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Groundwater Quality Survey of Aquifers in South Cowichan, Vancouver Island

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EXECUTIVE SUMMARY

The South Cowichan area relies predominantly on two sources of freshwater: groundwater aquifers and surface water supplies from streams and lakes (e.g. Shawnigan Lake, Koksilah River). While, overall, the region's residents enjoy groundwater of excellent quality and quantity, within recent years, after studies had revealed elevated concentrations of nitrate in groundwater within the Fisher Road area of Cobble Hill, concerns were raised regarding potential impacts of human activities on local aquifers.

A survey was conducted of groundwater quality in wells constructed in the Cobble Hill (aquifer 197) and Cherry Point (aquifer 198) aquifers. The project was completed in partnership between the Ministry of Forests, Lands, Natural Resource Operations and Rural Development (FLNR), Water Protection Section (Nanaimo) and the Cowichan Valley Regional District (CVRD), Engineering Services (Duncan). The objectives of this work were to:

- Conduct a point-in-time (snap-shot) survey of groundwater quality to describe the current geochemical conditions within unconsolidated (sand and gravel) and fractured bedrock aquifers in this area;
- 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 water potability;
- Recognize where anthropogenic impacts may be occurring, and establish a baseline from which one may evaluate changes that may occur in future;
- Provide residents with information on how to maintain and protect their wells.

In November 2013 to March 2014 samples were collected from a total of 82 wells including 70 private domestic wells and 12 water supply system wells. Access to the wells was given voluntarily to FLNR and CVRD by the well owners. Field staff also completed an inspection of the well head where possible. The analytical parameters included general chemistry, metals, and bacteria. For sites where nitrate-nitrogen concentrations exceeded 2 mg/L samples were analyzed for stable nitrate isotopes ($\delta^{15}N$ and $\delta^{18}O$) to identify the nitrogen source. Of the 82 wells sampled, 79% of the wells were constructed in an unconsolidated aquifer, including 62 drilled and 3 excavated (dug) wells. Another 17 wells (21%) were constructed in a fractured bedrock aquifer.

Ambient groundwater within the South Cowichan study area was generally excellent in quality, with a geochemistry indicative of fresh, groundwater that has been recharged relatively recently. A small number of samples exceeded the Guidelines for Canadian Drinking Water Quality (GCDWQ) for either health-related or aesthetic parameters.

Two naturally occurring contaminants that are widespread in the study area included manganese and arsenic. Arsenic is a naturally occurring element, with no taste or odour in water, that can cause short-term (toxic) and long-term (chronic) effects on health including diseases of the skin and some internal cancers. In the study samples arsenic was commonly present at lower concentrations below drinking water guidelines but at levels that could be harmful for vulnerable populations such as young children, elderly or people with compromised health over longer periods of exposure. While only 2% of samples exceeded the Maximum Allowable Concentration (MAC) for arsenic, 26% had arsenic between 1 and <5 µg/L, and 7% had arsenic from 5 to <10 µg/L. Median concentrations of arsenic were higher in samples from wells constructed in unconsolidated materials, likely due to the presence of arsenic containing minerals in the source rock making up the sand and gravel layers.

Manganese concentrations were relatively similar in samples from both unconsolidated and bedrock wells; 38% of the samples exceeded the MAC for manganese, while a greater percentage 49% exceeded the Aesthetic Objective (AO). Iron, which affects the taste and pleasantness of groundwater for drinking,

was higher in samples from wells drilled in unconsolidated aquifers, also reflecting the geochemistry of the parent materials.

There were no exceedances of drinking water guidelines for nitrate, and the concentration was low throughout the study area, less than the detection limit in 33% of samples, with median of 0.62 mg/L for remaining samples from all well types. Slightly higher nitrate concentrations were observed in samples from unconsolidated (median 0.95 mg/L) compared to bedrock wells (median 0.038 mg/L) which reflects the occurrence of this contaminant within shallower groundwater sources but is believed to be primarily related to the land use overlying the largest unconsolidated aquifer in the area (AQ197).

All samples represented raw (untreated) water, and there are numerous treatment options for removal of substances including manganese, iron, arsenic and nitrate to improve drinking water quality.

Thirteen sites (16%) had samples with nitrate concentrations above 2 mg/L; the isotope analysis from these samples indicated that the nitrate was from organic sources such as animal waste or human sewage, and not from inorganic sources like artificial fertilizer. Based on spatial analysis point and non-point sources of contamination from agricultural land use and permitted discharges, such as municipal scale septic fields, sewage lagoons or industrial sites, were believed to contribute to elevated nitrate in the groundwater. Samples with higher concentrations of nitrate were also observed in areas of higher aquifer vulnerability but this factor was thought to be less important in comparison to land use related hazards. The present-day background concentration of nitrate in the aquifer was estimated as in the range of 0.5 mg/L. Concentrations of nitrate above background are likely associated with impacts of human activities on groundwater quality.

Evaluating potential point and non-point sources of nutrients, implementing nutrient management and improved waste handling best practices, and ensuring adequate design installation, and maintenance of septic systems and sewage treatment systems that discharge to ground are some recommendations to improve aquifer protection in this area.

After sampling, all well owners were provided with their water quality test results, and information on how to protect their wells. Maintenance or upgrades to wells were recommended in 32 cases. Common concerns identified included buried well heads, well caps that were missing or in poor condition, wells located in a poorly maintained pit, enclosure or pump house and presences of animal grazing, paddocks or chicken coops <30 m from the well. Participation in the study enabled well owners to better protect their wells, find out the quality of groundwater that they are drinking, while enabling development of an understanding of aquifer health in this groundwater dependent area. The results were presented publicly at a community meeting in June 2014.

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1. INTRODUCTION

The South Cowichan area of Vancouver Island is a predominantly rural residential and agricultural area approximately 4 km south of Duncan, which includes the communities of Cowichan Bay, Cowichan Station, Cobble Hill and Shawnigan Lake (Figure 1). Within this region there are two primary sources of fresh water: surface water sources including Shawnigan Lake, and the Koksilah River, and groundwater from private domestic wells and community water supply system wells in serviced areas.

The quality of surface and groundwater is affected by both natural factors, such as geology or climate, and human-caused factors related to land-use. Agricultural activities, sewage discharges, landfills or industrial composting can provide sources of nutrients, such as phosphorus or nitrogen, that influence the water quality within nearby aquifers and streams. In recent years the presence of nitrates in groundwater has been an increasing concern within the South Cowichan area, in particular after a 2012 study found the presence of elevated nitrate contaminant plumes associated with industrial and agricultural activities in a localized zone of Cobble Hill (Thurber Engineering Ltd, 2013).

It was recognized that an understanding of baseline geochemistry within the region's aquifers was needed, to characterize ambient groundwater quality, and to evaluate if and where human impacts may be occurring. In 2013-2014 a groundwater quality survey was initiated in partnership with Cowichan Valley Regional District, Environmental Services and the Ministry of Forests, Lands and Natural Resource Operations and Rural Development, Water Protection Section, West Coast regional office in Nanaimo.

1.1 Objectives

The objectives of the South Cowichan groundwater quality study were to:

- Conduct a survey of groundwater quality in the South Cowichan, to describe the current geochemical conditions within unconsolidated (sand and gravel) and bedrock aquifers that are the primary water sources in this area;
- 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 groundwater;
- Establish a baseline from which one may evaluate changes in geochemistry within the region's aquifers that may occur in future;
- Determine if there are areas of elevated nitrate above background conditions that might indicate impacts from human land use; and,
- Provide residents with information on how to maintain and protect their wells.

2. STUDY AREA

The study focused on the South Cowichan area, Cherry Point (Aquifer 197), Cobble Hill (AQ203) and Cowichan Bay (AQ198) aquifers described in further detail below, covering a 51 km^2 area which extended from Cowichan Bay Road on the north end of the study area, to Kilmalu Road on the south end (Figure 1). The longitudinal extent included the area east of the E&N railway line (approximate western boundary) to the eastern coast along Cowichan Bay and Saanich Inlet, as shown in Figure 1. Aquifer boundaries, water sources, including wells, and areas served by a local water purveyor are illustrated in Figure 2 (Cowichan Valley Regional District, 2019).

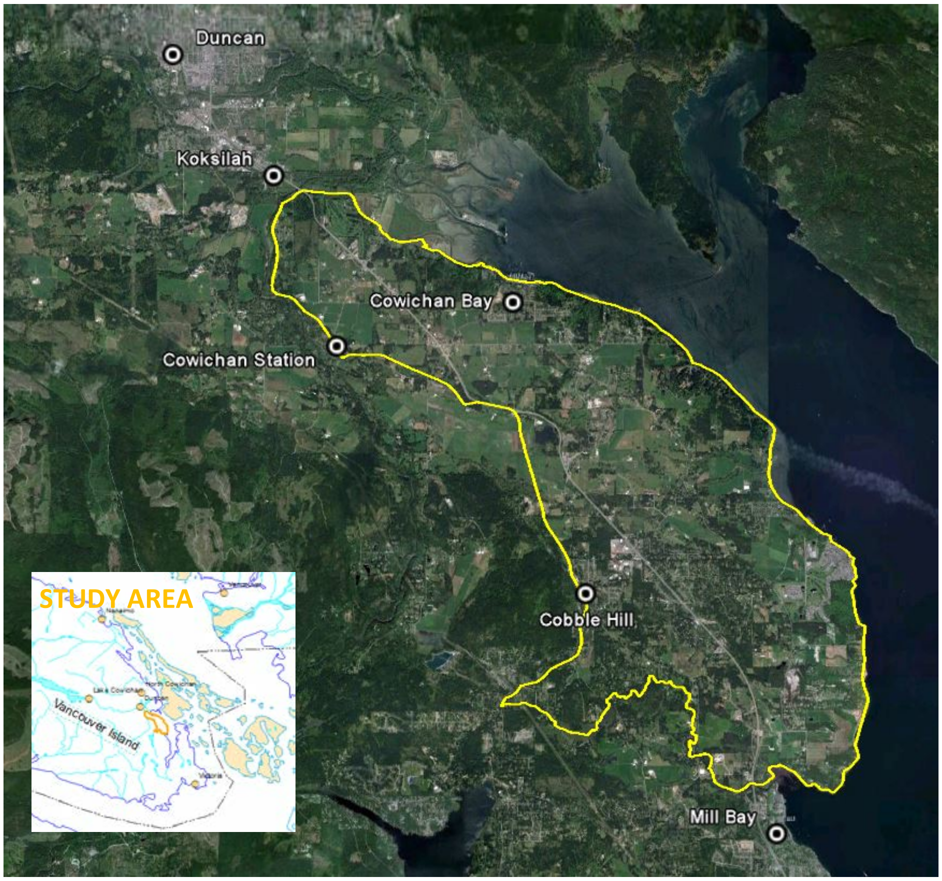

Figure 1: Study location

2.1 Climate

The study area has a temperate climate characterized by warm dry summers and cool wet winters (Peel, Finlayson, & McMahon, 2007). Precipitation patterns within this part of Vancouver Island are also influenced by the rain shadow effect of the Vancouver Island Range to the east 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). Most 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 stations to the study area are at Duncan Kelvin Creek (EC 1012573) approximately 3.3 km to the northwest and Shawnigan Lake (EC 1017230) approximately 2.4 km to the southwest. Based on climate normals from the Shawnigan Lake station for the years 1981 to 2010 the average annual temperature in this area is 9.9 °C and the average annual precipitation is 1250 mm, 95% of which occurs as rainfall (Environment Canada, 2014b). The average monthly temperature, rainfall and estimated evapotranspiration using data from the period 1981 to 2014 are shown in Figure 3. Potential evapotranspiration was calculated using a water balance model developed by the US Geological survey using the Thornthwaite method (McCabe & Markstrom, 2007).This plot shows that potential evapotranspiration exceeds rainfall for the months of May to September. Groundwater recharge would be expected to occur primarily during the months of October to April when average rainfall exceeds potential evapotranspiration.

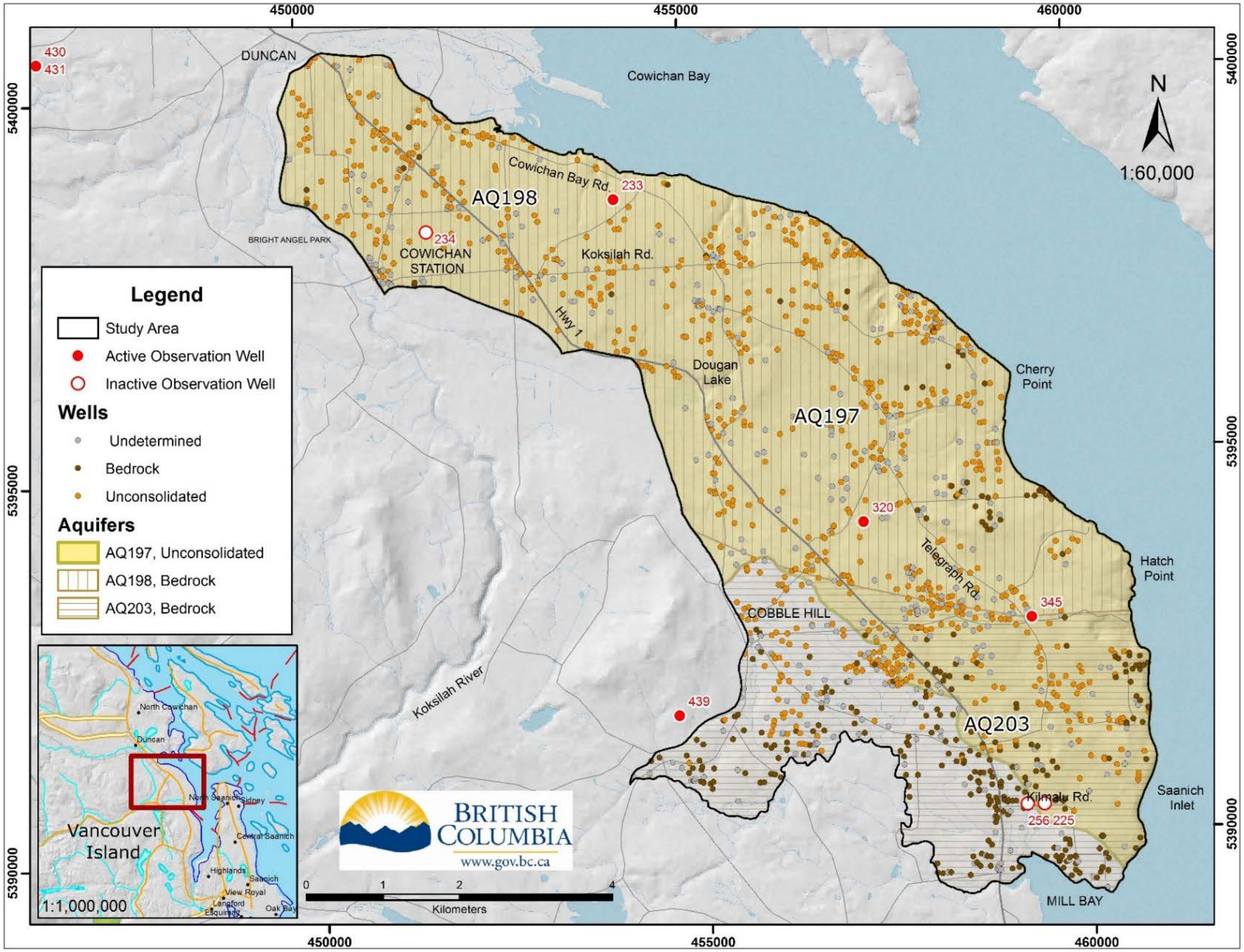

Figure 2: Overview map of study area

The monthly total precipitation and monthly average daily temperature for the period of July 2013 to June 2014 are shown in Figure 4. The long-term average data (1981-2014) are also plotted for comparison. From this analysis, during the study period temperatures were very close to the long-term average. However, total monthly precipitation during October 2013 to January 2014 was notably lower than the long-term average, and higher than average in February to March 2014.

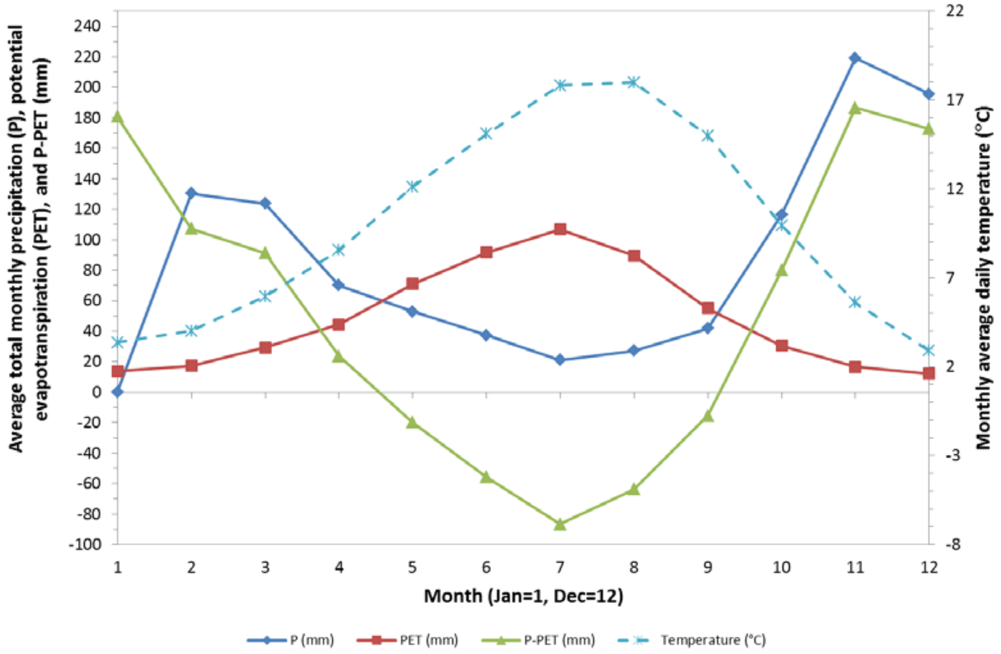

Figure 3: Monthly average total precipitation, average daily temperature, potential evapotranspiration, Shawnigan Lake weather station (EC1017230) 1981-2014.

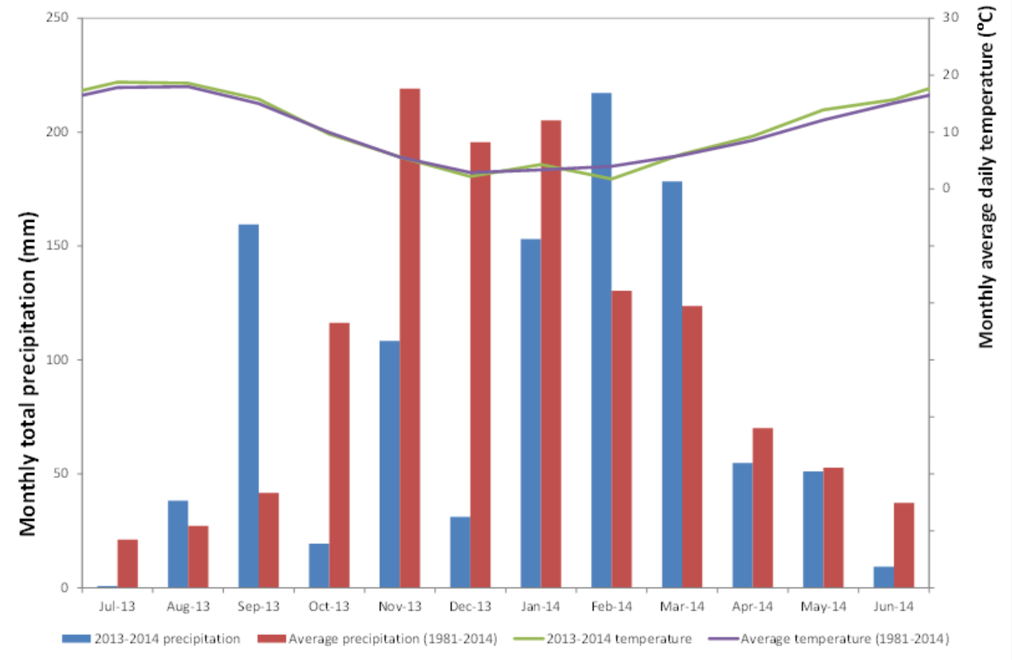

Figure 4: Monthly total precipitation and monthly average temperature July 2013 – June 2014 compared to long-term average temperature and precipitation (1981-2014), Shawnigan Lake weather station (EC1017230).

2.2 Surficial and bedrock geology

The study area is located within a gently sloping area of moderate to low relief that borders the Georgia Strait from Saanich Inlet to Cowichan Bay. The surficial geology of the study area is shown in Figure 5, based on terrain classification for Vancouver Island (Ministry of Environment, 2005). Unconsolidated sedimentary deposits in this area are the result of pre-glacial, glacial and more recent geologic events (Blyth, et al., 1993). Most of the northern part of the study area is overlain by sediments described as glacio-marine in origin, which were deposited overlying glacial and inter-glacial sediments during the period of higher sea level following the end of the Fraser Glaciation approximately 13,000 years ago. Glaciomarine deposits include poorly sorted to stratified sands, silts and clays. Moraine deposits such as diamicton or till (sand and rock debris within a clay or silt matrix) are found at the surface in the area around and south of Cobble Hill. Fluvial deposits are found within the Cowichan River delta and estuary at the northern boundary of the study area, while organic materials are noted in the west-central area around Dougan Lake and along Shawnigan Creek to the south. Localized deposits of marine sediments (i.e. marine clay) are mapped <1 km from the coast, in the area around Cherry Point. The surficial geology mapping represents a simplified summary of regional characteristics; at a site-scale deposits such as till can vary in presence/absence, and thickness.

In Figure 6, the predominant bedrock type in the study area consists of Nanaimo group sedimentary rocks, including shale, siltstone, and sandstone (Massey, et al., 2005). Granitic (igneous intrusive granodiorite, quartz diorite, diorite and gabbro) rocks of the Island Plutonic suite are mapped in the area north of Mill Bay (southern extent of the study area). In the Cobble Hill area toward the south-western area of the study are found volcanic-type rocks, including those associated with the Vancouver Group/Karmutsen Formation (basalt pillowed flows, tuff, breccia with limestone lenses), Buttle Lake Group/Mount Mark Formation (limestone, chert, siltstone, marble), and Sicker Group/Duck Lake Formation (pillowed and massive basalt flows, basalt breccia, chert, jasper, felsic tuff). Several major faults intersect and define the contacts between the various bedrock units.

2.3 Aquifers

The study focussed primarily on groundwater quality in aquifer 197 (Cherry Point), an unconsolidated aquifer that extends over much of the South Cowichan area. A smaller number of samples were collected from bedrock wells constructed in aquifer 203 (Shawnigan Lake/Cobble Hill, Mill Bay) in which wells are mainly constructed in fractured crystalline bedrock, and in aquifer 198 where the wells are constructed in sedimentary bedrock. The aquifers of this region are described in detail within (Hammond, et al., 2019), and (Harris & Usher, 2017) which provides a quantitative assessment of the water availability and demand. Aquifers in B.C. (Canadian Cordillera region), are characterized by sub-types based on their geologic materials and method of formation (Wei, et al., 2009). An agricultural water demand study was completed in 2013 (van der Gulik, et al., 2013). The basic characteristics of aquifers found in this study area summarized in Table 1.

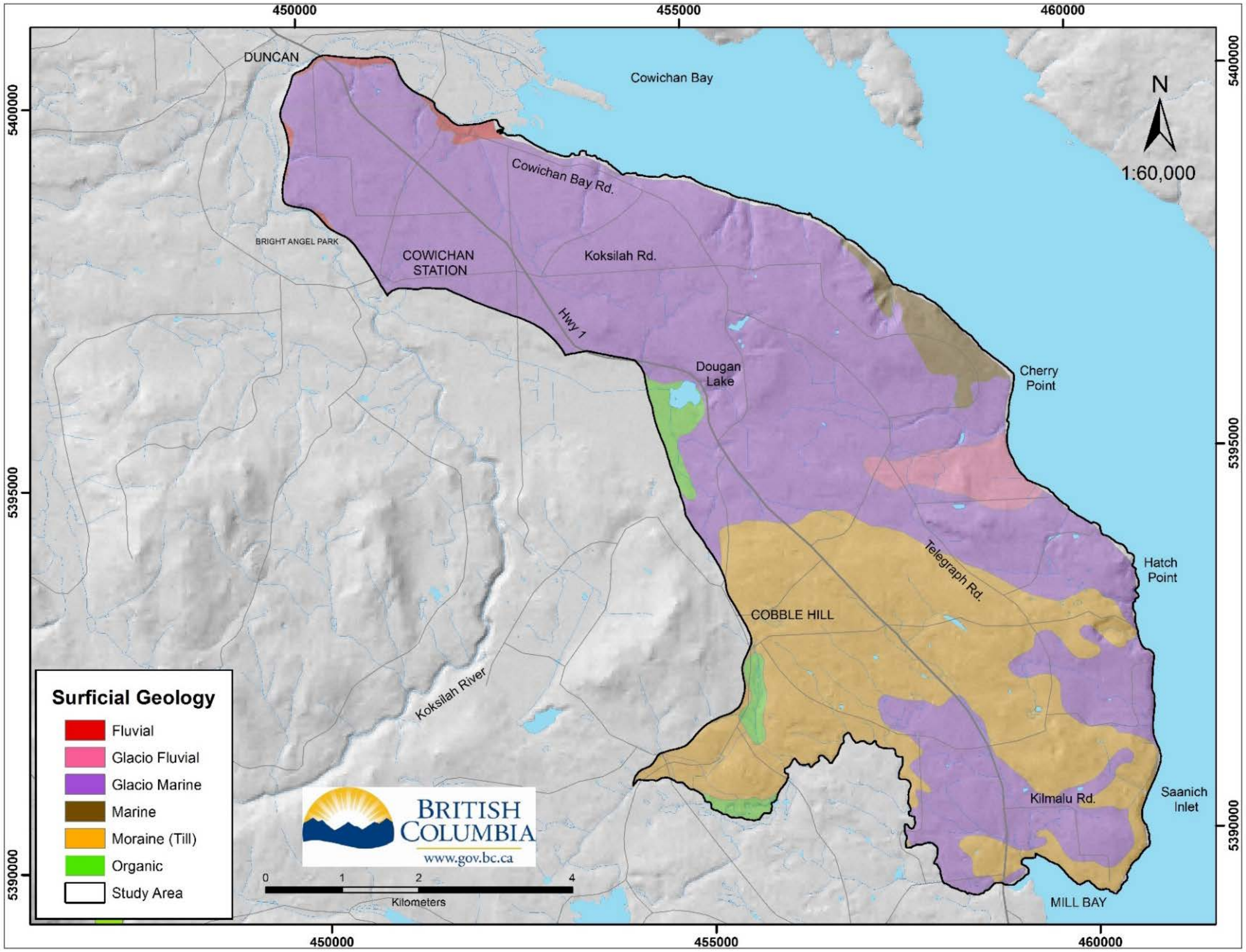

Figure 5: Surficial geology of the study area.

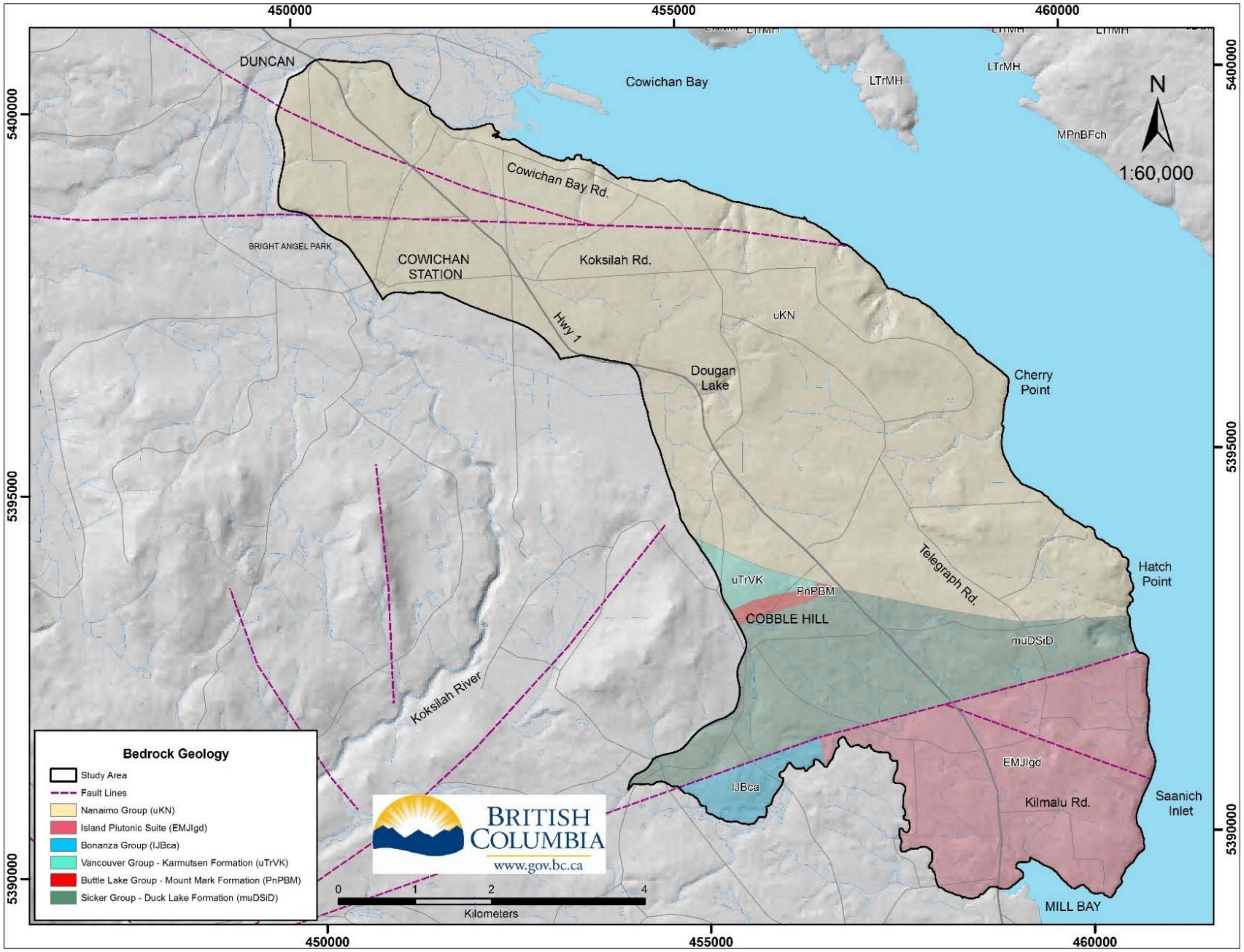

Figure 6: Bedrock geology of the study area.

Table 1: Aquifers in the South Cowichan study area.

Aquifer number	Aquifer name	Aquifer material	Lithostratigraphic unit	Aquifer sub-type	Area (km^2)	Active Provincial Observation wells
197	Cherry Point	Sand and gravel	Quadra Sand, Dashwood Drift	4b – Confined to partially confined sand and gravel aquifers with glacial or pre-glacial origin (glaciofluvial, glaciolacustrine materials)	39.7	233, 320, 345
203	Shawnigan Lake/Cobble Hill, Mill Bay	Crystalline bedrock	Intrusive igneous (Island Plutonic Suite) and volcanic (Duck Lake Formation, Mount Mark Formation)	6b – Fractured crystalline bedrock aquifers (igneous intrusive or metamorphic, meta-sedimentary, meta-volcanic, volcanic)	122.7	380, 439, 470
198	Cowichan Bay	Sedimentary bedrock (shale, sandstone)	Nanaimo Group	5a – Fractured sedimentary bedrock aquifers	104.7	

2.3.1 Aquifer 197 (Cherry Point), unconsolidated, sub-type 4b

Aquifer 197 (Figure 2) is an unconsolidated (sand and gravel) aquifer, that covers an approximately 39.5 km^2 area from the coast at Cowichan Bay and Satellite Channel on the east side, to the Koksilah River which forms a groundwater divide on the west side, and to the base of Cobble Hill on the southwest margin. The southern boundary of the aquifer extends roughly to Meredith Road, north of Mill Bay. The northern extent of the aquifer borders the south side of Cowichan River. Recent revisions to the aquifer mapping and classification have re-interpreted the aquifer boundary resulting in a minor change in the spatial extent, and expanding the boundary to encompass the area bordering Koksilah River from the confluence of Patrolas Creek to where the Koksilah River enters Cowichan River (Hammond, et al., 2019). The southern and southeastern aquifer boundaries were revised to a minor extent to exclude areas where most wells are constructed in bedrock, and sub-surface geologic mapping indicates the presence of a bedrock ridge (Hammond, et al., 2019).

Aquifer 197 is made up of stratified, coarse to fine grained glacial and glaciofluvial sedimentary deposits, including materials associated with the Quadra Sand and Vashon Drift stratigraphic units (Harris & Usher, 2017; Hammond, et al., 2019). In some areas these deposits are laterally contiguous, while in other areas, more permeable layers are separated by the presence of silt- and clay-rich moraine, lacustrine and glacio-marine deposits with lower permeability. The aquifer intrinsic susceptibility to contamination based on a DRASTIC methodology is shown in Figure 39 (Liggett & Gilchrist, 2010; Liggett, et al., 2011); note that this analysis applies to the surficial aquifer, and does not represent the vulnerability of deeper, confined deposits or underlying bedrock aquifers within a layered aquifer complex. Based on the characteristics of soil and surficial sediments, interpretation of well construction lithologic records, and depth to the water table aquifer 197 is considered to have an overall moderate vulnerability to contamination from the surface. Areas of higher vulnerability are encountered where more permeable sediments are present at the surface and where groundwater levels are shallower. Higher vulnerability areas are mapped in the Dougan Lake valley, in the area bordering Garnett Creek, and in the lowland area south of Cobble Hill. A total of 62 well sampled in this study were constructed in AQ197, and 3 sites were shallow excavated wells associated with unconsolidated materials overlying it.

2.3.2 Aquifer 203 (Shawnigan Lake/Cobble Hill, Mill Bay), fractured crystalline bedrock (sub-type 6b)

Aquifer 203 is found in the lower southeastern portion of the study area, north of Mill Bay. The aquifer extent (total area 122.7 km^2) was delineated based on bedrock geology mapping, and presence of materials described in well logs primarily as volcanic and granitic fractured rock (Hammond, et al., 2019). The vulnerability of aquifer 203 to contamination is considered low to moderate, based on intrinsic susceptibility mapping where the surficial aquifer is absent. A total of 13 wells sampled in this study were constructed in aquifer 203.

2.3.3 Aquifer 198 (Cowichan Bay), fractured sedimentary bedrock (sub-type 5a)

Aquifer 198 has a total area of 104.7 km^2 and is a sedimentary bedrock aquifer described in well records primarily as shale and sandstone. This bedrock unit is mapped underlying aquifer 197 within the northern approximately two-thirds of the study area; however, most wells here are constructed within the overlying, unconsolidated deposits. Aquifer 198 is considered to have a lower vulnerability, based on the presence of aerially extensive and moderately thick (geometric mean 9.8 m) deposits of lower permeability sediments present noted in 48% of well construction records (Hammond, et al., 2019). Four sample sites included in this study were wells constructed in aquifer 198.

2.4 Groundwater monitoring and regional groundwater flow

There are presently three active provincial groundwater observation wells in the study area with the characteristics summarized in Table 2. In addition to the observation wells in Table 2, monitoring locations within the sampled bedrock aquifers located outside of the immediate study boundary may be referred to for an indicator of groundwater level fluctuation and aquifer state in this area. Hydrographs for three monitoring wells in aquifer 197 are shown in Figure 7 (shown as groundwater elevation for comparison between sites). Figure 8, Figure 9, and Figure 10, showing long-term annual average compared to historical daily maximum and minimum depth. The annual groundwater fluctuation is greatest in OW345 (Arbutus Ridge) at approximate 14 m different annually between high and low groundwater level, followed by OW233 (Vee Road), compared to OW320 in central Cobble Hill area at Braithwaite Estates which has the least annual variation in groundwater level. All observation wells show interference from adjacent groundwater pumping. More information and all data associated with Provincial Groundwater Observation Well Network sites can be obtained online (Province of B.C., 2018). The regional direction of groundwater flow is from the central ridge of aquifer 197, westward toward Patrolas Creek and Koksilah River valleys, northeastward toward the coast, and southeastward toward the Shawnigan Creek valley as shown in Figure 11.

Table 2: Active provincial groundwater observation wells in the South Cowichan study area.

Observation well number	Location	Aquifer number and sub-type	Well Tag Number	Period of record	Well depth (m bgs)	Screened interval (m bgs)	Average annual ground water level fluctuation (m)
233	Cowichan Bay (Vee Road)	197 (4b)	21169	Oct. 1979-present	57.9	56.8 – 57.9	6.3
320	Cobble Hill (Braithwaite Estates)	197 (4b)	41479	Oct. 1992-present	36.1	33.2 – 36.1	1.4
345	Cobble Hill (Arbutus Ridge)	197 (4b)	75531	Dec. 1999-present	86.6	85.3 – 86.6	13.8

Figure 7: OW233 (Cowichan Bay, Vee Road), OW320 (Cobble Hill, Braithwaite Estates) and OW345 (Cobble Hill, Arbutus Ridge) groundwater elevation (metres above sea level, masl).

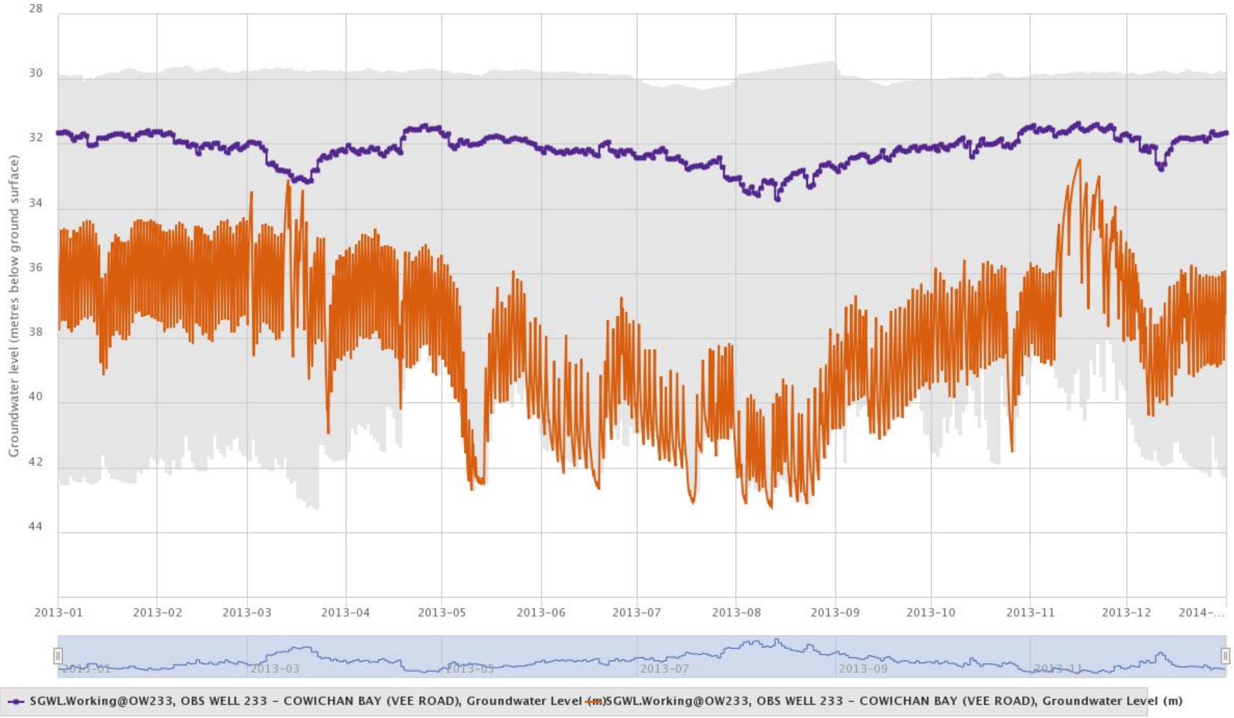

Figure 8: OW233 (Cowichan Bay, Vee Road) groundwater level (mbgs) in 2013/14 (orange). Statistics, average (purple line) and min/max (grey shading) are based on the entire period of record. Plot generated in Groundwater Level Data Interactive Map Tool (Province of B.C., 2019a).

