 µg/L, which may be a concern for long-term, chronic exposure in drinking water. The concentrations of other trace elements (antimony, barium, cadmium, chromium, lead, selenium, and uranium) for which Health Canada has established health related guidelines were very low or below the reported detection limit.

Sulfate, chloride, sodium, total dissolved solids (TDS), iron, manganese, copper, and zinc are aesthetic parameters that affect the taste and pleasantness of drinking water. Sulfate and chloride exceeded drinking water guidelines in one sample. A total of 6 samples (10%) had TDS greater than 500 mg/L; the median TDS was 315 mg/L in samples from bedrock wells, compared to 81 mg/L in samples from unconsolidated wells. Manganese concentrations were above the guideline for drinking water quality of 50 µg/L in six samples (10%); the median concentration was 8.5 µg/L in samples from bedrock wells, compared to 1.0 µg/L in unconsolidated wells. Two samples had iron above 300 µg/L; the median concentration was 7.0 µg/L in all samples. Five samples (8%) had sodium concentrations above the drinking water guidelines. Elevated concentrations of metals and other constituents were associated with natural processes such as the dissolution of mineral salts into water in contact with rock. All samples represented raw (untreated) water quality, and there are readily available treatment options for removal of arsenic, fluoride, manganese, iron, and nitrate.

The majority of wells sampled were wells drilled in fractured bedrock (30 wells, 49%), 25 wells (40%) were wells drilled in unconsolidated materials (sand and gravel), and 7 wells (11%) were excavated (large diameter, dug) wells in sand and gravel. Wells were sampled for the bacteriological indicators total coliform and *E. coli*. Approximately half of the samples from drilled wells tested positive for total coliforms, while the majority (88%) of samples from excavated wells contained total coliforms. The presence of *E.coli* was uncommon—samples from only three wells tested positive for this bacteria—and was not correlated to the aquifer material. In 42% of sites, the presence of total coliforms was associated with well maintenance concerns; e.g., missing or inadequate well cap, low casing stick-up, standing water around the well, or well location within a wet area or underground enclosure. Well owners were provided with the results of the groundwater testing and information on how to protect their wells. Maintenance or upgrades to wells were recommended in 28 cases (45%).

The Canadian Council of Ministers of the Environment (CCME) water quality index was calculated for the Upper and Lower Cassidy (sand and gravel) aquifers (160 and 161) and for fractured sedimentary bedrock aquifers in South Wellington and Cassidy-North Oyster (aquifers 165 and 964). For both aquifer types, the water quality index was ranked as “good”, indicating that the water quality may be impacted to a minor degree by pollution, but that in general, conditions are representative of natural levels.

Contents

1. INTRODUCTION

South Wellington, Cassidy, and North Oyster are three mixed rural residential and agricultural communities located approximately 7 to 17 km south of Nanaimo, Vancouver Island (Figure 1). The water supply in these communities for domestic, agricultural, and industrial use is predominantly groundwater obtained from private wells, augmented by surface water obtained from rivers, such as the Nanaimo River and Haslam Creek and their associated tributaries. In addition to providing an essential source of water for human use, groundwater contributes to river base flow in dry seasons and moderates water temperature in sensitive aquatic habitats.

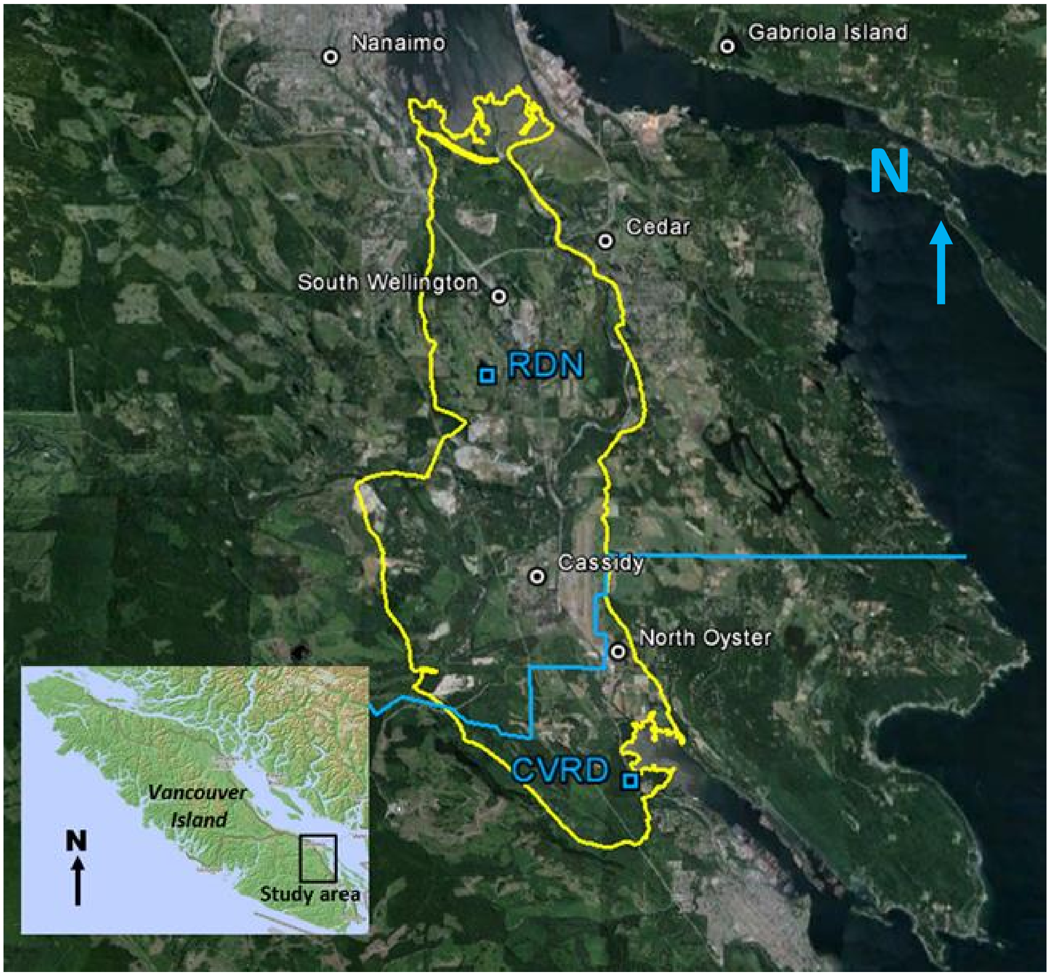


Figure 1 Overview map South Wellington, Cassidy, North Oyster study area, Vancouver Island, including boundary between the Regional District of Nanaimo (RDN) and the Cowichan Valley Regional District (CVRD).

Previous studies of this region have highlighted concerns about naturally occurring groundwater contaminants, such as boron and fluoride (Earle & Krogh, 2006). In addition, potential impacts on groundwater quality may result from human activities and land use, including historical coal mining, heavy industry, agriculture, and the high density of septic systems in some areas (GW Solutions and Vancouver Island University, 2010). The Upper Cassidy aquifer has been identified as highly vulnerable to surface contamination, in part due to shallow groundwater levels, high aquifer permeability, and potential interconnectivity with Nanaimo River and Haslam Creek (Kohut, 1979; Zubel, 1991). Recognizing the importance of the groundwater resource, the Regional District of Nanaimo Area A Official Community Plan identifies further research, resource inventory, and monitoring as priorities for protection of groundwater in this region (Regional District of Nanaimo, 2011). Similarly, the Cowichan Valley Regional District Area H Official Community Plan highlights the need to protect and manage valuable freshwater sources, including the Cassidy aquifer and other critical areas of groundwater recharge and supply (Cowichan Valley Regional District, 2011).

Beginning in 2011, the Ministry of Forests, Lands and Natural Resource Operations (FLNRO), in partnership with the Regional District of Nanaimo (RDN), initiated a groundwater quality survey of private domestic wells in the South Wellington and Cassidy areas (part of RDN Electoral Area A). In 2012 the Cowichan Valley Regional District (CVRD) also became involved in the study, and the survey area expanded in the north end of CVRD Electoral Area H in the neighbourhood commonly referred to as North Oyster.

1.1 Objectives

The objectives of this study were to:

a. Conduct a snap-shot survey of groundwater quality in the South Wellington-Cassidy (RDN) and North Oyster (CVRD) areas, in order to describe the geochemical conditions within four highly used unconsolidated (sand and gravel) and fractured bedrock aquifers in this region;
b. Determine if there are any water quality concerns, such as elevated concentrations of natural or anthropogenic parameters that may be a concern to human health or the potability of water;
c. Recognize where human impacts may be occurring, and to establish a baseline from which one may evaluate changes that may occur in future;
d. Provide residents with information on how to maintain and protect their wells.

2. STUDY AREA

2.1 Climate

The study area has a temperate climate characterized by warm, dry summers and cool, wet winters (Peel, et al., 2007). Precipitation patterns within this part of Vancouver Island are influenced by the rain shadow effect of the Vancouver Island Range to the west and the Olympic Mountains to the south. The area is found within the Coastal Douglas Fir moist maritime (CDFmm) biogeoclimatic zone (Ministry of Forests, Lands and Natural Resource Operations, Research Branch, 2014). The majority of annual precipitation is rainfall that occurs within the months of November to March, and there is very little rainfall during the months of July to September.

The closest Environment Canada weather monitoring station to the study area is at the Nanaimo airport (EC 1025370) in Cassidy, approximately 13 km south of Nanaimo. Based on climate normals calculated using data from the Nanaimo Airport station for the years 1981 to 2010, the annual average daily temperature in this area is 10.1°C, and the average annual precipitation is 1165 mm, 94% of which occurs as rainfall (Environment Canada, 2014a).

The average monthly temperature, rainfall, and estimated evapotranspiration from the period 1948 to 2013 are shown in Figure 2 (Environment Canada, 2014b). The potential evapotranspiration was calculated using a water balance model developed by the U.S. Geological Survey using the Thornthwaite method (McCabe & Markstrom, 2007). This plot shows that potential evapotranspiration exceeds rainfall for the months of May to September; consequently, groundwater recharge would be expected to occur primarily during the months of October to April, when average rainfall exceeds potential evapotranspiration.

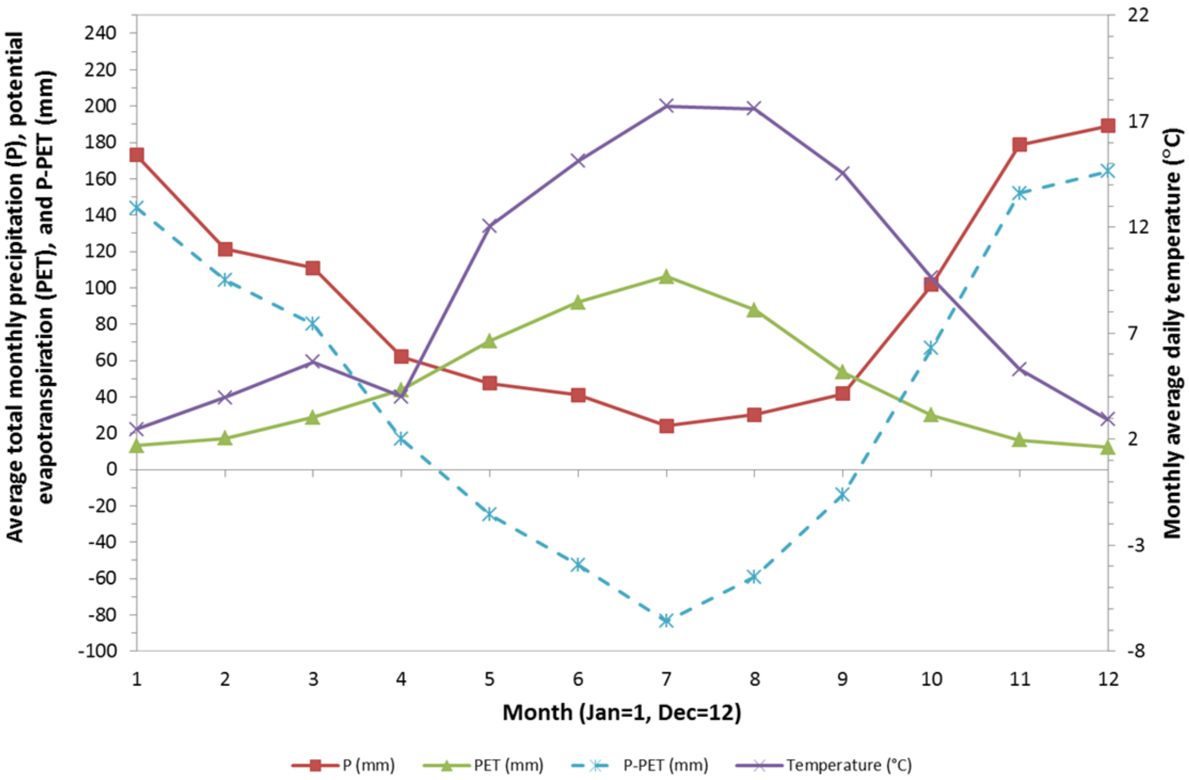


Figure 2 Monthly average total precipitation (P), monthly average daily temperature, and potential evapotranspiration (PET), Nanaimo Airport weather station (EC1025370) 1948–2013.

The monthly total precipitation and monthly average daily temperature for the period of January 2011 to December 2012 are shown in Figure 3. The long-term average data (1948–2013) are also plotted for comparison. This analysis shows that, during our well sampling period, temperatures were close to or higher than the long-term average. In contrast, total monthly precipitation was lower than the long-term average in April and June 2011 and higher in March 2012.

2.2 Surficial and Bedrock Geology

The study area is found in the eastern Vancouver Island coastal lowlands (or Nanaimo Lowlands), within a north-south trending valley that runs between the Nanaimo River estuary and head of Ladysmith Harbour. The elevation within this portion of the Nanaimo lowlands is generally less than 200 m, while higher elevation uplands border the study area to the west (Douglas Mountains, with elevations from 400 to 1200 m) and southeast (e.g., Woodley Range, elevation 220 m) (Halstead, 1961).

The surficial geology of the study area is shown in Figure 4 (Ministry of Environment, 2005). The area around Cassidy, along the Nanaimo River floodplain west of Highway 1, and encompassing much of the basin between Ladysmith Harbour and Nanaimo River estuary, is covered by fluvial and glaciofluvial sediments, described by Halstead (1961) as thick, terraced, deltaic, floodplain and channel deposits including gravel, sand, and cobble. Underlying this in some areas are glacial to glaciomarine sediments, such as silt and stoney clay, deposited when sea level was an estimated 150 m higher than at present, 12,000 years before present (y bp) following the Fraser Glaciation (Halstead, 1961). In contrast, within the South Wellington area, thinner (<2 m thick) deposits of glaciomarine and organic sediments, including clay, loam, till, and peat directly overlie bedrock.

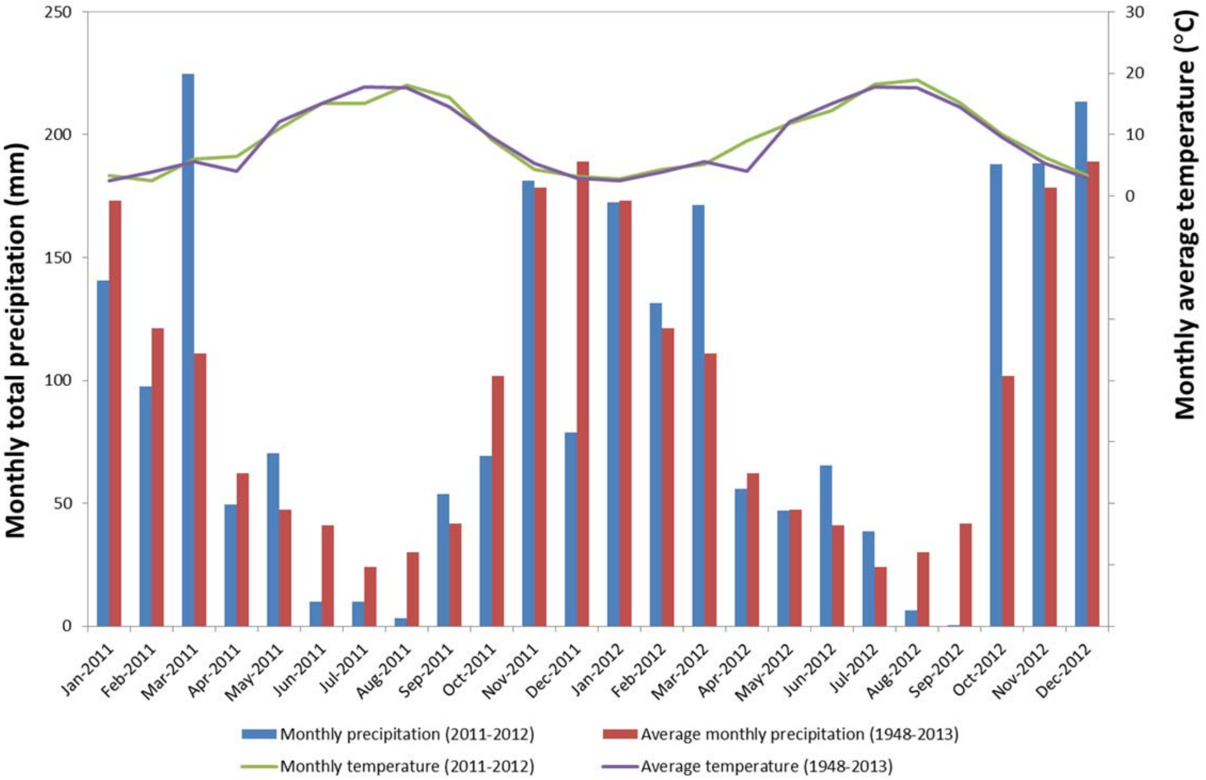


Figure 3 Monthly total precipitation and monthly average temperature Jan 2011–Dec 2012, compared to long-term averages (1948–2013), Nanaimo Airport weather station (EC1025370).

The bedrock geology of the study area (Figure 5) consists of sedimentary rocks of the Nanaimo Group (map symbol uKN) (BC Geological Survey, 2005). These thick sequences of sedimentary rocks were formed during the Late Cretaceous period, from 91 to 66 million years before present (Ma) (Mustard, 1994). Rocks of the Nanaimo Group are found in parts of eastern Vancouver Island from Duncan to Campbell River and comprise the majority of the southern Gulf Islands. Within the study area, the dominant rock types are interbedded mudstone, siltstone, and lesser sandstone of the Cedar District Formation, but the Protection (sandstone dominated), Pender (mudstone and siltstone), and Extension (pebble conglomerate, sandstone) Formations are also present. Coal from the Protection, Pender, and Extension Formations was mined until the early 1950s (Mustard, 1994; Bickford, 1993). Also shown in Figure 5, outside of the study area in the uplands west of Ladysmith Harbour are rocks of the Island Plutonic Suite (Ladysmith Pluton, map symbol EMJIgd), consisting mainly of coarse-grained gabbro, granodiorite, and granite (Massey, 1992).

A major fault line trends north-south along the eastern boundary of the study area, between Nanaimo and Ladysmith Harbours (BC Geological Survey, 2005). A set of northwest-southeast trending faults have been mapped west of the study area that intersect with a southwest-northeast trending fault that forms the lower segment of Haslam Creek. The Nanaimo River also follows an eastward-trending valley believed to have been formed from glacial erosion of weakened and faulted bedrock units. After emerging from the uplands, the Nanaimo River flows northward, forming a delta at the estuary boundary within Nanaimo Harbour (Halstead, 1961; Zubel, 1991).

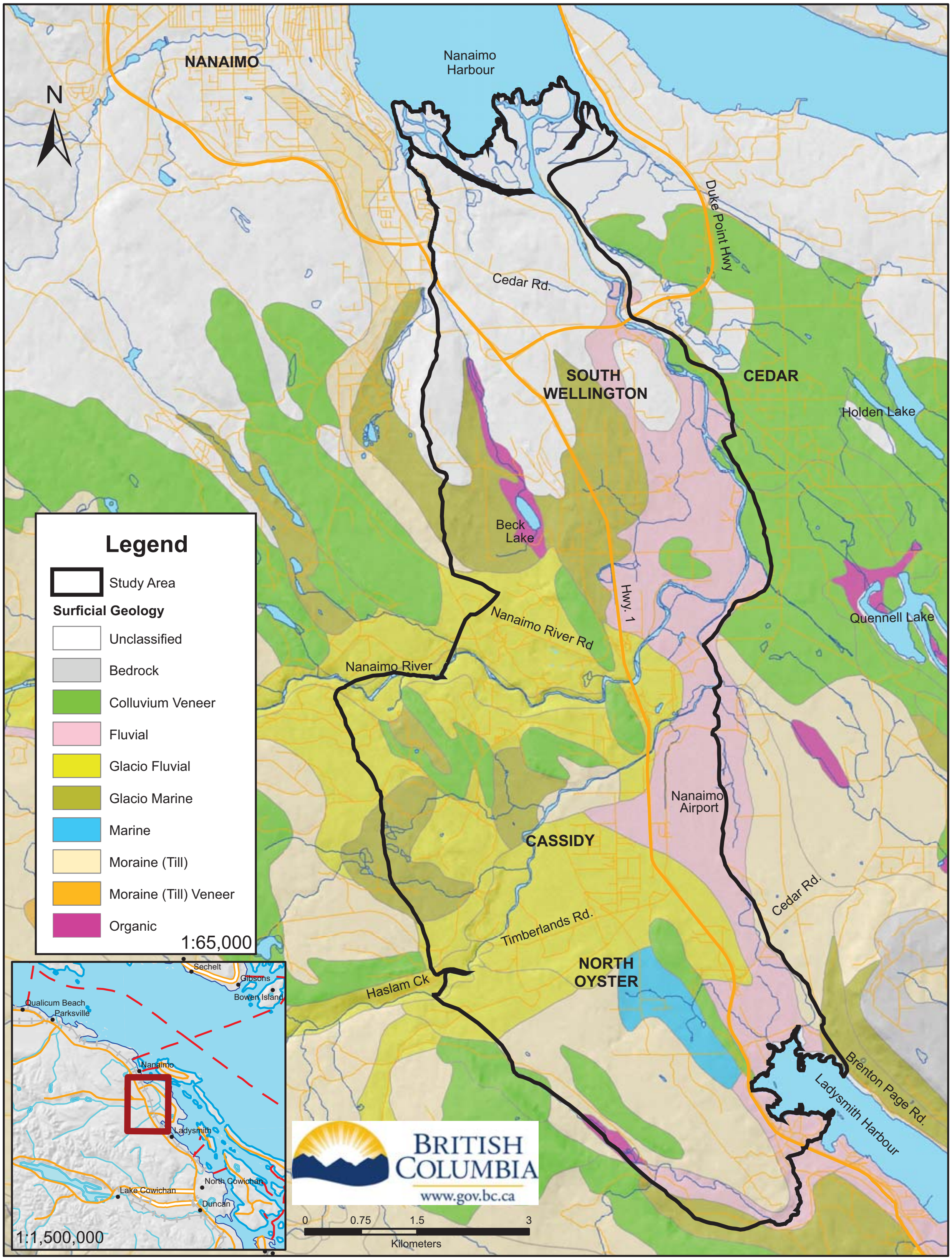


Figure 4 Surficial geology of study area

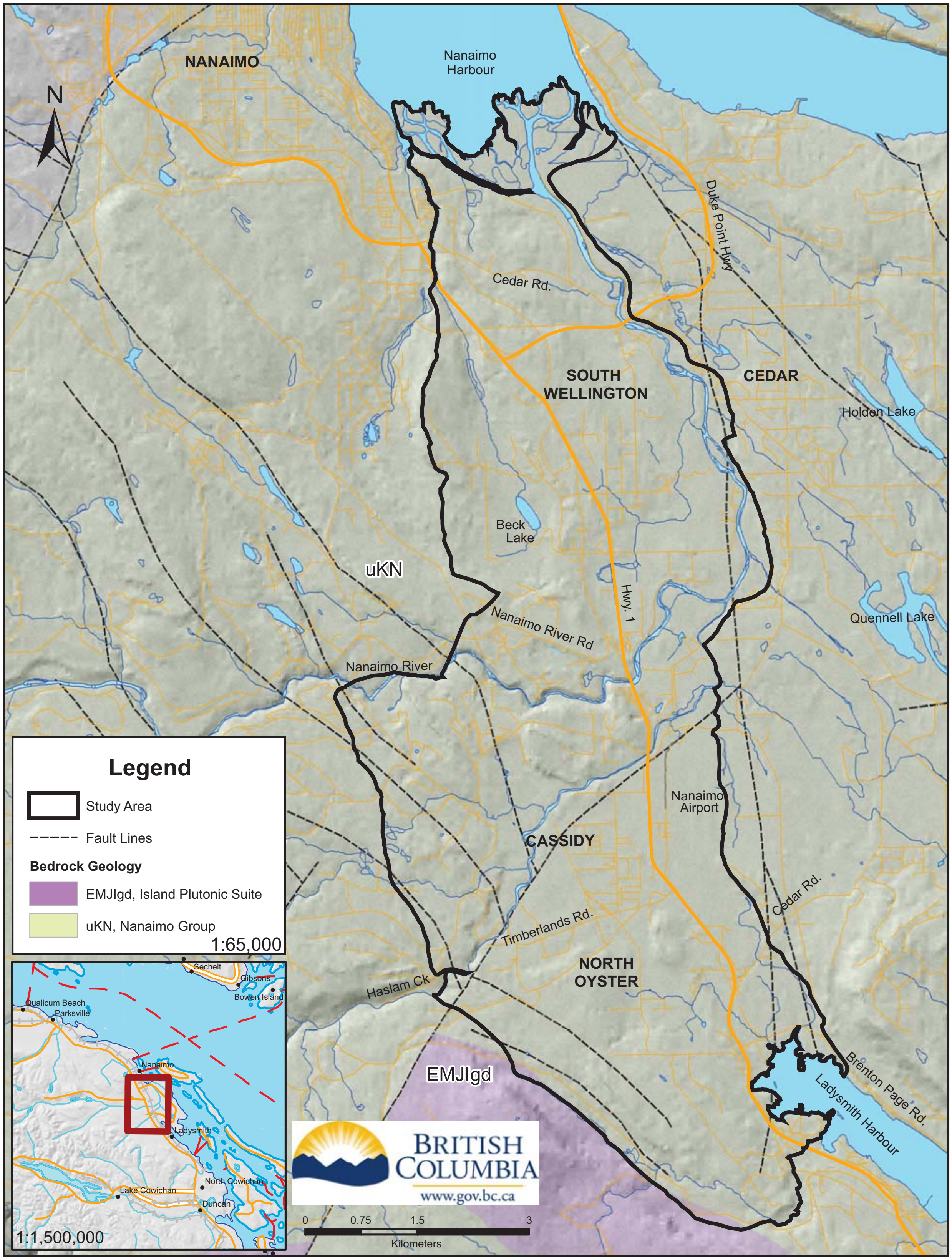
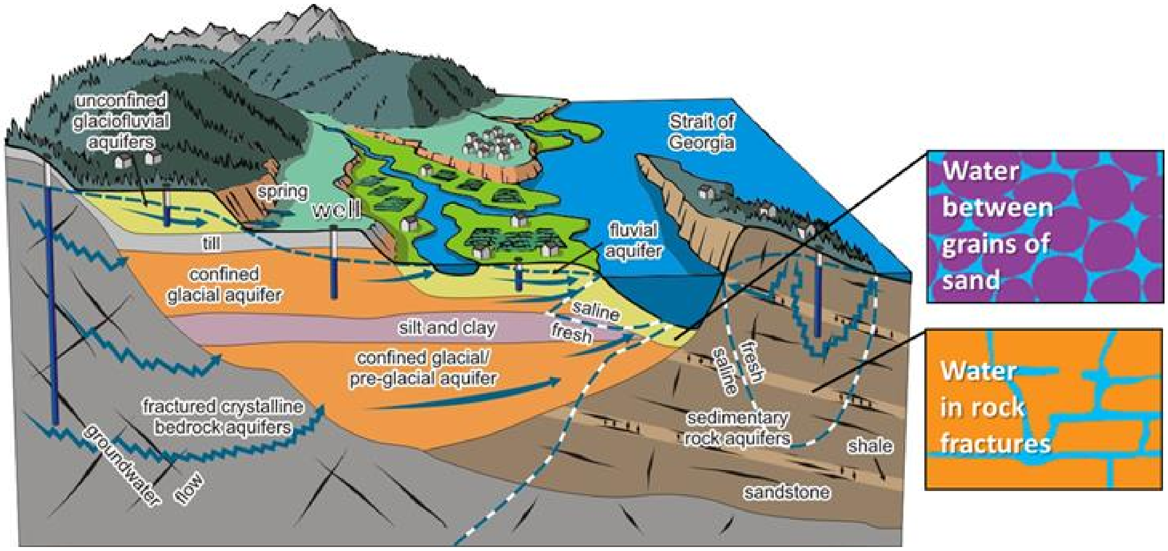


Figure 5   Bedrock geology of study area

2.3 Hydrogeology

Groundwater within the study area is obtained from both unconsolidated (sand and gravel) and fractured bedrock aquifers. Aquifers are geologic units where the pores or fractures are saturated with water; they yield water in varying quantities to wells, springs, and streams and receive water from infiltration of precipitation and surface water. Refer to description in Figure 6.



An aquifer is a geologic unit in which the pore spaces or fractures are saturated with water. Aquifers are made up of unconsolidated deposits such as sand and gravel, where water is held in the spaces between individual sediment particles; or bedrock, where water is held within a network of fractures. Aquifers are recharged by infiltration of rainfall and snowmelt, or from surface water in streams interconnected with the aquifer. In turn, water from an aquifer can be extracted from wells or obtained from the natural discharge of springs. On the Pacific coast the aquifers originate from glacial and geologic processes, for example, sediments deposited when glaciers melted, or more recently by rivers as they flowed toward the sea. Groundwater movement through silt and clay is slower, therefore if an aquifer has a clay or silt layer above it, it is described as being *confined,* and the aquifer may be more protected from contamination originating from the land surface. (Image sources: Environment Canada, 2013; Rivera, 2014.)

Figure 6 Aquifers in a coastal setting.

Within the study area boundary, there are approximately 942 known wells, although this may be an underestimate; this figure is based on well records submitted voluntarily by well owners and well drillers to the WELLS database (Ministry of Environment, 2014a). Approximately 19 water systems using wells are found in the Cassidy, North Oyster, and South Wellington areas, including commercial/industrial, agricultural, residential and recreational (e.g., camp sites) water use (Island Health, 2015). Using data from well construction reports, geologic mapping, and hydrogeologic studies, four developed aquifers in this area have been mapped and classified according to the B.C. Aquifer Classification System (Kreye, et al., 1994; Berardinucci & Ronneseth, 2002).

In this system, aquifers are classified by their level of development and their vulnerability to contamination. The level of development is designated heavy (I), moderate (II), or light (III) by comparing the demand on the aquifer to its productivity. The aquifer vulnerability is designated high

(A), moderate (B), or low (C) based on the potential for contamination from surface; this potential depends on the type, thickness, and extent of geologic materials overlying the aquifer, the depth to water (or top of confined aquifers), and the type of aquifer materials. The productivity and vulnerability designations are combined to prioritize aquifers into one of nine possible groups for more in-depth study. For example, an aquifer that is classified as IA has both a high level of development and is highly vulnerable, and therefore is considered a high priority for further characterization. The locations of classified aquifers within the study area are shown in Figure 7.

Another method to categorize aquifers in B.C. is to consider the aquifer materials, common hydrogeologic properties, and the geologic processes that contributed to their formation (Wei, et al., 2009; Rivera, 2014). Within the study area there are three such aquifer types identified: unconfined sand and gravel aquifers along moderate-sized rivers (aquifer 161); deeper sand and gravel aquifers formed from pre-glacial or glacial processes and confined by an overlying layer of clay or till (aquifer 160); and fractured sedimentary rock aquifers (165 and 964). The type and properties of aquifers in the study area are summarized in Table 1.

Table 1 Aquifers in the South Wellington, Cassidy and North Oyster areas.

Aquifer Number	Aquifer Name	Aquifer Material	Lithostratigraphic Unit	Aquifer type	Aquifer Classification	Area (km^2)
161	Upper Cassidy	Sand & gravel	Capilano and Salish sediments	1b – Unconfined fluvial or glaciofluvial aquifer along river/stream valley (high energy depositional environment)	IIA (15)	31.2
160	Lower Cassidy	Sand & gravel	Glacia-fluvial sediments (Vashon)	4b – Confined sand and gravel aquifers of glacial or pre-glacial origin (glaciofluvial or glaciolacustrine)	IIC (9)	8.9
165	South Wellington	Sandstone and shale	Nanaimo Group	5a – Sedimentary rock (fractured)	IIB (11)	17.4
964	Cassidy-Nanaimo Airport	Sandstone and shale	Nanaimo Group (primarily DeCourcey Formation)	5a – Sedimentary rock (fractured)	IIB (10)	17.3

2.3.1 Unconsolidated Aquifers

Within the Cassidy area, there is a system of layered sand and gravel aquifers, consisting of the shallower aquifer 161 (Upper Cassidy) and aquifer 160 (Lower Cassidy), a deeper sand and gravel deposit that underlies parts of aquifer 161. Bedrock aquifer 964 (discussed in section 2.3.2) is located below the two unconsolidated aquifers. The importance of the sand and gravel deposits around Cassidy as an abundant source of groundwater was recognized as early as the 1940s, when the area was evaluated as a water supply for the Nanaimo Sulphate Pulp Company, now the Harmac Pacific pulp mill (Dolmage, May 1948; Leggette, 1948; Odynsky, 1950). More recently, the Cassidy aquifers were also identified as a possible source to augment municipal water supplies for the City of Nanaimo, which presently relies on surface water from the upper Nanaimo River watershed (Associated Engineering Ltd., 2007; SRK Consulting, 2007). Water balance studies for this area show that while annual usage is not greater than the estimated supply from winter recharge, seasonal water table declines and potential reductions of well capacity may occur during long, dry summers (Waterline Resources Inc., 2013; GW Solutions and Vancouver Island University, 2010). Industrial and other larger volume diversions from the Upper Cassidy aquifer may also influence water levels in Nanaimo River and Haslam Creek.

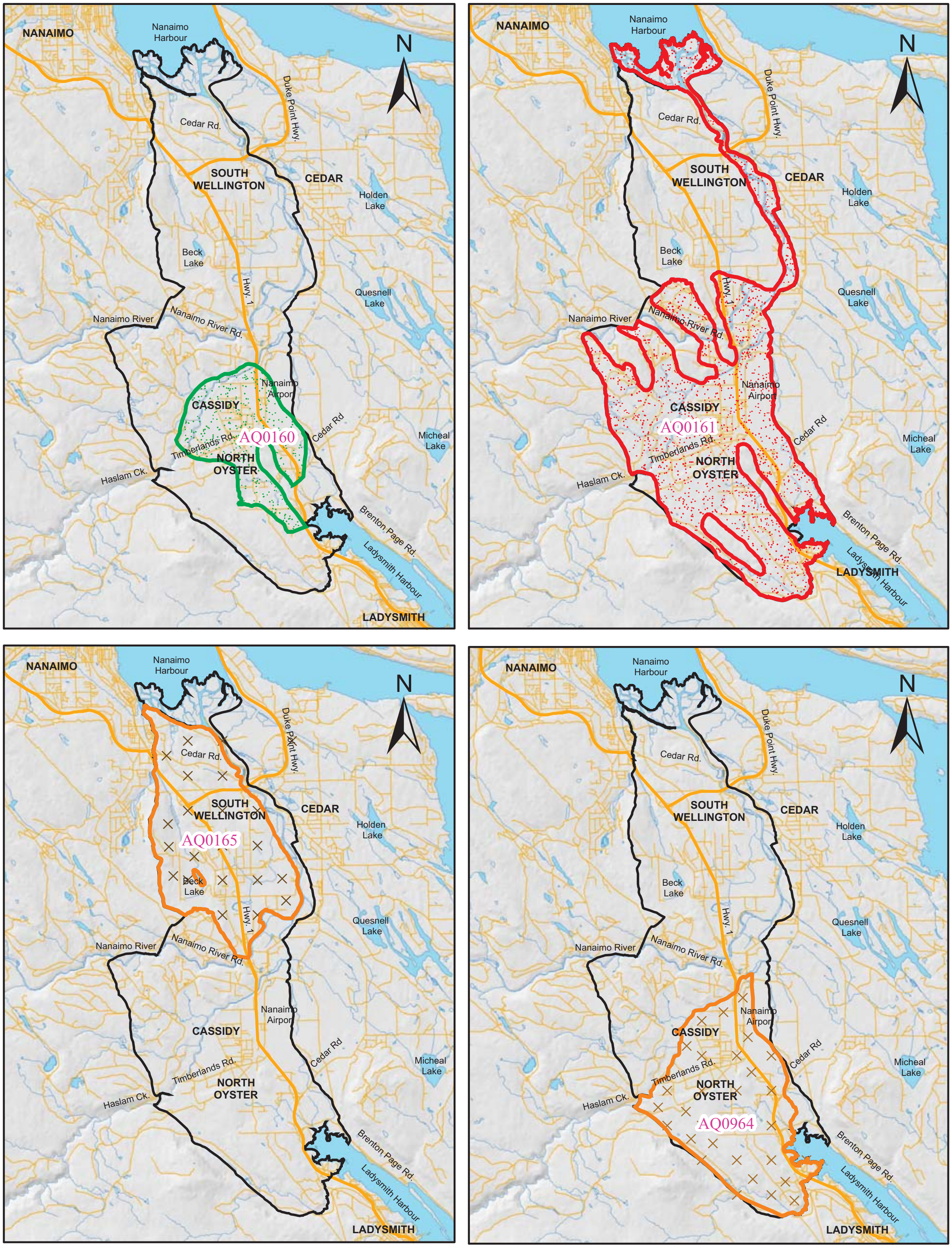


Figure 7 Aquifer locations and boundaries within the study area

The Upper Cassidy Aquifer (161), classified as a IIA aquifer using the B.C. Aquifer Classification System, is approximately 31 km^2 in area (Figure 7) and consists mainly of terraced fluvial/glaciofluvial sands and gravels (Capilano sediments) deposited in the lowlands between Ladysmith Harbour and the Nanaimo Harbour and distributed between a series of southeast to northwest trending bedrock ridges (Zubel, 1991). A thinner segment of the aquifer extends along the Nanaimo River floodplain, east of Highway 1, grading into mixed fluvial, shoreline/deltaic, and estuarine organic sediments where the river drains into Nanaimo Harbour.

Based on 192 records, wells constructed in aquifer 161 have a median depth of 12.2 m (40 ft) and range in depth from 1.2 to 70 m (4 to 230 ft). The yield of wells in the aquifer, estimated by the drillers at the time of well construction, range from 1.1 litres/minute (0.25 Imperial gallons per minute) to 15,460 L/min (3400 Igpm), with a median of 68 L/min (15 Igpm) (Gallo, 1995b). The aquifer is moderately developed, and the water is used for irrigation, commercial, industrial and domestic purposes. Because there are no confining sediments overlying the aquifer, its vulnerability to contaminants at the surface is high. The median transmissivity from pumping tests of three wells (N=3) constructed in aquifer 161 was 3784 m^2/d, and the median hydraulic conductivity was 689 m/d (Carmichael, 2013). Recharge is mainly from local precipitation in the lands overlying the aquifer, with the remainder from localized infiltration from Haslam Creek and the Nanaimo River (Gallo, 1995b; SRK Consulting, 2007). The map of groundwater elevation or potentiometric contours (Figure 8) indicates that, on average, groundwater likely flows from the uplands west of Cassidy and diverges from the central Cassidy area, northeastward towards the Nanaimo River and estuary, and southeastward toward Ladysmith Harbour.

The Lower Cassidy aquifer 160 underlies aquifer 161 around Cassidy/North Oyster in the southern part of the study area. Aquifer 160 is a deeper unconsolidated deposit, described as densely packed sand and gravel (Vashon drift) (Gallo, 1995a). Fewer wells are believed to be constructed in this unit, which has an approximate area of 9 km^2 (Figure 7). The aquifer classification of IIIC indicates that it has a low level of development and also that the aquifer has a low vulnerability to contamination because there is a layer of clay-rich sediments, described in well records as glaciofluvial clay or till, overlying much of the aquifer area. Based on data from 32 wells in this lower aquifer unit, the median well depth is 24 m (80 ft), ranging from 2 to 70 m (7 to 230 ft). Estimated yields range from 2.2 to 341 L/min (0.5 to 75 gpm), and the median estimated yield is 91 L/min (20 gpm). Aquifer 160 is confined and is not thought to be directly hydraulically connected to any surface water bodies. Recharge originates primarily from local precipitation and infiltration via overlying sediments.

2.3.2 Bedrock Aquifers

In addition to unconsolidated deposits, within the study area are two classified aquifers where the wells are mainly constructed in fractured bedrock. The first, aquifer 165 in South Wellington, is approximately 17 km^2 in area (Figure 7) and is made up of Nanaimo Group sedimentary rock (e.g., Protection, Newcastle, Cranberry, and Cedar Formations), mainly shale and sandstone and occasionally conglomerate. Several well records note the presence of coal seams at depth. The boundaries of aquifer 165 are approximate, as they were determined from the spatial extent of bedrock wells in this area at the time the aquifer was mapped. This aquifer may prove to be larger than was originally classified, and the boundaries could change as more wells are constructed in the area. The median depth of wells in aquifer 165 is 38 m (124 ft), based on records for 232 wells, while the median well yield estimated by drillers at the time of construction is 23 L/min (5 gpm) (Gallo, 1995c). The level of aquifer development was classified as moderate (II), and the level of vulnerability was also considered moderate (B), based on the presence of a clay or till confining layer with a geometric mean thickness of 3 m (11 ft) in roughly half of the wells (Gallo, 1995c). Recharge is believed to originate primarily from local precipitation above the aquifer.

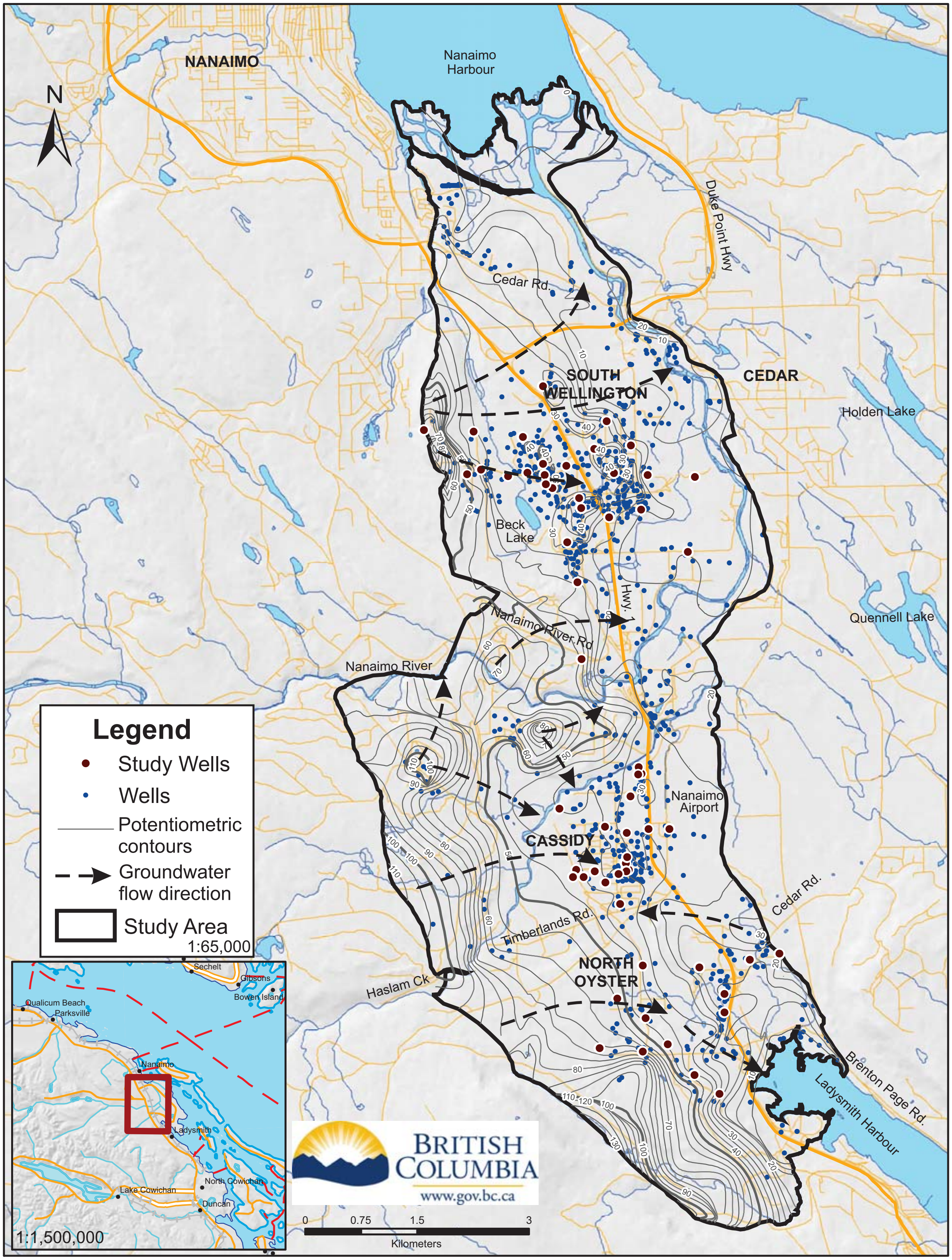


Figure 8 Potentiometric contours and estimated direction of groundwater flow

The second bedrock aquifer included within the study area is aquifer 964, covering 17.3 km^2, from the north side of Ladysmith Harbour up to Haslam Creek (Figure 7) (WorleyParsons, 2012). The aquifer materials consist mainly of sandstone with shale lenses of the Nanaimo Group, De Courcy Formation. The median depth of wells in the aquifer is 47.2 m (155 ft) based on 67 records. The aquifer is considered moderately productive (II) with a median estimated well yield of 13.2 L/min (2.9 gpm). It is also classified as moderately vulnerable (B); while over 80% of the well records indicate a confining layer of till or clay, the aquifer is bounded by or interconnected with several bedrock faults (for example, a fault that runs beneath Haslam Creek), which may provide preferential pathways for contaminant movement into the aquifer. Intrusion of salt water in the coastal zone bounding Ladysmith Harbour is also a potential concern (WorleyParsons, 2012). Recharge of this aquifer originates primarily from local precipitation and infiltration from overlying sedimentary deposits; groundwater from the aquifer likely discharges to Haslam Creek and Bush Creek ,on the southwest side of Ladysmith Harbour. The boundaries of aquifer 161 and aquifer 964 overlap. A small number (N=4) of wells constructed in aquifer 964 were sampled in the North Oyster area. However, the majority of wells sampled in this locale were constructed in the unconsolidated sand and gravel deposits of aquifer 161.

2.3.3 Aquifer Vulnerability

Figure 9 shows the intrinsic susceptibility of the area's aquifers: shades of green represent low vulnerability; yellow, moderate vulnerability; and red, high vulnerability. In this case, the aquifer vulnerability is assessed with the DRASTIC methodology originally developed by the US Environmental Protection Agency (Aller, et al., n.d.), which considers factors such as depth to water, amount of recharge, type and hydrogeologic properties of materials that make up the aquifer, and the surface materials overlying it to describe how vulnerable an aquifer is to contaminants introduced at the land surface. Detailed information on the methods used to prepare the intrinsic susceptibility maps and how to use the maps can be found in Liggett & Gilchrist (2010) and Liggett, et al. (2011). The susceptibility assessment applies only to the shallowest aquifer in the case where there are multiple aquifers overlapping one another; it also does not evaluate the relative risk of aquifer contamination based on the type of land use and the presence or location of potential sources of contamination.

Figure 9 shows that aquifers over the majority of the study area have a moderate to high vulnerability to contamination, in particular within the Cassidy area and along the Nanaimo River flood plain. Localized areas of low vulnerability exist in South Wellington, where the bedrock aquifer is overlain by low permeability sediments such as clay or till.

2.3.4 Groundwater Levels

ENV and FLNRO operate a network of observation wells throughout the province, where water levels are monitored continuously and groundwater quality is sampled semi-annually (Ministry of Environment, 2014b). In 2015, there were 73 active observation wells throughout the Vancouver Island and Gulf Islands region.

Within the study area there are five active provincial observation wells (OW), as listed in Table 2 (locations shown in Figure 9). Observation well 228 is located on Timberlands Road in Cassidy, across from the Nanaimo Regional Airport, and has been active since 1978 within the provincial network, although water level data are available from the well owner going back as far as 1954. Observation well 312 is located in the central part of the study area on the south bank of Haslam Creek. Observation well 330, located south of the Nanaimo River Hatchery beside an historical Nanaimo River side-channel, began in 1996 but was discontinued in 2007 because the water levels were highly influenced by the pumping of the adjacent Harmac pulp mill production wells.

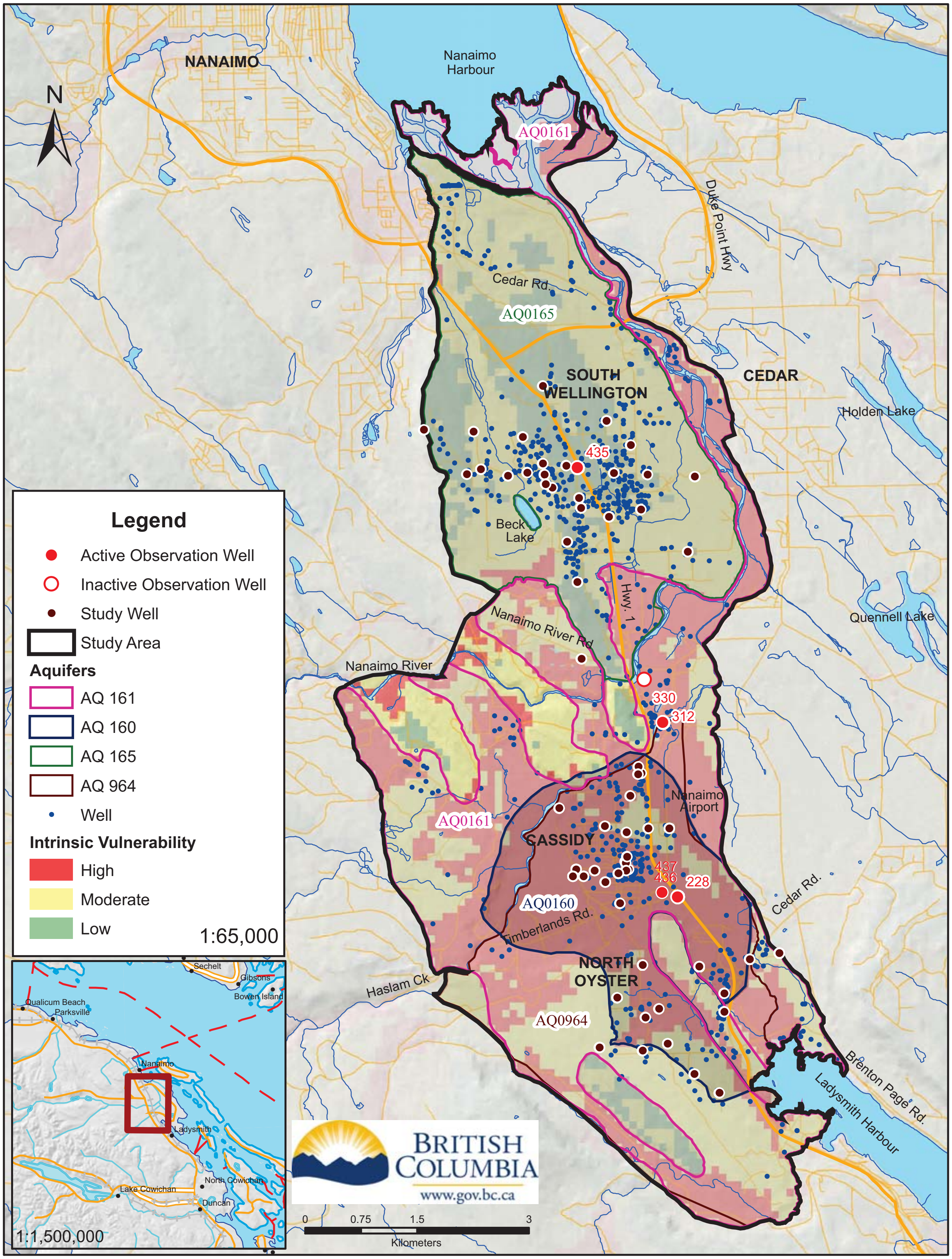


Figure 9   Study area aquifer boundaries, aquifer intrinsic vulnerability, wells, observation wells, and sample sites

Observation well 435 is located in the South Wellington area; monitoring began here in 2013. Two clustered wells, observation wells 436 and 437, were drilled in late 2015 on Timberlands Rd, adjacent to OW 228, for the purpose of monitoring the upper and lower aquifer Cassidy aquifer. Wells 435, 436, and 437 were not active during the study period; therefore monitoring data from these locations are not discussed in this report.

Table 2 Observation wells within the South Wellington and Cassidy areas

OW Number	Aquifer Number	Well Tag Number	Operational Status	Period of Record	Well Depth (m bgs)	Well Depth (ft bgs)	Screed interval (m bgs)
228	160	3155	Active	1978-present	41.5	136	Unknown
312	161	59559	Active	1991-present	23.8	78	Unknown
330	161	62730	Inactive	1996-2007	24.4	80	Unknown
435	165	108187	Active	2013-present	65.5	215	No screen (open hole)
436	161	40945	Active	2015-present	34.1	112	31-34
437	160	40924	Active	2015-present	15.2	50	12-15

The long-term hydrograph, illustrating water level fluctuation in observation well 228 from 1954 to 2012, is shown in Figure 10. The hydrograph indicates that there is a seasonal groundwater level fluctuation from approximately 3 to 8 m below ground surface (4 to 5 m annual range). The shallowest groundwater levels are generally observed from January to March. The deepest water levels tend to occur in late September to early November. The deepest level that groundwater reaches appears relatively consistent throughout the period of record, suggesting that summer low levels are not significantly influenced by pumping of adjacent wells. The depth to which groundwater rises in winter shows some long-term inter-annual variability, likely resulting from changes in precipitation and recharge, which are influenced by global scale climatic cycles such as the Pacific Decadal Oscillation (Allen, et al., 2014; Waterline Resources Inc., 2013). The hydrograph for observation well 228 for the period of 2011 and 2012 compared to daily precipitation for the same period is presented in Figure 11. It is noted that groundwater levels rise following periods of peak rainfall in the fall and winter season, with a lag time of approximately one to three weeks. During the dry summer season, the majority of precipitation evapotranspires and therefore does not reach the aquifer or affect groundwater levels.

The long-term hydrograph for observation well 312 from 1991 to 2012 is shown in Figure 12. The historical seasonal range in groundwater levels was approximately 5 to 6 m. However, after approximately 2003 there is a change in the well response pattern, with a reduced seasonal range of roughly 2 m, fluctuating from 2 to 6 m below ground surface; this change likely reflects an alteration in the timing and volume of extraction from nearby wells. Within observation well 312 the deepest groundwater levels are observed in August or early September, and the shallowest groundwater levels, or high water table, occur from late November to January. Groundwater levels correspond closely with stage height fluctuation on the Nanaimo River and Haslam Creek, which is consistent with the hypothesis that rivers are a significant source of recharge to aquifer sediments in the flood plain (SRK Consulting, 2007).

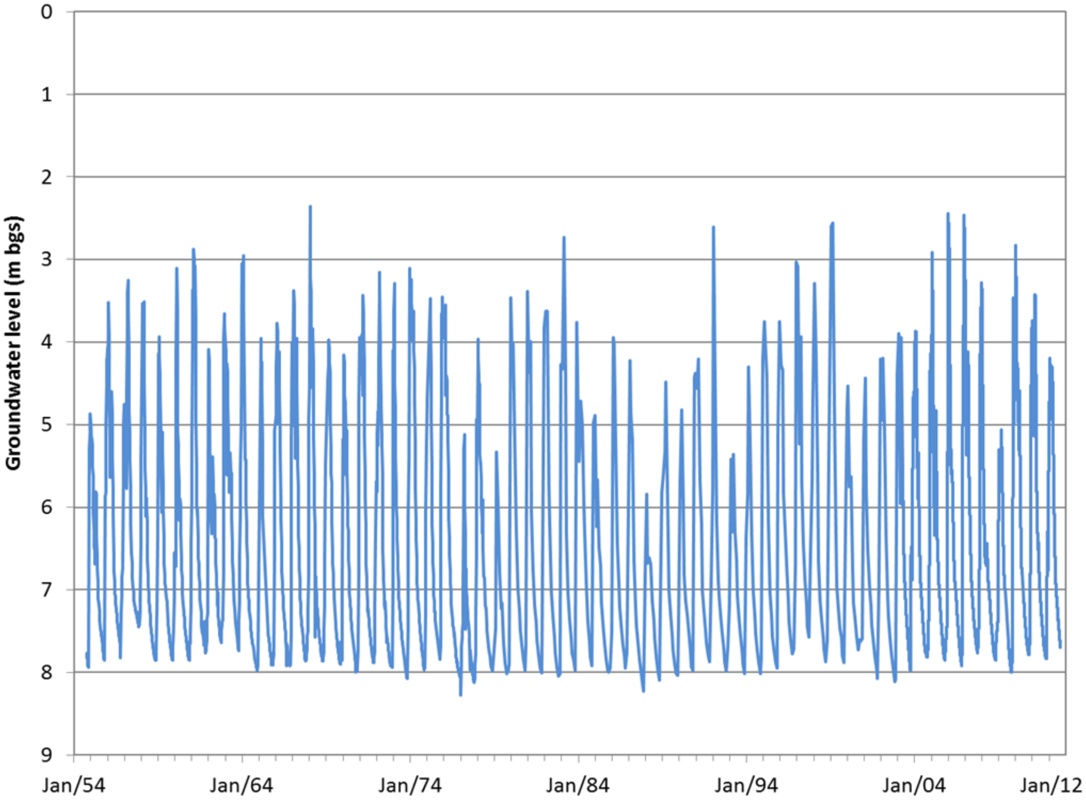


Figure 10 Observation Well 228 groundwater level fluctuation (1954–2012)

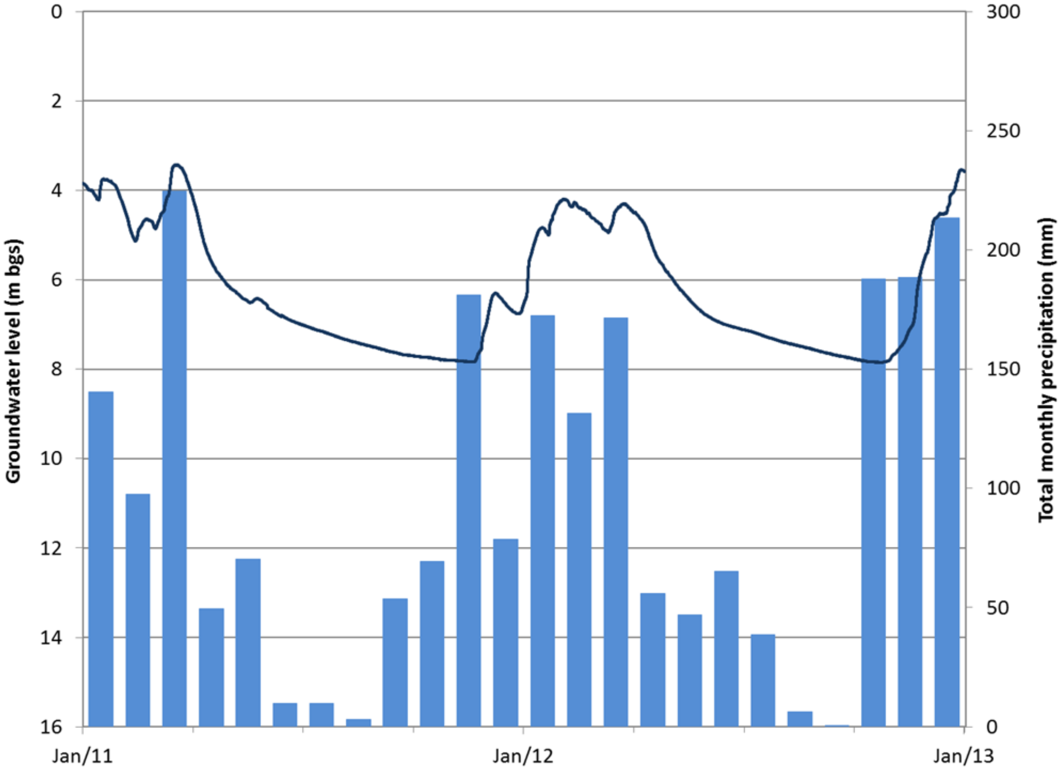


Figure 11 Observation Well 228 groundwater level (line) and monthly precipitation (2011–2012)(bars).

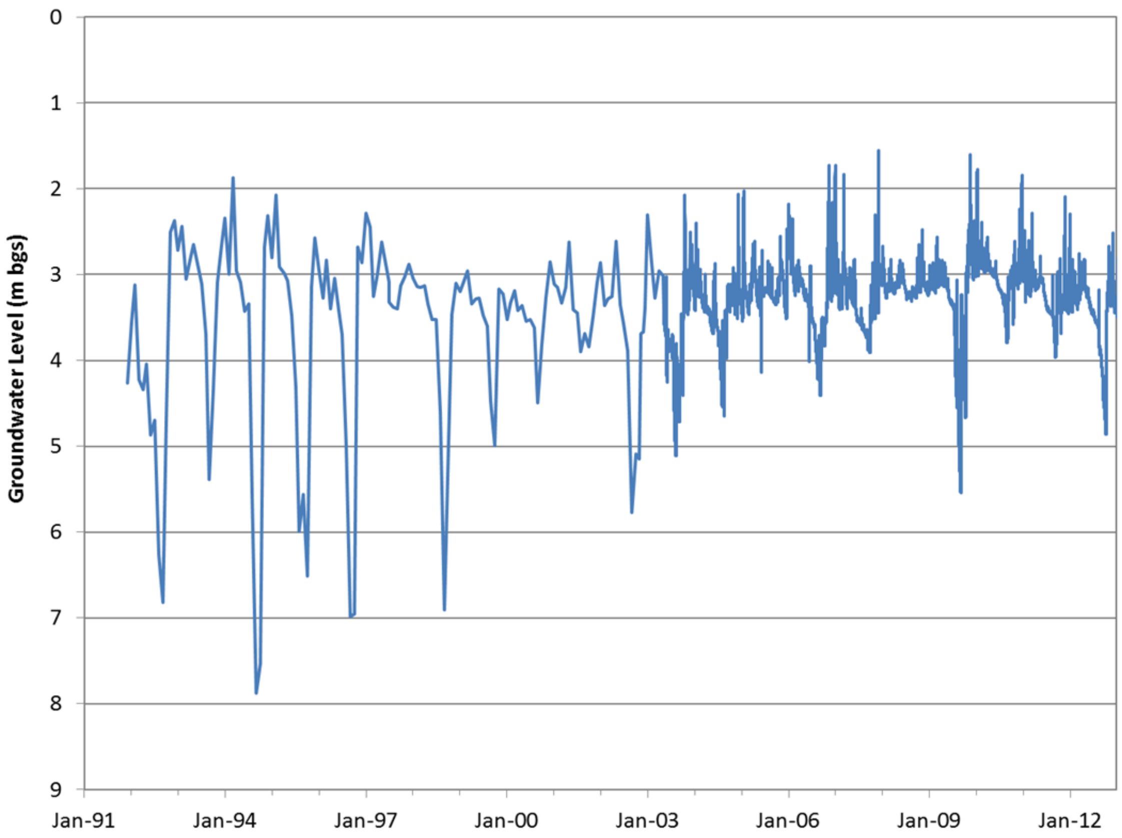


Figure 12 Observation Well 312 groundwater level fluctuation (1991–2012).

2.4 Land Use and Infrastructure

The majority of land in the study area is privately managed young forest, which covers approximately 43% (23018 hectares), according to Provincial land-use mapping (the most recent available is for 1997 (DataBC, 2013a)) shown in Figure 13. Another major land use is agriculture, covering an estimated 28% (1519 ha) of the land area. A total of 44% (2353.4 ha) is designated as Agricultural Land Reserve (DataBC, 2013b) but some of this land area may have been classified differently on the provincial land-use maps e.g. may be forested or used for mixed agricultural-residential purposes. Agriculture production involves primarily beef cattle, poultry, egg, and equine operations, hay, fruit/nut trees, vegetable farming, and greenhouses (Statistic Canada, 2014b).

The local population is distributed among rural agricultural properties, with some more concentrated centres of semi-rural to suburban residences around South Wellington and Cassidy, mainly within the central zone along the Island Highway (Hwy 1), which runs north-south through the study area. Approximately 21% (1141 ha) of the land is considered urban use (DataBC, 2013a). In 2011 there were 6,908 residents in RDN Area A and 3066 private dwellings (including single family households and mobile homes) (Statistics Canada, 2014a). Within the CVRD Area H, the 2011 population was 2,332 in an estimated 1108 private dwellings. During the period from 2006 to 2011 the population grew by 2.3% in RDN Area A and 2.8 % in CVRD Area H (Statistics Canada, 2014a), and additional growth is expected.