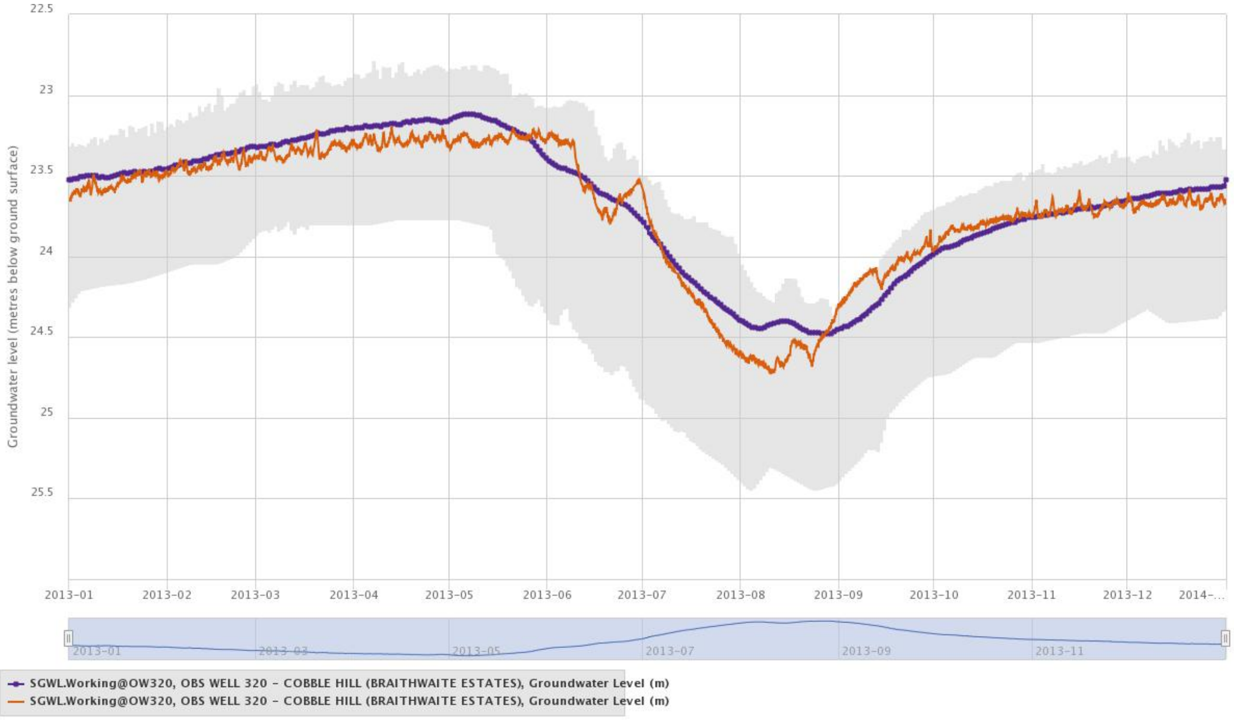

Figure 9: OW320 (Cobble Hill, Braithwaite Estates) groundwater level (mbgs) in 2013/14 (orange). Statistics, average (purple line) and min/max (grey shading) are based on the entire period of record. Plot generated in Groundwater Level Data Interactive Map Tool (Province of B.C., 2019a).

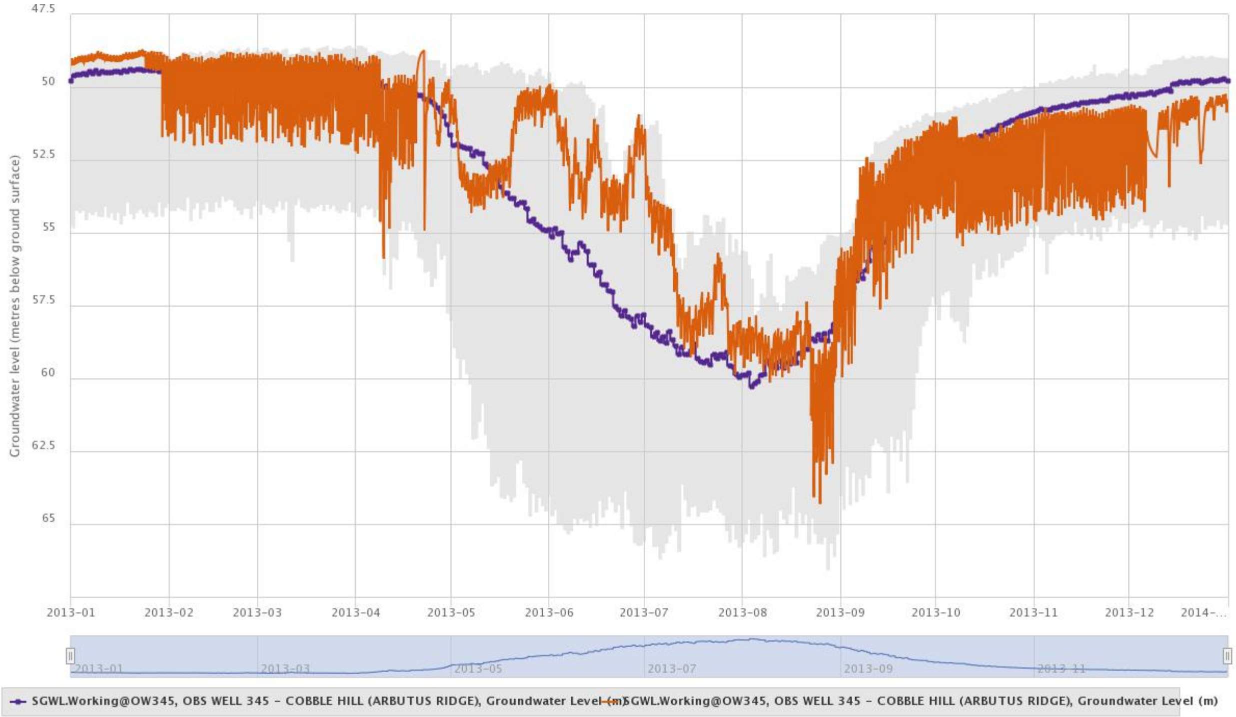

Figure 10: OW345 (Cobble Hill, Arbutus Ridge) groundwater level (mbgs) in 2013/14 (orange). Statistics, average (purple line) and min/max (grey shading) are based on the entire period of record. Plot generated in Groundwater Level Data Interactive Map Tool (Province of B.C., 2019a).

Liggett & Gilchrist (2010) using intrinsic susceptibility mapping methods, estimated recharge to the aquifers in this area to range from 103 to 178 mm/y (corresponding to approximately 4 to 7 million m^3/y, and approximately 15% of annual precipitation), with greater recharge in upland areas on the western margin of the study area. In comparison Harris and Usher (2017) estimated recharge to aquifer 197 to range from 246 mm/y (hot/dry year), 366 mm/y on average, up to 608 mm/y (cold/wet year) (9 to 24 million m^3/y). The different recharge estimates are like due to variations in methods (see original references for details).

Based on static groundwater levels from well records, and topographic elevation, the direction of groundwater flow is outward northeast toward Cowichan Bay and southwest toward the Koksilah River valley from a groundwater divide in the central part of the aquifer, as illustrated in Figure 11.

2.5 Population and land use

The study area is within the traditional territory of the Coast Salish peoples, including Cowichan Tribes and Malahat First Nation. It encompasses portions of Cowichan Valley Regional District (CVRD) Electoral Areas A (Mill Bay/Malahat), C (Cobble Hill) and D (Cowichan Bay) (Cowichan Valley Regional District, 2019a). Based on the 2016 Canadian census, the combined populations of these Electoral Areas is 12,995, up approximately 8% from 12,160 in 2011, and continued growth in these areas is expected (Cowichan Valley Regional District, 2019b).

Groundwater is the primary source of water supply for residential, agricultural and other water use in this area (Harris & Usher, 2017; Bennett, et al., 2019). There are 15 local water service providers (boundaries shown in Figure 2) including regional water systems operated by CVRD, improvement districts and private systems all of which utilize a groundwater source (Cowichan Valley Regional District, 2019). The population within this study area that obtains water from a local water service LWSA is approximately 6000 users (2845 connections, multiplied by approximate household occupancy of 2.1 people, not accounting for industrial or commercial use). In addition, we estimate there is a population of approximately 2600 users (1238 non-vacant residential lots outside of water service areas * 2.1 person per connection occupancy) that are inferred to be using groundwater for domestic purposes. An additional unquantified number of wells are relied for irrigation, commercial or industrial use. Land use in this area is primarily rural residential and agricultural. An area of 33 km^2 (~65% of the study area) is included in the Agricultural Land Reserve, but not all of this is actively farmed.

3. METHODS

The methods used to evaluate water groundwater quality in the South Cowichan area involved identification of representative sample sites distributed throughout the study area, collecting field parameter measurements and samples according to standard protocols, including applying Quality Assurance/Quality Control measures, and evaluating well head protection aspects at each site. The sample results were then compared to factors such as intrinsic aquifer susceptibility to contamination and hazard indicators, such as land-use, and proximity to potential pollutions sources.

3.1 Site selection

Site were selected with the aim of getting an even distribution of samples throughout the study area, while including areas of moderate to high aquifer intrinsic vulnerability and areas of moderate to high density of active wells.

Domestic well sample sites were identified by door-to-door canvassing within targeted locations in the study area and sites were selected from the volunteers that responded. A total of two phases of canvassing were completed in November 2013 and January 2014. In order for a site to be selected for sampling the following criteria had to be met: (a) the well owner had basic information about her/his well (location and depth and ideally lithology as shown on a well construction record); and (b) it was possible to sample raw (untreated) water quality, as close to the well as possible, prior to any cisterns, pressure tanks and/or water treatment equipment. Within some areas several volunteers responded, however due to limited budget it was not possible to sample all locations volunteered, and therefore a smaller set of wells were identified among the respondents, while aiming for optimum spatial distribution of sites.

The water supply system wells in the study area were identified via contacts within local government and Island Health. These sources were considered advantageous for sampling because they provide water to a larger number of users, extract higher volumes of water in comparison to domestic wells, and provide a sample that is representative of groundwater within a larger area of influence or capture zone around the well. Within areas serviced by a water improvement district or municipal water system it is believed that many of the domestic wells are no longer in use or may be used primarily for irrigation.

This study did not include sampling from production wells and dedicated monitoring wells on three sites at 1345, 1355 and 1360 Fisher Road, which are known locations of aquifer contamination from industrial and agricultural land use (Thurber Engineering Ltd, 2013; Western Water Associates Ltd., 2018; EBA Engineering Consultants Ltd., 2010; Thurber Engineering Ltd., 2012). The intent was to understand overall water quality in the area's aquifers, that might be used for a basis of comparison for water quality in impacted areas.

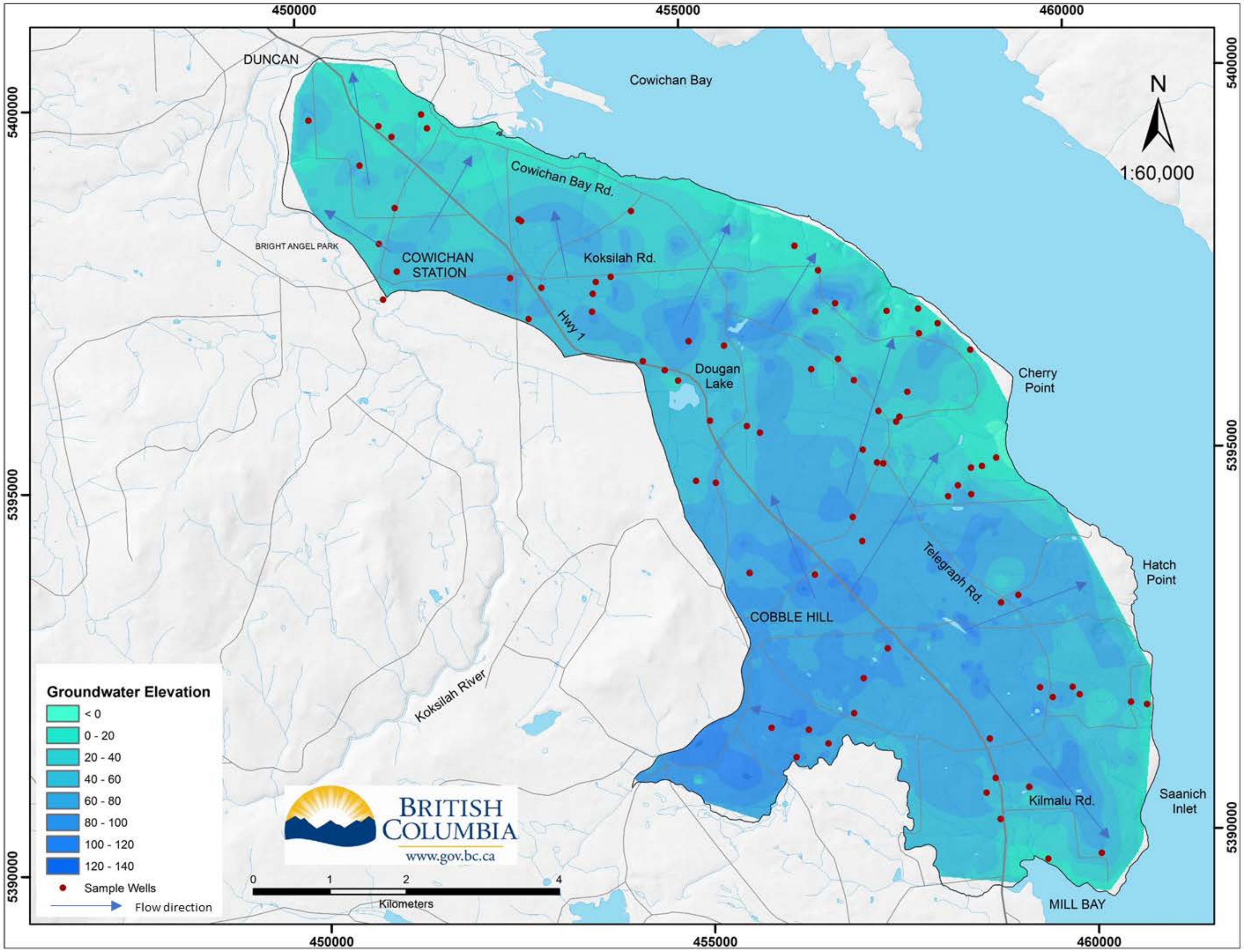

Figure 11: Aquifer 197 groundwater potentiometric contours and estimated regional direction of groundwater flow

3.2 Sampling and analytical methods

3.2.1 Field parameter monitoring and sample collection

At each sample site, an access location was identified as close to the well as possible, prior to 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% (by volume) 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 to discharged through a monitoring flow cell and filtration apparatus. This allowed staff to monitor field parameters prior to sampling with minimal contact of the discharge water with the atmosphere which could influence the parameter values. In some cases, in order to ensure water was discharged away from the sample location (i.e. pump house or basement) an additional specialized water hose suitable for potable water use was attached to the sample point and this hose was then attached to the flow monitoring cell and filtration apparatus.

Two teams were involved in the sampling program; each utilized a YSI Model Professional Plus 1030 multi-meter with probes inserted into the flow cell to monitor field parameters of temperature, pH, and specific electrical conductivity. Oxidation-reduction-potential (ORP) was only measurable using one of the YSI units, and therefore it was recorded where possible. The multi-meters were calibrated in the laboratory prior to going into the field following manufacturer's instructions using standard calibration solutions. Field parameters were measured and recorded on a continuous basis (i.e. every minute) allowing enough time for the flow cell to be completely refilled between readings. Prior to sample collection, water was purged 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 within 3 to 16 minutes and the average purge duration was 6 minutes.

ORP was corrected to Eh based on the half-cell potential of the Ag/AgCl reference code (correction factor 215 mv), considering an average groundwater temperature of 9 °C (closest reference temperature 10 °C) (U.S. Environmental Protection Agency, 2017).

Sampling was completed using aseptic technique including use of sterile gloves. Flow through to the monitoring flow cell was stopped and diverted through a sampling hose attached to the discharge apparatus. Flow was reduced and the samples were collected directly into the appropriate bottles with no pre-rinsing. Samples for microbiology (total coliforms and *Escherichia coli* bacteria), general chemistry, and major anions were not filtered. Samples for metals and major cations were filtered in the field using Waterra FMT-45 (0.45 µm) in-line filter attached to the discharge tube and preserved using pre-measured vials of nitric acid (HNO_3) solution obtained from the laboratory. Dissolved concentrations of trace metals and cations are considered more representative of the quality of groundwater within the aquifer, in comparison to total metals (Nielsen & Neilsen, 2007). Samples for nitrate isotopes were filtered in the field using an in-line filter as described above.

Variation to the above methods occurred at a small number of sites at which it was not possible to attach the flow cell and filtration apparatus to the sample point. In these cases, flow from the sample point was monitored within a secondary container (e.g. clean bucket) until field parameter stabilization was achieved as above. Unfiltered samples were collected directly into the standard bottles. Samples requiring filtration (dissolved metals, nitrate isotopes) were filtered in the field using a single-use plastic syringe and (0.45 µm) mini-cartridge filters and preserved as per standard procedures.

Figure 12: Example sampling set-up. Clockwise from top left: Sample point; discharge line; flow cell; sampling with in-line filter.

Samples for bacteria, general chemistry, major ions and metals were placed in coolers with ice, maintained at <4 °C during transport and delivered by courier within 24 hours to Maxxam Analytics laboratory following standard chain-of-custody procedures. Samples for nitrate isotope analysis (two 1 litre bottles for each site) were frozen immediately upon return from the field; when the results from Maxxam Analytics laboratory were received, samples with nitrate-nitrogen concentration ≥ 2 mg/L were couriered to University of Waterloo Environmental Isotopes Laboratory for analysis of nitrogen-15 and oxygen-18(nitrate).

Table 3: Geochemical, biological and isotope parameters analyzed in groundwater samples.

Field parameters	**General chemistry and anions**	**Cations and trace metals**
Temperature	Nitrate (N)	Aluminum Dissolved (Al)
Specific electrical 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 (CO_3)	Beryllium Dissolved (Be)
Microbiological parameters	Hydroxide (OH)	Bismuth Dissolved (Bi)
Total coliforms	Sulphate Dissolved (SO_4)	Boron Dissolved (B)
Escherichia coli	Chloride Dissolved (Cl)	Cadmium Dissolved (Cd)
	Organic Nitrogen Dissolved	Chromium Dissolved (Cr)
Isotope parameters	Phosphorus Dissolved (P)	Cobalt Dissolved (Co)
Oxygen18-Nitrate ($\delta^{18}O\text{-}NO_3$)	Total Kjeldahl Nitrogen Dissolved (Calc)	Copper Dissolved (Cu)
Nitrogen15-Nitrate ($\delta^{15}N\text{-}NO_3$)		Iron Dissolved (Fe)
	Ammonia	Lead Dissolved (Pb)
	Nitrate plus Nitrite	Lithium Dissolved (Li)
	Nitrite	Manganese Dissolved (Mn)
	Nitrogen Total Dissolved	Molybdenum Dissolved (Mo)
	Conductivity	Nickel Dissolved (Ni)
	pH	Selenium Dissolved (Se)
	Total Dissolved Solids (TDS)	Silicon Dissolved (Si)
	Turbidity	Silver Dissolved (Ag)
	Bromide (Br)	Strontium Dissolved (Sr)
	Hardness Dissolved	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

3.2.2 *Laboratory analytical methods and QA/QC*

Samples for geochemistry and microbiological analysis were analyzed at Maxxam Analytics Inc. laboratory in Burnaby, B.C. using standard analytical methods (Rice, Baird, Eaton, Clesceri, & Eds., 2012). Laboratory Quality Assurance and Quality Control (QA/QC) included reporting of temperature at arrival of the samples, completion of matrix spike, spiked blanks and calculation of the Relative Percent Difference (RPD%) for analytical replicate samples. Results outside the QA/QC limits would trigger a reanalysis of the sample(s) by the lab. The summary results of laboratory QA/QC were included in the digital report for each individual sample site but are not reproduced in this report. For geochemical parameters the precision of each sample analysis is shown in Appendix A, Table A-1 as the reportable detection limit or RDL.

3.2.3 Study design and field Quality Assurance and Quality Control

QA/QC measures in the study design and field methods involved collecting a minimum of 10% QA/QC samples in the field (e.g. duplicate samples, field blanks, or equipment blanks); calculating the charge balance error (balance of anions and cations) for each sample; and calculating the RPD% for duplicate samples. The detailed methods and results of the QA/QC protocols are provided in Appendix B.

3.3 Evaluating well head protection

Prior to collecting a groundwater sample, each well was inspected in order to assess compliance with the *Water Act*, now the *Water Sustainability Act* (*WSA*), and the Groundwater Protection Regulation (GPR) (Province of B.C., 2014; Province of B.C., 2016a). Recommendations were also made for best management practices to protect the well, 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, proximity to contaminant sources) and physical set-up of the well (diameter, casing stick-up, presence and condition of the well cap, condition of the well house, etc.). 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. Well construction reports were available for most sample sites; at one site a detailed record was not available, and a new well registration was created using field coordinates and well depth information provided by the well owner.

Three types of wells were 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. The different well types are depicted in Figure 13. Drilled wells tend to have a smaller diameter, typically 15 cm (6 inches), compared to dug wells, which have a diameter of 1.5 m (5 ft) on average.

The GPR 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 Sustainability Act* (Province of B.C., 2014), GPR (Province of B.C., 2016a) and *Public Health Act*, Health Hazards Regulation (Province of B.C., 2016b).

Table 4: Well inspection checklist.

- ☐ Well has water tight, vermin-proof cap[1]
- ☐ Top of well (well casing stick-up) extends a minimum of 30 cm 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 (assessed based on information in 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 an undrained underground pit or enclosure[2]
- ☐ Well located in high and 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)[1]
- ☐ If well is flowing artesian, flow is under control.[1]
- ☐ If there are unused wells on the property, and there is no intent to use them in future, these are deactivated or decommissioned (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 a minimum 3 m away from the well and not in the pumphouse[1]

[1] Requirement for all wells. Refer to *Water Sustainability Act (WSA)* and Groundwater Protection Regulation (GPR).

[2] Recommended for all wells, and requirement for wells constructed or altered since Nov. 1, 2005. Refer to *WSA* and GPR.

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

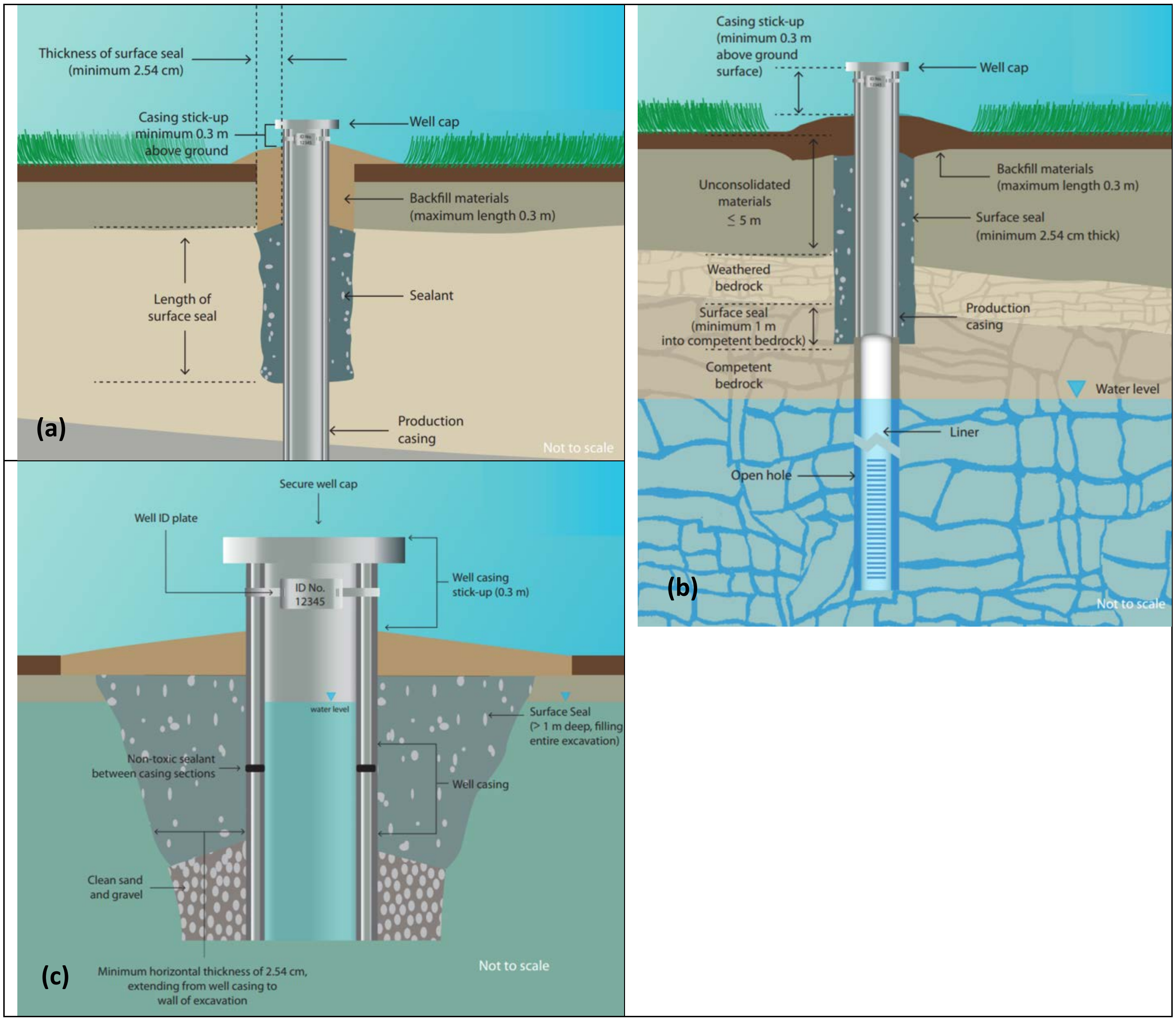

Figure 13: Features of properly constructed and maintained wells (a) drilled well in unconsolidated aquifer, (b) drilled well in bedrock aquifer, (c) excavated well. Image source: (B.C. Groundwater Association, 2017).

3.4 Hazard inventory and identification of potential pollution sources

Data regarding land use and potential point and non-point contaminant sources within the study area were compiled to produce a potential hazard inventory for comparison to observed water quality results. Spatial data from the Cowichan Valley Agricultural Land Use Inventory study (Ministry of Agriculture, 2013) provided field verified information on the types of farming practices utilized that could contribute to presence of nutrients such as nitrogen species (nitrate, ammonia) in the environment. Locations of point sources associated with discharges of pollution under the *Environmental Management Act* (Province of B.C., 2003) were obtained from online documentation (Ministry of Environment and Climate Change Strategy, 2019a) and cross-referenced spatially to data from the Environmental Monitoring System (EMS) database (Ministry of Environment and Climate Change Strategy, 2019b). The methods and results are further detailed in section 5.2.

3.5 Aquifer Vulnerability Index

The intrinsic aquifer susceptibility to contamination has been previously determined for this area and other areas on Vancouver Island and the Gulf Islands using DRASTIC methodology which considers factors including the depth to groundwater, recharge, and the hydraulic properties of shallow soil and unsaturated zone above the aquifer, and of the aquifer itself (Liggett & Gilchrist, 2010; Aller, et al., 2002) with intrinsic susceptibility classification for the study area in shown in Figure 38. Some characteristics of the DRASTIC method are that the results apply only to the shallow or uppermost aquifer, parameters such as recharge are difficult to quantify accurately due to the influence of local depression focussed recharge, and that the weighting scheme overemphasises the importance of factors such as topography, and may not adequately quantify the influence on confining layer thickness and properties on vertical contaminant movement (Van Stempvoort & Wassenaar, 1992).

For comparison to the aquifer intrinsic susceptibility calculated using the DRASTIC method, the Aquifer Vulnerability Index (AVI) method was used to calculate the vulnerability of each sampled well with sufficient lithological data in the construction record. The AVI estimates the thickness and hydraulic conductivity of sedimentary layers above the aquifer to determine a relative "travel time" of contaminants via vertical flow to the well (Van Stempvoort, et al., 1993). This method can apply to both confined and unconfined aquifers, and to wells constructed within the lower aquifer of a layered aquifer complex. The AVI was calculated using the formula:

$$c = \sum \left(\frac{d_i}{k_i}\right)$$

Equation 1

where,

c=hydraulic resistance of an aquitard or layer of unsaturated material to vertical flow (days)

d=thickness of each sediment layer above the saturated aquifer surface (m)

k=estimated hydraulic conductivity of each sediment layer (m/d)

Well lithology for all sampled wells was extracted as a MS Excel table from the GWELLS database (Province of B.C., 2019c), the lithology descriptions were standardized into a sediment type category, according the material descriptions and associated via a Lookup Table with ranges of hydraulic conductivity Table 5 based on literature values in (Van Stempvoort & Wassenaar, 1992; Van Stempvoort, et al., 1993; Freeze & Cherry, 1979). The depth of the aquifer layer was determined based on the screen installation details, description of the material as "saturated" or "water-bearing" and comparison to static water level, if recorded in the well log. It was not possible to calculate the AVI for wells in which the lithology was not described. The hydraulic resistance (converted from days to years) was then converted to $\log_{10}(c)$ to represent an AVI rating from extremely low to extremely high, as listed in Table 6. The hydraulic resistance is a relative measure, based on physical properties of the materials, of vertical travel time of water or contaminants through the unsaturated zone to the aquifer, but neglects factors including hydraulic gradient, diffusion and sorption that influence the actual rate of vertical and horizontal contaminant movement in groundwater.

Table 5: Standardized lithology code, sediment type and estimated vertical hydraulic conductivity (m/d), modified from (Van Stempvoort, et al., 1993).

Standardization code	Sediment type	k (m/d)
A	gravel	1000
AB	gravel and sand	100
B	sand	10
C	silty sand	1
D	silty sand	1.00E-01
E	fractured till, clay or shale (shallow, 0-5 m from ground surface)	1.00E-03
F	fractured till, clay or shale (5-10 m from ground surface)	1.00E-04
F	fractured till, clay or shale (moderate, 10 m from ground surface but weathered based on colour brown or yellow)	1.00E-04
G	massive till or mixed sand-silt-clay	1.00E-05
H	massive clay or shale	1.00E-06
AQ	aquifer or water-bearing layer (k not calculated)	
NC	not calculated (insufficient lithological info)	
0	not calculated (no depth interval indicated)	

Table 6: Relationship of Aquifer Vulnerability Index to Hydraulic Resistance, from (Van Stempvoort, et al., 1993).

Hydraulic resistance (c)(years)	Log (c)	Vulnerability (AVI)
0 to 10	<1	Extremely high
10 to 199	1 to 2	High
100 to 1000	2 to 3	Moderate
1000 to 10,000	3 to 4	Low
>10,000	>4	Extremely low

3.6 Determination of background concentration of nitrate in groundwater

One objective of the study was to understand the concentration of nitrate that likely represents background or baseline conditions indicating where the impact of human activities is minimal. Nitrate is ubiquitous in the environment, originating from multiple point and non-point sources, such as atmospheric emissions, infiltration of precipitation, irrigation of agricultural fields where organic or synthetic fertilizers are used, or septic field discharges. When samples are collected from existing wells within inhabited areas, it is a challenge to find pristine areas where anthropogenic sources of nitrate are not present for comparison to areas where impacts may have occurred. Adapting methods from exploration geochemistry, it is possible to use statistical techniques to define geochemical thresholds above which impact has likely occurred (Panno, et al., 2006; Sinclair, 1974). To complete this aspect of the study, all available data representing nitrate concentrations in groundwater from wells in the study area were compiled from various sources, including the provincial Environmental Monitoring System (EMS) database (Province of B.C., 2017d), and existing compilations (Western Water Associates Ltd., 2018). The data set also included results from sampling of CVRD monitoring wells and an industrial production well within the Fisher Road area where contamination of groundwater from nitrates is known to have occurred. Censored values below the reportable detection limit (RPD) were excluded, as were samples from bedrock wells, therefore all values represent water quality within aquifer 197. The detailed methods and results are discussed further in section 5.5.

4. RESULTS AND DISCUSSION

A total of 82 wells were sampled for this study, representing roughly 6% of the estimated 1456 wells in the study area registered in the WELLS database at the time the sampling was completed (Ministry of Environment, 2014a)[1]. It is recognized that the database may underestimate the actual number of wells. The sample sites were distributed within the areas of greatest density of registered wells (Figure 15). In total 62 (75%) of the sample locations were wells drilled in unconsolidated materials such as sand and gravel, and 3 sites (4%) were shallow, excavated wells dug in unconsolidated materials. The median depth of wells in unconsolidated aquifers was 38.1 m (125 ft) and the well depths ranged from 3.0 to 101.2 m (10 to 332 ft). Seventeen wells (21 %) sampled were drilled in a bedrock aquifer, and the median depth of these wells was 80.8 m (265 ft), ranging from 45.7 to 161.5 m (150 to 530 ft) deep. Within well construction records, the bedrock type was described as sandstone, shale and granite. Of all wells sampled, 70 (85%) were domestic wells, and 12 (15%) were water supply system wells operated by a local water service provider, such as the Cowichan Valley Regional District, a private improvement district or utility.

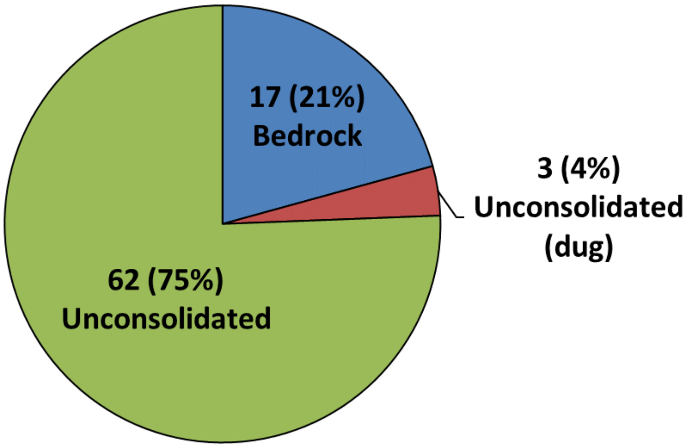

Figure 14: Proportion of sampled wells in different aquifer materials and by construction method.

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[1] For comparison, in February 2019 there were 1615 registered wells within the study area boundary.

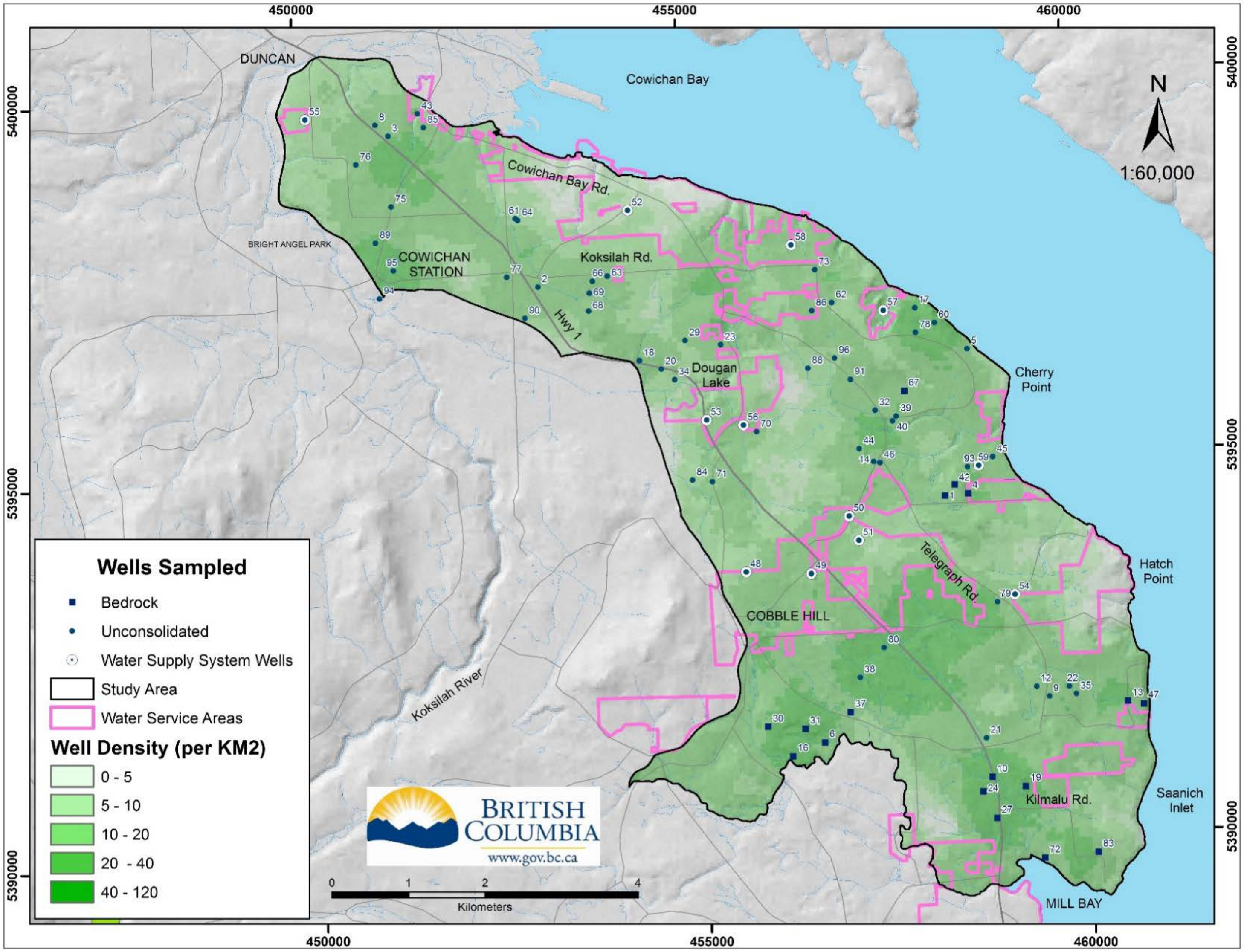


Figure 15: Sample sites and well density in the study area.

4.1 Quality Assurance/Quality Control (QA/QC)

A summary of QA/QC methods and results is provided in Appendix B. The QA/QC results were found to be acceptable, and all sample values were retained for further interpretation.

4.2 Geochemistry

Within this study, groundwater samples were analyzed for 60 different geochemical and physical parameters. Together, the parameters analyzed are part of a standard suite chosen because of their 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), or because they provide information regarding the geochemical and physical processes the water has been through.

Some parameters reflect the age of water in aquifers. 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.

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 (three part) 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. The position of the plotted sample point in the diamond indicates 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) (Freeze & Cherry, 1979; Appelo & Postma, 1993). Piper diagrams of the study samples prepared using Aquachem (v. 2014.2) are shown in Figure 16 and Figure 17.

The water type was determined for all samples using Aquachem and the results are summarized in Table 7 and illustrated in Figure 16 and Figure 17. The majority (82%) 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.

The second most frequent water type was sodium-bicarbonate (Na-HCO_3) type (16%), 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, or from wells installed in unconsolidated formations near the bedrock contact i.e. where the quality may be influenced by groundwater from the regional bedrock flow system. 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). The effects of the cation exchange process on groundwater quality within aquifers made up of Nanaimo Group sedimentary rock on eastern Vancouver Island and the Gulf Islands has been described in previous studies (Allen & Matsuo, 2002; Earle & Krogh, 2006).

A smaller group (2%) of samples were magnesium-bicarbonate (Mg-HCO_3) type groundwater, reflecting dissolution or cation exchange with magnesium containing rocks. These samples appear closer to the centre of the upper diamond on the Piper plot.

Table 7: Water type of geochemical samples.

	Water Type			
Well lithology	Ca-HCO_3	Mg-HCO_3	Na-HCO_3	Total
Bedrock	12%	0%	9%	21%
Unconsolidated	66%	2%	7%	76%
Unconsolidated (dug)	4%	0%	0%	4%
Total	82%	2%	16%	100%

4.3 Field Parameters

At each location, temperature, pH, and specific conductivity were measured in the field. Oxidation reduction potential (ORP) was measured in the field at some sites, as only one of the YSI meters utilized by the sampling teams was able to measure this parameter. All the samples were collected during the winter period therefore the groundwater temperatures reflected ambient conditions in the aquifer, e.g. in the case of warmer temperatures, average temperature of water recharging the aquifer, with colder water temperatures potentially observed in shallower or more recently recharged groundwater under the influence of atmospheric conditions. The median ambient temperature of water from unconsolidated wells was 9.6°C, compared to water from bedrock wells which had a median temperature of 9.9°C.

pH was relatively consistent between aquifer material types and ranged from 5.56 to 8.73 units (statistics for aquifer types summarized in Table 11 and described below in section 4.5.1). Samples from unconsolidated wells had a median specific electrical conductivity of 225 µS/cm. In comparison, the median specific electrical conductivity of samples from bedrock wells was 304 µS/cm. In general, the higher conductivity of water sampled from bedrock wells suggested that the groundwater had undergone more water-rock interaction and was present under more reducing (low oxygen) conditions.