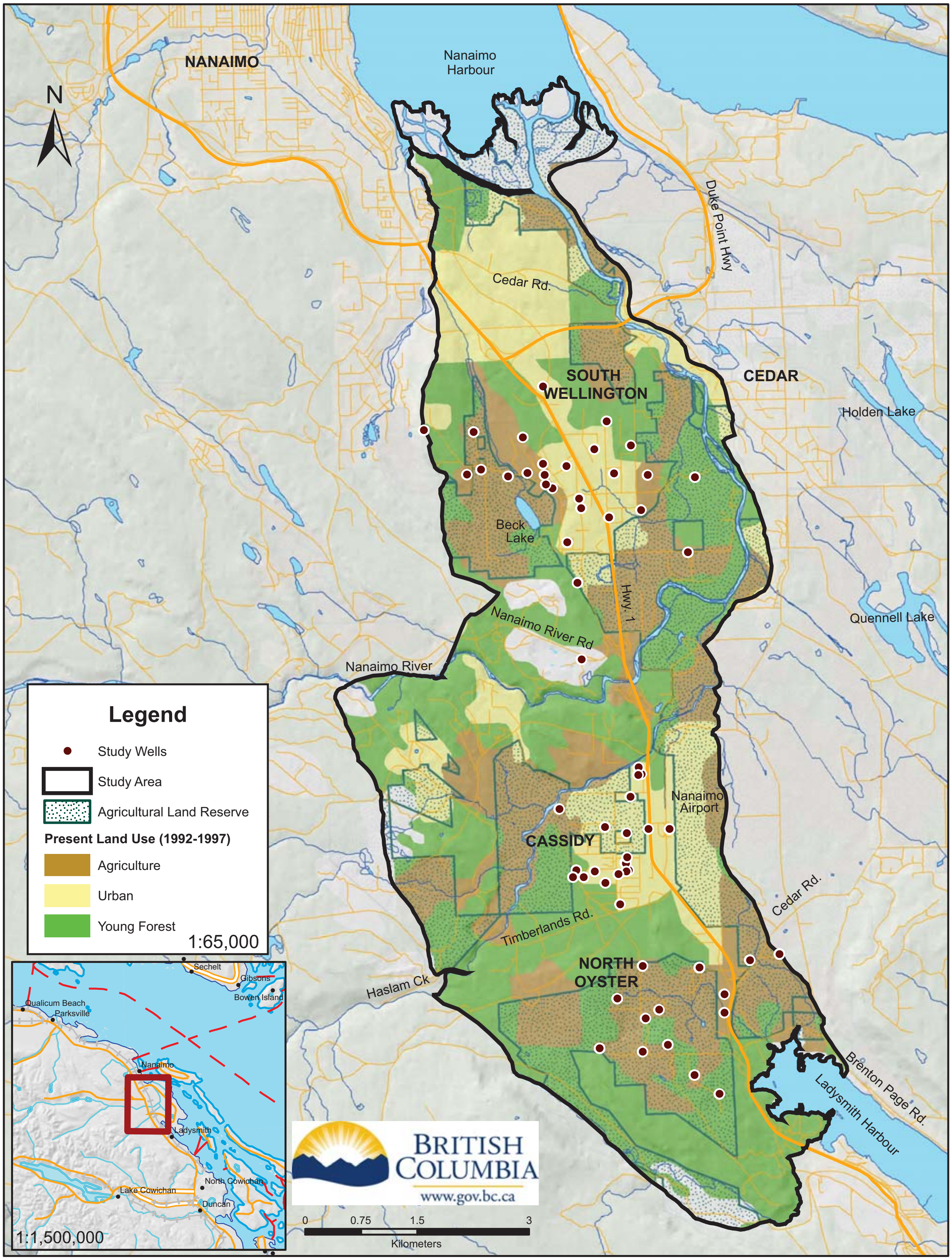


Figure 13 Land use within the study area

Along the Island Highway are mainly industrial and commercial properties, including automotive facilities (metal recycling, vehicle repair and sales) and other light industry and commerce. There is a large composting operation in South Wellington, south of the Duke Point Highway, and the Nanaimo Regional Landfill is located west of the Island Highway between the Duke Point Highway and Cedar Road. Several gravel pits operate here, mainly west of Hwy 1 on the terraced slopes north and south of the Nanaimo River. The Nanaimo Regional Airport is also located in Cassidy.

Because this area does not have municipal water or sewer services, the majority of households, farms, and businesses use a well for their water supply, and most properties also have a septic system. Within the South Wellington area in particular, there are areas with a high density of small lots, where some wells may be located less than the 30 m (100 ft) from the septic field and tank required by the Public Health Act, Health Hazards Regulation (Province of British Columbia, 2011).

3. <u>METHODS</u>

3.1 Site Selection

Participation of well owners within the study was voluntary, based on responses to mail outs and door to door surveys in the target areas. In South Wellington and Cassidy, there was an initial mail-out by the RDN of 688 letters to property owners. From the 120 positive responses received, 48 wells were selected for inclusion in the study based on the following selection criteria:

1. The well had to be in use with a pump installed and access to the water through a tap;
2. The water had to be accessible before holding tanks and treatment systems such as ultraviolet disinfection, chlorination, or water softeners; and
3. Well owners had to be willing to provide written permission for use of the results from their well and inclusion of the data in a provincial database.

In addition to these criteria, final selection of the wells was based on the well location, with the objective of obtaining a spatially distributed survey of the groundwater sources in the study area. In April 2011, samples were collected from 34 wells, and an additional 14 wells were sampled in June 2011, targeting increased sample numbers in areas of higher lot density.

For the North Oyster sites, well owners in Area H were contacted through flyers and a door to door survey in March 2012. Fourteen wells, selected based on the same criteria listed above, were sampled in March 2012.

3.2 Sampling and Analytical Methods

At each site, a sample location was identified as close to the well as possible, before any cisterns, pressure tanks, and/or water treatment equipment. In most cases, this was a hose bib adjacent to the well or pressure tank. Any screens, hoses, or other equipment were removed from the sample point, and the point was disinfected by spraying it or dipping it into a 10% v/v dilute bleach solution, allowing the solution to contact the surface for approximately two minutes. A hose apparatus was then connected to the sample point so that the water discharge flowed continuously through a flow-monitoring cell, allowing staff to monitor field parameters prior to sampling, with minimal contact of the discharge water with the atmosphere, which could influence the parameter values.

Field parameters, including temperature, pH, specific conductivity and oxidation-reduction-potential (ORP), were measured using a YSI Model ProPlus 1030 multi-meter. Prior to field sampling, the multi-meter was calibrated in the laboratory following manufacturer's instructions and using standard calibration solutions. Field parameters were measured and recorded on a continuous basis (every minute). Prior to sample collection, water was allowed to purge continuously until three successive stable readings had been achieved for each parameter (less than 10% variation observed between successive readings). Because the wells were all in active use, parameter stabilization was achieved rapidly, and the average purge duration was approximately 5 minutes.

Sampling was completed using aseptic techniques, including use of sterile gloves. Flow was diminished and the samples were collected directly into the appropriate bottles with no pre-rinsing. Filtration and preservation of samples for metals and dissolved constituents were performed in the laboratory. The samples were placed in coolers with ice, maintained at <4°C during transport, and delivered by courier to the laboratory within 24 hours, following conventional chain-of-custody procedures. The list of parameters analyzed is included in Table 3.

Table 3 Geochemical and biological parameters evaluated within study.

Field parameters	**General chemistry and anions**	**Cations and trace metals**
Temperature	Nitrate (N)	Aluminum Dissolved (Al)
Specific conductivity	Fluoride (F)	Antimony Dissolved (Sb)
pH	Alkalinity (Total as $CaCO_3$)	Arsenic Dissolved (As)
Oxidation-Reduction Potential (ORP)	Bicarbonate (HCO_3)	Barium Dissolved (Ba)
	Carbonate (CO3)	Beryllium Dissolved (Be)
	Sulphate Dissolved (SO_4)	Bismuth Dissolved (Bi)
Microbiological parameters	Chloride Dissolved (Cl)	Boron Dissolved (B)
	Organic Nitrogen Dissolved	Cadmium Dissolved (Cd)
	Total Kjeldahl Nitrogen Dissolved (Calc)	Chromium Dissolved (Cr)
Total coliforms	Ammonia	Cobalt Dissolved (Co)
Escericia coli	Nitrate plus Nitrite	Copper Dissolved (Cu)
	Nitrite	Iron Dissolved (Fe)
	Nitrogen Total	Lead Dissolved (Pb)
	Conductivity	Lithium Dissolved (Li)
	pH	Manganese Dissolved (Mn)
	Total Dissolved Solids (TDS)	Molybdenum Dissolved (Mo)
	Turbidity	Nickel Dissolved (Ni)
	Bromide (Br)	Selenium Dissolved (Se)
	Hardness Dissolved	Silicon Dissolved (Si)
		Silver Dissolved (Ag)
		Strontium Dissolved (Sr)
		Thallium Dissolved (Tl)
		Tin Dissolved (Sn)
		Titanium Dissolved (Ti)
		Uranium Dissolved (U)
		Vanadium Dissolved (V)
		Zinc Dissolved (Zn)
		Zirconium Dissolved (Zr)
		Calcium Dissolved (Ca)
		Magnesium Dissolved (Mg)
		Potassium Dissolved (K)
		Sodium Dissolved (Na)
		Sulphur Dissolved (S)

Calc=Calculated

The microbiological samples for sites 1 to 54 were analyzed at North Island Laboratories in Courtenay, B.C. Samples for microbiological analysis for sites 55 to 68 and geochemical samples for all sites (general chemistry, major ions, and metals) were analyzed at Maxxam Analytics Inc. in Burnaby, B.C. Both laboratories are accredited by the Standards Council of Canada and the Canadian Association for Laboratory Accreditation and use standard analytical procedures (Rice, et al., 2012). For geochemical parameters, the precision of each analytical method is shown in Appendix A, Table A-1 as the reportable detection limit (RDL). For trace metals and cations, the dissolved concentrations were analyzed, as this is considered more representative of the quality of groundwater within the aquifer, than is the total metals.

The data collected in this study were uploaded by the analytical laboratories into the ENV Environmental Monitoring Systems (EMS) database (Ministry of Environment, 2013). Data analysis was completed with Microsoft Excel®, except tri-linear Piper diagrams, which were completed with AquaChem v. 5.1.33 (Waterloo Hydrogeologic Inc., 2006).

3.3 Quality Assurance and Quality Control

The Quality Assurance and Quality Control (QA/QC) program consisted of a) determining the charge balance error for all samples; b) collecting field duplicate samples; and c) evaluating relative percent difference for all duplicate samples. For the field program, the objective was to obtain a minimum of 10% QA/QC samples (i.e., one duplicate bottle for every ten sample bottles) to be analyzed for the range of parameters (general chemistry, metals, and bacteria) and to collect a minimum of one bacteriological duplicate per sample date. The laboratory QA/QC program consisted of spikes, blanks, and replicate samples; the details of these tests were provided within the analytical report for each site.

All solutions are electrically neutral, meaning that the sum of the positively charged ions (cations) is equal to the sum of the negatively charged ions (anions). A completely neutral solution will have a charge balance error (CBE) of zero, reflecting the electroneutrality of the solution. Based on this observation, the integrity of a water sample analysis can be assessed by calculating the CBE as shown in equation (1) (Freeze & Cherry, 1979; Appelo & Postma, 1993):

$$CBE = \frac{\sum zm_c + \sum zm_a}{\sum zm_c - \sum zm_a} x\,100 \qquad (1)$$

where,

$$z_i m_i = \text{ionic charge} \times \frac{\text{analytical concentration}}{\text{molecular weight}} \qquad (2)$$

and where *z* is the absolute ionic charge (positive or negative), *m* is the molar concentration of the substance (mmol/L), the subscript (c) indicates the substance is a cation, and subscript (a) indicates the substance is an anion.

The CBE was calculated from the concentration of ionic species in solution, including anions bicarbonate (HCO_3^-), chloride (Cl^-), sulphate (SO_4^{2-}), nitrate-nitrogen (NO_3^- as N), and fluoride (F^-); and cations calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+), sodium (Na^+), iron (Fe3+), and ammonia-nitrogen (NH_3^+ as N). The major ions comprise the majority of ion concentrations in most groundwater, although the contribution of fluoride, nitrate, and ammonia is generally minor. If the analytical result for a cation or anion was less than the reportable detection limit (RDL), the concentration was assumed to be zero. A

CBE within a range of ± 5% is generally considered acceptable (Appelo & Postma, 1993; Maxxam Analytics Ltd., n.d.).

Field duplicate samples were obtained by taking two samples at the same time from the same source, as opposed to a replicate sample, defined as an analysis performed on different aliquots of the same sample (Geboy & Engle, 2011). Duplicates can provide information on the precision of the analysis or repeatability of the results and can also be an indicator of the heterogeneity of the sample material (in this case, water). The discrepancy between the duplicate samples was evaluated by using formula (3) (Nielsen & Nielsen, 2007) to calculate the relative percent difference (RPD) of the analytical concentration of the two samples:

$$RPD = \left[\frac{C_1 - C_2}{(C_1 + C_2) \div 2}\right] \times 100 \qquad (3)$$

where C_1 and C_2 are the reported concentrations of samples 1 and 2, respectively. It was not possible to calculate the RPD when the results for one or both parameters were below the Method Detection Limit (MDL). A RPD of ≤ 25% is considered an acceptable level of error, and a RPD > 25% is considered acceptable if the analytical result is less than five times the reportable detection limit (RDL) (Ministry of Environment, Lands and Parks, Land Data BC and Geographic Data BC, 1998).

3.4 Wellhead Inspection

Prior to sampling, each wellhead was inspected in order to assess the well compliance with the Ground Water Protection Regulation (GWPR) (Province of British Columbia, 2009) and to make recommendations for best management practices to protect the well and aquifer and the health of groundwater users. The inspection involved collecting basic information on the well location (GPS coordinates, address, and description of the physical location on the property) and physical set-up of the well (diameter, casing stickup, presence and condition of the well cap). Wherever possible, detailed information on the well construction was obtained either by searching the WELLS database (Ministry of Environment, 2014a) prior to the site visit or by obtaining the well construction record from the property owner. If a construction record was not available, basic information was recorded, including approximate depth, year of construction, and type of aquifer material. In a small number of cases, the well owners did not have any information on their well, and therefore depth was listed as unknown (6 sites) and the aquifer material was inferred from the well type (e.g., shallow dug wells in unconsolidated sediments) or from records of wells on adjacent properties.

There were three main types of wells sampled in the study: (a) wells drilled in unconsolidated materials (sand and gravel), where water enters the well within the lowest, screened, section of the well bore; (b) wells drilled in fractured bedrock, where water enters the well via fractures intercepted at various depths along the well bore; and (c) shallow excavated wells which have been dug within unconsolidated materials, where water enters the well through the bottom or base of the excavation. Drilled wells tend to have a smaller diameter, typically 15 cm (6 inches), compared to dug wells, which are 1.5 m (5 ft) wide on average.

The GWPR protects groundwater by regulating activities associated with well construction, operation, maintenance, and closure. The checklist in Table 4 includes criteria used during the inspection to assess compliance with the regulations and potential vulnerability of the well to contamination. Diagrams of correctly set up wells are shown in Figure 14. For further details, refer directly to the *Water Act (Water Sustainability Act)* and GWPR (Province of British Columbia, 2014; Province of British Columbia, 2009).

Table 4 Well inspection checklist.

☐ Well has water tight, vermin-proof cap;[1]
☐ Top of well (well casing stickup) extends a minimum of 30 cm (12 inches) above the ground surface;[2]
☐ Well has identification plate;[2]
☐ Space around well casing is sealed and water-tight to a depth of at least 5 m (15 ft) (assessed based on well construction record and no annular space visible around well casing);[2]
☐ Ground around well is mounded to deflect surface run-off;[2]
☐ Well not located within underground pit or enclosure;
☐ Well located in high/dry location, away from standing water, wetland or swampy areas (no standing water around well);
☐ Well easily accessible for maintenance (e.g. visible, not buried or overgrown with vegetation);
☐ If well is flowing artesian, flow is stopped or controlled.[1]
☐ If there are unused wells on the property, and there is no intent to use them in future, these are deactivated or closed;[1]
☐ Well located a minimum of 30 m (100 ft) from potential sources of contamination (if known) such as a septic field, septic tank, dog run, chicken coop, animal range or pasture, compost pile, garbage and refuse storage, pesticide or fertilizer use or storage, underground storage tank, parking area;[3]
☐ Hazardous materials (pesticides, fuel, paints, solvents) are stored away from the well and not in the pumphouse;

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[1] Requirement for all wells. Refer to *Water Act* and Ground Water Protection Regulation. After February 29, 2016 refer to *Water Sustainability Act*.

[2] Recommended for all wells, and requirement for wells constructed since Nov. 1, 2005. Refer to *Water Act* (*Water Sustainability Act*) and GWPR.

[3] Refer to the *Public Health Act*, Health Hazards Regulation.

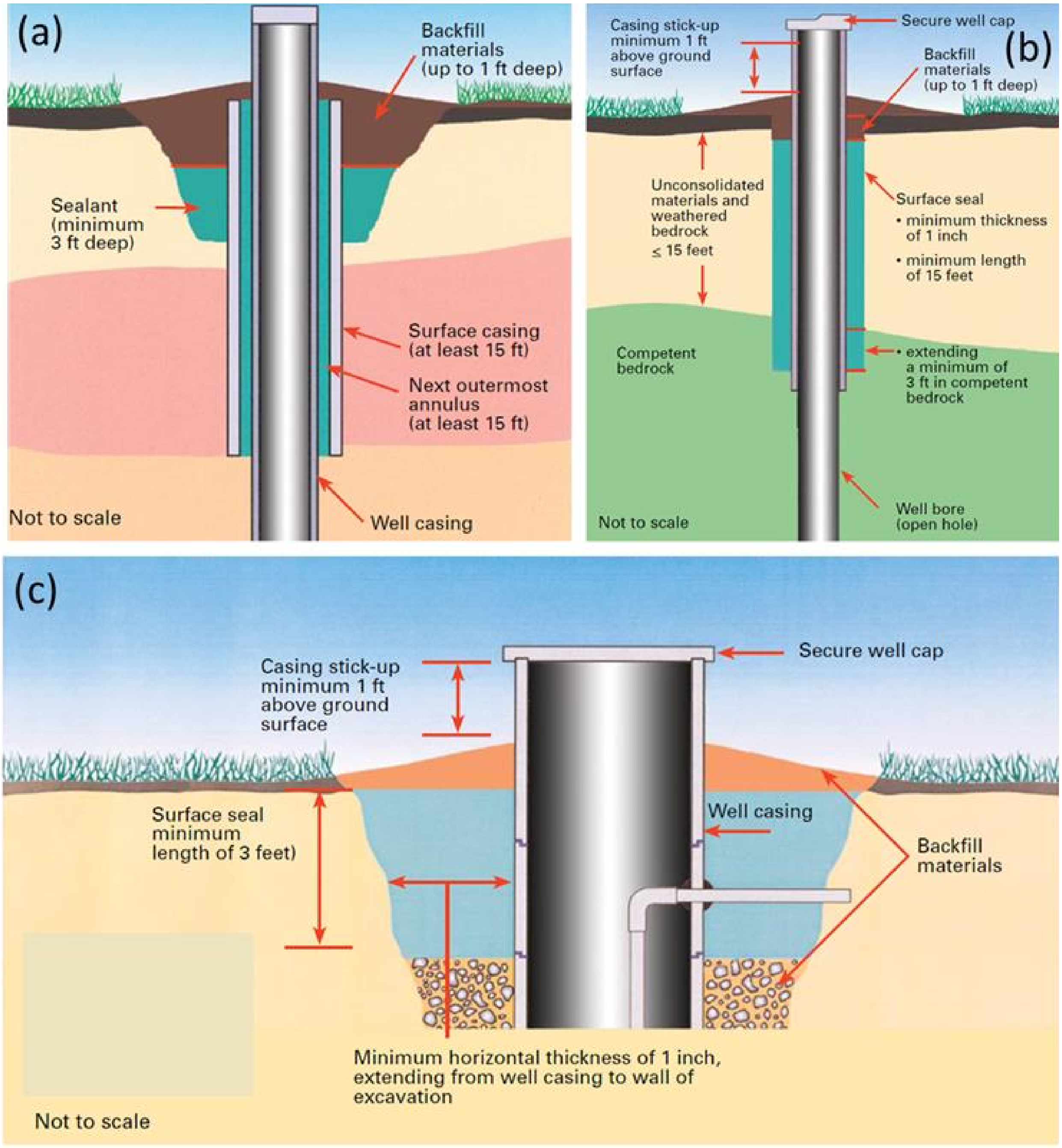

Figure 14 Features of properly constructed and maintained wells (a) drilled well in unconsolidated aquifer, (b) drilled well in bedrock aquifer, (c) excavated well. Image source: (BC Ground Water Association, 2007).

4. RESULTS AND DISCUSSION

A total of 62 wells were sampled for this study, representing roughly 7% of the estimated 942 wells within this area and included in the WELLS database (Ministry of Environment, 2014a). Although it is recognized that the database may underestimate the actual number of wells, the sample sites were distributed within the areas of greatest well density, as shown in Figure 16. In total, 25 (40%) of the wells sampled for geochemistry were drilled in unconsolidated materials (sand and gravel) (Figure 15). The median depth of wells in unconsolidated aquifers was 14.2 m (47 ft) and ranged from 3.7 m to 58.2 m (12 to 191 ft). In comparison, 30 wells (49%) sampled were drilled in a bedrock aquifer, and the median depth of these wells was 61.3 m (201 ft), ranging from 30.5 to 146.3 m (100 to 480 ft). Within the well logs, the bedrock type was identified mainly as shale and sandstone. Seven (11%) wells sampled for geochemistry were excavated in a sand and gravel aquifer; while eight excavated wells were sampled for bacteria (i.e. one excavated well was sampled for bacteria only).

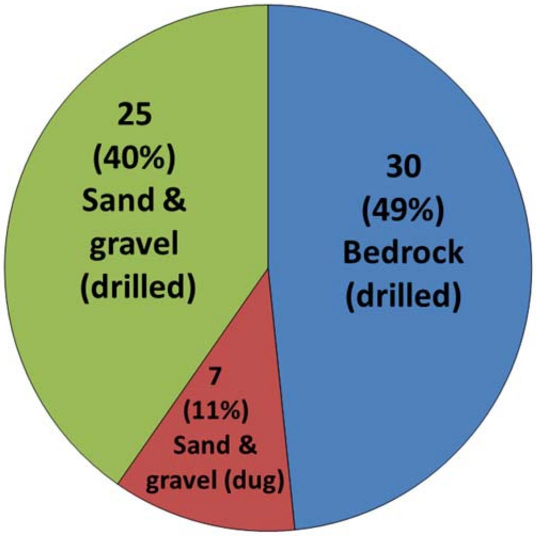

Figure 15 Distribution of sample sites in different aquifer materials and by well construction method.

4.1 Quality Assurance/Quality Control (QA/QC)

The complete QA/QC results are provided in Appendix B. The QA/QC results were found to be acceptable, and all sample results were retained for further interpretation.

4.2 Geochemistry

Within this study, groundwater samples were analyzed for 27 different geochemical parameters. The parameters were chosen because they are of importance to the health of individuals using the water (health related parameters), because they affect the taste, odor or colour of the water and therefore the pleasantness of the water for drinking (aesthetic parameters), and because they provide clues regarding the geochemical and physical processes the water has been through.

For example, when water first infiltrates into the subsurface and enters a groundwater system, it is typically “fresh”, with lower concentrations of metals and minerals, as opposed to water that has been present in the aquifer longer and has interacted with rock and subsurface materials and therefore may have higher concentrations of dissolved elements such as arsenic, fluoride, iron, or sodium.

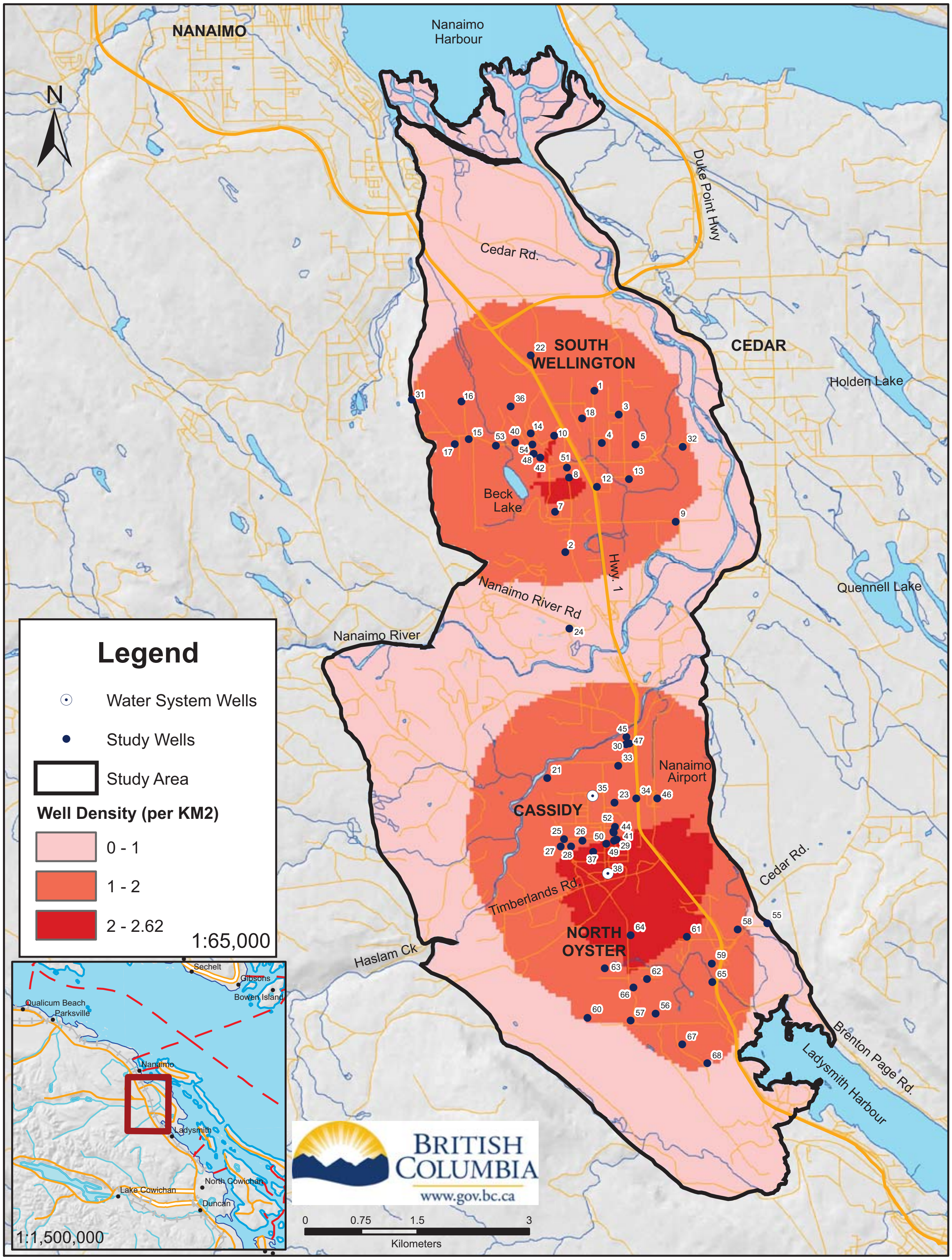

Figure 16 Sample sites and well density in the study area

Other parameters may indicate a source of pollution close to the aquifer. For example, high chloride concentration in wells close to the coast may indicate that an aquifer is affected by salt water intrusion, as a result of either natural processes or over-pumping from one or more wells. Similarly, elevated nitrate in groundwater can be an indicator of human impacts, because its concentration is normally low unless there is a source of pollution to the aquifer, such as human or animal waste or agricultural fertilizer. The detailed sample results are discussed below with respect to major ion chemistry and water types, and health related or aesthetic concerns.

4.2.1 Major Ions and Water Type

The composition of a water sample includes both major (dominant) and minor (trace) components. A Piper diagram is a ternary diagram that illustrates the relative concentrations of major ions in a sample. The proportional concentration of the cations (positively charged ions) calcium, magnesium, sodium, and potassium are shown by the location of a sample point within the triangle on the bottom left side. The proportional concentration of the anions (negatively charged ions) bicarbonate, chloride, and sulfate are shown by the location of the sample point within the triangle on the bottom right side. The points from the bottom triangles are then projected to where they intersect on the upper diamond. Based on the position of the plotted sample point in the diamond, one can draw conclusions about the groundwater type. When multiple samples are plotted on the same graph, one can draw conclusions about geochemical processes occurring within the area or aquifer(s) (Appelo & Postma, 1993; Freeze & Cherry, 1979). A Piper diagram of the study samples prepared using Aquachem (v. 5.1.33) is shown in Figure 17.

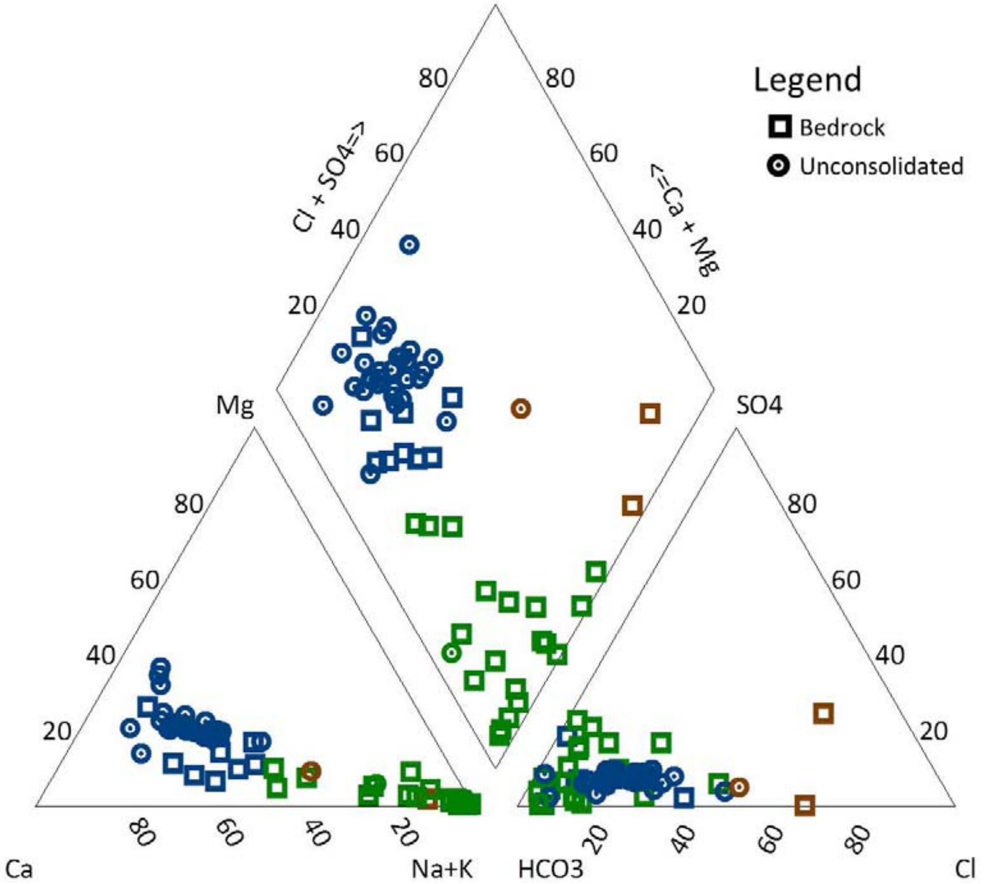

Figure 17 Piper diagram South Wellington, Cassidy and North Oyster groundwater samples (blue= Ca-HCO3 water type, green=Na-HCO3 type and brown=Na-Cl type).

The water type was determined for all geochemical samples using Aquachem (V. 5.1.33); results are summarized in Table 5 below. The majority (61%) of samples were calcium-bicarbonate ($Ca-HCO_3$) type water, representing recently recharged, immature groundwater, such as that sampled from wells in unconsolidated sand and gravel formations and shallow aquifers (including some bedrock wells). This water type appears in the left corner of the upper diamond of the Piper plot.

Table 5 Water type of geochemical samples.

Water type	Total	
Ca-HCO3	39	61%
Na-Cl	3	5%
Na-HCO3	20	34%

The second most frequent water type was sodium-bicarbonate ($Na-HCO_3$) type (34%), representing more mature groundwater that has undergone some cation exchange. These samples appear in the bottom corner of the diamond in the Piper diagram and were mainly from bedrock wells. Cation exchange is a process whereby, in exchange for calcium ions, sodium ions are released into solution from negatively charged exchange sites on the microscopic surfaces of rocks and sediment particles (Appelo & Postma, 1993). This process has been well documented within aquifers made up of Nanaimo Group sedimentary rock on eastern Vancouver Island and the Gulf Islands (Allen & Matsuo, 2002; Earle & Krogh, 2006).

A smaller group (5%) of samples were sodium-chloride (Na-Cl) type groundwater, suggesting that there is a source of chloride in the aquifers, such as dissolution of minerals from sedimentary rocks formed in a marine setting or groundwater that was trapped in the deeper formations during periods of higher sea level (Allen & Suchy, 2001). These samples appear on the right side of the diamond on the Piper plot.

4.3 Field Parameters

At each location, temperature, pH, specific conductivity, and oxidation reduction potential (ORP) were measured in the field. The median ambient temperature of water from unconsolidated wells was 9.9°C, compared to water from bedrock wells which had a median temperature of 10.5°C. The coldest water was 7.7°C, taken from a dug well in March and therefore reflecting the influence of cold air, and the warmest was 12.8°C, from a bedrock well sampled in June. The pH results are described below in Section 4.5.1. Samples from unconsolidated wells had a median specific electrical conductivity of 122.5 µS/cm and a median standard oxidation potential (Eh) of 339.2. In comparison, the specific electrical conductivity of samples from bedrock wells was higher (median 484.2 µS/cm), and the median Eh was lower, 208.6 mv, indicating that in general, bedrock wells contained water that had undergone more water-rock interaction and chemical maturation, and that was present under more reducing (low oxygen) conditions.

4.4 Health Related Parameters

The results of the geochemical analyses were compared to the Health Canada Guidelines for Canadian Drinking Water Groundwater Quality (GCDWQ) (Health Canada, 2014). The GCDWQ identify a Maximum Acceptable Concentration (MAC) for parameters that are health related, where drinking water with concentrations above the guidelines may be associated with immediate or long-term health concerns. In comparison, an Aesthetic Objective (AO) is the upper limit for parameters that can affect the taste, odour, or pleasantness of the water for drinking. Health-related parameters evaluated within the laboratory analysis for this study included nitrate, fluoride, antimony, arsenic, barium, boron, cadmium, chromium, lead, selenium, and uranium. Sampled aesthetic parameters included pH, sulfate, chloride, total dissolved solids, sodium, copper, iron, manganese, and zinc, which are discussed further in Section 4.5. Table 6 summarizes the number and percent of samples that exceeded drinking water guidelines. Apart from fluoride, the majority of samples that exceeded water quality guidelines were for aesthetic parameters.

Table 6 Number and percent of samples exceeding drinking water quality guidelines for health related or aesthetic parameters.

Parameter	# Exceedences	% of samples
Fluoride (F)	4	6%
pH (Field)	36	58%
Sulphate Dissolved (SO4)	1	2%
Chloride Dissolved (Cl)	1	2%
Total Dissolved Solids (TDS)	6	10%
Sodium Dissolved (Na)	5	8%
Iron Dissolved (Fe)	2	3%
Manganese Dissolved (Mn)	6	10%

Table 7 shows the arithmetic mean, median, geometric mean, minimum, and maximum concentrations of health-related parameters of groundwater from wells in unconsolidated and bedrock aquifers. The complete geochemical results for all sites are provided in Appendix A, Table A-1. Box plots and comparisons of median concentrations of these elements within unconsolidated (sand and gravel) and bedrock aquifers are shown in Figure 18 and Figure 19.

Four groundwater samples from bedrock wells had fluoride above the drinking water guideline. Apart from this, no other samples exceeded health-related drinking water quality limits. As shown in Figure 18 and Figure 19, the median concentrations of fluoride, arsenic, and barium were higher within groundwater from bedrock than in unconsolidated aquifers and exhibited a wider range in values. Lead may be present in water due to its use in older pipes and plumbing fixtures; there was no difference in lead concentrations between samples from different aquifer types. The median nitrate concentration was higher in groundwater from wells in unconsolidated aquifers. Because of the common occurrence of arsenic, fluoride, and nitrate in groundwater in B.C., a more detailed description of their results is provided below.

One difficulty in calculating statistics for substances at low concentration is evaluating values that are below the Method Detection Limit (MDL)—in other words, the lowest concentration that can be measured by the laboratory procedure. These data are referred to as "censored", because the actual concentration is not known (Helsel & Hirsch, 2002). Various methods are used to find an appropriate replacement for censored data; for example, arbitrary substitution, assuming the concentration is equivalent to the MDL, equivalent to 0, to the MDL/2 or the MDL/$\sqrt{2}$. Alternately one can approximate replacement values (for example, from the sample distribution), or other approaches (Cohen, 1959; El-Shaarawi & Dolan, 1989; Ganser & Hewett, 2010). However, without using any of these methods, it is possible to calculate the median concentration from a data set if less than 50% of the data are below the MDL, and similarly, if less than 25% of the data are censored, then the Inter-Quartile Range (25th, 50th,and 75th percentile) can be calculated from the known values (Helsel & Hirsch, 2002). For this study, no replacement values were used for the censored data; instead, these were excluded from the calculated statistics. Table 7 shows the percentage of censored data for each parameter.

Table 7 Statistical summary of sample results for health related parameters.

	Nitrate-Nitrogen (NO_3-N)	Fluoride (F)	Arsenic Dissolved (As)	Barium Dissolved (Ba)	Boron Dissolved (B)	Antimony Dissolved (Sb)	Cadmium Dissolved (Cd)	Chromium Dissolved (Cr)	Lead Dissolved (Pb)	Selenium Dissolved (Se)	Uranium Dissolved (U)
Units	**mg/L**	**mg/L**	**µg/L**	**mg/L**	**mg/L**	**µg/L**	**µg/L**	**µg/L**	**µg/L**	**µg/L**	**µg/L**
Reportable Detection Limit (RDL)	0.002	0.01	0.02	0.00002	0.05	0.002	0.005	0.10	0.005	0.04	0.002
Maximum Acceptable Concentration (Health Canada)	10 mg/L	1.5 mg/L	10 µg/L	1 mg/L	5 mg/L	6 µg/L	5 µg/L	50 µg/L	10 µg/L	10 µg/L	20 µg/L
Unconsolidated											
Arithmetic mean	1.09	0.049	0.22	0.012	nc	nc	nc	nc	0.14	nc	nc
Median	0.63	0.040	0.060	0.0059	nc	nc	nc	nc	0.059	0.060	0.007
Geometric mean	0.68	0.041	0.084	0.0067	nc	nc	nc	nc	0.060	nc	nc
Min	0.079	0.020	0.020	0.0012	0.13	0.02	0.005	0.10	0.007	0.040	0.002
Max	7.25	0.22	3.05	0.078	0.35	0.07	0.014	1.7	0.91	0.74	0.33
N=32											
Exceedences	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Bedrock											
Arithmetic mean	0.19	0.58	0.72	0.06	nc	nc	nc	nc	0.13	nc	nc
Median	0.068	0.21	0.18	0.04	nc	nc	nc	nc	0.070	0.050	0.026
Geometric mean	0.059	0.26	0.25	0.04	nc	nc	nc	nc	0.061	nc	nc
Min	0.002	0.04	0.030	0.003	0.06	0.02	0.01	0.10	0.005	0.040	0.003
Max	1.3	3.0	5.6	0.39	2.7	0.30	0.10	0.50	0.50	1.1	0.25
N=30											
Exceedences	**0**	**4**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
% <RDL (all)[1]	19%	0%	11%	0%	55%	65%	65%	52%	8%	45%	26%

[1] *Percentage of samples less than RDL (unconsolidated and bedrock)*

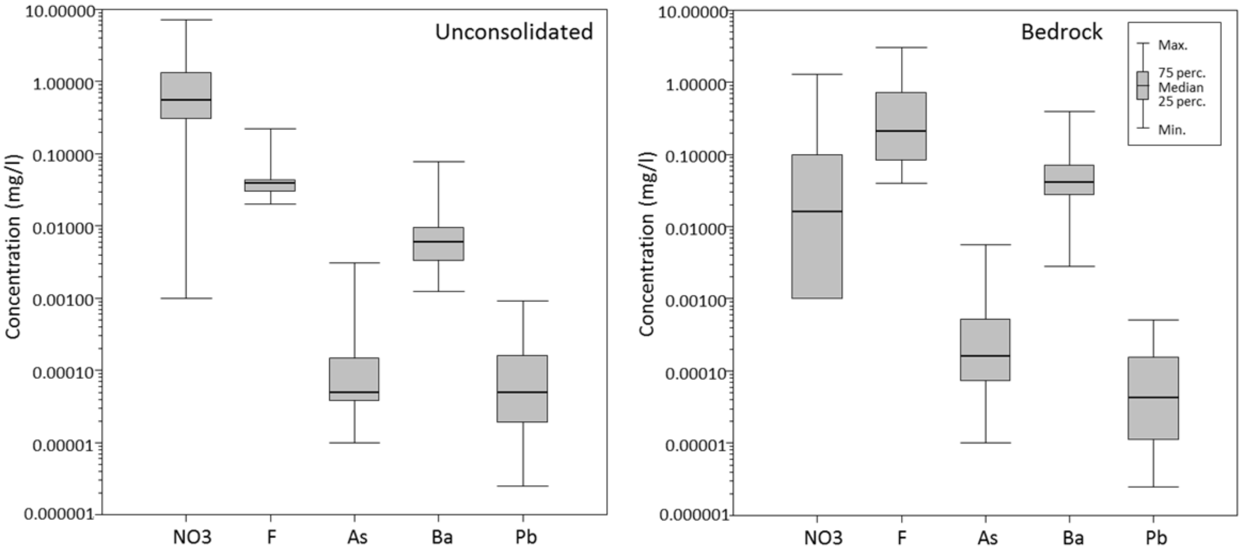

Figure 18 Boxplots of concentrations of health related parameters nitrate, fluoride, arsenic, barium, and lead in unconsolidated and bedrock aquifers.

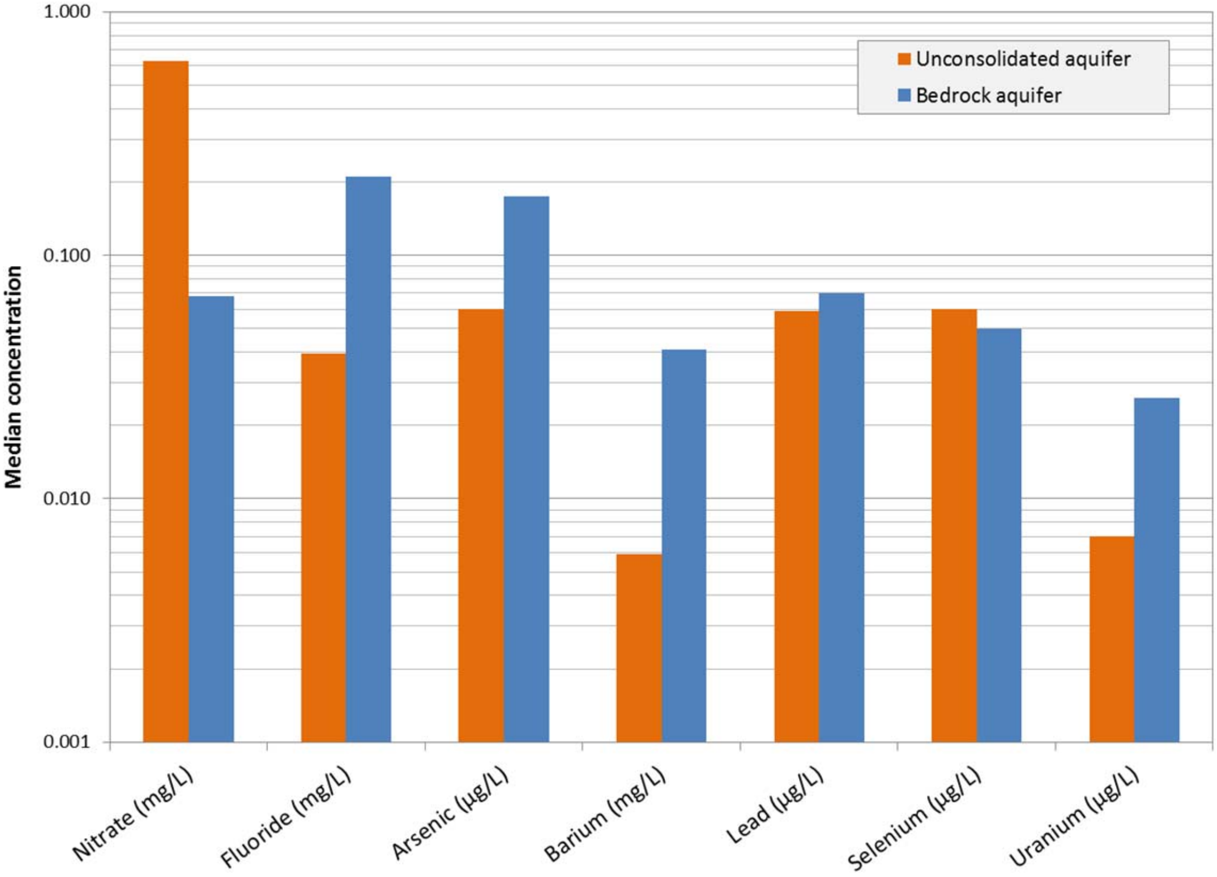

Figure 19 Comparison of median concentrations of health related parameters in unconsolidated and bedrock aquifers.

The median and average concentrations of boron, cadmium, chromium, and antimony are not reported because more than 50% of concentrations were below the MDL, indicating that for the most part their concentrations were very low. For selenium and uranium, the median was calculated, but the average (arithmetic mean) concentration was not reported because more than 25% of the results were below the MDL. Looking at the breadth of values for these parameters, boron concentrations ranged from 0.13 to 0.35 mg/L in groundwater from unconsolidated aquifers, compared to 0.06 to 2.7 mg/L in water from bedrock aquifers; antimony ranged from a minimum of 0.02 µg/L to a maximum of 0.07 µg/L and 0.10 µg/L in groundwater from unconsolidated and bedrock wells respectively; cadmium ranged from 0.005 to 0.014 µg/L in groundwater from unconsolidated wells, compared to 0.01 to 0.10 µg/L in groundwater from bedrock; and chromium had a minimum concentration of 0.10 µg/L in wells constructed in either unconsolidated or bedrock aquifers, and a maximum concentration of 1.7 µg/L and 0.50 µg/L in samples from unconsolidated and bedrock wells respectively.

4.4.1 Arsenic

Arsenic is a metalloid that occurs in water as a result of either the dissolution of arsenic-bearing minerals or contamination from human activities (such as infiltration or runoff from mining or industrial effluent). Arsenic is known to be present naturally at low to moderate concentrations within groundwater in some areas of Vancouver Island and the Gulf Islands.

The Maximum Acceptable Concentration (MAC) for arsenic in drinking water is 10 µg/L (Health Canada, 2014). Arsenic has no colour, smell, or taste when it is dissolved in water, so a laboratory test is the only way to know if it is present. Drinking or cooking with water above the GCDWQ for arsenic can cause short-term or acute symptoms such as cardiovascular or gastrointestinal illness, neurological impairment, and skin diseases (Health Canada, 2006). Long-term (years to decades) exposure to even relatively low concentrations of arsenic in drinking water can increase the risk of developing some cancers, including skin, lung, kidney, and bladder cancer. Cancer is the critical health effect used in setting the Canadian guideline for arsenic in drinking water, considering exposure to arsenic in water by children, as they are the population with the least tolerance due to their lower body weight. Arsenic can be removed from water by reverse osmosis and distillation and with specialized filters. Inhalation and skin contact with water containing arsenic above the drinking water guidelines are not considered harmful, therefore the water can be safely used for bathing and other non-potable uses.

The median concentration of arsenic in groundwater from unconsolidated aquifers was 0.060 µg/L, compared to a median of 0.18 µg/L in groundwater from bedrock aquifers, and the concentrations ranged from less than the detection limit (7 sites) up to 5.6 µg/L. Although none of the samples had arsenic above drinking water guidelines, samples from 6 wells (10%) had arsenic between 1 and 6 µg/L, which may be a concern with long-term exposure. Figure 20 shows the distribution of arsenic concentrations within groundwater samples in the study area.

4.4.2 Fluoride

In Canadian groundwater, fluoride often occurs naturally at low concentrations. Natural sources of fluoride include the dissolution of fluoride contained in rocks and soils, the weathering and deposition of volcanic ash. Elevated fluoride from human activities can originate from runoff and infiltration of chemical fertilizers in agricultural areas, septic and sewage treatment system discharges in communities with fluoridated water supplies, or liquid waste from industrial sources, such as aluminum, glass, and cement manufacturing (Health Canada, 2010).

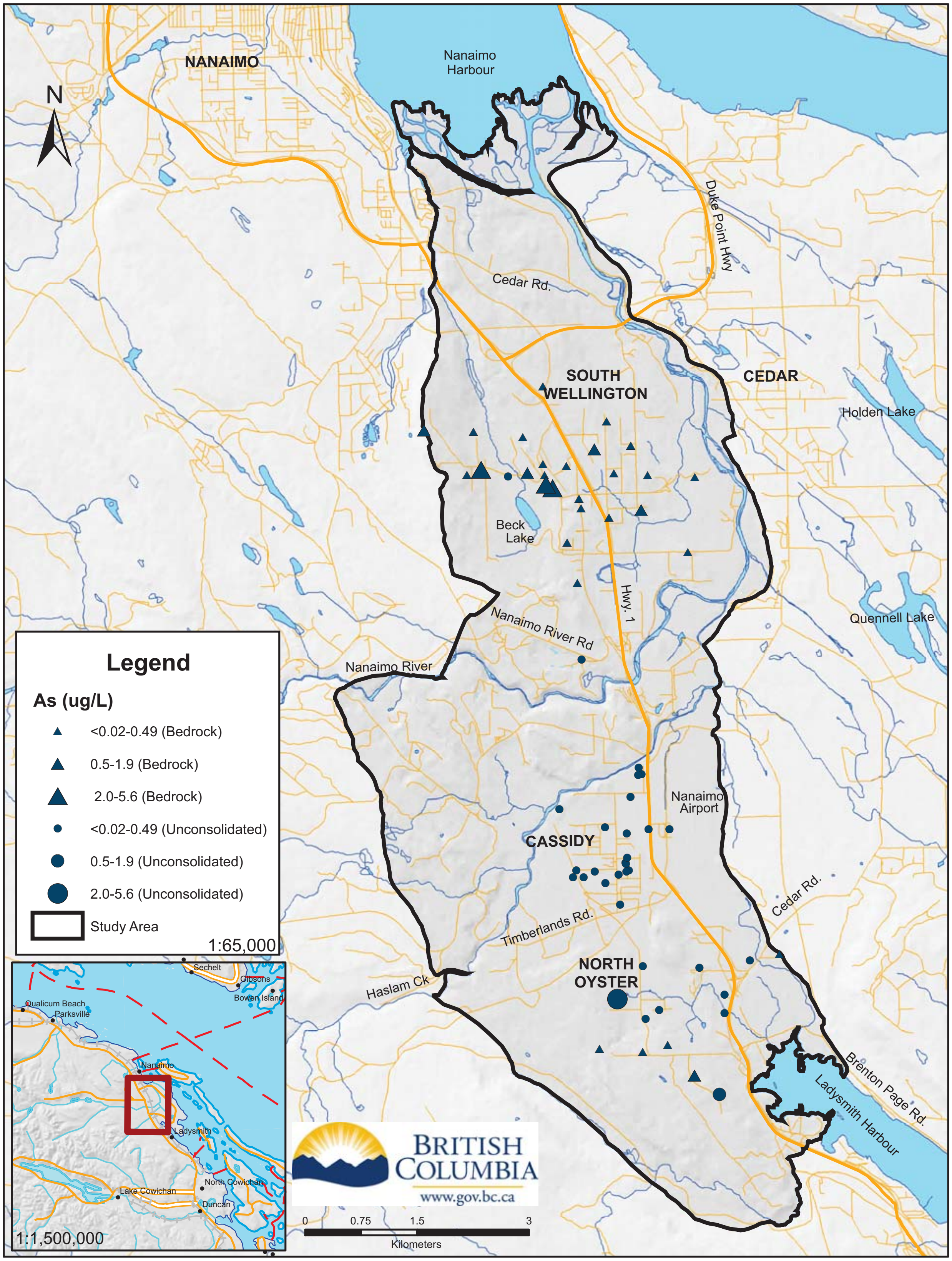

Figure 20   Arsenic concentration in groundwater samples

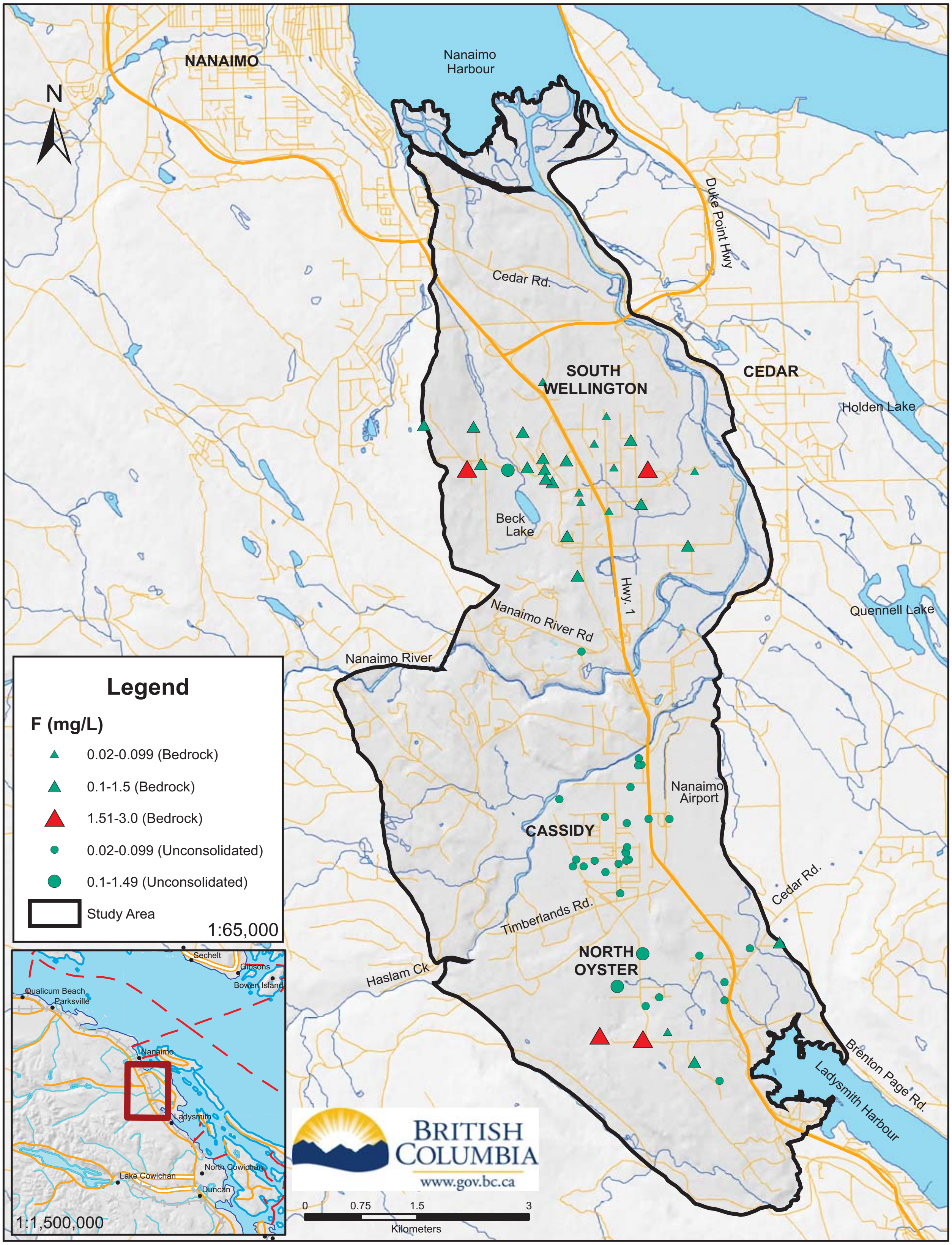

Figure 21 Fluoride concentration in groundwater samples

The Health Canada Maximum Acceptable Concentration for fluoride in groundwater is 1.5 mg/L, and the concentration can only be measured using a laboratory test (Health Canada, 2014). At a low concentration of 0.7 to 0.9 mg/L, fluoride in drinking water may have a beneficial effect on the prevention of dental caries. Ingesting elevated concentrations of fluoride from food, water, or other sources is associated with possible negative effects, including increased risk of dental or skeletal fluorosis—causing white spots on teeth and changes to bone density and brittleness—and neurological and reproductive problems (Health Canada, 2010). Water treatment methods used for reduction of fluoride include reverse osmosis, activated alumina, or ion exchange (water softening).

Within this study, the fluoride concentration ranged from 0.02 mg/L up to 3.0 mg/L. Three samples from bedrock wells had concentrations above the Maximum Acceptable Concentration. Fluoride was higher in samples from bedrock aquifers. The median concentration of fluoride in groundwater from unconsolidated aquifers was 0.040 mg/L, compared to 0.18 mg/L in bedrock. The distribution of fluoride concentrations within groundwater samples in the study area is shown in Figure 21.

A previous study of the geochemistry of wells in the Nanaimo Group sedimentary rocks of Yellow Point and Gabriola Island reported a greater occurrence of fluoride above drinking water guidelines in wells constructed in sandstone-dominant units (Earle & Krogh, 2006). Fluoride concentrations are believed to increase in groundwater as a result of base-exchange (cation exchange) processes; for example, fluoride ions are released from and calcium ions are adsorbed onto exchange sites on the surfaces of the rock, resulting in a corresponding increase in pH. Within the sample set for this study, a weak correlation between fluoride and pH was observed in samples from both bedrock and unconsolidated wells and is shown in Figure 22.

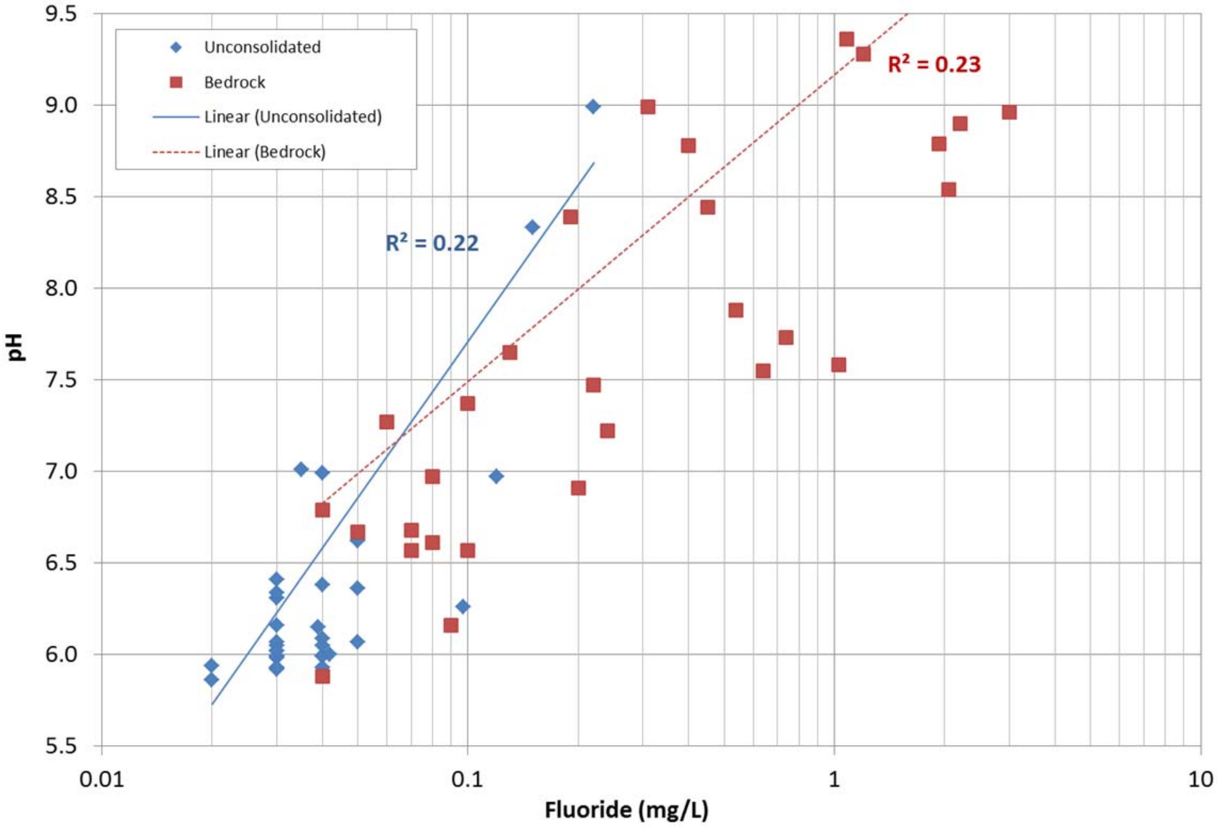

Figure 22 pH versus fluoride in samples from unconsolidated and bedrock wells.

4.4.3 Nitrate

Nitrate, indicated by the symbol NO_3-N when it is reported as nitrate-nitrogen, is a dissolved molecule in water made up of nitrogen and oxygen. As there are few natural geologic sources of nitrate, it is usually present in water as a result of human activities. The ambient concentration of nitrate within groundwater in B.C. is typically very low, less than 0.1 mg/L (Wei, et al., 1993), and concentrations greater than 3 mg/L indicate anthropogenic impacts (Madison & Brunett, 1985; Wei, et al., 2010). Elevated nitrate concentrations in groundwater can often be attributed to non-point sources, such as infiltration of surface water run-off containing chemical fertilizers or animal manure, and septic tanks or sewer discharges (Health Canada, 2013).

The GCDWQ MAC for nitrate in drinking water when measured as nitrate-nitrogen is 10 mg/L (Health Canada, 2014). Nitrate has no taste, smell, or colour in water but can be measured using a field kit or laboratory test. It is a health concern because if a person drinks water with elevated nitrate, it is metabolized and enters the bloodstream, where it can lead to the transformation of haemoglobin, the carrier of oxygen in the blood, to methaemoglobin, which cannot release oxygen to body tissues. The resulting oxygen deprivation or *methaemoglobinaemia,* commonly referred to as blue baby syndrome*,* affects infants, particularly those under six months old and can cause death in extreme cases. Water treatment methods for removal of nitrate include ion exchange, reverse osmosis, and distillation (Health Canada, 2013).

The range and median concentrations of nitrate-nitrogen were higher in groundwater from unconsolidated wells than in water from bedrock wells. In unconsolidated well samples, the median concentration of nitrate-nitrogen was 0.63 mg/L and ranged from 0.079 to 7.25 mg/L, while the median concentration of nitrate in samples from bedrock wells was 0.068 mg/L and ranged from 0.002 to 1.3 mg/L. Nineteen percent of samples had concentrations below the MDL. The median concentration of nitrate for all samples was 0.35 mg/L. The higher nitrate concentrations in unconsolidated wells may be because these wells were located in a shallower aquifer. However, there was no apparent correlation between nitrate concentration and well depth, and wells with moderate to high nitrate were found in both agricultural and rural residential areas. The distribution of nitrate concentrations within groundwater samples in the study area is shown in Figure 23.