Oxidation reduction potential (ORP) is an indicator of the oxygen content in the water, which tends to decline with aquifer depth, or where the groundwater velocity is slow. ORP was highest for unconsolidated dug wells (ORP 202 mv, corrected to Eh 417 mv), and similar for unconsolidated drilled (ORP 129 mv, Eh 344 mv) and bedrock (ORP 83 mv, Eh 298 mv).

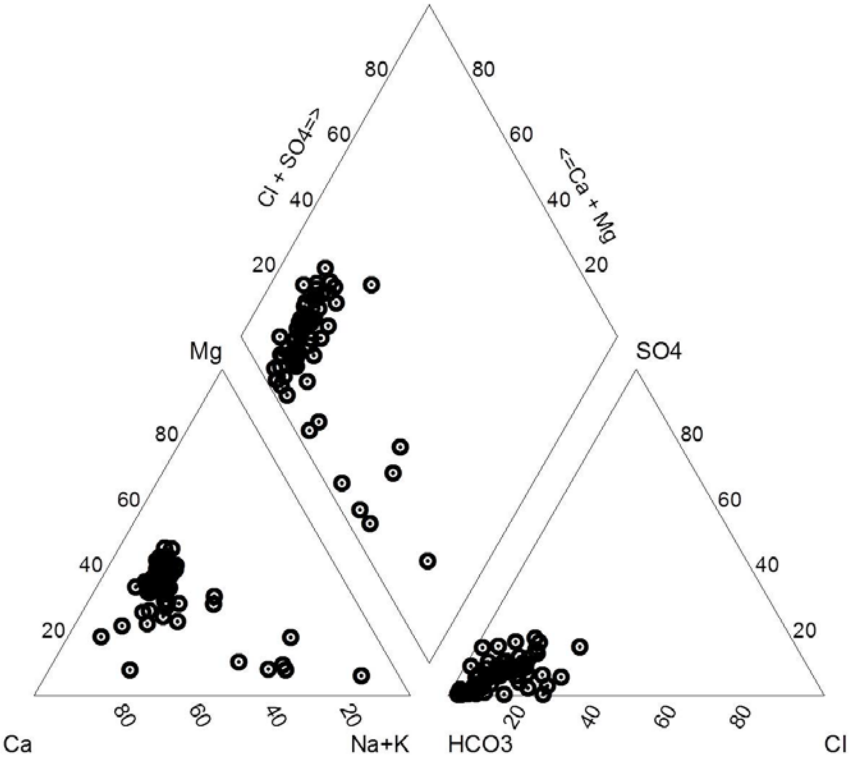


Figure 16: Piper diagram of South Cowichan groundwater samples from wells in unconsolidated aquifers.

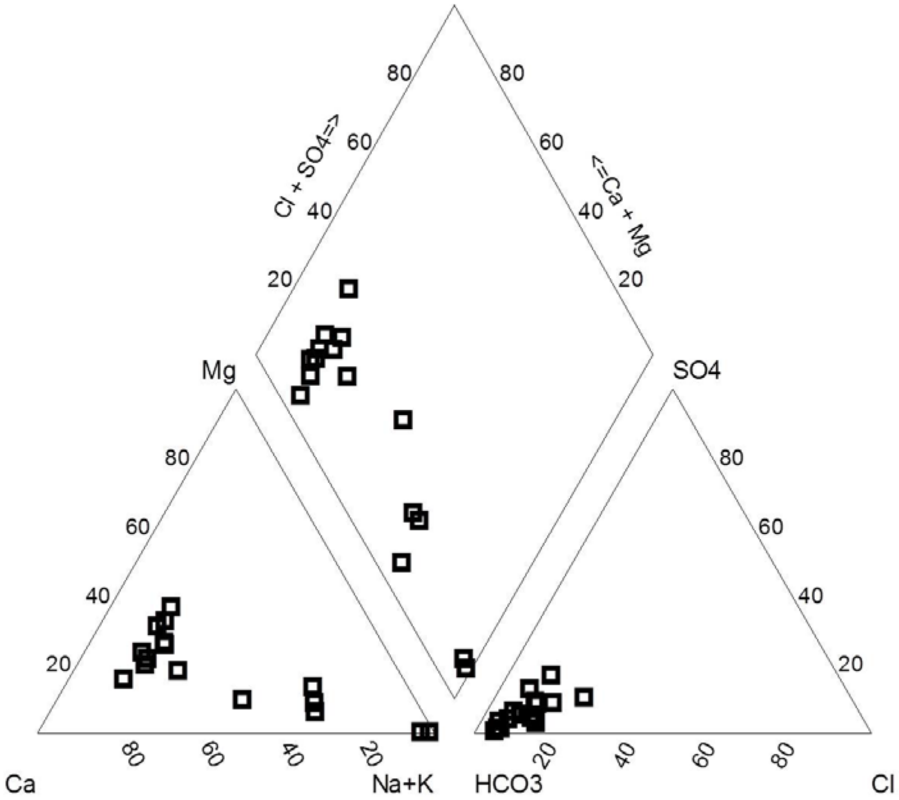


Figure 17: Piper diagram of South Cowichan groundwater samples from wells in fractured bedrock aquifers.

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) initially based on 2014 standards, and modified for parameters for which the guidelines changed in 2019, such as lead, manganese, pH and selenium (Health Canada, 2014; Health Canada, 2019a). 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 concentration limit for parameters that can affect the taste, odour, or pleasantness of the water for drinking. Health-related parameters evaluated by 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, and zinc, which are described in Section 4.5. In 2019, Health Canada established separate health-related and aesthetic guidelines for manganese (Health Canada, 2019b). Table 8 summarizes the number and percent of samples that exceeded drinking water guidelines. These numbers to not reflect the independent number of sites with exceedances, as some sites exceeded the GCDWQ for more than one parameter.

Table 8: Number and percent of samples exceeding drinking water quality guidelines for health-related or aesthetic parameters (manganese values displayed separately for AO and MAC, results for unconsolidated and bedrock aquifer combined).

Parameter	# Exceedences	% of samples	Guideline (µg/L or as indicated)	Objective type
Arsenic	2	2%	10	MAC
Iron	14	17%	300	AO
Manganese	24	38%	120	MAC
Manganese	40	49%	20	AO
pH	21	26%	<7 or >10.5 pH units	AO

Table 9 shows the arithmetic mean, median, geometric mean, minimum, and maximum concentrations of health-related parameters in groundwater from wells in unconsolidated and bedrock aquifers. The complete geochemical results for all sites are provided in Appendix A, Table A-1. The comparison of median concentrations of these elements within unconsolidated (sand and gravel) and bedrock aquifers is shown in Figure 18.

From wells in unconsolidated aquifers two samples (2%) had arsenic, and twenty-four samples (38%) had manganese concentrations above the health-related maximum acceptable concentration (MAC). Forty samples from bedrock wells (49%) had manganese above drinking water guideline aesthetic objective (AO). Fourteen samples (17%) had iron above the AO, and the pH was above or below the AO in 21 samples (26%). Apart from this, no other samples exceeded health-related drinking or aesthetic water quality limits. As shown in Table 9 and Figure 18, the median concentrations of nitrate, arsenic, and selenium were higher in groundwater from unconsolidated materials, and the concentrations for nitrate and arsenic exhibited a greater range for this aquifer type.

Table 9: Statistical summary of sample results for health-related parameters.

	Nitrate (N)	**Fluoride (F)**	**Antimony Dissolved (Sb)**	**Arsenic Dissolved (As)**	**Barium Dissolved (Ba)**	**Boron Dissolved (B)**	**Cadmium Dissolved (Cd)**	**Chromium Dissolved (Cr)**	**Lead Dissolved (Pb)**	**Manganese (Mn)**	**Selenium Dissolved (Se)**	**Uranium Dissolved (U)**
Units	**mg/L**	**mg/L**	**µg/L**	**µg/L**	**mg/L**	**mg/L**	**µg/L**	**µg/L**	**µg/L**	**µg/L**	**µg/L**	**µg/L**
Health Canada Guideline (MAC)*	10 mg/L	1.5 mg/L	6 µg/L	10 µg/L	1 mg/L	5 mg/L	5 µg/L	50 µg/L	5 µg/L	120 µg/L	5 µg/L	20 µg/L
Unconsolidated												
Mean	nc	0.09	nc	1.91	0.014	nc	nc	nc	0.114	83.4	nc	0.17
Median	0.95	0.07	nc	0.62	0.006	nc	nc	nc	0.055	14.9	nc	0.05
Geometric mean	0.28	0.08	nc	0.71	0.008	nc	nc	nc	0.056	8.75	nc	0.05
Min	0.002	0.03	0.020	0.07	0.002	0.059	0.005	0.110	0.005	0.060	0.041	0.002
Max	5.25	0.35	0.070	17.30	0.104	0.226	0.033	5.23	1.26	460	1.38	2.08
N=65												
Exceedences	**0**	**0**	**0**	**2**	**0**	**0**	**0**	**0**	**0**	**20**	**0**	**0**
%				**3%**						**31%**		
Bedrock												
Mean	nc	0.15	nc	1.24	0.048	nc	nc	nc	0.071	76.3	nc	1.55
Median	0.038	0.09	nc	0.38	0.016	nc	nc	nc	0.044	18.8	nc	0.25
Geometric mean	0.051	0.10	nc	0.43	0.014	nc	nc	nc	0.037	14.2	nc	0.19
Min	0.002	0.03	0.025	0.04	0.002	0.122	0.008	0.230	0.005	0.108	0.043	0.00
Max	2.26	0.76	0.099	9.91	0.519	1.08	0.077	0.230	0.306	315	0.316	14.2
N=17												
Exceedences	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**4**	**0**	**0**
%										**24%**		
# <RDL (all)	27	0	59	1	0	65	68	49	4	0	42	19
% <RDL (all)[1]	33%	0%	72%	1%	0%	79%	83%	60%	5%	0%	51%	23%

[1] Percentage of samples less than Reportable Detection Limit (RDL) for samples from both unconsolidated and bedrock wells

*Health Canada. 2019. Guidelines for Canadian Drinking Water Quality. Ottawa, ON. https://www.canada.ca/en/health-canada/services/environmental-workplace-health/reports-publications/water-quality/guidelines-canadian-drinking-water-quality-summary-table.html. (Accessed: September 2019)

nc=not calculated

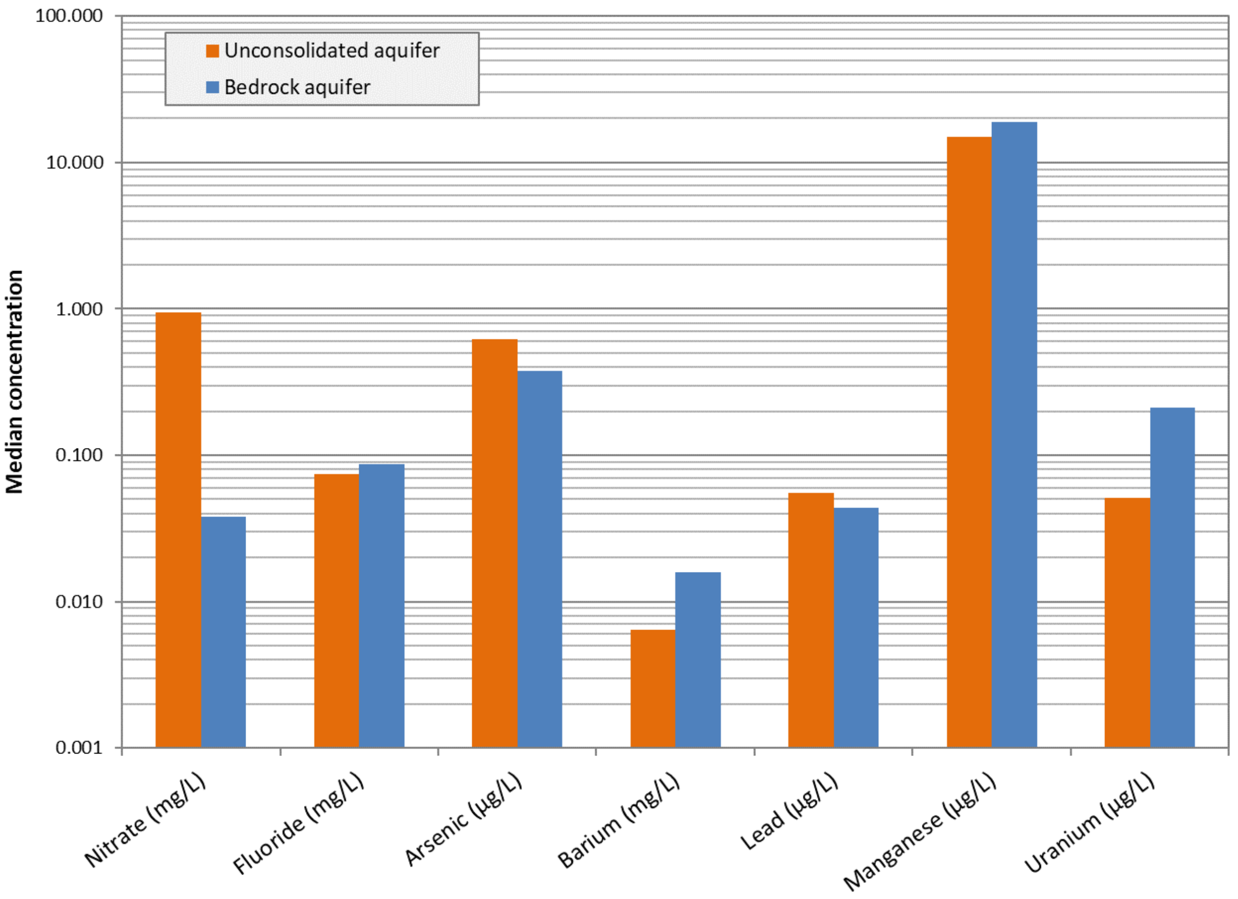


Figure 18: Comparison of median concentrations of health-related parameters in unconsolidated and bedrock aquifers.

In comparison the median concentrations of fluoride, barium, boron, manganese and uranium were higher in samples from fractured bedrock wells. Lead may be present in water due to its use in pipes and plumbing fixtures and is not related to aquifer type. Because of the common occurrence of arsenic, fluoride, and nitrate in groundwater in B.C., a more detailed evaluation of the results for these parameters is provided below.

One difficulty in calculating statistics for substances at low concentration is evaluating values that are below the Method Detection Limit (MDL) or Reportable Detection Limit (RDL)—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/√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 statistically valid 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 the statistics shown in Table 9 and Table 10, and Table A-1 (Appendix A), no replacement values were used for the censored data; instead, these data were excluded from the calculated statistics. Tables 9 and 11 show the percentage of censored data for each parameter. The effect of the statistical approach toward censored values for the specific parameter nitrate is discussed in section 4.4.4.

Summary statistic were not calculated (“nc”) when greater than 50% of samples had concentrations below the MDL and therefore only the range in parameter values is provided. For example, the concentrations of antimony, boron, cadmium, chromium, and selenium were very low. Looking at the breadth of values for these parameters, antimony ranged from a minimum of 0.020 µg/L to a maximum of 0.070 µg/L and 0.099 µg/L in groundwater from unconsolidated and bedrock wells respectively; boron concentrations ranged from 0.059 to 0.226 mg/L in groundwater from unconsolidated wells, compared to 0.122 to 1.08 mg/L in water from bedrock wells; cadmium ranged from 0.005 to 0.033 µg/L in groundwater from unconsolidated wells, and from 0.008 to 0.077 µg/L in groundwater from bedrock wells; and chromium ranged in concentration from 0.110 to 5.23 µg/L in groundwater from unconsolidated materials, while only one sample in a bedrock well had chromium (0.230 µg/L) above the detection limit.

4.4.1 Arsenic

Arsenic is a metalloid that occurs in water from 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 low concentrations of arsenic in drinking water may 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 based on lifetime exposure (70 years) and considering the reasonable effectiveness of available treatment technologies to reduce the concentration. Due to the potential for both acute and long-term health impacts, Health Canada recommends that arsenic concentrations in drinking water should be reduced to a concentration that is as low as reasonably achievable (ALARA) (Health Canada, 2006). An essential negligible risk of internal cancers over a lifetime exposure is associated with concentrations at or below 0.3 µg/L (defined by Health Canada as a range from one new cancer above background per 100 000 people to one new cancer above background per 1 million people (i.e., 10^{-5} to 10^{-6}) over a lifetime. Arsenic can be removed from water by various methods including lime softening, coagulation/filtration, reverse osmosis, distillation, ion exchange or greensand filters, or other specialized adsorptions/filtration technologies. 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 presence of arsenic at low concentrations was widespread throughout the study area, shown in Figure 19, and arsenic was higher in samples from unconsolidated compared to bedrock aquifers. In groundwater sampled from unconsolidated wells, the median concentration of arsenic was 0.062 µg/L, while 25% of samples had a concentration of 2 µg/L or more, and two samples had arsenic concentrations above the GCDWQ. In comparison, the median concentration was lower in samples from bedrock wells at 0.38 µg/L and there were no exceedances of the GCDWQ, although one sample had an arsenic concentration of 9.91 µg/L, just below the drinking water guidelines. From all sites (N=82), only one sample had arsenic below the reportable detection limit (RDL). These results highlight the value of geochemical sampling for well owners in the study area, to identify where dissolved arsenic is present and if treatment may be required to reduce its concentration.

4.4.2 Fluoride

In 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).

The Maximum Acceptable Concentration (MAC) for fluoride in groundwater is 1.5 mg/L (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 cavities. 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 or reproductive problems (Health Canada, 2010). Water treatment methods used for reduction of fluoride include reverse osmosis, activated alumina, or ion exchange (water softening).

In this study measured fluoride concentrations ranged from 0.03 mg/L up to 0.76 mg/L, and no samples had concentrations above the Maximum Acceptable Concentration. Fluoride was only slightly higher in samples from bedrock aquifers; the median concentration of fluoride in groundwater from unconsolidated aquifers was 0.07 mg/L, compared to 0.09 mg/L in bedrock. The spatial distribution of fluoride concentrations within groundwater samples in the study area is shown Figure 20. The prevalence of fluoride in Vancouver Island and Gulf Island aquifers comprised of Nanaimo Group sedimentary rocks has been documented in previous studies (Earle & Krogh, 2006; Barroso, et al., 2016) but may be less evident in this data set due to the smaller proportion of bedrock wells sampled. It is noted that concentrations of fluoride appear slightly higher within samples from AQ197 where it overlies AQ198, possibly reflecting upward regional flow of groundwater which has been in contact with the underlying sedimentary bedrock aquifer.

4.4.3 Manganese

Manganese is a metal that may be present naturally in groundwater from the dissolution of manganese-bearing minerals and rocks. Manganese sources from human activities include landfill leachate, and discharges from mining or industries such as the manufacturing of steel, dry-cell batteries, fertilizers, fungicides, paints and cosmetics (Health Canada, 2019b). Elevated concentrations of manganese can cause staining of plumbing fixtures or laundry and give the water an unpalatable taste. While manganese is an essential nutrient and most manganese is ingested in food, at higher concentrations in drinking water and with long-term or chronic exposure it may be associated with neurological effects. For example, some studies have linked manganese exposure in tap water to intellectual impairment in children (Health Canada, 2019b; Bouchard, et al., 2011).

In 2019 Health Canada established two separate water quality objectives for manganese, a higher health-based Maximum Acceptable Concentration (MAC) of 0.12 mg/L (120 µg/L) and a lower aesthetic objective (AO) of 0.020 mg/L (20 µg/L). Manganese is often also associated with presence of iron in drinking water, as it originates from similar sources (see section 4.5.6 below). Treatment to remove manganese and iron is typically done at the same time, using methods such as water softening, injection of chlorine dioxide, potassium permanganate, or ozone, which causes the metals to form a solid precipitate that is then allowed to settle or is filtered out. Other techniques used for manganese

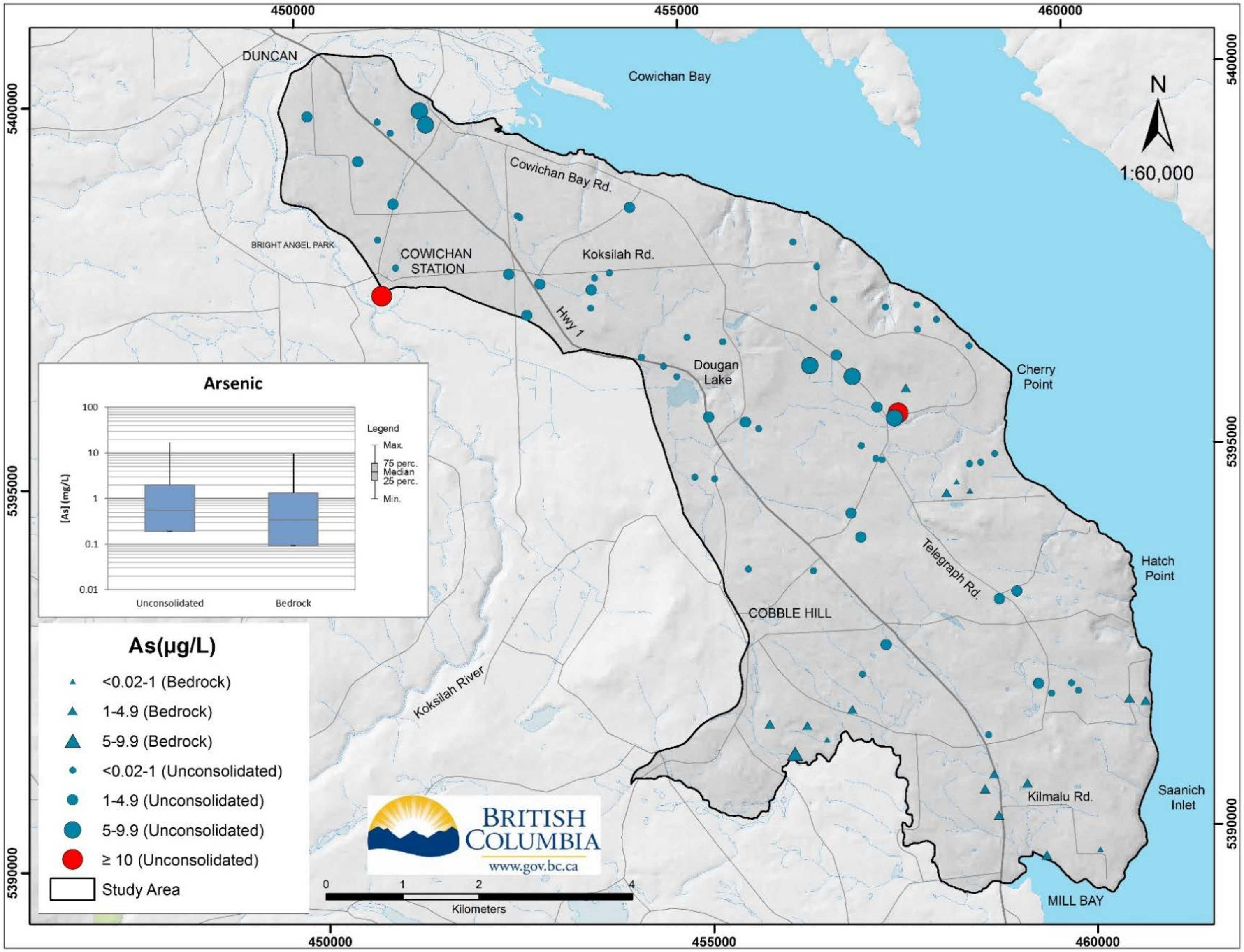


Figure 19: Map of arsenic concentration in groundwater samples.

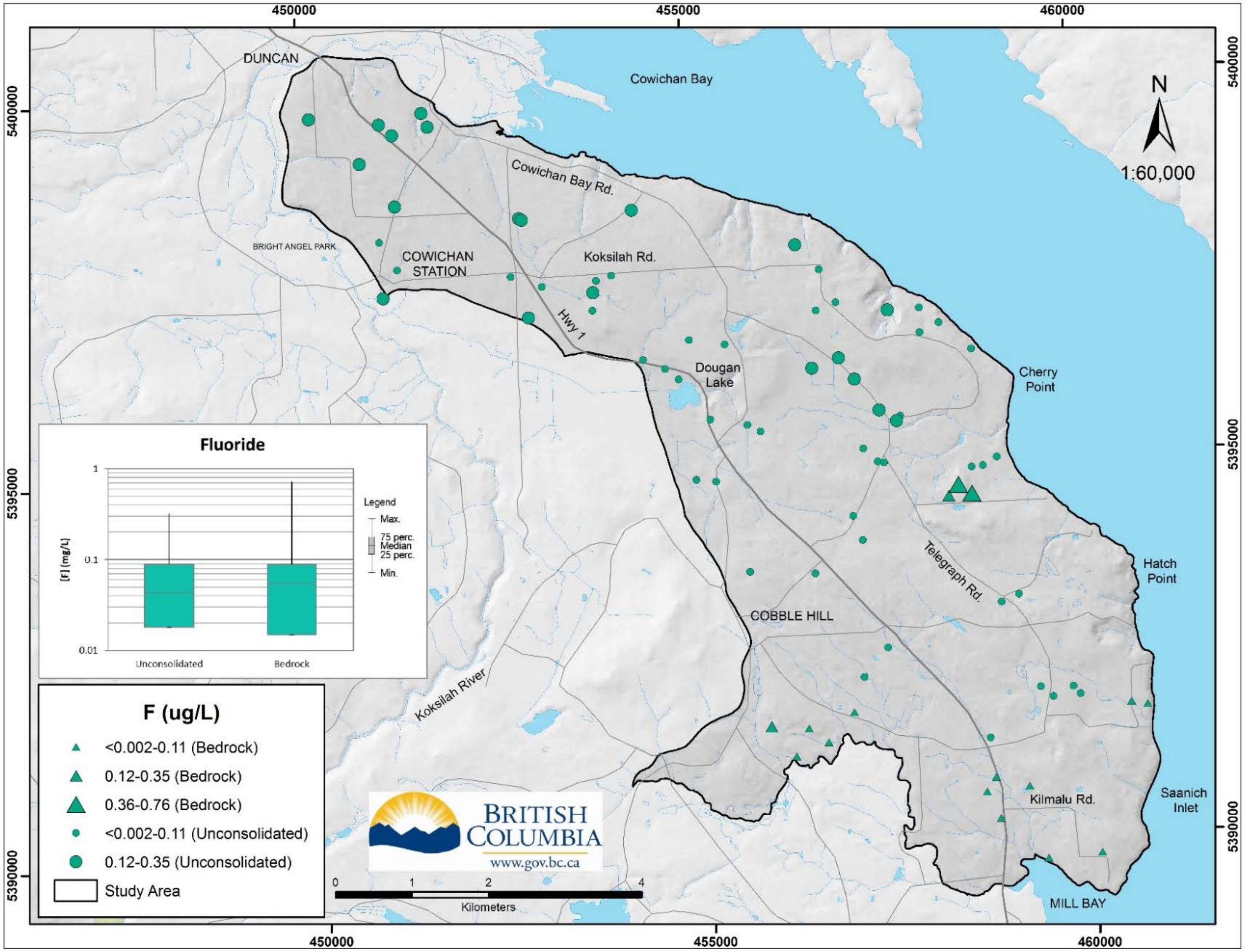


Figure 20: Map of fluoride concentration in groundwater samples.

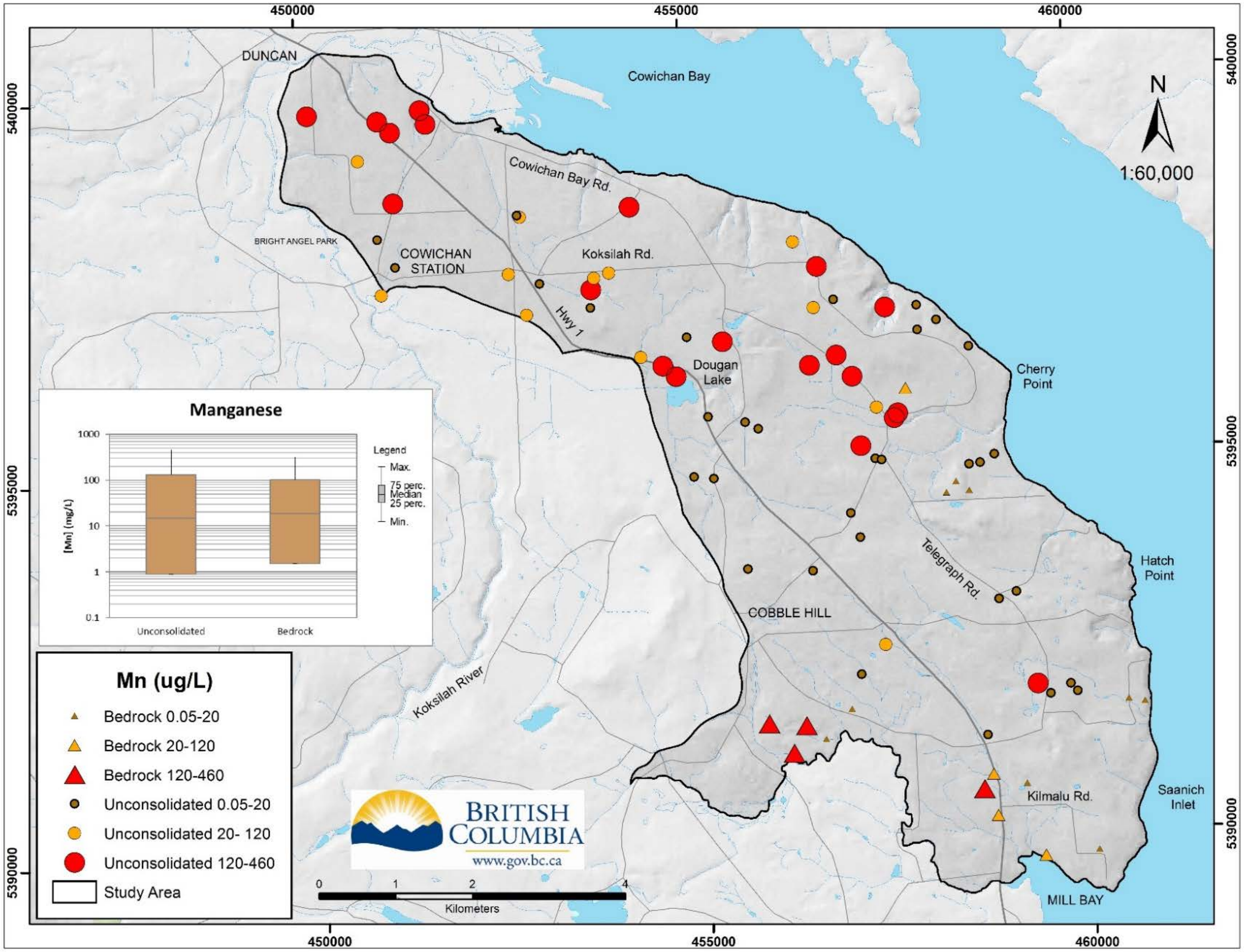


Figure 21: Map of manganese concentration in groundwater samples.

treatment involve specialized filtration media (greensand, manganese oxides, pyrolusite, or biological filters containing manganese reducing bacteria) (Health Canada, 2019b).

Within samples from unconsolidated wells, the median manganese concentration was 14.9 μg/L and the range was from 0.06 to 460 μg/L. In samples from bedrock wells the median concentration was 18.8 mg/L, and the range was from 0.108 to 315 μg/L. In total 24 samples (29%) exceeded the 120 μg/L MAC, 20 from unconsolidated wells, and 4 from bedrock wells. In comparison, 40 samples (49%), 32 from unconsolidated wells, and 8 samples from bedrock wells, exceeded the 20 μg/L AO for manganese. The spatial distribution of manganese concentrations in the samples is shown in Figure 21.

4.4.4 Nitrate

Nitrate (NO_3) is a dissolved molecule in water made up of nitrogen and oxygen. As there are few natural geologic sources of nitrate, it is often present in surface and groundwater because of human activities and land use. In Canada and worldwide, nitrate contamination from point and non-point sources is a significant environmental problem impacting both surface and groundwater quality (Rivett, et al., 2008; Rudolph, et al., 2015). The ambient concentration of nitrate within groundwater in B.C. is typically very low, less than 0.1 mg/L (Wei, et al., 1993; Wei, et al., 2010). Nitrate concentrations greater than 1 mg/L in surface or groundwater are considered indicative of anthropogenic impacts associated with industry, agriculture and urban development (Dubrovsky, et al., 2010). Elevated nitrate concentrations (above 2 mg/L) in groundwater can often be attributed to pollution sources, such as infiltration of surface water or run-off containing residues of chemical fertilizers or animal manure, or from human waste discharges from septic tanks or sewage systems (Health Canada, 2013; U.S. Geological Survey, 1999). Within this summary, unless otherwise stated, all nitrate values are reported as nitrate-nitrogen, or the equivalent nitrogen present as a component within nitrate ion (i.e. the N part of NO_3).

The GCDWQ MAC for nitrate in drinking water when measured as nitrate-nitrogen (NO_3-N) is 10 mg/L (Health Canada, 2019a). Nitrate has no taste, smell, or colour in water, but it 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. Several recent studies, including meta-analysis of populations in North America and Europe, have linked nitrate ingestion in drinking water at concentrations below current drinking water guidelines with impacts on normal thyroid function, elevated risk of some cancers (colorectal, ovarian, thyroid, kidney and bladder), and adverse birth outcomes such as low birth rate and preterm birth (Schullehner, et al., 2018; Ward, et al., 2018; Temkin, et al., 2019). Water treatment methods for removal of nitrate include anion exchange, reverse osmosis, biological denitrification, and distillation; boiling of the water for a continuous or extended period may increase nitrate concentration (Health Canada, 2013; World Health Organization, 2016).

Within this study, 33% of samples had a nitrate concentration < 0.0020 mg/L (the Reportable Detection Limit (RDL)). Excluding censored values, the range and median concentrations of nitrate-nitrogen were higher in groundwater sampled from unconsolidated wells than in water from bedrock wells. The median concentration of nitrate-nitrogen was 0.95 mg/L and ranged from 0.002 to 5.25 mg/L in samples from unconsolidated wells. The median nitrate was 0.038 mg/L and ranged from 0.002 to 2.26 mg/L in bedrock wells. The distribution of nitrate concentrations within groundwater in the study area is shown in Figure 22. A total of 13 samples, including 3 from water system wells, had nitrate concentrations ≥2 mg/L and therefore were analyzed for stable isotope composition, results provided in section 4.45. The potential sources of nitrate from land use in the study area are discussed further in section 5.

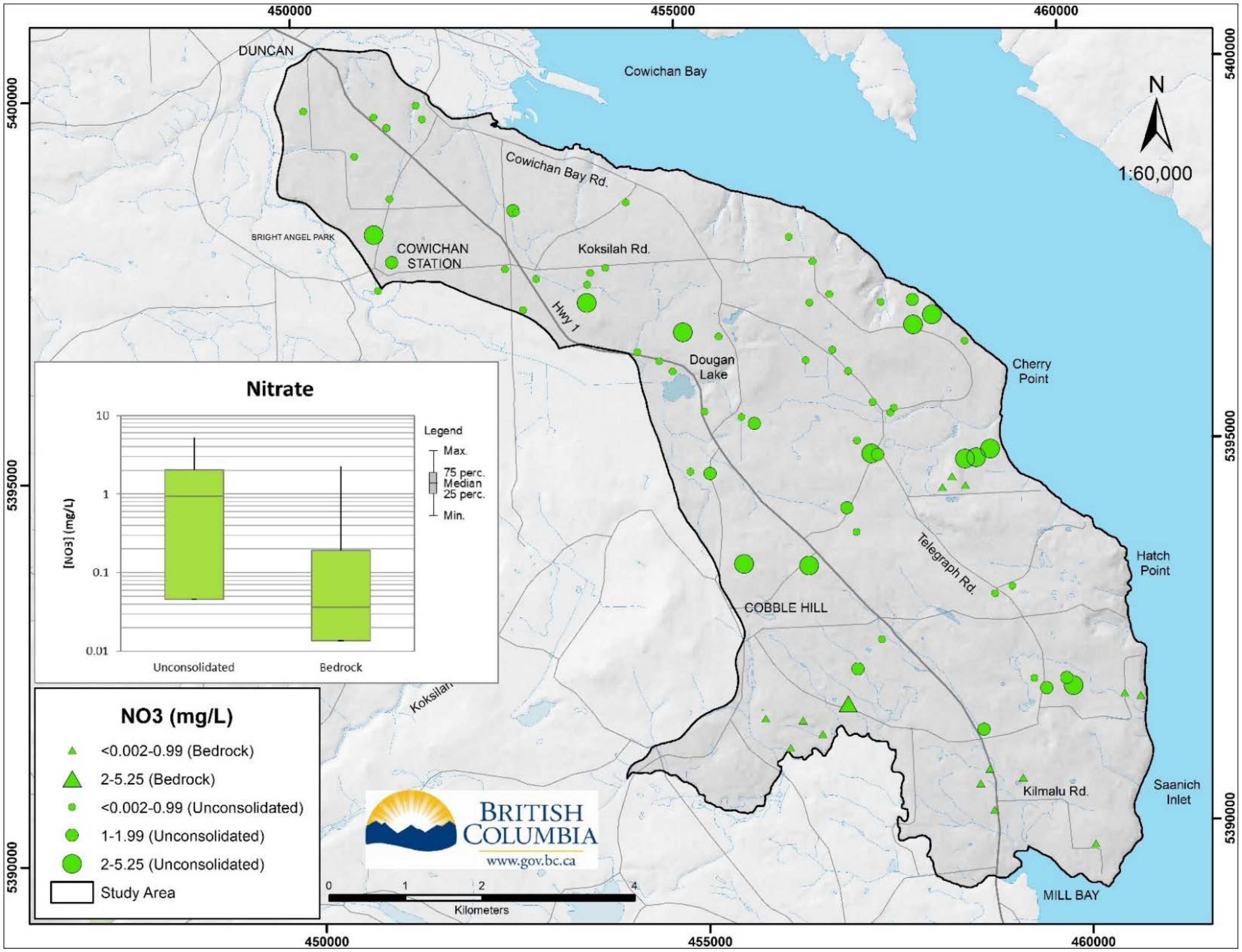


Figure 22: Map of nitrate concentration in groundwater samples.

4.4.5 Nitrate isotopes (δ^{15}N and δ^{18}O-NO_3)

Select samples with nitrate concentration >2 mg/L were analyzed for nitrate isotope composition, to gain insight into its possible source (e.g. from fertilizer, animal or human waste or another source). Nitrogen undergoes natural chemical and biological reactions cycling to and from different reservoirs in the environment including the atmosphere, soil, and organic material (Kendall, 1998). Understanding the link between land use and observed concentrations of nitrate in groundwater or surface water is complicated by the presence of various overlapping point and non-point nitrate sources. Determining the source of nitrate can be assisted by evaluation of the concentrations of nitrogen and oxygen isotopes that make up nitrate molecules within a water sample. Some fundamental concepts of isotope geochemistry are summarized briefly below, based on reference texts (Clark, 2015; Sharp, 2007; Aravena & Mayer, 2010) and other sources as noted.

Isotopes are elements with the same number of protons, but a different number of neutrons within the atom's nucleus, which results in a very small difference in the atomic weight. This variation in atomic weight affects how the element is involved in different physical, geochemical, and biological processes. The abundance of the different stable isotopes in nature and within different reference standards is known. For example, there are three stable isotopes of oxygen (^{16}O, ^{17}O, and ^{18}O), the lightest (^{16}O) being the most abundant. Stable isotope concentrations are reported by the laboratory as the relative fraction within the sample of the heavy (rare) isotope, compared to the light (more abundant) isotope.

The nitrate molecule (NO_3) is made up of one nitrogen atom and three oxygen atoms. Therefore, the laboratory analyzes the relative proportion within the nitrate molecule of nitrogen and oxygen isotopes. This is shown conceptually in Figure 23.