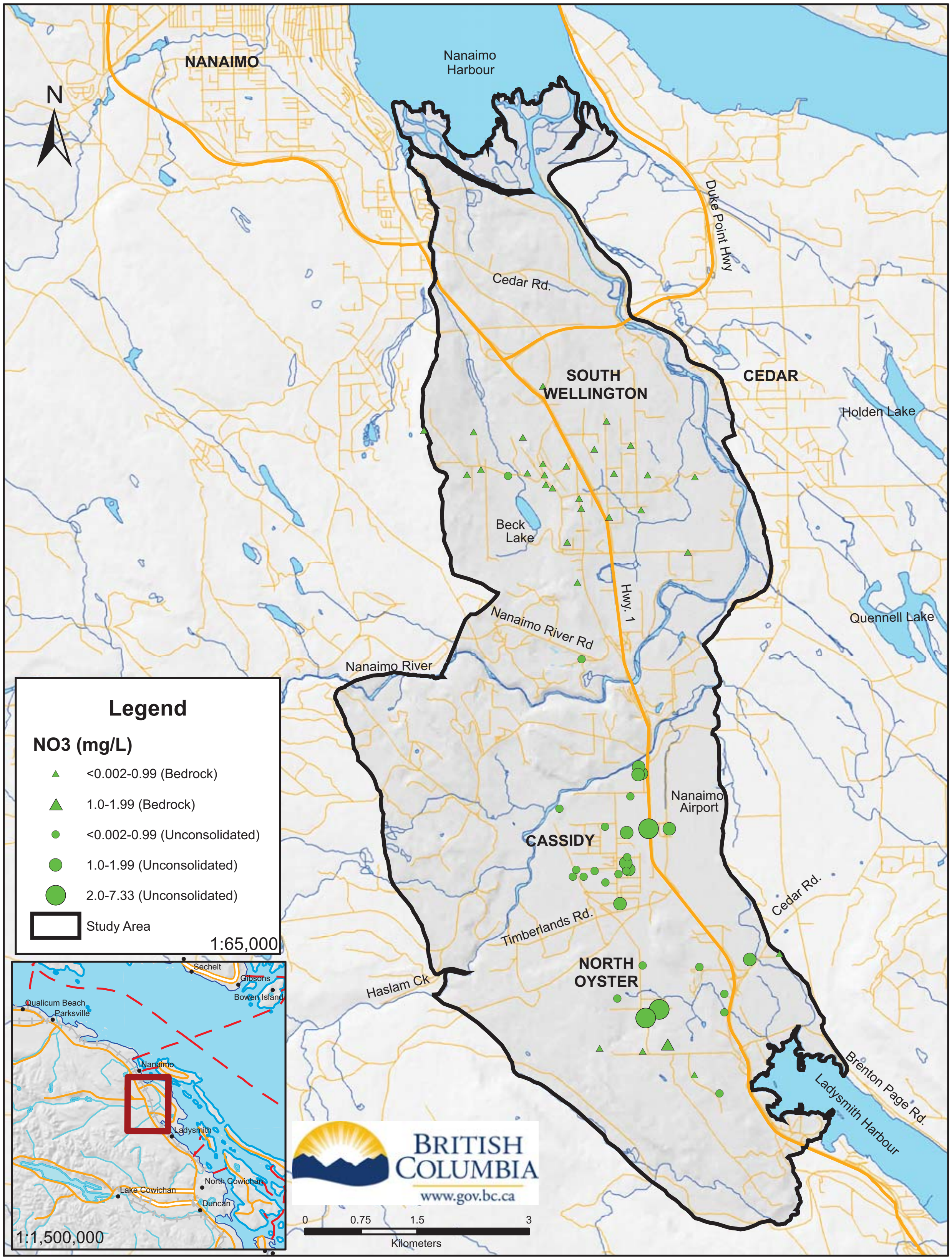

Figure 23 Nitrate concentration in groundwater samples

4.5 Aesthetic Parameters

For some drinking water parameters, the Guidelines for Canadian Drinking Water Quality (GCDWQ) have established an Aesthetic Objective as the water quality upper limit, because these constituents are not associated with specific health concerns but affect the taste or odour of water and its pleasantness for drinking (Health Canada, 2014). Aesthetic parameters analyzed for this study include pH, sulfate, chloride, total dissolved solids, sodium, copper, iron, manganese, and zinc.

The arithmetic mean, median, geometric mean, and minimum and maximum concentrations of these parameters in groundwater from wells in unconsolidated and bedrock aquifers are shown in Table 8. The complete geochemical results for all sites are provided in Appendix A, Table A-1. Box plots comparing the median concentration and measured ranges of these parameters within unconsolidated (sand and gravel) and bedrock aquifers are shown in Figure 24 and Figure 25. A comparison of median concentrations in samples from unconsolidated and bedrock wells is shown in Figure 26.

Table 8 Statistical summary of sample results for aesthetic parameters.

	pH (Field)	Sulphate Dissolved (SO_4)	Chloride Dissolved (Cl)	Total Dissolved Solids (TDS)	Sodium Dissolved (Na)	Copper Dissolved (Cu)	Iron Dissolved (Fe)	Manganese Dissolved (Mn)	Zinc Dissolved (Zn)
Units	**pH units**	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**µg/L**	**µg/L**	**µg/L**	**µg/L**
Reportable Detection Limit (RDL)	na	0.5	0.5	10	0.05	0.05	1	0.05	0.1
Aesthetic Objective (Health Canada)	6.5:8.5 pH units	500 mg/L	250 mg/L	500 mg/L	200 mg/L	1000 ug/L	300 μg/L	50 μg/L	5000 ug/L
Unconsolidated									
Arithmetic mean	6.36	4.7	14	100	11	9.0	9	6.5	16
Median	6.07	4.0	8.7	81	6.0	3.8	5.0	1.0	2.6
Geometric mean	6.33	4.1	9.0	88	7.3	3.7	4.9	1.8	3.5
Min	5.86	1.0	1.6	48	4.0	0.09	1.0	0.16	0.30
Max	8.99	21	150	470	114	49.8	63	49	360
N=32									
Exceedences	**26**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Bedrock									
Arithmetic mean	7.65	45	66	420	124	5.3	80	63	11
Median	7.55	17	18	315	101	3.7	8.5	8.5	2.8
Geometric mean	7.59	16	21	313	77	2.6	16	10	2.4
Min	5.88	0.50	2.4	108	3.9	0.06	2.0	0.35	0.10
Max	9.36	530	920	2700	750	18	787	794	143
N=30									
Exceedences	**10**	**1**	**1**	**6**	**5**	**0**	**2**	**6**	**0**
%<RDL (all)[1]		3%	0%	0%	0%	13%	5%	0%	5%

[1] *Percentage of samples less than RDL (unconsolidated and bedrock)*

4.5.1 pH

The GCDWQ Aesthetic Objective (AO) for pH is from 6.5 to 8.5 pH units (Health Canada, 2014). The reason for establishment of the guideline is primarily related to the effects of high or low pH on water fixtures, distribution systems, and infrastructure (Health Canada, 1979). At pH lower than 6.5, the water may cause corrosion of pipes and fittings, while at pH higher than 8.5, problems with encrustation and scaling are more likely. The pH level also influences the choice and effectiveness of different water treatment methods. In this study, the pH of samples measured in the field ranged from 5.86 to 9.36, and a total of 36 samples exceeded the pH guidelines—26 in unconsolidated wells and 10 in bedrock wells. The median pH of samples from unconsolidated wells was 6.07 and lower than for bedrock wells, which had a median pH of 7.55. In general, the pH of rainfall is low (approximately 5.86) and increases as a result of mineral dissolution and water-rock interaction processes (Drever, 1997), therefore the chemistry of groundwater from deeper bedrock wells is reflective of water that has undergone more geochemical maturation than shallower groundwater sources.

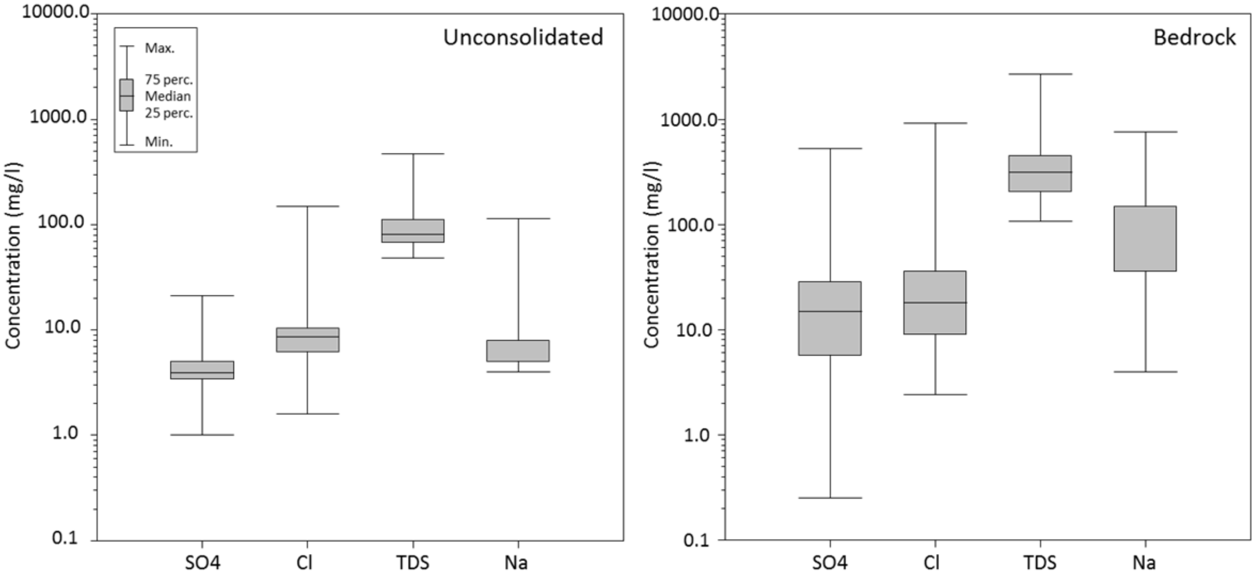

Figure 24 Boxplots of concentrations of aesthetic parameters sulfate, chloride, total dissolved solids, and sodium in unconsolidated and bedrock aquifers.

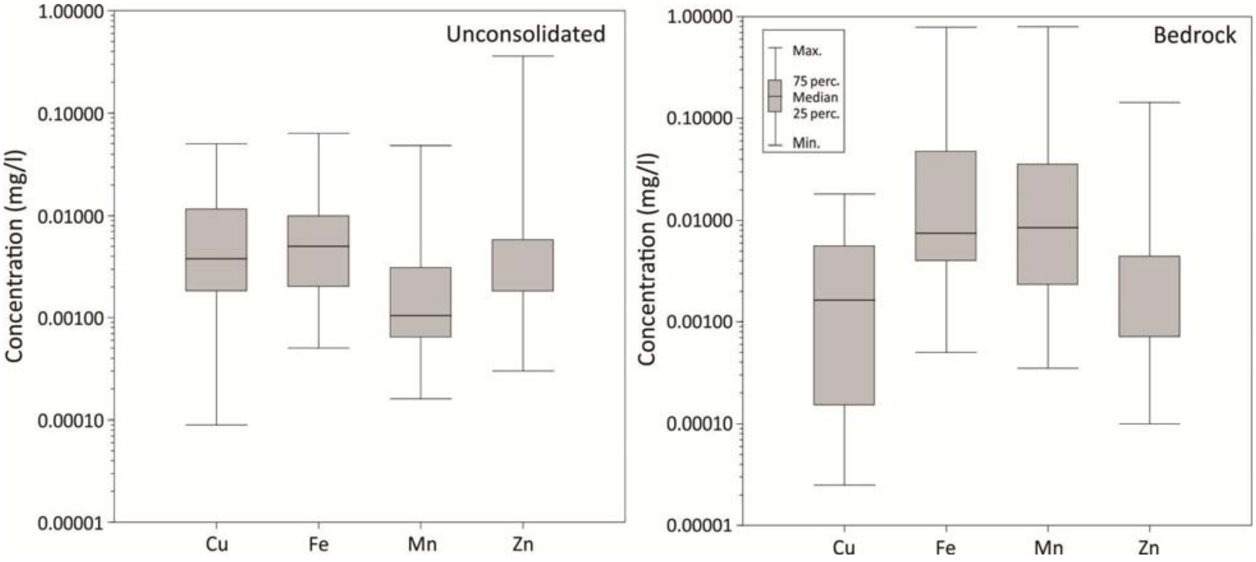

Figure 25 Boxplots of concentrations of aesthetic parameters copper, iron, manganese, and zinc in unconsolidated and bedrock aquifers.

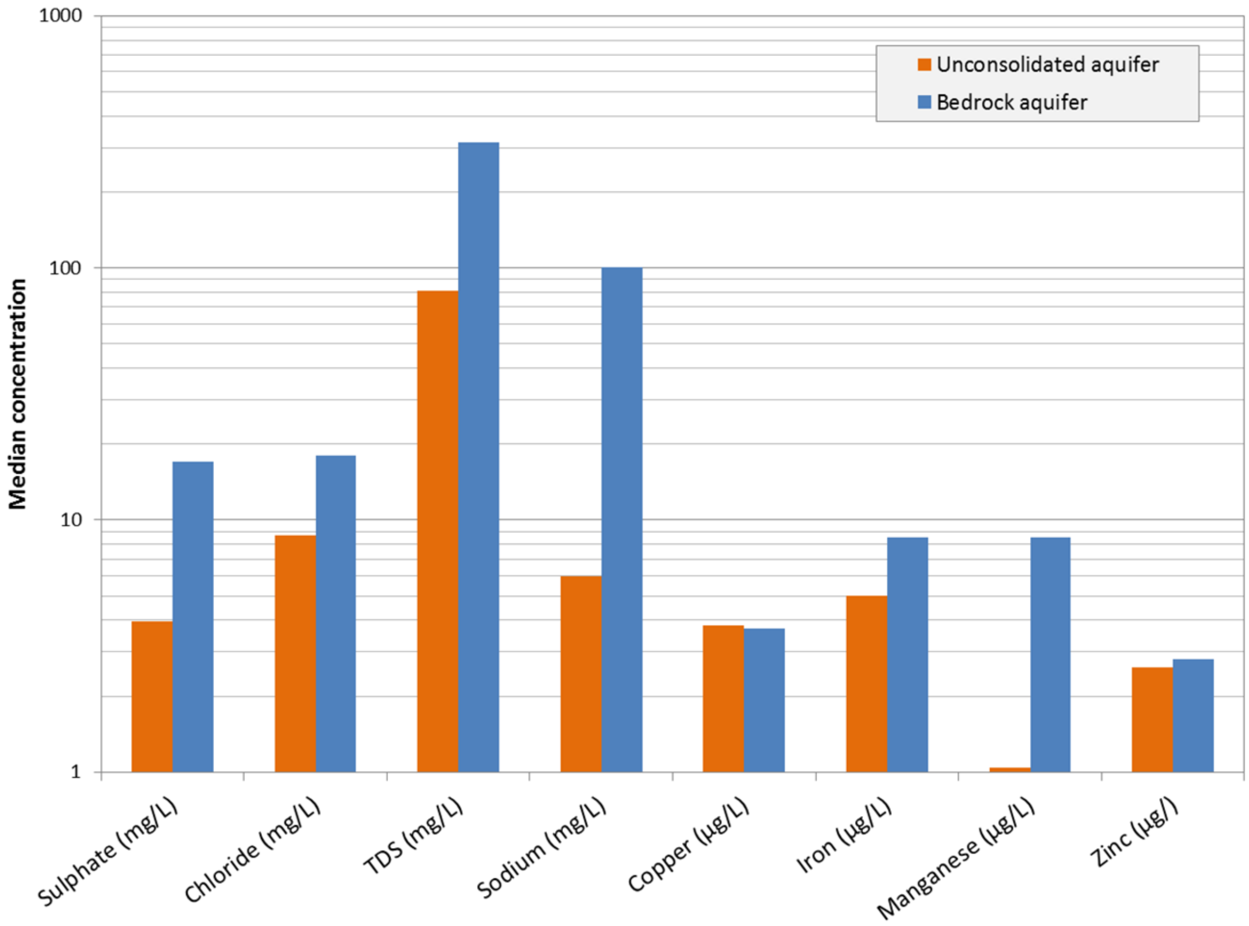

Figure 26 Comparison of median concentrations of aesthetic parameters in unconsolidated and bedrock aquifers.

4.5.2 Sulfate

Sulfate (SO_4^{2-}) is a negatively charged ion dissolved in water. Natural sources of sulfate in groundwater include atmospheric emissions from volcanoes, and sea spray, which enter the aquifer via recharge from precipitation, as well as the dissolution of sulfide minerals such as pyrite, barite, or gypsum (Health Canada, 1987). Sulfate can also originate from industrial discharges from kraft pulp and paper mills, mining and smelting operations, sewage treatment facilities, the manufacturing of fertilizers, dyes, textiles and pesticides, and burning of fossil fuels or organic matter. Other forms of sulfur include hydrogen sulfide gas, which has a characteristic rotten egg odour and is produced by iron- and sulfur-reducing bacteria commonly present in soils and sediments. The GCDWQ AO for sulfate is 500 mg/L (Health Canada, 2014); at concentrations above this, the water may have an unpleasant taste or can cause gastrointestinal irritation, including laxative effects (World Health Organization, 2004). Sulfur can be removed using treatment methods such as reverse osmosis, distillation, ionization, or similar demineralization processes (Health Canada, 1987).

Sulfate concentrations in the study area were low, with a median concentration of 4.0 mg/L (ranging from 1.0 to 21 mg/L) in samples from unconsolidated wells and a higher median of 17 mg/L (ranging from 0.50 to 530 mg/L) in samples from bedrock wells. One sample from the South Wellington area exceeded the water quality guidelines.

4.5.3 Chloride

Chloride is an element found in salt (NaCl) and is naturally occurring in groundwater due to the dissolution of minerals in soil and rocks. It can also originate from infiltration of surface water containing road salts, pollution from septic systems, industrial discharges, or irrigation drainage (Health Canada, 1979). In coastal areas, elevated chloride concentrations may indicate the intrusion of marine saltwater into a freshwater aquifer (Klassen, et al., 2014). The GCDWQ Aesthetic Objective for chloride in drinking water is 250 mg/L (Health Canada, 2014). At levels above this, the water will have a noticeable salty taste and may enhance corrosion of water pipes and plumbing fixtures. Chloride concentrations exceeding 250 mg/L are generally not considered to be a health risk, except for individuals required to follow a low-salt diet. Chloride can be removed from water through reverse osmosis or distillation.

The chloride concentrations measured in this study ranged from 1.6 to 920 mg/L and were likely naturally occurring from the interaction of groundwater with rocks containing mineral salts. The median concentration of chloride in bedrock wells was 18 mg/L, which was higher than samples from unconsolidated wells (median chloride concentration of 8.7 mg/L). One sample from a bedrock well exceeded the GCDWQ AO.

4.5.4 Total Dissolved Solids

Total dissolved solids (TDS) is a measure of the combined concentration of all dissolved inorganic salts in the water along with lesser amounts of organic material. Calcium, magnesium, sodium, potassium, bicarbonate, chloride, sulfate, and nitrate all contribute to TDS, which may come from natural sources (such as minerals that dissolve into water as it infiltrates the ground and aquifer materials) or may be an indicator of contaminants (such as sewage, urban or agricultural runoff, or industrial activity) (Health Canada, 1978). The GCDWQ AO for TDS is 500 mg/L (Health Canada, 2014). Higher concentrations of TDS can indicate that the water is very hard (high concentrations of calcium and magnesium) and unpleasant to drink and can cause mineral deposition, scaling, and corrosion of plumbing fixtures. TDS can be reduced by treatment using reverse osmosis or electrodialysis; however, methods such as water softening may increase TDS, because the process adds soluble salts.

The spatial distribution of TDS concentrations in the samples is shown in Figure 27. Within samples from unconsolidated wells, the median TDS was 81 mg/L and ranged from 48 to 470 mg/L. In bedrock wells, the TDS readings were much higher, ranging from 108 to 2700 mg/L, with a median of 315 mg/L. A total of 7 samples exceeded the GCDWQ for TDS—all of these from bedrock wells in the South Wellington area. Bedrock wells with naturally high dissolved salts are known to occur in South Wellington, where these minerals have dissolved into the groundwater from shale and sandstone of the Nanaimo Group, sedimentary rocks, which were originally formed within a marine setting.

4.5.5 Sodium

Sodium is commonly found in groundwater because most rocks and soil contain sodium compounds that are dissolved as water infiltrates the ground. Within fractured sedimentary bedrock such as the sandstone and shale of the Nanaimo Group, sodium concentrations are known to increase in older, mature groundwater as a result of cation exchange, during which calcium and magnesium are adsorbed and sodium is released from negatively charged adsorption sites on the rock matrix (Allen & Suchy, 2001). Elevated sodium concentrations in groundwater can result from industrial pollution and from infiltration of surface water containing road salt. In coastal areas, elevated sodium concentrations may indicate saltwater intrusion, although in general chloride is a better indicator of intrusion (Klassen, et al., 2014).

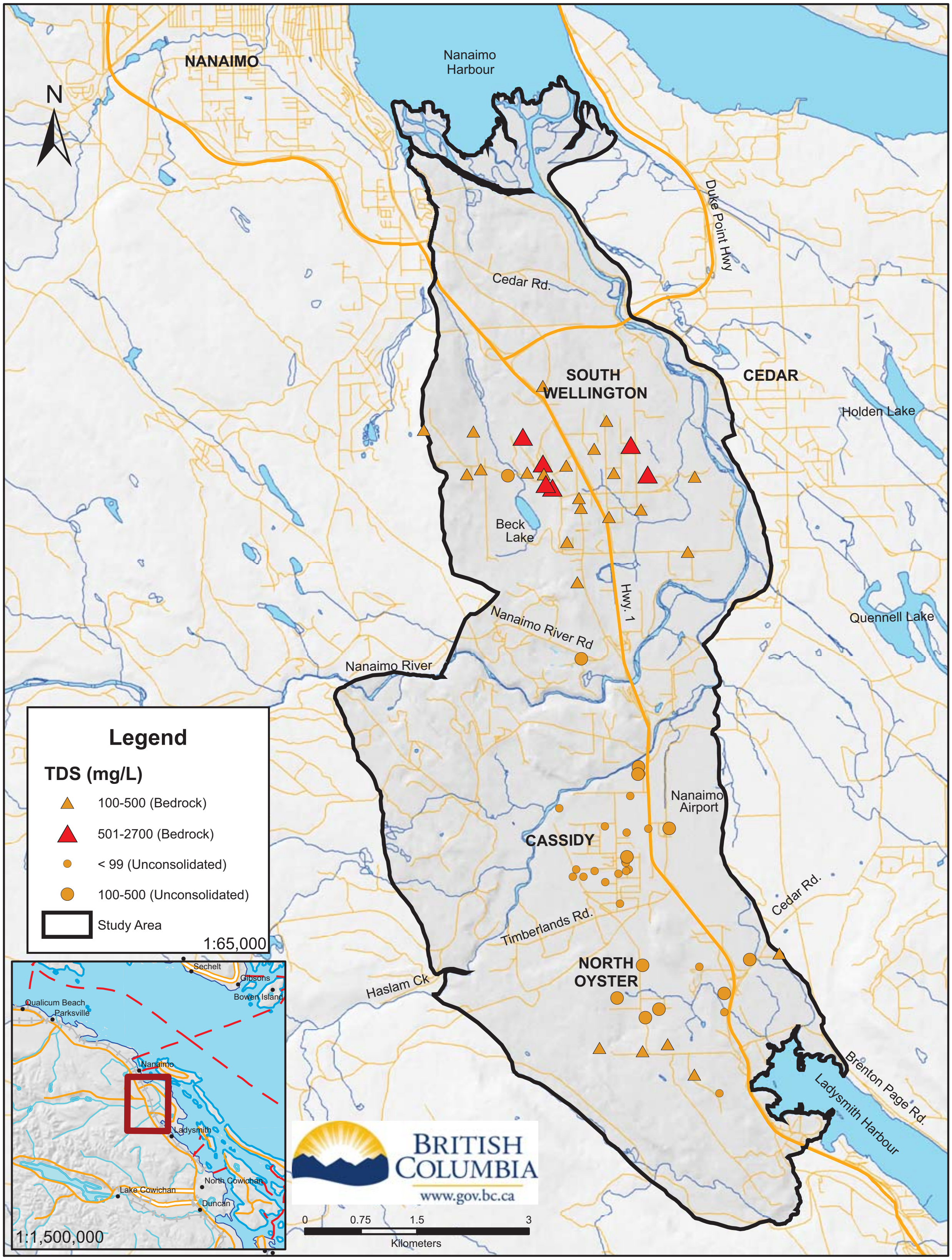

Figure 27   TDS concentration in groundwater samples

The GCDWQ AO for sodium in drinking water is 200 mg/L (Health Canada, 2014). A concentration of sodium exceeding the guideline may produce an unpleasant taste but is generally not considered to be a health risk. Individuals with sodium restricted diets are recommended to avoid consumption of water containing more than 20 mg/L of sodium. Elevated sodium levels can also make water unsuitable for irrigation. Treatment methods effective for removal of sodium include reverse osmosis and distillation (Health Canada, 1992).

Within samples from unconsolidated aquifers, sodium concentrations were very low. The median sodium concentration was 6.0 mg/L, and the range was from 4.0 to 115 mg/L. Sodium concentrations in samples from bedrock aquifers were much higher, ranging from 3.9 mg/L to 750 mg/L, with a median of 101 mg/L.

4.5.6 Iron and Manganese

Iron and manganese are metals that are commonly present in groundwater as a result of the dissolution of iron- and manganese-bearing minerals and rocks. Elevated concentrations of iron may also originate from industrial or sewage effluent, acid mine drainage, and landfill leachate (Health Canada, 1978). Sources of manganese from human activities include air or liquid waste discharges from industrial steel and battery manufacturing, and chemical production (Health Canada, 1987).

Elevated concentrations of iron or manganese cause staining of plumbing fixtures or laundry and give the water an unpalatable taste. At near-neutral pH, iron forms a rust-coloured silt in water. Iron also provides a nutrient source for iron bacteria, which produce a slimy coating within water pipes and distribution systems. While iron is an essential nutrient, it can be harmful in larger quantities. The AO for iron is 0.3 mg/L.

Like iron, manganese forms deposits within pipes and water tanks and black particulates in water. It is also an essential trace nutrient, which is not thought to be harmful to health at typical levels of exposure in food and water. The GCDWQ AO for manganese is 30 µg/L (Health Canada, 1987). A more recent study in Quebec reported that manganese may be associated with neurotoxic effects in and reduction of the intelligence quotient (IQ) of children exposed to low to moderate concentrations in groundwater (median concentrations of 34 µg/L). Treatment to remove iron and manganese is typically done at the same time, using methods such as injection of chlorine, potassium permanganate, or ozone, which causes the metals to form a solid precipitate that is then allowed to settle or is filtered out (Health Canada, 1978).

Iron concentrations ranged from 1.0 mg/L to 787 mg/L, and the median concentration was 5.0 mg/L in samples from unconsolidated wells and 8.5 mg/L in samples from bedrock wells. Two samples from bedrock wells exceeded the drinking water quality guidelines. Iron concentrations of samples in the study area are shown in Figure 28.

In comparison to iron, there was a greater difference in manganese concentrations in different aquifer types. Within unconsolidated wells, the median manganese concentration was 1.0 mg/L and the range was from 0.16 to 49 mg/L, while in samples from bedrock wells, the median was 8.5 mg/L and the range was from 0.35 to 794 mg/L. Six samples exceeded drinking water quality guidelines, all in bedrock aquifers. The spatial distribution of manganese concentrations in the samples is shown in Figure 29.

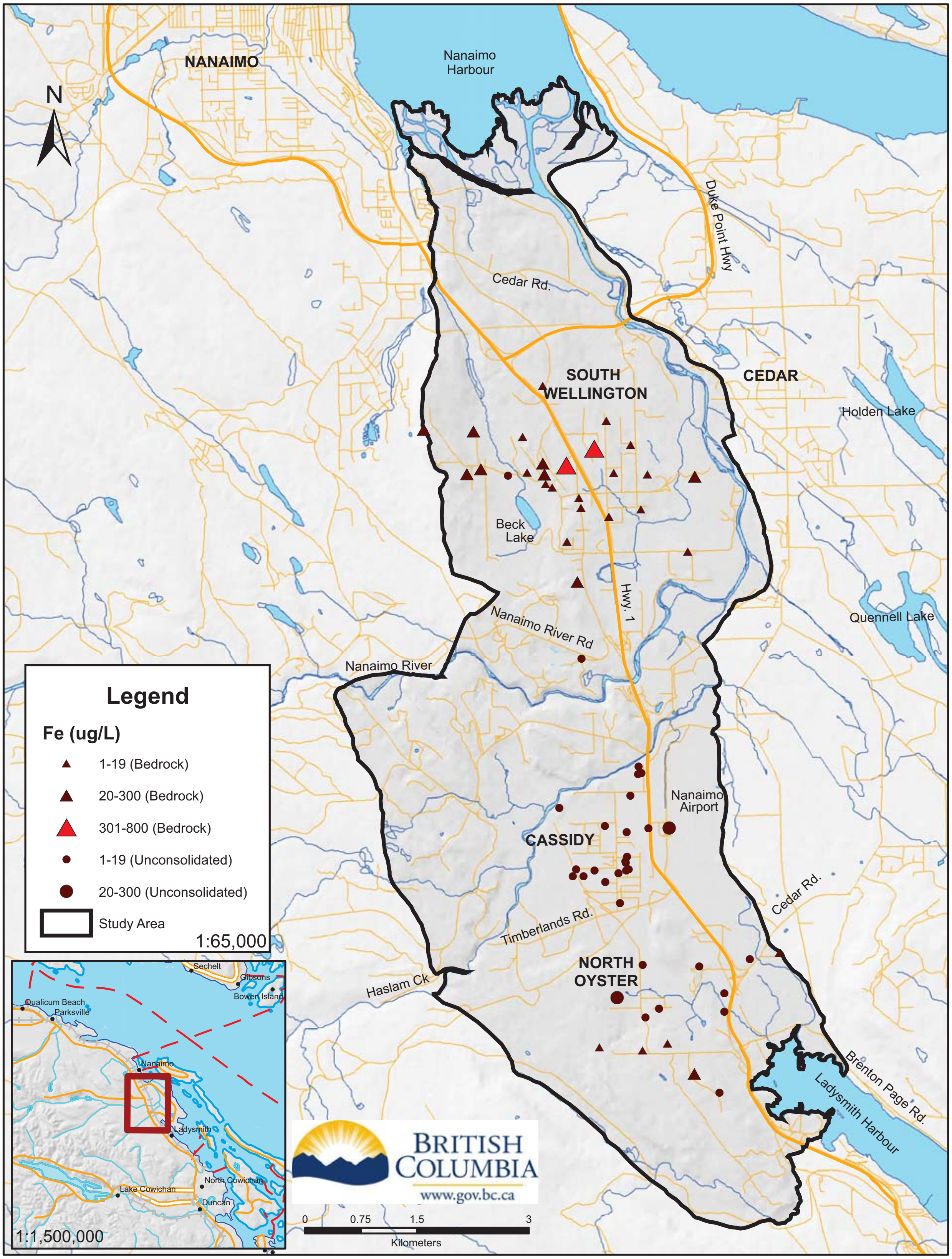

Figure 28   Iron concentration in groundwater samples

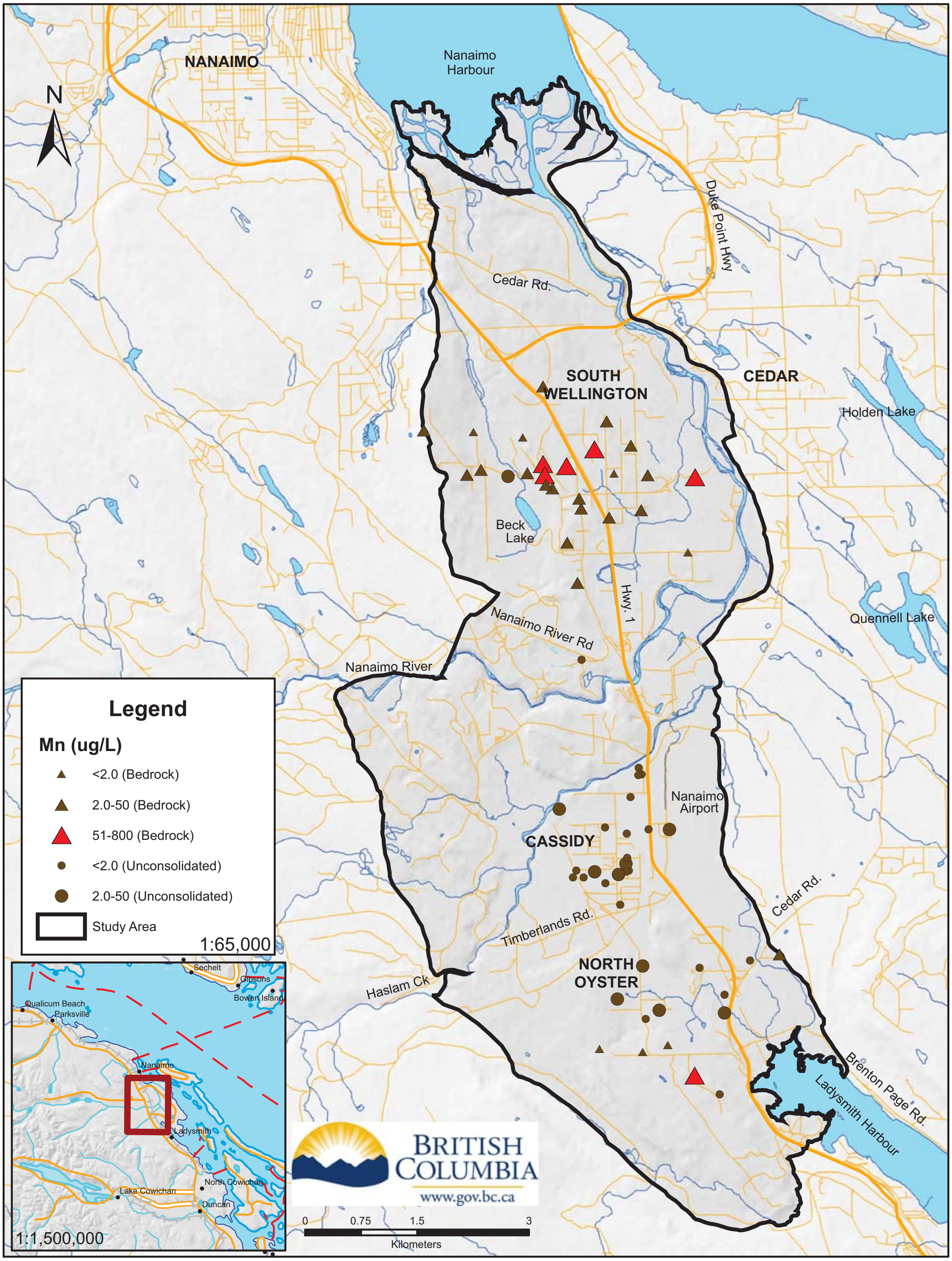

Figure 29 Manganese concentration in groundwater samples

4.5.7 Copper and Zinc

Copper is a metal found in mineral form in some rock types and is also present in drinking water that has been transmitted through copper pipes. Other human-derived sources of copper include pesticides, such as fungicides used for wood preservation (Health Canada, 1992).