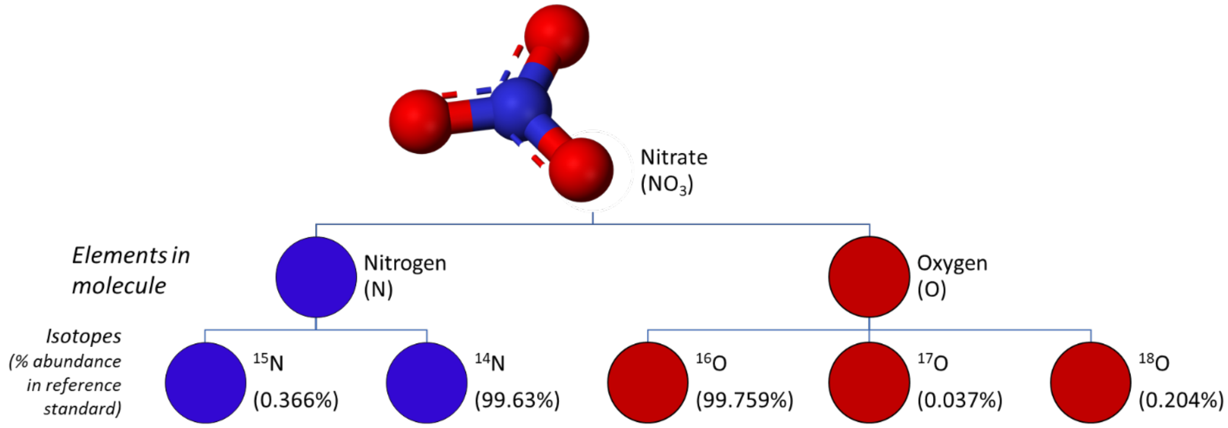


Figure 23: Nitrogen molecule is made up of both nitrogen (with two different isotopes) and oxygen (with three different isotopes). Percent abundance of isotopes is relative to the reference standard (AIR, or the atmosphere, for nitrogen, and Vienna Standard Mean Ocean Water (VSMOW) for oxygen. Upper NO3 molecule illustration from (CleanPNG, 2019).

There are two nitrogen isotopes ^{15}N and ^{14}N, therefore the relative proportion of these isotopes within a sample is compared to the relative proportion of the isotopes in air:

$$\delta^{15}N(‰\ vs\ AIR) = \left(\frac{(^{15}N/^{14}N)_{sample}}{(^{15}N/^{14}N)_{AIR}} - 1\right) * 1000 \qquad \text{Equation 2}$$

There are three different oxygen isotopes, and the relative proportion of the heaviest (^{18}O) compared to the lightest (^{16}O) within a sample, is compared to their known proportions within the laboratory standard referred to as Vienna Standard Mean Ocean Water (VSMOW):

$$\delta^{18}O(‰\ vs\ VSMOW) = \left(\frac{(^{18}O/^{16}O)_{sample}}{(^{18}O/^{16}O)_{VSMOW}} - 1\right) * 1000 \qquad \text{Equation 3}$$

Stable isotopes of oxygen and nitrogen are incorporated into the major nitrogen containing compounds NH_4^+, NO_3^-, NO_2^-, N_2O and N_2 that are present in groundwater. The range of isotopic signatures for different nitrogen sources has been determined from various studies (Kendall, 1998). For example, most materials on earth have $\delta^{15}N$ (delta-15N) values from -20 to +30 ‰(permil). Nitrogen in air (atmospheric $\delta^{15}N$ 0 ‰) is utilized by plants, and then recycled into soil by microorganisms, so nitrogen isotopes in natural (unfertilized) soil are low ($\delta^{15}N$ 2 to 5 ‰). Animal (including human) waste has nitrogen isotopes in the range of $\delta^{15}N$ 10 to 20 ‰. Agricultural fertilizers have a low $\delta^{15}N$ values depending on their composition and process in which they are made e.g. urea 0 to 2‰, ammonia 1 to 3 ‰, and nitrate 3 to 4 ‰. By comparing the isotopic values for $\delta^{15}N$ and $\delta^{18}O$ in a sample to the range of values for known sources, and in combination with other geochemical indicators, it is possible to trace environmental processes which have influenced the nitrate composition in the sample.

The statistical averages and range of isotope values obtained from samples in this study are summarized in Table 10. The median $\delta^{15}N$ = 9.03 ±2.63 ‰, and median $\delta^{18}O$ = -1.83 ±1.69 ‰. The isotope data is consistent with a source from animal or human waste. Further examination of the potential sources of nitrate, and spatial occurrence of elevated nitrate in groundwater above background concentrations are discussed in section 5.

Table 10: Statistical summary of sample results for nitrate isotopes.

	$\delta^{15}N$ (‰)	$\delta^{18}O$ (‰)
Mean	8.83	-1.36
Median	9.03	-1.84
Geometric mean	8.42	nc
Standard deviation	2.63	1.69
Minimum	4.51	-3.33
Maximum	13.54	1.31

nc=Geometric mean not calculated for values less than zero

4.5 Aesthetic Parameters

The Guidelines for Canadian Drinking Water Quality (GCDWQ) have Aesthetic Objectives, which are the upper concentration limits for parameters that are not associated with specific health concerns but that mainly 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 11. The complete geochemical results for all sites are provided in Appendix A, Table A-1. A comparison of median concentrations in samples from unconsolidated and bedrock wells is shown in Figure 24.

Table 11: Statistical summary of sample results for aesthetic parameters.

	pH (Field) pH units	Sulfate Dissolved (SO_4) mg/L	Chloride Dissolved (Cl) mg/L	Total Dissolved Solids TDS mg/L	Sodium Dissolved (Na) mg/L	Copper Dissolved (Cu) µg/L	Iron Dissolved (Fe) µg/L	Manganese Dissolved (Mn) µg/L	Zinc Dissolved (Zn) µg/L
Health Canada Guideline (AO)*	7.0:10.5 pH units	500 mg/L	250 mg/L	500 mg/L	200 mg/L	1000 ug/L	300 µg/L	20 µg/L	5000 ug/L
Unconsolidated									
Mean	7.41	8.55	8.96	145	12.1	1.65	244	83.4	15.3
Median	7.49	8.67	8.30	147	8.37	0.59	39.5	14.9	2.84
Geometric mean	7.38	6.61	7.34	139	9.53	0.60	39.1	8.75	3.47
Min	5.56	0.53	1.80	64	3.49	0.05	1.50	0.060	0.11
Max	8.73	22.3	33.0	254	84.3	8.61	2150	460	219
N=65									
Exceedences	**18**	**0**	**0**	**0**	**0**	**0**	**12**	**32**	**0**
	28%						**18%**	**49%**	
Bedrock									
Mean	7.69	12.0	13.8	196	35.0	1.36	82.4	76.3	74.7
Median	7.66	6.54	7.80	198	22.1	0.98	13.9	18.8	6.38
Geometric mean	7.65	8.31	10.2	186	23.2	0.76	18.1	14.2	11.3
Min	6.25	1.31	3.60	109	6.51	0.15	1.20	0.108	0.28
Max	8.70	35.3	56.0	334	90.1	5.15	315	315	680
N=17									
Exceedences	**3**	**0**	**0**	**0**	**0**	**0**	**2**	**8**	**0**
	18%						**12%**	**47%**	
# <RDL (all)	0	13	0	1	0	16	4	0	0
% <RDL (all)[1]	0%	16%	0%	1%	0%	20%	5%	0%	0%

[1] Percentage of samples less than Reportable Detection Limit (RDL) for samples from both unconsolidated and bedrock well

*Health Canada. 2019. Guidelines for Canadian Drinking Water Quality. Ottawa, ON. https://www.canada.ca/en/health-canada/services/environmental-workplace-health/reports-publications/water-quality/guidelines-canadian-drinking-water-quality-summary-table.html. (Accessed: September 2019)

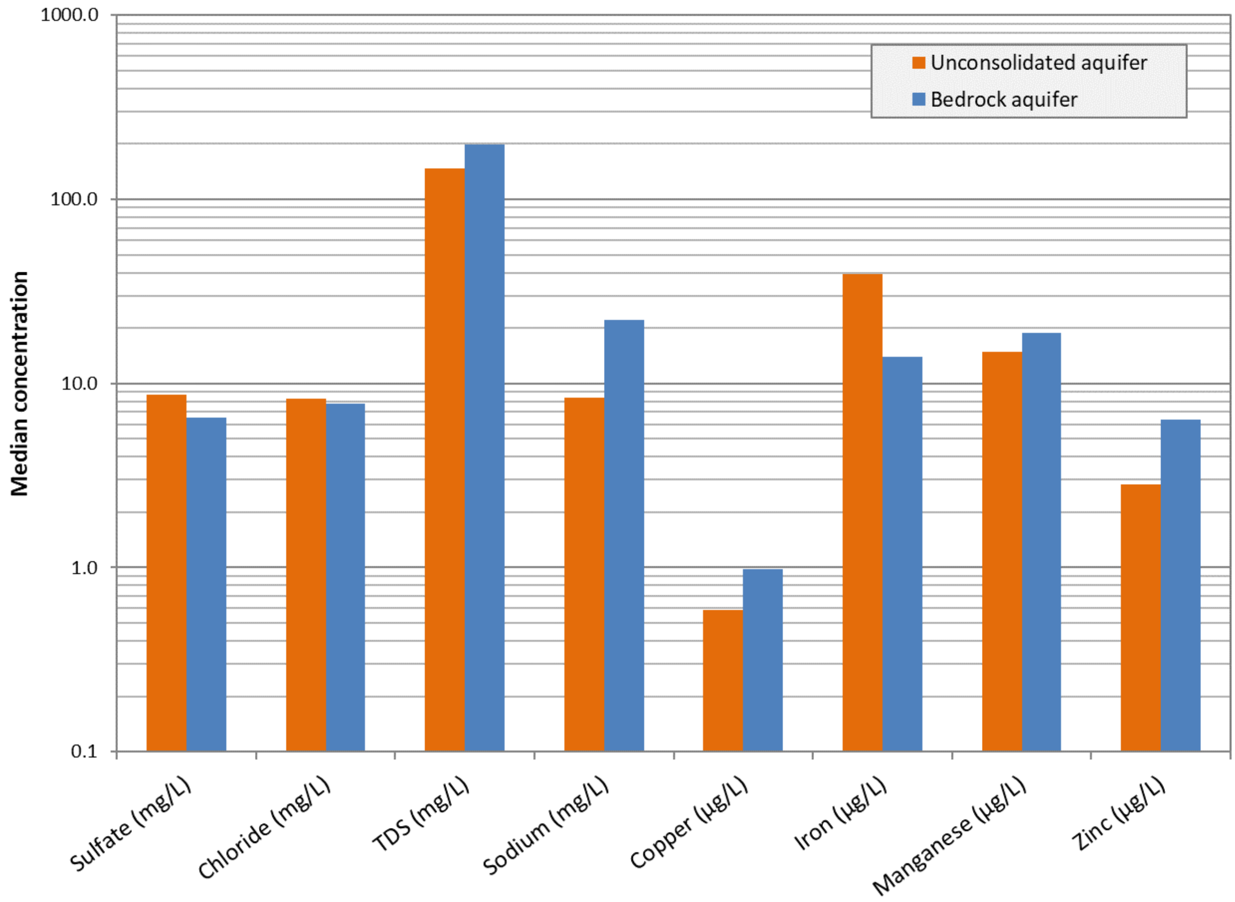


Figure 24: Comparison of median concentrations of aesthetic parameters in unconsolidated and bedrock aquifers.

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 5.56 to 8.73, and a total of 12 samples exceeded the pH guidelines—9 in samples from unconsolidated wells and 3 in samples from bedrock wells. The median pH of samples from unconsolidated wells was 7.38 slightly lower than for samples from bedrock wells which had a median pH of 7.66. 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 pH is expected to be lower in shallow and more recently recharged groundwater in comparison to groundwater in deeper wells, and bedrock aquifers that has undergone more geochemical maturation.

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).

The median concentration of sulfate in the study area was low, with a median 8.67 mg/L (range 0.53 mg/L to 22.3 mg/L) in samples from unconsolidated wells, and median 6.54 mg/L (range 1.31 to 35.3 mg/L) in samples from bedrock wells. There were no exceedances of the GCDWQ for sulfate, and 16% of samples had a sulfate concentration below the laboratory Reportable Detection Limit (RDL).

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. In coastal areas, elevated chloride (150 mg/L or higher) may be observed in wells affected by intrusion of marine saltwater into freshwater aquifers (Klassen, et al., 2014). Chloride also originates from infiltration of surface water containing road salts, septic or sewage system discharges, landfill leachate or irrigation drainage (Health Canada, 1979). The GCDWQ Aesthetic Objective for chloride in drinking water is 250 mg/L (Health Canada, 2014). At levels above the guideline, 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 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 1.80 to 56.0 mg/L and are considered naturally occurring from the interaction of groundwater with rocks containing mineral salts. The median concentration of chloride in bedrock wells was 7.80 mg/L, compared to a median chloride concentration of 7.34 mg/L in samples from unconsolidated wells. There were no exceedances of the GCDWQ AO for chloride. For wells located in proximity to the coast, baseline assessment and periodic monitoring of chloride concentrations is recommended to assess potential saltwater intrusion impacts. Based on compiled geochemical data from the Gulf Islands and eastern Vancouver Islands, chloride concentrations above 150 mg/L are considered indicative of saltwater intrusion (Klassen, et al., 2014; Province of B.C., 2016); operating a well in a manner that causes saltwater intrusion is a violation of the *Water Sustainability Act*, S.58 (Province of B.C., 2014).

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, with 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 25. Within samples from unconsolidated wells, the median TDS was 147 mg/L and ranged from 64 to 254 mg/L. In bedrock wells, the TDS ranged from 109 to 334 mg/L, with a median of 198 mg/L. No samples exceeded the GCDWQ for TDS.

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 occur as a result of saltwater intrusion, although in general chloride is a better indicator of intrusion impacts (Klassen, et al., 2014).

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 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 wells, the median sodium concentration was 8.37 mg/L, and the range was from 3.49 to 84.3 mg/L. Sodium concentrations in samples from bedrock wells ranged from 6.51 mg/L to 90.1 mg/L, with a median of 22.1 mg/L. Overall the sodium concentrations observed are consistent with groundwater that is fresh and recently recharged, and no samples exceeded the GCDWQ.

4.5.6 Iron

Iron is a metal that is abundant in nature and present in minerals and rocks, where it contributes to dissolved iron in groundwater that is in contact with those rocks. Industrial emissions from acid mine drainage, landfill leachate, metal refining and recycling, or sewage may also contribute to groundwater contamination by iron (Health Canada, 1978). Elevated concentrations of iron can 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. Elevated iron and manganese are often found together, therefore treatment to remove them is typically done at the same time, using methods such as injection of chlorine, potassium permanganate, or ozone injection, which causes the metals to form a solid precipitate that is then allowed to settle or is filtered out (Health Canada, 1978). The results for manganese, which has both a health-related MAC and aesthetic AO are described above in 4.4.3.

In the study area iron concentrations ranged from 1.5 μg/L to 2150 μg/L with a median concentration of 39.5 μg/L in samples from unconsolidated wells, compared to a range of 1.20 μg/L to 315 μg/L and median concentration 13.9 μg/L in samples from bedrock wells. Twelve samples from unconsolidated wells (18%) and two samples from bedrock wells (12%) exceeded the drinking water quality guidelines. Iron concentrations of samples in the study area are shown in Figure 26.

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 GCDWQ for copper, and the overall concentrations were very low compared to drinking water quality guidelines. The median concentration in samples from unconsolidated wells was 0.59 µg/L compared to a median of 0.98 µg/L in samples from bedrock wells. The overall range was from 0.05 µg/L up to 8.61 µg/L.

Zinc is another metal that is essential for human metabolism and 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. Sources of zinc from human activities 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 the South Cowichan area, zinc concentrations in samples were well below the AO, ranging from 0.11 to 680 µg/L overall, with a median concentration of 2.84 µg/L in samples from unconsolidated wells and 6.38 µg/L in samples from 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 sub-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. *E.coli* may be found in surface water or shallow groundwater that has been contaminated by septic or animal waste and if present, can indicate that other pathogens that occur in fecal matter may also be present in the water (Health Canada, 2013).

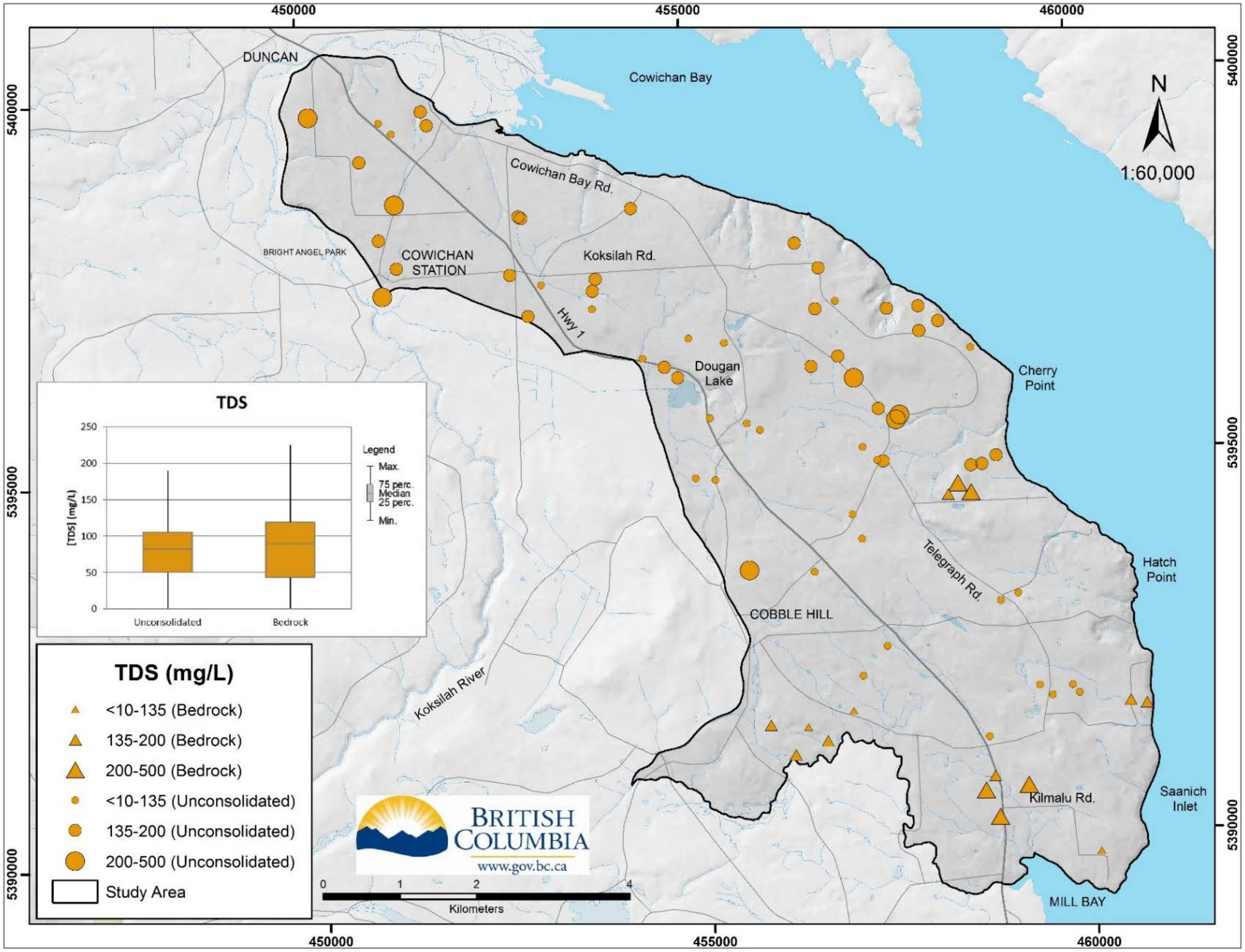


Figure 25: Map of Total Dissolved Solids (TDS) concentration in groundwater samples.

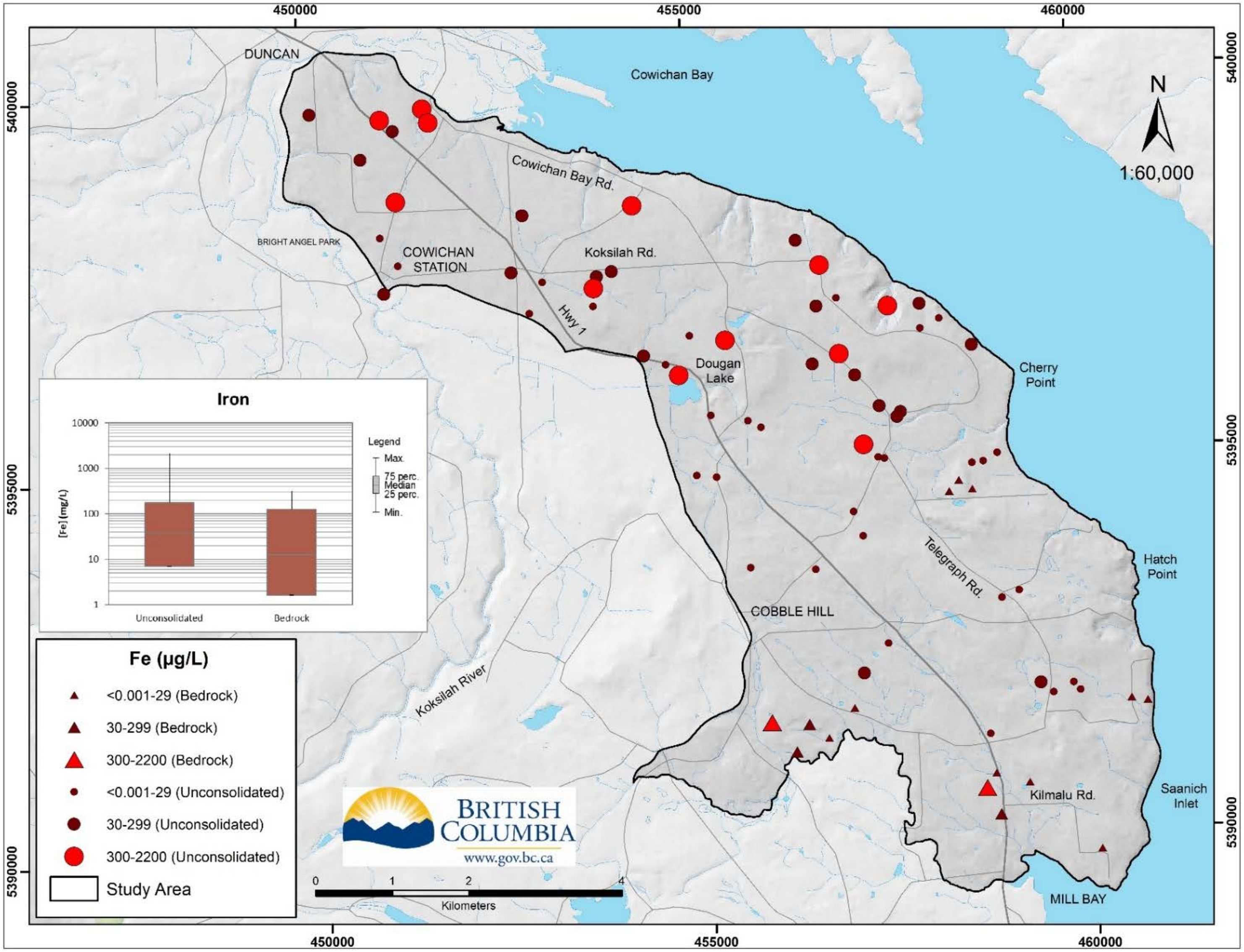


Figure 26: Map of iron concentration in groundwater samples.

The drinking water guideline for total coliforms and *E. coli* is zero (<1) detectable per 100 mL (Health Canada, 2014). In untreated groundwater, it is not unusual to see total coliforms between 1 and 10 CFU/100 mL, in particular within shallow and dug wells, and it is generally not be a cause for concern. However, if *E.coli* are detected in a sample, this is a cause for concern, and steps should be taken to: disinfect the water prior to use until the cause can be identified; disinfect and retest the well; assess the well for possible sources of contamination; and, fix any problems noted (see section 4.7). Instructions for testing and disinfecting a well can be found in "Water Well Disinfection Using the Simple Chlorination Method" (Province of B.C., 2018a).

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 rapidly in fractures than in an unconsolidated aquifer, where groundwater must flow 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.

In this study, 82 wells were sampled for bacteria (total coliforms and *E. coli*), including 9 duplicates, for a total of 91 bacterial samples. The results are summarized in Table 12, Figure 27, and in Appendix A, Table A-2. Neither total coliforms nor *E. coli* were present in most samples (79 samples, 87%, including duplicates), while a smaller number of samples (12 samples, 13%) had either total coliforms or *E. coli* present. Total coliform concentrations ranged from less than 1 (not detected) up to 880 Colony Forming Units (CFU) per 100 mL (CFU/100 mL). The occurrence of bacterial contamination was uncommon, and only 4 samples (4%) overall had both total coliforms and *E.coli*, indicating that groundwater in the well may have been contaminated with fecal matter. The linkage between bacteria occurrence and well construction type was most evident for dug (excavated wells), in which total coliforms were detected in all samples, which is not unexpected as they draw upon shallow groundwater; only one sample from a dug well had *E. coli* present. In comparison, there did not appear to be a relationship between aquifer material and presence of total or fecal coliforms for drilled wells; 20% of samples from wells drilled in unconsolidated materials had bacteria present, compared to 12% of samples from bedrock wells.

Contamination from bacteria and other pathogens may 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, a total of 34 wells had one or more identified concerns related to well maintenance or siting of potential sources of contamination within the sanitary zone (30 m) around the well. From this subgroup of wells, roughly one-quarter or 24% of the samples contained total coliforms, while 4 (12%) had *E.coli.* Maintenance concerns were identified at an additional 26 sites where no bacteria were detected in the water samples.

Table 12: Summary of bacteriological sample results.

Bacteriological sample summary: N=82 samples*		
Sample sites with no bacteria	72	84%
Sample sites with only total coliform bacteria	10	12%
Sample sites with total coliform and *E. coli* bacteria	4	5%
Total	86	100%
Samples from wells drilled in unconsolidated aquifers with total coliforms[ǂ] (N=65)	6	9%
Samples from wells in unconsolidated aquifers with fecal coliforms	2	3%
Samples from wells drilled in bedrock aquifers with total coliforms (N=17)	1	6%
Samples from wells in bedrock aquifers with fecal coliforms	1	6%
Samples from dug wells with total coliforms (N=3)	3	100%
Samples from dug wells with fecal coliforms	1	33%
Wells or sites with maintenance concerns[V] (N=34)		
Wells with total coliforms that had maintenance concerns	8	24%
Wells *E.coli* that had maintenance concerns	4	12%
Wells with no bacteria that had maintenance concerns	26	76%

*Results exclude duplicates

ǂ Not including dug wells

[V] Not including two sites with unused wells required to be decommissioned

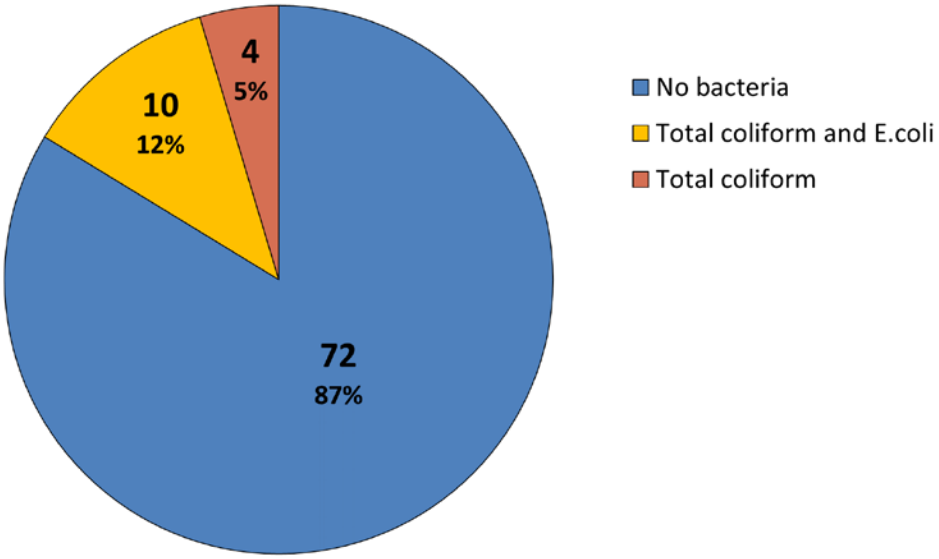


Figure 27: Proportion of samples with no bacteria, with total coliforms or with both total coliforms and E. coli.

4.7 Wellhead Protection

As described in section 3.3, at the time of sampling, each well was inspected for compliance with the *Water Act*, Ground Water Protection Regulation (Province of B.C., 2016a), and other general concerns related to well protection and maintenance. At most locations (48 sites, 59%), there were no concerns noted. At 34 sites (41%) concerns identified included: wellhead that had been covered or buried below ground; inadequate well cap; unfilled annular space around the casing; well location in a poorly maintained pit, enclosure or pump house, including presence of vermin such as rodents in the enclosure; standing water around the well; and animal grazing, paddocks or chicken coops within <30 m from the well.

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 28 to Figure 36.

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 Figure 33 and refer to the publication “Best Practices for Dug Wells” (Province of B.C., 2018b). Dug wells capture shallow groundwater and are naturally more vulnerable to contamination; therefore, the groundwater often requires some form of disinfection, such as ultraviolet (UV) or chlorination to remove potentially harmful bacteria and pathogens prior to use for potable purposes.

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 30 and Figure 34. Wells in pits or below ground enclosures should be upgraded to remove the enclosure and extend the casing so that the top of well head is >0.3 m above ground (Figure 31). Refer to the publication, “Upgrading Wells in Pits” (Province of B.C., 2018c). If it is not possible to remove the enclosure, the well vault or pit must have a water-tight and vermin proof cap, and an interior drain to prevent flooding of the well.

If a well is located within a pump house, the building should be kept clean, tidy, and in good repair (as in Figure 29), 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 decommissioned (backfilled) if there is no intent to use them in the future.

Figure 28: Excavation of materials around the casing allowed standing water to accumulate around this well head. Rodents also inhabited the pump house which was in poor repair. Groundwater samples from the well indicated concentrations of total coliform 880 CFU/100 mL and E. coli *3 CFU/100 mL.*

Figure 29: Ensuring the well head has 30 cm or more stickup above the floor of the pump house and keeping the pump house clean, free of potential contaminants, and maintained to prevent entry of vermin including rodents and insects helps ensure the groundwater remains safe to drink.

Figure 30: Below ground enclosures must have a water-tight lid and interior drain to prevent accumulation of standing water around the well. Groundwater from this drilled well contained total coliform 20 CFU/100 mL indicating it had been contaminated by entry of surface water.

Figure 31: A registered qualified well driller or well pump installer can be hired remove a well pit or enclosure. In this case, a water-tight coupling was attached to the casing to raise the casing stickup above ground and prevent unintended entry of contaminants into the well.

Figure 32: The design of the access port on the top of this excavated (dug) well allows rain and contaminants to enter the well. The site is also located in a cattle pasture with no setback of animals from the well. The groundwater sample had total coliform 87 CFU/100mL and E. coli *5 CFU/100 mL.*

Figure 33: A proper cap/cover should be water-tight and prevent entry of water and foreign matter. Dug wells capture shallow groundwater and are naturally more vulnerable to contamination. The groundwater typically requires some form of disinfection, such as ultraviolet (UV), to remove potentially harmful bacteria and pathogens (Photo source: Regional District of Nanaimo, WellSmart, 2018).

Figure 34: This sanitary seal well cap was covered in saturated soil in an outside enclosure. The groundwater sample had total coliform 34 CFU/100mL and E. coli *19 CFU/100 mL mL.*

Figure 35: Ensuring the well is properly capped and not buried below ground protects the well from potential contaminants. Probable sources of contamination such as septic systems, animal paddocks, coops and manure storage areas should be set back a minimum of 30 m from the well.

Figure 36: Drain line and ditching installed to direct water away from this flowing artesian well put it at risk from erosion of materials around the casing, and loss of pressure in the aquifer. Under the Water Sustainability Act*, Section 53 artesian flow must be controlled, there must be the ability to stop the flow indefinitely, and the overflow pipe requires a backflow preventer to stop contaminants from re-entering the well.*

5. PROCESSES AND CONTAMINANT SOURCES INFLUENCING NITRATE IN GROUNDWATER

Nitrogen in groundwater is commonly linked to environmental factors, including those that influence groundwater movement and recharge, processes that nitrogen undergoes as it changes from one chemical form to another (the nitrogen cycle), and nutrient discharges originating from human activities, and land use. Each of these influences is discussed in greater detail below.

5.1 Nitrogen cycle

Nitrogen undergoes a range of processes that can influence what form it occurs in within the environment, referred to as the nitrogen cycle, depicted in Figure 37. Some of these processes involve physical or geochemical reactions, while many occur due to biological activity of bacteria, algae and plants.

Beginning with atmospheric nitrogen gas (N_2) which makes up 78% of air, *fixation* via lightening or metabolism of soil bacteria and algae, such as in the root nodules of legumes, allows nitrogen to become available in organic form for plant *uptake* or *assimilation*. Nitrogen oxides emitted from industry and burning of fossil fuels are captured as aerosols in precipitation and deposited to the ground (*deposition*).

Industrial *fixation* is the mechanism for producing synthetic nitrate fertilizer, which revolutionized farming in the latter half of the 20th century. Human inputs of nitrate and ammonia fertilizer and organic materials (manure, organic waste) are added to the soil, where they may undergo *volatilization* (ammonia converts to N_2 or N_2O gas) or are transformed by *nitrification* to nitrite and nitrate via microbiological metabolism. The movement of ammonia and nitrate near the ground surface in shallow soils deeper into the soil profile, into the unsaturated zone, and eventually to the groundwater table is facilitated by infiltration of rainfall, irrigation and groundwater recharge; while groundwater leaching and runoff of nitrogen-rich water contributes to algal over-growth and eutrophication in surface water bodies (Aravena & Mayer, 2010; Rivett, et al., 2008).

The main process that contributes to the removal of nitrate from groundwater is when bacteria in the subsurface facilitate *denitrification*, whereby nitrate and nitrite are converted to nitrous oxide (N_2O) and nitrogen gas (N_2); this process occurs most efficiently under low oxygen, anaerobic conditions, and when there is a source of organic carbon or other molecular species present (e.g. ferrous iron in sulfide minerals) that can act as an electron donor in the denitrification process.

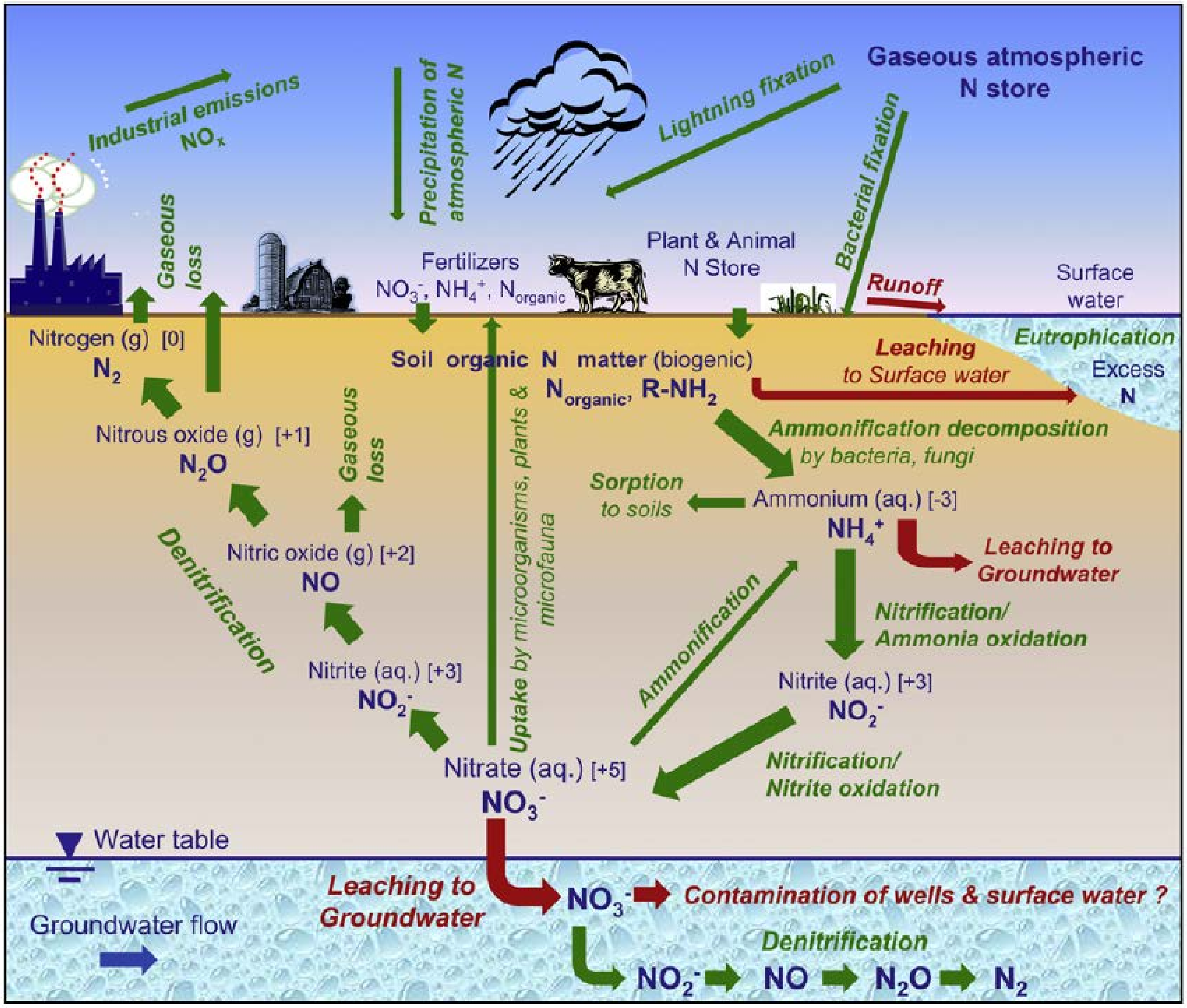


Figure 37: Stages within the nitrogen cycle and the influence on the environment. Reproduced from (Rivett, et al., 2008) *with permission.*

5.2 Links between land use, nitrogen sources and groundwater pollution

From numerous field studies worldwide, three primary factors appear to have the greatest control on nitrate concentrations in groundwater:

a) the quantity of nitrogen available from different point and non-point pollution sources (dependent on land use);
b) how much water can infiltrate or leach into the ground (dependent on hydraulic properties of soil and subsurface sediments); and
c) the ability for nitrate to be attenuated in the soil, subsurface and aquifer via reduction and denitrification (dependent on oxidation-reduction conditions or dissolved oxygen concentration in the subsurface) (Canter, 1996).

Elevated nitrate in groundwater has been observed in agricultural areas, linked with practices such as higher density livestock operations, and larger amounts of fertilizer application (Canter, 1996). The link between agricultural land use practices and elevated nitrate in groundwater has been well documented elsewhere in B.C., including in the Abbotsford-Sumas area within an unconsolidated aquifer which serves as a water supply for over 100,000 people in B.C. and Washington State, U.S.A., (Zebarth, et al., 1998; Wassenaaar, 1995; Wassenaar, et al., 2006), in Grand Forks (Wei, et al., 1993), and in Hullcar (Golder Associates, 2017).

A surplus of nitrogen and phosphorus below agricultural areas results from application of more nutrients than can be utilized by the crop type. Manure is commonly utilized for land application as a nutrient source, and as a method to re-utilize farm waste. The impact of manure application on environmental quality, like excessive phosphorus or nitrogen entering water supplies, depends upon the amount, seasonal timing and method of application (e.g. as solid soil additive or mixed with irrigation water as fertilizer) (Poon & Schmidt, 2010). A larger density of livestock is also linked with increased environmental impacts (Shröder, et al., 2004). Some crops are grown using applied synthetic, ammonia or nitrate based, fertilizers, which when dissolved in irrigation water or rainfall can also leach to groundwater, or run-off to surface water bodies affecting the health of aquatic ecosystems (Zebarth, et al., 2015). Irrigation can influence infiltration and leaching of nutrients, resulting in higher nitrate concentrations beneath irrigated fields potentially affecting the temporal and seasonal fluctuation of nitrate concentrations in groundwater (Böhlke, 2002).

In addition to land use, nitrate concentrations in groundwater are closely linked to factors that influence groundwater recharge, including precipitation rates and intensity, local scale topographic depressions and larger cracks or voids in the soil and sediments that increase infiltration and leaching from the upper soil. Soil characteristics affect both physical and geochemical processes: coarse permeable soils allow nitrate to leach downward; fine clay-rich soils adsorb and retain ammonia in the upper layers where can be lost via volatilization, while enabling greater rooting depth so that more nitrogen can be removed by plant uptake (Canter, 1996).

Discharges from septic systems have been shown to contribute to nutrients and other contaminants in groundwater in rural residential and urban areas (Seiler, 1996). Within a septic disposal system, domestic waste is treated first in the septic tank by anaerobic digestion, promoting some nitrogen loss by denitrification; around 10 to 30% of total nitrogen is retained in the tank as organic nitrogen septic sludge which can be pumped out periodically. Effluent from the septic tank discharges to a dispersal field, where under aerobic conditions some ammonia converts to NH^3 gas by volatilization, and some undergoes nitrification, converting to ammonium (NH_4^+) and then nitrate (NO_3^-). Ammonium is adsorbed or attached to soil particles, while nitrate is highly soluble in water and mobile forming a shallow plume of contamination downgradient of the septic field. If conditions within the plume are not conducive to denitrification, nitrate can continue to leach downward to the groundwater table during recurrent periods of infiltration and groundwater recharge (Seiler, 1996). Dried or abandoned septic fields also provide a source of nitrate contamination over longer time periods (Canter, 1996).

The ability of nutrients from septic systems to be attenuated in the subsurface depends on factors that promote denitrification such as whether oxygen is present to inhibit bacteriological denitrification processes, the separation depth between the septic field and the groundwater table, dilution and other factors (Seiler, 1996). Septic fields will have a localized contaminant plume that contains nutrients (nitrate, phosphate), household chemicals, bacteria and pathogens such as viruses; groundwater protection is improved in areas with larger lot sizes, where there is a greater separation distance between a well and an adjacent septic field, and for deeper wells accessing groundwater recharged from areas with fewer contaminant sources (Wilcox, et al., 2010).

Elevated nitrate concentrations in groundwater are often indicative of historical land use, because of the time lag between when a nitrogen source is introduced to the upper soil and when it is leached through the unsaturated zone to the aquifer. In the Abbotsford-Sumas aquifer long-term trends in nitrate concentrations in groundwater sampled from monitoring wells could be associated with land use from up to 20 years prior; landscape indicators such as loss of forest cover, and increased proportion of forage pasture, raspberry cultivation and field renovations (new tilling and planting) within a radial zone of influence around the wells were linked to increases in nitrate concentration in the groundwater (Gallagher & Gergel, 2017). Likewise, this delay results in a longer time to observe improvements in groundwater quality in response to changes in land use, such as implementation of best management practices (Wassenaar, et al., 2006; Rudolph, et al., 2015).

Due to patterns of recharge and groundwater movement, if one were to sample groundwater from different depths along a vertical profile, groundwater from a deeper well is likely to capture older groundwater recharged from an area at a larger distance away from it. Therefore, nitrate concentrations in the well may not be directly relatable to land use in the immediate area, but due to practices within a larger capture zone (Böhlke, 2002). At the same time, water system production wells with higher rates of pumping may be influenced by land use within a capture zone at greater distance from the well site. Abandoned wells and wells lacking a surface seal may contribute to contamination by allowing a direct pathway for surface water and runoff containing elevated nitrate to more rapidly enter the groundwater system (Harter, et al., 2012).

5.3 Nitrogen sources and hazards influencing groundwater quality in the study area

Environmental contaminants are often referred to as originating form either point source (PS) or non-point sources (NPS). Point sources typically originate from a single defined location or discharge point, are often regulated, with limits on the amount or type of contaminants released; in comparison, non-point sources do not get collected or discharged from a single point, but are released at unknown locations, times or volumes. NPS pollution may be challenging to link to a specific activity or site, and usually have fewer regulatory standards to limit their environmental impacts (U.S. Geological Survey, 1999).

Land use in the South Cowichan study area is predominantly rural residential and agricultural. Potential non-point sources of nitrogen associated with agricultural activities include: agricultural fields in which manure or other organic waste or compost are applied as fertilizer; fields or areas where nitrogen fixing crops such as alfalfa are grown or where artificial nitrogen fertilizer is applied (including greenhouses); locations where livestock mortalities are buried; and domestic septic disposal fields which are present on many non-urban properties as a method of sewage waste disposal. Point sources of nitrogen include: locations of manure or waste effluent discharges (e.g. cesspits, soakaway basins or treatment lagoons) from larger dairy and poultry operations or horse ranches (Böhlke, 2002; Rivett, et al., 2008; Ministry of Agriculture, 2013; Cowichan Valley Regional District, 2019).

Point sources of nitrogen pollution may also be associated with discharges permitted under the *Environmental Management Act* which are also believed to contribute to nutrient concentrations in groundwater from the study area. These could include leachate collection ponds for waste handling or composting operations; and regional or municipal sewage treatment facilities discharging to ground (i.e. municipal scale septic disposal fields or sewage treatment lagoons). Although not a specific focus of this study, contamination of groundwater in AQ197 around Fisher Road has been well documented, originating from two composting facilities, one with a waste discharge permit under the Organic Matter Recycling Regulation, and a historical greenhouse operation (Western Water Associates Ltd., 2018); unlined leachate collection ponds at the compost facilities would be considered point-sources, while diffuse recharge through surface materials and soils stored on unpaved areas might constitute non-point sources.

In the Abbotsford-Sumas aquifer, long-term trends in nitrate concentration in groundwater was linked to well and aquifer properties, land cover and agricultural practices over the prior two decades

(Gallagher & Gergel, 2017; Gallagher, 2018). Following a similar approach for the South Cowichan study, to examine the link between land use and groundwater quality, available data on point and non-point sources associated with nitrate in groundwater were compiled in a geospatial database for comparison to the groundwater sample observations. Land use indicators within the study area and their hypothesized relationship to nitrogen in groundwater are discussed in the following sections and summarized in Table 13.

5.3.1 Agricultural point and non-point nitrogen sources

Agricultural activities can constitute either point-source or non-point sources of contamination that may contribute to nitrate concentrations in groundwater. An Agricultural Land Use Inventory (ALUI) for Cowichan Valley was completed in 2012, providing a field-verified survey of activities on agricultural and non-agricultural parcels (Ministry of Agriculture, 2013). Using metadata from the agricultural land use field guide (Ministry of Agriculture, 2012), land use categories potentially associated within nitrogen discharge to the environment were identified from the land use inventory. Non-point sources included parcels where the onsite activity involved a particular category or scale of livestock e.g. medium and large-scale dairy, beef, chicken and equine (horse) operations. Potential nitrogen point-sources identified from the land use inventory included activities within the agricultural land use-support category: manure (e.g. collection tanks, storage pads, concrete or earthen lagoons, or other storage structures). Moderate and large-scale operations with other categories of livestock such as pigs, turkeys were not identified in the data set.

Table 13: Landscape indicators of point-source and non-point sources of nitrogen in the study area

Landscape Indicator	**Data selection and analytical approach**	**Potential relationship to nitrate in groundwater**
Land use – Agriculture – Livestock – Equines (Horse) Categorized by livestock type and operational scale (NON-POINT SOURCE)	Identify parcels associated with cattle (combined dairy and beef), poultry, and horse (equine) categories. Select only parcels with medium and large-scale activity. Medium scale (examples): less than 100 cows or horses, less than 10,000 chickens Large scale (e.g.): more than 100 cows, horses, more than 10,000 chickens Indicator: distance of sampled well from property boundary of parcel (closest parcel in category).	Livestock manure generated, stored and used on farm is a source of nitrate. Medium and large-scale operations have more animals present, therefore generate a large quantity of manure. Manure commonly applied over fields creating diffuse source.
Land use – Agriculture – Support: Manure (POINT SOURCE)	Ancillary structures on farm for collection, storage or treatment of manure e.g. treatment facility, tank, pad, concrete lagoon, earthen lagoon, bin or other. ALUI reports presence of manure structure on parcel; approximate coordinates of manure storage structures identified via air photo interpretation (Google Earth). Indicator: distance of sampled well from point source.	Locations where concentrated manure source is present and able to infiltrate directly to ground below or adjacent to the structure.
Waste Discharge Authorizations (POINT SOURCE)	Locations of permitted waste discharge. Select sites associated with sewage or nitrogen containing leachate discharging to ground (municipal-scale septic fields, sewage treatment lagoons, industrial composting leachate collection ponds). Indicator: distance of sampled well from point source.	Locations where concentrated nitrate source is discharged or infiltrates to the subsurface.

5.3.2 Authorized waste discharges to the environment

A list of locations associated with waste discharge authorizations permitted under the *Environmental Management Act* (Province of B.C., 2003), was obtained from online documentation (Ministry of Environment and Climate Change Strategy, 2019a); the sites were generated into a spatial feature layer, and locations cross-referenced to Environmental Monitoring System (EMS) monitoring sites (Ministry of Environment and Climate Change Strategy, 2019b) to ensure known sites were captured. These sites were considered point sources for the purposes of comparison to nitrate concentrations in sampled wells. Examples were primarily locations of municipal-scale sewage discharges (sewage lagoons, effluent discharges to ground). Composting facilities in the Fisher Road area were also included as potential point sources, but not included in the non-point source data set. Effluent discharges to marine outfalls along the coast were excluded from the analysis.

5.3.3 Sources not considered in spatial analysis

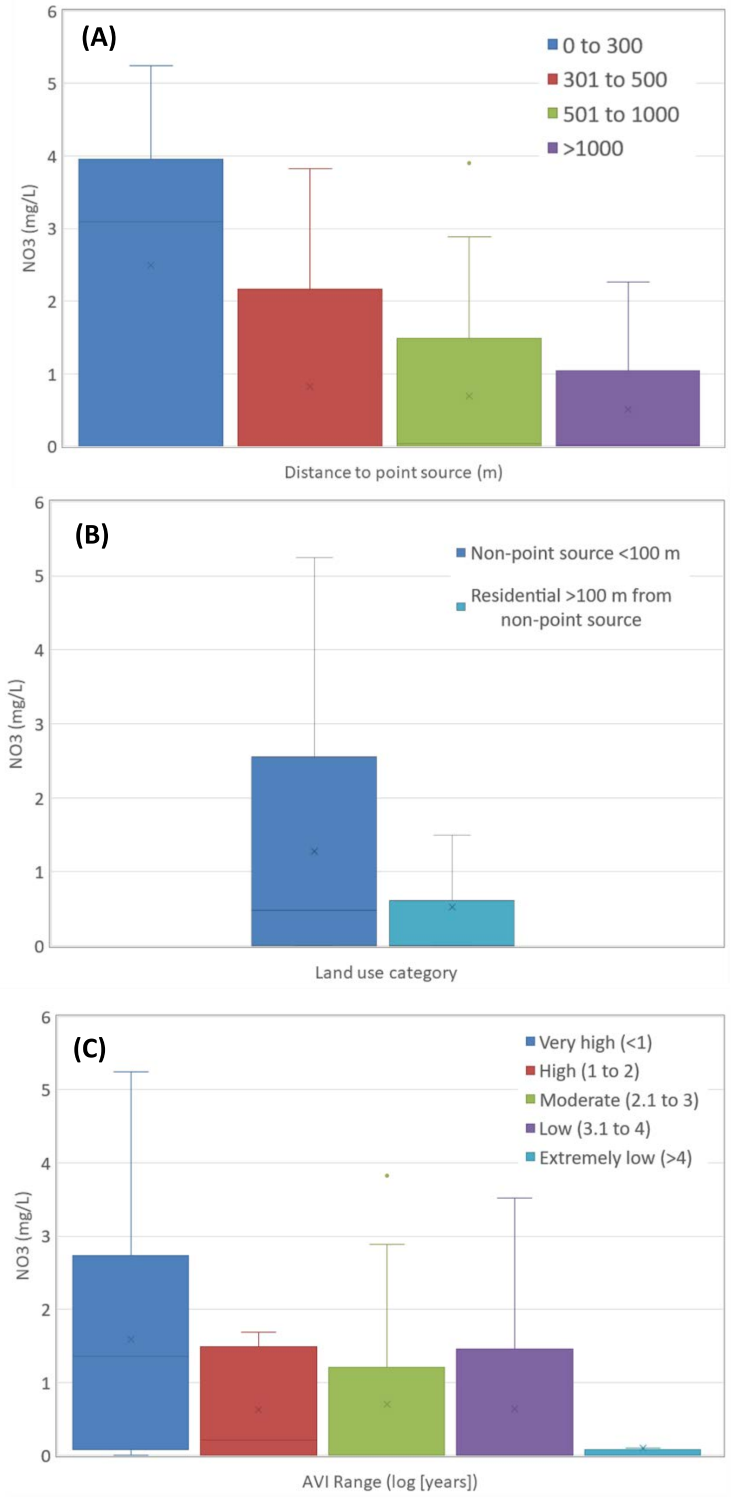
Residential scale septic systems were assumed to be present on all non-vacant residential lots outside of sewered areas but were not included within the inventory of nitrate sources for spatial analysis as public data are not available on their locations or capacity. Atmospheric deposition of nitrogen-containing aerosols from industry and transportation (nitrous oxides), and particulates containing fertilizer residue from agriculture can be a significant contributor to nitrogen loading in groundwater and surface water but were not evaluated, also due to insufficient data to identify these sources.

5.3.4 Spatial comparison of nitrate concentrations in comparison to source proximity

Box and whisker plots showing nitrate concentrations at sites in relation to the landscape indicators are shown in Figure 38(A) and (B). The median, average and range of nitrate values was greatest for sites <300 m from a point-source, while nitrate concentrations were lower in samples from sites at increasing distance. Similarly, nitrate concentrations were higher in samples from sites <100 m from a parcel associated with an agricultural non-point source; and nitrate was low, and within a narrower range in samples from wells on residential properties >100 m from a parcel with a non-point pollution source.

This preliminary analysis has inherent limitations. The approach considers simple horizontal proximity of the sample location to a potential contaminant source, and the total number of samples within each category are small. The approach does not consider the relative proportion of risk activities within a theoretical capture zone around the well or cumulative effects including factors such as well depth, direction of groundwater flow, or groundwater pumping rates which would affect the size of the capture zone around the well. The land use data were representative of agricultural activities inventoried within one to two years of when the groundwater sampling occurred. While there is often a delayed effect of land use on groundwater quality, we did not have data sets representing historic land use with the same categorization as the ALUI. The Waste Discharge Authorizations were all present for the period prior to the sample collection, but the site-specific operational and waste handling aspects and duration of activities were not considered.

Based on available information domestic septic systems are not thought to be a major contributor of nitrate to the aquifer in comparison to other sources. Domestic scale (single household) septic systems are the primary means of sewage disposal, apart from a small number of strata subdivisions and neighbourhoods such as central Cobble Hill or Cowichan Bay with a community sewerage system. Residential lots (>100 m away from agricultural NPS) represented in Figure 38(B) are likely to have an onsite domestic septic system. Average nitrate concentrations from these sites are relatively low (0.52 mg/L). Failing or poorly designed and maintained septic systems, or disposal fields sited with smaller separation distance to a well could represent a localized contaminant source on some parcels.



Point source proximity

	N=	Mean	Median	StDev
0 to 300 m	6	2.49	3.10	2.1
301 to 500 m	11	0.82	0.003	1.3
500 to 1000 m	23	0.69	0.04	1.1
>1000 m	42	0.51	0.01	0.8

Agricultural non-point source proximity

	N=	Mean	Median	StDev
Non-point source <100 m	21	1.28	0.48	1.6
Residential >100 m from NPS	48	0.52	0.005	1.0

AVI rating

	N=	Mean	Median	StDev
Extremely high (<1)	18	1.58	1.36	1.6
High (1 to 2)	15	0.78	0.85	0.7
Moderate (2.1 to 3)	14	0.70	0.002	1.3
Low (3.1 to 4)	15	0.64	0.003	1.1
Extremely low (>4)	11	0.04	0.003	0.1

Figure 38: Box and whisker plots of nitrate concentration in relation to different land use categories (A) [NO3] compared to distance from a point-source; (B) [NO3] <100 m from agricultural non-point source vs [NO3] on residential properties >100 m from NPS; (C) [NO3] compared to Aquifer Vulnerability Index (AVI) categories, low AVI indicates higher vulnerability. Samples with nitrate <Reportable Detection Limit included as equivalent to the detection limit (NO_3=0.020 mg/L). Box outlines 25th, 50th (median) and 75th percentile values, x plotted at mean, whiskers represent max-min range, dots indicate data outliers.

5.4 Influence of aquifer properties on nitrate concentrations

Aquifer 197, AQ198 and AQ203 are partially confined; portions of the aquifers are overlain by low permeability sediments such as clay or till, while windows in the confining layers are thin or absent in other areas. Land forms and surficial sediment characteristics have also changed and been modified by logging, land-clearing, residential development, soil removal, aggregate extraction, tilling and other activities, so that the description of sediments within historical well construction records may not represent the sediment sequences present at a location today. The intrinsic aquifer susceptibility to contamination or aquifer vulnerability mapped using the DRASTIC method is shown in Figure 39 with sample nitrate concentrations divided into low, medium and high categories. When observed spatially, some samples from wells located in areas of high intrinsic vulnerability to contamination had elevated nitrates, however the converse is also true, where aquifer vulnerability is low and elevated nitrates occur.

In comparison to the aquifer intrinsic vulnerability calculated using the DRASTIC method, the Aquifer Vulnerability Index (AVI) estimates the thickness and hydraulic conductivity of sedimentary layers above the aquifer to determine a relative “travel time” of contaminants via vertical flow to a well (Van Stempvoort, et al., 1993). A low AVI rating, log of travel time (years), indicates that there is a very short time of travel for water or contaminants to travel vertically from the surface to the aquifer. The AVI cannot be interpreted as a literal travel time, as it does not take into account the local hydraulic gradient, or processes such as diffusion or sorption that influence contaminant movement.

The statistical variation in nitrate compared to categories of Aquifer Vulnerability Index is shown in Figure 38(c). Average nitrate concentrations were higher in samples from wells with a very low AVI rating (extremely high vulnerability). In comparison, the lowest average and narrowest range of nitrate concentrations were observed in wells with a high AVI rating (extremely low vulnerability). Within the intermediate (low, moderate and high) vulnerability categories, the average nitrate concentrations were similar. This suggests that aquifer vulnerability does have an influence on the occurrence of elevated nitrate in groundwater. However, the land use and presence of contaminant sources may be equally or more important.

5.5 Estimation of nitrate background in AQ197

A key question for well owners, community members and government regulators is, what concentration of an element or other measured value represents the background or baseline condition, unimpacted by human activities. For example, if one could determine what the background concentration of nitrate was within an area, then an observed concentration above that threshold might indicate that some “event” or action has contributed to a change from natural conditions.

One approach to estimate background conditions is to evaluate larger data sets. For example, a commonly cited study using samples from over 87,000 wells, determined that the background nitrate concentration in the United States was 0.2 mg/L and that concentrations of nitrate >3.0 mg/L were indicative of human impacts (Madison & Brunett, 1985). One could also look at historical data, if available, or collect samples from pristine areas. Some limitations of these approaches are that contaminated areas may be over-represented within existing data sets, there may be large proportion of censored values below laboratory detection levels limiting the statistical analysis of the data, or the samples may have been collected under unknown conditions out of control of the researchers (Panno, et al., 2006). Dedicated monitoring wells in undeveloped areas are costly to install, therefore programs typically rely on sampling existing water supply wells as being more cost effective.

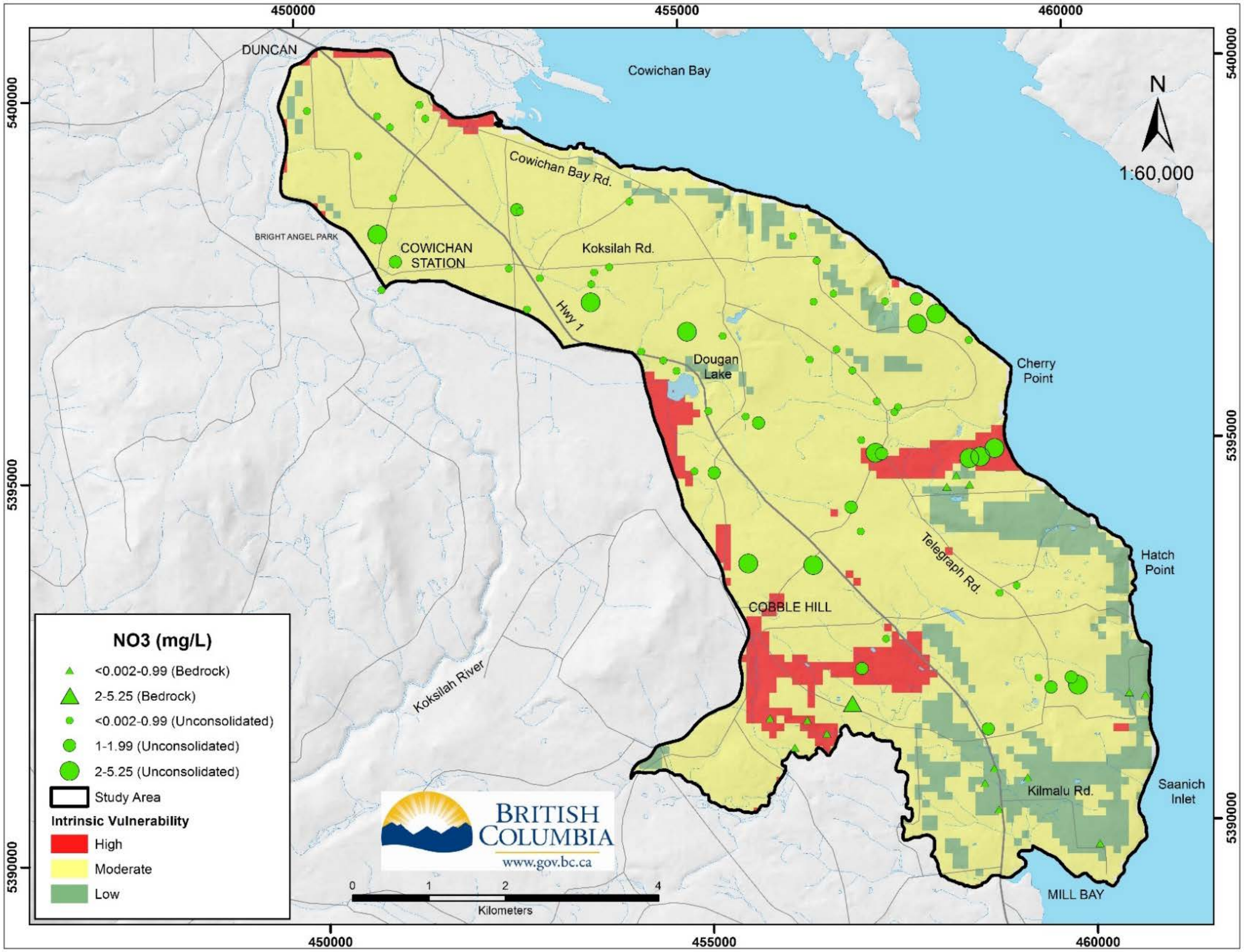


Figure 39: Aquifer intrinsic vulnerability to contamination (DRASTIC method) compared to nitrate concentration.

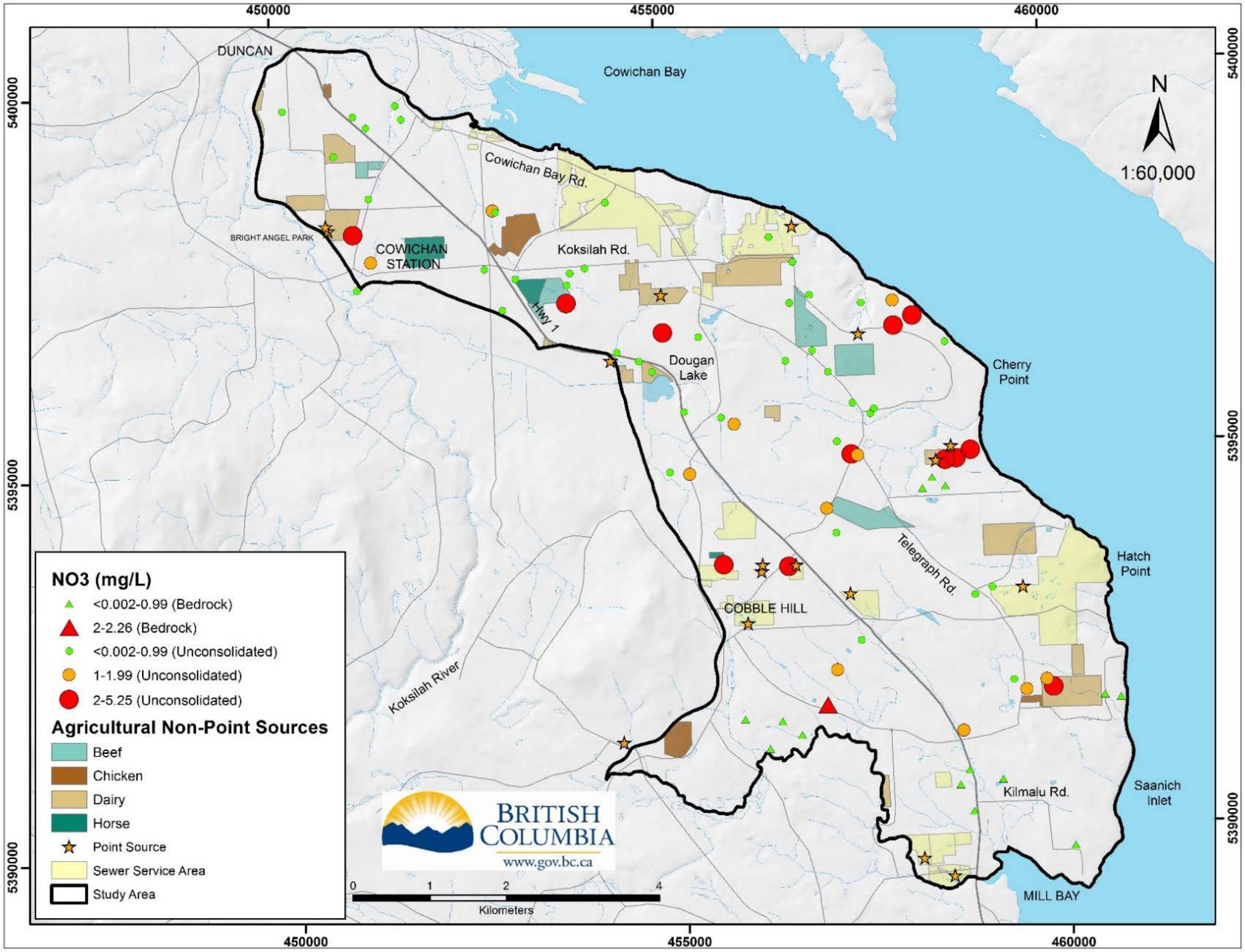


Figure 40: Map of land use and potential pollution sources and nitrate concentrations in groundwater samples.

A statistical method using cumulative frequency or probability plots to estimate background concentrations has evolved from exploration geochemistry, where atypical concentrations of certain elements in surface or groundwater can indicate the presence of a target mineral or ore body (Sinclair, 1974). For example, this method was adapted to estimate background nitrate concentrations in groundwater wells and springs in an Illinois agricultural community (Panno, et al., 2006). Measured environmental variables often have a log-normal distribution, i.e. there is a larger number of values centred around the lower end of the measurement scale. The plotting of a probability plots is a method to identify if there is a single or multiple groups or modes within a measured population. On a cumulative frequency (probability) plot datasets with log-normal distribution will plot as a straight line. If there are multiple straight segments, variations in the slope of the line highlight thresholds which define the boundaries between different populations within the data set.

To estimate background nitrate concentration within AQ197, all available data representing nitrate concentrations in groundwater from wells in the study area were compiled from various sources, including: data from the 2013-14 sampling program; tests of the Provincial Groundwater Observation Well Network wells; historical groundwater sample data found in the B.C. Environmental Monitoring System (EMS) database (Province of B.C., 2017d); and existing compilations (Western Water Associates Ltd., 2018). The data set also included results from sampling CVRD monitoring wells and the industrial production well within the Fisher Road area where contamination of groundwater from nitrates is known to have occurred. Censored values below the reportable detection limit (RPD) were excluded, as were samples from bedrock wells, therefore all values represent water quality within the unconsolidated aquifer (AQ197). A total of 261 individual values were obtained, from samples collected from 1979 to 2019. The nitrate concentration data were log-transformed, and histograms were plotted in MS Excel™ to determine appropriate frequency distribution bins. The optimum bin width was estimated as 0.15 units ($\log_{10}$ [mg/L]). The cumulative frequency was calculated and plotted relative to log of nitrate concentration. Figure 41 shows that threshold values were identified at three points, equivalent to nitrate concentrations of 0.01 mg/L, 0.5 mg/L and 7.4 mg/L.

The first threshold value (NO_3 0.01 mg/L) is believed to represent the lowest background concentration in groundwater that has not been impacted from human activities. For comparison, precipitation sampled within the North Cowichan and Cowichan Lake areas had a median NO_3 equal to 0.030 mg/L (FLNR data, unpublished). The second threshold (NO_3 0.5 mg/L) is considered the upper end of present-day background nitrate concentrations in groundwater in South Cowichan. Observed concentrations above this may be observed where land use, including agricultural activities, and nearby point and non-point nitrogen sources, have influenced groundwater quality.

Figure 41 inset histogram shows there are three distinctive modes or sub-populations within the compiled data set. The first sub-population is associated with wells having very low nitrate concentrations, within the range of present-day background. The second sub-population is representative of samples from wells with moderate nitrate concentrations below drinking water guidelines, that are likely impacted by anthropogenic point- and non-point nitrogen sources such as agricultural land use, or municipal scale sewage discharges. The upper sub-population is representative of samples from dedicated monitoring wells and an industrial water supply well in the Fisher Road area with elevated nitrate concentrations that have been impacted by historic land use and more concentrated pollution inputs to groundwater; it is noted that the monitoring wells in this area are screened within the upper portion of the water table, compared to the majority of drinking water wells which are deeper, where contaminant concentrations may be lower due to dilution, dispersion and denitrification processes (discussed in section 5.6 below).

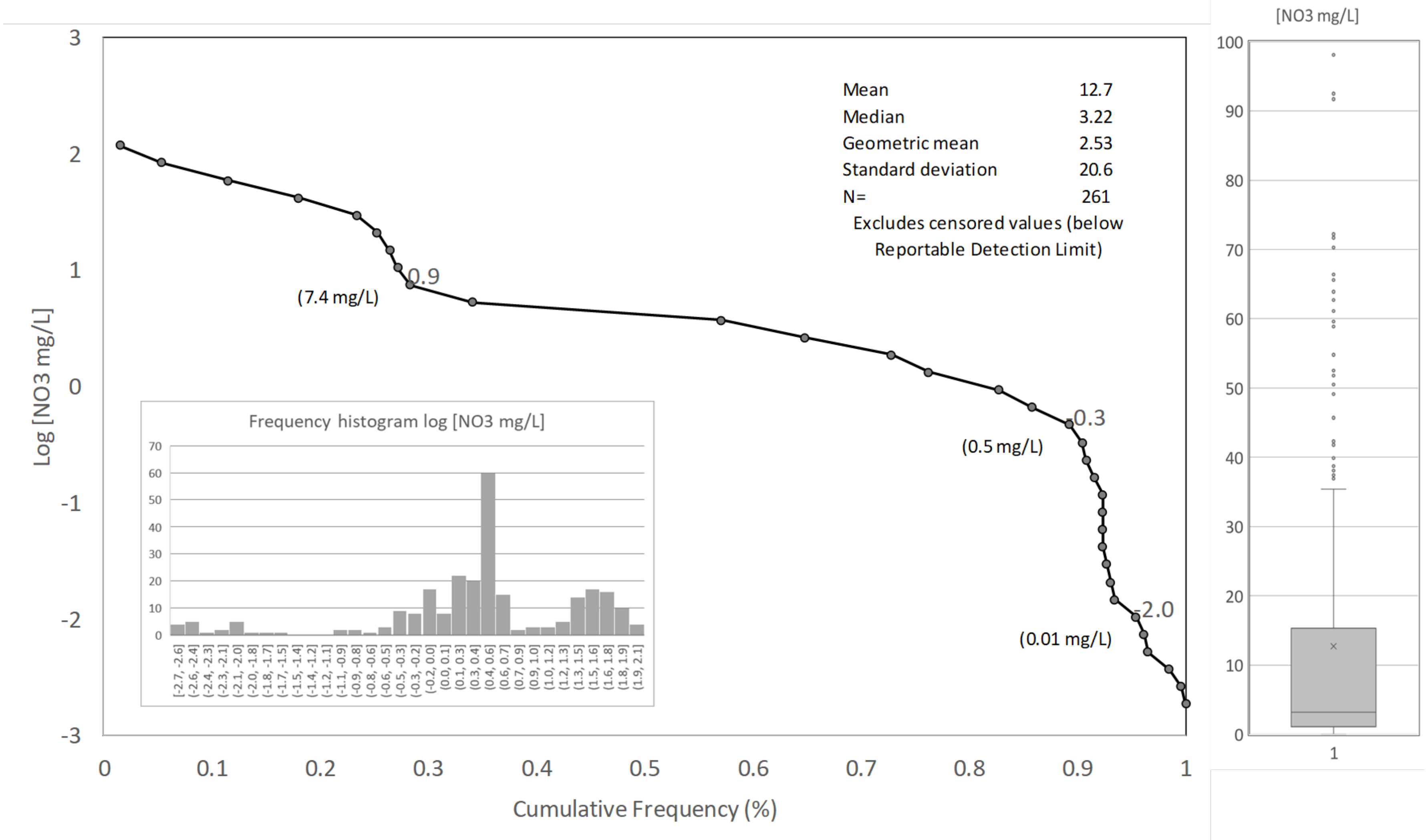


Figure 41: Probability plot of nitrate vs cumulative frequency. The inset histogram highlights three modes or populations within the data centred around a low, moderate and high nitrate concentration. Box and whisker plot (right) illustrates statistics for compiled data set; nitrate values above 35 mg/L represent outliers from samples in a known contaminate area around Fisher Road.

From the 2013-14 results (this study) in samples from unconsolidated wells (AQ197 only), the average nitrate concentration was 1.26 mg/L (median 0.95 mg/L), while 19 samples (29%) had censored values below the reportable detection limit. Thirty-eight samples (58%, including censored data) were below a threshold of 0.5 mg/L. Samples from 27 (42%) of wells had concentrations above what would be considered background or ambient conditions.

Table 14: Nitrate concentrations in 2013/14 samples from unconsolidated wells (AQ197) in comparison to estimated present-day background

Nitrate concentration	*Total*	*%*
Censored values <0.002 mg/L	*19*	*29*
Samples below 0.5 mg/L	*38*	*58*
Samples above 0.5 mg/L	*27*	*42*
Total samples	*65*	

5.6 Nitrate isotopes as an indicator of pollution sources and aquifer processes

Evaluation of nitrate isotopes in a sample, in comparison to the known range in different materials, is a method used to identify the potential source of pollution when multiple overlapping point and non-point sources are present (Kendall, 1998). Because the ratios change in predictable ways as nitrogen compounds are involved in different biological and geochemical reactions, isotopic data also allow us to understand processes that are influencing the movement, transformation and attenuation of nitrogen sources in the environment.

Each transition or phase of the nitrogen cycle enables a potential change in the isotopic composition of the materials. The isotopic signature is likely to stay relatively similar when physical processes such as dilution occur, whereas within biologically mediated processes including nitrification, ammonification, and denitrification the bacteria prefer to utilize lighter isotopes within their metabolic processes, leaving the remaining water or material with a more concentrated or elevated heavy isotopic signature. An exponential increase in values of $\delta^{15}N$ and $\delta^{18}O\text{-}NO_3$ is a characteristic indicator of the denitrification process, illustrated in Figure 42, as the denitrification pathway (Aravena & Mayer, 2010; Kendall, 1998). Fresh animal waste has a $\delta^{15}N$ in the range of 2 to 8 ‰; during volatilization of ammonia in manure storage lagoons or stockpiles and in the unsaturated zone, $^{14}NH_3$ is preferentially off-gassed, leaving the residual NH_3 with a higher $\delta^{15}N$ concentration in comparison to the original source material.

Figure 42 shows the sample results for the South Cowichan samples, in comparison to typical ranges of $\delta^{15}N$ and $\delta^{18}O\text{-}NO_3$. In this case, sample values are within the typical range for manure and septic waste, which partially overlaps with the isotope concentration of nitrogen in soil (e.g. nitrogen fixed in the soil by microbiological processes). None of the samples fell within the range of artificial fertilizer (either as nitrate, NO_3, or ammonia, NH_4). The sample collection for this study was completed during the wet season (November to February) consistent with when nitrate concentrations are expected to be highest from the influx of nutrients during fall and winter groundwater recharge (Chesnaux, et al., 2007; Zebarth, et al., 1998). The $\delta^{15}N$ nitrate isotope value can exhibit seasonal effects, with lower values during winter from dilution, and higher levels in the dry season resulting from increased volatilization. Nitrogen fixation from leguminous crops like alfalfa produces organic material with a low to negative isotope signature close to $\delta^{15}N$ 0‰ (Böhlke, 2002) which is not observed in this data.

Nitrate concentration did not appear to vary according to well depth (Figure 43A). An increase in $\delta^{15}N$ with depth (Figure 43B) is an indicator that denitrification is occurring in the aquifer (Aravena & Mayer, 2010). Similarly, a decrease in the ratio of NO_3/Cl with depth is also indicative of denitrification occurring (Figure 43C) because nitrate concentration decreases while chloride is conservative in groundwater, therefore the ratio between the two diminishes (Canter, 1996).

Field measurements of Oxidation Reduction Potential (ORP) corrected to Eh can indicate if groundwater is present in an aquifer under either anaerobic conditions, Eh from +150 to 300 mv, or aerobic conditions (Eh >300) (U.S. Environmental Protection Agency, 2017). In this study, there was a range in Eh indicating oxidizing conditions in shallower wells transitioning to more reducing conditions in deeper wells (Figure 43D). The median Eh was 344±140 mv in groundwater from unconsolidated (drilled) wells, compared to median Eh 298±129 mv in groundwater from bedrock wells. In comparison the median Eh was 417 mv in groundwater from unconsolidated dug wells, consistent with aerobic or oxidizing conditions in shallow groundwater. Reducing conditions in the deeper parts of the aquifers are favourable to denitrification. While a low concentration of dissolved carbon (electron donor) may be a limiting factor influencing natural attenuation and removal of nitrate from the groundwater system, sulphide minerals are also capable of acting as electron donors within the denitrification process (Rivett, et al., 2008).

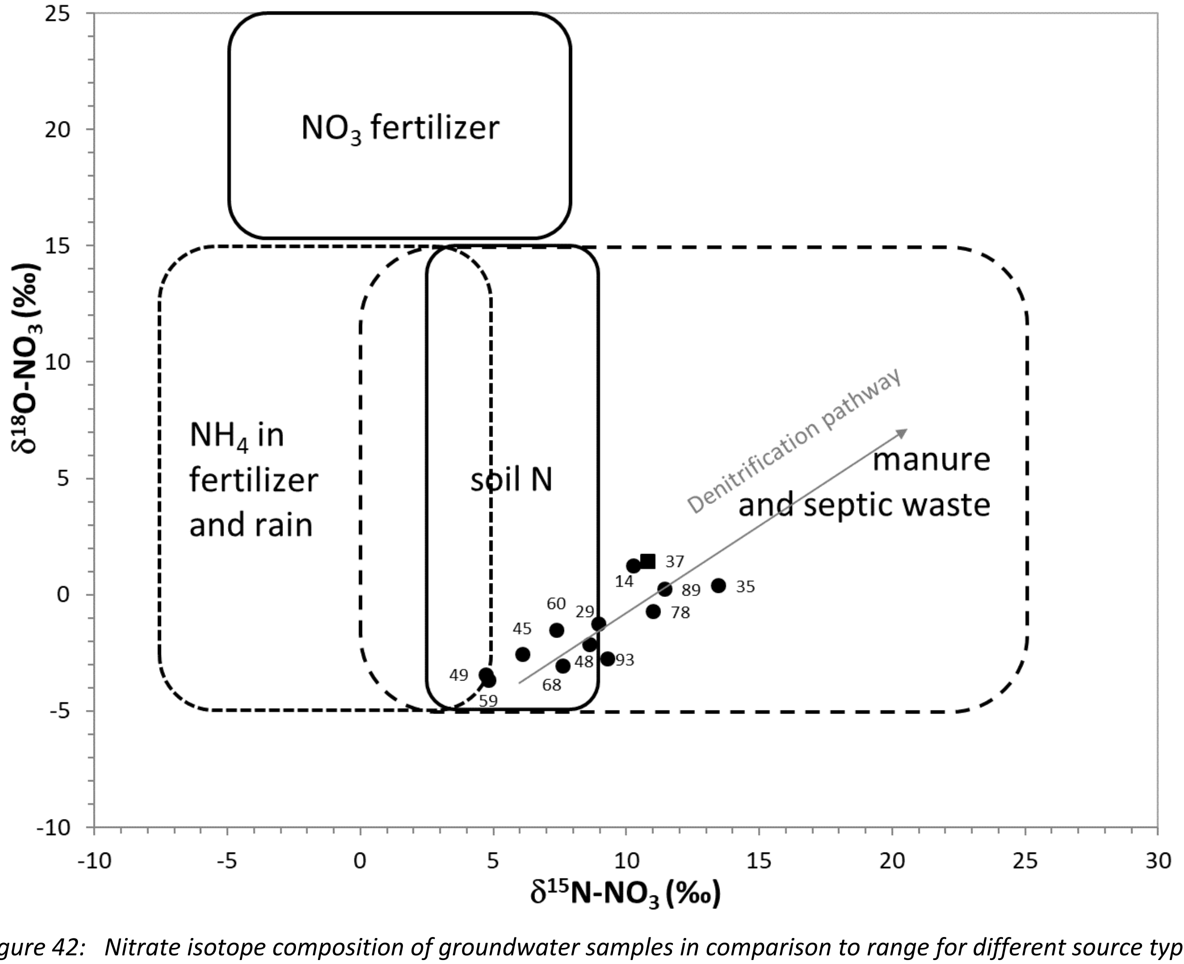


Figure 42: Nitrate isotope composition of groundwater samples in comparison to range for different source types, square=bedrock well, circle=unconsolidated aquifer (N=13)(after Kendall, 1998, Fig 16.9).