Copper is an essential trace element for human health, and intake of less than 2 mg/day from food, water, and other sources may be associated with anemia. The GCDWQ AO for copper is 1.0 mg/L (1000 µg/L), because at this concentration or higher, the water may have an unpleasant, metallic taste, and may cause green stains on plumbing fixtures and laundry. At higher concentrations, copper can also enhance the corrosion of metal pipes and solder containing aluminum or zinc. Gastrointestinal irritation may occur from ingestion of greater than 5 mg/d of copper (combined exposure from drinking water and food), and toxic effects may be noted at 15 mg/d or higher (Health Canada, 1992).

In this study there were no samples that exceeded the GCWQ for copper, and the overall concentrations were very low compared to drinking water quality guidelines. The median concentration was slightly higher in samples from unconsolidated wells (6.0 µg/L) than in samples from bedrock wells (3.7 µg/L), and the range was from 0.06 mg/L up to 49.8 µg/L in samples from all sources. The dissolution of copper and other metals is pH dependent, therefore the higher concentration in samples from unconsolidated wells may relate to the lower average pH in groundwater from these sources.

Zinc is another metal that is essential for human metabolism; it is mainly ingested through food. The CGDWQ AO for zinc is 5 mg/L (5000 µg/L) because of the unpleasant taste of water containing zinc at higher concentrations than this. Man-made sources of zinc include galvanized iron and steel pipes and industrial discharges (e.g., from metal processing, textile dying, printing, and battery manufacturing industries). Concentrations of zinc in drinking water are typically low (Health Canada, 1979).

In South Wellington-Cassidy-North Oyster, zinc concentrations in samples were considerably below the AO, ranging from 0.10 to 360 µg/L, with a median concentration of 2.6 µg/L in samples from unconsolidated wells and 2.8 µg/L in bedrock wells.

4.6 Microbiology

Microbiological parameters that are commonly sampled in groundwater include total coliform bacteria and *Escherichia coli* (*E. coli*) bacteria. With the exception of some species of *E. coli*, these bacteria are usually not harmful themselves but are used as an indicator that other potential pathogenic organisms may be present in the water (Janicki, 2011; Health Canada, 2013). For example, total coliforms are a type of bacteria that are naturally present in soil, organic materials such as leaf litter, and in surface water (Health Canada, 2012). The presence of total coliforms may indicate that surface water or groundwater from shallow infiltration is getting into the well and consequently that pathogens (such as *Giardia*, *Cryptosporidium*, viruses, and other harmful organisms found in untreated surface water) may also be present in the groundwater.

E. coli are a family of bacteria that live only in the digestive systems of warm-blooded animals, including humans. Potential sources include surface water or shallow groundwater contaminated by septic or animal waste. If *E. coli* are detected, this is an indicator that the groundwater or the sample itself have been contaminated by fecal matter and therefore pathogens may also be present (Health Canada, 2013).

The drinking water guideline for total coliforms and *E. coli* is zero (<1) detectable per 100 mL. In untreated groundwater, it is not unusual to see total coliforms between 1 and 10 CFU/100 mL, and this may not be a major cause for concern. However, if *E.coli* are found, this may be a cause for concern, and steps should be taken to disinfect and retest the well, as described in Table 9 (Ministry of Environment, 2008).

Table 9 What to do if a groundwater sample from your well tests positive for E.coli bacteria.

- ☐ Until you are able to re-test the well, boil the water for a minimum of one minute before using it for drinking or preparing food;
- ☐ Disinfect the well and distribution system (water pipes);[1]
- ☐ A few days after the well has been disinfected, re-test the water for bacteria ensuring that steps are taken to avoid introducing contamination to the sample;
  Sterile sampling technique:
    - -Disinfect the sampling point and remove aeration screens from tap;
    - -Use sterile gloves or wash hands thoroughly with soap before collecting the sample;
    - -Hold the bottle cap in your hand while taking the sample and avoid touching the inside of the cap;
    - -Maintain the sample at a cold temperature (<4°C) and deliver it to the laboratory within 24 hours after it was collected;
- ☐ Assess the well for possible causes of contamination and fix these (see section 3.4 for a well inspection checklist).

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[1] For details refer to the Ministry of Environment resource: "Water well disinfection using the simple chlorination method." www.env.gov.bc.ca/wsd/plan_protect_sustain/groundwater/wells/factsheets/PFRA_simple_chlorification.pdf

In this study, 63 wells were sampled for bacteria (total coliforms and *E. coli*), including 12 duplicates, for a total of 75 bacterial samples. The results are summarized in Table 10 and Figure 30 and in Appendix A, Table A-2. Neither total coliforms nor *E. coli* were present in almost half of all samples (32 samples, 48%, excluding duplicates), while a smaller number (28 samples, 44%) had total coliforms present. Total coliform concentrations ranged from less than 1 (not detected) up to 600 Colony Forming Units (CFU) per 100 mL. Only 3 samples (5%) had both total coliforms and *E.coli*, indicating that groundwater in the well may have been contaminated with fecal matter; however, two of these sites had only 1 CFU/100 mL (possibly attributable to sampling error), and only one site had a high concentration of *E. coli* (250 CFU/100 mL).

A link is often made between the type of aquifer and its vulnerability to contamination. In general, bacterial indicators and pathogens are present at lower concentrations in groundwater than in surface water (rivers and lakes). As water infiltrates an aquifer, the pathogens may be filtered out, attach to sedimentary particles, or die off (McDowell-Boyer, et al., 1986).

Within an unconfined aquifer, where there are no overlying low-permeability sediments, such as clay or till, or where groundwater levels are shallow, there is likely to be relatively rapid movement of water from the surface into the aquifer, and therefore bacteria or other pathogens are more likely to be present (Ministry of Health, November 2015). For this reason, excavated (dug) wells commonly contain total coliform bacteria that are naturally present within soil and shallow sediments. Within a bedrock aquifer, groundwater is transported within small fractures and cracks in the rock, but very little movement occurs within the solid rock itself; as a result, the speed of groundwater movement may be more rapid than in an unconsolidated aquifer, where groundwater moves through the complex pathways between grains of sand and gravel. If a well in a bedrock aquifer is recharged by water from shallow fractures and there is rapid movement into the well during recharge events such as a heavy rainfall, total coliforms are more likely to be present. If there is a source of potential pathogens, such as onsite sewage disposal or animal waste, then these may also enter the shallow groundwater and affect water quality in the well.

Table 10 Summary of bacteriological sample results.

Bacteriological sample summary: N=63 wells*		
Samples with no bacteria	32	51%
Samples with total coliform and *E. coli* bacteria	3	5%
Samples with only total coliform bacteria	28	44%
Total	63	100%
Wells in unconsolidated aquifers with total coliforms* (N=25)	11	44%
Wells in unconsolidated aquifers with *E. coli*	1	4%
Wells in bedrock aquifers with total coliforms* (N=30)	16	53%
Wells in bedrock aquifers with *E. coli*	1	3%
Dug wells with total coliforms* (N=8)	7	88%
Dug wells with *E. coli*	1	13%
Wells with maintenance concerns	21	33%
Wells with total coliforms that had maintenance concerns	13	21%
Wells with *E.coli* that had maintenance concerns	1	2%
Wells with no bacteria that had maintenance concerns	8	13%

**Excluding duplicate samples*

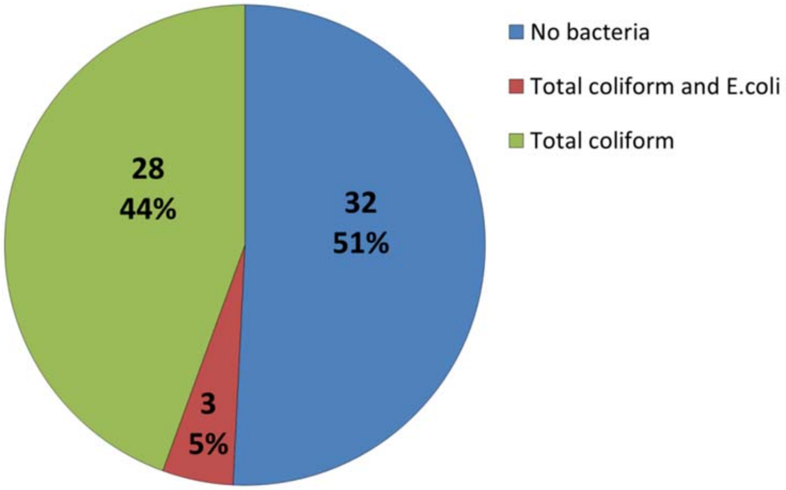

Figure 30 Proportion of wells with no bacteria, total coliforms or total coliforms and E. coli

In this study, a slightly higher proportion of bedrock wells (53%) tested positive for total coliforms compared to wells constructed in unconsolidated materials (44%). Nearly all (88%) dug wells had total coliforms. The occurrence of *E.coli* was uncommon—only three wells sampled had *E.coli*—and did not appear to be related to aquifer type.

Contamination from bacteria and other pathogens may also occur where there is a problem with well construction or maintenance (Macler & Merkle, 2000). Comparing our analytical results to the information gathered during well inspection, it was found that 44% of the wells with total coliforms had identified maintenance concerns (e.g., buried wells or wells with low stick-up, inadequate well cap, or standing water around the well head), while at 13% of sites where well maintenance concerns were identified, the samples contained no bacteria. Within this area there are also a high proportion of older wells which were installed without a bentonite surface seal, because they were constructed before November 2005, when new standards of well construction were required under the *Water Act*, Groundwater Protection Regulation (Province of British Columbia, 2009). Refer to Section 4.7 for more discussion of the results from the well inspections.

4.7 Wellhead Protection

As described in section 3.4, at the time of sampling, each well was inspected for compliance with the *Water Act*, Ground Water Protection Regulation (Province of British Columbia, 2009), and other general concerns related to well protection and maintenance. At the majority of locations (40 sites, 66%), there were no concerns noted. At eight sites, the well did not have an adequate cap; for example, the well was partially covered using a metal plate, there was a sanitary seal cover but it was in poor condition or with gaps/openings that could allow contaminants to enter, the cap was not affixed properly, or there was no well cap at all. At three locations, the well head was buried below ground and not visible, which is a significant concern because soil microbes and other contaminants could easily be entering the groundwater through seepage from sediments overlying the well. At four sites there was a depression or excavated area around the well, which promotes preferential movement of surface water drainage toward the well head. Standing water around the well or well location in a marshy/wetland area was noted at three sites. A very short stickup was observed at one site, and at another there was a cut in the casing close to ground level. At one site there was an unused dug well at the property. If any concerns about well protection were observed, FLNRO staff followed up with well owners to provide information on how to address them; this was especially important in cases where the sampling results indicated that poor well maintenance was causing a water quality problem; e.g., presence of total coliform or *E. coli*. Some pictures of typical well heads are included in Figure 31 to Figure 38.

Recommended improvements that would help to protect wells from contamination include replacing or upgrading caps and removing below ground well enclosures. For example, dug wells are often vulnerable to contamination because they access groundwater from a shallow source and also because the well cover or cap may be inadequate for keeping out water and contaminants. Well owners should ensure that the cap or cover is sealed, such as with a plastic lockable hatch or metal lid that covers the entire well, not just the access port. See picture in Figure 32 and refer to the Ministry of Environment publication, "Best Practices for Dug Wells."

Similarly, wells within outside enclosures or pits are a particular concern, because these enclosures provide a preferred habitat for vermin such as rodents and insects and also can allow standing water to accumulate around the well, as shown in Figure 37. Wells in pits should be upgraded so that the well head is located sufficiently above ground. Refer to the publication, "Upgrading Wells in Pits."

If a well is located within a pump house, the building should be kept clean, tidy, and in good repair, and solvents, paints, fuel, pesticides, and any other hazardous materials must never be kept in the pump house. Any foreign materials such as these must be kept a minimum of 3 m distance from a well. Unused wells must be properly closed (backfilled) if there is no intent to use them in the future.

Figure 31 Older dug well with access hatch in the centre. Surface water and contaminants can enter in the gap around the cement insert/cover

Figure 32 Dug well retrofitted with sealable lid that can be removed by loosening the bolts, and when in place provides a water-tight and vermin-proof seal

Figure 33 Well in pump house with sanitary seal type cap that has been partially removed allowing contaminants to enter the well

Figure 34 Well in pump house with sanitary seal that is properly installed and prevents contaminants from entering the well

Figure 35 Well head located outside within wooden enclosure, with casing cut low to ground and no cap. The sample from this source had 260 CFU/100 ml total coliforms but no E. coli

Figure 36 Well head located outside with pitless adapter and bolted cap is protected from contamination

Figure 37 Well head located within a cement enclosure allowing accumulation of standing water around the well making it vulnerable to contamination

Figure 38 Well head located outside. Casing has been extended above ground with a bolted gasket so standing water does not accumulate within a depression around the well

4.8 CCME Water Quality Index

The Canadian Council of Ministers of the Environment (CCME) developed a Water Quality Index (WQI) that ranks water quality based on three factors: the percentage of parameters that do not meet the objective; the percentage of tests that do not meet the objective; and the amount by which failed test values do not meet the objective (Canadian Council of Ministers of the Environment, 2001). The WQI was developed from the Guidelines for the Protection of Aquatic Life (Canadian Council of Ministers of the Environment, 1999). The WQI does not evaluate water potability nor distinguish between inherent water quality and human impacts. The WQI was used to characterize the South Wellington, Cassidy, and North Oyster groundwater analytical results in a way that facilitates comparison of water quality in separate aquifers. The WQI has five categories, with values ranging from 0 to 100. The highest value, 100, represents "excellent" water quality and the lowest value, 0, represents "poor" water quality. The CCME WQI was calculated according to the user manual but with the following exceptions:

a. Bacteria results were not included when the CCME WQI was calculated. The WQI was developed by comparing results to aquatic life guidelines, and bacteria results skew the WQI due to the 0 CFU/100 mL drinking water guideline.
b. Parameters without either an AO or a MAC were excluded from the WQI calculations.
c. The pH values from the field were used, rather than laboratory values.
d. Values below the Reported Detection Limit (RDL) were treated as equal to the RDL value.
e. For each aquifer type (i.e., unconsolidated or bedrock), the WQI was calculated using the results for each individual sample location, and the median of the results for all sites in the aquifer was then calculated.
f. For unconsolidated aquifers in Cassidy and North Oyster, there was no differentiation or separate calculation made for shallow compared to deep aquifer units (i.e., the results for aquifers 160 and 161 were combined).
g. For bedrock aquifers, the majority of sample sites were in the South Wellington area, but the results from a smaller number of bedrock wells in North Oyster were also included (i.e. the results for aquifers 165 and 964 were combined).

The CCME WQI was 93 for the unconsolidated aquifers in Cassidy and North Oyster, which corresponds to a ranking of "good," meaning that "the water quality is protected with only a minor degree of threat or impairment, and that conditions rarely depart from natural or desirable levels." The CCME WQI was also 93 for bedrock aquifers in South Wellington and North Oyster, with a rank of "good." For comparison, in a previous study, aquifers 186/187 in the Lower Cowichan Valley had a CCME WQI of 100 or "excellent," indicating close to natural or pristine conditions (Barroso, et al., 2013).

5. SUMMARY AND RECOMMENDATIONS

An evaluation of groundwater quality in the South Wellington, Cassidy, and North Oyster areas of eastern Vancouver Island found that overall groundwater quality within the study area is good. Within the sample set from 62 sites, there were only four samples with parameters that exceeded drinking water quality guidelines for fluoride, and no other samples had parameters which exceeded of the guidelines for other health-related constituents. Although there were no samples where the concentration of arsenic exceeded of drinking water guidelines, 10% of samples had arsenic concentrations between 1 and 6 μg/L, which may be a concern when considering long-term exposure in drinking water. Nitrate is an indicator of anthropogenic impacts at concentrations greater than approximately 3 mg/L; in this study area, only three samples had nitrate above 2 mg/L, the maximum nitrate concentration was 7.25 mg/L, and no samples had nitrate-nitrogen above drinking water guidelines. In total, 95% of samples from unconsolidated wells had nitrate concentration below 2 mg/L, while 95% of samples from bedrock wells had nitrate below 0.6 µg/L.

At a small number of sites, drinking water quality guidelines were exceeded for aesthetic parameters such as manganese (6 samples, 10%), total dissolved solids (6 samples), sodium (5 samples, 8%), iron (2 samples, 3%), chloride (1 sample), and sulfate (1 sample).

In general, the concentrations of metals and dissolved constituents were higher in wells constructed within fractured sedimentary bedrock (sandstone and shale of the Nanaimo Group) than in wells constructed in unconsolidated fluvial and glaciofluvial sand and gravel deposits. The samples were collected during the spring and early summer (April to June), and many dissolved constituents may be expected to reach higher concentrations during the late summer to early fall when groundwater levels are lower and there is less dilution.

Differences in geochemistry between sites were attributable to natural dissolution processes and water-rock interactions. The majority of samples, including most unconsolidated wells and several from bedrock wells, had Ca-HCO_3 type water, which is considered “fresh” or from more recent sources of recharge. The second most common water type was categorized as Na-HCO_3 type and mostly from bedrock well sources, where the groundwater quality has been influenced by cation exchange. Only three samples of the Na-Cl water type.

All four classified aquifers in the study area are important sources of drinking water for local communities. While the aquifers range in relative vulnerability from high (for the Upper Cassidy aquifer) to moderate (the bedrock aquifers in North Oyster and South Wellington) down to low (the lower Cassidy aquifer), all may be susceptible to anthropogenic impacts from land use, including industry, agriculture, and rural residential activities such as discharge of septic waste. The presence of bacteria within groundwater samples was in many cases associated with problems with well construction and maintenance, and well owners within this study benefitted from information provided on maintenance and protection of their wells.

The following are recommendations from this work:

a. Enhance the groundwater monitoring network in this area. Following completion of this study, a new Provincial observation well (OW 435) was constructed in the South Wellington area, and two new clustered observation wells (OW 436 and OW 427) were installed on Timberlands Road in Cassidy to monitor water levels in both the Upper Cassidy and Lower Cassidy aquifers. Observation wells enable monitoring of groundwater levels over time and are periodically sampled for groundwater quality analysis. The value of the network is in developing a record of natural seasonal variability in groundwater levels in order to evaluate changes resulting from inputs from precipitation (recharge) and outputs from groundwater extraction and use (discharge).
b. Evaluate hazards and risks to groundwater quality. Future studies could include identifying existing and potential hazards from different land use activities and evaluating the risk of groundwater contamination based on the relative vulnerability and presence of hazards in each area.
c. Find ways to consider groundwater protection in land use decisions. For example, identifying and protecting key groundwater recharge areas or limiting certain land uses in areas of high intrinsic vulnerability.
d. Encourage best management practices for operation and testing of private wells through public outreach and education. Groundwater quality can be impacted by failing septic systems, by

wells situated too close to a septic system, or by poor well construction methods and maintenance (such as absence of a surface seal). Well owners will also benefit from knowledge of potential risks, such as naturally occurring arsenic or anthropogenic nitrate, that can impact their drinking water source. Often these risks can be eliminated by upgrading the well construction or by disinfecting or treating the groundwater for the contaminants of concern. All well owners are encouraged to ensure that the water from their wells is safe to drink by testing it for bacteria once or twice per year (e.g., during the wet and dry seasons) and for geochemical parameters, including metals, every three to five years. As of November 2013, the Regional District of Nanaimo (RDN) has offered rebate funds to encourage residents to test their well water quality (full spectrum analysis) to identify and understand water quality concerns and also to upgrade their well construction (surface seal, casing stick up, cap, etc.) to protect water quality. For more information on these programs, refer to the RDN Drinking Water and Watershed Protection Program.

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APPENDIX A: ANALYTICAL RESULTS

Notes

GCDWQ	Health Canada, Guidelines for Canadian Drinking Water Quality (2012)
MAC	Maximum Allowable Concentration (health based guideline)
AO	Aethetic Objective (parameters affecting water taste or odor)
Bold#	Result exceeds drinking water quality guidelines
RDL	Reportable detection limit *RDL varies on different sample dates due to changes in lab procedures for parameters e.g. bromide, antimony, arsenic, berillium, cadmium, chromium, copper, lead, nickel, selenium, silver, thallium, tin, titanium, uranium, zinc, zirconium, and sulfur.
ORP	Oxidation-Reduction Potential
Eh	Oxidation reduction potential relative to a Standard Hydrogen Electrode (calculated from ORP)
CBE	Charge Balance Error (Italics=CBC Exceeds 5%)
NC	Not calculated
NR	Not recorded
<VALUE	Values less than detection limit excluded from statistical calculations
OG	Operational Guideline (GCDWQ) - for water systems requiring treatment, not discussed in report

Table A-1 Field and laboratory geochemical results

				GCDWQ (MAX)		-	-	-	-	-
				GCDWQ (AO)		-	-	**6.5-8.5**	-	-
				Units		**°C**	**µS/cm**	**ph units**	**mV**	**mV**
				RDL*		**Field**	**Field**	**Field**	**Field**	**Calc**
Site	**Well Depth (ft)**	**Well depth (m)**	**Water system**	**Lithology**	**Sample date**	**Temp**	**Cond**	**pH**	**ORP**	**Eh**
24	20	6.1	N	Unconsolidated (dug)	12-Apr-11	10.0	218	**6.38**	139.2	339.2
26	40	12.2	N	Unconsolidated (dug)	12-Apr-11	9.3	101	**5.99**	153.5	353.5
27	27	8.2	N	Unconsolidated (dug)	12-Apr-11	9.0	95	**5.99**	161.8	361.8
33	24	7.3	N	Unconsolidated (dug)	13-Apr-11	9.5	98	**6.05**	248.7	448.7
47	25	7.6	N	Unconsolidated (dug)	21-Jun-11	10.2	153	**5.94**	131.6	331.6
53	UNK	UNK	N	Unconsolidated (dug)	20-Jun-11	12.3	706	6.97	-73.2	126.8
62	12	3.7	N	Unconsolidated (dug)	6-Mar-12	7.7	210	7.01	126.0	326.0
34	48	14.6	N	Unconsolidated	13-Apr-11	9.9	125	**5.93**	249.3	449.3
21	25	7.6	N	Unconsolidated	12-Apr-11	9.1	112	**6.05**	124.2	324.2
23	50	15.2	N	Unconsolidated	12-Apr-11	10.1	110	**5.92**	153.5	353.5
25	52	15.8	N	Unconsolidated	12-Apr-11	9.4	49	**6.31**	120.2	320.2
28	50	15.2	N	Unconsolidated	12-Apr-11	9.5	124	**6.36**	86.2	286.2
29	48	14.6	N	Unconsolidated	13-Apr-11	10.5	45	**5.98**	348.6	548.6
30	25	7.6	N	Unconsolidated	13-Apr-11	9.7	123	**5.99**	282.2	482.2
35	30	9.1	Y	Unconsolidated	14-Apr-11	8.7	47	**5.93**	195.3	395.3
37	87	26.5	N	Unconsolidated	14-Apr-11	9.3	48	**6.07**	201.5	401.5
38	191	58.2	Y	Unconsolidated	14-Apr-11	10.3	111	**6.16**	217.3	417.3
41	UNK	UNK	N	Unconsolidated	20-Jun-11	9.7	112	**6.34**	145.9	345.9
44	45	13.7	N	Unconsolidated	21-Jun-11	11.3	112	**6.07**	130.1	330.1
45	25	7.6	N	Unconsolidated	21-Jun-11	11.5	170	**5.86**	173.6	373.6
46	175	53.3	N	Unconsolidated	21-Jun-11	11.6	123	**6.09**	118.2	318.2
49	40	12.2	N	Unconsolidated	21-Jun-11	10.2	103	**6.02**	140.0	340.0
50	70	21.3	N	Unconsolidated	23-Jun-11	9.9	127	**6.41**	108.5	308.5
52	63	19.2	N	Unconsolidated	20-Jun-11	10.7	107	**6.02**	166.0	366.0
58	39	11.9	N	Unconsolidated	5-Mar-12	9.7	149	**6.15**	137.3	337.3
59	29	8.8	N	Unconsolidated	5-Mar-12	10.1	186	6.62	75.3	275.3
61	48	14.6	N	Unconsolidated	6-Mar-12	9.3	89	**6.00**	142.6	342.6
63	135	41.0	N	Unconsolidated	6-Mar-12	10.4	200	8.33	-189.2	10.8
64	65	19.8	N	Unconsolidated	6-Mar-12	10.2	230	**8.99**	-239.2	-39.2
65	30	9.1	N	Unconsolidated	6-Mar-12	8.9	145	**6.26**	56.0	256.0
66	95	29.0	N	Unconsolidated	7-Mar-12	9.1	238	6.99	82.3	282.3
68	125	38.1	N	Unconsolidated	7-Mar-12	NR	NR	NR	NR	NR
MEAN	58	17.7				10	147	6.36	126.2	326.2
MEDIAN	47	14.2				10	123	6.07	139.2	339.2
GEOMETRIC MEAN	46	14.1				10	124	6.33	NC	NC
MINIMUM	12	3.7				8	45	5.86	-239.2	-39.2
MAXIMUM	191	58.2				12	706	8.99	348.6	548.6
COUNT	32	32	2			32	32	32	32	32

Table A-1 Field and laboratory geochemical results (continued)

Site	Well Depth (ft)	Well depth (m)	Water system	Lithology	Sample date	Temp	Cond	pH	ORP	Eh
				GCDWQ (MAX)		-	-	-	-	-
				GCDWQ (AO)		-	-	**6.5-8.5**	-	-
				Units		**°C**	**µS/cm**	**ph units**	**mV**	**mV**
				RDL*		**Field**	**Field**	**Field**	**Field**	**Calc**
1	100	30.5	N	Bedrock	6-Apr-11	10.6	365	6.57	155.2	355.2
2	110	33.5	N	Bedrock	6-Apr-11	10.5	293	6.57	85.8	285.8
3	UNK	UNK	N	Bedrock	6-Apr-11	9.7	816	7.73	-211.8	-11.8
4	UNK	UNK	N	Bedrock	6-Apr-11	10.0	197	6.67	60.4	260.4
5	UNK	UNK	N	Bedrock	6-Apr-11	10.0	1289	**8.54**	-244.3	-44.3
7	UNK	UNK	N	Bedrock	7-Apr-11	11.0	486	7.37	8.6	208.6
8	239	72.8	N	Bedrock	7-Apr-11	10.5	374	7.27	72.6	272.6
9	220	67.1	N	Bedrock	7-Apr-11	10.0	807	7.88	-235.4	-35.4
10	202	61.6	N	Bedrock	13-Apr-11	10.5	696	7.22	466.3	666.3
12	140	42.7	N	Bedrock	7-Apr-11	11.4	371	6.68	89.2	289.2
13	105	32.0	N	Bedrock	7-Apr-11	11.3	484	8.44	-247.7	-47.7
14	200	61.0	N	Bedrock	11-Apr-11	10.0	1079	6.91	-176.8	23.2
15	105	32.0	N	Bedrock	11-Apr-11	11.5	540	**8.99**	-5.8	194.2
16	265	80.8	N	Bedrock	11-Apr-11	10.5	495	**9.36**	-184.1	15.9
17	345	105.2	N	Bedrock	11-Apr-11	10.0	472	**8.79**	-252.3	-52.3
18	UNK	UNK	N	Bedrock	11-Apr-11	10.4	350	**6.16**	4.2	204.2
22	140	42.7	N	Bedrock	13-Apr-11	9.8	610	6.61	397.2	597.2
31	480	146.3	N	Bedrock	13-Apr-11	8.0	244	7.65	253.4	453.4
32	UNK	UNK	N	Bedrock	13-Apr-11	8.4	234	**5.88**	232.4	432.4
36	168	51.2	N	Bedrock	11-Apr-11	11.7	1062	7.47	64.3	264.3
40	120	36.6	N	Bedrock	20-Jun-11	12.8	771	7.55	-125.4	74.6
42	120	36.6	N	Bedrock	20-Jun-11	12.0	321	**8.78**	17.3	217.3
48	207	63.1	N	Bedrock	21-Jun-11	12.0	1807	7.58	-89.5	110.5
51	220	67.1	N	Bedrock	23-Jun-11	12.4	218	6.97	100.4	300.4
54	140	42.7	N	Bedrock	23-Jun-11	12.3	578	8.39	71.5	271.5
55	315	96.0	N	Bedrock	5-Mar-12	10.5	536	**9.28**	-230.1	-30.1
56	113	34.4	N	Bedrock	5-Mar-12	8.9	137	6.79	64.3	264.3
57	268	81.7	N	Bedrock	5-Mar-12	8.9	325	**8.96**	-257.4	-57.4
60	360	109.7	N	Bedrock	6-Mar-12	9.6	356	**8.90**	-159.1	40.9
67	204	62.2	N	Bedrock	7-Mar-12	NR	NR	NR	NR	NR
MEAN	204	62.1				10.5	563	7.65	-9.5	190.5
MEDIAN	201	61.3				10.5	484	7.55	8.6	208.6
GEOMETRIC MEAN	184	56.2				10.5	472	7.59	NC	NC
MINIMUM	100	30.5				8.0	137	5.88	-257.4	-57.4
MAXIMUM	480	146.3				12.8	1807	9.36	466.3	666.3
COUNT	30	30				30	30	30	30	30
All aquifer types										
MEAN	123	37.4				10.2	347.9	6.99	60.6	260.6
MEDIAN	103	31.2				10.1	218.1	6.62	94.8	294.8
GEOMETRIC MEAN	85	26.0				10.1	236.8	6.91	NC	NC
MINIMUM	12	3.7				7.7	44.7	5.86	-257.4	-57.4
MAXIMUM	480	146.3				12.8	1807	9.36	466.3	666.3
COUNT	62	62				62	62	62	62	62
<DETECTS (#)										
<DETECTS (%)										

Table A-1 Field and laboratory geochemical results (continued)

	GCDWQ (MAX)	**10**	**1.5**	**-**	**-**	**-**	**-**	**-**	**-**
	GCDWQ (AO)	**-**	**-**	**-**	**-**	**-**	**-**	**500**	**250**
	Units	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**
	RDL*	**0.002**	**0.010**	**0.50**	**0.5**	**0.5**	**0.5**	**0.5**	**0.50**
Site	**Lithology**	**Nitrate (N)**	**Fluoride (F)**	**Alkalinity (Total as CaCO3)**	**Alkalinity (PP as CaCO3)**	**Bicarbonate (HCO3)**	**Carbonate (CO3)**	**Sulphate Dissolved (SO4)**	**Chloride Dissolved (Cl)**
24	Unconsolidated (dug)	0.303	0.04	51	<0.5	63	<0.5	3.8	33
26	Unconsolidated (dug)	0.334	0.04	38	<0.5	46	<0.5	3.4	5.9
27	Unconsolidated (dug)	0.079	0.04	39	<0.5	47	<0.5	3.1	4.4
33	Unconsolidated (dug)	0.369	0.04	29	<0.5	35	<0.5	2.6	9.6
47	Unconsolidated (dug)	1.93	0.02	47	<0.5	58	<0.5	6	8.3
53	Unconsolidated (dug)	0.286	0.12	200	<0.5	250	<0.5	21	150
62	Unconsolidated (dug)	2.58	0.035	81.5	<0.5	99.5	<0.5	3.09	12
34	Unconsolidated	2.27	0.04	35	<0.5	42	<0.5	3.5	9.7
21	Unconsolidated	0.379	0.03	32	<0.5	39	<0.5	4	12
23	Unconsolidated	1.88	0.03	32	<0.5	39	<0.5	4.1	8.4
25	Unconsolidated	0.399	0.03	32	<0.5	40	<0.5	3.9	8.5
28	Unconsolidated	0.156	0.05	46	<0.5	56	<0.5	4.3	8.8
29	Unconsolidated	1.09	0.03	34	<0.5	42	<0.5	3.5	5.6
30	Unconsolidated	1.46	0.03	35	<0.5	43	<0.5	4.1	10
35	Unconsolidated	0.645	0.03	32	<0.5	39	<0.5	3.3	7.8
37	Unconsolidated	0.428	0.05	38	<0.5	46	<0.5	2.5	6.2
38	Unconsolidated	1.2	0.03	36	<0.5	44	<0.5	3.3	8
41	Unconsolidated	0.287	0.03	40	<0.5	49	<0.5	5	9.4
44	Unconsolidated	1.22	0.03	42	<0.5	51	<0.5	4.5	7
45	Unconsolidated	1.95	0.02	64	<0.5	78	<0.5	7.7	9.6
46	Unconsolidated	1.43	0.04	45	<0.5	55	<0.5	6.5	13
49	Unconsolidated	0.615	0.03	41	<0.5	50	<0.5	3.7	5.9
50	Unconsolidated	0.266	0.03	59	<0.5	72	<0.5	4	6.3
52	Unconsolidated	0.824	0.03	40	<0.5	49	<0.5	4.7	10
58	Unconsolidated	1.28	0.039	57.6	<0.5	70.2	<0.5	5.06	8.9
59	Unconsolidated	0.358	0.05	64.4	<0.5	78.5	<0.5	3.9	20
61	Unconsolidated	0.475	0.042	33.8	<0.5	41.2	<0.5	3.52	5.8
63	Unconsolidated	<0.002	0.15	96.9	<0.5	118	<0.5	8.72	1.6
64	Unconsolidated	<0.002	0.22	120	4.7	135	5.64	1.01	3.7
65	Unconsolidated	0.282	0.097	48.2	<0.5	58.8	<0.5	5.67	14
66	Unconsolidated	7.25	0.04	70	<0.5	85.3	<0.5	6.06	17
68	Unconsolidated	0.749	0.047	73.8	<0.5	90.1	<0.5	1.74	3.6
MEAN		1.09	0.05	54	4.7	66	5.6	4.7	14
MEDIAN		0.63	0.04	42	4.7	51	5.6	4.0	8.7
GEOMETRIC MEAN		0.68	0.04	48	4.7	59	5.6	4.1	9.0
MINIMUM		0.08	0.02	29	4.7	35	5.6	1.0	1.6
MAXIMUM		7.25	0.22	200	4.7	250	5.6	21	150
COUNT		32	32	32	32	32	32	32	32