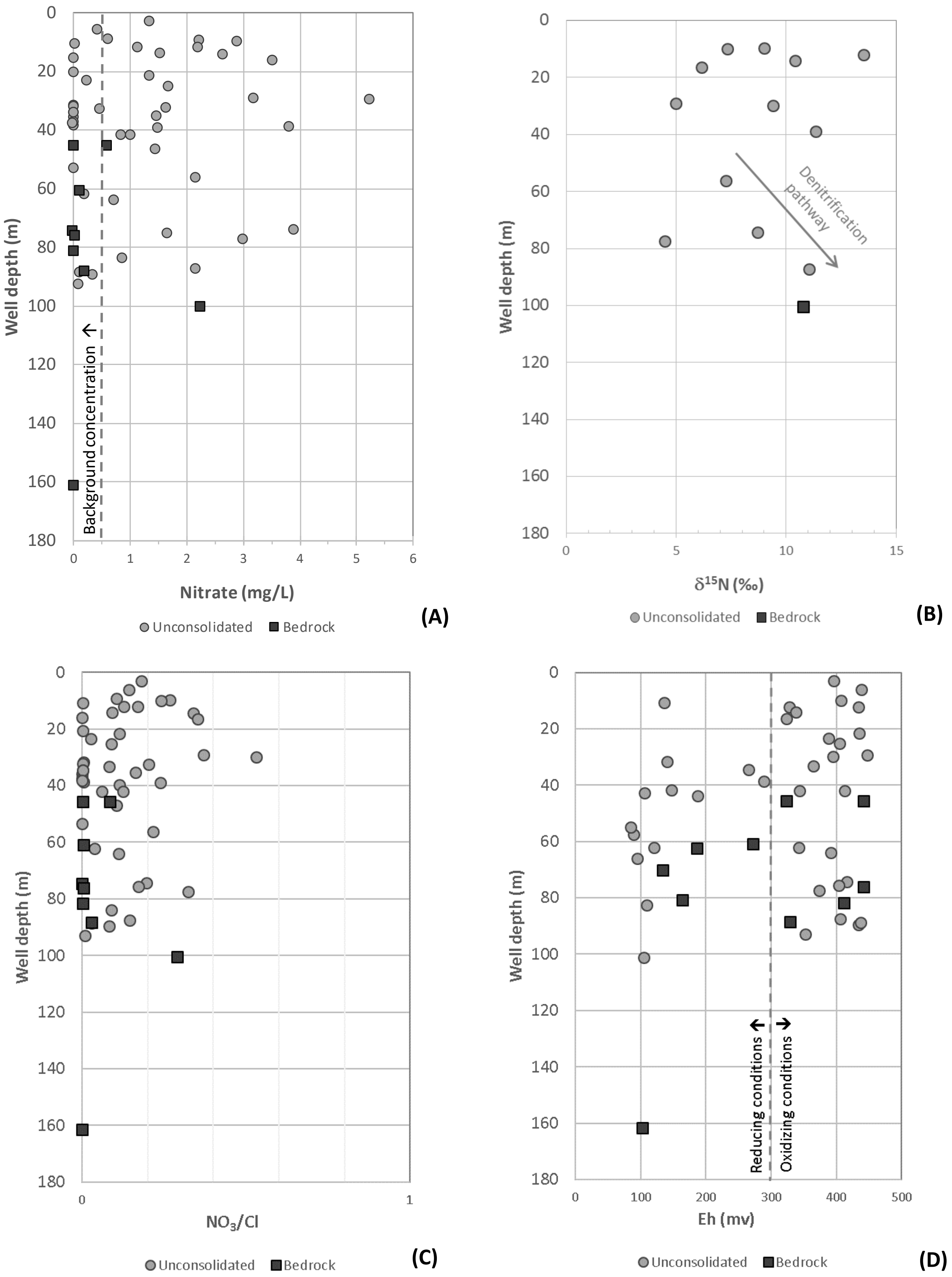


Figure 43: Depth profiles of (A) nitrate, (B) δ15N, (C) NO3/Cl and (D) Eh (redox state), square=bedrock well, circle=unconsolidated aquifer (N=13).

Additional geochemical data may be used to examine the potential contributing sources and gain insight into the processes occurring in the aquifer. In our data there were few significant correlations observed between major ion concentrations typically used in the literature to differentiate between different source types (e.g. strontium, chloride/bromide ratios). Samples were obtained from water wells which are screened or obtain water from deeper below the water table, where concentrations of chemical indicators were relatively dilute, and representative samples of contaminants at the source were not obtained for comparison, challenging the ability to differentiate between different contaminant origins.

Further lines of evidence that could be use in future studies could include sampling groundwater for substances that are present in human waste, such as caffeine or food additives, artificial sweeteners, wastewater indicators such as $\delta^{11}B$ or indicators of animal agriculture such as pharmaceuticals used in veterinary treatment (Fenech, et al., 2012; Robertson, et al., 2016). Information on aquifer processes could be obtained from sampling for stable isotopes of water ($\delta^{18}O$ and $\delta^{2}H$), and determination of groundwater residence times through age dating e.g. $\delta^{3}H/He$ (tritium-helium) (Chesnaux, et al., 2007; Aravena & Robertson, 1998; Wassenaar, et al., 2006). It would also be useful to sample waste discharge sources such as manure pits, septic leachate, to further develop locally representative values of isotope and other geochemical parameters within these contaminant sources.

5.7 Study implications for policy and land use practices

The results illustrate that groundwater quality within the South Cowichan area is very good overall. Focusing on nitrate as a parameter of concern, the majority of sites sampled (58%) had nitrate concentrations within a range consistent with a present-day background (undetected to 0.5 mg/l). Where nitrate concentrations were above 2 mg/L, the nitrate isotopic signatures were consistent with a source derived from either animal and human waste.

Land use and the spatial proximity of potential contaminant sources on the landscape, including manure storage, moderate to large scale livestock operations, industrial liquid waste discharges, and sewage treatment plant disposal to ground were associated with spatial differences in groundwater nitrate concentrations. Elevated nitrates were observed within areas that were highly vulnerable, based on the aquifer vulnerability index (AVI) or DRASTIC ratings; however, intrinsic vulnerability of the aquifer in the area of a well was one of several factors apparently influencing nitrate in groundwater. Nitrate concentrations also varied according to spatial proximity to either point-source or non-point sources of pollution. Thus, while the presence of confining sediments overlying an aquifer may provide some protection from contaminant hazards, management and reduction of contaminant inputs is key.

It is clear from this work and related literature cited that specific activities on the land that involve storage, utilization, and discharges to the environment of nutrient rich materials such as manure, compost, and human waste should be carefully managed in all areas to reduce negative environmental impacts. Ideally, we would aim to maximize the benefits such as the need to produce food, and the right to work, farm, and live on the land, while at the same time protecting precious drinking water supplies.

A new *Environmental Management Act*, Code of Practice for Agricultural Environmental Management (AEM Code) (Province of B.C., 2019b) was enacted in February 2019. The AEM Code has requirements for air emissions and odours, setback requirements of farm activities from water sources, and practices for storage, composting and usage of farm waste associated with nutrients like phosphorus and nitrate. Enhanced measures for management of nutrient sources such as manure are required in some areas or under specific environmental and weather conditions. For example, the AEM Code identifies “vulnerable recharge areas” around the province based on assessment of annual and seasonal precipitation rates, and aquifer properties. The Cobble Hill area (AQ197) is included in the list of vulnerable recharge areas in Schedule B of the AEM Code, indicating that farms here may be required to undertake more enhanced pollution control measures, such as ensuring that modified or new permanent manure storage structures have a protective base, or implementing a nutrient management plan.

While the new AEM Code is welcomed, some of the provisions could be improved to ensure better protection of water sources. For example, our results suggested a link between the proximity of a well to point sources (such as manure cesspits, locations of concentrated liquid waste storage, or sewage system discharges to ground) and higher nitrate concentrations in groundwater. The AEM Code requires an arbitrary minimum setback of 30 m of these manure storage structures from “drinking water sources” yet when very concentrated and high-volume sources are present, a 30 m setback may be inadequate. The requirement for an impermeable protective base applies primarily to modified or new storage structures and in vulnerable areas. Whereas we suggest there is a need for a protective base for these types of structures in all locations, regardless of aquifer properties. We also believe there is value in supporting or requiring farm operations to improve their existing facilities; provincial programs of this nature could be developed in collaboration with Ministry of Agriculture. The Polis report on nutrient management options to address nitrate contamination in the Hullcar aquifer provides a useful summary of current and proposed regulatory and other approaches that could be improved to enhance source water protection in B.C. (Brandes, et al., 2017).

We also note that the potential contaminant sources from land use, and hydrogeologic conditions observed are not unique to the South Cowichan/Cobble Hill area. Locations in the West Coast and Vancouver Island that should be added to vulnerable recharge areas in the AEM Code include agricultural areas on Saanich Peninsula, in the Comox Valley, Chemainus and on the Gulf Islands.

In the central Cobble Hill area, for the past 17 years since 2002 when elevated nitrates more than four times drinking water limits were first identified in an industrial water supply well, attention has been drawn to pollution from three sites: two industrial scale organic waste composting facilities, and a historical greenhouse operation (Thurber Engineering Ltd, 2013; Western Water Associates Ltd., 2018). Although not a specific focus of our study, it is worthwhile discussing it here in the context of groundwater source protection, and due to the regulatory and policy gaps identified when considering the long-term community concerns related to these properties.

From published data and reports on the properties at 1355, 1345 and 1360 Fisher Road nitrate concentrations in groundwater at and near these sites are significantly higher in comparison to other sampled areas. Since concerns were first raised in the community, division of jurisdiction over onsite practices and operations has made it difficult to address some of the activities potentially contributing to groundwater contamination. Composting facilities are regulated under the *Environmental Management Act*, Organic Matter Recycling Regulation (OMRR) (Province of B.C., 2002), which is currently under review by the Ministry of Environment and Climate Change Strategy (ENV) (Ministry of Environment and Climate Change Strategy, 2018). The industrial site at 1355 Fisher Road has a waste discharge permit from ENV for composting residential food waste and yard refuse (ENV, 2019a). It is believed that changes and practices in recent years such as installation of impervious bases for all compost processing and storage areas and enhanced leachate collection and recycling are likely to significantly reduce or eliminate nitrogen releases from this site to the underlying aquifer. However, ongoing monitoring is necessary to verify compliance with their permit. In comparison, a second composting site at 1345 Fisher Road, which has historically processed mainly yard waste, and sold finished compost, soil and landscaping supplies, does not require an ENV permit, and different provisions of the OMRR apply to this site due to the volume and type of materials accepted. Until changes are made to onsite practices such as reducing pervious areas, and improving onsite leachate collection and retention, this operation is likely to continue to be a source of nitrogen contamination.

Greenhouses have previously had minimal regulation in B.C. At 1360 Fisher Road historical practices including intensive fertilizer application, and lack of impermeable barrier underlying the greenhouses are believed to have migrated off-site and contributed to elevated nitrate in one industrial water supply well and a monitoring well downgradient of the property. Land use at this property has now changed, however legacy contaminants in the soil and underlying groundwater table may continue to be present for years to come (Western Water Associates Ltd., 2018). Some changes to the AEM Code will apply to greenhouse activities, such as requirement for an impervious base for greenhouses in vulnerable areas. Since 2017, the Cobble Hill Interagency Task Group (CHIATG) with representatives from the Cowichan Valley Regional District, ENV, FLNR, Ministry of Health and Island Health, continue to work together to coordinate compliance enforcement, monitoring, and other strategies to reduce further impacts to groundwater quality in this area of Cobble Hill.

Provincial laws and regulations such as the AEM Code, or the OMRR typically consider impact to groundwater or surface water as having occurred when nitrate exceeds the 10 mg/L drinking water guidelines. Yet using the drinking water limit of 10 mg/L to identify the need for enhanced protection, compliance enforcement or other measures is disadvantageous because at this level, impacts have already occurred. Once nitrate enters the groundwater system, it is often slow to attenuate or respond to changes in land use practices (Rudolph, et al., 2015). Thyroid disease, some cancers, and negative birth outcomes have been linked with concentrations of nitrate in drinking water significantly below the drinking water guidelines (Schullehner, et al., 2018; Temkin, et al., 2019). A more conservative threshold or indicator of impacts would ideally be lower than drinking water guidelines and based on observations of elevated levels as a proportion above a regional or local “background” concentrations, to flag concerns earlier so that changes can be made to prevent more significant impacts.

Case studies have shown that nutrient management practices can be employed to reduce nitrogen loading and improve groundwater quality over the long-term without compromising agricultural productivity (Chesnaux, et al., 2007; Harter, et al., 2012; Rudolph, et al., 2015). Combining appropriate regulatory controls, with education, and implementation of voluntary best practices are cost-effective methods to prevent contamination and reduce the need for more expensive groundwater monitoring and testing, water quality treatment, or drilling of new wells, the costs of which are typically borne by private property owners and local water purveyors.

6. CONCLUSION AND RECOMMENDATIONS

A geochemical snap-shot survey was completed in winter 2013-14 in the South Cowichan area, near Duncan on Vancouver Island, where the primary source of water for drinking, irrigation and industrial use is obtained from aquifers. A total of 82 wells were sampled, including 12 operated by local water service providers. Most wells sampled (65, 80%) were constructed in unconsolidated materials (AQ197), while 17 (20%) were constructed in sedimentary or igneous bedrock (AQ198 and AQ203 respectively).

Ambient groundwater within the South Cowichan study area was generally excellent in quality, with a geochemistry indicative of fresh groundwater that has been recently recharged. Few samples exceeded the GCDWQ for either health-related or aesthetic parameters.

Two naturally occurring contaminants that are widespread in the study area included manganese and arsenic. Groundwater users in this area should be made aware of the widespread occurrence of arsenic, at lower concentrations below drinking water guidelines but at levels that could be harmful for vulnerable populations (young children, elderly or people with compromised health) or over longer periods of exposure. While only 2% of samples exceeded the 10 µg/L MAC for arsenic, 26% had arsenic between 1 and <5 µg/L, and 7% had arsenic from 5 to <10 µg/L. Median concentrations of arsenic were higher in samples from wells constructed in unconsolidated materials, likely due to the presence of arsenic containing minerals in the source rock making up the sand and gravel layers. Arsenic may have a different level of toxicity, depending on the form of arsenic compound present in the water; in addition to routine testing of dissolved arsenic, more specialized sampling techniques may be useful for future studies to identify the arsenic species present, and ensure that, if required, an appropriate treatment method is used to reduce its concentration in potable water (Le & Jensen-Fontane, 2015). Health Canada recommends that arsenic concentration in drinking water should be treated to a concentration as low as reasonably achievable (ALARA) (Health Canada, 2006).

Manganese concentrations were relatively similar in samples from both unconsolidated and bedrock wells, and approximately 38% of the samples exceeded the MAC for manganese, while a larger percentage 49% exceeded the aesthetic objective for manganese. Iron was also widespread affecting the pleasantness of groundwater for drinking. Iron was higher in samples from wells drilled in unconsolidated aquifers, also reflecting the geochemistry of the parent materials making up the sand and gravel deposits.

Well maintenance concerns such as missing or broken well caps, flooded well pits, buried well heads or low casing stick-ups were identified at 41% sites and well owners were provided with information on how to fix and protect their wells. Total coliform bacteria, typically found in surficial soils, were present in all samples from dug wells (3 sites), and in samples from 11 (21%) drilled wells. Presence of *E. coli* bacteria was rare and found in only 4 samples from either drilled or dug wells.

Groundwater treatment technologies such as reverse osmosis, chlorine injection, or specialized filters are available to reduce the concentrations of dissolved metals including iron, manganese and arsenic improving the safety and aesthetic quality of groundwater for drinking. If treatment is required, well owners may contract a qualified well pump installer or water treatment specialist to ensure their water treatment system is effectively treating the water to potable standards.

Nitrate was a parameter of concern previously identified within the community due to concerns related to local industrial land use and therefore examined in greater detail within this study. Nitrate was undetected (concentration below the Reportable Detection Limit (RDL) of 0.002 mg/L NO_3-N) in 29% of samples from unconsolidated wells, and 47% of samples from bedrock wells. Where nitrate was detected, the median concentration was 0.95 mg/L in samples from wells in unconsolidated materials compared to median of 0.038 mg/L in bedrock. When compare to land-use indicators, nitrate was higher in samples at sites in closer proximity to point and non-point nitrogen sources, such as moderate to large-scale livestock operations, or locations of authorized waste discharges e.g. municipal-scale sewage treatment and disposal sites. Nitrate concentrations were greater in samples from wells with a low Aquifer Vulnerability Index (indicating high vulnerability or rapid “travel time” of water or contaminants from the ground surface to the aquifer) but this factor was thought to be less important in comparison to land use related factors. For residential lots outside of sewered subdivisions, domestic septic systems were not believed to contribute significantly to observed nitrate concentrations in groundwater, possibly due to the depth of the water table, and larger lot sizes enabling sufficient setbacks between domestic wells and residential septic systems. Stable isotopes of nitrate were analyzed in samples where the nitrate concentration exceeded 2 mg/L. The isotopic signatures were consistent with a source derived from animal and human waste. Anaerobic conditions favourable to denitrification, and evidence of denitrification processes were present at depth within the aquifer.

To estimate a background nitrate concentration in AQ197, the primary data set from this study was expanded to include nitrate concentrations from 261 samples collected from 1979 to 2019 at multiple sites, including contaminated wells with elevated nitrate concentrations in the Fisher Road area. All available data were compiled to develop a probability plot of nitrate percent frequency distribution. The analysis using this method suggested the present-day background concentration of nitrate in the aquifer was in the range of 0.5 mg/L. Concentrations of nitrate above this were thought to be associated with impacts of human activities on groundwater quality.

The results demonstrated that the presence of point-source and non-point sources has likely contributed to elevated nitrate in some areas. However, concentrations of nitrate remain below drinking water guidelines in most areas, apart from at sites of previously known contamination concerns. Enforcement of new and existing regulations and codes of practice and implementing nutrient management strategies are recommended prevent additional impacts to water quality in this groundwater dependent region.

Recommendations based on the results of this study are outlined below.

Science and monitoring:

a) Continue to monitor and report on groundwater quality. Private-domestic well owners are recommended to sample their wells annually or twice annually in the dry and wet season for bacterial water quality, and once every three to five years for general chemistry, nutrients (including nitrate) and metals. The regional health authority and Ministry of Health recommend that water supply systems collect groundwater samples at a frequency based on the requirements of the operational permit and operator discretion. Owners/operators of wells with elevated nitrate concentrations (e.g. above 0.5 mg/L) are recommended review their sampling protocols and to monitor nutrient concentrations at a higher frequency (e.g. annually or bi-annually) to identify potential risks to water users and track trends over time.

b) Re-evaluate water quality at sites sampled within this study with nitrate above background concentration (>0.5 mg/L NO3-N) in future to determine if there is a change in concentration over time. Future studies could also include additional wells near sites where higher nitrate was observed e.g. NO3-N ≥2 mg/L. Locations where higher nitrate concentrations were observed could be resampled during different periods of the year (i.e. wet season, dry season) to verify if there is a seasonal variation in groundwater quality.

c) Promote uploading of water quality data from surface and groundwater sources, including from local water purveyors and monitoring locations associated with pollution discharges, to the provincial Environmental Monitoring System database, so that the data are accessible for development of regional assessments and related studies. ENV/FLNR staff could work with water supply systems operators to catalogue sites and capture data via automated uploading by water quality laboratories. This would capture data that are already being collected for health authority requirements but are not consistently maintained within an electronic database (see (Saarinen, 2012);

d) Estimate groundwater travel times, recharge rates and age for sources in the study area using methods including sampling for stable water isotopes, tritium, chlorofluorocarbons and other methods;

e) Utilize other geochemical and isotopic tracers to differentiate pollution inputs from agriculture compared to residential development (i.e. septic discharges, stormwater inputs from road systems), examples include use of boron isotopes coupled with nitrogen isotopes, artificial sweeteners, caffeine, or pharmaceuticals used for human treatment or in the animal/agriculture industry;

f) Ensure adequate monitoring provisions for sites associated with nitrogen loading to groundwater from permitted pollution discharges under the *Environmental Management Act* (Province of B.C., 2003) and associated statutes (e.g. Code of Practice for Agricultural

Environmental Management, Code of Practice for the Slaughter and Poultry Processing Industries, Municipal Wastewater Regulation, Organic Matter Recycling Regulation);

g) Develop nitrogen budgets for the South Cowichan area or other Vancouver Island areas at moderate to high risk of nitrate contamination from land use. A nutrient budget could consider estimates of nitrogen inputs from permitted discharges (e.g. community or municipal scale sewage treatment disposal to ground or to surface water that is hydraulically connected to groundwater), agricultural sewerage lagoons and ground disposal, cropland nitrogen inputs and outputs (manure or artificial fertilizer application, estimated plant requirements compared to application rates).

h) As a companion to intrinsic vulnerability assessment for aquifers, conduct an inventory of hazards associated with groundwater protection, which combined with the vulnerability can be used to determine overall risk of groundwater contamination. Risk mapping can be used as a regulatory/planning tool to influence what activities are undertaken or best practices that are implemented to mitigate impacts to groundwater sources.

i) Evaluate the contribution of elevated nutrient concentrations in groundwater quality within surface water bodies, where groundwater and surface water are hydraulically connected.

Source protection and nutrient input reductions:

a) Ensure adequate setbacks and waste-source separation between contaminant sources such as manure, compost, septic fields, wastewater treatment lagoons or fertilizer storage and groundwater sources. Consider amending the requirements within the AEM Code for all areas—independent of aquifer sensitivity designation—to require larger setback distances between concentrated contaminant sources and wells, and require liners and covers for all concentrated waste/nutrient sources;

b) Ensure sewage disposal systems (from moderate- to large-scale utilities to residential septic systems) are designed, installed and maintained properly, with adequate separation distance between the depth of the discharge plume and the groundwater table; where nutrient concentrations and discharge quantities are higher, designs can include higher levels of pre-treatment prior to discharge and monitoring of effluent and receiving environment;

c) Undertake frequent maintenance of sewer systems to reduce/prevent leakage;

d) Dug wells and shallow drilled wells in unconfined aquifers may be more vulnerable to nitrate contamination. Dug wells can be protected somewhat by siting them upgradient and with adequate set-back distance from potential contaminant sources;

e) Promote agricultural best management practices to reduce surface and groundwater contamination from fertilizers. Examples include testing soils and matching fertilizer application to nutrient needs; applying fertilizers in the spring to reduce leaching during fall and winter rains and time fertilization to the period of maximum plant uptake; utilizing low till and conservation tillage practices. The Environmental Farm Plan Program Reference guide has links to guidance documents and incentives programs for promotion of agricultural BMP's (B.C. Ministry of Agriculture, November 2010). Management of manure could be included within liquid waste management planning processes to allow for development of agriculture related policy at the regional level.

f) Promote compliance enforcement of authorized (and unauthorized) discharges under the *Environmental Management Act* and associated regulations.

Policy and planning:

a) Assess current regulations under the *Environmental Management Act* and identify policy gaps to address potential contaminant sources not currently captured under regulation or code of practice guidelines.
b) Review and add to the list of vulnerable recharge areas for which enhanced measures are required under the Code of Practice for Agricultural Environmental Management (AEM Code) Schedule A.
c) As nitrate is persistent in groundwater, a prevention-based rather than reactive approach to groundwater nitrate contamination from agricultural contaminants would identify sensitive areas with nitrate concentrations exceeding lower threshold, i.e. above background but below the 10 mg/L Guidelines for Canadian Drinking Water Quality. A lower threshold could be established in identified areas as a regional groundwater quality objective, for example.
d) Incorporate relevant findings of this study into revision of the Liquid Waste Management Plan (LWMP). The South Sector LWMP is presently being updated by the Cowichan Valley Regional District, with Stage 1 public input sessions in fall 2019 (Cowichan Valley Regional District, 2019c).

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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	Aesthetic Objective (parameters affecting water taste or odor)
OG	Operational Guideline (GCDWQ) - for water systems requiring treatment (not discussed in report)
Bold	Result exceeds drinking water quality guidelines
Bold	Exceeds MAC (for manganese only)
RDL	Reportable Detection Limit
	RDL provided by laboratory. Varied on different sample dates due to changes in lab procedures for parameters e.g. bromide, antimony, arsenic, beryllium, 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)
*	Field equipment error, specific conductivity values not retained for further use
CBE	Charge Balance Error (Italics=CBC Exceeds 5%)
NC	Not calculated
NR	Not recorded
<VALUE	Values less than detection limit excluded from statistical calculations
‰	Permil (one part per thousand), units for isotope results
m	metres
mv	millivolts
µS/cm	microSiemens per centimetre, units for specific conductivity
mg/L	milligrams per litre
ug/L	micrograms per litre
	Geometric mean not calculated for values less than zero (negative values)

Table A1: Geochemical and isotopic analytical results

GCDWQ-MAC						-	-		-	-	-	10	1.5	-	-
GCDWQ-AO						-	-	7.0-10.5	-	-	-	-	-	-	-
RDL												0.002	0.010	0.50	0.50
Units	ft	m	m			°C	µS/cm	pH units	mv	mv	minutes	mg/L	mg/L	mg/L	mg/L
RDL												0.002	0.010	1	0.50
Site	Well Depth (ft)	Well depth (m)	Static water level	Local Water Service Provider	Lithology	Temperature (field)	Specific conductivity (field)	pH (field)	Oxidation Reduction Potential (field)	Eh (calc)	Purge duration	Nitrate (N)	Fluoride (F)	Alkalinity (Total as CaCO3)	Alkalinity (PP as CaCO3)
21	10	3.05	UNK	N	Unconsolidated (dug)	8.1	5.9*	**6.64**	181	396	8	1.350	0.041	48	<0.50
84	30	9.14	UNK	N	Unconsolidated (dug)	5.9	167	**5.98**	nr	nr	6	0.617	0.047	68	<0.50
92	20	6.10	UNK	N	Unconsolidated (dug)	6.4	80	**6.16**	223	438	5	0.439	0.041	34	<0.50
2	109	33.22	24.38	N	Unconsolidated	10.2	5.6*	7.70	150	365	8	0.481	0.085	88	<0.50
3	127	38.71	30.48	N	Unconsolidated	10.2	8.5*	7.76	73	288	11	0.009	0.150	143	<0.50
5	77	23.47	19.51	N	Unconsolidated	7.1	6.2*	7.40	174	389	6	0.245	0.052	97	<0.50
8	104	31.70	25.91	N	Unconsolidated	10.6	9.6*	7.82	-75	140	10	0.009	0.170	127	<0.50
9	138	42.06	35.36	N	Unconsolidated	9.3	12.4*	7.44	197	412	3	1.010	0.049	78	<0.50
12	175	53.34	35.97	N	Unconsolidated	8.2	212	7.49	nr	nr	13	0.003	0.086	101	<0.50
14	47	14.33	6.10	N	Unconsolidated	8.8	223	**6.36**	nr	nr	6	2.640	0.046	85	<0.50
17	130	39.62	30.78	N	Unconsolidated	9.6	271	7.06	nr	nr	7	1.490	0.082	86	<0.50
18	217	66.14	15.24	N	Unconsolidated	7.6	238	8.34	nr	nr	6	<0.0020	0.042	118	<0.50
20	117	35.66	5.49	N	Unconsolidated	9.2	292	**6.94**	nr	nr	7	<0.0020	0.034	93	<0.50
22	71	21.64	12.19	N	Unconsolidated	10.2	12.7*	7.33	220	435	4	1.360	0.055	78	<0.50
23	225	68.43	62.18	N	Unconsolidated	8.5	195	7.41	nr	nr	6	<0.0020	0.080	90	<0.50
29	32	9.75	1.22	N	Unconsolidated	10.1	164	**6.18**	nr	nr	4	2.240	0.062	49	<0.50
32	106	32.31	12.19	N	Unconsolidated	10.1	290	7.55	nr	nr	6	0.006	0.130	141	<0.50
34	225	68.58	54.86	N	Unconsolidated	8.8	248	7.41	nr	nr	5	<0.0020	0.081	112	<0.50
35	40	12.19	3.66	N	Unconsolidated	10.6	7.9*	7.07	220	435	4	2.210	0.061	91	<0.50
38	40	12.19	UNK	N	Unconsolidated	9.7	121	**5.56**	113	328	3	1.150	0.031	54	<0.50
39	52	15.85	8.53	N	Unconsolidated	9.8	425	7.58	nr	nr	6	0.004	0.100	200	<0.50
40	117	35.66	16.46	N	Unconsolidated	8.2	402	7.80	nr	nr	4	<0.0020	0.120	195	<0.50
43	50	15.24	9.14	N	Unconsolidated	5.9	278	7.35	nr	nr	5	<0.0020	0.190	139	<0.50
44	68	20.73	7.92	N	Unconsolidated	8.8	184	7.13	nr	nr	3	0.003	0.068	86	<0.50
45	54	16.46	6.71	N	Unconsolidated	9.6	201	**6.82**	109	324	3	3.520	0.047	94	<0.50
46	46	14.02	11.89	N	Unconsolidated	9.9	158	**6.67**	123	338	4	1.550	0.050	109	<0.50
48	244	74.37	32.00	Y	Unconsolidated	9.7	268	7.73	202	417	nr	3.900	0.035	119	<0.50
49	254	77.42	45.72	Y	Unconsolidated	9.1	138	8.08	159	374	3	3.000	0.039	61	<0.50
50	248	75.59	20.73	Y	Unconsolidated	9.7	154	8.43	189	404	3	1.660	0.049	72	<0.50
51	210	64.01	27.13	Y	Unconsolidated	9.7	163	8.16	177	392	3	0.734	0.054	69	<0.50
52	217	66.14	41.15	Y	Unconsolidated	10.4	225	8.08	-120	95	5	<0.0020	0.170	141	<0.50
53	204	62.18	11.58	Y	Unconsolidated	9.4	118	8.39	128	343	3	0.208	0.060	63	<0.50
54	294	89.61	10.06	Y	Unconsolidated	8.2	118	8.25	219	434	4	0.344	0.054	69	<0.50
55	189	57.61	45.11	Y	Unconsolidated	6.9	285	8.42	-126	89	8	<0.0020	0.130	137	<0.50
56	138	42.06	22.86	Y	Unconsolidated	9.4	145	7.53	129	344	3	0.851	0.064	73	<0.50
57	144	43.89	28.04	Y	Unconsolidated	9.7	191	7.60	-28	187	5	<0.0020	0.140	106	<0.50
58	204	62.18	UNK	Y	Unconsolidated	9.7	231	8.01	-94	121	5	<0.0020	0.130	131	<0.50
59	96	29.26	18.29	Y	Unconsolidated	8.4	181	**6.63**	233	448	9	3.190	0.053	84	<0.50
60	185	56.39	50.29	N	Unconsolidated	10.4	281	7.03	nr	nr	6	2.170	0.110	108	<0.50
61	116	35.36	UNK	N	Unconsolidated	9.9	287	7.67	nr	nr	8	1.470	0.120	121	<0.50
62	305	92.96	86.87	N	Unconsolidated	9.6	171	7.39	137	352	4	0.103	0.042	62	<0.50
63	332	101.19	44.50	N	Unconsolidated	10.3	207	8.57	-110	105	6	<0.0020	0.047	109	<0.50
64	113	34.44	UNK	N	Unconsolidated	10.1	211	7.91	51	266	7	0.007	0.120	123	<0.50
66	281	85.65	43.28	N	Unconsolidated	9.8	240	8.20	nr	nr	5	<0.0020	0.042	119	<0.50
68	33	10.06	2.13	N	Unconsolidated	10.6	115	**6.22**	192	407	8	2.890	0.049	35	<0.50
69	140	42.67	31.09	N	Unconsolidated	10.3	198	7.76	-110	106	8	<0.0020	0.120	128	<0.50
70	107	32.61	UNK	N	Unconsolidated	7.6	207	7.14	nr	nr	5	1.640	0.083	82	<0.50
71	154	46.94	16.46	N	Unconsolidated	8	175	**6.60**	nr	nr	8	1.460	0.034	56	<0.50
73	271	82.60	67.06	N	Unconsolidated	9.9	309	7.62	-106	109	4	<0.0020	0.100	129	<0.50
75	118	35.97	26.52	N	Unconsolidated	8.7	377	**6.86**	nr	nr	8	0.003	0.130	176	1.58
76	206	62.79	36.58	N	Unconsolidated	7.2	268	7.53	nr	nr	8	<0.0020	0.140	127	<0.50
77	137	41.76	UNK	N	Unconsolidated	9.2	232	8.27	-67	148	3	<0.0020	0.099	134	<0.50
78	287	87.48	76.20	N	Unconsolidated	10.5	294	7.44	191	406	5	2.160	0.087	118	<0.50
79	291	88.70	39.01	N	Unconsolidated	9	125	8.16	223	438	4	0.109	0.048	60	<0.50
80	123	37.49	13.11	N	Unconsolidated	9.6	171	7.73	nr	nr	8	0.003	0.074	71	<0.50
85	113	34.44	28.04	N	Unconsolidated	8.7	266	**6.96**	nr	nr	3	0.003	0.180	132	<0.50
86	275	83.82	76.20	N	Unconsolidated	9.6	218	**6.78**	nr	nr	6	0.881	0.083	81	<0.50
88	119	36.27	31.55	N	Unconsolidated	5.5	329	7.89	nr	nr	9	<0.0020	0.200	157	1.56
89	128	39.01	29.26	N	Unconsolidated	10.2	318	**6.97**	nr	nr	4	3.830	0.069	115	<0.50
90	125	38.10	24.69	N	Unconsolidated	9.8	242	7.58	nr	nr	4	0.002	0.120	99	0.88
91	50	15.24	7.62	N	Unconsolidated	10.3	464	7.37	nr	nr	4	<0.0020	0.150	233	<0.50
93	98	29.87	15.85	N	Unconsolidated	9.6	257	**6.46**	180	395	3	5.250	0.051	91	<0.50
94	35	10.67	UNK	N	Unconsolidated	10.1	390	8.73	-79	136	12	0.029	0.270	178	1.11
95	83	25.30	11.89	N	Unconsolidated	10.5	257	**6.75**	190	405	13	1.680	0.061	102	<0.50
96	180	54.86	UNK	N	Unconsolidated	10	293	8.06	-130	85	12	<0.0020	0.350	154	<0.50
Arithmetic mean	143	43.49	27.72			9.18	233	7.41	90	305	6	1.26	0.09	105.03	1.28
Median	125	38.10	25.30			9.60	225	7.49	137	352	5	0.946	0.07	101.00	1.34
Geometric mean	114	34.82	20.36			9.08	219	7.38	NC	268	5	0.283	0.08	97.59	1.25
Min	10	3.05	1.22			5.50	80	5.56	-130	85	3	0.002	0.03	34.00	0.88
Max	332	101.19	86.87			10.60	464	8.73	233	448	13	5.25	0.35	233.00	1.58
N=	65	65	65	12		65	65	65	65	65	65	65	65	65	65

GCDWQ-MAC	-	-		-	-	-	-	-	-	1.0	-	-	-	-	-
GCDWQ-AO	-	-		500	250	-	-	-	-	-	-	-	-	-	500
RDL	0.50	0.50	0.50	0.50	0.50	0.020	0.020	0.020	0.005	0.002	0.0020	0.020	1.0		10
Units	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	uS/cm	pH	mg/L
RDL	1	0.50	0.50	0.50	0.5	0.020	0.0020	0.020	0.0050	0.0020	0.0020	0.020	1.0		10
Site	Bicarbonate (HCO3)	Carbonate (CO3)	Hydroxide (OH)	Dissolved Sulphate (SO4)	Dissolved Chloride (Cl)	Dissolved Organic Nitrogen (N)	Dissolved Phosphorus (P)	Dissolved Total Kjeldahl Nitrogen (Calc)	Ammonia (N)	Nitrate plus Nitrite (N)	Nitrite (N)	Dissolved Nitrogen (N)	Conductivity (lab)	pH (lab)	Total Dissolved Solids
21	59	<0.50	<0.50	5.18	7.5	0.024	0.0078	0.024	<0.0050	1.35	<0.0020	1.37	137	7.43	80
84	83	<0.50	<0.50	4.53	5.9	<0.020	0.0152	<0.020	0.0053	0.617	<0.0020	0.630	163	8.04	74
92	42	<0.50	<0.50	2.43	3.1	0.130	0.0137	0.136	0.0060	0.443	0.0042	0.579	84.6	7.25	64
2	107	<0.50	<0.50	5.27	5.8	<0.020	0.0541	<0.020	0.0099	0.481	<0.0020	0.486	201	8.07	106
3	175	<0.50	<0.50	2.57	2.6	0.036	0.249	0.201	0.166	0.0134	0.0042	0.215	274	8.17	134
5	119	<0.50	<0.50	20.70	9.4	<0.020	0.0109	<0.020	0.0071	0.245	<0.0020	0.260	259	8.03	130
8	156	<0.50	<0.50	<0.50	2.4	0.028	0.368	0.300	0.271	0.0093	<0.0020	0.309	246	8.14	116
9	95	<0.50	<0.50	6.56	17.0	<0.020	0.0114	<0.020	<0.0050	1.01	<0.0020	1.00	221	7.83	120
12	123	<0.50	<0.50	<0.50	3.7	<0.020	0.286	0.038	0.0218	0.0026	<0.0020	0.041	208	8.13	76
14	104	<0.50	<0.50	6.01	7.8	<0.10	0.0337	<0.10	0.0057	2.64	<0.0020	2.72	220	7.69	116
17	105	<0.50	<0.50	21.40	13.0	0.037	0.0163	0.047	0.0103	1.49	<0.0020	1.54	260	7.70	150
18	144	<0.50	<0.50	<0.50	4.7	0.022	0.292	0.371	0.349	<0.0020	<0.0020	0.371	228	8.20	110
20	114	<0.50	<0.50	7.42	27.0	0.022	0.0065	0.039	0.0174	<0.0020	<0.0020	0.039	286	8.08	152
22	95	<0.50	<0.50	9.44	12.0	<0.020	0.0032	<0.020	0.0052	1.36	<0.0020	1.37	215	7.96	126
23	109	<0.50	<0.50	<0.50	5.0	0.031	0.0834	0.586	0.556	<0.0020	<0.0020	0.586	186	7.89	112
29	60	<0.50	<0.50	11.20	8.4	<0.040	0.0137	<0.040	0.0071	2.24	<0.0020	2.18	162	7.42	96
32	171	<0.50	<0.50	1.64	7.1	0.030	0.456	0.260	0.230	0.0059	<0.0020	0.266	289	8.25	152
34	137	<0.50	<0.50	1.10	8.4	0.033	0.0847	1.01	0.976	<0.0020	<0.0020	1.01	242	8.10	140
35	110	<0.50	<0.50	11.60	13.0	<0.040	0.0259	<0.040	0.0080	2.21	<0.0020	2.22	251	7.85	<10
38	66	<0.50	<0.50	10.40	9.0	<0.020	0.0049	<0.020	<0.0050	1.15	<0.0020	1.15	159	7.06	114
39	244	<0.50	<0.50	11.40	7.7	0.026	0.231	0.370	0.344	0.0035	<0.0020	0.374	417	8.17	254
40	238	<0.50	<0.50	11.30	8.4	0.036	0.214	0.386	0.350	<0.0020	<0.0020	0.386	408	8.13	238
43	170	<0.50	<0.50	<0.50	2.8	0.104	1.24	0.833	0.729	<0.0020	<0.0020	0.833	265	8.18	157
44	105	<0.50	<0.50	<0.50	3.4	0.035	0.170	0.338	0.303	0.0033	<0.0020	0.341	173	7.80	114
45	114	<0.50	<0.50	9.22	10.0	<0.10	0.0071	<0.10	<0.0050	3.52	<0.0020	3.37	252	7.41	162
46	133	<0.50	<0.50	16.20	17.0	<0.020	0.0802	<0.020	<0.0050	1.55	<0.0020	1.56	307	7.83	180
48	145	<0.50	<0.50	9.95	20.0	<0.10	0.0062	<0.10	0.0051	3.90	<0.0020	3.73	338	7.86	212
49	74	<0.50	<0.50	3.04	9.3	<0.10	0.0132	<0.10	0.0071	3.00	<0.0020	2.87	175	7.82	126
50	88	<0.50	<0.50	5.20	9.7	0.036	0.0559	0.041	0.0053	1.66	<0.0020	1.70	199	7.87	122
51	84	<0.50	<0.50	5.76	6.6	<0.020	0.0630	<0.020	<0.0050	0.734	<0.0020	0.729	171	8.06	102
52	172	<0.50	<0.50	<0.50	3.2	0.118	0.973	1.37	1.25	<0.0020	<0.0020	1.37	288	7.97	192
53	76	<0.50	<0.50	7.76	5.5	<0.020	0.0341	<0.020	0.0118	0.208	<0.0020	0.180	152	7.96	112
54	85	<0.50	<0.50	1.85	4.2	<0.020	0.0763	<0.020	0.0057	0.344	<0.0020	0.334	150	7.93	106
55	167	<0.50	<0.50	<0.50	33.0	0.034	0.492	0.410	0.376	<0.0020	<0.0020	0.410	363	8.26	210
56	89	<0.50	<0.50	7.24	6.8	<0.020	0.0207	<0.020	<0.0050	0.851	<0.0020	0.840	183	7.97	122
57	129	<0.50	<0.50	3.98	8.4	<0.020	0.125	0.216	0.202	<0.0020	<0.0020	0.216	240	8.04	151
58	160	<0.50	<0.50	12.20	6.5	<0.020	0.373	0.465	0.450	<0.0020	<0.0020	0.465	295	8.19	174
59	103	<0.50	<0.50	7.18	8.6	<0.10	0.0052	<0.10	<0.0050	3.19	<0.0020	3.01	231	7.51	144
60	132	<0.50	<0.50	13.60	10.0	<0.10	0.0349	<0.10	<0.0050	2.17	<0.0020	2.22	276	8.09	156
61	148	<0.50	<0.50	12.60	9.1	0.131	0.0794	0.131	<0.0050	1.47	<0.0020	1.60	284	8.15	152
62	76	<0.50	<0.50	10.90	11.0	0.023	0.0245	0.032	0.0088	0.103	<0.0020	0.135	176	7.99	114
63	133	<0.50	<0.50	0.71	3.0	0.022	0.262	0.324	0.302	<0.0020	<0.0020	0.324	216	8.26	142
64	150	<0.50	<0.50	14.40	6.0	<0.020	0.0681	<0.020	0.0082	0.0072	<0.0020	0.026	265	8.15	160
66	145	<0.50	<0.50	0.53	4.2	0.027	0.251	0.375	0.348	<0.0020	<0.0020	0.375	233	8.21	156
68	43	<0.50	<0.50	8.71	12.0	0.200	0.0150	0.20	0.0058	2.89	<0.0020	3.10	145	7.24	114
69	156	<0.50	<0.50	<0.50	3.6	0.152	0.687	0.596	0.443	<0.0020	<0.0020	0.596	245	8.09	154
70	100	<0.50	<0.50	6.52	8.1	0.026	0.0128	0.033	0.0067	1.64	<0.0020	1.67	204	8.07	114
71	69	<0.50	<0.50	2.12	14.0	0.030	0.0172	0.037	0.0068	1.46	<0.0020	1.50	173	7.92	96
73	157	<0.50	<0.50	10.80	13.0	0.037	0.370	0.751	0.714	0.0029	0.0023	0.754	318	8.18	186
75	211	1.90	<0.50	12.30	6.9	0.035	0.137	0.273	0.238	0.0028	<0.0020	0.276	370	8.31	207
76	155	<0.50	<0.50	12.00	1.8	0.072	0.143	0.123	0.0514	<0.0020	<0.0020	0.123	262	8.09	168
77	163	<0.50	<0.50	22.30	2.2	0.166	0.0696	0.223	0.0570	<0.0020	<0.0020	0.223	294	8.23	180
78	144	<0.50	<0.50	12.20	15.0	<0.10	0.0351	<0.10	0.0084	2.16	<0.0020	2.11	309	8.16	166
79	74	<0.50	<0.50	1.82	3.9	<0.020	0.0820	0.023	0.0062	0.109	<0.0020	0.131	131	8.03	80
80	86	<0.50	<0.50	13.00	3.8	<0.020	0.0696	<0.020	0.0286	0.0030	<0.0020	<0.020	169	8.06	102
85	161	<0.50	<0.50	<0.50	2.4	0.151	1.45	1.11	0.961	0.0033	<0.0020	1.12	250	8.08	164
86	98	<0.50	<0.50	12.20	10.0	0.125	0.0484	0.159	0.0345	0.881	<0.0020	1.04	212	7.80	136
88	188	1.87	<0.50	7.87	9.4	0.054	0.352	0.282	0.228	<0.0020	<0.0020	0.282	328	8.35	174
89	140	<0.50	<0.50	8.67	16.0	<0.10	0.0310	<0.10	<0.0050	3.83	<0.0020	3.85	306	7.97	176
90	119	1.06	<0.50	11.60	8.3	<0.020	0.142	0.193	0.177	0.0020	<0.0020	0.195	239	8.32	149
91	285	<0.50	<0.50	6.15	10.0	0.038	0.191	0.093	0.0544	<0.0020	<0.0020	0.093	458	8.30	234
93	111	<0.50	<0.50	9.64	9.9	<0.10	0.0044	<0.10	0.0063	5.25	<0.0020	5.11	273	7.65	150
94	215	1.33	<0.50	<0.50	22.0	0.067	0.704	0.542	0.476	0.0325	0.0035	0.575	410	8.32	242
95	125	<0.50	<0.50	2.87	19.0	<0.020	0.0186	0.026	0.0098	1.68	<0.0020	1.71	271	7.75	172
96	188	<0.50	<0.50	<0.50	4.0	<0.020	0.606	0.315	0.310	<0.0020	<0.0020	0.315	307	8.22	178
Arithmetic mean	128	1.54	NC	8.55	8.96	0.06	0.19	0.32	0.21	1.23	NC	1.10	247	7.97	145
Median	123	1.60	NC	8.67	8.30	0.04	0.07	0.26	0.04	0.88	NC	0.61	245	8.06	147
Geometric mean	119	1.50	NC	6.61	7.34	0.05	0.06	0.19	0.05	0.26	NC	0.63	235	7.97	139
Min	42	1.06	NC	0.53	1.80	0.02	0.00	0.02	0.01	0.00	0.002	0.03	85	7.06	64
Max	285	1.90	NC	22.3	33.0	0.20	1.45	1.37	1.25	5.25	0.004	5.11	458	8.35	254
N=	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65

GCDWQ-MAC	-	-	500	-	6	10	1000	-	-	5000	5	50	-	-	-	10
GCDWQ-AO	-	-	-	100	-	-	-	-	-	-	-	-	-	1000	300	-
RDL	0.10	0.10	0.50	0.50	0.020	0.020	0.020	0.010	0.005	50	0.005	0.10	0.0050	0.050	1.0	0.0050
Units	NTU	mg/L	mg/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L
RDL	0.10	0.1	0.50	0.50	0.020	0.020	0.020	0.010	0.0050	50	0.0050	0.10	0.0050	0.050	1.0	0.0050
Site	Turbidity	Bromide (Br)	Dissolved Hardness (CaCO3)	Dissolved Aluminum (Al)	Dissolved Antimony (Sb)	Dissolved Arsenic (As)	Dissolved Barium (Ba)	Dissolved Beryllium (Be)	Dissolved Bismuth (Bi)	Dissolved Boron (B)	Dissolved Cadmium (Cd)	Dissolved Chromium (Cr)	Dissolved Cobalt (Co)	Dissolved Copper (Cu)	Dissolved Iron (Fe)	Dissolved Lead (Pb)
21	<0.10	0.014	53.0	1.16	0.033	0.090	4.13	<0.010	<0.0050	<50	<0.0050	0.14	0.0100	4.21	<1.0	0.430
84	0.15	0.013	69.7	1.97	0.025	0.532	3.03	<0.010	<0.0050	<50	<0.0050	1.35	<0.0050	7.37	2.0	0.338
92	10.2	<0.010	33.1	26.2	<0.020	0.093	1.54	<0.010	<0.0050	<50	<0.0050	0.16	0.0310	8.57	41.1	0.0520
2	0.38	0.017	90.9	1.04	<0.020	1.12	5.47	<0.010	<0.0050	<50	<0.0050	0.39	0.0060	5.23	24.8	0.0950
3	3.75	0.011	128	1.08	0.023	0.254	6.68	<0.010	<0.0050	<50	<0.0050	<0.10	0.0070	0.815	36.6	0.101
5	1.11	0.033	122	0.87	<0.020	0.261	8.17	<0.010	<0.0050	<50	<0.0050	1.40	0.0130	0.320	45.0	0.0540
8	1.41	0.012	111	2.22	<0.020	0.845	10.9	<0.010	<0.0050	<50	<0.0050	<0.10	0.0110	<0.050	386	0.0430
9	0.17	0.025	98.9	1.01	<0.020	0.321	3.89	<0.010	<0.0050	<50	<0.0050	0.46	0.0050	8.03	3.9	0.207
12	1.09	0.027	89.7	0.93	<0.020	1.62	3.32	<0.010	<0.0050	<50	<0.0050	<0.10	0.027	0.094	180	0.0120
14	0.17	0.031	93.0	3.27	0.020	0.315	3.49	<0.010	<0.0050	<50	<0.0050	0.39	0.0180	4.45	2.7	0.179
17	0.77	0.028	112	0.65	0.030	0.198	8.75	<0.010	<0.0050	<50	<0.0050	<0.10	0.0180	2.82	33.5	0.240
18	0.17	0.020	44.3	1.43	<0.020	0.421	32.7	<0.010	<0.0050	69	<0.0050	<0.10	0.0050	0.140	68.2	0.0180
20	4.04	0.054	125	0.76	<0.020	0.393	17.0	<0.010	<0.0050	<50	<0.0050	<0.10	0.0160	<0.050	13.2	<0.0050
22	0.64	0.025	91.3	0.69	<0.020	0.251	4.29	<0.010	<0.0050	<50	<0.0050	0.34	0.0290	1.08	28.6	0.376
23	1.58	<0.010	80.4	1.24	<0.020	0.339	11.4	<0.010	<0.0050	<50	<0.0050	<0.10	<0.0050	0.053	**814**	0.0080
29	<0.10	0.011	65.4	0.89	<0.020	0.215	1.82	<0.010	<0.0050	<50	<0.0050	0.41	0.0130	2.02	<1.0	0.357
32	5.98	0.025	103	1.13	<0.020	1.98	34.5	<0.010	<0.0050	83	<0.0050	<0.10	0.0090	0.132	72.3	0.0700
34	1.88	0.018	111	24.1	<0.020	0.424	13.1	<0.010	<0.0050	<50	<0.0050	<0.10	0.0150	<0.050	**561**	0.0300
35	<0.10	0.029	109	3.20	<0.020	0.154	4.47	<0.010	<0.0050	<50	<0.0050	0.39	0.0160	0.968	3.9	0.0920
38	2.40	0.013	59.6	1.08	<0.020	0.113	3.35	<0.010	<0.0050	<50	<0.0050	0.21	0.0220	3.16	60.4	0.202
39	0.18	0.032	178	1.15	<0.020	**10.4**	21.4	<0.010	<0.0050	65	0.0050	<0.10	0.0060	0.126	42.7	0.0690
40	0.34	0.033	161	0.96	<0.020	7.97	23.8	<0.010	<0.0050	78	<0.0050	<0.10	0.0080	4.55	39.5	0.0330
43	5.29	0.012	116	1.63	<0.020	5.17	16.4	<0.010	<0.0050	<50	<0.0050	0.14	0.0070	0.063	**1480**	0.0180
44	5.04	0.014	75.7	1.10	<0.020	0.144	11.7	<0.010	<0.0050	<50	<0.0050	<0.10	<0.0050	0.074	**1700**	0.0100
45	0.15	0.024	110	0.59	<0.020	0.069	3.83	<0.010	<0.0050	<50	0.0050	0.20	<0.0050	1.19	8.5	0.334
46	0.20	0.065	132	0.84	0.042	0.883	5.37	<0.010	<0.0050	<50	0.0330	<0.10	0.0150	0.620	7.2	0.204
48	0.14	0.095	152	0.77	<0.020	0.097	4.37	<0.010	<0.0050	<50	<0.0050	0.51	<0.0050	0.408	4.4	0.0550
49	0.15	0.020	74.9	9.84	<0.020	0.380	2.83	<0.010	<0.0050	<50	<0.0050	2.91	0.0110	0.526	9.1	0.181
50	<0.10	0.015	80.0	1.43	0.040	2.05	2.69	<0.010	<0.0050	<50	<0.0050	2.04	<0.0050	0.500	1.7	0.0690
51	0.45	0.014	67.4	1.50	0.066	2.33	2.42	<0.010	<0.0050	<50	<0.0050	2.34	<0.0050	0.632	1.7	0.187
52	5.00	0.020	115	1.22	<0.020	3.20	19.1	<0.010	<0.0050	<50	<0.0050	<0.10	0.0050	<0.050	**1140**	0.0160
53	<0.10	0.020	66.1	25.5	0.031	1.72	2.89	<0.010	<0.0050	<50	<0.0050	2.79	<0.0050	0.190	2.9	0.0370
54	<0.10	0.010	63.7	1.61	0.049	2.82	3.77	<0.010	<0.0050	<50	<0.0050	5.16	0.0060	0.359	1.5	0.0960
55	0.15	0.054	76.9	1.48	<0.020	1.91	59.2	<0.010	<0.0050	59	<0.0050	<0.10	0.0050	<0.050	126	0.0170
56	<0.10	0.019	87.1	1.11	0.030	1.25	3.49	<0.010	<0.0050	<50	<0.0050	1.48	<0.0050	0.115	3.5	0.0290
57	4.03	0.021	112	1.38	<0.020	0.088	19.5	<0.010	<0.0050	<50	<0.0050	<0.10	<0.0050	<0.050	**889**	0.0510
58	0.33	0.021	131	1.83	<0.020	0.135	19.5	<0.010	<0.0050	<50	<0.0050	<0.10	<0.0050	0.061	178	0.0110
59	<0.10	0.019	103	0.57	<0.020	0.071	2.75	<0.010	<0.0050	<50	<0.0050	0.11	0.0100	0.798	<1.0	0.136
60	0.15	0.027	117	0.78	0.021	0.722	4.72	<0.010	<0.0050	<50	<0.0050	0.52	0.0130	0.779	8.1	0.0930
61	0.62	<0.010	125	1.08	0.032	0.330	5.91	<0.010	<0.0050	<50	<0.0050	1.25	0.0050	0.588	8.9	0.0540
62	0.15	0.019	70.4	0.75	0.024	0.624	5.19	<0.010	<0.0050	<50	<0.0050	1.33	0.0060	2.73	9.5	0.0790
63	0.27	0.013	56.5	2.13	<0.020	0.537	41.4	<0.010	<0.0050	<50	0.0050	<0.10	<0.0050	<0.050	68.1	0.0170
64	1.40	0.012	120	0.98	<0.020	0.882	6.44	<0.010	<0.0050	<50	<0.0050	<0.10	0.0140	0.121	39.6	0.0080
66	0.28	0.015	50.2	3.34	<0.020	0.657	49.4	<0.010	<0.0050	60	0.0060	<0.10	<0.0050	<0.050	46.0	0.0680
68	<0.10	0.016	52.3	0.75	<0.020	0.069	2.19	<0.010	<0.0050	<50	<0.0050	0.54	0.0140	1.97	3.9	0.0800
69	4.66	0.016	121	0.82	<0.020	1.73	19.8	<0.010	<0.0050	<50	<0.0050	<0.10	0.0110	<0.050	**1060**	0.0150
70	0.15	0.020	85.1	0.81	<0.020	0.539	5.23	<0.010	<0.0050	<50	<0.0050	0.91	<0.0050	1.98	3.8	0.104
71	1.11	0.026	67.0	0.92	0.032	0.934	3.17	<0.010	<0.0050	<50	0.0060	2.19	<0.0050	1.31	19.9	0.0840
73	18.2	0.033	137	0.85	<0.020	0.678	26.7	<0.010	<0.0050	<50	0.0080	<0.10	<0.0050	0.050	**2150**	0.0170
75	6.08	0.027	157	0.61	<0.020	3.82	15.0	<0.010	<0.0050	<50	<0.0050	<0.10	<0.0050	<0.050	**684**	0.0050
76	1.92	0.010	119	1.07	<0.020	4.65	7.93	<0.010	<0.0050	<50	<0.0050	<0.10	0.0050	<0.050	239	<0.0050
77	0.34	0.012	118	0.94	<0.020	2.76	34.7	<0.010	<0.0050	<50	<0.0050	<0.10	<0.0050	0.127	91.5	<0.0050
78	0.64	0.035	126	0.59	0.022	0.470	9.48	<0.010	<0.0050	<50	<0.0050	0.76	0.0070	0.475	13.0	0.111
79	0.14	0.013	54.3	1.90	0.056	2.70	3.18	<0.010	<0.0050	<50	<0.0050	5.23	<0.0050	0.460	3.5	0.0520
80	0.25	0.011	64.9	3.24	0.070	3.66	4.64	<0.010	<0.0050	<50	<0.0050	<0.10	<0.0050	0.161	13.6	0.0050
85	5.01	0.013	110	1.57	<0.020	7.89	12.7	<0.010	<0.0050	<50	<0.0050	0.14	0.0060	0.103	**1570**	0.0180
86	1.32	0.024	91.7	0.78	<0.020	0.340	7.17	<0.010	<0.0050	<50	<0.0050	<0.10	0.0200	4.03	224	0.141
88	0.35	0.025	143	1.52	<0.020	8.49	16.8	<0.010	<0.0050	<50	<0.0050	<0.10	0.0100	0.050	86.7	0.0150
89	1.46	0.027	128	0.73	0.027	0.405	9.06	<0.010	<0.0050	<50	<0.0050	0.46	0.0170	8.61	10.6	0.0530
90	0.23	0.033	45.0	1.47	<0.020	3.28	81.1	<0.010	<0.0050	<50	<0.0050	<0.10	<0.0050	0.165	26.1	0.0130
91	0.17	0.044	217	0.97	0.032	7.71	6.05	<0.010	<0.0050	<50	0.0090	<0.10	0.0230	0.369	46.4	0.0180
93	<0.10	0.019	112	0.54	<0.020	0.066	3.19	<0.010	<0.0050	<50	0.0060	<0.10	0.0070	2.01	<1.0	1.26
94	2.04	0.062	35.2	4.05	<0.020	**17.3**	104	<0.010	<0.0050	226	<0.0050	<0.10	0.0090	0.181	40.4	0.0540
95	0.17	0.022	117	1.08	<0.020	0.103	1.59	<0.010	<0.0050	<50	0.0070	0.32	0.0220	1.55	24.0	0.116
96	1.37	0.021	107	1.01	<0.020	2.05	6.87	<0.010	<0.0050	65	<0.0050	<0.10	0.0090	<0.050	**388**	<0.0050
Arithmetic mean	1.92	0.02	99.06	2.53	0.04	1.91	13.86	NC	NC	88	0.009	1.16	0.01	1.65	244	0.114
Median	0.64	0.02	103.00	1.08	0.03	0.62	6.44	NC	NC	67	0.006	0.52	0.01	0.59	39.5	0.055
Geometric mean	0.74	0.02	92.39	1.37	0.03	0.71	7.94	NC	NC	79	0.007	0.65	0.01	0.60	39.1	0.056
Min	0.14	0.01	33.10	0.54	0.02	0.07	1.54	NC	NC	59	0.005	0.11	0.01	0.05	1.5	0.005
Max	18.20	0.10	217.00	26.20	0.07	17.30	104.00	NC	NC	226	0.033	5.23	0.03	8.61	2150	1.26
N=	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65

GCDWQ-MAC	-	120	-	-	10	-	-	-	-	-	-	20	-	-	-
GCDWQ-AO	-	20	-	-	-	-	-	-	-	-	-	-	-	5000	-
RDL	0.50	0.050	0.05	0.020	0.040	100	0.0050	0.050	0.0020	0.20	0.50	0.0020	0.20	0.10	0.10
Units	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L
RDL	0.50	0.050	0.050	0.020	0.040	100	0.0050	0.050	0.0020	0.20	0.50	0.0020	0.20	0.10	0.10
Site	Dissolved Lithium (Li)	Dissolved Manganese (Mn)	Dissolved Molybdenum (Mo)	Dissolved Nickel (Ni)	Dissolved Selenium (Se)	Dissolved Silicon (Si)	Dissolved Silver (Ag)	Dissolved Strontium (Sr)	Dissolved Thallium (Tl)	Dissolved Tin (Sn)	Dissolved Titanium (Ti)	Dissolved Uranium (U)	Dissolved Vanadium (V)	Dissolved Zinc (Zn)	Dissolved Zirconium (Zr)
21	<0.50	0.346	0.068	0.105	0.053	11700	<0.0050	48.3	<0.0020	<0.20	<0.50	0.0070	1.16	3.39	<0.10
84	<0.50	0.109	0.101	0.101	0.170	10200	<0.0050	52.4	<0.0020	<0.20	<0.50	0.0460	4.06	3.69	<0.10
92	<0.50	0.976	<0.050	0.240	0.076	7300	<0.0050	37.9	<0.0020	<0.20	2.23	0.0040	0.51	3.90	<0.10
2	0.59	1.73	0.182	0.977	0.191	12300	<0.0050	126	<0.0020	<0.20	<0.50	0.0400	2.68	2.22	<0.10
3	<0.50	**186**	0.335	1.34	<0.040	11500	<0.0050	87.2	<0.0020	<0.20	<0.50	0.0030	<0.20	28.6	<0.10
5	0.52	4.99	0.198	0.216	0.235	10300	<0.0050	69.7	<0.0020	<0.20	<0.50	0.213	2.19	75.5	<0.10
8	<0.50	**185**	0.294	0.032	<0.040	11900	<0.0050	88.5	<0.0020	<0.20	<0.50	0.0100	0.27	3.86	<0.10
9	<0.50	1.07	0.090	0.058	0.085	10200	<0.0050	64.2	<0.0020	<0.20	<0.50	0.0400	2.02	3.21	<0.10
12	1.08	**170**	0.877	0.193	<0.040	9410	<0.0050	106	<0.0020	0.30	<0.50	0.268	1.43	0.96	<0.10
14	0.59	0.953	0.133	0.138	0.160	10600	<0.0050	64.8	<0.0020	<0.20	<0.50	0.0260	2.11	2.38	<0.10
17	<0.50	14.9	0.847	0.244	0.086	9110	<0.0050	77.3	<0.0020	<0.20	<0.50	0.229	1.04	6.31	<0.10
18	0.75	**30.5**	1.45	0.076	<0.040	7960	<0.0050	259	<0.0020	<0.20	<0.50	<0.0020	<0.20	2.06	<0.10
20	<0.50	**220**	0.152	0.058	<0.040	9740	<0.0050	205	<0.0020	0.40	<0.50	0.0050	<0.20	0.98	<0.10
22	<0.50	1.36	0.188	10.4	0.262	10400	<0.0050	58.2	<0.0020	<0.20	<0.50	0.0710	2.09	2.16	<0.10
23	<0.50	**156**	0.106	0.094	<0.040	13200	<0.0050	63.1	<0.0020	0.30	<0.50	<0.0020	<0.20	2.84	<0.10
29	<0.50	0.088	0.094	0.067	0.066	11400	<0.0050	49.9	<0.0020	<0.20	<0.50	0.0030	0.94	4.45	<0.10
32	1.11	**61.1**	1.49	0.249	<0.040	8870	<0.0050	118	<0.0020	<0.20	<0.50	0.0050	<0.20	0.88	<0.10
34	<0.50	**460**	0.103	0.125	<0.040	14000	<0.0050	73.6	<0.0020	<0.20	<0.50	<0.0020	<0.20	1.83	<0.10
35	<0.50	3.88	0.243	0.190	0.215	11600	<0.0050	65.2	<0.0020	<0.20	<0.50	0.0560	1.67	0.56	<0.10
38	0.89	3.26	<0.050	0.241	0.050	11600	<0.0050	52.1	0.0040	<0.20	<0.50	0.0080	0.94	1.42	<0.10
39	<0.50	**125**	0.606	0.145	<0.040	8390	<0.0050	220	<0.0020	<0.20	<0.50	0.0510	<0.20	17.7	<0.10
40	<0.50	**127**	0.853	0.214	<0.040	8330	<0.0050	209	<0.0020	<0.20	<0.50	0.0940	<0.20	6.40	<0.10
43	<0.50	**311**	0.390	0.052	<0.040	13700	<0.0050	113	<0.0020	<0.20	0.58	<0.0020	0.39	0.81	<0.10
44	<0.50	**164**	0.310	0.236	<0.040	11900	<0.0050	74.2	<0.0020	<0.20	<0.50	<0.0020	0.36	3.51	<0.10
45	0.71	0.312	0.110	0.157	0.171	11100	<0.0050	89.3	<0.0020	<0.20	<0.50	0.0410	0.95	2.16	<0.10
46	<0.50	0.538	9.22	0.121	0.649	8370	0.0070	252	0.0140	<0.20	<0.50	2.08	5.54	219	<0.10
48	<0.50	0.282	0.127	0.147	0.102	10700	<0.0050	87.3	<0.0020	<0.20	<0.50	0.0900	2.04	4.59	<0.10
49	<0.50	0.725	0.065	0.089	0.078	12000	<0.0050	68.4	<0.0020	<0.20	<0.50	0.0430	4.18	2.24	<0.10
50	0.91	0.060	0.385	0.082	0.148	8970	<0.0050	95.5	<0.0020	<0.20	<0.50	0.222	6.72	7.46	<0.10
51	0.86	0.108	0.653	0.025	0.251	8230	<0.0050	84.9	<0.0020	<0.20	<0.50	0.213	7.68	11.8	<0.10
52	<0.50	**244**	0.544	0.027	<0.040	11600	<0.0050	122	<0.0020	<0.20	<0.50	<0.0020	0.43	1.05	<0.10
53	<0.50	3.58	0.210	0.040	0.221	9690	<0.0050	47.6	<0.0020	<0.20	<0.50	0.106	7.65	2.34	<0.10
54	0.68	0.505	0.131	<0.020	0.160	10300	<0.0050	56.9	<0.0020	<0.20	<0.50	0.184	8.16	4.19	<0.10
55	8.62	**125**	0.602	0.045	<0.040	9380	<0.0050	384	<0.0020	<0.20	<0.50	<0.0020	<0.20	0.51	<0.10
56	0.74	0.128	0.266	0.070	0.487	11500	<0.0050	70.7	<0.0020	<0.20	<0.50	0.280	6.35	2.72	<0.10
57	<0.50	**138**	0.286	0.033	<0.040	13000	<0.0050	89.3	<0.0020	<0.20	<0.50	<0.0020	0.26	3.04	<0.10
58	<0.50	**114**	0.680	0.033	<0.040	11300	0.0080	168	<0.0020	<0.20	<0.50	<0.0020	0.43	1.37	<0.10
59	<0.50	0.078	0.107	0.111	0.114	11000	<0.0050	84.9	<0.0020	<0.20	<0.50	0.0160	0.80	1.30	<0.10
60	<0.50	0.920	0.671	3.46	0.354	9550	<0.0050	85.4	<0.0020	<0.20	<0.50	0.264	3.03	124	<0.10
61	0.50	0.951	0.493	0.053	1.38	8320	<0.0050	80.6	<0.0020	<0.20	<0.50	0.472	4.80	1.27	<0.10
62	<0.50	2.96	0.291	0.075	0.311	9070	<0.0050	49.5	<0.0020	<0.20	<0.50	0.169	2.82	4.99	<0.10
63	0.99	**48.7**	0.711	0.030	<0.040	9800	<0.0050	349	<0.0020	<0.20	<0.50	<0.0020	<0.20	8.05	<0.10
64	<0.50	**36.8**	0.565	0.492	0.059	7020	<0.0050	92.8	<0.0020	<0.20	<0.50	0.902	1.40	1.70	<0.10
66	1.57	**49.4**	0.969	<0.020	<0.040	8890	<0.0050	311	<0.0020	<0.20	<0.50	<0.0020	<0.20	4.07	<0.10
68	0.91	0.419	<0.050	0.186	0.041	12700	<0.0050	74.9	<0.0020	<0.20	<0.50	<0.0020	0.71	2.06	<0.10
69	<0.50	**285**	0.246	0.136	<0.040	15000	<0.0050	251	<0.0020	<0.20	<0.50	<0.0020	0.25	109	<0.10
70	<0.50	1.06	0.274	0.088	0.578	9020	<0.0050	53.3	<0.0020	<0.20	<0.50	0.281	2.86	2.83	<0.10
71	<0.50	2.31	0.085	0.128	0.067	9380	<0.0050	58.0	<0.0020	<0.20	<0.50	0.0660	4.78	2.64	<0.10
73	<0.50	**452**	0.517	0.170	<0.040	11200	<0.0050	122	<0.0020	<0.20	<0.50	<0.0020	<0.20	83.8	<0.10
75	<0.50	**301**	1.20	0.071	<0.040	11700	<0.0050	145	<0.0020	<0.20	<0.50	0.0240	<0.20	8.66	<0.10
76	<0.50	**89.9**	0.631	0.035	<0.040	9030	<0.0050	88.6	<0.0020	<0.20	<0.50	<0.0020	<0.20	5.86	<0.10
77	<0.50	**103**	0.826	0.034	<0.040	9830	<0.0050	229	<0.0020	<0.20	<0.50	0.0020	<0.20	1.24	<0.10
78	<0.50	1.40	0.784	0.086	0.558	9430	<0.0050	103	<0.0020	<0.20	<0.50	0.598	2.01	14.2	<0.10
79	0.64	0.259	0.159	0.056	0.160	10200	<0.0050	53.7	<0.0020	<0.20	<0.50	0.120	8.05	3.21	<0.10
80	<0.50	**22.1**	0.386	0.029	<0.040	6000	<0.0050	84.3	<0.0020	<0.20	<0.50	0.352	2.38	0.26	<0.10
85	<0.50	**332**	0.214	0.063	<0.040	14700	<0.0050	108	<0.0020	<0.20	<0.50	<0.0020	0.68	157	<0.10
86	0.89	**27.8**	0.199	0.519	0.054	11700	<0.0050	56.8	<0.0020	<0.20	<0.50	0.0460	1.30	2.45	<0.10
88	<0.50	**132**	0.749	0.053	<0.040	9270	<0.0050	77.4	<0.0020	<0.20	<0.50	0.0100	<0.20	0.61	<0.10
89	0.53	1.06	0.174	0.173	0.405	9560	<0.0050	95.9	<0.0020	<0.20	<0.50	0.131	1.63	6.31	<0.10
90	1.06	**36.0**	0.131	0.029	<0.040	7970	<0.0050	466	<0.0020	<0.20	<0.50	<0.0020	<0.20	0.63	<0.10
91	1.25	**460**	0.221	0.514	0.259	9300	<0.0050	116	<0.0020	<0.20	<0.50	0.0490	1.93	0.43	<0.10
93	0.65	0.162	0.091	0.178	0.110	11000	<0.0050	98.0	<0.0020	<0.20	<0.50	0.0140	0.50	2.01	<0.10
94	3.31	**20.4**	1.57	0.283	<0.040	6670	<0.0050	211	<0.0020	0.23	<0.50	0.0130	0.25	2.95	<0.10
95	<0.50	1.16	0.098	0.122	0.100	12600	<0.0050	94.0	0.0040	<0.20	<0.50	0.0190	1.83	3.76	<0.10
96	<0.50	**155**	0.904	0.066	<0.040	11000	<0.0050	133	<0.0020	<0.20	<0.50	<0.0020	<0.20	0.11	<0.10
Arithmetic mean	1.26	83.39	0.575	0.379	0.24	10349	0.008	120	0.007	0.308	1.41	0.170	2.47	15.3	NC
Median	0.88	14.90	0.289	0.105	0.16	10200	0.008	89	0.004	0.300	1.41	0.051	1.83	2.84	NC
Geometric mean	0.94	8.75	0.318	0.119	0.16	10178	0.007	99	0.006	0.302	1.14	0.053	1.56	3.47	NC
Min	0.50	0.06	0.065	0.025	0.04	6000	0.007	38	0.004	0.230	0.58	0.002	0.250	0.110	NC
Max	8.62	460	9.22	10.4	1.38	15000	0.008	466	0.014	0.400	2.23	2.08	8.16	219	NC
N=	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65

GCDWQ-MAC	-	-	-	-	-										
GCDWQ-AO	-	-	-	200	-										
RDL	0.050	0.050	0.050	0.050	3.0										
Units	mg/L	mg/L	mg/L	mg/L	mg/L	meq	meq	%	‰	‰	‰	‰	‰	‰	$\log_{10}$ years
RDL	0.050	0.050	0.050	0.050	3.0	-	-	-	Result 1	Result 2	Median	Result 1	Result 2	Median	
Site	Dissolved Calcium (Ca)	Dissolved Magnesium (Mg)	Dissolved Potassium (K)	Dissolved Sodium (Na)	Dissolved Sulphur (S)	Sum cations	Sum anions	Charge balance error	$\delta^{15}N$	$\delta^{15}N$	$\delta^{15}N$	$\delta^{18}O$	$\delta^{18}O$	$\delta^{18}O$	Aquifer Vulnerability Index, hydraulic resistance, c
21	13.9	4.46	0.563	6.46	<3.0	1.4	-1.4	-0.9							0.0
84	14.7	8.03	0.574	4.85	<3.0	1.6	-1.7	-1.3							nc
92	7.83	3.29	0.399	3.49	<3.0	0.8	-0.8	-1.6							nc
2	20.6	9.61	1.03	6.80	<3.0	2.1	-2.1	1.9							4.2
3	26.1	15.3	1.21	8.98	<3.0	3.0	-3.0	-0.2							7.0
5	26.1	13.7	1.17	8.56	9.2	2.8	-2.7	3.1							3.0
8	23.6	12.7	1.21	9.42	<3.0	2.7	-2.6	0.5							4.2
9	24.0	9.48	0.623	5.99	<3.0	2.3	-2.2	0.2							3.8
12	24.6	6.89	0.676	8.52	<3.0	2.2	-2.1	1.2							5.9
14	20.5	10.1	0.838	7.45	<3.0	2.2	-2.2	-0.9	10.25	10.56	10.41	1.27	1.23	1.25	0.0
17	24.5	12.3	1.80	8.36	7.2	2.6	-2.6	0.1							3.9
18	14.0	2.30	1.08	34.3	<3.0	2.4	-2.5	-1.9							7.5
20	24.3	15.6	1.26	7.25	<3.0	2.8	-2.8	1.0							3.4
22	22.1	8.78	0.584	6.28	<3.0	2.1	-2.2	-1.8							3.4
23	18.7	8.15	1.05	5.21	<3.0	1.9	-1.9	-2.1							nc
29	15.4	6.56	0.764	5.95	<3.0	1.6	-1.6	-0.6	8.96	9.09	9.03	-1.24	-1.57	-1.40	6.2
32	23.9	10.6	3.73	22.2	<3.0	3.1	-3.0	1.4							7.1
34	27.9	10.0	1.21	5.28	<3.0	2.5	-2.5	-0.6							5.3
35	26.4	10.4	0.767	7.77	<3.0	2.5	-2.6	-0.7	13.46	13.61	13.54	0.40	0.84	0.62	3.3
38	15.2	5.26	0.407	6.75	<3.0	1.5	-1.6	-4.3							4.1
39	43.4	16.9	5.24	16.8	4.0	4.4	-4.5	-0.4							5.0
40	40.4	14.5	4.44	21.6	4.2	4.3	-4.4	-1.3							5.4
43	24.7	13.3	1.70	11.1	<3.0	2.9	-2.9	-0.4							4.7
44	18.7	7.07	0.756	5.91	<3.0	1.8	-1.8	-1.0							6.9
45	25.7	11.2	0.891	7.76	3.1	2.6	-2.6	-0.6	6.09	6.26	6.18	-2.54	-2.47	-2.50	6.2
46	40.1	7.81	0.571	8.78	5.3	3.0	-3.1	-1.1							4.4
48	48.9	7.32	0.426	6.61	3.7	3.3	-3.4	-1.3	8.61	8.83	8.72	-2.11	-2.11	-2.11	1.7
49	17.3	7.71	0.521	5.82	<3.0	1.8	-1.8	0.2	4.71	4.31	4.51	-3.43	-2.82	-3.12	1.5
50	22.3	5.88	0.809	6.68	<3.0	1.9	-1.9	-0.7							4.2
51	19.7	4.44	0.820	6.91	<3.0	1.7	-1.7	-1.7							6.3
52	29.1	10.2	1.06	13.8	<3.0	2.9	-2.9	0.0							3.5
53	14.4	7.28	0.685	5.34	<3.0	1.6	-1.6	-0.5							4.0
54	14.9	6.42	0.886	6.14	<3.0	1.6	-1.6	-0.2							7.1
55	17.3	8.19	0.871	51.4	<3.0	3.8	-3.7	1.6							6.0
56	18.8	9.74	0.759	6.47	3.0	2.0	-1.9	4.8							4.1
57	25.4	11.8	1.28	9.86	<3.0	2.7	-2.4	*5.2*							0.8
58	33.1	11.8	2.04	9.44	4.8	3.1	-3.1	0.4							3.5
59	25.6	9.58	0.833	7.48	<3.0	2.4	-2.3	2.2	4.81	5.17	4.99	-3.66	-3.00	-3.33	1.3
60	24.8	13.4	1.58	9.86	3.9	2.8	-2.9	-1.3	7.37	7.20	7.28	-1.49	-2.18	-1.84	5.5
61	27.0	13.9	0.979	8.37	3.4	2.9	-3.0	-2.9							6.3
62	16.5	7.05	0.823	6.12	3.1	1.7	-1.8	-2.8							6.9
63	18.1	2.76	0.993	24.8	<3.0	2.2	-2.3	-1.0							6.7
64	26.5	13.2	1.04	9.69	3.8	2.9	-2.9	-1.2							0.0
66	16.3	2.33	1.01	31.9	<3.0	2.4	-2.5	-1.8							6.8
68	14.5	3.91	0.420	8.64	<3.0	1.4	-1.4	0.1	7.62	7.05	7.33	-3.05	-2.95	-3.00	4.8
69	30.6	11.0	0.841	8.76	<3.0	2.8	-2.7	3.0							5.4
70	17.1	10.3	0.747	6.01	<3.0	2.0	-2.1	-3.4							3.8
71	14.4	7.52	0.639	5.12	<3.0	1.6	-1.7	-2.9							5.7
73	30.2	14.8	1.42	8.86	5.1	3.1	-3.2	-0.3							5.1
75	34.6	17.2	1.54	15.2	4.2	3.8	-3.9	-0.9							4.2
76	24.4	14.1	1.03	8.52	3.4	2.8	-2.8	-1.2							6.5
77	32.5	8.88	0.943	15.1	6.4	3.0	-3.2	-2.6							6.9
78	27.8	13.7	1.59	10.8	4.2	3.0	-3.2	-2.7	11.00	11.14	11.07	-0.72	-0.91	-0.81	0.8
79	13.0	5.32	0.794	5.01	<3.0	1.3	-1.4	-1.4							1.7
80	23.4	1.56	1.37	7.48	3.3	1.7	-1.8	-3.9							6.0
85	24.0	12.2	1.54	9.00	<3.0	2.6	-2.7	-1.6							7.1
86	21.1	9.51	0.916	7.83	3.7	2.2	-2.2	-0.2							5.2
88	29.4	16.8	2.63	12.8	<3.0	3.5	-3.5	-0.5							5.9
89	26.5	15.1	0.896	7.95	<3.0	2.9	-3.2	-4.3	11.42	11.31	11.36	0.25	0.29	0.27	5.2
90	13.7	2.65	0.503	32.9	3.2	2.3	-2.4	-1.7							5.8
91	41.5	27.6	1.81	15.5	<3.0	5.1	-5.1	-0.2							6.8
93	27.2	10.7	0.927	9.26	3.3	2.7	-2.7	-0.2	9.27	9.57	9.42	-2.75	-3.24	-3.00	-0.9
94	8.76	3.23	2.71	84.3	<3.0	4.4	-4.2	3.3							0.0
95	24.9	13.4	0.544	7.08	<3.0	2.7	-2.8	-1.8							4.4
96	23.6	11.7	2.73	22.5	<3.0	3.2	-3.2	-0.2							3.8
Arithmetic mean	23.5	9.82	1.21	12.11	4.34				8.63	8.68	8.65	-1.59	-1.57	-1.58	4.44
Median	24.0	9.74	0.93	8.37	3.85				8.78	8.96	8.87	-1.80	-2.15	-1.97	4.74
Geometric mean	22.1	8.60	1.01	9.53	4.14				8.23	8.24	8.24	NC	NC	NC	NC
Min	7.83	1.56	0.40	3.49	3.00				4.71	4.31	4.51	-3.66	-3.24	-3.33	-0.88
Max	48.9	27.6	5.24	84.30	9.20				13.46	13.61	13.54	1.27	1.23	1.25	7.54
N=	65	65	65	65	65				12	12	12	12	12	12	65