Table A-1 Field and laboratory geochemical results (continued)

	GCDWQ (MAX)	**10**	**1.5**	**-**	**-**	**-**	**-**	**-**	**-**
	GCDWQ (AO)	**-**	**-**	**-**	**-**	**-**	**-**	**500**	**250**
	Units	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**
	RDL*	**0.002**	**0.010**	**0.50**	**0.5**	**0.5**	**0.5**	**0.5**	**0.50**
Site	**Lithology**	**Nitrate (N)**	**Fluoride (F)**	**Alkalinity (Total as CaCO3)**	**Alkalinity (PP as CaCO3)**	**Bicarbonate (HCO3)**	**Carbonate (CO3)**	**Sulphate Dissolved (SO4)**	**Chloride Dissolved (Cl)**
1	Bedrock	0.415	0.07	160	<0.5	190	<0.5	18	26
2	Bedrock	<0.002	0.10	130	<0.5	160	<0.5	29	2.4
3	Bedrock	<0.002	0.74	600	4.7	720	5.6	5.5	69
4	Bedrock	0.325	0.05	91	<0.5	110	<0.5	6	5.8
5	Bedrock	<0.002	**2.05**	250	8.2	290	9.9	<0.5	**320**
7	Bedrock	0.012	0.1	250	<0.5	310	<0.5	20	4.2
8	Bedrock	0.062	0.06	150	<0.5	180	<0.5	16	24
9	Bedrock	0.074	0.54	240	<0.5	290	<0.5	64	69
10	Bedrock	0.007	0.24	320	<0.5	390	<0.5	57	18
12	Bedrock	0.102	0.07	170	<0.5	210	<0.5	14	15
13	Bedrock	0.002	0.45	240	2.9	280	3.5	8.2	64
14	Bedrock	<0.002	0.20	470	<0.5	570	<0.5	90	25
15	Bedrock	0.057	0.31	210	17	220	20	23	32
16	Bedrock	<0.002	1.08	240	43	180	51	33	18
17	Bedrock	<0.002	**1.93**	320	9.9	370	12	14	12
18	Bedrock	<0.002	0.09	170	<0.5	210	<0.5	11	15
22	Bedrock	0.619	0.08	260	<0.5	320	<0.5	20	40
31	Bedrock	0.135	0.13	120	<0.5	150	<0.5	4.7	2.5
32	Bedrock	0.019	0.04	68	<0.5	83	<0.5	2.1	29
36	Bedrock	0.309	0.22	450	<0.5	550	<0.5	130	9.4
40	Bedrock	0.005	0.64	400	1.9	490	2.3	11	37
42	Bedrock	0.019	0.40	260	8.9	290	11	26	140
48	Bedrock	0.16	1.03	410	<0.5	500	<0.5	**530**	**920**
51	Bedrock	0.041	0.08	230	<0.5	280	<0.5	27	12
54	Bedrock	0.088	0.19	270	2	330	2.4	74	17
55	Bedrock	<0.002	1.2	267	28.3	256	34	3.26	21
56	Bedrock	1.29	0.04	51.2	<0.5	62.5	<0.5	5.47	8.8
57	Bedrock	<0.002	**3.00**	175	8.8	192	10.6	<0.5	5.5
60	Bedrock	<0.002	**2.20**	182	6.91	206	8.29	0.5	7.5
67	Bedrock	0.0131	0.13	91.4	0.6	110	0.72	6.15	4.9
MEAN		0.19	0.58	242	11	283	13	45	66
MEDIAN		0.068	0.21	240	8.2	268	10	17	18
GEOMETRIC MEAN		0.059	0.26	210	6.4	245	8	16	21
MINIMUM		0.002	0.040	51	0.6	63	1	1	2
MAXIMUM		1.3	3.0	600	43	720	51	530	920
COUNT		30	30	30	30	30	30	30	30
All aquifer types									
MEAN		0.73	0.31	144.8	11	171.1	13	23	39
MEDIAN		0.35	0.06	86.3	7.6	104.8	9.1	5.5	9.9
GEOMETRIC MEAN		0.26	0.10	98.3	6.2	117.3	7.5	7.8	13.4
MINIMUM		0.002	0.02	29.0	0.6	35.0	0.7	0.5	1.6
MAXIMUM		7.3	3.0	600	43	720	51	530	920
COUNT		62	62	62	62	62	62	62	62
<DETECTS (#)		12	0					2	0
<DETECTS (%)		19%	0%					3%	0%

Table A-1 Field and laboratory geochemical results (continued)

	GCDWQ (MAX)	-	-	-	-	1	-	-	-
	GCDWQ (AO)	-	-	-	-	-	-	-	-
	Units	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**uS/cm**	**pH**
	RDL*	**0.02**	**0.02**	**0.005**	**0.002**	**0.002**	**0.02**	**1**	
Site	**Lithology**	**Organic Nitrogen Dissolved (N)**	**Total Kjeldahl Nitrogen Dissolved (Calc)**	**Ammonia (N)**	**Nitrate plus Nitrite (N)**	**Nitrite (N)**	**Nitrogen Total (N)**	**Conductivity**	**pH**
24	Unconsolidated (dug)	<0.02	<0.02	<0.005	0.303	<0.002	0.3	211	7.87
26	Unconsolidated (dug)	<0.02	<0.02	0.005	0.334	<0.002	0.32	104	7.06
27	Unconsolidated (dug)	<0.2	<0.2	0.005	0.079	<0.002	<0.2	99	6.49
33	Unconsolidated (dug)	0.06	0.08	0.022	0.372	0.003	0.45	97	6.99
47	Unconsolidated (dug)	0.38	0.39	0.010	1.93	<0.002	2.32	172	7.41
53	Unconsolidated (dug)	0.2	0.25	0.047	0.291	0.006	0.54	891	7.98
62	Unconsolidated (dug)	0.08	0.096	0.012	2.58	<0.002	2.68	230	7.95
34	Unconsolidated	0.3	0.3	0.007	2.28	0.003	2.6	130	6.71
21	Unconsolidated	<0.02	<0.02	0.014	0.379	<0.002	0.4	114	7.02
23	Unconsolidated	0.02	0.02	<0.005	1.88	<0.002	1.9	118	6.98
25	Unconsolidated	<0.02	<0.02	0.016	0.399	<0.002	0.42	107	6.59
28	Unconsolidated	<0.02	0.02	0.008	0.156	<0.002	0.18	126	6.79
29	Unconsolidated	<0.02	<0.02	0.005	1.1	0.003	1.05	103	6.87
30	Unconsolidated	0.13	0.14	0.007	1.46	0.003	1.6	128	6.76
35	Unconsolidated	0.06	0.12	0.056	0.648	0.003	0.76	104	6.7
37	Unconsolidated	<0.02	0.06	0.042	0.43	0.003	0.49	105	6.78
38	Unconsolidated	0.04	0.08	0.033	1.2	<0.002	1.28	116	6.82
41	Unconsolidated	0.09	0.1	0.008	0.287	<0.002	0.39	123	7.41
44	Unconsolidated	0.22	0.23	0.006	1.22	<0.002	1.45	125	7.32
45	Unconsolidated	0.4	0.4	0.009	1.95	<0.002	2.3	189	7.17
46	Unconsolidated	0.14	0.19	0.056	1.43	<0.002	1.62	157	7.24
49	Unconsolidated	0.12	0.13	0.014	0.615	<0.002	0.75	114	7.17
50	Unconsolidated	0.09	0.1	0.011	0.266	<0.002	0.36	145	7.14
52	Unconsolidated	0.13	0.14	0.011	0.824	<0.002	0.96	117	7.15
58	Unconsolidated	0.05	0.061	0.008	1.28	<0.002	1.34	158	7.21
59	Unconsolidated	0.05	0.055	0.009	0.358	<0.002	0.413	198	7.36
61	Unconsolidated	0.06	0.073	0.009	0.475	<0.002	0.548	96.2	6.95
63	Unconsolidated	0.03	0.06	0.030	<0.002	<0.002	0.06	215	8.19
64	Unconsolidated	0.12	0.551	0.430	<0.002	<0.002	0.551	249	8.62
65	Unconsolidated	0.04	0.073	0.031	0.285	0.003	0.359	153	7.13
66	Unconsolidated	<0.2	<0.20	0.028	7.25	<0.002	6.88	257	7.66
68	Unconsolidated	<0.02	<0.02	0.029	0.749	<0.002	0.769	162	7.89
MEAN		0.13	0.15	0.033	1.1	0.003	1.2	169	7.23
MEDIAN		0.09	0.10	0.01	0.63	0.003	0.75	127	7.15
GEOMETRIC MEAN		0.09	0.11	0.02	0.68	0.003	0.76	148	7.21
MINIMUM		0.02	0.02	0.005	0.08	0.003	0.06	96	6.49
MAXIMUM		0.40	0.55	0.430	7.3	0.006	6.9	891	8.62
COUNT		32	32	32	32	32	32	32	32

Table A-1   Field and laboratory geochemical results (continued)

	GCDWQ (MAX)	-	-	-	-	1	-	-	-
	GCDWQ (AO)	-	-	-	-	-	-	-	-
	Units	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	uS/cm	pH
	RDL*	0.02	0.02	0.005	0.002	0.002	0.02	1	
Site	Lithology	Organic Nitrogen Dissolved (N)	Total Kjeldahl Nitrogen Dissolved (Calc)	Ammonia (N)	Nitrate plus Nitrite (N)	Nitrite (N)	Nitrogen Total (N)	Conductivity	pH
1	Bedrock	0.39	0.39	<0.005	0.417	0.002	0.8	417	7.38
2	Bedrock	0.12	0.13	0.010	<0.002	<0.002	0.13	309	7.49
3	Bedrock	0.05	0.11	0.065	<0.002	<0.002	0.11	1350	8.33
4	Bedrock	0.06	0.06	<0.005	0.325	<0.002	0.39	194	7.48
5	Bedrock	0.13	0.19	0.058	<0.002	<0.002	0.19	1760	8.64
7	Bedrock	0.13	0.16	0.030	0.012	<0.002	0.17	523	7.86
8	Bedrock	0.28	0.28	<0.005	0.062	<0.002	0.34	389	7.8
9	Bedrock	0.06	0.11	0.046	0.074	<0.002	0.18	808	7.91
10	Bedrock	0.3	0.4	0.160	0.01	0.002	0.4	763	7.99
12	Bedrock	0.13	0.14	0.005	0.106	0.004	0.25	402	7.22
13	Bedrock	0.1	0.15	0.050	0.002	<0.002	0.15	664	8.4
14	Bedrock	0.13	0.21	0.078	<0.002	<0.002	0.21	1080	7.58
15	Bedrock	<0.02	0.07	0.050	0.062	0.005	0.13	566	9.06
16	Bedrock	<0.2	0.3	0.210	<0.002	<0.002	0.3	600	9.49
17	Bedrock	<0.2	0.2	0.110	<0.002	<0.002	0.2	666	8.89
18	Bedrock	0.4	0.4	0.009	<0.002	<0.002	0.4	393	6.85
22	Bedrock	<0.02	<0.02	0.017	0.622	0.003	0.58	651	7.48
31	Bedrock	<0.2	<0.2	0.042	0.138	0.003	0.3	246	8.01
32	Bedrock	<0.2	<0.2	0.020	0.019	<0.002	<0.2	240	6.67
36	Bedrock	0.06	0.06	<0.005	0.309	<0.002	0.37	1100	8
40	Bedrock	0.17	0.33	0.168	0.005	<0.002	0.34	861	8.32
42	Bedrock	0.09	0.32	0.237	0.019	<0.002	0.34	980	8.71
48	Bedrock	0.19	0.88	0.693	0.16	<0.002	1.04	4560	8.27
51	Bedrock	0.08	0.1	0.023	0.041	<0.002	0.15	532	7.7
54	Bedrock	<0.02	0.08	0.061	0.133	0.046	0.21	718	8.33
55	Bedrock	0.08	0.248	0.160	<0.002	<0.002	0.248	571	9.18
56	Bedrock	0.07	0.08	0.011	1.29	<0.002	1.37	146	7.48
57	Bedrock	0.09	0.145	0.052	<0.002	<0.002	0.145	347	8.8
60	Bedrock	0.04	0.1	0.065	<0.002	<0.002	0.1	389	8.69
67	Bedrock	0.054	0.13	0.076	0.0131	<0.002	0.143	201	8.31
MEAN		0.14	0.21	0.10	0.19	0.009	0.33	748	8.08
MEDIAN		0.10	0.15	0.06	0.07	0.003	0.25	569	8.01
GEOMETRIC MEAN		0.11	0.17	0.05	0.06	0.004	0.26	559	8.05
MINIMUM		0.04	0.06	0.01	0.002	0.002	0.10	146	6.67
MAXIMUM		0.40	0.88	0.69	1.3	0.046	1.4	4560	9.49
COUNT		30	30	30	30	30	30	30	30
All aquifer types									
MEAN		0.13	0.19	0.06	0.73	0.006	0.76	449	7.64
MEDIAN		0.09	0.13	0.03	0.35	0.003	0.40	223	7.48
GEOMETRIC MEAN		0.10	0.14	0.03	0.26	0.004	0.45	281	7.61
MINIMUM		0.02	0.02	0.01	0.002	0.002	0.06	96	6.49
MAXIMUM		0.40	0.88	0.69	7.3	0.046	6.9	4560	9.49
COUNT		62	62	62	62	62	62	62	62
<DETECTS (#)									
<DETECTS (%)									

Table A-1 Field and laboratory geochemical results (continued)

	GCDWQ (MAX)	-	-	-	500	-	6	10	1000
	GCDWQ (AO)	**500**	**-**	**-**	**-**	**$100^{(OG)}$**	**-**	**-**	**-**
	Units	**mg/L**	**NTU**	**mg/L**	**mg/L**	**ug/L**	**ug/L**	**ug/L**	**ug/L**
	RDL*	**10**	**0.1**	**0.4 (0.1)**	**0.5**	**0.5**	**0.02 (0.1)**	**0.02 (0.1)**	**0.02**
Site	**Lithology**	**Total Dissolved Solids**	**Turbidity**	**Bromide (Br)**	**Hardness Dissolved (CaCO3)**	**Aluminum Dissolved (Al)**	**Antimony Dissolved (Sb)**	**Arsenic Dissolved (As)**	**Barium Dissolved (Ba)**
24	Unconsolidated (dug)	130	0.2	<0.4	86.3	4.4	<0.02	0.1	2.5
26	Unconsolidated (dug)	58	0.1	<0.4	37.5	5.5	<0.02	0.06	5.25
27	Unconsolidated (dug)	48	0.3	<0.4	37.2	6.2	0.07	0.05	11.2
33	Unconsolidated (dug)	50	<0.1	<0.4	33.5	2.6	<0.02	0.03	6.77
47	Unconsolidated (dug)	110	0.1	<0.4	52.3	2.5	0.03	0.06	42.9
53	Unconsolidated (dug)	470	0.5	<0.4	178	8	0.05	0.18	78.1
62	Unconsolidated (dug)	120	0.46	<0.1	96	19.5	0.05	0.47	11.9
34	Unconsolidated	72	0.2	<0.4	48	2.6	<0.02	0.02	8.21
21	Unconsolidated	80	2.6	<0.4	34.2	4.5	<0.02	0.04	6.07
23	Unconsolidated	60	0.8	<0.4	38.7	4.3	<0.02	0.05	8.94
25	Unconsolidated	62	0.4	<0.4	37.6	4.6	<0.02	0.04	4.81
28	Unconsolidated	76	0.2	<0.4	44	4.6	<0.02	0.2	5.01
29	Unconsolidated	86	0.6	<0.4	37.3	1.6	<0.02	0.02	2.97
30	Unconsolidated	68	0.2	<0.4	44.4	2.3	0.03	0.05	31
35	Unconsolidated	56	<0.1	<0.4	35.9	2.8	<0.02	0.04	6.99
37	Unconsolidated	66	<0.1	<0.4	42	4.4	0.02	0.06	6.06
38	Unconsolidated	68	<0.1	<0.4	47	4.6	<0.02	0.03	2.81
41	Unconsolidated	88	61.6	<0.4	60.1	1.8	0.02	0.03	1.25
44	Unconsolidated	78	1.5	<0.4	43.4	2.3	<0.02	<0.02	3.3
45	Unconsolidated	100	0.2	<0.4	59.1	6.8	0.03	0.07	39
46	Unconsolidated	110	0.6	<0.4	52	1.4	<0.02	0.49	4.22
49	Unconsolidated	70	<0.1	<0.4	40.6	2.8	<0.02	<0.02	3.17
50	Unconsolidated	72	5.4	<0.4	56.9	2.9	<0.02	0.04	1.23
52	Unconsolidated	100	0.3	<0.4	42.6	3.7	<0.02	<0.02	1.89
58	Unconsolidated	114	0.39	<0.1	67.1	1.4	<0.02	0.15	5.76
59	Unconsolidated	128	0.93	<0.1	67.1	1.4	<0.02	0.15	5.76
61	Unconsolidated	52	0.3	<0.1	31.4	2.5	<0.02	0.05	2.56
63	Unconsolidated	116	0.66	<0.1	74.3	3.8	0.03	3.05	6.03
64	Unconsolidated	146	0.18	<0.1	30.8	7.8	<0.02	0.08	22.6
65	Unconsolidated	82	3.24	<0.1	39.5	1.8	<0.02	0.05	41.8
66	Unconsolidated	156	0.95	<0.1	107	2	<0.02	0.17	4.25
68	Unconsolidated	96	<0.1	<0.1	71.3	2.1	0.03	0.62	6.27
MEAN		100	3.2	nc	55	4.0	0.04	0.22	12
MEDIAN		81	0.4	nc	44	2.9	0.03	0.06	5.9
GEOMETRIC MEAN		88	0.6	nc	51	3.3	0.03	0.08	6.7
MINIMUM		48	0.1	nc	31	1.4	0.02	0.02	1.2
MAXIMUM		470	62	nc	178	20	0.07	3.05	78
COUNT		32	32		32	32	32	32	32

Table A-1 Field and laboratory geochemical results (continued)

	GCDWQ (MAX)	**-**	**-**	**-**	**500**	**-**	**6**	**10**	**1000**
	GCDWQ (AO)	**500**	**-**	**-**	**-**	**$100^{(OG)}$**	**-**	**-**	**-**
	Units	**mg/L**	**NTU**	**mg/L**	**mg/L**	**ug/L**	**ug/L**	**ug/L**	**ug/L**
	RDL*	**10**	**0.1**	**0.4 (0.1)**	**0.5**	**0.5**	**0.02 (0.1)**	**0.02 (0.1)**	**0.02**
Site	**Lithology**	**Total Dissolved Solids**	**Turbidity**	**Bromide (Br)**	**Hardness Dissolved (CaCO3)**	**Aluminum Dissolved (Al)**	**Antimony Dissolved (Sb)**	**Arsenic Dissolved (As)**	**Barium Dissolved (Ba)**
1	Bedrock	220	0.1	<0.4	115	13.6	0.06	0.18	75
2	Bedrock	180	0.3	<0.4	157	29.9	0.04	0.19	122
3	Bedrock	**800**	0.4	<0.4	40.5	7.8	<0.02	<0.02	101
4	Bedrock	110	0.8	<0.4	49.4	18.9	0.03	0.15	16
5	Bedrock	**820**	0.3	<0.4	20.5	5.7	<0.02	<0.02	59.1
7	Bedrock	300	0.2	<0.4	66.7	4.2	0.02	0.07	27.6
8	Bedrock	230	0.3	<0.4	135	2.8	<0.02	0.06	72.7
9	Bedrock	440	0.7	<0.4	5.4	5.4	<0.02	0.11	25.6
10	Bedrock	450	0.7	<0.4	96.7	5.9	<0.02	0.17	28.4
12	Bedrock	220	27.5	<0.4	157	3	0.02	0.1	57.5
13	Bedrock	370	0.1	<0.4	37.6	5.4	<0.02	0.89	38.5
14	Bedrock	**630**	2.6	<0.4	244	4.4	<0.02	0.04	52.7
15	Bedrock	310	5.5	<0.4	13.2	**170**	<0.1	3.2	79.6
16	Bedrock	320	0.7	<0.4	1.5	45	<0.1	0.5	6.6
17	Bedrock	360	0.4	<0.4	7.2	14	<0.4	<0.4	34.8
18	Bedrock	200	1.8	<0.4	135	8	0.02	0.54	38.9
22	Bedrock	370	0.1	<0.4	204	2.8	0.09	0.14	119
31	Bedrock	130	1.2	<0.4	19.8	15	0.3	1.3	33.1
32	Bedrock	130	0.2	<0.4	73	39.9	0.03	0.1	12.7
36	Bedrock	**640**	0.4	<0.4	111	5.5	0.05	0.08	62.8
40	Bedrock	500	1.7	<0.4	65.6	6	<0.1	0.2	42.8
42	Bedrock	**520**	0.8	<0.4	14.5	8	<0.1	5.6	68.4
48	Bedrock	**2700**	1.5	1	213	5	<0.1	2.1	14.8
51	Bedrock	270	1.1	<0.4	136	12.1	0.08	0.38	118
54	Bedrock	400	4.5	<0.4	23.1	9.9	0.06	0.88	17
55	Bedrock	344	1.68	<0.1	9.9	10.8	<0.02	0.03	56.2
56	Bedrock	108	4.12	<0.1	63.7	1.5	<0.02	0.08	2.81
57	Bedrock	184	0.16	<0.1	5.3	7	<0.1	<0.1	27.9
60	Bedrock	212	0.13	<0.1	6.3	4.5	<0.02	0.07	27.2
67	Bedrock	120	0.24	<0.1	68.5	2.47	<0.02	1.45	394
MEAN		420	2.0	1.0	77	16	0.07	0.72	61
MEDIAN		315	0.70	1.0	65	7	0.05	0.18	41
GEOMETRIC MEAN		313	0.67	1.0	41	8	0.05	0.25	40
MINIMUM		108	0.10	1.0	2	2	0.02	0.03	3
MAXIMUM		2700	28	1.0	244	170	0.30	5.60	394
COUNT		30	30	30	30	30	30	30	30
All aquifer types									
MEAN		254	2.6	1.0	66	9.7	0.05	0.46	36
MEDIAN		129	0.5	1.0	48	4.6	0.03	0.10	17
GEOMETRIC MEAN		163	0.6	1.0	46	5.1	0.04	0.14	16
MINIMUM		48	0.1	1.0	1.5	1.4	0.02	0.02	1.2
MAXIMUM		2700	62	1.0	244	170	0.30	5.6	394
COUNT		62	62	62	62	62	62	62	62
<DETECTS (#)		0					40	7	0
<DETECTS (%)		0%					65%	11%	0%

Table A-1 Field and laboratory geochemical results (continued)

Site	Lithology	Beryllium Dissolved (Be)	Bismuth Dissolved (Bi)	Boron Dissolved (B)	Cadmium Dissolved (Cd)	Chromium Dissolved (Cr)	Cobalt Dissolved (Co)	Copper Dissolved (Cu)	Iron Dissolved (Fe)
	GCDWQ (MAX)	-	-	5000	5	50	-	-	-
	GCDWQ (AO)	-	-	-	-	-	-	1000	300
	Units	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L
	RDL*	0.01 (0.05)	0.005 (0.03)	50 (<300)	0.005 (0.03)	0.1 (0.5)	0.005 (0.03)	0.05 (0.3)	1
24	Unconsolidated (dug)	<0.01	<0.005	<50	<0.005	0.2	0.009	8.23	1
26	Unconsolidated (dug)	<0.01	<0.005	<50	<0.005	0.2	0.02	29.7	6
27	Unconsolidated (dug)	<0.01	<0.005	<50	0.009	0.3	0.023	49.8	2
33	Unconsolidated (dug)	<0.01	<0.005	<50	<0.005	0.2	0.018	1.63	2
47	Unconsolidated (dug)	<0.01	<0.005	<50	0.012	<0.1	0.037	3.57	10
53	Unconsolidated (dug)	<0.01	<0.005	253	<0.005	<0.1	0.043	2.31	14
62	Unconsolidated (dug)	<0.01	<0.005	<50	0.006	0.3	0.024	3.49	19
34	Unconsolidated	<0.01	<0.005	<50	0.013	0.3	0.019	14.5	1
21	Unconsolidated	<0.01	<0.005	<50	<0.005	<0.1	0.014	4.09	6
23	Unconsolidated	<0.01	<0.005	<50	0.005	0.2	0.027	33.9	10
25	Unconsolidated	<0.01	<0.005	<50	<0.005	0.2	<0.005	1.1	2
28	Unconsolidated	<0.01	<0.005	<50	<0.005	0.3	0.01	0.98	4
29	Unconsolidated	<0.01	<0.005	<50	<0.005	0.2	0.008	1.87	4
30	Unconsolidated	<0.01	<0.005	<50	0.013	0.2	0.047	15	3
35	Unconsolidated	<0.01	<0.005	<50	0.006	0.2	0.026	13.1	2
37	Unconsolidated	<0.01	<0.005	<50	<0.005	0.3	0.007	20.5	<1
38	Unconsolidated	<0.01	<0.005	<50	<0.005	0.5	0.018	0.22	2
41	Unconsolidated	<0.01	<0.005	<50	<0.005	0.2	0.017	0.39	19
44	Unconsolidated	<0.01	<0.005	<50	0.007	<0.1	0.025	4.8	9
45	Unconsolidated	<0.01	<0.005	<50	0.014	0.1	0.037	32	9
46	Unconsolidated	<0.01	<0.005	<50	<0.005	<0.1	0.059	4.01	63
49	Unconsolidated	<0.01	<0.005	<50	0.006	0.2	<0.005	3.12	1
50	Unconsolidated	<0.01	<0.005	<50	0.007	0.1	0.011	2.32	2
52	Unconsolidated	<0.01	<0.005	<50	<0.005	0.2	0.017	3.59	10
58	Unconsolidated	<0.01	<0.005	<50	<0.005	<0.1	0.012	4.81	5
59	Unconsolidated	<0.01	<0.005	<50	<0.005	<0.1	0.012	4.81	5
61	Unconsolidated	<0.01	<0.005	<50	<0.005	<0.1	0.012	11.1	8
63	Unconsolidated	<0.01	<0.005	125	<0.005	<0.1	0.008	0.16	38
64	Unconsolidated	0.02	<0.005	347	<0.005	<0.1	0.012	0.09	7
65	Unconsolidated	<0.01	<0.005	<50	<0.005	<0.1	0.127	1.36	19
66	Unconsolidated	<0.01	<0.005	<50	0.005	1.3	0.01	2.24	4
68	Unconsolidated	<0.01	<0.005	<50	<0.005	1.7	<0.005	9.14	1
MEAN		nc	nc	242	0.009	0.35	0.02	9.0	9.3
MEDIAN		nc	nc	253	0.007	0.20	0.02	3.8	5.0
GEOMETRIC MEAN		nc	nc	222	0.008	0.26	0.02	3.7	5.1
MINIMUM		nc	nc	125	0.005	0.10	0.01	0.09	1.0
MAXIMUM		nc	nc	347	0.014	1.70	0.13	49.8	63
COUNT				32	32	32	32	32	32

Table A-1 Field and laboratory geochemical results (continued)

	GCDWQ (MAX)	-	-	5000	5	50	-	-	-
	GCDWQ (AO)	-	-	-	-	-	-	1000	300
	Units	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L
	RDL*	0.01 (0.05)	0.005 (0.03)	50 (<300)	0.005 (0.03)	0.1 (0.5)	0.005 (0.03)	0.05 (0.3)	1
Site	Lithology	Beryllium Dissolved (Be)	Bismuth Dissolved (Bi)	Boron Dissolved (B)	Cadmium Dissolved (Cd)	Chromium Dissolved (Cr)	Cobalt Dissolved (Co)	Copper Dissolved (Cu)	Iron Dissolved (Fe)
1	Bedrock	0.02	<0.005	107	0.01	<0.1	0.061	12	14
2	Bedrock	0.07	<0.005	82	0.009	0.2	0.073	1.63	45
3	Bedrock	0.06	<0.005	979	0.008	<0.1	0.021	<0.05	7
4	Bedrock	<0.01	<0.005	<50	<0.005	0.2	0.015	5.42	9
5	Bedrock	0.09	<0.005	886	0.008	<0.1	0.014	<0.05	2
7	Bedrock	<0.01	<0.005	115	<0.005	<0.1	0.007	3.53	<1
8	Bedrock	<0.01	<0.005	<50	<0.005	<0.1	0.01	9.57	3
9	Bedrock	0.01	<0.005	946	<0.005	<0.1	0.007	0.11	3
10	Bedrock	0.01	<0.005	393	<0.005	0.1	0.032	3.73	**702**
12	Bedrock	<0.01	<0.005	59	<0.005	<0.1	0.016	1.64	4
13	Bedrock	0.01	<0.005	315	<0.005	<0.1	0.012	0.06	7
14	Bedrock	<0.01	<0.005	423	<0.005	<0.1	0.024	0.34	66
15	Bedrock	<0.05	<0.03	307	0.04	0.5	0.07	4.5	142
16	Bedrock	<0.05	<0.03	1150	<0.03	<0.5	<0.03	0.8	21
17	Bedrock	<0.2	0.5	1590	0.1	<2	<0.1	<1	52
18	Bedrock	0.03	<0.005	83	<0.005	<0.1	4.45	3.66	**787**
22	Bedrock	0.01	<0.005	104	<0.005	0.1	0.044	13.9	4
31	Bedrock	<0.05	<0.03	<300	0.05	<0.5	<0.03	5.7	69
32	Bedrock	<0.01	<0.005	<50	0.018	0.3	0.551	10.5	40
36	Bedrock	<0.01	<0.005	316	<0.005	0.1	0.017	11	5
40	Bedrock	<0.05	<0.03	1210	<0.03	<0.5	0.03	<0.3	160
42	Bedrock	<0.05	<0.03	1430	<0.03	<0.5	<0.03	<0.3	6
48	Bedrock	<0.05	<0.03	2680	<0.03	<0.5	<0.03	6.1	<5
51	Bedrock	<0.01	<0.005	170	0.012	0.1	0.03	18.3	4
54	Bedrock	<0.01	<0.005	209	0.007	<0.1	0.016	1.81	11
55	Bedrock	<0.01	<0.005	255	<0.005	<0.1	<0.005	0.97	6
56	Bedrock	<0.01	<0.005	<50	<0.005	0.4	0.015	0.77	4
57	Bedrock	<0.05	<0.03	1160	<0.03	<0.5	<0.03	<0.3	8
60	Bedrock	0.03	<0.005	856	<0.005	<0.1	<0.005	<0.05	2
67	Bedrock	<0.01	<0.005	56	<0.005	<0.1	<0.005	<0.05	49
MEAN		0.03	nc	635	0.03	0.2	0.26	5.3	80
MEDIAN		0.03	nc	316	0.01	0.2	0.02	3.7	9
GEOMETRIC MEAN		0.02	nc	362	0.02	0.2	0.03	2.6	16
MINIMUM		0.01	nc	56	0.01	0.1	0.01	0.1	2
MAXIMUM		0.09	nc	2680	0.10	0.5	4.5	18.3	787
COUNT		30		30	30	30	30	30	30
All aquifer types									
MEAN		0.03	nc	593	0.017	0.3	0.12	7.5	42.7
MEDIAN		0.02	nc	316	0.009	0.2	0.018	3.7	7.0
GEOMETRIC MEAN		0.02	nc	343	0.011	0.2	0.024	3.2	8.8
MINIMUM		0.01	nc	56	0.005	0.1	0.007	0.06	1.0
MAXIMUM		0.09	nc	2680	0.10	1.7	4.5	50	787
COUNT		62		62	62	62	62	62	62
<DETECTS (#)				34	40	32		8	3
<DETECTS (%)				55%	65%	52%		13%	5%