APPENDIX A - TABLE A1

GCDWQ-MAC						-	-		-	-	-	10	1.5	-	-
GCDWQ-AO						-	-	7.0-10.5	-	-	-	-	-	-	-
RDL												0.002	0.010	0.50	0.50
Units	ft	m	m			°C	µS/cm	pH units	mv	mv	minutes	mg/L	mg/L	mg/L	mg/L
RDL												0.002	0.010	1	0.50
Site	Well Depth (ft)	Well depth (m)	Static water level	Local Water Service Provider	Lithology	Temperature (field)	Specific conductivity (field)	pH (field)	Oxidation Reduction Potential (field)	Eh (calc)	Purge duration	Nitrate (N)	Fluoride (F)	Alkalinity (Total as CaCO3)	Alkalinity (PP as CaCO3)
1	265	80.77	41.15	N	Bedrock	9.8	334	8.62	nr	nr	5	<0.0020	0.220	160	3.85
4	530	161.54	21.34	N	Bedrock	10.1	6.8*	8.41	-113	102	7	0.003	0.760	175	2.67
6	507	154.53	UNK	N	Bedrock	7.9	205	8.40	nr	nr	7	<0.0020	0.110	99	<0.50
10	150	45.72	2.13	N	Bedrock	10.4	355	**6.80**	108	323	10	0.021	0.040	151	<0.50
13	268	81.69	UNK	N	Bedrock	10	3.4*	8.29	197	412	5	0.016	0.083	162	<0.50
16	245	74.68	UNK	N	Bedrock	9.5	274	7.31	nr	nr	10	0.002	0.088	134	<0.50
19	390	118.87	20.12	N	Bedrock	13.2	392	7.62	nr	nr	11	<0.0020	0.039	143	<0.50
24	265	80.77	4.57	N	Bedrock	10.2	252	7.66	-51	164	6	<0.0020	0.040	208	<0.50
27	205	62.48	1.83	N	Bedrock	10	681	7.35	-28	187	15	<0.0020	0.032	241	<0.50
30	445	135.64	UNK	N	Bedrock	9.7	251	**6.94**	nr	nr	4	<0.0020	0.120	114	<0.50
31	230	70.10	UNK	N	Bedrock	7.7	208	8.19	-81	134	7	<0.0020	0.087	93	<0.50
37	330	100.58	3.05	N	Bedrock	nr	nr	nr	nr	nr	nr	2.260	0.047	79	<0.50
42	520	158.50	UNK	N	Bedrock	10	355	8.70	nr	nr	3	<0.0020	0.460	172	9.25
47	290	88.39	15.24	N	Bedrock	8.6	198	7.08	114	329	3	0.195	0.068	105	<0.50
67	200	60.96	UNK	N	Bedrock	8.5	580	7.66	57	272	9	0.108	0.170	274	0.93
72	250	76.20	UNK	N	Bedrock	9.7	379	7.69	227	442	3	0.038	0.110	189	<0.50
83	150	45.72	2.44	N	Bedrock	10.7	173	**6.25**	226	441	4	0.604	0.063	72	<0.50
Arithmetic mean	308	93.95	12.43			9.75	331	7.69	66	281	7	0.361	0.149	151	4.18
Median	265	80.77	4.57			9.90	304	7.66	83	298	7	0.038	0.087	151	3.26
Geometric mean	286	87.12	6.91			9.68	306	7.65	NC	250	6	0.051	0.096	142	3.07
Min	150	45.72	1.83			7.70	173	6.25	-113	102	3	0.002	0.032	72	0.93
Max	530	161.54	41.15			13.2	681	8.70	227	442	15	2.26	0.760	274	9.25
N=	17	17	17	0		17	17	17	17	17	17	17	17	17	17
ALL AQUIFER TYPES															
Mean	177	53.95	25.54			9.29	252	7.47	85	300	6	1.11	0.104	115	2.73
Median	147	44.81	21.34			9.70	238	7.53	128	343	6	0.617	0.081	109	1.57
Geometric mean	138	42.11	17.44			9.20	234	7.43	NC	264	6	0.214	0.081	105	1.95
Min	10	3.05	1.22			5.50	80	5.56	-130	85	3	0.002	0.031	34	0.88
Max	530	161.5	86.9			13.2	681	8.73	233	448	15	5.25	0.760	274	9.25
N=	82	82	82	12		82	82	82	82	82	82	82	82	82	82

APPENDIX A - TABLE A1

GCDWQ-MAC	-	-		-	-	-	-	-	-	1.0	-	-	-	-	-
GCDWQ-AO	-	-		500	250	-	-	-	-	-	-	-	-	-	500
RDL	0.50	0.50	0.50	0.50	0.50	0.020	0.020	0.020	0.005	0.002	0.0020	0.020	1.0		10
Units	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	uS/cm	pH	mg/L
RDL	1	0.50	0.50	0.50	0.5	0.020	0.0020	0.020	0.0050	0.0020	0.0020	0.020	1.0		10
Site	Bicarbonate (HCO3)	Carbonate (CO3)	Hydroxide (OH)	Dissolved Sulphate (SO4)	Dissolved Chloride (Cl)	Dissolved Organic Nitrogen (N)	Dissolved Phosphorus (P)	Dissolved Total Kjeldahl Nitrogen (Calc)	Ammonia (N)	Nitrate plus Nitrite (N)	Nitrite (N)	Dissolved Nitrogen (N)	Conductivity (lab)	pH (lab)	Total Dissolved Solids
1	185	4.62	<0.50	5.41	5.0	0.031	0.0051	0.131	0.101	<0.0020	<0.0020	0.131	320	8.60	180
4	207	3.20	<0.50	5.47	10.0	0.047	0.0105	0.146	0.0994	0.0031	<0.0020	0.149	365	8.43	210
6	121	<0.50	<0.50	1.31	3.6	<0.020	0.0979	<0.020	<0.0050	<0.0020	<0.0020	<0.020	202	8.12	152
10	184	<0.50	<0.50	16.30	14.0	0.033	0.0507	0.033	<0.0050	0.0210	<0.0020	0.054	361	7.73	198
13	197	<0.50	<0.50	5.43	19.0	0.040	0.0182	0.045	0.0055	0.0157	<0.0020	0.061	368	8.29	200
16	164	<0.50	<0.50	<0.50	4.7	0.081	0.367	0.325	0.244	0.0022	<0.0020	0.327	267	8.17	156
19	175	<0.50	<0.50	31.50	15.0	0.038	0.0633	0.043	0.0054	<0.0020	<0.0020	0.043	383	8.24	228
24	253	<0.50	<0.50	22.90	29.0	0.025	0.0209	0.035	0.0101	<0.0020	<0.0020	0.035	532	8.13	286
27	294	<0.50	<0.50	35.30	56.0	0.046	0.0119	0.046	<0.0050	<0.0020	<0.0020	0.046	701	8.03	296
30	140	<0.50	<0.50	4.96	5.7	0.062	0.546	0.114	0.0524	<0.0020	<0.0020	0.114	244	8.02	154
31	114	<0.50	<0.50	5.68	6.7	<0.020	0.147	0.141	0.138	<0.0020	<0.0020	0.141	211	8.08	110
37	97	<0.50	<0.50	4.60	7.8	<0.040	0.0752	<0.040	<0.0050	2.26	<0.0020	2.19	201	7.44	116
42	187	11.10	<0.50	2.17	6.5	0.031	0.0046	0.115	0.0838	0.0063	0.0055	0.121	343	8.93	212
47	128	<0.50	<0.50	15.90	6.8	<0.020	0.0051	<0.020	<0.0050	0.195	<0.0020	0.196	252	7.59	150
67	332	1.12	<0.50	14.10	27.0	0.053	0.0356	0.228	0.176	0.112	0.0041	0.340	606	8.31	334
72	230	<0.50	<0.50	12.80	10.0	<0.020	0.0464	<0.020	0.0122	0.0383	<0.0020	0.032	391	8.29	234
83	88	<0.50	<0.50	7.40	7.2	0.037	0.0059	0.045	0.007	0.604	<0.0020	0.648	181	7.38	109
Arithmetic mean	182	5.01	NC	12.0	13.8	0.04	0.09	0.11	0.08	0.33	0.00	0.29	349	8.10	196
Median	184	3.91	NC	6.54	7.80	0.04	0.04	0.11	0.07	0.03	0.00	0.13	343	8.13	198
Geometric mean	171	3.68	NC	8.31	10.2	0.04	0.03	0.09	0.04	0.04	0.00	0.13	323	8.10	186
Min	88	1.12	NC	1.31	3.60	0.03	0.00	0.03	0.01	0.00	0.00	0.03	181	7.38	109
Max	332	11.10	NC	35.3	56.0	0.08	0.55	0.33	0.24	2.26	0.01	2.19	701	8.93	334
N=	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17
ALL AQUIFER TYPES															
Mean	139	3.28	NC	9.34	9.96	0.06	0.17	0.27	0.18	1.07	0.00	0.94	268	8.00	155
Median	133	1.89	NC	7.87	8.20	0.04	0.06	0.20	0.05	0.60	0.00	0.44	252	8.07	152
Geometric mean	128	2.35	NC	6.97	7.86	0.05	0.06	0.16	0.05	0.19	0.00	0.46	251	7.99	147
Min	42	1.06	NC	0.53	1.80	0.02	0.00	0.02	0.01	0.00	0.00	0.03	85	7.06	64
Max	332	11.1	NC	35.30	56.0	0.20	1.45	1.37	1.25	5.25	0.01	5.11	701	8.93	334
N=	82	82	82	82	82	82	82	82	82	82	82	82	82	82	82

GCDWQ-MAC	-	-	500	-	6	10	1000	-	-	5000	5	50	-	-	-	10
GCDWQ-AO	-	-	-	100	-	-	-	-	-	-	-	-	-	1000	300	-
RDL	0.10	0.10	0.50	0.50	0.020	0.020	0.020	0.010	0.005	50	0.005	0.10	0.0050	0.050	1.0	0.0050
Units	NTU	mg/L	mg/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L
RDL	0.10	0.1	0.50	0.50	0.020	0.020	0.020	0.010	0.0050	50	0.0050	0.10	0.0050	0.050	1.0	0.0050
Site	Turbidity	Bromide (Br)	Dissolved Hardness (CaCO3)	Dissolved Aluminum (Al)	Dissolved Antimony (Sb)	Dissolved Arsenic (As)	Dissolved Barium (Ba)	Dissolved Beryllium (Be)	Dissolved Bismuth (Bi)	Dissolved Boron (B)	Dissolved Cadmium (Cd)	Dissolved Chromium (Cr)	Dissolved Cobalt (Co)	Dissolved Copper (Cu)	Dissolved Iron (Fe)	Dissolved Lead (Pb)
1	1.10	0.018	6.71	4.23	<0.020	0.230	22.7	<0.010	<0.0050	139	<0.0050	<0.10	<0.0050	<0.050	1.2	0.0050
4	2.61	<0.10	7.05	4.30	<0.020	0.038	19.5	<0.010	<0.0050	309	<0.0050	<0.10	0.0050	<0.050	27.0	0.0050
6	0.29	0.019	34.9	1.14	<0.020	<0.020	7.95	<0.010	<0.0050	658	<0.0050	<0.10	0.0050	0.165	16.6	0.0090
10	0.19	0.035	139	0.76	<0.020	0.346	16.0	<0.010	<0.0050	<50	<0.0050	<0.10	0.0160	0.976	13.7	0.119
13	0.19	0.050	67.8	1.95	0.099	1.26	2.27	<0.010	<0.0050	325	<0.0050	<0.10	0.0150	1.87	2.2	0.235
16	0.71	0.012	119	1.00	<0.020	9.91	7.48	<0.010	<0.0050	1080	<0.0050	<0.10	0.0210	0.537	241	0.306
19	0.42	0.031	103	1.11	0.029	1.83	11.7	<0.010	<0.0050	<50	<0.0050	<0.10	0.0120	5.15	13.9	0.0310
24	2.12	0.039	223	0.89	<0.020	1.14	68.5	<0.010	<0.0050	<50	<0.0050	<0.10	0.0170	<0.050	**302**	0.0370
27	1.74	<0.10	301	0.72	<0.020	0.629	15.9	<0.010	<0.0050	<50	<0.0050	<0.10	0.0610	<0.05	124	0.0660
30	1.73	0.016	109	1.05	<0.020	1.78	64.4	<0.010	<0.0050	572	<0.0050	<0.10	0.0090	0.495	**315**	0.0700
31	2.21	0.018	88.2	1.05	<0.020	0.314	9.17	<0.010	<0.0050	228	<0.0050	<0.10	0.0050	0.145	128	0.0100
37	0.12	0.025	84.8	0.69	<0.020	0.405	2.27	<0.010	<0.0050	<50	<0.0050	0.23	0.0090	1.75	2.1	0.0440
42	10.4	0.020	2.93	6.35	<0.020	0.078	17.6	<0.010	<0.0050	210	<0.0050	<0.10	<0.0050	0.151	1.5	0.0110
47	0.21	0.023	113	0.61	0.025	0.102	3.53	<0.010	<0.0050	<50	0.0770	<0.10	0.0180	1.15	4.8	0.0580
67	6.91	0.098	120	1.31	<0.020	0.139	519	<0.010	<0.0050	122	0.0090	<0.10	0.0240	0.329	202	0.0200
72	0.49	0.025	177	0.63	<0.020	1.62	22.0	<0.010	<0.0050	<50	0.0220	<0.10	<0.0050	1.38	2.8	0.0720
83	2.69	0.030	73.5	2.66	<0.020	0.081	3.26	<0.010	<0.0050	<50	0.0080	<0.10	0.0180	3.57	3.5	0.105
Arithmetic mean	2.01	0.03	104.11	1.79	0.05	1.24	47.84	NC	NC	405	0.029	0.230	0.017	1.36	82.43	0.07
Median	1.10	0.03	103.00	1.05	0.03	0.38	15.90	NC	NC	309	0.016	0.230	0.016	0.98	13.90	0.04
Geometric mean	0.93	0.03	64.23	1.34	0.04	0.43	14.18	NC	NC	318	0.019	0.230	0.013	0.76	18.12	0.04
Min	0.12	0.01	2.93	0.61	0.03	0.04	2.27	NC	NC	122	0.008	0.230	0.005	0.15	1.20	0.01
Max	10.40	0.10	301.00	6.35	0.10	9.91	519.00	NC	NC	1080	0.077	0.230	0.061	5.15	315	0.31
N=	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17
ALL AQUIFER TYPES																
Mean	1.94	0.03	100	2.38	0.037	1.78	20.90	NC	NC	256	0.01	1.13	0.01	1.59	208.88	0.10
Median	0.68	0.02	103	1.08	0.031	0.54	7.71	NC	NC	139	0.01	0.51	0.01	0.60	31.05	0.05
Geometric mean	0.78	0.02	86	1.36	0.034	0.64	8.96	NC	NC	165	0.01	0.63	0.01	0.63	33.07	0.05
Min	0.12	0.01	2.93	0.54	0.020	0.038	1.54	NC	NC	59.0	0.01	0.11	0.01	0.05	1.20	0.01
Max	18.2	0.10	301	26.2	0.099	17.3	519	NC	NC	1080	0.08	5.23	0.06	8.61	2150	1.26
N=	82	82	82	82	82	82	82	82	82	82	82	82	82	82	82	82

GCDWQ-MAC	-	120	-	-	10	-	-	-	-	-	-	20	-	-	-
GCDWQ-AO	-	20	-	-	-	-	-	-	-	-	-	-	-	5000	-
RDL	0.50	0.050	0.05	0.020	0.040	100	0.0050	0.050	0.0020	0.20	0.50	0.0020	0.20	0.10	0.10
Units	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L
RDL	0.50	0.050	0.050	0.020	0.040	100	0.0050	0.050	0.0020	0.20	0.50	0.0020	0.20	0.10	0.10
Site	Dissolved Lithium (Li)	Dissolved Manganese (Mn)	Dissolved Molybdenum (Mo)	Dissolved Nickel (Ni)	Dissolved Selenium (Se)	Dissolved Silicon (Si)	Dissolved Silver (Ag)	Dissolved Strontium (Sr)	Dissolved Thallium (Tl)	Dissolved Tin (Sn)	Dissolved Titanium (Ti)	Dissolved Uranium (U)	Dissolved Vanadium (V)	Dissolved Zinc (Zn)	Dissolved Zirconium (Zr)
1	46.3	2.17	0.429	0.065	<0.040	5390	<0.0050	89.3	<0.0020	<0.20	<0.50	0.0380	<0.20	0.28	<0.10
4	84.9	7.43	0.500	0.099	<0.040	4390	<0.0050	75.8	<0.0020	<0.20	<0.50	<0.0020	<0.20	1.43	<0.10
6	3.26	13.1	0.719	0.340	<0.040	8150	<0.0050	273	<0.0020	<0.20	<0.50	0.286	<0.20	2.72	<0.10
10	1.18	**78.6**	0.636	0.233	0.043	8690	<0.0050	287	<0.0020	<0.20	<0.50	1.35	0.54	5.11	<0.10
13	4.90	1.53	2.65	0.167	<0.040	8840	<0.0050	106	<0.0020	<0.20	<0.50	14.2	0.94	5.56	<0.10
16	1.17	**315**	2.26	0.075	<0.040	17000	<0.0050	337	<0.0020	0.53	<0.50	0.113	<0.20	176	<0.10
19	2.84	18.8	4.10	0.095	<0.040	7670	<0.0050	480	<0.0020	<0.20	<0.50	3.79	1.46	36.2	<0.10
24	2.11	**123**	4.26	0.119	<0.040	7750	<0.0050	685	<0.0020	<0.20	<0.50	1.10	<0.20	11.4	<0.10
27	1.65	**80.3**	0.815	0.324	<0.040	7910	<0.0050	763	<0.0020	<0.20	<0.50	2.13	0.57	6.38	<0.10
30	0.77	**263**	3.25	0.158	<0.040	17300	<0.0050	364	0.0030	<0.20	<0.50	0.0200	0.30	680	<0.10
31	<0.50	**259**	0.463	0.046	<0.040	9950	0.0110	85.8	0.0180	<0.20	<0.50	0.0040	<0.20	4.75	<0.10
37	<0.50	0.108	0.093	0.137	0.086	10600	<0.0050	67.6	0.0070	<0.20	<0.50	0.0160	1.61	6.62	<0.10
42	71.8	1.53	0.415	0.267	<0.040	4130	<0.0050	53.1	<0.0020	0.34	<0.50	0.0030	<0.20	2.37	<0.10
47	<0.50	1.64	0.882	0.175	0.316	11000	<0.0050	110	0.0050	<0.20	<0.50	0.931	1.51	17.0	<0.10
67	23.0	**101**	1.47	0.172	<0.040	8080	<0.0050	1370	<0.0020	<0.20	<0.50	0.0430	<0.20	116	<0.10
72	1.20	**30.3**	2.29	0.061	<0.040	10000	<0.0050	690	<0.0020	<0.20	<0.50	0.513	<0.20	195	<0.10
83	<0.50	0.471	0.176	0.137	0.052	9460	<0.0050	50.5	<0.0020	<0.20	<0.50	0.210	0.26	2.73	<0.10
Arithmetic mean	18.9	76.29	1.49	0.16	0.12	9195	NC	346	0.008	0.44	NC	1.55	0.90	74.7	NC
Median	2.84	18.80	0.82	0.14	0.07	8690	NC	273	0.006	0.44	NC	0.248	0.76	6.38	NC
Geometric mean	5.03	14.22	0.92	0.13	0.09	8587	NC	209	0.007	0.42	NC	0.192	0.73	11.3	NC
Min	0.77	0.11	0.09	0.05	0.04	4130	NC	51	0.003	0.34	NC	0.003	0.26	0.28	NC
Max	84.9	315	4.26	0.34	0.32	17300	NC	1370	0.018	0.53	NC	14.2	1.61	680	NC
N=	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17
ALL AQUIFER TYPES															
Mean	7.44	81.92	0.77	0.33	0.22	10109	NC	167	0.008	0.35	1.41	0.52	2.24	27.6	NC
Median	1.06	16.85	0.39	0.12	0.16	9890	NC	89	0.005	0.32	1.41	0.07	1.51	3.21	NC
Geometric mean	1.69	9.68	0.40	0.12	0.15	9826	NC	116	0.006	0.34	1.14	0.07	1.40	4.43	NC
Min	0.50	0.06	0.07	0.03	0.04	4130	NC	37.9	0.003	0.23	0.58	0.00	0.25	0.11	NC
Max	84.9	460	9.22	10.4	1.38	17300	NC	1370	0.018	0.53	2.23	14.2	8.16	680	NC
N=	82	82	82	82	82	82	82	82	82	82	82	82	82	82	82

GCDWQ-MAC	-	-	-	-	-										
GCDWQ-AO	-	-	-	200	-										
RDL	0.050	0.050	0.050	0.050	3.0										
Units	mg/L	mg/L	mg/L	mg/L	mg/L	meq	meq	%	‰	‰	‰	‰	‰	‰	$\log_{10}$ years
RDL	0.050	0.050	0.050	0.050	3.0	-	-	-	Result 1	Result 2	Median	Result 1	Result 2	Median	
Site	Dissolved Calcium (Ca)	Dissolved Magnesium (Mg)	Dissolved Potassium (K)	Dissolved Sodium (Na)	Dissolved Sulphur (S)	Sum cations	Sum anions	Charge balance error	$\delta^{15}N$	$\delta^{15}N$	$\delta^{15}N$	$\delta^{18}O$	$\delta^{18}O$	$\delta^{18}O$	Aquifer Vulnerability Index, hydraulic resistance, c
1	2.52	0.100	0.154	78.3	<3.0	3.5	-3.3	3.8							5.1
4	2.55	0.168	0.151	85.8	<3.0	3.9	-3.8	1.2							5.4
6	11.4	1.55	0.165	31.9	<3.0	2.1	-2.1	-0.6							5.8
10	41.9	8.22	0.537	22.1	5.2	3.7	-3.8	-0.1							3.6
13	20.4	4.12	0.356	57.9	<3.0	3.9	-3.9	0.1							3.7
16	36.4	6.89	0.873	10.7	<3.0	2.9	-2.8	0.7							5.3
19	34.0	4.49	0.175	41.1	9.8	3.9	-3.9	-1.1							5.4
24	61.1	17.1	0.504	23.7	7.6	5.5	-5.4	0.5							0.0
27	98.9	13.1	0.186	21.7	11.2	7.0	-7.1	-1.2							3.7
30	32.3	6.84	0.402	9.67	<3.0	2.6	-2.6	0.9							0.3
31	21.7	8.26	0.950	6.85	<3.0	2.1	-2.2	-2.1							6.0
37	19.3	8.88	0.725	6.51	<3.0	2.0	-2.1	-1.7	10.79	11.06	10.93	1.45	1.16	1.31	-1.5
42	1.17	<0.050	0.113	80.0	<3.0	3.5	-3.3	3.7							6.4
47	28.8	9.88	0.458	8.37	5.2	2.6	-2.6	-0.2							0.0
67	30.9	10.4	1.53	90.1	5.8	6.4	-6.5	-1.2							5.9
72	51.6	11.8	0.282	13.4	4.4	4.1	-4.3	-2.2							3.6
83	20.0	5.75	0.343	7.51	<3.0	1.8	-1.8	-1.1							0.3
Arithmetic mean	30.3	7.35	0.46	35.04	7.03				10.79	11.06	10.93	1.45	1.16	1.31	3.5
Median	28.8	7.56	0.36	22.10	5.80				10.79	11.06	10.93	1.45	1.16	1.31	3.7
Geometric mean	19.2	4.42	0.35	23.19	6.65				10.79	11.06	10.93	1.45	1.16	1.31	NC
Min	1.2	0.10	0.11	6.51	4.40				10.79	11.06	10.93	1.45	1.16	1.31	-1.5
Max	98.9	17.1	1.53	90.1	11.2				10.79	11.06	10.93	1.45	1.16	1.31	6.4
N=	17	17	17	17	17				1	1	1	1	1	1	17
ALL AQUIFER TYPES															
Mean	24.9	9.33	1.05	16.86	4.99				8.80	8.86	8.83	-1.35	-1.36	-1.36	4.23
Median	24.0	9.51	0.86	8.70	4.20				8.96	9.09	9.03	-1.49	-2.11	-1.84	4.69
Geometric mean	21.5	7.54	0.82	11.46	4.65				8.40	8.43	8.42	NC	NC	NC	NC
Min	1.17	0.10	0.11	3.49	3.00				4.71	4.31	4.51	-3.66	-3.24	-3.33	-1.47
Max	98.9	27.6	5.24	90.1	11.2				13.5	13.6	13.5	1.45	1.23	1.31	7.54
N=	82	82	82	82	82				13	13	13	13	13	13	82

Table A2: Bacteriological water quality results

Site	Lithology	Total coliform	E. coli
83	Bedrock	880	3
1	Bedrock	<1	<1
4	Bedrock	<1	<1
6	Bedrock	<1	<1
10	Bedrock	<1	<1
13	Bedrock	<1	<1
16	Bedrock	<1	<1
19	Bedrock	<1	<1
24	Bedrock	<1	<1
27	Bedrock	<1	<1
30	Bedrock	<1	<1
31	Bedrock	<1	<1
37	Bedrock	<1	<1
42	Bedrock	<1	<1
47	Bedrock	<1	<1
67	bedrock	<1	<1
72	bedrock	<1	<1
38	Unconsolidated	3	<1
45	Unconsolidated	10	<1
94	Unconsolidated	20	<1
79	Unconsolidated	34	19
60	Unconsolidated	58	<1
14	Unconsolidated	89	1
2	Unconsolidated	<1	<1
3	Unconsolidated	<1	<1
5	Unconsolidated	<1	<1
8	Unconsolidated	<1	<1
9	Unconsolidated	<1	<1
12	Unconsolidated	<1	<1
17	Unconsolidated	<1	<1
18	Unconsolidated	<1	<1
20	Unconsolidated	<1	<1
22	Unconsolidated	<1	<1
23	Unconsolidated	<1	<1
29	Unconsolidated	<1	<1
32	Unconsolidated	<1	<1
34	Unconsolidated	<1	<1
35	Unconsolidated	<1	<1
39	Unconsolidated	<1	<1
40	Unconsolidated	<1	<1
43	Unconsolidated	<1	<1
44	Unconsolidated	<1	<1
46	Unconsolidated	<1	<1
48	Unconsolidated	<1	<1
49	Unconsolidated	<1	<1
50	Unconsolidated	<1	<1
51	Unconsolidated	<1	<1
52	Unconsolidated	<1	<1
53	Unconsolidated	<1	<1
54	Unconsolidated	<1	<1
55	Unconsolidated	<1	<1
56	Unconsolidated	<1	<1
57	Unconsolidated	<1	<1
58	Unconsolidated	<1	<1
59	Unconsolidated	<1	<1
61	Unconsolidated	<1	<1
62	Unconsolidated	<1	<1
63	Unconsolidated	<1	<1
64	Unconsolidated	<1	<1
66	Unconsolidated	<1	<1
68	Unconsolidated	<1	<1
69	Unconsolidated	<1	<1
70	Unconsolidated	<1	<1
71	Unconsolidated	<1	<1
73	Unconsolidated	<1	<1
75	Unconsolidated	<1	<1
76	Unconsolidated	<1	<1
77	Unconsolidated	<1	<1
78	Unconsolidated	<1	<1
80	Unconsolidated	<1	<1
85	Unconsolidated	<1	<1
86	Unconsolidated	<1	<1
88	Unconsolidated	<1	<1
89	Unconsolidated	<1	<1
90	Unconsolidated	<1	<1
91	Unconsolidated	<1	<1
93	Unconsolidated	<1	<1
95	Unconsolidated	<1	<1
96	Unconsolidated	<1	<1
21	Unconsolidated (dug)	3	<1
84	Unconsolidated (dug)	6	<1
92	Unconsolidated (dug)	87	5
12(REP)	Unconsolidated	4	<1
20(REP)	Unconsolidated	<1	<1
24(REP)	Bedrock	<1	<1
40(REP)	Unconsolidated	<1	<1
58(REP)	Unconsolidated	<1	<1
60(REP)	Unconsolidated	60	<1
68(REP)	Unconsolidated	<1	<1
9(REP)	Unconsolidated	<1	<1
94(REP)	Unconsolidated	<1	<1

APPENDIX B: QUALITY ASSURANCE AND QUALITY CONTROL (QA/QC) SUMMARY

B1. Laboratory analytical methods Quality Assurance and Quality Control (QA/QC)

Samples for geochemistry and microbiological analysis were analyzed at Maxxam Analytics Inc. laboratory in Burnaby, B.C. using standard analytical methods (Rice, et al., 2012). Laboratory Quality Assurance and Quality Control (QA/QC) included reporting of temperature at arrival of the samples, completion of matrix spike, spiked blanks and calculation of the Relative Percent Difference (RPD%) for analytical replicate samples. For geochemical parameters the precision of each sample is shown in Appendix A, Table A-1 as the reportable detection limit or RDL.

B2. Study design and field procedures QA/QC

QA/QC measures in the study design and field methods involved: measuring field parameters and sampling after the these had stabilized within an established range; ensuring the samples were maintained at a temperature <4 °C during transport to the laboratory; collecting a minimum of 10% QA/QC samples (e.g. duplicate samples, field blanks, equipment blanks); calculating charge balance error (balance of anions and cations) for all samples; and calculating the RPD% for duplicate samples.

Field parameter stabilization

All sites had a dedicated pump within the well and all wells were in active use (i.e. used within the previous 24 hours). During purging field parameters were measured using a YSI Model Professional Plus 1030 multi-meter inserted into a closed in-line flow cell. The multi-meters were calibrated in the laboratory prior to going into the field following manufacturer’s instructions using standard calibration solutions. Field parameters were allowed to stabilize, and sampling proceeded after a minimum of three successive measurements were within 10% variation, for example temperature (±0.5 °C), pH (±0.2), specific electrical conductivity (±10%), oxidation-reduction-potential (±10 mV)(if measured). The average purge duration was 6 minutes, ranging from 3 to 15 minutes.

Charge balance error

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 (2) and (3) (Freeze & Cherry, 1979; Appelo & Postma, 1993):

$$CBE = \frac{\sum zm_c + \sum zm_a}{\sum zm_c - \sum zm_a} x\,100 \qquad \text{Equation 4}$$

where,

$$z_i m_i = \text{ionic charge} \times \frac{\text{analytical concentration}}{\text{molecular weight}} \qquad \text{Equation 5}$$

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 primary elements in typical 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 considered acceptable (Appelo & Postma, 1993; Maxxam Analytics Ltd., 2012).

The charge balance error (CBE%) was calculated for all samples, based on the balance of cations and anions in the sample, and all samples had a CBE <5%.

Duplicate and blank samples

Field duplicate samples were obtained by taking two samples in succession 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 (i.e. the quality of groundwater discharged at any one time may vary). The discrepancy between the duplicate samples was evaluated by using formula (4) (Nielsen & Nielsen, 2007) to calculate the relative percent difference (RPD) of the analytical concentration of the two samples:

$$RPD = \left[\frac{C_1 - C_2}{(C_1 + C_2) \div 2}\right] \times 100 \qquad \text{Equation 6}$$

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).

A total of 82 well were sampled, with 5 different parameter sets sampled at each site (4 different sample bottles at each location, including one each for bacteria, general chemistry, metals, and nitrate isotopes). A minimum of 10% extra samples were included, with at least one sample per parameter category per sample date and team (i.e. two sample teams deployed per day), based on random assignment of either blank or duplicate sample collection. Duplicate nitrate isotope samples were collected at several sites, but only those where the nitrate concentration of the sample was ≥2 mg/L were forwarded for isotope analysis therefore three duplicate samples were not analysed for this parameter.

Table B-1: Summary of QA/QC samples collected.

QA/QC samples	#
Blank-Bacteria	1
Blank-General Chemistry 120 mL	4
Blank-Metals	2
Duplicate-Bacteria	8
Duplicate-General chemistry 1000 mL	7
Duplicate-General chemistry 120 mL	10
Duplicate-Metals	8
Duplicate-Nitrate isotopes (not analyzed)	3
Number blank samples (field)	7
Number duplicate samples	36

Table B-2: Relative Percent Difference of duplicate samples (number (%) of parameters meeting the criteria).

	RPD≤25%	RPD>25% and <5 x RDL	RPD>25% and >5 x RDL
Number of duplicates*	15	8	5
Percentage of duplicates*	54%	29%	18%

*Based on 28 replicates, excludes replicates for bacteria and nitrate isotopes

For duplicate samples, the relative percent difference (RPD) was calculated for each individual parameter analyzed (i.e. not the sample as a whole). For most analyses, the RPD was <25% which is considered an acceptable level of precision (Ministry of Environment, Lands and Parks, Land Data BC and Geographic Data BC, 1998). In a smaller number of cases the RPD was >25% but the value of the parameter was less than 5 times the Reportable Detection Limit, which is also considered an acceptable level of precision; when the analytical value or concentration of a parameter is very low, and close to the Reportable Detection Limit, the RPD (i.e. standard deviation) increases. The last case is for sample parameters where the RPD was greater than 25% and the analytical value is more than 5 times the RDL. This could occur for a variety of reasons, for example, there could be some variability introduced because the samples were taken in succession (rather than analysing a true replicate sample collected at one time and then split into two different aliquots). A summary of sample parameters that exceeded the third RPD evaluation criteria are shown in Table B-3. It is noted that the RPD exceedances were for elements such as copper, lead and zinc that may be present in plumbing pipes and fixtures. Exceedences of the 25% RPD may have been due to actual variability in concentration of the parameters in the water being discharged from via the pump and pipes and not due to an error in sample methods or laboratory analysis. There is also a possibility that the variability in these parameters was introduced during transport (see below). Results for these sites/parameters were retained for further analysis.

Table B-3: Sites and duplicate sample parameters exceeding the RPD criteria (>25% RPD and >5 x RDL)

Sites RPD>25% and >5 x RDL	Parameters	Result	Duplicate	RPD	RDL	GCDWQ
Site 3	Copper (µg/L)	0.815	1.430	40%	0.05	1000
	Lead (µg/L)	0.101	0.180	41%	0.05	10
Site 52	Aluminum (µg/L)	1.22	2.46	51%	0.5	100
	Lead (µg/L)	0.016	0.034	55%	0.05	
	Zinc (µg/L)	1.05	2.18	53%	0.1	5000
Site 55	Zinc (µg/L)	0.5	1.44	77%	0.1	
Site 71	Copper (µg/L)	1.31	0.463	55%	0.05	
	Nickel (µg/L)	0.128	0.037	62%	0.02	NA
Site 72	Copper (µg/L)	1.38	0.702	39%	0.05	

RPD=Relative Percent Difference

RDL=Reportable Detection Limit

GCDWQ=Guideline for Canadian Drinking Water Quality (for comparison purposes only)

Blank samples collected consisted of:

a) Field blanks: De-ionized water collected in the sample container at the sample site, which is exposed to the same sampling environment, and handled (filtered, preserved) in the same way as the real sample providing an indication of contaminants that might have been introduced to the samples due to field procedures;

b) Trip blanks: De-ionized water that is prepared in the laboratory (i.e. FLNR office), and is transported with the other samples, but remains unopened during the trip, which provides and indication of possible contaminants introduced during transportation of the samples.

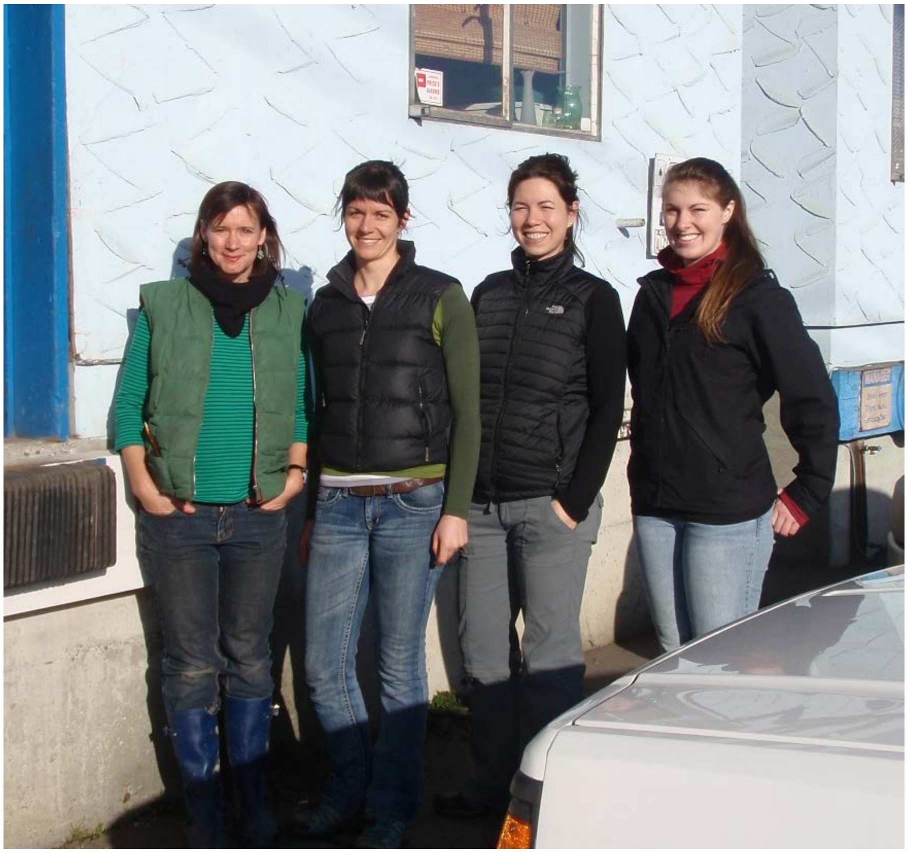
A review of the blank results indicated that for two blank samples (one analyzed for general chemistry and one for bacteria) the analytes were <RDL for all parameters (i.e. no detectable concentrations). Five samples had trace quantities ≤2 times the RDL for a small percentage of analytes (e.g. aluminum, lead, zinc, nitrate and in one sample, chloride). When field blanks were collected for dissolved metals analysis, de-ionized water was filtered through a new field filter prior to collection of the other sample parameters (not through the entire sampling apparatus), and then preserved using the standard preserving agent. A new in-line filter was used at each site.

Upon review of the blank results, two of the bottles of de-ionized water were returned to the laboratory for re-analysis. The de-ionized water in a partially used jug that had been brought into the field for preparation of field blanks contained trace quantities of metals (total aluminum, copper, iron, lead, manganese, nickel and zinc were present, whereas dissolved metals were all <RDL); the partially used jug also had trace nitrate (e.g. 0.0029 mg/L NO3-N compared to RDL 0.0020 mg/L). A sealed, unused jug that had not been transported to the field, but that had been stored in the FLNR warehouse contained trace quantities of nitrate (e.g. 0.0029 mg/L compared to the RDL 0.0020 mg/L) and zinc (0.11 ug/L). The advice provided by the laboratory was that the de-ionized water may have been contaminated prior to being shipped from the laboratory, may have surpassed its recommended two-week holding time enabling contaminants to be introduced by leaching from the surrounding environment through the plastic bottle, or as a result of de-adsorption/leaching of trace elements from the plastic bottle itself. It is also possible that water in the partially used de-ionized water was contaminated by handling in the field.

When blanks show contamination, the decision of how to treat the sample data depends in part on the objectives of the study (Ministry of Environment, Lands and Parks, Land Data BC and Geographic Data BC, 1998). In this case, the study was intended to evaluate ambient concentrations of major ions and general chemistry parameters in to evaluate ambient groundwater quality in the study area in comparison to drinking water standards, and not to evaluate variability of metals such as aluminum, lead or zinc in trace quantities. In all cases the concentrations of potential contaminants present were at or ≤2 times the RDL (i.e. very low concentration), and significantly below the drinking water quality guidelines and therefore unlikely to alter the study findings, and the results of the blank analysis were not used to remove any data from analysis.

The results of the QA/QC program illustrate the value of these protocols to highlight potential sources of error in a sampling study. The use of fresh (<2-week-old) de-ionized water is recommended for future work as is development and review of a QA/QC plan during the study program design.

APPENDIX C – ADDITIONAL FIELD PICTURES



Core sampling team (from left): Sylvia Barroso, Cali Melnechenko, Emily Doyle-Yamaguchi and Melissa Nowicky