Table A-1 Field and laboratory geochemical results (continued)

	GCDWQ (MAX)	10	-	-	-	-	10	-	-
	GCDWQ (AO)	-	-	50	-	-	-	-	-
	Units	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L
	RDL*	0.005 (0.03)	0.5	0.05	0.05 (0.3)	0.1 (0.4)	0.04 (0.2)	100	0.005
Site	**Lithology**	**Lead Dissolved (Pb)**	**Lithium Dissolved (Li)**	**Manganese Dissolved (Mn)**	**Molybdenum Dissolved (Mo)**	**Nickel Dissolved (Ni)**	**Selenium Dissolved (Se)**	**Silicon Dissolved (Si)**	**Silver Dissolved (Ag)**
24	Unconsolidated (dug)	0.356	<0.5	0.74	0.1	0.12	0.06	10900	<0.005
26	Unconsolidated (dug)	0.211	<0.5	2.45	0.06	0.11	0.05	7240	<0.005
27	Unconsolidated (dug)	0.908	<0.5	0.65	0.06	0.17	0.06	7980	<0.005
33	Unconsolidated (dug)	0.041	0.5	0.34	<0.05	1.61	0.09	6740	<0.005
47	Unconsolidated (dug)	0.067	0.7	0.99	<0.05	0.32	0.14	5550	<0.005
53	Unconsolidated (dug)	0.089	46	43.3	0.22	0.59	0.15	6800	<0.005
62	Unconsolidated (dug)	0.059	1.1	22.4	0.15	0.25	0.74	7530	0.021
34	Unconsolidated	0.139	<0.5	1.5	<0.05	0.11	0.05	7880	<0.005
21	Unconsolidated	0.014	<0.5	3.25	0.05	0.13	0.06	6400	<0.005
23	Unconsolidated	0.557	<0.5	1.96	<0.05	0.19	0.05	6490	<0.005
25	Unconsolidated	0.024	<0.5	0.46	0.07	0.14	0.05	6710	0.018
28	Unconsolidated	0.019	<0.5	0.43	0.17	0.23	0.06	6670	<0.005
29	Unconsolidated	<0.005	<0.5	0.92	<0.05	0.08	<0.04	9210	<0.005
30	Unconsolidated	0.106	0.6	0.99	<0.05	0.35	0.16	6000	<0.005
35	Unconsolidated	0.23	<0.5	0.6	<0.05	0.18	0.05	6560	<0.005
37	Unconsolidated	0.223	<0.5	0.39	0.08	0.06	0.06	8130	<0.005
38	Unconsolidated	0.016	<0.5	1.77	<0.05	0.07	<0.04	11600	<0.005
41	Unconsolidated	0.007	<0.5	0.56	0.06	0.03	0.08	13000	<0.005
44	Unconsolidated	0.021	<0.5	11.2	0.3	0.17	<0.04	9170	<0.005
45	Unconsolidated	0.416	0.6	1.23	0.15	0.38	0.11	5590	<0.005
46	Unconsolidated	0.028	<0.5	17.1	0.12	0.34	0.07	10400	<0.005
49	Unconsolidated	0.187	<0.5	0.17	0.21	0.08	0.05	8570	<0.005
50	Unconsolidated	0.01	<0.5	3.05	0.07	0.13	0.06	11000	<0.005
52	Unconsolidated	0.061	<0.5	1.06	<0.05	0.07	0.05	9140	0.009
58	Unconsolidated	0.012	0.8	1.03	0.06	0.32	0.13	12400	<0.005
59	Unconsolidated	0.012	0.8	1.03	0.06	0.32	0.13	12400	<0.005
61	Unconsolidated	0.105	<0.5	0.98	0.15	0.15	<0.04	8070	0.011
63	Unconsolidated	0.023	<0.5	29.8	3.05	0.04	<0.04	4780	0.022
64	Unconsolidated	0.018	<0.5	8.04	5.08	0.04	<0.04	5240	<0.005
65	Unconsolidated	0.04	6.5	48.7	0.22	0.43	0.05	8810	0.009
66	Unconsolidated	0.036	0.6	1.82	0.09	0.21	0.04	10100	<0.005
68	Unconsolidated	0.15	0.7	0.16	0.08	0.24	0.14	9500	<0.005
MEAN		0.135	5	6.5	0.46	0.24	0.11	8330	0.02
MEDIAN		0.059	1	1.0	0.10	0.17	0.06	8025	0.01
GEOMETRIC MEAN		0.060	1	1.8	0.14	0.16	0.08	8045	0.01
MINIMUM		0.007	1	0.2	0.05	0.03	0.04	4780	0.01
MAXIMUM		0.908	46	49	5.1	1.6	0.74	13000	0.02
COUNT		32	32	32	32	32	32	32	32

Table A-1 Field and laboratory geochemical results (continued)

	GCDWQ (MAX)	**10**	**-**	**-**	**-**	**-**	**10**	**-**	**-**
	GCDWQ (AO)	**-**	**-**	**50**	**-**	**-**	**-**	**-**	**-**
	Units	**ug/L**	**ug/L**	**ug/L**	**ug/L**	**ug/L**	**ug/L**	**ug/L**	**ug/L**
	RDL*	**0.005 (0.03)**	**0.5**	**0.05**	**0.05 (0.3)**	**0.1 (0.4)**	**0.04 (0.2)**	**100**	**0.005**
Site	**Lithology**	**Lead Dissolved (Pb)**	**Lithium Dissolved (Li)**	**Manganese Dissolved (Mn)**	**Molybdenum Dissolved (Mo)**	**Nickel Dissolved (Ni)**	**Selenium Dissolved (Se)**	**Silicon Dissolved (Si)**	**Silver Dissolved (Ag)**
1	Bedrock	0.502	13.8	21.7	0.14	0.84	<0.04	7870	<0.005
2	Bedrock	0.333	6.3	49.5	0.07	1.25	<0.04	5270	<0.005
3	Bedrock	<0.005	39.3	11.8	<0.05	0.11	<0.04	5120	<0.005
4	Bedrock	0.073	6.8	0.35	0.12	0.24	<0.04	7890	<0.005
5	Bedrock	0.005	66.6	4.06	<0.05	0.09	<0.04	4020	<0.005
7	Bedrock	0.026	14.2	2.02	0.21	0.39	0.21	5400	0.054
8	Bedrock	0.105	7.9	7.13	0.07	0.21	<0.04	6530	<0.005
9	Bedrock	0.041	44.3	1.67	0.16	0.15	<0.04	5810	<0.005
10	Bedrock	0.297	25.7	**156**	0.29	0.37	<0.04	4750	<0.005
12	Bedrock	0.006	6.1	3.94	<0.05	0.35	0.04	9520	<0.005
13	Bedrock	0.007	22.9	7.05	0.2	0.08	<0.04	6720	<0.005
14	Bedrock	<0.005	19.3	**195**	0.13	0.69	<0.04	4130	<0.005
15	Bedrock	0.11	26	3.2	3.5	0.8	<0.2	5100	<0.03
16	Bedrock	0.03	31	1.6	1.8	0.1	<0.2	4140	<0.03
17	Bedrock	0.4	24	5	5	<0.4	1.1	4610	0.1
18	Bedrock	0.06	8.4	**794**	0.16	5.47	<0.04	8660	<0.005
22	Bedrock	0.045	14.1	3.47	<0.05	0.8	<0.04	7350	<0.005
31	Bedrock	0.2	5	15.5	<0.3	0.5	<0.2	2320	<0.03
32	Bedrock	0.251	<0.5	**309**	0.05	0.82	0.06	7130	<0.005
36	Bedrock	0.169	11.7	0.94	0.55	0.49	1.04	2130	<0.005
40	Bedrock	0.07	44	**129**	<0.3	0.5	<0.2	6250	<0.03
42	Bedrock	0.04	58	14.6	<0.3	0.1	<0.2	4270	<0.03
48	Bedrock	<0.03	80	39.5	1.2	<0.1	<0.2	3650	0.04
51	Bedrock	0.425	8	24.4	0.08	0.9	0.04	3710	<0.005
54	Bedrock	0.112	13	12.1	1.71	0.31	0.04	5290	<0.005
55	Bedrock	0.014	17.6	9.9	0.2	0.26	<0.04	6320	<0.005
56	Bedrock	<0.005	<0.5	1.69	0.09	0.8	0.04	10600	<0.005
57	Bedrock	<0.03	14	1.2	0.5	<0.1	<0.2	3950	0.03
60	Bedrock	0.009	30.6	1.17	0.67	0.05	<0.04	3280	0.012
67	Bedrock	0.01	2.55	**71.1**	0.426	0.038	<0.04	6280	<0.005
MEAN		0.134	24	63	0.75	0.62	0.32	5602	0.05
MEDIAN		0.070	16	9	0.20	0.37	0.05	5280	0.04
GEOMETRIC MEAN		0.061	17	10	0.30	0.33	0.12	5246	0.04
MINIMUM		0.005	3	0	0.05	0.04	0.04	2130	0.01
MAXIMUM		0.502	80	794	5.0	5.5	1.10	10600	0.10
COUNT		30	30	30	30	30	30	30	30

All aquifer types

MEAN		0.13	18.5	34.0	0.61	0.41	0.2	7010	0.03
MEDIAN		0.06	13.0	2.8	0.15	0.23	0.1	6690	0.02
GEOMETRIC MEAN		0.06	8.1	4.2	0.21	0.23	0.1	6542	0.02
MINIMUM		0.01	0.5	0.2	0.05	0.03	0.0	2130	0.01
MAXIMUM		0.91	80	794	5.1	5.5	1.1	13000	0.10
COUNT		62	62	62	62	62	62	62	62
<DETECTS (#)		5		0			28		
<DETECTS (%)		8%		0%			45%		

Table A-1 Field and laboratory geochemical results (continued)

	GCDWQ (MAX)	**-**	**-**	**-**	**-**	**20**	**-**	**-**	**-**
	GCDWQ (AO)	**-**	**-**	**-**	**-**	**-**	**-**	**5000**	**-**
	Units	**ug/L**	**ug/L**	**ug/L**	**ug/L**	**ug/L**	**ug/L**	**ug/L**	**ug/L**
	RDL*	**0.05**	**0.002 (0.01)**	**0.01 (0.05)**	**0.5 (3)**	**0.002 (0.01)**	**0.2**	**0.1 (0.5)**	**0.1 (0.5)**
Site	**Lithology**	**Strontium Dissolved (Sr)**	**Thallium Dissolved (Tl)**	**Tin Dissolved (Sn)**	**Titanium Dissolved (Ti)**	**Uranium Dissolved (U)**	**Vanadium Dissolved (V)**	**Zinc Dissolved (Zn)**	**Zirconium Dissolved (Zr)**
24	Unconsolidated (dug)	75.6	<0.002	0.02	<0.5	0.009	1.2	360	<0.1
26	Unconsolidated (dug)	52.4	<0.002	<0.01	<0.5	<0.002	0.6	1.5	<0.1
27	Unconsolidated (dug)	50.8	<0.002	0.02	<0.5	0.004	0.4	3.8	<0.1
33	Unconsolidated (dug)	57	<0.002	<0.01	<0.5	<0.002	0.3	26	<0.1
47	Unconsolidated (dug)	88.5	<0.002	<0.01	<0.5	0.004	<0.2	4.4	<0.1
53	Unconsolidated (dug)	1100	0.003	0.03	<0.5	0.181	0.9	13.6	<0.1
62	Unconsolidated (dug)	56	0.002	<0.2	0.5	0.123	3.9	1.6	<0.1
34	Unconsolidated	73.8	<0.002	<0.01	<0.5	<0.002	0.3	5.4	<0.1
21	Unconsolidated	69.7	<0.002	0.01	<0.5	<0.002	0.2	7.2	<0.1
23	Unconsolidated	66.1	<0.002	0.02	<0.5	<0.002	0.3	1.8	<0.1
25	Unconsolidated	65.6	<0.002	<0.01	<0.5	0.003	0.5	0.6	<0.1
28	Unconsolidated	72.2	<0.002	0.04	<0.5	0.007	0.7	1.8	<0.1
29	Unconsolidated	43.5	<0.002	<0.01	<0.5	<0.002	0.4	2	<0.1
30	Unconsolidated	74.6	<0.002	<0.01	<0.5	0.002	<0.2	8	<0.1
35	Unconsolidated	57.8	<0.002	<0.01	<0.5	<0.002	0.3	7.1	<0.1
37	Unconsolidated	49	<0.002	<0.01	<0.5	0.003	0.6	2.6	<0.1
38	Unconsolidated	46	<0.002	<0.01	<0.5	<0.002	0.8	2.1	<0.1
41	Unconsolidated	55.3	<0.002	<0.01	<0.5	0.009	0.4	2.6	<0.1
44	Unconsolidated	55.1	<0.002	<0.01	<0.5	<0.002	<0.2	5.2	<0.1
45	Unconsolidated	94.9	<0.002	<0.01	<0.5	<0.002	<0.2	7.5	<0.1
46	Unconsolidated	74.6	<0.002	<0.01	<0.5	<0.002	<0.2	27.3	<0.1
49	Unconsolidated	49.8	<0.002	<0.01	<0.5	<0.002	0.4	2.5	<0.1
50	Unconsolidated	57.6	<0.002	<0.01	<0.5	0.008	0.6	3.8	<0.1
52	Unconsolidated	56	<0.002	<0.01	<0.5	0.003	0.6	2.8	<0.1
58	Unconsolidated	65.1	<0.002	<0.2	<0.5	0.007	0.2	1.9	<0.1
59	Unconsolidated	65.1	<0.002	<0.2	<0.5	0.007	0.2	1.9	<0.1
61	Unconsolidated	43.9	<0.002	<0.2	<0.5	0.006	0.5	2.3	<0.1
63	Unconsolidated	191	<0.002	<0.2	<0.5	0.325	0.9	0.4	<0.1
64	Unconsolidated	68.8	<0.002	<0.2	<0.5	0.009	0.3	0.3	<0.1
65	Unconsolidated	72.1	<0.002	<0.2	<0.5	0.004	<0.2	1.3	<0.1
66	Unconsolidated	76.4	<0.002	<0.2	<0.5	0.015	2	1.7	<0.1
68	Unconsolidated	39.1	<0.002	<0.2	<0.5	0.053	4.1	4.5	<0.1
MEAN		99	0.00	0.02	0.50	0.039	0.8	16	nc
MEDIAN		65	0.00	0.02	0.50	0.007	0.5	2.6	nc
GEOMETRIC MEAN		69	0.00	0.02	0.50	0.010	0.6	3.5	nc
MINIMUM		39	0.00	0.01	0.50	0.002	0.2	0.3	nc
MAXIMUM		1100	0.00	0.04	0.50	0.325	4.1	360	nc
COUNT		32	32	32	32	32	32	32	

Table A-1 Field and laboratory geochemical results (continued)

	GCDWQ (MAX)	-	-	-	-	**20**	-	-	-
	GCDWQ (AO)	-	-	-	-	-	-	**5000**	-
	Units	**ug/L**	**ug/L**	**ug/L**	**ug/L**	**ug/L**	**ug/L**	**ug/L**	**ug/L**
	RDL*	**0.05**	**0.002 (0.01)**	**0.01 (0.05)**	**0.5 (3)**	**0.002 (0.01)**	**0.2**	**0.1 (0.5)**	**0.1 (0.5)**
Site	**Lithology**	**Strontium Dissolved (Sr)**	**Thallium Dissolved (Tl)**	**Tin Dissolved (Sn)**	**Titanium Dissolved (Ti)**	**Uranium Dissolved (U)**	**Vanadium Dissolved (V)**	**Zinc Dissolved (Zn)**	**Zirconium Dissolved (Zr)**
1	Bedrock	670	0.004	<0.01	<0.5	0.098	<0.2	3.4	<0.1
2	Bedrock	843	0.002	<0.01	<0.5	0.026	<0.2	2.4	<0.1
3	Bedrock	611	<0.002	<0.01	<0.5	0.003	<0.2	0.1	0.2
4	Bedrock	247	<0.002	0.09	<0.5	0.02	0.3	4.3	<0.1
5	Bedrock	256	<0.002	<0.01	<0.5	0.003	<0.2	0.1	0.2
7	Bedrock	175	0.004	0.08	<0.5	0.026	0.2	1.9	<0.1
8	Bedrock	528	<0.002	<0.01	<0.5	0.035	<0.2	53.5	<0.1
9	Bedrock	149	0.004	<0.01	<0.5	0.008	0.2	32.9	<0.1
10	Bedrock	454	<0.002	0.01	<0.5	0.114	0.4	7.1	<0.1
12	Bedrock	211	<0.002	<0.01	<0.5	0.063	<0.2	1.3	<0.1
13	Bedrock	128	<0.002	<0.01	<0.5	0.079	<0.2	0.2	<0.1
14	Bedrock	691	<0.002	<0.01	<0.5	0.079	<0.2	1	<0.1
15	Bedrock	26.4	<0.01	0.14	5	<0.01	1	1.1	<0.5
16	Bedrock	10.4	<0.01	0.17	<3	<0.01	<1	<0.5	<0.5
17	Bedrock	36	0.06	<0.2	<10	0.21	<4	<2	<2
18	Bedrock	517	0.026	<0.01	<0.5	0.035	<0.2	5.6	<0.1
22	Bedrock	635	<0.002	<0.01	<0.5	0.106	<0.2	10.5	<0.1
31	Bedrock	63.4	<0.01	0.11	<3	0.01	<1	143	<0.5
32	Bedrock	142	0.004	<0.01	<0.5	0.016	0.6	4.5	<0.1
36	Bedrock	696	<0.002	<0.01	<0.5	0.252	<0.2	4.3	<0.1
40	Bedrock	135	0.01	<0.05	<3	0.03	2	14.8	<0.5
42	Bedrock	148	<0.01	<0.05	<3	0.02	3	3.9	<0.5
48	Bedrock	3370	<0.01	<0.05	<3	0.01	<1	1.3	<0.5
51	Bedrock	334	0.013	0.01	<0.5	0.087	<0.2	3.9	<0.1
54	Bedrock	122	<0.002	0.03	<0.5	0.016	<0.2	2.8	<0.1
55	Bedrock	93.2	<0.002	<0.2	<0.5	0.005	<0.2	0.3	<0.1
56	Bedrock	44.3	<0.002	<0.2	<0.5	0.005	1.1	1.5	<0.1
57	Bedrock	89.7	<0.01	<1	<3	<0.01	<1	<0.5	<0.5
60	Bedrock	68.4	<0.002	<0.2	<0.5	0.005	<0.2	0.2	<0.1
67	Bedrock	334	<0.002	<0.2	<0.5	<0.002	<0.2	0.61	<0.1
MEAN		394	0.01	0.08	5.0	0.05	1.0	11	nc
MEDIAN		193	0.004	0.09	5.0	0.03	0.6	3	nc
GEOMETRIC MEAN		201	0.01	0.05	5.0	0.03	0.6	2	nc
MINIMUM		10	0.00	0.01	5.0	0.003	0.2	0	nc
MAXIMUM		3370	0.06	0.17	5.0	0.252	3.0	143	nc
COUNT		30	30	30	30	30	30	30	
All aquifer types									
MEAN		242	0.01	0.06	2.8	0.05	0.87	13.9	nc
MEDIAN		75	0.004	0.03	2.8	0.01	0.50	2.6	nc
GEOMETRIC MEAN		116	0.01	0.04	1.6	0.02	0.58	2.9	nc
MINIMUM		10	0.002	0.01	0.5	0.00	0.20	0.1	nc
MAXIMUM		3370	0.06	0.17	5.0	0.33	4.10	360	nc
COUNT		62	62	62	62	62	62	62	
<DETECTS (#)						16		3	
<DETECTS (%)						26%		5%	

Table A-1 Field and laboratory geochemical results (continued)

Site	Lithology	Calcium Dissolved (Ca)	Magnesium Dissolved (Mg)	Potassium Dissolved (K)	Sodium Dissolved (Na)	Sulphur Dissolved (S)	CBE%
	GCDWQ (MAX)	-	-	-	-	-	
	GCDWQ (AO)	-	-	-	**200**	-	
	Units	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**	
	RDL*	**0.1**	**0.05 (0.3)**	**0.05 (0.3)**	**0.05**	**10 (50)**	
24	Unconsolidated (dug)	26.6	4.86	0.55	5	<10	-2
26	Unconsolidated (dug)	10.8	2.56	0.58	5	<10	-1
27	Unconsolidated (dug)	11.1	2.31	0.54	4	<10	0
33	Unconsolidated (dug)	9.7	2.25	0.46	7	<10	4
47	Unconsolidated (dug)	14.9	3.68	2.04	9	<10	4
53	Unconsolidated (dug)	55.4	9.63	1.74	114	<10	0
62	Unconsolidated (dug)	22.8	9.51	0.63	5	<10	-1
34	Unconsolidated	14.1	3.13	0.62	8	<10	*6*
21	Unconsolidated	10.2	2.14	0.41	7	<10	-2
23	Unconsolidated	11.3	2.53	0.51	6	<10	0
25	Unconsolidated	11.1	2.39	0.46	5	<10	2
28	Unconsolidated	12.9	2.84	0.57	7	<10	-1
29	Unconsolidated	10.4	2.79	0.40	5	<10	0
30	Unconsolidated	12.6	3.15	1.94	8	<10	*7*
35	Unconsolidated	10.6	2.32	0.67	6	<10	4
37	Unconsolidated	12.6	2.59	0.57	5	<10	4
38	Unconsolidated	13.8	3.08	0.46	7	<10	*7*
41	Unconsolidated	20.0	2.45	0.38	6	<10	*12*
44	Unconsolidated	12.6	2.94	0.49	5	<10	-3
45	Unconsolidated	17.5	3.73	0.99	11	<10	-3
46	Unconsolidated	15.1	3.46	1.14	8	<10	-1
49	Unconsolidated	11.9	2.67	0.49	4	<10	-2
50	Unconsolidated	16.6	3.77	0.56	5	<10	-1
52	Unconsolidated	12.3	2.88	0.54	6	<10	-3
58	Unconsolidated	18.9	4.83	0.54	6	<10	2
59	Unconsolidated	18.9	4.83	0.54	6	<10	*-9*
61	Unconsolidated	8.7	2.36	0.44	5	<10	-2
63	Unconsolidated	21.1	5.25	1.24	16	<10	3
64	Unconsolidated	9.4	1.76	3.07	41	<10	3
65	Unconsolidated	11.1	2.88	0.73	13	<10	-2
66	Unconsolidated	26.2	10.10	0.55	6	<10	-1
68	Unconsolidated	18.1	6.31	0.47	5	<10	-1
MEAN		16	4	1	11	nc	
MEDIAN		13	3	1	6	nc	
GEOMETRIC MEAN		15	3	1	7	nc	
MINIMUM		9	2	0	4	0	
MAXIMUM		55	10	3	114	0	
COUNT		32	32	32	32	32	

Table A-1 Field and laboratory geochemical results (continued)

	GCDWQ (MAX)	-	-	-	-	-	
	GCDWQ (AO)	-	-	-	**200**	-	
	Units	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**	
	RDL*	**0.1**	**0.05 (0.3)**	**0.05 (0.3)**	**0.05**	**10 (50)**	
Site	**Lithology**	**Calcium Dissolved (Ca)**	**Magnesium Dissolved (Mg)**	**Potassium Dissolved (K)**	**Sodium Dissolved (Na)**	**Sulphur Dissolved (S)**	**CBE%**
1	Bedrock	37.1	5.53	0.68	42	<10	1
2	Bedrock	37.2	2.64	0.16	29	12	*5*
3	Bedrock	13.3	1.77	0.28	**293**	<10	-1
4	Bedrock	16.0	2.32	0.15	22	<10	-3
5	Bedrock	7.3	0.55	0.21	**255**	<10	*-9*
7	Bedrock	23.9	1.71	0.42	89	<10	-2
8	Bedrock	47.8	3.87	0.49	29	<10	2
9	Bedrock	1.9	0.16	0.53	135	19	*-10*
10	Bedrock	30.8	4.81	2.26	127	22	0
12	Bedrock	53.5	5.73	0.32	25	<10	2
13	Bedrock	9.9	3.10	0.40	123	<10	-3
14	Bedrock	80.3	10.50	1.39	154	34	3
15	Bedrock	3.3	1.20	<0.3	114	<50	5
16	Bedrock	0.6	<0.3	<0.3	113	<50	*13*
17	Bedrock	3.0	<1	<1	134	<200	*-5*
18	Bedrock	42.4	7.09	0.27	33	<10	3
22	Bedrock	68.3	8.14	0.30	66	<10	2
31	Bedrock	6.6	0.80	0.40	46	<50	-4
32	Bedrock	21.0	5.02	1.37	23	<10	*6*
36	Bedrock	23.6	12.70	1.00	**217**	46	5
40	Bedrock	22.1	2.50	3.50	177	<50	-1
42	Bedrock	4.5	0.80	1.30	**204**	<50	1
48	Bedrock	72.1	8.00	1.60	**750**	172	-4
51	Bedrock	49.0	3.25	1.36	69	11	5
54	Bedrock	6.7	1.56	0.50	156	26	4
55	Bedrock	2.7	0.77	0.39	121	<10	*6*
56	Bedrock	17.9	4.61	0.42	4	<10	1
57	Bedrock	2.1	<0.3	<0.3	82	<50	3
60	Bedrock	2.4	0.08	0.17	72	<10	*-7*
67	Bedrock	19.8	4.64	0.67	15	<10	1
MEAN		24	4	1	124	43	
MEDIAN		19	3	0	101	24	
GEOMETRIC MEAN		13	2	1	77	28	
MINIMUM		1	0	0	4	11	
MAXIMUM		80	13	4	750	172	
COUNT		30	30	30	30	30	
All aquifer types							
MEAN		20	3.8	0.8	66	43	
MEDIAN		14	2.9	0.5	15	24	
GEOMETRIC MEAN		14	2.9	0.6	23	28	
MINIMUM		0.6	0.1	0.2	3.9	11	
MAXIMUM		80	13	3.5	750	172	
COUNT		62	62	62	62	62	
<DETECTS (#)					0		
<DETECTS (%)					0%		
						Total CBE>5%	11
						Total samples	62
						Percent CBE>5%	18

Table A-2 Microbiological sample results

Site ID	Total Coliforms (CFU/100 mL)	E. Coli (CFU/100 mL)
1	**14**	<1
2	**8**	<1
3	<1	<1
4	**2**	<1
5	**1**	<1
7	<1	<1
8	<1	<1
9	<1	<1
10	<1	<1
12	present*	<1
13	<1	<1
14	<1	<1
15	<1	<1
16	<1	<1
17	<1	<1
18	<1	<1
21	<1	<1
22	<1	<1
23	<1	<1
24	<1	<1
25	<1	<1
26	7	<1
27	2	<1
28	<1	<1
29	<1	<1
30	<1	<1
31	**600**	**250**
32	**210**	<1
33	**3**	<1
34	<1	<1
35	<1	<1
36	<1	<1
37	<1	<1
38	**106**	<1
40	**39**	<1
41	**44**	<1
42	**7**	<1
44	**22**	<1
45	**550**	**1**
46	<1	<1
47	**260**	<1
48	**8**	<1
49	**1**	<1
50	<1	<1
51	**86**	<1
52	**260**	<1
53	**present***	**1**
54	**present***	<1
55	**9**	<1
56	<1	<1
57	**110**	<1
58	**110**	<1
59	<1	<1
60	<1	<1
60B	**360**	<1
61	<1	<1
62	**460**	<1
63	**2**	<1
64	**1**	<1
65	<1	<1
66	<1	<1
67	<1	<1
68	**1**	<1

APPENDIX B: QA/QC RESULTS

Laboratory QA/QC

No exceedences of internal laboratory QA/QC criteria were noted.

Charge Balance Error

The charge balance error (CBE) was calculated for all 62 geochemical samples. Fifty-one sites (82%) had a charge balance error ≤5%, while 11 sites (18%) had a charge balance error >5% (see Table B-1 and complete results in Appendix A, Table A-1). A higher CBE can sometimes be estimated if the calculation does not take into account one or more major ions in the sample. In this case, all sample results were retained for further interpretation as the CBE was <10% in all but two instances and no sites had CBE>15%.

Table B-1 Summary of charge balance error results

	CBE <5%	CBE >5%
Number of wells	51	11
%	82%	18%

Field duplicates

Thirty-five duplicate samples were collected for QA/QC evaluation. Twenty-three field duplicate samples were collected for chemical analyses (either general chemistry, major ions, or trace metals), representing 12% of geochemical samples, taking into account that at each site the geochemical samples consisted of three individual sample bottles (i.e. three bottles at 62 sites is equal to 186 individual bottles). The RPD results for the individual sites are provided in Table B-3.

Table B-2 Duplicate sample summary

QA/QC samples	Total
Duplicate-Bacteria	12
Duplicate-General chemistry (120 mL and 1000 mL bottle)	15
Duplicate-Metals (120 mL bottle)	8
Total duplicate samples	35

Duplicate samples are generally considered acceptable if the RDP is <25% or if the RPD is >25% and the analytical result is less than 5 times the reportable detection limit (RDL) (Ministry of Environment, Lands and Parks, Land Data BC and Geographic Data BC, 1998).

For the geochemistry samples, 10 duplicates (43%) had acceptable RPD values for all parameters. For 13 duplicates, the RPD was greater than 25%, and the analytical results were greater than 5 times the RDL for one or more parameters.

Table B-3 Relative percent difference (RPD) of geochemical duplicate samples

Site	QA/QC parameter category	RPD <25%	RPD >25% but <5*MDL	RPD >25% (# parameters)	RPD exceedence parameters
4	General*	Y			
5	General			Y (3)	Kjeldahl nitrogen, organic nitrogen, total nitrogen
8	General	Y			
13	General			Y (2)	Alkalinity (PP), carbonate
14	General	Y			
16	General			Y (3)	Ammonia, Kjeldahl nitrogen, Total nitrogen
22	General		Y		
26	General		Y		
37	General		Y		
41	General			Y (2)	Sulfate, hardness
46	General		Y		
51	General			Y (1)	Total nitrogen
57	General			Y (1)	Kjeldahl nitrogen
65	General	Y			
67	General	Y			
22	Metals			Y (1)	Lead
26	Metals			Y (1)	Zinc
37	Metals	Y			
41	Metals			Y (3)	Aluminum, iron, silicon, calcium
46	Metals			Y (5)	Aluminum, copper, iron, lead, molybdenum
51	Metals			Y (1)	Zinc
65	Metals			Y (3)	Copper, iron, zinc
67	Metals			Y (1)	Zinc
	23	6	4	13	Total

*General chemistry replicate included two bottles (120 mL and 1000 mL)

Table B-4 Relative percent difference (RPD) of bacteriological duplicate samples

Site	RPD≤25%	RPD>25% and <5*RDL	RPD>25% and >5*RDL	Exceedence parameter
4		Y		
12		Y		
28	Y			
30	Y			
35	Y			
36	Y			
42		Y		
44			Y	Total coliforms
50	Y			
57	Y			
65		Y		
67		Y		
12	6	5	1	Total

*RDL for bacteria is 1 CFU per 100 mL

The parameters that were more likely to have an unacceptable RPD included constituents with a short sample holding time (e.g., nitrogen or carbonate species that tend to change rapidly following extraction from the well) and some trace metals (such as aluminum, copper, lead, and zinc), which may be introduced from well casing or plumbing fixtures and therefore may vary to a greater degree in water as it is being pumped. Another reason that the RPD criteria were exceeded might be that the duplicates were collected in sequence. If pre-sample groundwater purging was incomplete or if there was real variation within the aquifer (sample source heterogeneity), the water quality may have varied between successive samples. All geochemical sample results were retained for further analysis.

A minimum of one microbiological field duplicate was collected each sample date, for a total of 12 duplicates, representing 19% of the 63 bacteria samples. For the majority of samples, the reportable detection limit for total coliform and *E. coli* was one Colony Forming Unit (CFU) per 100 mL. The samples for sites 1 to 5 were reported as Most Probable Number, rather than CFU/100 mL. In addition, at three sites, the high concentration of suspended solids in the sample interfered with the bacterial analysis, and the results were reported as bacteria “present” rather than a number. Only one sample had an unacceptable RPD for total coliform, likely attributable to heterogeneity of the sample source. All microbiological data were retained for further evaluation.

Table B-5 Summary of RPD calculations for duplicate samples

Duplicate parameters	Total samples	RPD≤25%	RPD>25% and <5*RDL	RPD>25% and >5*RDL
Geochemistry	23	6 26%	4 17%	13 57%
Bacteria	12	6 50%	5 42%	1 8%